Eddy Covariance Method

for Scientific, Industrial, Agricultural, and Regulatory Applications

George Burba

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LI-COR® Biosciences

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A Field Book on Measuring
Ecosystem Gas Exchange and
Areal Emission Rates

LI-COR® Biosciences

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This book has been created to familiarize a reader with general theoretical principles, requirements, applications, as well as planning and processing steps of the eddy covariance method. It is intended to assist readers in furthering of their understanding of the method, and provide references such as micrometeorology textbooks, network guidelines and journal papers. In particular, it is designed to help scientific, industrial, agricultural, and regulatory research projects and monitoring programs in the field deployment of the eddy covariance method in applications beyond micrometeorology.

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Table of Contents

Introduction

- Measurements of gas fluxes in and out of an ecosystem, quantifying evaporative water losses from an agricultural field, or monitoring of gas emission rates over a carbon sequestration injection site can be done with a wide variety of techniques
- Of these techniques, the eddy covariance method is one of the most accurate, direct and defensible approaches available to date for determining emission and consumption rates of various gases and water vapor over areas with sizes ranging from a few hundred to millions of square meters
- The method relies on direct and fast measurements of actual gas transport by a 3-dimensional wind in real time *in situ*, resulting in calculations of turbulent fluxes within the atmospheric boundary layer

The eddy covariance method provides measurements of gas emission and consumption rates, and also allows measurements of momentum, sensible heat, and latent heat (*e.g.*, evapotranspiration, evaporative water loss, *etc.*) fluxes integrated over areas of various sizes.

Fluxes of H_2O, CO_2, CH_4, N_2O and other gases are characterized above soil and water surfaces, plant canopies, and urban or industrial areas, from a single-point measurement using permanent or mobile stations.

This method was widely used in micrometeorology for over 30 years, but now, with firmer methodology and advanced instrumentation, it is available to any discipline, including science, industry, agriculture, environmental monitoring and inventory, and emission regulations.

While the applications are quite diverse in scope and requirements, there are many methodological commonalities in using the eddy covariance technique in all of these applications.

This book focuses primarily on these commonalities, and then explains the specific steps needed to tailor the method for a particular application or research project.

Below are a few examples of books that broadly cover and compare various flux measurement methods, including the eddy covariance technique.

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Monteith, J., and M. Unsworth, 2008. Principles of Environmental Physics. Academic Press, Elsevier, Burlington, San Diego, London, 434 pp.

Hatfield, J., and J. Baker (Eds.), 2005. Micrometeorology in Agricultural Systems. ASA-CSSA-SSSA, Madison, Wisconsin, 588 pp.

Rosenberg, N., B. Blad, and S. Verma, 1983. Microclimate: The Biological Environment. Wiley-Interscience Publishers, 528 pp.

Sala, O., R. Jackson, H. Mooney, and R. Howarth (Eds.), 2000. Methods in Ecosystem Science. Springer-Verlag, New York, USA, 426 pp.

Baldocchi, D., 2013. A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective. FluxLetter, 5(2):1-8

- Modern instruments and software make the eddy covariance method easily available and widely-used in studies beyond micrometeorology, such as ecology, hydrology, environmental and industrial monitoring, agricultural and regulatory applications, *etc.*
- The main remaining challenge of the eddy covariance method for a non-expert is the sheer complexity of system design and implementation, and processing of the large volume of data
- Although modern instrument systems and software take care of most of these complexities, some basic understanding of eddy covariance principles and resulting requirements may still be helpful in successful implementation of the method

The specific applications of the eddy covariance method are numerous, and may require specific mathematical approaches and processing workflows.

Thus, there is no one single recipe for using the method, and it is helpful to further study key aspects of the method in relation to a specific measurement site and a specific measurement purpose.

The basic information presented in this book is intended to provide a foundational understanding of the eddy covariance method, and to help new eddy covariance users design experiments for their specific needs.

A deeper understanding of the method can be obtained via more advanced sources, such as micrometeorology textbooks, flux network guidelines, and journal papers.

Below are a few examples of such sources of information focused specifically on the eddy covariance methodology and field deployment.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

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Yamanoi, K., et al. (Eds.), 2012. Practical Handbook of Tower Flux Observations. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp. (Electronic Edition in English)

- To help those new to eddy covariance gain a basic understanding of the method and to point out valuable references
- To provide explanations in a simplified manner first, and then elaborate with specific details
- To promote a further understanding of the method via more advanced sources (micrometeorology textbooks, scientific papers, *etc.*)
- To help design experiments for the specific needs of a new eddy covariance user for scientific, industrial, agricultural and regulatory applications

In this book, we will try to help those new to eddy covariance understand the general principles, requirements, applications, and processing steps.

Explanations are given in a simplified manner first, and are then elaborated on with specific examples. Alternatives to the traditionally used approaches are also mentioned.

Each page is divided into a top portion, with key points and summaries, and a bottom portion, with explanations, details, and recommended further reading.

In most cases, the top part of the page describes the concept or formulation, or lists what needs to be done, and how. The bottom part of the page explains the reasoning behind the steps that need to be performed.

For those who prefer to read this book in electronic format on an e-reader, illustrations and text are formatted such that they are easily read in daylight and in black-and-white text. Links throughout the text are hyperlinked, and can be clicked to navigate to other pages in the electronic version of the book.

We intend to keep the content of this book current and easy to use, so please do not hesitate to write with any questions, updates and suggestions to 'george.burba@licor.com' with the subject '2013 EC Book'.

The following icons are used throughout the text to indicate critical moments and key literature:

An exclamation point icon indicates warnings, information of high importance, or describes potential pitfalls related to the topic on a specific page.

A book icon indicates scientific references and other useful sources of information related to the topic on a specific page. These are listed, when possible, in order from most relevant or easy to understand, to broader or more complex.

There are eight main parts in this book. The first part, Overview of Eddy Covariance Principles, explains the basics of the eddy covariance theory, key derivations and assumptions, resulting requirements for the method, and main steps in the workflow to address all of the key requirements.

The second part, Designing an Eddy Covariance Experiment, provides a detailed description of each sequential step in the design of the eddy covariance experiment, highlights the most critical moments in this process and the most important concepts to consider before moving to the field.

Part 3, Implementing an Eddy Covariance Experiment, describes key steps during the field installation of the eddy covariance station.

Part 4, Processing Eddy Covariance Data, explains the data processing steps. These steps are usually done in software, but it is helpful to understand what exactly is being done to the data, and why, in order to make sure that the software is configured correctly and the results make sense.

Part 5, Overview of Alternative Flux Methods, briefly outlines the principles, and the pros and cons of other meteorological methods that can be used in cases where eddy covariance is not suitable or may provide unreliable results.

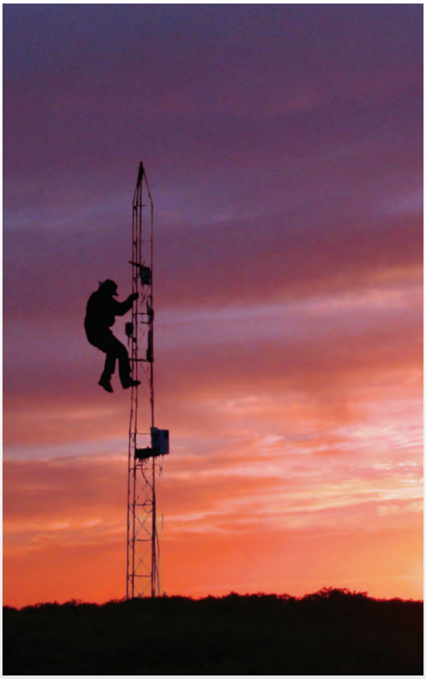
Part 6, Future Developments, describes the very latest upcoming developments of the eddy covariance method, its use, and scope.

Part 7 provides a brief summary of the book, and Part 8 describes further resources on the topic, such as books, lectures, guides, and web-sites.

The Appendix contains a detailed example of a fairly comprehensive eddy covariance field facility at LI-COR Biosciences to give the reader a more practical feel for the method and its implementation.

We would like to acknowledge a number of scientists who have contributed to this book directly via valuable advice and indirectly via scientific collaborations, papers, textbooks, data sets, and personal communications.

Particularly we thank Drs. Dennis Baldocchi, Dave Billesbach, Christian Bruemmer, Robert Clement, Tanvir Demetriades-Shah, Joe von Fischer, Thomas Foken, Gerardo Fratini, Achim Grelle, Sami Haapanala, Andreas Ibrom, James Kathilankal, Joon Kim, Olaf Kolle, Andrew Kowalski, Beverly Law, Ray Leuning, Anders Lindroth, Hank Loescher, William Massman, Dayle McDermitt, Stefan Metzger, Akira Miyata, William Munger, Taro Nakai, Dario Papale, Elizabeth Pattey, Janne Rinne, Borja Ruiz Reverter, Susanna Rutledge, Russ Scott, Peter Schreiber, HaPe Schmid, Andrew Suyker, Shashi Verma, Timo Vesala, Patrik Vestin, Jon Welles, Georg Wohlfahrt, Sebastian Wolf, Donatella Zona, and many others for their expertise in the area of flux studies.



We thank FluxNet and its regional networks, both past and active (*e.g.*, AmeriFlux, AsiaFlux, CCP and FluxNet-Canada, Carbo-Europe, Japan-Flux, IMECC, OzFlux, *etc.*), as well as ICOS, NEON, InGos, iLEAPS and other organizations, and their members, for providing access to the field data, setup guidelines, collection and processing instructions, and formats for their eddy covariance stations.

We particularly thank Dr. James Kathilankal, and Mr. Israel Begashaw for peer-reviewing the book, Dr. Gerardo Fratini for reviewing parts of the book related to EddyPro® and flux processing, and Mr. Bill Miller for reviewing parts related to analyzer specifications. We would also like to thank Dr. Dayle McDermitt for valuable advice for sections on instrument principles and surface heating.

In addition, we would like to acknowledge valuable input from, and interactions between, teachers and students at LI-COR Eddy Covariance Training Courses, and specifically hard work and input from the teachers: Dave Johnson, Jason Hupp, Peter Martin, and Drs. Liukang Xu, Jiahong Li, Richard Garcia, Tanvir Demetriades-Shah, Frank Griessbaum, and Oliver Marx.

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We thank a large number of people who provided valuable feedback and suggestions for the 2007 and 2010 eddy covariance guides, including Jim Amen, Dan Anderson, Doc Chaves, and Drs. Dave Billesbach, Dayle McDermitt, Jon Welles, and Rommel Zulueta.

Acknowledgments are also due to the LI-COR Advanced Research and Development group (Robert Eckles, Mark Johnson, Alex Kachanov, Anatoly Komissarov, Serguei Koulikov, Dayle McDermitt, and Jon Welles) and to the LI-COR Engineering team (Tyler Anderson, Kevin Ediger, Antonio Forgione, Dan Konz, Adam Krueger, Brad Riensche, Derek Trutna, Michael Velgersdyk, and many others) for valuable interactions on methodological aspects of eddy covariance technique, and for indispensible advice on instrument operation and performance.

Also, we would like to thank numerous other researchers, technicians and students who, through years of use in the field, have developed the eddy covariance method to its present level and have proven its effectiveness with studies and scientific publications.

Part One:

Overview of Eddy Covariance Principles

- Flux measurements
- State of the methodology
- Air flow in ecosystems
- How to measure flux
- Derivation of key equations
- Major assumptions
- Major sources of errors
- Use in non-traditional terrains
- Summary of the theory
- Resulting workflow

The first part of this book is dedicated to the basics of the eddy covariance theory.

The following topics are discussed: flux measurements; state of methodology; air flow in ecosystems; surface with and without a flux; how to measure flux; derivation of key equations; major assumptions; major sources of errors; error treatment overview; use in non-traditional terrains; and summary of the resulting workflow when designing the experiment and conducting eddy covariance measurements.

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Swinbank, W., 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. Journal of Meteorology, 8: 135-145

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- Flux measurements are widely used to estimate the exchange of heat, water, and carbon dioxide, as well as methane and other trace gases
- The eddy covariance method is one of the most direct and defensible ways to measure such fluxes
- The method is mathematically complex, and requires a lot of care setting up and processing data – *but it is worth it!*

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

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Munger, B., and H. Loescher, 2008. AmeriFlux Guidelines for Making Eddy Covariance Flux Measurements. AmeriFlux: http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

- Uniform terminology and a single methodology are still being developed for the eddy covariance method
- Much of the effort is being done by networks (*e.g.*, FluxNet, ICOS, NEON, *etc.*) to unify various approaches
- Here we present one of the conventional ways to implement the eddy covariance method

In the past several years, efforts of the flux networks have led to significant progress in unifying the terminology and general standardization of processing steps.

The methodology itself, however, is more difficult to unify. Various experimental sites and different purposes of studies dictate different treatments. For example, if turbulence is the focus of the studies, the gas density corrections may not be necessary.

Meanwhile, if CO_2 and CH_4 emission rates are measured for the purpose of cap-and-trade compliance, then computing momentum fluxes and wind components' spectra may not be crucial.

Here we will describe the conventional ways of implementing the eddy covariance method and give some information on newer, less established venues.

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Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, London, New York, 442 pp.

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

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Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

- Flux – how much of something moves through a unit area per unit time
- Flux is dependent on:
  1. the number of things crossing the area
  2. the size of the area being crossed
  3. the time it takes to cross this area

In very simple terms, flux describes how much of something moves through a unit area per unit time.

For example, if 100 birds fly through a 1 x 1 meter window each minute – the flux of birds is 100 birds per 1 square meter per 1 minute (100 B m^{-2} min^{-1}). If the window was 10 x 10 meters, the flux would be 1 bird per 1 square meter per 1 minute, because 100 birds/100 sq. meters = 1, so now the flux is 1 B m^{-2} min^{-1}.

Flux is dependent on: (1) the number of things crossing an area, (2) the size of an area being crossed, and (3) the time it takes to cross this area.

In more scientific terms, flux can be defined as an amount of an entity that passes through a closed (*i.e.*, a Gaussian) surface per unit of time.

If net flux is away from the surface, the surface may be called a source. For example, a lake surface is a source of H_2O released into the atmosphere in the form of water vapor through the process of evaporation.

If the opposite is true, the surface is called a sink. For example, a green canopy may be a sink of CO_2 during the day, because green leaves take up CO_2 from the atmosphere through the process of photosynthesis.

- Air flow can be imagined as a horizontal flow of numerous rotating eddies
- Each eddy has 3-D components, including a vertical wind component
- The diagram looks chaotic, but components can be measured from a tower

Air flow can be imagined as a horizontal flow of numerous rotating eddies. Each eddy has 3-D components, including vertical movement of the air. The situation looks chaotic at first, but these components can be easily measured from the tower. On the diagram above, the air flow is represented by the large arrow that passes through the tower, and consists of differently sized eddies.

Conceptually, this is the framework for atmospheric eddy transport.

Closer to the ground, there is a stronger probability of smaller eddies being responsible for the transport of most of the flux. Smaller eddies rotate faster, and hence, more transport is done by higher frequency movements of air.

Further away from the ground, there is a stronger probability of larger eddies being responsible for the transport of most of the flux. Larger eddies rotate slower, and hence, more transport is done by lower frequency movements of air.

In practical terms, there is always a mix of different eddy sizes, so some transport is done at higher frequencies and some at lower ones, covering the whole range of frequencies: from large movements on the order of hours, to small ones on the order of 1/10 of a second.

Closer to the ground, the flux transport is shifted to higher frequencies, and further away from the ground it is shifted to lower frequencies.

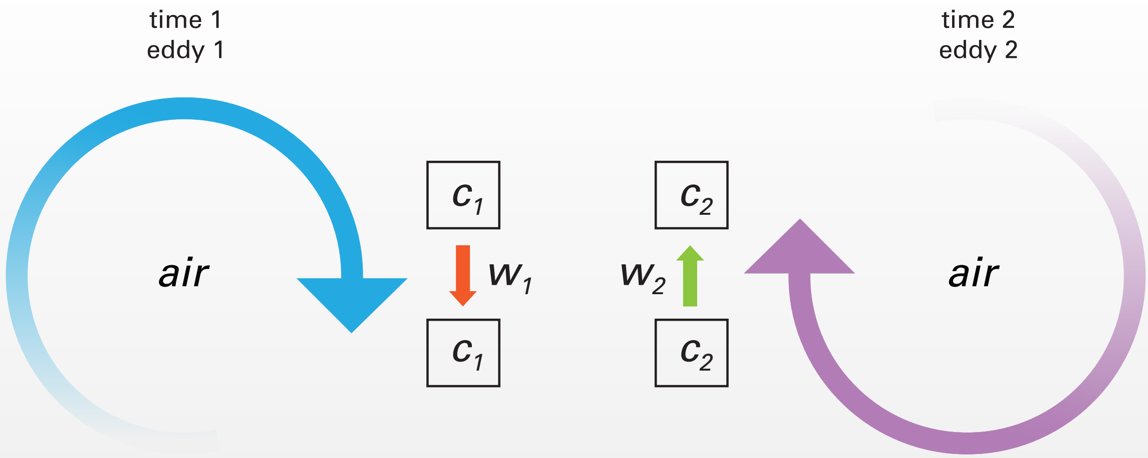
Conceptually, this is the mechanism of atmospheric eddy transport.

References

Kaimal, J., and J. Finnigan, 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, UK, 289 pp.

Swinbank, W., 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. Journal of Meteorology, 8: 135-145

Wyngaard , J., 1990. Scalar fluxes in the planetary boundary layer-theory, modeling and measurement. Boundary-Layer Meteorology, 50: 49-75



At a single point on the tower:

Eddy 1 moves parcel of air c_1 down with the speed w_1,
then eddy 2 moves parcel c_2 up with the speed w_2

Each parcel has concentration, temperature, humidity;
if we know these and the speed – we know the flux

On the previous page, the air flow was shown to consist of numerous rotating eddies. Here, let us look closely at the eddies at a single point on the tower.

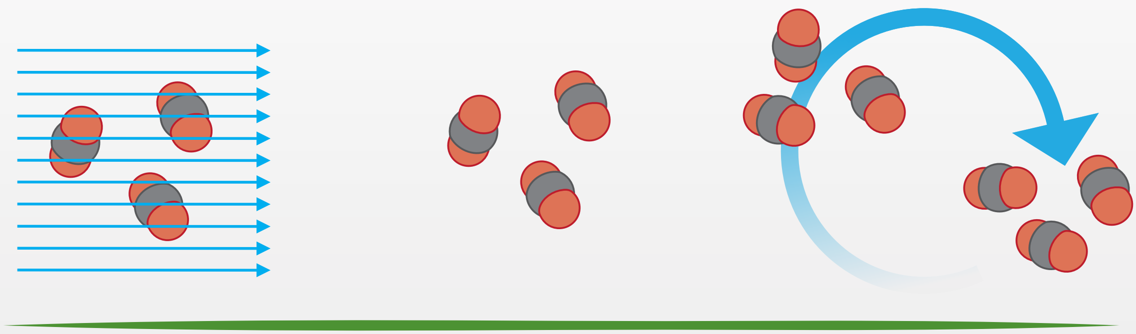
At one moment (time 1), eddy number 1 moves air parcel c_1 downward with the speed w_1. At the next moment (time 2) at the same point, eddy number 2 moves air parcel c_2 upward with speed w_2. Each air parcel has its own characteristics, such as gas concentration, temperature, humidity, *etc.*

If we can measure these characteristics and the speed of the vertical air movement, we will know the vertical upward or downward fluxes of gas and water vapor concentrations, temperature, and humidity.

For example, if at one moment we know that three molecules of CO_2 went up, and in the next moment only two molecules of CO_2 went down, then we know that the net flux over this time was upward, and equal to one molecule of CO_2.

This is the general principle of eddy covariance measurements: covariance between the concentration of interest and vertical wind speed.

- The eddy covariance method works by measuring vertical turbulent transport of gas to and from the surface
- With no flux added into the mean flow by the measured area, the eddies move the same number of gas molecules up and down



Another way to visualize the key physical principle behind the eddy covariance measurements is to first imagine an area that adds *no* molecules of the gas of interest to the mean flow, and then compare it to the same area that adds molecules into the flow.

For example, let us imagine a mean flow that carries 3 molecules of CO_2 over the area of interest from left to right, as shown in the diagram above.

Since the area in the middle did not add anything to the flow, the eddy movements at the downwind measurement point on the right would carry, on average, 3 molecules upwards, and 3 molecules downward, with no net flux. Thus, over a long period, such as a half hour or an hour, the eddy covariance station would measure a flux of zero from the area of interest in the middle.

In this example, we make several assumptions to keep the situation simple for now. These assumptions are addressed later in the mathematical expressions for eddy covariance, and are primarily dealt with by proper site selection, installation and flux processing. They do not fundamentally affect the visualization of the main physical principle of how instruments on the station measure the eddy transport of flux.

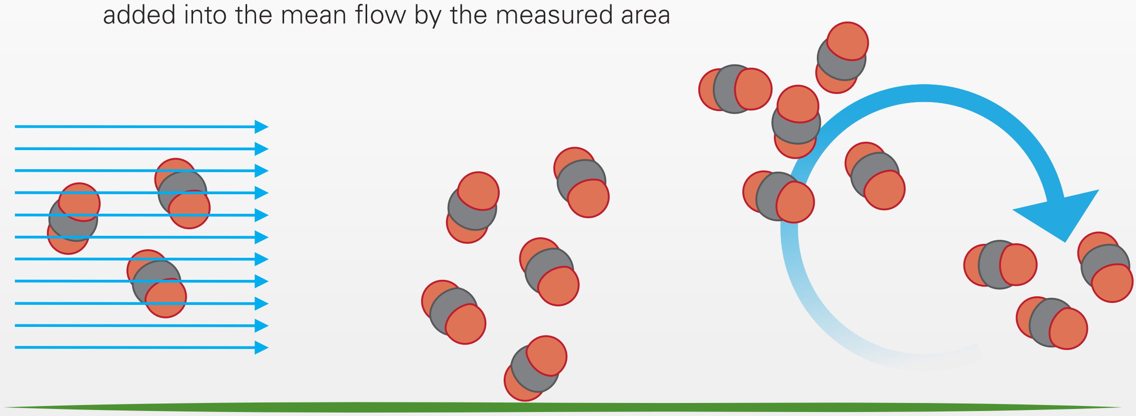
For now, we assume that the surface has the same temperature as the air, such that no temperature flux (*e.g.*, sensible heat flux) is added to the air, and thus, no thermal expansions or contractions affect the density of the air or the CO_2 content.

We also assume that the surface does not add any water molecules to the mean flow, such that no water vapor flux (*e.g.*, latent heat flux) is added to the air, and thus, no water dilution affects the density of the air or the CO_2 content.

Furthermore, we assume that surface does not move with the wind, and does not make air pressure fluctuate in synch with the wind, such that no pressure-related expansions or contractions affect the density of the air or the CO_2 content.

Finally, we assume that no additional air flow or CO_2 injection comes from the sides (*e.g.*, from the direction perpendicular to this page or the picture above) or from above, and there is no convergence of two different flows into one, or divergence of a single flow into multiple flows that occurs over the surface shown.

- With flux added into the mean flow by the measured area, the eddies move more gas up than down, transporting it from the surface into the atmosphere
- If we know the bias between up and down motions, we know how much was added into the mean flow by the measured area



In the previous page, we imagined a mean flow that carried 3 molecules of CO_2 over the area of interest from left to right, and *no* molecules of the CO_2 were added to the mean flow.

Now let us imagine the same situation, but with the surface in the middle adding 2 molecules to the mean flow. Since the area in the middle added 2 molecules to the mean flow, the eddy motions at the downwind measurement point on the right would carry, on average, more molecules upward than downward, with some net CO_2 flux.

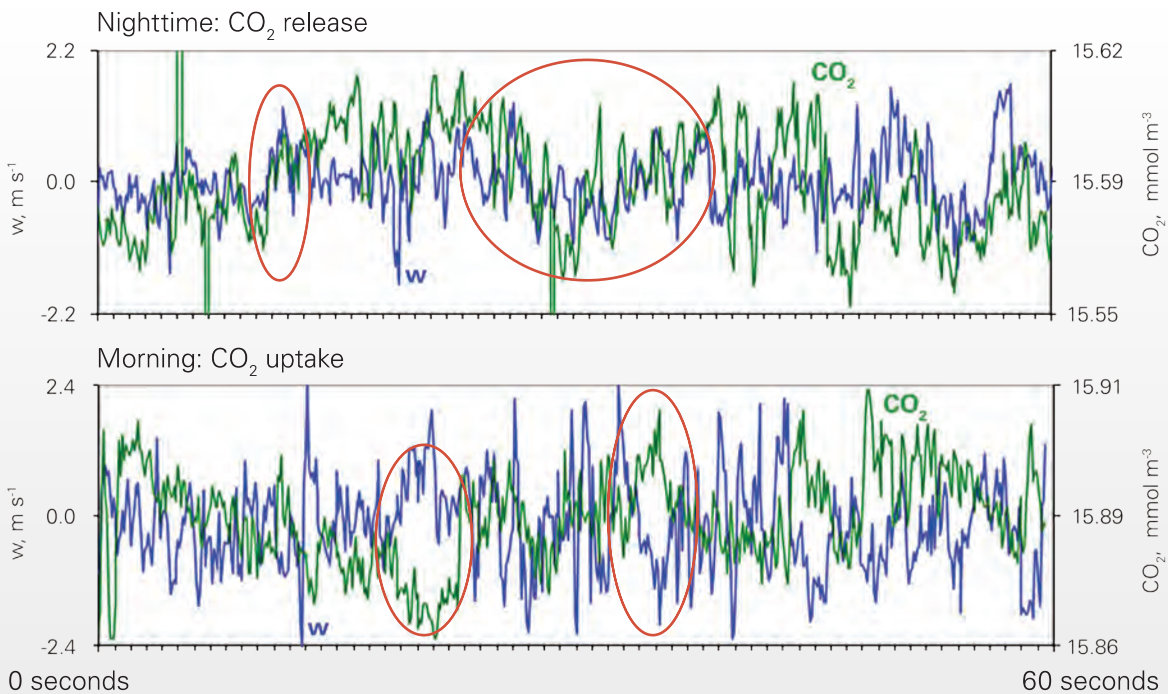
Thus, over a long period, such as 30-60 minutes, the eddy covariance station located on the right would measure some flux from the area of interest in the middle.

Compare the situation when no molecules of CO_2 are added to the mean flow by the area of interest with the situation when such an area adds molecules into the mean flow; this describes the physical essence of eddy covariance measurements. Flux is measured from the area of interest, which adds gas or energy to the mean flow or takes them away.

It is also important to note that in this way we only measure the turbulent transport of the CO_2, and must have well-developed turbulence such that other mechanisms of transport (*e.g.*, molecular diffusion, advection, *etc.*) are negligibly small. This generally is the case during the day, and during nights with wind speeds above 1.0 meter per second or 2.2 miles per hour.

Alternatively, the impact of other mechanisms of transport can be estimated, or measured directly using gas concentration and wind speed profiles and transects.

The ability of the eddy covariance method to provide direct measurements of half-hourly or hourly fluxes integrated over an area of interest, continuously throughout the years, covering most of the days and significant portions of the nights, is an important practical advantage over other present flux measurement methods.



- Actual 10 Hz data from the field – 10 times per second
- Note the difference with CO_2 uptake in the morning

The actual field data look remarkably similar to the thought experiments described on the previous three pages. The picture above shows vertical wind speed (w) and CO_2 measured simultaneously at a fast rate by an eddy covariance station located in the middle of a field covered with green vegetation.

At night, photosynthesis is not occurring, and respiration from the soil and the canopy adds a small CO_2 flux to the atmosphere. This process can be observed in the top plot by looking at what happens to the CO_2 content when wind is moving upwards (positive *w*) and downwards (negative *w*).

On many occasions, the upward movement of the wind carries a higher CO_2 content than the downward movement. The covariance is not very strong due to small nighttime fluxes, but is still visible at higher frequency movements (smaller red oval on the left) and at lower frequency movements (large red oval on the right). In such situations, the covariance of *w* and CO_2 is positive, and the flux of CO_2 is away from the canopy and soil surface.

In the morning, the sun is up and canopy photosynthesis is occurring, overcoming respiration. This process removes CO_2 from the atmosphere, and also can be observed in the bottom plot by watching what happens to the CO_2 content and vertical wind speed.

On many occasions, the upward movement of the wind carries a lower CO_2 content than the downward movement. The covariance is still not very strong due to a small flux rate, but is visible at lower frequency movements (smaller red oval on the left) and at higher frequency movements (large red oval on the right). In such situations, the covariance of *w* and CO_2 is negative, and the flux of CO_2 is directed toward the canopy.

Please notice the scale on the x-axes above, and note how rapidly the turbulent transport happens. This will have significant implications for the experiment and system design described later in the book in Part 2.

The physical principle:

If we know how many molecules went up with eddies at time 1, and how many molecules went down with eddies at time 2 at the same point – we can calculate vertical flux at that point and over that time period

The mathematical principle:

Vertical flux can be represented as a covariance of the vertical velocity and concentration of the entity of interest

The instrument challenge:

Turbulent fluctuations occur very rapidly, so measurements of up-and-down movements and of the number of molecules should be done very rapidly

Overall, the general physical principle for eddy flux measurement is to measure how many molecules are moving upward and downward over time, and how fast they travel.

Mathematically such vertical flux can be represented as a covariance between measurements of vertical velocity, the upward and downward movements, and the concentration of the entity of interest.

Such measurements require very sophisticated instrumentation, because turbulent fluctuations happen very quickly, and respective changes in concentration, density or temperature are quite small, and must be measured both very fast and very well.

The traditional eddy covariance method (also known as eddy correlation method, or EC) calculates only turbulent vertical flux, involves a lot of assumptions, and requires high-end instruments. On the other hand, it provides nearly direct continuous flux measurements if the assumptions are satisfied, or corrected for.

In the next few pages, we will discuss the math behind the method, and its major assumptions.

Strictly speaking, there is a difference between the terms "eddy covariance" and "eddy correlation", and "eddy covariance" is a proper term for the commonly used method of flux measurements described in this book. Please refer to the textbook entitled 'Micrometeorology' by T. Foken (2008) for detailed explanations of the differences between these two terminologies.

In turbulent flow, vertical flux can be presented as:
(s is the dry mole fraction of the gas of interest in the air)

$$F = \overline{\rho_d w s}$$

Reynolds decomposition is then used to break terms into means and deviations:

$$F = \overline{(\overline{\rho}_d + \rho'_d)(\overline{w} + w')(\overline{s} + s')}$$

Opening the parentheses:

$$F = \overline{(\overline{\rho}_d \overline{w}\,\overline{s} + \cancel{\overline{\rho}_d \overline{w} s'} + \cancel{\overline{\rho}_d w' \overline{s}} + \overline{\rho}_d w' s' + \cancel{\rho'_d \overline{w}\,\overline{s}} + \rho'_d \overline{w} s' + \rho'_d w' \overline{s} + \rho'_d w' s')}$$

averaged deviation from the average is zero

Equation is simplified:

$$F = (\overline{\rho}_d \overline{w}\,\overline{s} + \overline{\rho}_d \overline{w's'} + \overline{w}\,\overline{\rho'_d s'} + \overline{s}\,\overline{\rho'_d w'} + \overline{\rho'_d w' s'})$$

In very simple terms, when we have turbulent flow, vertical flux can be represented by the equation at the top of this page: flux is equal to a mean product of air density (ρ_d), vertical wind speed (w), and the dry mole fraction (s) of the gas of interest. The dry mole fraction is often called the mixing ratio.

Reynolds decomposition can be used to break the right-hand side of the top equation into means and deviations from these means. Air density is presented now as a sum of a mean over some time (a half hour, for example) and an instantaneous deviation from this mean, for example for every 0.05 or 0.1 seconds (denoted by a prime). A similar procedure is done with vertical wind speed, and with dry mole fraction of the substance of interest.

In the third equation, the parentheses are opened, and averaged deviations from the average are removed, because averaged deviation from an average is zero. So, the flux equation is simplified into the form at the bottom.

The term 'mixing ratio' is historically defined differently in chemistry and in micrometeorology. In chemistry, it describes the ratio of the constituent to the total mixture without this constituent. For example, moles of CO_2 would be divided by moles of non-dried air without CO_2.

In micrometeorology, it usually describes the ratio of the constituent to the dry air. For example, moles (or grams) of CO_2 in the air would be divided by moles (or grams) of dry air with CO_2.

Perhaps, the better, more universally understood alternative term to use in the context of this book would be 'dry mole fraction', or 'mole fraction in dry air'.

References

For detailed and thorough calculations of this portion of the derivations, please see Lecture #3 (Part 1) in: Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Now an important assumption is made (for conventional eddy covariance) – air density fluctuations are assumed to be negligible:

$$F = (\overline{\rho}_d \overline{w}\overline{s} + \overline{\rho}_d \overline{w's'} + \cancel{\overline{w}\,\overline{\rho'_d s'}} + \cancel{\overline{s}\,\overline{\rho'_d w'}} + \cancel{\overline{\rho'_d w's'}}) = \cancel{\overline{\rho}_d \overline{w}\overline{s}} + \overline{\rho}_d \overline{w's'}$$

Then another important assumption is made – mean vertical flow is assumed to be negligible for horizontal homogeneous terrain (no divergence/convergence):

$$\boxed{F \approx \overline{\rho}_d \overline{w's'}}$$

'Eddy Flux'

On this page, we see two important assumptions that are made in the conventional eddy covariance method.

First, the air density fluctuations are assumed to be negligible. Theoretically, with strong winds over a mountain ridge, for example, density fluctuations in the member $\overline{s}\,\overline{\rho'_d w'}$ may be non-negligible in comparison with the gas flux. However, in most cases when eddy covariance is used conventionally over reasonably flat and vast spaces, such as fields or plains, the air density fluctuations can be safely assumed to be negligible, for the purposes of this derivation.

Secondly, the mean vertical flow is assumed to be negligible for horizontal homogeneous terrain, so that no flow diversions or conversions occur.

With diversion and conversions assumed negligible, we arrive at the classical equation for eddy flux. Flux is equal to the product of the mean air density and the mean covariance between instantaneous deviations in vertical wind speed and mixing ratio.

There is increasing evidence, however, that if the experimental site is located on even a small slope, then the second assumption might not hold on some occasions. Thus, one needs to examine the specific experimental site in terms of flow diversions or conversions, and decide how to best correct for their effects.

References

For a more detailed derivation up to this point, please refer to: Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California (Lecture 3, Part 1): http://nature.berkeley.edu/biometlab/espm228

For the advanced reader, the complex derivation of a fundamental flux equation can be found in: Gu, L., W. Massman, R. Leuning, S. Pallardy, T. Meyers, *et al.*, 2012. The fundamental equation of eddy covariance and its application in flux measurements. Agricultural and Forest Meteorology, 152: 135– 148

Any gas (CO_2, CH_4, N_2O, H_2O, *etc.*):

$$F = \overline{\rho}_d \overline{w's'}$$

Sensible heat flux:

$$H = \overline{\rho} C_p \overline{w'T'}$$

Traditional H_2O flux:

$$E = \frac{M_w / M_a}{\overline{P}} \overline{\rho_d} \overline{w'e'}$$

Latent heat flux (H_2O flux in energy units):

$$LE \equiv \lambda E = \lambda \frac{M_w / M_a}{\overline{P}} \overline{\rho_d} \overline{w'e'}$$

The top equation describes a classical formula for the eddy flux of virtually any gas of interest, such as CO_2, CH_4, N_2O, O_3, *etc*. The flux is computed from the mean dry air density multiplied by the mean covariance between deviations in instantaneous vertical wind speed and dry mole fraction (*e.g.*, mixing ratio).

Sensible heat flux is equal to the mean air density multiplied by the covariance between deviations in instantaneous vertical wind speed and temperature; conversion to energy units is accomplished by including the specific heat term.

There are multiple forms of the flux equation for water vapor, depending on the units of fast water vapor content. One typical example is shown in the third equation above. In addition, the water vapor flux is often computed in energy units (W m^{-2}), and called latent heat flux, as shown in the last equation above. Latent heat flux describes the energy used in the process of evaporation, transpiration, or evapotranspiration.

Hourly or integrated values of latent heat flux can be converted into other frequently used units (*e.g.*, mm d^{-1}, inches ha^{-1}, kg m^{-2} h^{-1}, *etc.*). When converted to volume or mass units, the latent heat flux is often called evapotranspiration rate (ET), evaporation rate (over wet non-vegetated surfaces), or evaporative water loss.

Please note that older instruments usually do not output fast dry mole fraction (fast mixing ratio), but rather measure fast density. So, the density corrections are required in post-processing as described in Section 4.4. These corrections are not required for instruments outputting true mixing ratio at high speed, for example, the enclosed LI-7200 CO_2/H_2O gas analyzer.

References

More details on practical formula are given in: Rosenberg, N., B. Blad, and S. Verma, 1983. Microclimate. The biological environment. A Wiley-Interscience, New York: 255-257

More details on mixing ratio and other relevant units are given by Foken *et al.* in Table 1.2, and resulting forms of the flux equation are given by Rebmann *et al.* in Table 3.1 in: Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

- Measurements at a point can represent an upwind area
- Measurements are done inside the boundary layer of interest
- Fetch/footprint is adequate – fluxes are measured from the area of interest
- Flux is fully turbulent – most of the net vertical transfer is done by eddies
- Terrain is horizontal and uniform: average of fluctuations of *w′* is zero, air density fluctuations, flow convergence and divergence are negligible
- Instruments can detect very small changes at high frequency
- Air flow is not distorted by the installation structure or the instruments

In addition to the assumptions listed on the previous three pages, there are other important assumptions in the eddy covariance method:

- Measurements at a point are assumed to represent an upwind area
- Measurements are assumed to be done inside the boundary layer of interest, and inside the constant flux layer (details in Sections 2.6 and 3.2)
- Fetch and footprint are assumed adequate, so flux is measured from the area of interest (details in Section 2.7)
- Flux is fully turbulent
- Terrain is horizontal and uniform
- Air density fluctuations are negligible
- Flow divergences and convergences are negligible
- The instruments can detect very small changes at very high frequency
- Mean air flow and turbulence at the measurement point are not appreciably distorted by the installation structure or the instruments themselves

The degree to which some of these assumptions hold true depends on proper site selection and experimental setup. For others, it will largely depend on atmospheric conditions and weather. We will go into the details of these assumptions later.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Measurements are not perfect: due to assumptions, physical phenomena, instrument problems, and specifics of terrain and setup

Fluxes could be over- or underestimated if errors are not prevented during the design and setup, or not corrected during data processing

Frequency response errors can be due to:

- System time response
- Tube attenuation
- Path and volume averaging
- Sensor separation
- Sensor response mismatch
- Low-pass filtering
- High-pass filtering
- Digital sampling
- *etc.*

Measurements are of course never perfect, due to assumptions, physical phenomena, instrument problems, and specifics of the particular terrain or setup. As a result, there are a number of potential flux errors, but they can be prevented, minimized, or corrected out.

First, there is a family of errors called frequency response errors. They include errors due to instrument time response, tube attenuation, path and volume averaging, sensor separation, sensor response mismatch, low and high pass filtering, and digital sampling.

Time response errors occur because instruments may not be fast enough to catch all the rapid changes that result from the eddy transport. Tube attenuation error is observed in closed-path analyzers, and is caused by attenuation of the instantaneous fluctuation of the concentration in the sampling tube. Path averaging error is caused by the fact that the sensor path is not a point measurement, but rather is an integration over some distance; therefore, it can average out some of the changes caused by eddy transport.

Sensor separation errors occur due to the physical separation between the places where wind speed and concentration are measured, so covariance is computed for parameters that were not measured at the same point. There can also be frequency response errors caused by sensor response mismatch, and by filtering and digital sampling.

Other key error sources:

- Spikes and noise
- Unleveled anemometer
- Wind angle of attack
- Sensor time delay
- Sonic heat flux errors
- Density fluctuations (WPL)
- Spectroscopic effects for LASERs
- Band-broadening for NDIR
- Oxygen in the 'krypton' path
- Gas flux storage
- Data filling
- *etc.*

In addition to frequency response errors, other key sources of errors include spikes and noise in the measurements, unleveled anemometer, wind angle of attack, sensor time delay (especially important in closed-path analyzers with long intake tubes), sonic heat flux errors, the Webb-Pearman-Leuning density terms (WPL), spectroscopic effects (for LASER-based measurements), band-broadening effects (for NDIR measurements), oxygen sensitivity, gas flux storage, and data filling errors. Later in Part 4, we will go through each of these terms and errors in greater detail.

References

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Massman, W., and X. Lee, 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agricultural and Forest Meteorology, 113(4): 121-144

Billesbach, D., 2011. Estimating uncertainties in individual eddy covariance flux measurements: a comparison of methods and a proposed new method. Agricultural and Forest Meteorology, 151: 394–405

Moncrieff, J., Y. Malhi, and R. Leuning, 1996. The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water, Global Change Biology, 2: 231-240

- These errors are not trivial - they may sum up to over 100% of the flux
- To minimize or avoid such errors a number of procedures can be performed

Errors due to	Affected fluxes	Approximate range
Spikes and noise	all	0-15%
Unleveled anemometer	all	0-25%
Wind angle of attack	all	0-25%
Time delay	mostly closed path	0-50%
Frequency response	all	0-50%
Sonic heat flux error	sensible heat flux	0-10%
Density fluctuations	any gas	0-50%
Spectroscopic effects for LASERs	any gas	0-25%
Band-broadening for NDIR	mostly CO_2	0-5%
Oxygen in the path	some H_2O	0-10%
Gas flux storage under tower	any gas	0-5%
Missing data filling	all	0-20%

None of these errors are trivial. Combined, they may sum up to over 100% of the initial measured flux value. To minimize such errors, a number of procedures exist within the eddy covariance technique. Here we show the relative size of errors on a typical summer day over a green vegetative canopy, and then provide a brief overview of the remedies for such errors.

Step-by-step instructions on how to minimize or eliminate these and other errors with proper experimental planning, design, and implementation are provided in Parts 2 and 3 of this book. Detailed descriptions of how to apply the corrections in data processing software are provided in Part 4. Below are a few highlights.

Spikes and noise may affect all fluxes, but usually not by more than fifteen percent of the flux. Proper instrument selection, maintenance, along with a spike removal routine and filtering in data processing software, help to minimize the effect of such errors.

An unleveled sonic anemometer will affect all fluxes as well, because of contamination of the vertical wind speed with a horizontal component. The error can be twenty-five percent or more, but it is easily reduced by having a steady tower, and by leveling the anemometer during the station setup. The remaining error can be fixed relatively easily by using a processing procedure called coordinate rotation.

Errors due to unadjusted time delay can affect all fluxes, but are most severe in closed-path systems with long intake tubes, especially for water vapor and other "sticky" gases (*e.g.*, ammonia). These errors can be up to 25% for non-sticky gases, and may exceed 50% for H_2O and NH_3. Time delay errors can be minimized by using shorter tubes when possible, by using instruments with matching clocks, and by minimizing the separation distance between the intake of the gas analyzer and the sonic anemometer.

The time delay errors can be virtually eliminated by adjusting the delay during data processing. This is implemented by shifting the two time series in such a way that the covariance between them is maximized. Alternatively, the delay between two time series can be computed from the known flow rate and tube diameter.

Frequency response errors also affect all fluxes. Usually they range between 5% (for example, in fast open-path devices) and 50% of the flux (in long-tube closed-path or any slower devices), and can be partially remedied by choosing fast instrumentation, and by proper experimental setup. They can be further corrected by applying frequency response corrections in the data processing software.

- Many of the potential errors can be minimized or eliminated by proper station and experimental design, data collection settings, and site maintenance; the remainder can be corrected by proper software setup during data processing

Errors	Planning and design remedy	Data processing remedy
Spikes and noise	Instrument selection and setup	Spike removal
Unleveled anemometer	Tower and instrument installation	Coordinate rotation
Wind angle of attack	Instrument selection, setup	Angle-of-attack correction
Time delay	Instrument selection, setup, clocks	Time delay adjustment
Frequency response	Instrument selection, system setup, and data collection settings	Frequency response corrections
Sonic heat flux error	--	Sonic heat flux correction
Density fluctuations	Type of instrument selection	Dry mole fraction output, or WPL density terms
Spectroscopic effects for LASERs	--	Instrument-specific correction; no standardized widely used form
Band-broadening for NDIR	--	Band-broadening correction
Oxygen in the path	--	Oxygen correction
Gas flux storage	Gas profile measurements	Gas flux storage term
Missing data filling	Instrument selection, well-planned maintenance	Methodology/tests: Monte-Carlo *etc.*

Sonic heat errors affect sensible heat flux, but usually by no more than ten percent, and they are fixed by applying a straightforward sonic heat flux correction.

The density fluctuations mostly affect gas and water fluxes, and only when instruments output fast density, as opposed to the fast dry mole fraction. Size and direction of the related errors vary greatly. It can be three hundred percent of the small flux in winter, or it could be only a few percent in summer. These errors can be eliminated by choosing instruments that output fast dry mole fraction, or can be corrected using Webb-Pearman-Leuning density terms.

Spectroscopic effects for recent laser-based technologies may affect fast concentrations and fluxes. The extent is generally specific to the technology, little studied in eddy covariance applications, and should be treated with caution.

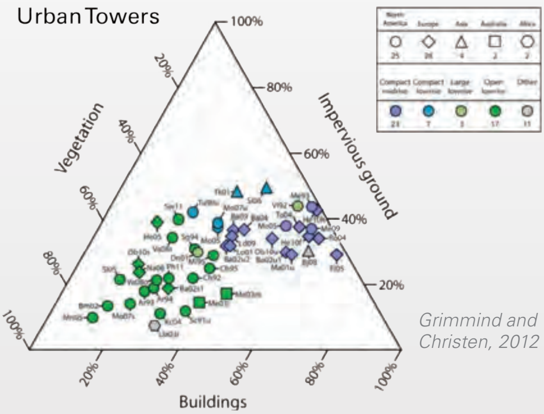
Band-broadening errors affect gas fluxes measured by the NDIR technique, and depend greatly on the instrument used. The error is usually on the order of zero to five percent, and corrections are either applied in the instrument's software, or described by the instrument manufacturer. Oxygen in the path affects krypton hygrometer readings, but usually not more than ten percent, and the error is fixed with an oxygen correction.

Missing data will affect all fluxes, especially if they are integrated over long periods of time. The effects can be minimized by choosing the proper instrument for the site conditions, and by a well-planned maintenance schedule. For example, in a rainy site, an enclosed or closed-path instrument will lose significantly less data than an open-path instrument, while having a spare instrument as part of the maintenance plan may also reduce the data gaps due to malfunctions, lightning strikes, *etc.*

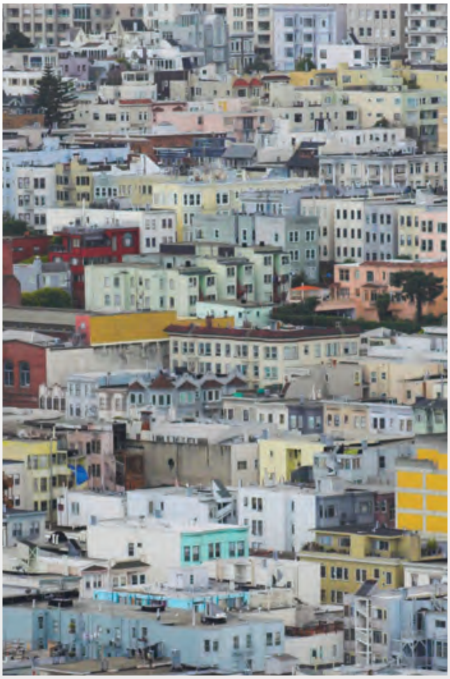
There are also a number of different mathematical methods to test and compute what the resulting errors would be for a specific set of data due to gap-filling. One good example is the Monte Carlo Method. Other methods are mentioned in Section 4.10 of this book.

Please note that even though modern flux programs will automatically correct most of the errors as part of the standard flux processing sequence, it is still extremely important to minimize or eliminate the majority of these errors during the experiment setup, and only then to correct the remaining errors during data processing. This is especially important for small fluxes and for yearly integrations.

- All principles described previously were developed and tested for traditional settings: reasonably horizontal and uniform terrain, with negligible air density fluctuations, negligible flow convergence and divergence, and with prevailing turbulent flux transport
- The latest developments of the eddy covariance method have revisited these assumptions to measure over complex sites, such as urban or hilly terrains



Grimmind and Christen, 2012



All principles described previously were developed and tested for traditional settings, over reasonably horizontal and uniform terrains, with negligible air density fluctuations, negligible flow convergence and divergence, and with prevailing turbulent flux transport.

The latest developments of the method have revisited many of these assumptions in order to be able to use the method in complex terrains: over cities, on hills, and under conditions of various flow obstructions.

There are several groups in the FluxNet and other networks who work specifically in complex terrains, and have became experts in this area of the eddy covariance method.

Success of these latest applications is growing, with over 60 urban flux stations deployed in 2012 for both scientific and regulatory purposes (http://www.geog.ubc.ca/urbanflux). At least 25 additional stations operate in complex mountainous terrains across the globe.

References

Great review of the modern urban flux measurements and related literature is provided by: Grimmond, S., and A. Christen, 2012. Flux measurements in urban ecosystems. FluxLetter, 5(1): 1-8 http://fluxnet.ornl.gov/sites/default/files/FluxLetter_Vol5_no1.pdf

Other measurements in complex conditions described in: Gu, L., W. Massman, R. Leuning, S. Pallardy, T. Meyers, *et al.*, 2012. The fundamental equation of eddy covariance and its application in flux measurements. Agricultural and Forest Meteorology, 152: 135-148

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McMillen, R., 1988. An eddy correlation technique with extended applicability to non-simple terrain. Boundary-Layer Meteorology, 43: 231-245

Raupach, M., and J. Finnigan, 1997. The influence of topography on meteorological variables and surface-atmosphere interactions. Hydrology, 190: 182-213

- Measures fluxes transported by eddies
- Most direct way to measure flux
- Requires turbulent flow
- Requires state-of-the-art instruments
- Calculates flux as covariance of *w′* and *c′*
- Many assumptions to satisfy
- Complex calculations, mostly automated
- Proper workflow is vital

Eddy covariance is the most direct approach to measure vertical fluxes of water vapor, trace gases (*e.g.*, CO_2, CH_4, N_2O, *etc.*), heat and momentum between the soil, vegetation, urban or industrial terrains and the atmosphere.

Flux is calculated as a covariance of instantaneous deviations in vertical wind speed and instantaneous deviations in the entity of interest.

The method relies on the prevalence of the turbulent transport, and requires state-of-the-art instruments. It uses complex calculations, and utilizes many assumptions.

Modern instrument systems and processing software take care of most of the challenges when using the eddy covariance method. Nevertheless, proper station design, experiment planning and execution, and correct data processing steps help to minimize or eliminate the errors resulting from failure to meet theoretical assumptions, and system deficiencies.

In this way the method can be tuned to the particular purpose (scientific, industrial, agricultural, regulatory, *etc.*), and to the particular measurement site (maize field, forest, wetland, ocean, city, landfill, *etc.*) to provide reliable hourly or half-hourly fluxes continuously over months and years.

Proper execution of the eddy covariance method is perhaps the second biggest challenge for a novice, after mastering the theoretical part of the method.

The rest of this book is primarily dedicated to providing a sequential step-by-step description of the method’s workflow, from designing and implementation of the experiment, to processing the data.

- Eddy covariance method workflow is a challenge
- Mistakes in experimental design and implementation may render data worthless, or lead to gaps
- Mistakes during data processing are not as bad, but require re-calculation

Proper execution of the workflow may become a significant challenge for a novice, second only to mastering the theoretical part of the eddy covariance method.

Oversights in experimental design and implementation may lead to collecting bad data for a prolonged period of time, and can result in large data gaps.

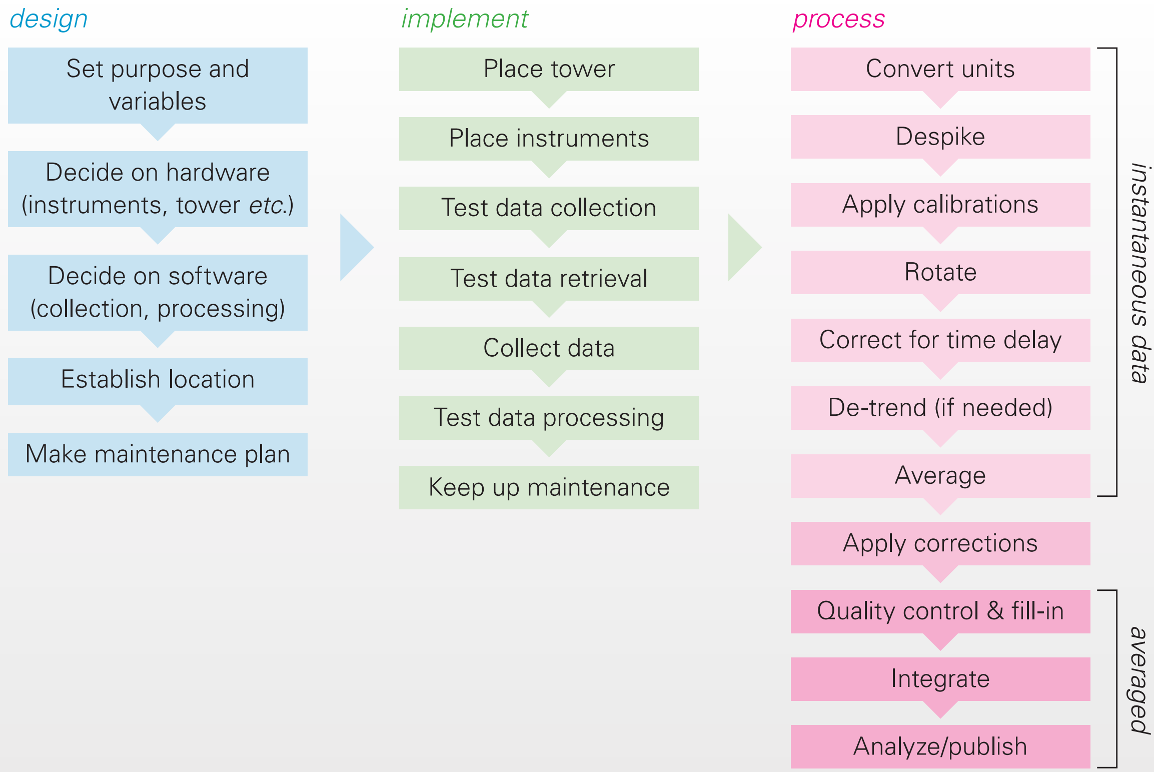
These are especially undesirable for the integration of the long-term data sets, which is the prime goal for measuring fluxes of carbon dioxide, methane or other greenhouse gases in scientific applications.

Errors in data processing may not be as bad, as long as there is a backup of the original raw data files, but they can also lead to time-consuming re-calculations, or to wrong data interpretation.

There are several different ways to execute the eddy covariance method and get substantially the same results. Here we will give an example of one traditional sequence of actions needed for successful experimental setup, data collection and processing.

This sequence may not fit some specific measurements goals, but it will provide a general understanding of what is involved in eddy covariance study, and will point out the most difficult parts and frequent pitfalls.

It is extremely important to always keep and store original 10Hz or 20Hz data collected using the eddy covariance method. The data can then be reprocessed at any time using, for example, new frequency response correction methods, or correct calibration coefficients. Some of the processing steps cannot be confidently recalculated without the original high-frequency data.



Above is an example of one traditional sequence of actions needed for successful experimental setup, data collection, and processing. One can break the workflow into three major parts: design of the experiment, implementation, and data processing.

The key elements of the design portion of eddy covariance experiment are as follows: setting the purpose and variables for the study, deciding on instruments and hardware to be used, creating new or adjusting existing software to collect and process the data, establishing appropriate experiment location and a feasible maintenance plan.

The major elements of the implementation portion are: placing the tower, placing the instruments on the tower, testing data collection and retrieval, collecting data, and keeping up the maintenance schedule.

The processing portion includes: processing the real time, "instantaneous" data (usually at a 10-20 Hz sample rate), processing averaged data (usually from 0.5 hrs to 2 hrs), quality control, and long-term integration and analysis.

The main elements of data processing include: converting voltages into units, de-spiking, applying calibrations, rotating the coordinates, correcting for time delay, de-trending if needed, averaging, applying corrections, quality control, gap filling, integrating, and finally, data analysis and publication.

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Part Two:

Designing An Eddy Covariance Experiment

Section 2.1 Setting Purpose and Selecting Variables

- Setting purpose and variables
- Selecting hardware
- Selecting software
- Selecting location
- Developing maintenance plan

Determining the purpose for the eddy covariance measurements and selecting the required outputs and variables is an important first step in the eddy covariance workflow. It should ideally be accomplished before selecting the instruments and software, and prior to selecting the location and developing the maintenance plan.

Often, for practical reasons, the location is prescribed. Even then, selecting the purpose and variables should be the first step in the workflow.

The list of variables, built carefully to satisfy the measurement purpose will, in turn, help to determine what instruments should be used, and what measurements should be conducted, and how.

The purpose may also help to determine the requirements for the measurement site, location of the tower within the site, and instrument placement on the tower. Data collection and processing programs can also be adjusted to accommodate the previously outlined variables, instruments, processing steps, and station conditions.

While this may seem like an obvious step, the errors at this stage are quite frequent, and specifically due to apparent simplicity of this stage of planning.

For example, if one wanted to measure instantaneous water use efficiency (hourly rates of CO_2 absorbed by canopy per H_2O evapotranspirated) of a soybean crop, the obvious products would be an eddy flux of CO_2 and H_2O, and these will require fast measurements of (i) vertical wind speed, (ii) CO_2 and (ii) H_2O content of the air.

Although these three variables would indeed be critical, and may satisfy monitoring applications, they are not sufficient for agricultural or research applications.

This is because the results will be virtually impossible to interpret and quality control without a list of key supporting variables, such as precipitation/irrigation amounts or soil moisture, growth stage of soybean or its green leaf area, incoming solar or photosynthetic radiation, air temperature, and perhaps soil temperature.

- Eddy covariance is a statistical method for computing turbulent fluxes, and can be used for a number of different purposes
- Researchers should be aware of the particular requirements, make a list of required variables, and plan accordingly for each project
- Main application areas are scientific, industrial, agricultural, regulatory

Eddy covariance is a statistical method for computing turbulent fluxes, and can be used for many different purposes.

For example, if the main interest of the experiment is in turbulent characteristics of the flow above the wind-shaken canopy, one may not need to collect water and trace gas data, but may need to collect higher frequency (20+ Hz) wind components and temperature data. Instruments may need to be placed on several different levels, including those very close to the canopy.

On the other hand, if one is interested in the response of the evapotranspiration from an alfalfa field to a nitrogen regime, there may not be a need for profiles of atmospheric turbulence, and 10 Hz data may be adequate for sampling.

However, a study such as this would require instantaneous measurements of water vapor along with sonic measurements well above the canopy, but within the fetch for the studied field.

Another example is computing CO_2 net ecosystem exchange. This may require not only instantaneous wind speed and CO_2 concentration measurements, but also latent and sensible heat flux measurements (for Webb-Pearman-Leuning terms), mean temperature, mean humidity and mean pressure (for unit conversions and other corrections).

Mean CO_2 concentration profiles would also be highly desirable for computing the CO_2 storage term.

Next we will show a few examples of mainstream applications as well as some rare applications, to illustrate the versatility of the method and to help the reader to define the scope for their measurement goals.

Minimal Eddy Station	Typical Eddy Station	Full Eddy Station
Product: flux of 1 gas and/or H_2O	Product: flux of 1 gas and H_2O, + supporting weather data	Product: flux of 1 gas and H_2O, + supporting weather, radiation, and soil data
u, v, w, T_s *(fast 3D sonic anemometer)*	u, v, w, T_s *(fast 3D sonic anemometer)*	u, v, w, T_s *(fast 3D sonic anemometer)*
+ concentration of 1 gas *(fast gas analyzer)*	+ concentration of 1 gas *(fast gas analyzer)*	+ concentration of 1 gas *(fast gas analyzer)*
+ concentration of H_2O *(fast H_2O analyzer)*	+ concentration of H_2O *(fast H_2O analyzer)*	+ concentration of H_2O *(fast H_2O analyzer)*
	+ mean T_{air}, RH, U, P, W_{dir}, precipitation, *etc.* *(slow weather sensors)*	+ mean T_{air}, RH, U, P, W_{dir}, precipitation, *etc.* *(slow weather sensors)*
		+ gas concentration profile *(slow gas analyzer)*
		+ Rn, Rs_{in}, Rs_{out}, PAR_{in}, PAR_{out} *(slow radiation sensors)*
		+ soil heat flux, T, moisture *(slow soil sensors)*

- Approximate list of variables provided by commonly used eddy covariance stations
- Minimal station contains a list of essential variables needed in every application

Common variables required by all applications are those describing the turbulent transport itself, such as three components of the 3-dimensional wind speed (u, v, w), sonic temperature (T_s), concentration of the gas of interest, and water vapor. These measurements have to be fast to be able to compute the gas flux, and are captured by a "minimal" eddy covariance station.

The term "fast" usually refers to devices capable of adequately measuring processes at about 10 Hz (10 times per second), while the term "slow" usually refers to mean quantities measured on the scale of many seconds and/or minutes, and then averaged down to ½-1 hour.

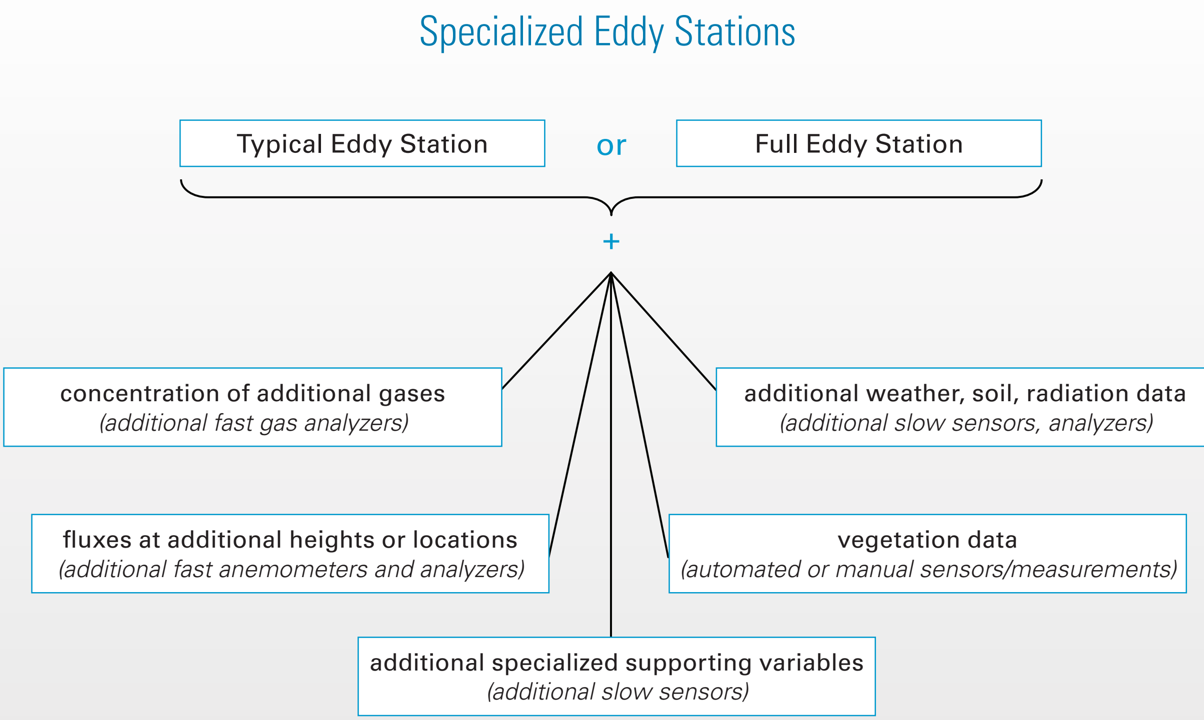
The "minimal" stations are used relatively infrequently, and are suitable primarily for regulatory, monitoring and inventory purposes, and in some industrial and agricultural applications. This is because data from these stations may be difficult to interpret in the absence of weather parameters and other supporting variables.

The "typical" stations are used quite frequently, especially in non-scientific applications. Additional measured weather variables (*e.g.*, mean air temperature, relative humidity, wind speed, direction, and precipitation amounts, *etc.*) help interpret the flux data, and fill in the missing gaps using slow variables measured at the same location at the same time.

The "full" eddy covariance stations include everything from the "typical" stations, but in addition may have gas and water vapor concentration profiles below the flux measurement level, solar radiation data (*e.g.*, net radiation, incoming and outgoing shortwave and photosynthetically active radiation), and soil heat flux, temperature and moisture data.

Concentration profiles are used for computing gas flux storage at sites with tall canopies and low winds, when flux generated at the surface does not fully reach the tower height. Solar radiation and soil heat fluxes are used to compute energy budget components at the measurement site, and can help quality control the data.

In addition, the combination of weather, radiation and soil data describes the state of the ecosystem, field or other measurement territory in terms of key functional parameters to help interpret, explain and model the site-specific flux behavior and emission rates.



In addition to the variables collected by typical or full eddy covariance stations, specialized stations can have variables specifically tailored for the purpose of a given project.

Such variables differ from station to station and from project to project, and may include concentrations of additional gases for the purpose of flux measurements (for example, CH_4, N_2O, NH_3, *etc.*).

The stations may also include additional flux measurement heights (for tall towers over forests, cities, or industrial zones) or locations (for heterogeneous regions, or for comparative purposes).

The stations may have specific water, soil and radiation parameters (for example, water level or salinity in wetlands, or freeze depth in permafrost regions).

Many specialized stations include detailed canopy measurements (canopy height, growth stage, leaf area, leaf wetness, leaf nitrogen, sap flow, *etc.*).

Other examples of project-specific variables may include pivot irrigation or fertilizer amounts at irrigated or fertilized agricultural sites, gas or water injection amounts and rates at carbon sequestration or hydraulic fracturing sites, *etc.*

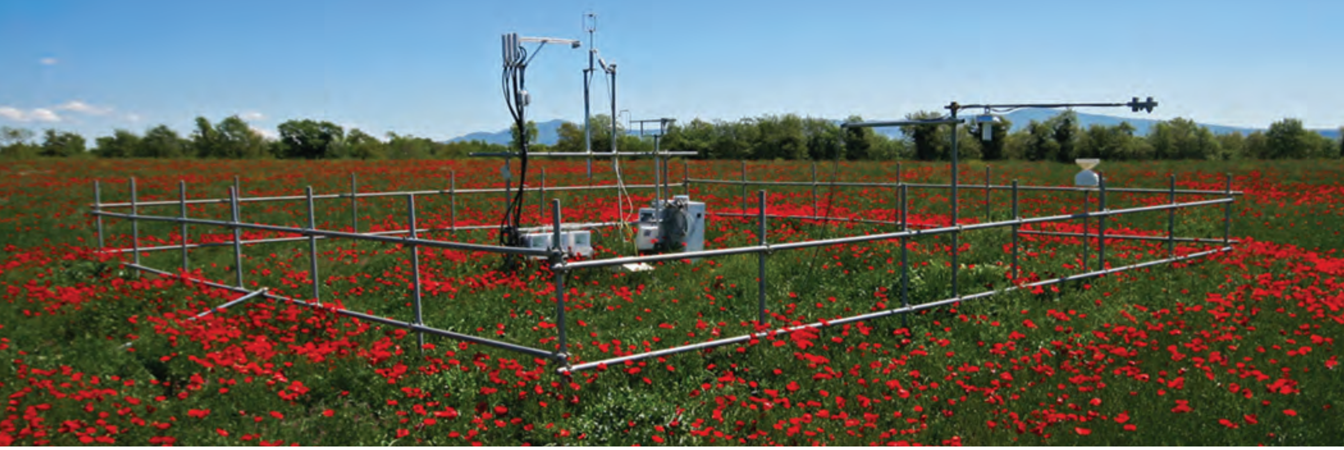
We will next provide a very brief overview of the range of applications to give a general feel for the flexibility and breadth of the usage of the eddy covariance method.

The overview will cover scientific applications, including climate change research, ecosystem gas exchange, *etc.*; industrial applications, such as geological carbon sequestration, leak detection, *etc.*; agricultural applications, including agricultural research, carbon sequestration, and water use efficiency; and regulatory applications.

Scientific applications of the eddy covariance method are numerous; they generally focus on studies of ecosystem dynamics of natural, agricultural and urban ecosystems, on quantification of emission rates from various ecosystems and regions, and on verification of the climate models.

The following few examples illustrate the scope and range of scientific usage of the eddy covariance method:

- Complex multiple-ecosystem studies
- Single ecosystem studies
- Flux studies over oceans
- Hydrological applications



Eddy covariance has been widely used in scientific applications for over 30 years. In fact, up until a few years ago the method was considered to be of primary use only by trained micrometeorologists, or those with a background in physics, engineering, and numerical meteorology.

With significant developments in instrument technology in early 2000's, and with effective work by FluxNet organizations to standardize the method, it became widely used by ecologists, climate scientists and other natural science professionals to study climate change, various aspects of ecosystem dynamics, and gas exchange in natural, agricultural and urban ecosystems, including oceanographic and hydrological applications.

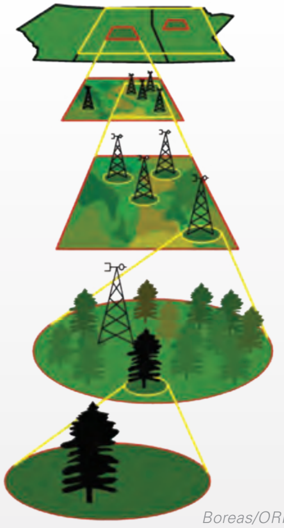
Complex multi-ecosystem studies focus primarily on regional and global climate change ecosystem responses. Studies such as these are perhaps the most demanding scientific applications in terms of global scope, planning, budget, the amount of supporting variables, requirements for data coverage, format standardization, and flux processing quality.

Multiple regions are often studied at a very detailed level over multiple years, covering soil, canopy, and lower layers of the atmosphere to describe the ecosystem responses to the changing climate or management in a quantitative manner, and to verify climate models.

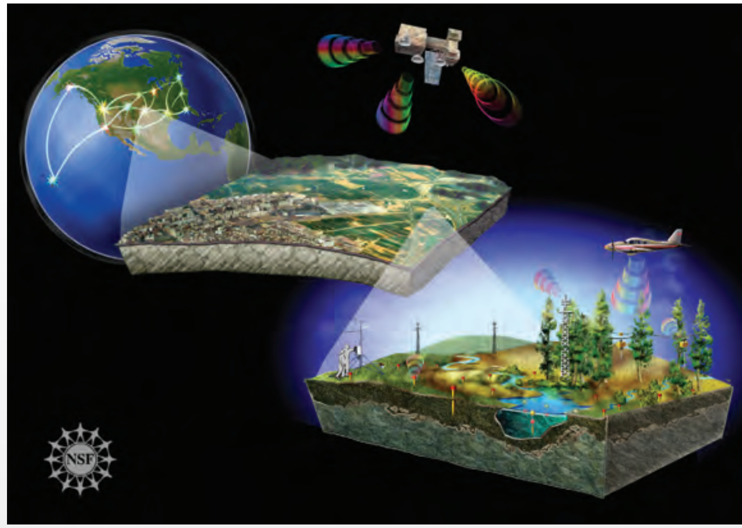
Such studies must also have consistent methodology over time, and preferably, must use standardized instrumentation in all covered regions to avoid year-to-year and site-to-site biases.

This is important because such studies are designed to detect small temporal changes or small regional differences in large processes, such as net ecosystem exchange, or soil or canopy carbon accumulation.

Some of the early examples of such comprehensive, large-scale climate change research projects are the FIFE experiment in the late 1980's, HAPEX-Sahel experiment in the early 1990's, and BOREAS experiment in the mid-1990's.



Boreas/ORNL



- Multi-scale measurement strategies in BOREAS project in the 1990's (left), and in NEON continental-scale ecological observations in the 2010's (right)
- While NEON coverage and level of details are extremely comprehensive, and go well beyond an eddy covariance experiment, the overall structure of large-scale ecosystem measurements remains similar in both cases

Although earlier experiments (*e.g.*, FIFE, HAPEX, and BOREAS) focused on different areas (prairie region in Kansas, sub-Saharan region in Africa, and boreal regions in Canada, respectively), methodologically they had a lot of commonalities, which remain similar in modern-day major infrastructure projects, such as FluxNet, ICOS, NEON, *etc.*

In such studies, the number of variables is typically very large, including fully equipped flux stations, often at different levels in the ecosystem. Fluxes of various trace gases, water vapor, heat and momentum are measured at hourly rates continuously, along with net radiation and soil heat storage to describe the energy budget at an ecosystem level.

Radiation measurements may additionally include incoming and outgoing solar radiation and photosynthetically active radiation above and below the canopy to help interpret flux data and ecosystem models. Soil measurements may include soil temperature and moisture at different depths, soil chemical and physical properties, and soil water seepage and drainage measurements. Soil and radiation are often sampled at multiple places within the same site to assure better spatial averaging.

Canopy measurements may include green and total leaf area, leaf-level flux measurements, sap flow, and leaf nitrogen and phosphorus content. Belowground biomass may also be sampled or monitored.

Sampling of multiple other ecosystem parameters, as well as airborne and satellite measurements may also be conducted during intensive field campaigns.

References

Specific details on the above mentioned projects, procedures, list of variables, and further references can be found here:

FIFE: daac.ornl.gov/FIFE/FIFE_About.html

HAPEX: www.cesbio.ups-tlse.fr/hapex/

BOREAS: daac.ornl.gov/BOREAS/bhs/Introduction.html

NEON: www.neoninc.org

ICOS: www.icos-infrastructure.eu/

FluxNet: fluxnet.ornl.gov

Single-station ecosystem projects: drylands, wetlands, permafrost, *etc.*

Research at a single ecosystem level may or may not be part of a larger multi-scale research project. In the latter case, such research may have a narrow, specific focus and a much smaller list of required variables.

For example, study of a single ecosystem may focus on the effects of a bark beetle invasion on pine forest growth and recovery over several years. In this case, the main products will be CO_2 and H_2O fluxes from the forest, the number of dead and live trees, and possibly, understory fluxes and biomass. At a minimum, the variables may include those in a typical flux station, as well as the biomass data for the trees and understory.

The list of additional variables for such a project will significantly depend on whether the research is intended to describe and model the entire ecosystem response to the beetle invasion, or if it is intended to only register the tree die-off and quantify the decrease in resulting CO_2 uptake by the ecosystem.

A different example may be a wetland study of the effects of an invasive canopy on the CO_2 uptake and CH_4 emission by the ecosystem. A typical flux station would no longer be sufficient for the eddy covariance portion of the study, because an additional gas (*e.g.*, CH_4) would be measured at the station. Also, tower height will be significantly lower, turbulent transport contribution at high frequency will be significantly higher, and grid power will likely be unavailable. This may lead to a selection of different instruments (open-path or enclosed low-power devices). Water properties data may also be required.

Another example may be a study of CH_4 emission from a permafrost ecosystem. If this study is simply a quantification of the CH_4 emission rates, it may involve a minimal station with measurements of fast wind speed, CH_4 and H_2O, and with no CO_2.

If, on the other hand, it is a study focused on the response of the permafrost ecosystem to gradual warming, other parameters of the ecosystem functioning would need to be measured. For example, CO_2 flux may help determine canopy state and soil microbial activity, and a full set of weather, radiation and soil data may help explain changes in CH_4 flux and gap-fill the missing data.

- Oceanography
- Hydrology

Courtesy of Hamish McGowan, University of Queensland

Ocean studies have a unique set of challenges when compared to most other scientific applications. First, the flux rates of CO_2 are typically quite small. Second, the measurement platform is usually moving (roll, pitch, ship vibrations *etc*.). Salt water exposure, air flow distortion by the ship, and low power restrictions are often significant challenges. Also, the experiments themselves may be quite expensive, involved, and short-term, making any data loss highly undesirable.

In addition to the variables in a typical eddy station, ocean-borne stations often have 3-D accelerometers and gravitometers to compensate for platform movement, and detailed water parameters, such as temperature, salinity, oxygen, pCO_2 and pCH_4 content. Fast pressure measurements may also be required to assess the pressure term effects on small fluxes.

Open-path instruments may not be the best choice for ocean-borne CO_2 measurements, because large density corrections may overwhelm the small flux rates, so closed-path or enclosed devices may be recommended instead.

While ocean-borne applications usually focus on ecosystem aspects and CO_2 fluxes, the hydrological applications may be only interested in H_2O fluxes, and may focus on an ecosystem, water body or a watershed territory. The main advantage of the eddy covariance method for hydrology is broad spatial coverage and fairly accurate water flux measurements (*e.g.*, latent heat flux, evapotranspiration, evaporation). The station may or may not need to collect CO_2 data to help interpret H_2O flux rates.

If measurements are primarily intended to quantify water losses, a minimal eddy station without CO_2 may be sufficient. Weather parameters would be highly desirable to determine equilibrium and potential rates. Supporting measurements of precipitation, soil moisture, seepage and drainage rates may also be helpful. Energy budget components are desirable, but not essential. In humid regions, open-path analyzers may be replaced with enclosed devices to avoid data loss due to frequent precipitation. Closed-path devices would be undesirable because of increased uncertainty due to water vapor attenuation in the long intake tubes.

- Emission rates from industries, landfills, *etc.*
- Carbon capture and sequestration
- Cap-and-trade compliance and quantification
- Line efficiencies and leak detection

Industrial applications usually focus on very concrete goals of quantifying emissions of gases, capture and line efficiencies, and leakage rates over industrial zones, geological carbon sequestration and hydraulic fracturing (*e.g.*, fracking) sites, landfills, and along the pipelines.

Industrial use of the eddy covariance method is a relatively new area. In the past, the measurements were done with a range of modeling techniques (from emission indices and remote sensing, to plume modeling) and more direct measurements (*e.g.*, stack detectors, chamber techniques, flask sampling, *etc.*).

Modern eddy stations allow direct measurements of the gas emissions from a specific territory reported in weight or volume of gas per unit area per unit time.

The required eddy stations, in general, may be much simpler than those used in scientific applications. Most supporting variables are not required because the purpose of the project is to quantify the emission, adjust the industrial or management process or design, and determine if there is a resulting improvement.

However, industrial applications often involve large territories with complex surfaces, so more than one minimal or typical eddy station may be required for confident measurements of fluxes from large upwind areas.

References

Multiple examples of industrial emission and leakage monitoring methods, including eddy covariance, along with useful references and explanations, are provided in:

Chapter 13, "Carbon Dioxide Geological Storage: Monitoring Technologies Review" in Liu, G. (Ed.), 2012. Greenhouse Gases: Capturing, Utilization and Reduction. Intech, 338 pp.

LI-COR Biosciences, 2011. Surface Monitoring for Geologic Carbon Sequestration Monitoring: Methods, Instrumentation, and Case Studies. Technical report, LI-COR Biosciences, Publication No. 980-11916, 15 pp.

U.S. Department of Energy, 2012. Best Practices for Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations.

Holloway, S., A. Karimjee, M. Akai, R. Pipatti, and K. Rypdal, 2006-2011. Carbon Dioxide Transport, Injection and Geological Storage, in Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (Eds.), IPCC Guidelines for National Greenhouse Gas Inventories, IPCC National Greenhouse Gas Inventories Programme, WMO/UNEP

Finley, MGSC

- Large carbon capture and sequestration project
- Midwest Geological Sequestration Consortium
- Eddy station setup at Decatur Injection Site
- Sonic anemometer (u, v, w, T_s), and fast CO_2/H_2O gas analyzer (gas concentrations)

One example of a novel use of the eddy covariance method in industrial applications is a carbon capture and sequestration project by the Midwest Geological Sequestration Consortium at their Decatur, Illinois site.

One million tons of CO_2 captured from a nearby ethanol plant are to be injected at 1,000 tons per day over a three year period into the 1,500 ft. thick sandstone, at a depth of about 6,500 ft.

The minimal solar-powered eddy covariance station shown above consists of a 3-D sonic anemometer and a fast CO_2/H_2O gas analyzer, and is augmented with a mean wind speed and wind direction sensor.

Measurements are conducted at this site concurrently with chamber techniques and other measurement and modeling methods (details are available at www.sequestration.org).

References

Details for this project are provided in:

Finley, R., 2009. An Assessment of Geological Carbon Sequestration in the Illinois Basin Overview of the Decatur-Illinois Basin Site. Midwest Geological Sequestration Consortium. Presentation.

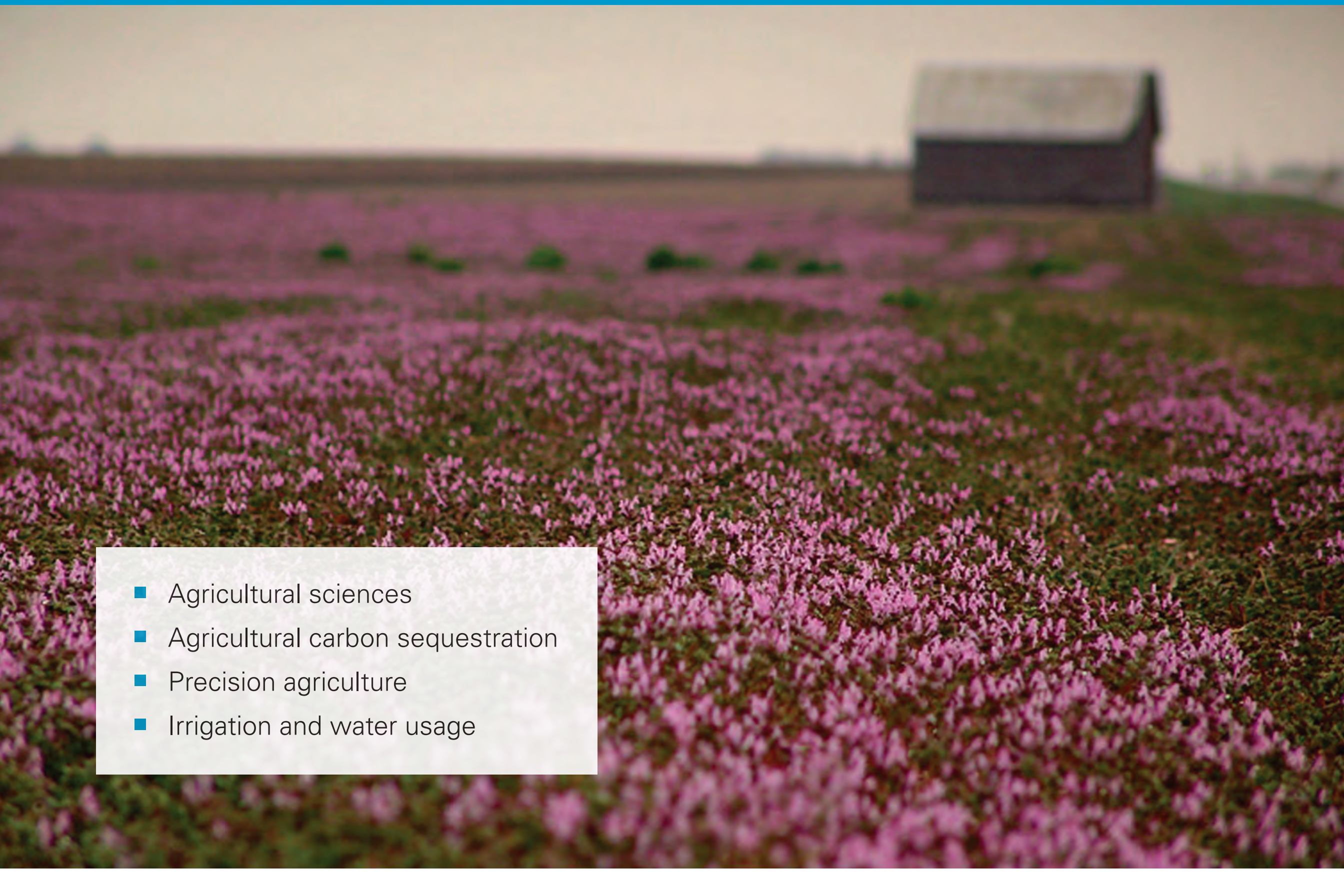
Forward, K. (Ed.), 2012. Carbon Capture Journal, 25: 22-23

LI-COR Biosciences, 2011. Surface Monitoring for Geologic Carbon Sequestration Monitoring: Methods, Instrumentation, and Case Studies. Technical report, LI-COR Biosciences, Publication No. 980-11916, 15 pp.

Additional resources on industrial applications can be found in: Benson, S., 2006. Monitoring carbon dioxide sequestration in deep geological formations for inventory verification and carbon credits, SPE-102833, San Antonio, Texas, Presentation

Miles, N., Davis, K., and J. Wyngaard, 2004. Using eddy covariance to detect leaks from CO_2 sequestered in deep aquifers. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, 5 pp.

Lewicki, J., G. Hilley, M. Fischer, L. Pan, C. Oldenburg, C. Dobeck, and L. Spangler, 2009. Eddy covariance observations of leakage during shallow subsurface CO_2 releases. Journal of Geophysical Research, 114: D12302



- Agricultural sciences
- Agricultural carbon sequestration
- Precision agriculture
- Irrigation and water usage

The eddy covariance method has been used in agricultural sciences for over 30 years in the areas of yield research, light and water use efficiencies, agricultural carbon sequestration research, bio-fuel investigations, crop management, *etc*.

The use of the method in commercial production agriculture was limited, and only now with increased demands of precision agriculture, the method is starting to gain some interest.

Similar to hydrological and industrial applications, the method offers the advantage of directly measuring half-hourly or hourly emission rates integrated over a large area such as an agricultural field, using a minimal low-power eddy station.

The method could provide the ability to determine, for example, how much carbon dioxide was taken up by the vegetation in a specific field at a given hour, day, month or year. In conjunction with yield and biomass removal data, such measurements can provide an idea of the rates of the agricultural carbon sequestration for a specific field and for specific management practices. The same information on carbon dioxide fluxes will describe the hourly and long-term photosynthetic and canopy growth rates.

In conjunction with the knowledge of growing degree days and the crop type, this information may indicate the health of the canopy or describe the nearly instantaneous reaction (within hours) of a crop to a fertilizer or pesticide treatment. It could also tell a biomass producer how efficiently sunlight is used by a given crop after a particular treatment.

The carbon dioxide uptake and emission measurements as a gauge of canopy growth and health, nitrous oxide or ammonia emission measurements as a gauge of fertilization efficiency, and other similar applications may be in the future for high-precision agricultural production.

However, the accurate evapotranspiration rates provided hourly by eddy covariance have the potential to significantly benefit commercial water use applications and increase irrigation efficiencies immediately, as briefly illustrated on the next page.

- High-precision irrigation
- Irrigation efficiency
- Water use and water use efficiency

The main advantage of the eddy covariance method for water use optimization in production agriculture is field-scale coverage and accurate ET rates (*e.g.*, evapotranspiration, evaporative water loss, latent heat flux, evaporation, *etc.*) comparable to those from lysimeters.

A minimal eddy station does not require carbon dioxide data, and can focus exclusively on evapotranspiration. In this case, the sonic anemometer will measure three wind components, and the fast gas analyzer will measure water vapor concentration. The result will be an hourly ET rate integrated over the upwind portion of the field.

In conjunction with soil moisture measurements and knowledge of the crop, the ET rates can, for example, help determine the need, or absence of a need, for irrigation. When pivot position is known, the ET rates may provide a measure of irrigation efficiency.

If an eddy station reports carbon dioxide fluxes in addition to water (or uses a single CO_2/H_2O gas analyzer), one can also compute field-scale hourly water use efficiency.

The concept of water use efficiency is widely used, but its meaning differs in different applications. In production agriculture it is often determined as the amount of yield per amount of water used. In biofuel investigations it may be an amount of harvested aboveground biomass per amount of water used. In ecology, it may be total or net photosynthetic uptake of carbon dioxide per amount of water transpired by plants, or lost by the entire ecosystem via evapotranspiration.

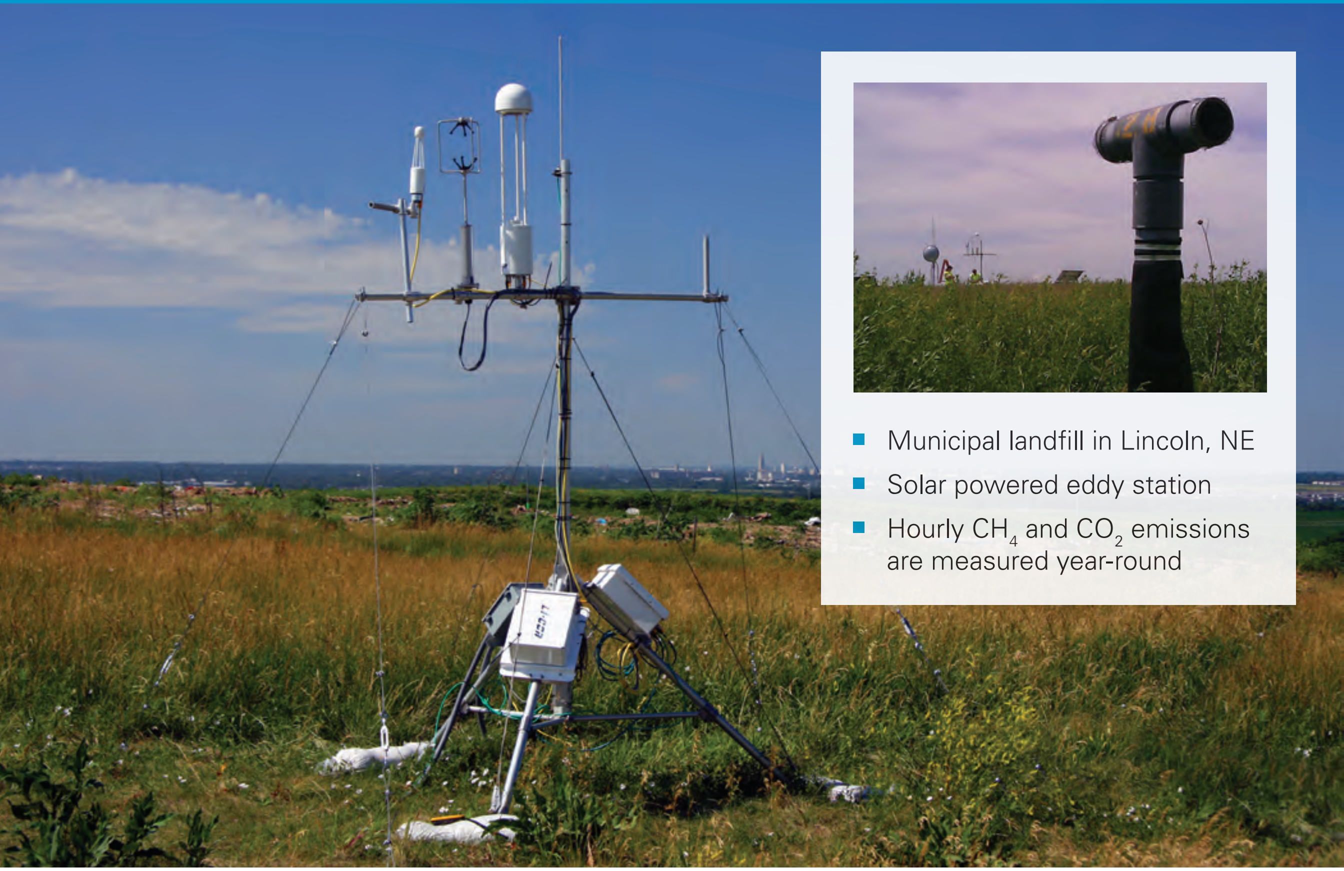
Eddy stations may readily offer hourly values of water use efficiency, defined as carbon dioxide flux divided by evapotranspiration. This approximately describes the rate of canopy growth per amount of water used, and can provide significant benefits to high-precision agriculture.

References

Further details on eddy covariance applications in agricultural systems are described in: Hatfield, J., and J. Baker (Eds.), 2005. Micrometeorology of Agricultural Systems. ASA Monograph Series No. 47. ASA-CSSA-SSSA. Madison, Wisconsin, 584 pp.

Bezerra, B., 2012 (Accessed). Crop Evapotranspiration and Water Use Efficiency: http://cdn.intechopen.com/pdfs/34107/InTech-Crop_evapotranspiration_and_water_use_efficiency.pdf

Mavi, H., and G. Tupper, 2004. Agrometeorology: principles and applications of climate studies in agriculture. CRC Press, 447 pp.



- Municipal landfill in Lincoln, NE
- Solar powered eddy station
- Hourly CH_4 and CO_2 emissions are measured year-round

Regulatory governmental institutions, as well as some non-governmental organizations, are tasked with monitoring the concentration of particular gases and gas emission rates from regulated areas, such as landfills, feedlots, lagoons, industrial zones, municipal areas, *etc*., to prevent pollution, increase air quality, comply with emissions trading (cap-and-trade, *etc*.) programs, and mitigate the effects of gas emissions on global climate change. The focus of such measurements is accurate quantification of the concentration or emission with the purpose of enforcing the existing regulations, or developing new ones.

In these cases, it is quite important to distinguish between monitoring the concentration and monitoring the emission rate (*e.g.*, flux). While concentration can show the result of the emission, it is not a measurement of this emission in all cases, except single source emission monitoring (such as stack pipe, single leak or a vent) or when using a large-scale integrated horizontal flux method.

It is also important to distinguish between actual measurements and models. Actual direct measurements are much more defensible and reliable, while models can provide a good idea of the process, often without an accurate quantification of the result. For example, modeling landfill methane emissions from emission indices and landfill load amounts may differ on the order of several times from actual emissions measured directly.

Semi-empirical measurements with plume tracing and other similar techniques will likely improve the estimate of the methane emissions, but are not continuous, and rely on models describing concentration distribution in the plume or a tracer.

In such contexts, the eddy covariance method provides a good alternative, or an addition, for directly and continuously measuring emission rates of the gases of interest from an upwind area on a half-hourly and hourly basis.

Continuous data coverage is especially important for relatively porous or open-surface substrates containing high concentrations of the gas of interest (such as CH_4 in active landfills, or NH_3 in cattle yards), because the effects of changing atmospheric pressure and wind direction may change the emission rates several times from one hour to the next. Such changes would be missed by most other indirect discrete methods, and can result in significant error in the emission estimates over the long term.

References

Xu, L., X. Lin, J. Amen, K. Welding, and D. McDermitt, 2013. Impact of Changes in Barometric Pressure on Landfill Methane Emission. Global Biogeochemical Cycles. *Submitted*

Part Two:

Designing An Eddy Covariance Experiment

Section 2.2 Instrument Principles Helpful in Designing the Station

- Sonic anemometer: key elements of physical design
- Gas analyzer: key elements of optical design
- Gas analyzer: key elements of physical design
- Implications of gas analyzer design for eddy covariance

The instrumentation shown above is a classic example of a minimal eddy covariance station: a 3-dimensional sonic anemometer and an open-path gas analyzer. An enclosed or closed-path gas analyzer can be used instead of, or in addition to, the open-path device.

The gas analyzer is usually positioned at or slightly below the sonic anemometer level. The horizontal separation between the anemometer and other instruments should be kept to a minimum, preferably not exceeding 15 to 20 cm. However, all instruments near the anemometer, including the analyzer, should be arranged very carefully with the specific goal to minimize distortion of the natural air flow going into the sonic anemometer from all major wind directions for a given measurement site.

With an open-path gas analyzer, the head can be slightly tilted to minimize the amount of precipitation accumulating on the windows.

With an enclosed or closed-path analyzer, the intake tube should have a rain-protection cap to prevent water from entering the sampling cell of the analyzer.

With this simple scheme in mind, we will now cover the key elements of instrument design and operation that have the most significant implications for eddy covariance flux measurements.

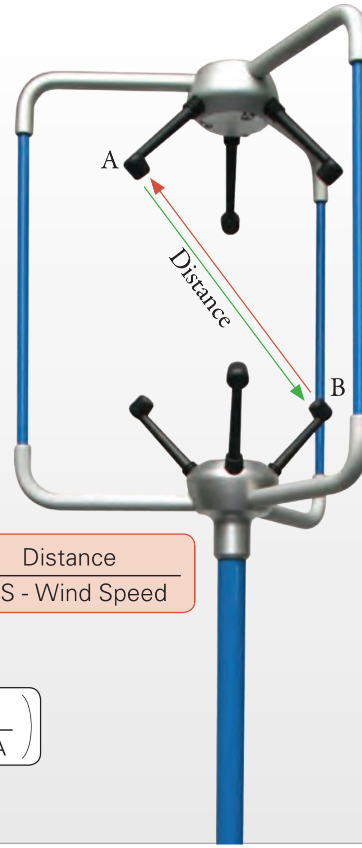
References

Yamanoi, K., R. Hirata, K. Kitamura, T. Maeda, S. Matsuura, *et al.*, (Eds.), 2012. Practical Handbook of Tower Flux Observations. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp. (Electronic Edition in English)

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Foken, T., 2008. Micrometeorology. Springer-Verlag, Berlin Heidelberg, Germany, 310 pp.

- Sonic anemometers measure speed of sound (SoS) from travel times and distance between transducers
- Wind speed is computed from speed of sound for each of three wind components (u, v, w)
- Vertical wind component (w) is then used in eddy covariance flux calculations



$$\text{Travel time A to B} = \frac{\text{Distance}}{\text{SoS + Wind Speed}}$$

$$\text{Travel time B to A} = \frac{\text{Distance}}{\text{SoS - Wind Speed}}$$

$$\text{Wind Speed} = \frac{\text{Distance}}{2}\left(\frac{1}{\text{Time A to B}} - \frac{1}{\text{Time B to A}}\right)$$

A 3-dimensional sonic anemometer uses 3 pairs of transducers to measure the speed of sound for each pair. Three vector components of wind speed are then computed, and the vertical wind speed component (w) is used for the eddy covariance calculations.

Speed of sound is computed from the distance between the transducers and the time it takes for an acoustic signal (usually an ultrasound wave burst) to travel from one transducer in the pair to another. To help eliminate the various biases, the transducers in the pair may take turns sending bursts of ultrasound signal so that each can act as both a transmitter and a receiver.

The wind speed is computed from the difference in time it takes for an acoustic signal to travel the same path in opposite directions, or from the difference between the known speed of sound in the still air and the measured speed of sound in moving air.

The speed of sound in the still air is generally well known. In the lower portion of the atmosphere it is affected primarily by air temperature and humidity, and to a much lesser extent by the air density, pressure and air content.

Speed of sound is also used to compute sonic temperature, but such temperature is different from actual air temperature, and requires a special correction described in Section 4.3.

3-D sonic anemometers designed for eddy covariance applications are very fast. They have a fine temporal resolution of at least 10-20 Hz, and also have a high resolution of small fluctuations in the vertical wind speed. However, sonic anemometers have a physical structure, and thus distort the very same flow they try to measure.

The fundamental calculations and major corrections in eddy covariance applications rely on the three wind components, especially on w, and distortion of natural air flow in the sonic path is the major challenge in anemometer design for such applications.

- Main 3-D sonic anemometer arrangements used in eddy covariance

The three main types of physical arrangement of sonic anemometers most used in eddy covariance are:

- omni-directional design with *u*, *v* and *w* components measured in the same physical space by non-orthogonal off-axis pairs of transducers (*e.g.*, not at 90° to each other), as shown in the left photo above
- non-omni-directional c-clamp design with *u*, *v* and *w* components measured in the same physical space by non-orthogonal pairs of transducers (top right photo)
- c-clamp design with *u*, *v* and *w* components measured in the same or different physical spaces by orthogonal transducers, with *w* measured by a pair of vertically aligned transducers (bottom right)

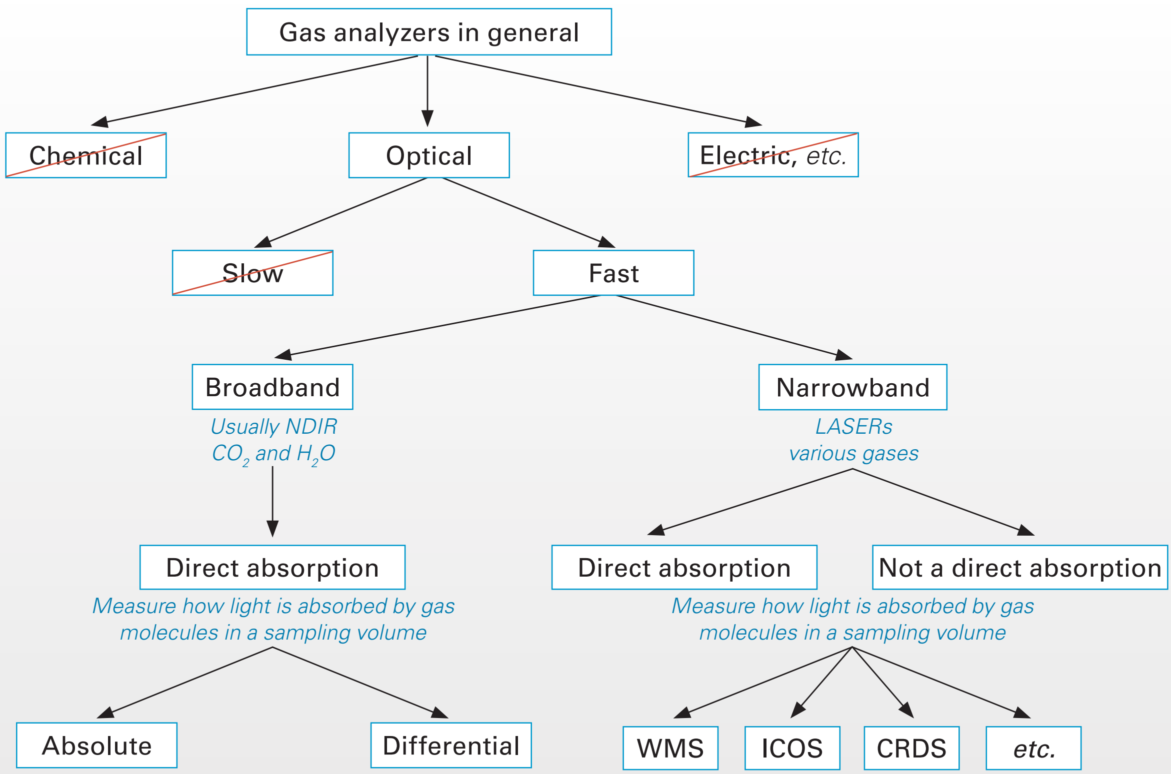
There are other less common physical arrangements of the transducers, and combinations of those shown above.

Commonalities between all designs include high temporal resolution, durability, and low power. Also, while each model design may react differently to light rain events, none produce accurate readings in heavy precipitation. Rain, dew, snow and frost on the sonic transducers may change the path length used to estimate speed of sound, and can lead to errors.

The differences in designs lay primarily in the different levels of air flow distortion at different wind directions. An omni-directional design may accept data from all directions, but may slightly distort air flow from the three vertical spars supporting the transducer structure. C-clamp designs do not have such spars, but are not omni-directional and may significantly distort the flow from 30% or more of wind directions coming from the back side of the anemometer.

The other differences are in the different levels of flow distortion at different angles of attack. When wind comes from the bottom, the omni-directional design may distort the flow more than C-clamps, because of the larger housing structure. However, all designs will distort the flow coming from the junctions of the transducers, and from the back sides of the transducers themselves.

In this context, the c-clamp design with *u, v* and *w* components measured by orthogonal transducers, with *w* measured by a pair of vertically aligned transducers (bottom right photo above), may have some advantage over other designs, because of the lesser distortion of vertical wind from the transducer support structure and transducers themselves. See page 69 for details.



Gas analyzers suitable for eddy flux measurements have been available for at least 40 years. Development of commercially available designs and their routine field use accelerated in the last 25 years, and especially in the last 10 years.

It is difficult to describe all the details about such a broad range of instruments within several pages, so this section is focused only on the few key considerations that are particularly important for the eddy covariance method.

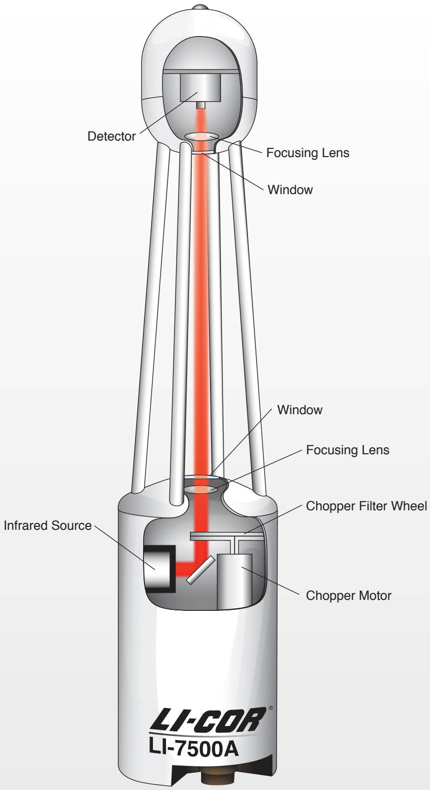
There are many different ways to measure gas content in the air. These may be based on chemical, electric, optical and other types of technology. However, not all of these measurements are suitable for eddy covariance.

In the eddy covariance method, fast fluctuations in atmospheric gas concentration need to be sampled with high resolution at a frequency of about 10 Hz or faster, in order to capture most of the transport under most conditions. Chemical sensors are usually too slow for such sampling, and electric sensors generally do not work well with the low concentrations of gases typically found in the atmosphere. Optical analyzers may or may not be sufficiently fast for use in eddy covariance, depending on the performance of the specific instruments.

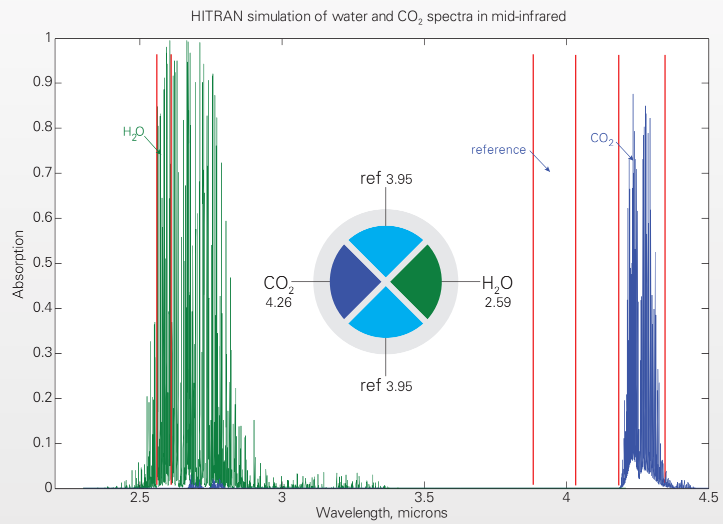
Optical analyzers with sufficiently high temporal resolution of the small signal (*e.g.*, "fast analyzers") can be used in eddy covariance, and generally can be classified into two groups: broadband and narrowband devices. Broadband analyzers operate by measuring light absorbed over some broad range of the electromagnetic spectrum. These are typically NDIR (non-dispersive infrared) analyzers well suited for fast, high-resolution CO_2 and H_2O measurements, and may be of absolute or differential design.

Narrowband devices utilize various laser spectroscopy techniques (Wavelength Modulation Spectroscopy, Integrated Cavity Output Spectroscopy, Cavity Ringdown and Photoacoustic Spectroscopy, *etc.*) to measure light absorption in a single line or narrow band of the electromagnetic spectrum. When sufficiently fast, they can be used for flux measurements of many different gas species.

It is important to keep in mind that all optical gas analyzers, regardless of the type of technology used, measure how known light is transformed by gas molecules in a known sampling volume. Thus, fundamentally, they measure gas *density*. This has very important implications for eddy covariance flux measurements.



- NDIR – nondispersive infrared
- LI-7500A – fast NDIR, absolute, single cell



The principles of operation of a fast, broadband, direct absorption, absolute gas analyzer can be illustrated using an LI-7500A non-dispersive infrared (NDIR) CO_2/H_2O analyzer.

A broadband infrared beam is transmitted through the cell to the detector. An absorption band centered at 4.26 µm is used to measure CO_2, and an absorption band centered at 2.59 µm is used to measure H_2O. The beam is modulated to distinguish it from the background using a chopper wheel.

The chopper wheel is equipped with four filter windows. When the chopper rotates, the CO_2 window passes in front of the source, and only allows light at the 4.26 µm band to pass through . This band can be seen as blue lines in the plot at right above. At this instant light transmitted in the CO_2 absorption band is measured.

In the next instant of chopper rotation, the reference window passes in front of the source. This band can be seen between two red lines named "reference" in the right plot above. This is a non-absorbing window for CO_2 or H_2O, and the no-CO_2 reference is measured.

A similar process occurs when the H_2O window passes in front of the source, allowing only the light at the 2.59 µm band to pass (green lines with red borders), and then returns to the non-CO_2/non-H_2O reference filter.

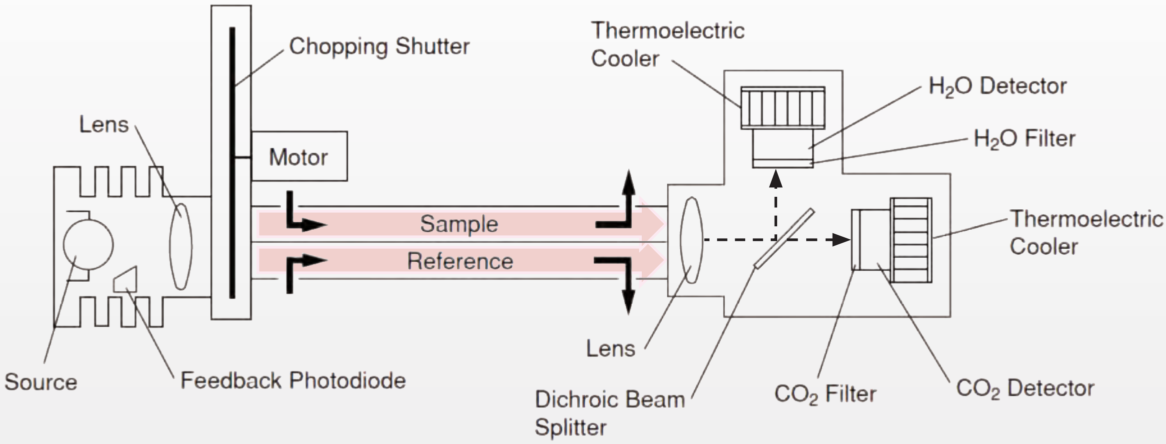
The chopper rotates at hundreds of Hz, and many single readings are averaged into the 10 or 20 Hz samples of CO_2 and H_2O, providing good resolution for both variables.

The ratio of light transmitted in the sample band to the light transmitted in the reference band is used to measure light absorptance by CO_2 and H_2O, and compute their densities.

References

LI-COR Biosciences, 2009. LI-7500A Open-path CO_2/H_2O Analyzer Instruction Manual. Publication No.984-10563, 127 pp.

Welles, J., and D. McDermitt, 2005. Measuring carbon dioxide in the atmosphere. In: Hatfield J. and J Baker (Eds). Micrometeorology in Agricultural Systems. ASA-CSSA-SSSA, Madison, Wisconsin, 588 pp.



LI-7000 fast NDIR, differential, two cells

The principles of operation of a fast, broad band, direct absorption, differential gas analyzer can be illustrated using an LI-7000 non-dispersive infrared (NDIR) CO_2/H_2O analyzer. Instead of an optical reference, this design uses a mechanical reference: the instrument has two cells, with one cell used as a reference and another one as a sample. Typically, the zero gas is provided to the reference cell.

The chopper wheel in this device is different from that in the absolute device. It does not have a filter and only chops the light at the source, letting the light pass through one cell at a time.

When the chopper rotates, light passes through the sample cell containing CO_2 and H_2O. At this instant the light transmitted in the CO_2 and H_2O absorption bands is measured simultaneously by the two respective detectors. In the next instant of chopper rotation, light passes through the reference cell containing no CO_2 or H_2O, providing a reference reading.

The CO_2 detector has a filter at the 4.26 μm absorption band, and the H_2O detector has a filter at the 2.59 μm absorption band. Non-absorbing bands are no longer used, as their function is taken over by the reference cell.

As in the LI-7500A, the chopper rotates at hundreds of Hz, averaged into 10 or 20 Hz samples, providing fast well-resolved measurements of gas concentration.

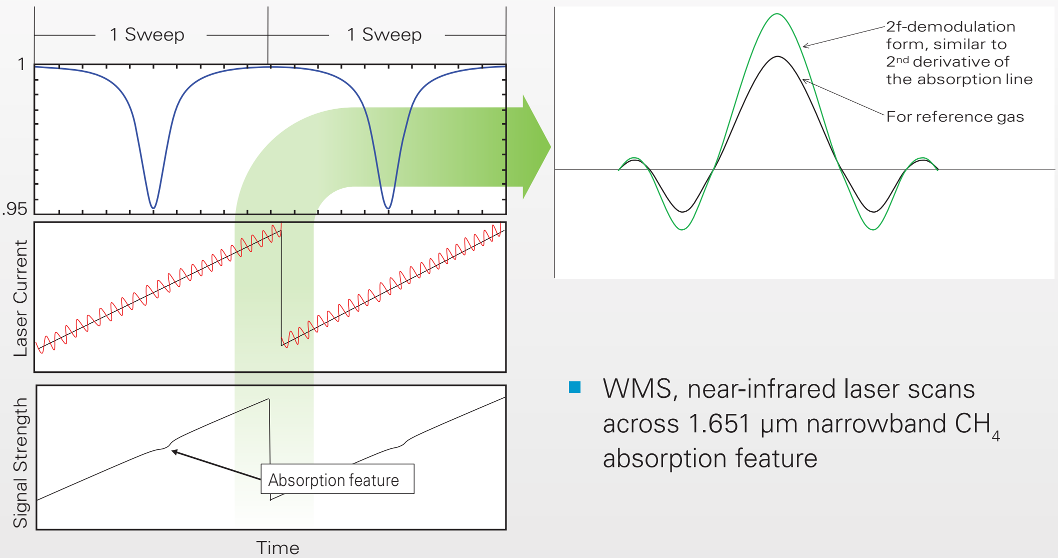
References

A comprehensive review and additional details can be found in: Welles, J., and D. McDermitt, 2005. Measuring carbon dioxide in the atmosphere. In: Hatfield J. and J Baker (Eds). Micrometeorology in Agricultural Systems. ASA-CSSA-SSSA, Madison, Wisconsin, 588 pp.

McDermitt, D., J. Welles, and R. Eckles, 1993. Effects of Temperature, Pressure, and Water Vapor on Gas Phase Infrared Absorption by CO_2. LI-COR, Lincoln, Nebraska, 6 pp.

The instrument can also operate with a known non-zero gas in a reference cell. The details of such operation are provided in: LI-COR Biosciences, 2005. LI-7000 CO_2/H_2O Analyzer Instruction Manual. Publication No.984-07364, 237 pp.

- Laser, narrow-band or single line, not NDIR
- LI-7700 is a fast laser-based analyzer for CH_4
- Does not use direct absorption, but looks at changes in the light due to the presence of CH_4



- WMS, near-infrared laser scans across 1.651 µm narrowband CH_4 absorption feature

Like broadband devices, narrow-band analyzers also measure light absorption, however, this light is now in a very narrow absorption band of the gas of interest, and is usually provided by a laser. This allows for sampling of gases other than CO_2 and H_2O. Techniques for fast laser-based measurements are many and varied.

In most methods, the laser is scanned over an absorption feature of the gas and absorption is measured by a variety of methods. One example of such methods is called Wavelength Modulation Spectroscopy (WMS), and is utilized in the LI-7700, a fast low-power CH_4 analyzer. Here, the laser beam is emitted from the source, passes through the open cell, reflecting multiple times from the two mirrors, and then enters a detector.

The laser is rapidly modulated by the electrical current, scanning across an absorption feature near 1.65 µm, and substantially reducing sensitivity to intrinsic noise of the laser source. The signal is then demodulated, normalized, and the resulting waveform is projected onto an ideal waveform stored in the instrument.

The relation between the actual waveform and the ideal waveform is proportional to gas density.

References

A great review of various laser spectroscopy approaches for atmospheric gas analysis is: Fiddler, M., I. Begashaw, K. Mickens, M. Collingwood, Z. Assefa, and S. Bibilign, 2009. Laser Spectroscopy for Atmospheric and Environmental Sensing. Sensors 9(12): 10447-10512

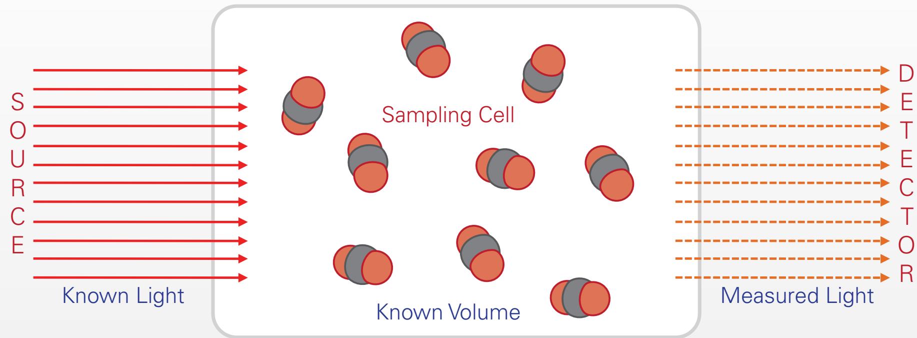
Additional details and techniques are described in: Duckett, S., and B. Gilbert, 2011. Foundation of Spectroscopy. Oxford University Press, New York, 90 pp.

Hollas, M., 2010. Modern Spectroscopy. Wiley Academic Publishers, London, 452 pp.

Details on the LI-7700 WMS device are provided in: McDermitt, D., G. Burba, L. Xu, T. Anderson, A. Komissarov, *et al.*, 2011. A new low-power, open-path instrument for measuring methane flux by eddy covariance. Applied Physics B: Lasers and Optics, 102(2): 391-405

LI-COR Biosciences, 2010. LI-7700 Open-path CH_4 Analyzer Instruction Manual. Publication No.984-10751, 170 pp.

- A common feature of all optical gas analyzers is that they measure how known light is transformed by gas molecules in a known sampling volume



- Fundamentally, they measure density q_c (per m^3), which is different from mole fraction S (per mole of air), due to temperature *(T)* and pressure *(P)*
- Density is different from dry mole fraction *s*, also called mixing ratio (per mole of dry air), due to 3 variables, water mole fraction X_w, T and P:

$$S = q_c \frac{RT}{P} \Rightarrow s = \frac{S}{(1 - X_w)} = q_c \frac{RT}{P(1 - X_w)}$$

In the context of eddy covariance, the ideal measurement of a turbulent flux is a covariance between vertical wind speed (w) and dry mole fraction (s) as described in Basic Derivations in Part 1.

One of the relevant common features of all optical gas analyzers, regardless of their technology, is that they are based on molecules absorbing the light passed through the sampling cell. Such measurements reflect the number of molecules in a volume. The latter is fundamentally a density (*e.g.*, gas content per volume).

Density q_c (per m^3) is different from mole fraction S (per mole of air) and from the dry mole fraction s, also called mixing ratio (per mole of dry air).

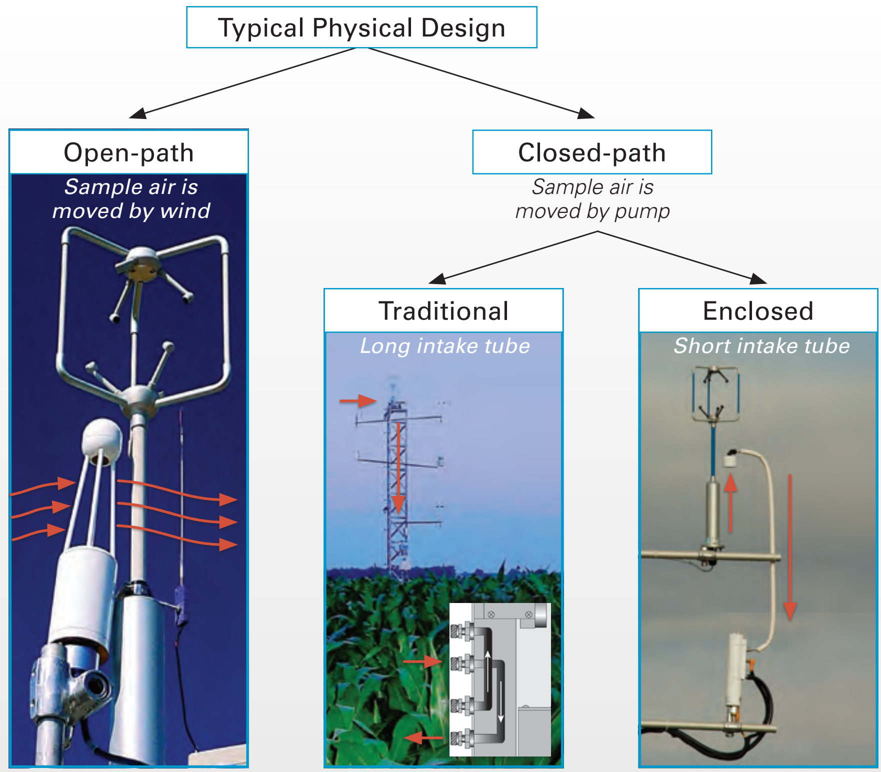
Density and mole fraction are different due to only two variables: gas temperature (T) and pressure (P), and one constant (gas constant R).

Density and dry mole fraction are different due to only three variables: water mole fraction X_w, temperature and pressure.

These differences become very important for eddy flux calculations as will be demonstrated later in Part 4, Sections 4.4-4.7.

Intrinsic measurement of gas density is one of the most important characteristics common to all optical designs of gas analyzers in the context of the eddy covariance method.

> ⚠ The term 'mixing ratio' is historically defined differently in chemistry and in micrometeorology. In chemistry, it describes the ratio of the constituent to the total mixture without this constituent. For example, moles of CO_2 would be divided by moles of non-dried air without CO_2.
>
> In micrometeorology, it usually describes the ratio of the constituent to the dry air. For example, moles (or grams) of CO_2 in the air would be divided by moles (or grams) of dry air with CO_2.
>
> Perhaps, the better, more universally understood alternative term to use in the context of this book would be 'dry mole fraction', or 'mole fraction in dry air'.



Traditionally, high-speed gas analyzers with response rates of 10 Hz or higher utilized for measurements of eddy covariance fluxes were designed in one of two configurations: open-path or closed-path. Both designs are well known, firmly established, and widely used.

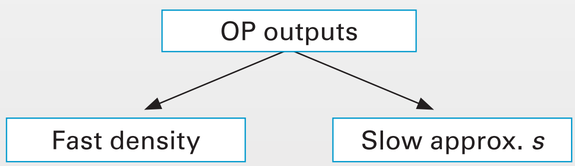
In the open-path design, the instrument is usually compact and does not need an enclosure or climate control box. The air sample is moved through the open cell of the gas analyzer by the wind. The sampling cell of the instrument is usually positioned near the sonic anemometer, with a horizontal separation of about 10-20 cm, as close as possible, but not so close as to significantly distort the natural air flow through the anemometer by the analyzer head. The cell windows are naturally cleaned by rain, and by routine maintenance on the tower.

In the closed-path design, the instrument is usually relatively large and needs a weather enclosure or a climate control box. The air sample is moved via an intake tube and then through the gas analyzer cell by a pump. The sampling cell of the instrument is usually positioned near the bottom of the tower, or several meters below the sonic anemometer to avoid significant flow distortion from large boxes. The air intake is positioned near the sonic anemometer, with a horizontal separation of about 5-10 cm, as close as possible, but not so close as to significantly distort the natural air flow by the rain cap. The setup usually involves many meters of intake tubing, often heated and insulated, to get the air sample from the top of the tower to the sampling cell; it requires one or more fine-particle intake filters to avoid cell contamination, and a strong pump to draw the flow through the long tubing and the filters. The cell may not be cleanable in the field, and often, may not be cleanable outside of a factory clean-room.

The enclosed design is a combination of the open-path and closed-path designs, intended to retain their respective strengths and minimize their weaknesses. The enclosed instrument is usually compact and does not need a weather enclosure or climate control box. The air sample is moved through the cell of the gas analyzer via a short intake tube by a low-power fan or pump. The sampling cell of the instrument is positioned closely below or away from the sonic anemometer. The air intake is positioned near the sonic anemometer, with a horizontal separation of about 5-10 cm, as close as possible, but not so close as to significantly distort the natural air flow. The setup usually involves very short intake tubes (10-100 cm). In clean environments fine-particle intake filters and strong pumps are not required. In dusty environments, a fine particle filter and stronger pump may be required. In all cases, the cell is easily cleanable on the tower during routine maintenance.

Open-path analyzers – *in situ* measurements

- Key advantages:
  - very fast, excellent frequency response
  - no pressure drop
  - no pump, low power
  - low sensitivity to window contamination
  - long-term stability, infrequent calibrations
- Key disadvantages:
  - data loss during precipitation and icing-over
  - no *T* attenuation, large density corrections



The advantages of open-path systems are *in situ* measurements, good-to-excellent frequency response for both trace gases and H_2O, no pressure drop, long-term stability, low or moderate sensitivity to window contamination, and no need for frequent calibrations. Since they do not require pumps, the power demand is quite low.

However, due to the open cell design, data collected during precipitation events and icing are often unusable. And, because of the open cell, they experience full-scale temperature, humidity and pressure fluctuations, which affect the measured gas density, but are not related to the gas flux from the area of interest. Thus, open-path fluxes may require large density corrections (Section 4.4), including a traditionally neglected pressure term. Some older models may also need a surface heating correction in very cold conditions.

Open-path analyzers usually output gas density, and can output dry density when fast H_2O is measured. But it is difficult for them to confidently compute the dry mole fraction (*e.g.*, mixing ratio) because fast temperature is measured elsewhere, and can be difficult to integrate accurately over the entire path. Furthermore, fast pressure is notoriously difficult to measure in the open air due to static/dynamic pressure issues.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

LI-COR Biosciences, 2009. LI-7500A Open-path CO_2/H_2O Analyzer Instruction Manual. Publication No.984-10563, 127 pp.

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399

Nakai T., Iwata H, and Y. Harazono, 2011. Importance of mixing ratio for a long-term CO_2 flux measurement with a closed-path system. Tellus B, DOI: 10.1111/j.1600-0889.2011.00538.x

Closed-path analyzers – air arrives via long tube

- Key advantages:
  - negligible data loss during precipitation
  - strong *T* attenuation
  - small density corrections
  - can be climate-controlled
- Key disadvantages:
  - significant frequency losses, especially for H_2O
  - may need powerful pump
  - usually not low-power

CP outputs

Fast density

Slow correct *s*

Closed-path analyzers are able to gather data during precipitation events, can often be climate-controlled, and are not subject to surface heating issues. Since long intake tubes attenuate most of the high frequency temperature fluctuations, the density correction in closed-path devices is much smaller than those for open-path analyzers.

However, closed-path devices are associated with significant frequency loss in long intake tubes, which especially affect fluxes of H_2O and other sticky gases, due to sorption and desorption of water molecules on the tubing walls. They may also need a high power pump, leading to greater power consumption — a significant challenge for remote locations.

Closed-path instruments, measuring H_2O in addition to the gas of interest, can compute fast dry density. However, computing fast dry mole fraction may be a challenge, because these instruments usually measure effectively slow temperature (for example, the temperature of the cell block and not the air stream). Also, depending on the specific model, they may or may not be able to measure fast pressure fluctuations, or control these to the negligible levels.

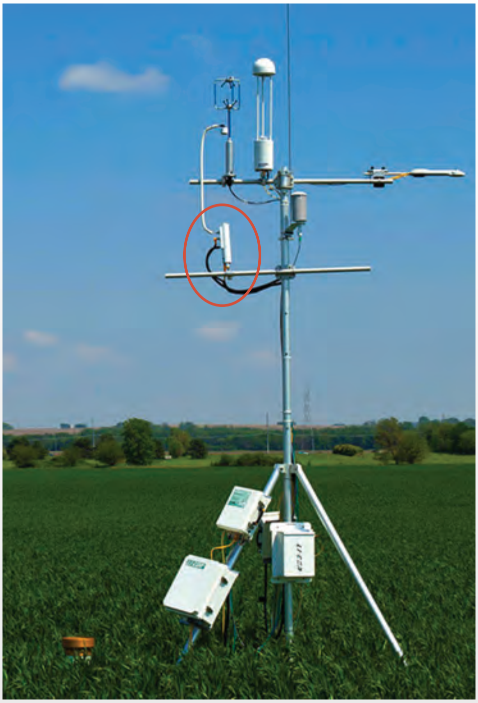
Slow temperature measurements may be adequate to compute fast dry mole fraction in cases with strong temperature attenuation by the long intake tubes. However, fast pressure measurements, or strict control of instantaneous pressure fluctuations, would still be required for accurate calculations of fast dry mole fraction.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

LI-COR Biosciences, 2005. LI-7000 CO_2/H_2O Analyzer Instruction Manual. Publication No.984-07364, 237 pp.

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399



Enclosed design combines advantages of open-path and closed-path designs

- Fast *T* and *P* are measured in the cell synchronously with gas and H_2O
- This provides the ability to compute fast dry mole fraction (mixing ratio) on-the-fly
- Using fast dry mole fraction eliminates the need for density corrections, and simplifies and improves flux calculations

Enclosed outputs

Fast density

Fast correct *s*

The enclosed design is fairly new, developed during 2006-2010, and field-deployed by a number of groups since 2011. Although mechanically similar to the traditional long-tube closed-path design, the enclosed design is a low-power solution with a short intake tube. This design is intended to solve most of the issues of the two traditional designs without sacrificing their positive attributes, maximizing their strengths and minimizing weaknesses.

Like the closed-path solution, the enclosed design experiences minimal data loss due to precipitation and icing, and is not subject to surface heating phenomena. Like the open-path solution, the enclosed design leads to improved frequency response because of the short intake tube, does not require frequent calibrations, and operates with low power consumption.

Another important feature of an enclosed design is the ability to output fast dry mole fraction (*e.g.*, mixing ratio), because native density measurements can be converted to dry mole fraction using instantaneous measurements of temperature, water vapor content, and pressure of the gas inside the sampling cell.

Outputting fast dry mole fraction implies that the instantaneous thermal and pressure-related expansion and water dilution of the sampled air have been accounted for in such a conversion. Thus, density corrections (Section 4.4) are not required to compute fluxes when the instantaneous dry mole fraction is used. This significantly simplifies the eddy flux calculations and reduces the flux uncertainty.

Fast measurements of air temperature and pressure in enclosed cell, measured in the sampled air stream and time-aligned with gas density and water vapor content, are critical for determining the correct dry mole fraction and adequate WPL terms for density-based gas fluxes. Large errors in the fluxes can result if these measurements are not available, ignored, or misaligned as further explained in Section 4.7

References

Burba, G., D. McDermitt, D. Anderson, M. Furtaw, and R. Eckles, 2010. Novel design of an enclosed CO_2/H_2O gas analyzer for eddy covariance flux measurements. Tellus B: Chemical and Physical Meteorology, 62(5): 743-748

LI-COR Biosciences, 2009. LI-7200 CO_2/H_2O Analyzer Instruction Manual. Publication No.984-10564, 141 pp.

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399

	Open-path design (*e.g.*, LI-7500A, LI-7700)	Enclosed design (*e.g.*, LI-7200)	Traditional closed-path (various models)
Sampling cell position	next to the sonic anemometer	within 1.5 m from the sonic anemometer	away from the sonic anemometer
Intake tube length	none	few centimeters to 1.5 m	4.0-40.0 m or more
Frequency losses	very small frequency dampening; path averaging	small tube dampening for non-sticky gases, medium for sticky gases and H_2O; path averaging	medium tube dampening for non-sticky gases, large for sticky gases and H_2O; path averaging
Time delay	very small	small	medium-to-large
Fast *T* and *P*, ability to output dry mole fraction	none	yes	somewhat, assuming zero *T'* and *P'*
Temperature attenuation	none	on average, 90-99%	on average, 95-99%
Size of WPL terms	*large (corrected by processing)*	*no WPL needed for s-based flux; small for density-based flux*	*small, mostly LE-term*
Cell cleaning	easy, user-cleanable; cleaned by rain; doesn't need intake filter	easy, user-cleanable; may need intake filter or manual cleaning	moderate-to-hard; often not user cleanable; need fine-particle intake filter
Calibration, zero-check	manual only	manual or automated	manual or automated
Data loss during precipitation events	medium-to-large	minimal-to-none	minimal-to-none
Power demand	very low	low-to-medium	medium-to-high

The choice between an open-path, enclosed, or closed-path design is largely a function of power availability and frequency of precipitation events. The key criteria for all designs are summarized in the table above.

The open-path analyzer measures *in situ* gas. No external air pump is required, thus reducing power consumption. Open-path analyzers' frequency losses are quite small, and are primarily related to path averaging and spatial separation between the sonic and the open-path analyzer. Flux calculations based on *in situ* density measurement require significant density corrections. Precipitation events are the main cause of loss of data. Low-power remote sites with little precipitation but fairly large fluxes would be good candidates for the open-path device. In addition, the open-path design is well-suited for measurements of fluxes of H_2O and other "sticky" gases.

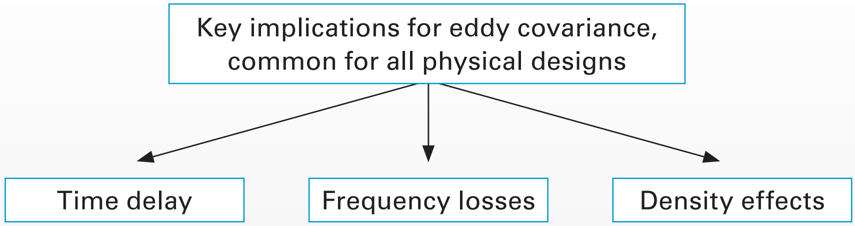
Closed-path gas analyzers require the sample air to be mechanically drawn to the sample cell by a high flow rate air pump, thus increasing system power requirements. The limiting factors in closed-path system are the capability of the sonic anemometer to operate during precipitation events, and loss of flux due to tube attenuation. Grid-power sites with large amounts of precipitation that are focused on fluxes other than H_2O would be good candidates for the closed-path device.

Enclosed analyzers are designed to be used with short intake tubes and fast temperature and pressure measurements of the gas in the cell, thus reducing tube attenuation of gas and water vapor fluctuations, eliminating density corrections, and lowering power consumption, without incurring susceptibility to precipitation-related data loss. The enclosed design is well suited for most types of sites and fluxes, but will require more power than the open-path design.

References

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399

LI-COR Biosciences, 2009. LI-7200 CO_2/H_2O Analyzer Instruction Manual. Publication No.984-10564, 141 pp.



Intrinsic measurement of gas density is one of the most important implications common to all *optical designs* of gas analyzers in the context of the eddy covariance method. The important implications common to all *physical designs* are mainly time delay, frequency losses, and density effects (*e.g.*, Webb-Pearman-Leuning terms, *etc.*). These will be discussed in detail in Part 4 (Sections 4.1, 4.2, and 4.4), and here we briefly describe their nature.

A time delay is the difference in time between when vertical wind speed and gas concentration signals are registered in the system. The delay comes from the separation distance between the analyzer and the anemometer, from the speed of electronic processing and logging, and from tube delays. In the open-path design, the time delay is small, usually a fraction of a second. In the closed-path design, the tube adds to all other delays, resulting in a large delay on the order of many seconds. Without correcting for the delay, fluctuations in w' and c' will not align or correlate well, and flux may be underestimated.

The frequency response of a system is lost for a number of reasons: tube attenuation, scalar path averaging, sensor separation, instrument time response, *etc*. In the open-path design, most frequency loss comes from path averaging, sensor separation, and instrument time response, and such frequency loss is usually very small, on the order of 5-10%.

In the closed-path design, tube attenuation adds to all other frequency losses, resulting in relatively high losses, on the order of 15-30% or more.

In the enclosed design with a short tube, the frequency response for non-sticky gases is closer to that of the open-path system, and for sticky gases the loss is intermediate between the open-path and the closed-path systems.

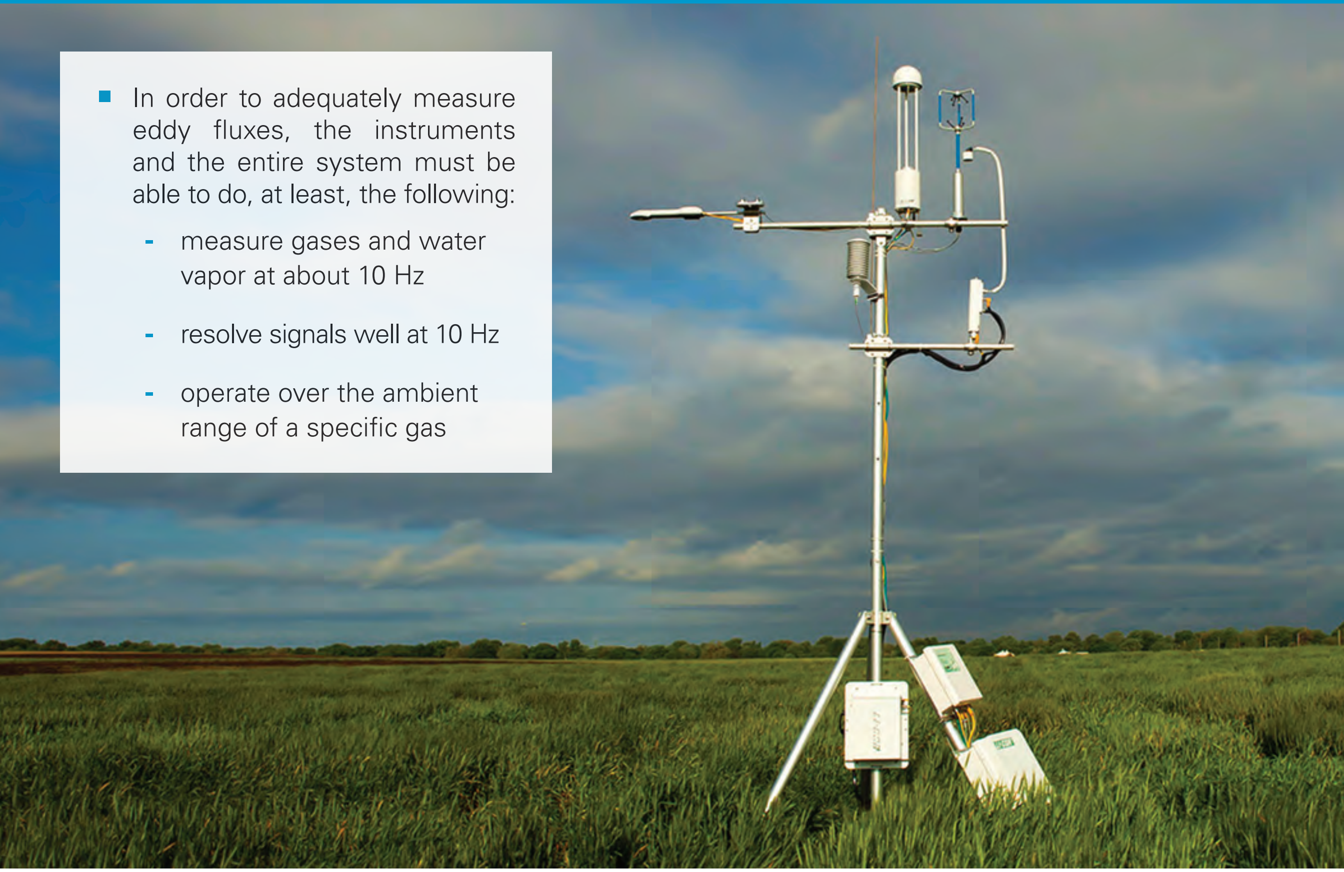
Density effects are related to fast fluctuations in temperature, humidity and pressure, affecting measured gas density, but are not related to the gas flux. In the open-path design, these can get quite large, often larger than the flux itself. In the closed-path design, these are usually quite small. In the enclosed design with fast dry mole fraction output, density terms are not required.

There are also various other design-specific implications in both optical and physical domains. For example these may include spectroscopic effects in LASER-based devices (Section 4.5), oxygen effects in krypton lamp-based devices (Section 4.8), surface heating effects in older open-path devices (Section 4.6), *etc*.

Part Two:

Designing An Eddy Covariance Experiment

Section 2.3 Selecting Eddy Covariance Instrumentation



- In order to adequately measure eddy fluxes, the instruments and the entire system must be able to do, at least, the following:
  - measure gases and water vapor at about 10 Hz
  - resolve signals well at 10 Hz
  - operate over the ambient range of a specific gas

The selection of the instruments has the foremost objective to satisfy the measurement purpose in the best possible manner. The first step here is to make sure that the system meets essential criteria, and is capable of delivering high quality data. Only then can any compromises be made regarding additional criteria to make the project less costly and more manageable.

Good eddy covariance instruments are not necessarily, and often not at all, the same as good analytical laboratory instruments or high-precision monitoring instruments, because of unique method requirements and the severity of outdoor deployment.

The essential instrument selection criteria, which are vital for eddy flux measurements, with no good substitutes, are: (i) fast time response of a system, (ii) good resolution at high frequency for gases and water vapor, and (iii) wide operational range of gas concentrations.

Instruments and systems need to be fast, ideally with a time response of about 0.1 s or less (*e.g.*, about 10 Hz), incurring minimal frequency losses. A response of 5-10 Hz would still be acceptable in most cases, incurring typical frequency losses and related corrections. A response below 5 Hz would be less desirable and would require larger corrections.

If instruments or systems are not capable of fast measurements, they will not be able to adequately sample high-frequency contributions to flux transport over a wide range of sites and conditions. One way to determine if the instruments or systems have a sufficient time response is to make sure that their time constant is less than 0.1-0.2 s.

Good resolution at such a high frequency is crucial for being able to distinguish the differences in gas density between upward and downward motions of the air. If an instrument does not have high enough resolution at high frequency, it will not be able to detect these differences and compute small fluxes. Indicators, such as RMS noise at 10 Hz, and comparisons with established eddy covariance instruments are helpful in making sure that the new or unknown instrument has sufficient resolution.

Concentration range is obviously critical, because if the instrument overranges after a certain ambient gas concentration, it will not be able to compute fluxes for that time period.

Fast sampling: usually refers to sampling at about 10 times per second (10 Hz) or faster

Time response: usually refers to system time constant, how fast a system can detect 63.2 % of the change it measures

10 Hz system: usually means that system can detect 63.2 % of change in 0.1 sec

Key points: A 10 Hz cell may not always mean a 10 Hz instrument, or a 10 Hz system: system response is important for eddy covariance

Sampling rate is not a system response: very slow instruments can be updated 1000 times per second (1000 Hz), which is not helpful for eddy flux computations

Much of turbulent transport happens at frequencies between 0.0001 Hz and 5 Hz, so eddy covariance system needs to have both fast response *and* fast sampling, otherwise it will miss a lot of transport and resulting flux

Instrument specifications can be reported using numerous parameters and wide ranging terminology.

As a result, it may not always be easy to understand if the three essential criteria for eddy flux system described in the previous page are satisfied. Here are a few details on how to read specifications and what questions to consider.

Can measure changes in concentration at about 10 Hz.

Relevant specifications can describe parameters such as "bandwidth", "sampling frequency", "sampling rate", "output rate", *etc*. These are suggestive of the actual time response, but they do not guarantee it.

Parameters such as "resolution at 10 Hz", "RMS at 10 Hz", "standard error at 10 Hz", *etc*. are stronger evidence that changes in gas concentration can be detected sufficiently fast. Yet even these do not guarantee the fast response needed for eddy covariance.

A more definitive criteria proving that the entire system is capable of measuring fast changes in gas concentration would be a system time response, often described by a system time constant.

However, it is quite difficult for manufacturers to specify a system time constant. This is because the gas sampling portion of an eddy covariance system is usually either built by the user from components (*e.g.*, gas analyzer, tubing, filters, pump, data collection electronics, *etc*.) or the user has a broad range of choices to rearrange a pre-built system to fit to a specific experiment.

System time response is not merely a cell time constant related to cell shape and size, nor is it a combination of the cell size and the detection speed of the gas analyzer. For all practical reasons during the planning stage, it should also include sampling arrangements (pump, filters and tubing in the case of closed-path instrumentation), and data collection arrangements (logging and memory).

Some instruments can accomplish 10 Hz sampling using just 8 liters per minute flow, and operate at normal pressure; others may need over 100 liters per minute flow and operate in a partial vacuum. This can make a substantial difference in what it will take to provide a fast system response in the field.

Filtering complexity, cost of the pump, short- and long-term pump operational expenses, acceptable temperature range for the pump and the related need for climate control, grid power, *etc*. can become quite important when considering practicability of a field deployment of the fast eddy covariance system.

Can resolve changes well at 10 Hz.

If the instrument is fast and the system can be configured using reasonable efforts to sample rapidly under field conditions, the next important consideration is to assess how well the instrument can resolve fast changes.

The relevant specifications are usually reported at a given gas concentration as Root Mean Square (RMS) at 10 Hz, resolution at 10 Hz, precision at 0.1 seconds, sigma at 0.1 second, *etc*.

The gas concentration used in such specifications is usually atmospheric ambient for field instruments, but can be quite low or quite high for industrial or laboratory instruments. In these cases, the measure of high-speed resolution should be recalculated at ambient concentrations. Manufacturers can generally provide all the necessary parameters for the recalculation.

Although there is no absolute cutoff number for required fast resolution, the smaller the change in gas concentration an instrument can resolve at 10 Hz, the smaller the flux it can detect, and the smaller are the errors bars that would be expected for the final flux numbers.

The caveat here is that if the error in gas concentration is random and does not correlate with vertical wind speed, this 'noise' would be filtered out by a covariance. So, the resulting flux error could be greatly reduced or eliminated. In a broad sense, this makes fast resolution somewhat more important than low noise or high absolute accuracy when reliable eddy covariance measurements are considered.

Other frequently used specifications are long-term stability, long-term precision, drifts, *etc*. These are all desirable characteristics for any measurement system, and are essential for high-precision mean concentration monitoring. However, these are not nearly as critical for eddy covariance flux measurements as fast response and good resolution at 10 Hz. This is because one of the first steps in the eddy covariance flux computation is the removal of half-hourly or hourly means (details are in Part 1 and Section 4.1). When the mean concentration is removed and only deviations from the mean (s') remain in further flux computations, most of the specifications related to mean gas values become less critical.

The exception would be (i) significant mean drifts affecting calibration slopes or gain of the instrument, and thus, translating directly into flux errors, and (ii) drifts so large that they appreciably affect calculation of Webb-Pearman-Leuning density terms (Section 4.4).

Can measure over the ambient range of a specific gas.

Relevant specifications can be termed "operating range", "calibration range", "gas range", "range", *etc.*

Many instruments do not overrange, but rather reduce resolution and overall performance outside the specified range. Manufacturers are usually able to provide details on how a particular model acts outside the specified range of gas concentrations.

In some cases, the operational range of gas concentrations may be broad, but resolution and other specifications are reported for a much narrower range. In such cases, it is important to assess what gas concentration range is expected in the field experiment, and how well the instrument will perform outside this range.

Assessing system time response may be difficult for both researchers and manufacturers. One tool to help accomplish this task in a direct and quantitative manner is spectral and cospectral analyses, described in detail in Section 4.10. The quality and shape of daytime gas flux cospectra in comparison with sensible heat flux cospectra provides a snapshot of how well the system measures gas flux transport at different frequencies.

This is a powerful but a fairly advanced tool. Modern programs will compute cospectra of relevant parameters, but will not be able to analyze them. So, cospectral analysis for a specific system will have to be conducted by a researcher, or will have to be found for a similar system in the available literature.

Other important criteria

- There are many additional important criteria aside from good frequency response, high temporal resolution, and operation over the ambient range of a gas concentration
- These additional criteria will not preclude the eddy flux measurements in principle, but may significantly affect data quality, costs of the experiment, and amount of site management

Modern instruments that satisfy the three main criteria (*e.g.*, time response of about 10 Hz, good resolution at 10 Hz, operation over ambient range of gas concentration) are fairly expensive high-end devices. In general, they are designed in such a way that other technical specifications of the instrument itself are usually sufficient for eddy covariance, or at least can be easily deduced from careful reading of the technical description and field tests.

There are still a number of additional criteria, which are sometimes not published in specifications, yet result in significant practical differences between the instruments, especially after their integration into the station. These important criteria will not preclude the eddy flux measurements in principle, but may significantly affect measurement quality, costs of the experiment and setup, and cost and amount of site management efforts.

The full list and the relative weight of such criteria in relation to each other will strongly depend on the purpose and design of the experiment, and on the location and setup of the station. It is difficult to describe these in all possible combinations, so here are few examples of the criteria important for flux data quality in most experiments and setups:

- level of flow distortion to sonic anemometer
- degree of sample distortion by intake tube
- amount of data loss due to non-omni-directional setup
- amount of data loss due to precipitation
- other instrument performance characteristics (calibration slope stability, accuracy, *etc.*)
- *etc.*

And here are few examples of criteria affecting experiment costs and site maintenance:

- operating temperature and pressure ranges
- power consumption and carbon footprint
- ruggedness and weatherproofing
- contamination sensitivity and filtering needs
- communications and memory size
- ease of use by non-technical user
- portability, size, weight, *etc.*

Examples of additional criteria affecting data quality in most situations:

- flow distortion to sonic anemometer
- sample disturbance by intake tube
- data loss in non-omni-directional setup
- data loss due to precipitation events
- other instrument characteristics
- *etc.*

Examples of criteria affecting experiment costs and site maintenance:

- temperature and pressure ranges
- power consumption
- ruggedness and weatherproofing
- contamination sensitivity
- communications and memory size
- ease of use by non-technical user
- portability, size, weight, *etc.*

Effects of many of these criteria are self-evident. For instance, it is clear that sampled air will be disturbed more if the analyzer is designed so that it must be located at the bottom of the tower, and must use a long intake tube. All gas fluxes will be affected, but water vapor and sticky gases (*e.g.*, ammonia) will be affected much more than, for example, CO_2 and CH_4.

Losses from distorted wind directions in systems relying on non-omni-directional anemometers (*e.g.*, C-clamp design, *etc.*) may exclude parts of the ecosystem or other territory from data coverage, and may result in biases or gaps. Sites with a single or few prevailing wind directions can have the anemometer's back side facing a tower positioned in an infrequent wind direction, so data will be affected less than at the sites with multiple wind directions.

Data are normally lost during precipitation or irrigation events due to sonic anemometer limitations, but additional losses and prolonged periods of recovery afterwards may degrade the overall data quality and coverage. Sites with frequent precipitation will be affected more than those with little or no precipitation.

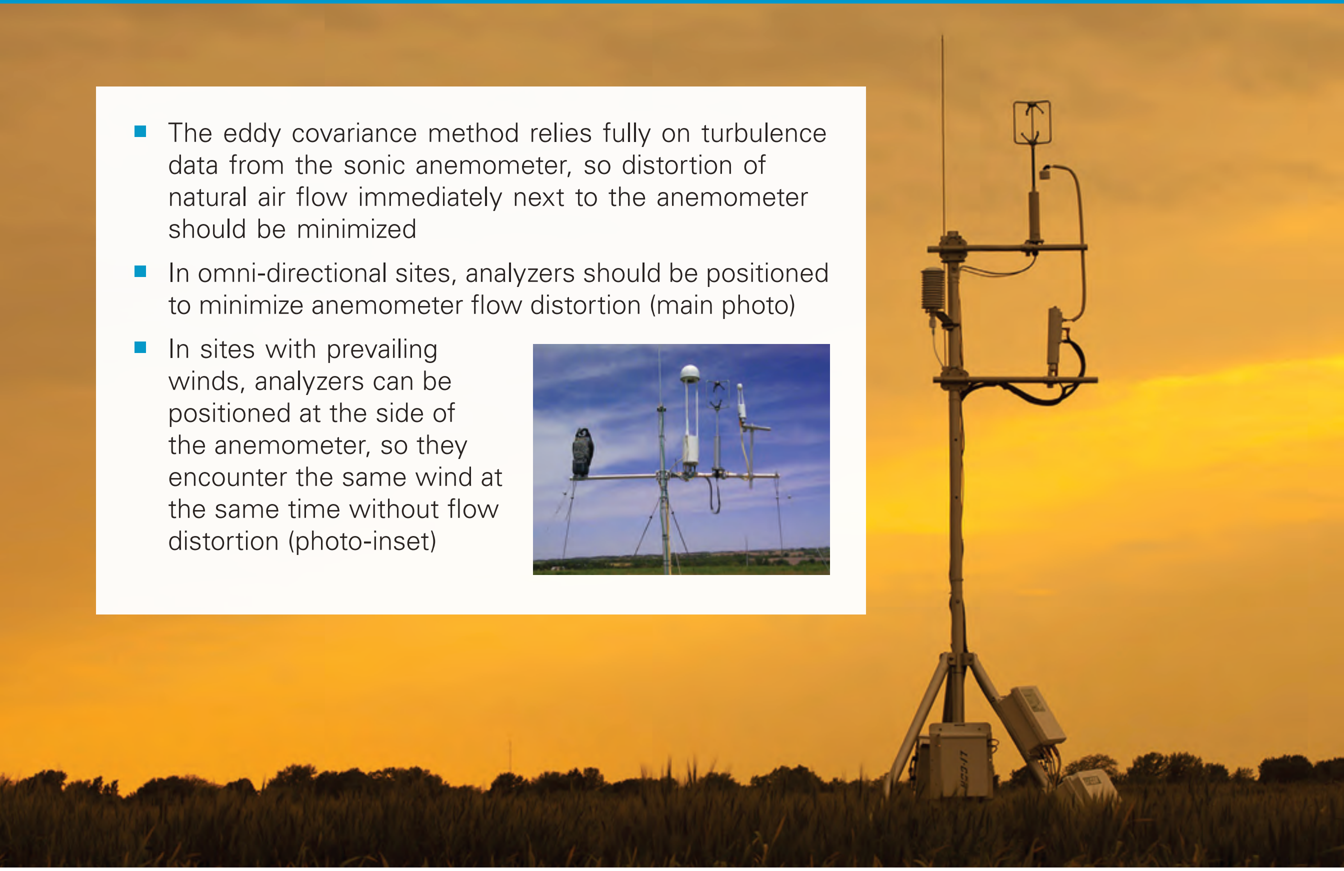
A narrow temperature range for the analyzer or the need for a fast pump may require building and maintaining a climate controlled enclosure, or in some cases a hut, increasing power demand, costs and maintenance. Remote low-power sites are affected the most.

A narrow pressure range may require building a pressure-control system, increasing power demand, costs and complexity.

Hyper-sensitivity of an analyzer to cell contamination, particularly in cases when high-finesse mirrors are involved, will require a stack of multiple fine-particle intake filters, so grid power will likely be required. Low-power sites are affected the most.

Small system logging memory will lead to the need for more frequent data downloads, and more maintenance visits will be required at a site without remote data access.

Other criteria are not as self-evident as those listed above, may have certain caveats, or require special considerations. In the next few pages we will discuss details on a few of the most frequently overlooked aspects of instrument selection, in addition to the prime criteria of frequency response and concentration range. These aspects are flow distortion, power requirements, and overall setup and maintenance needs.



- The eddy covariance method relies fully on turbulence data from the sonic anemometer, so distortion of natural air flow immediately next to the anemometer should be minimized
- In omni-directional sites, analyzers should be positioned to minimize anemometer flow distortion (main photo)
- In sites with prevailing winds, analyzers can be positioned at the side of the anemometer, so they encounter the same wind at the same time without flow distortion (photo-inset)

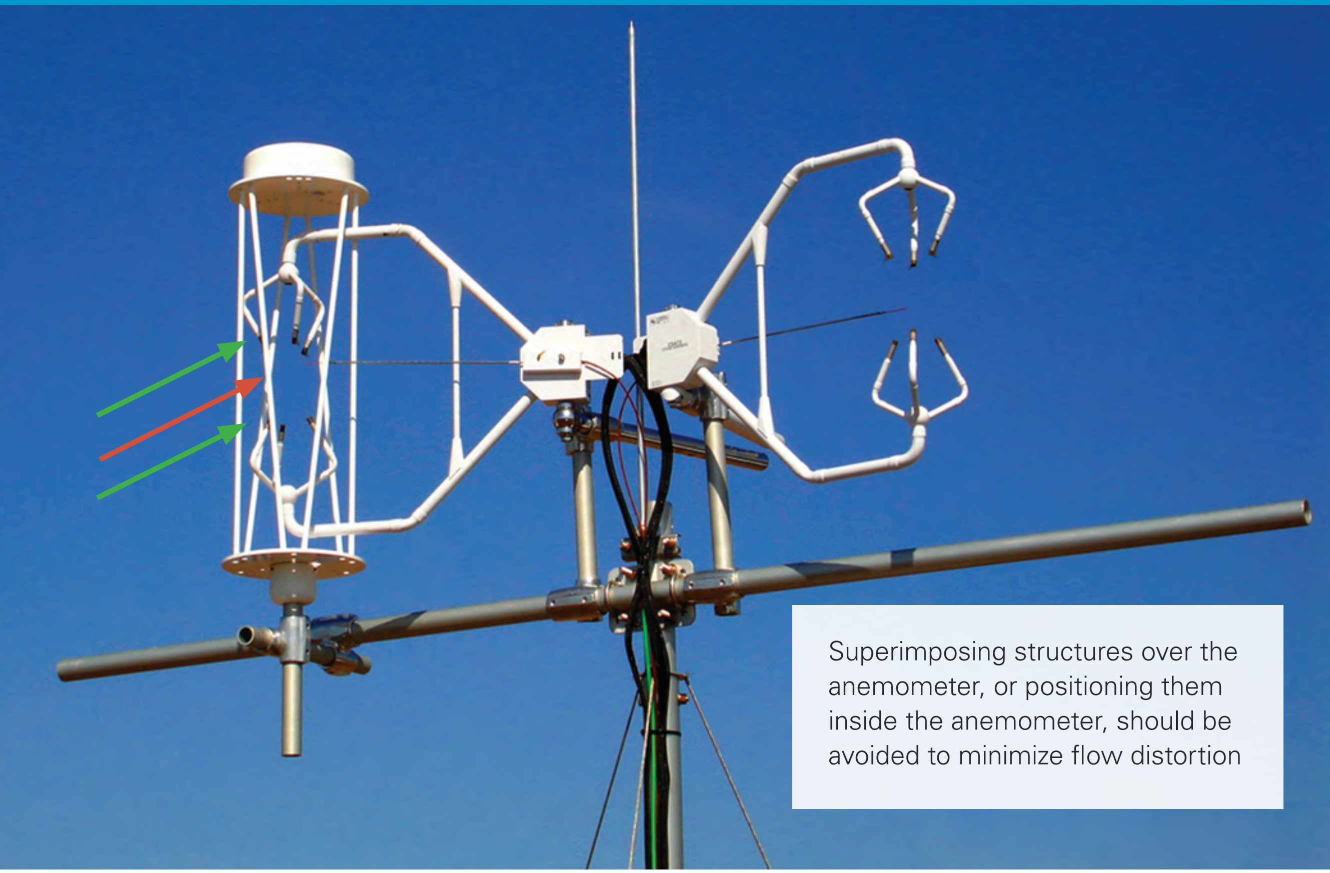
The eddy covariance method is fully reliant upon the measurements of a turbulent transport of mass and energy from the surface into the atmosphere. As a result, most of the calculations are based on the sonic anemometer's measurements of three wind components (*u*, *v*, and *w*) and sonic temperature, which describe the turbulent transport at a fast rate. Because of these fundamentals of the eddy covariance approach, distortion of the natural air flow immediately adjacent to the sonic anemometer's path (*e.g.*, within 1-2 cm) is highly undesirable, and can affect flux measurements.

In fact, keeping the flow distortion next to the sonic anemometer to a minimum is more critical than that next to the gas analyzer. This is because distortion in the analyzer path can be corrected relatively easily by looking at the reference temperature cospectra from the sonic anemometer (*e.g.*, *w'T'* described in Section 4.2) or related Kaimal model, but distortion in the anemometer path is difficult to correct, since directly measured reliable reference cospectra would no longer be available in the distorted flow next to the anemometer.

At experimental sites with strong prevailing wind directions, or with one or more infrequent wind directions, virtually any gas analyzer can be used when positioned on the side of the anemometer from the least frequent direction, or between the anemometer and the tower; these wind directions are excluded from the data as a matter of course.

At sites with multiple wind directions and an omni-directional setup on top of the tower, gas analyzers should ideally be chosen so that they allow positioning of the instrument on the tower with minimal or no flow distortion to the anemometer. Any device (*e.g.*, analyzer head, supporting bars, lightning rods, *etc.*) should be positioned at least 10-20 cm away from the anemometer, or placed below it, as shown in the main photo above.

Any type of structure should never be superimposed, or positioned inside the sonic anemometer path, as it can both obstruct sonic signal and significantly distort the flow near sonic transducers.



Superimposing structures over the anemometer, or positioning them inside the anemometer, should be avoided to minimize flow distortion

A good example of the consequences of positioning the structure immediately adjacent to (*e.g.*, within 1-2 cm) the sonic anemometer's transducers is shown in the picture above.

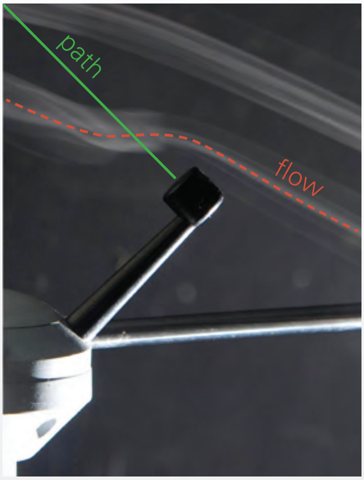
In this field experiment at a 3 m height above a short canopy, the 6 mm diameter tube (red arrow in the photo above) was positioned about 1.5 cm away from the two sonic transducers (green arrows).

When wind was coming through this tube and into the sonic path (direction perpendicular to the photo), *w* was distorted. This led to a reduction in midday flux by 3-4 % in relation to the unobstructed anemometer on the right. When wind was passing between two tubes, or when it was passing through the tubes located 5-10 cm away from the transducers, distortion was minimal or was not detected.

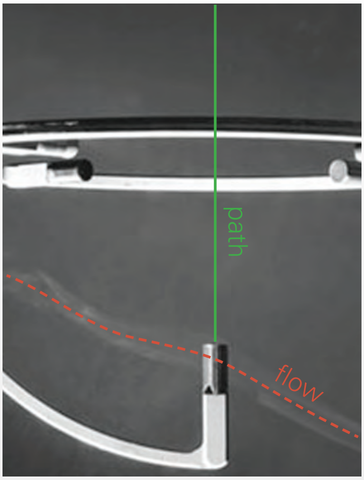
However, large plates at the top and bottom of the structure still distorted between 7% and 9% of the *w* depending on the angle of the 3-D wind in relation to the structure, probably as a result of blocking the sonic path from the parts of the vertical wind flow.

This example illustrates that an aerodynamically shaped analyzer positioned 10-20 cm away from the anemometer in the least frequent wind direction, or below the anemometer path, is perhaps the safest way of setting up the system, and a good guide for selecting instrumentation.

In addition to the analyzers and other structures potentially distorting the natural flow into the anemometer, the anemometers themselves have a physical structure, and thus, they can distort some portion of the very same flow they try to measure. There are several kinds of such distortion: direction-biased mean flow distortion from the back side of C-clamp anemometers; direction-biased turbulence distortion from the back side of C-clamp anemometers and from support spars of omni-directional anemometers; angle of attack–based vertical movement distortion by transducer support structures and transducers themselves; *etc*.



Non-orthogonal arrangement, with angled path



Orthogonal arrangement, with vertical path

Adopted from Kochendorfer, et al. (2012)

The anemometer should be chosen with flow distortion aspects in mind. Onmi-directional anemometers may accept data from all directions, but may distort air flow from the three vertical spars supporting the transducer structure. C-clamp designs do not have such spars, but are not omni-directional and can distort the flow from 30% or more of wind directions coming from the back side.

In addition, both designs can distort the flow due to the presence of junctions supporting the transducers, and due to the transducers themselves. Recent studies by Frank *et al.*; Frank and Massman; Kochendorfer, Meyers and Heuer; and by Nakai and Shimoyama have observed a reduction in measured flux on the order of 8-12% as a result of the flow distortion by the anemometers themselves, observed in many common designs with off-axis sampling (photo above left).

The exception was a design where transducers for *w* were small, positioned vertically, and located away from the transducers for the other two wind components (right photo above). Errors in fluxes measured using this type of design were within 1%.

There are ways of potentially solving these types of issues via angle of attack corrections for particular angles, and via matrix corrections for all angles of wind in relation to the anemometer. Parts of such corrections are applied by the manufacturers, while the rest are being developed by the scientific community, and may be included in modern flux processing programs.

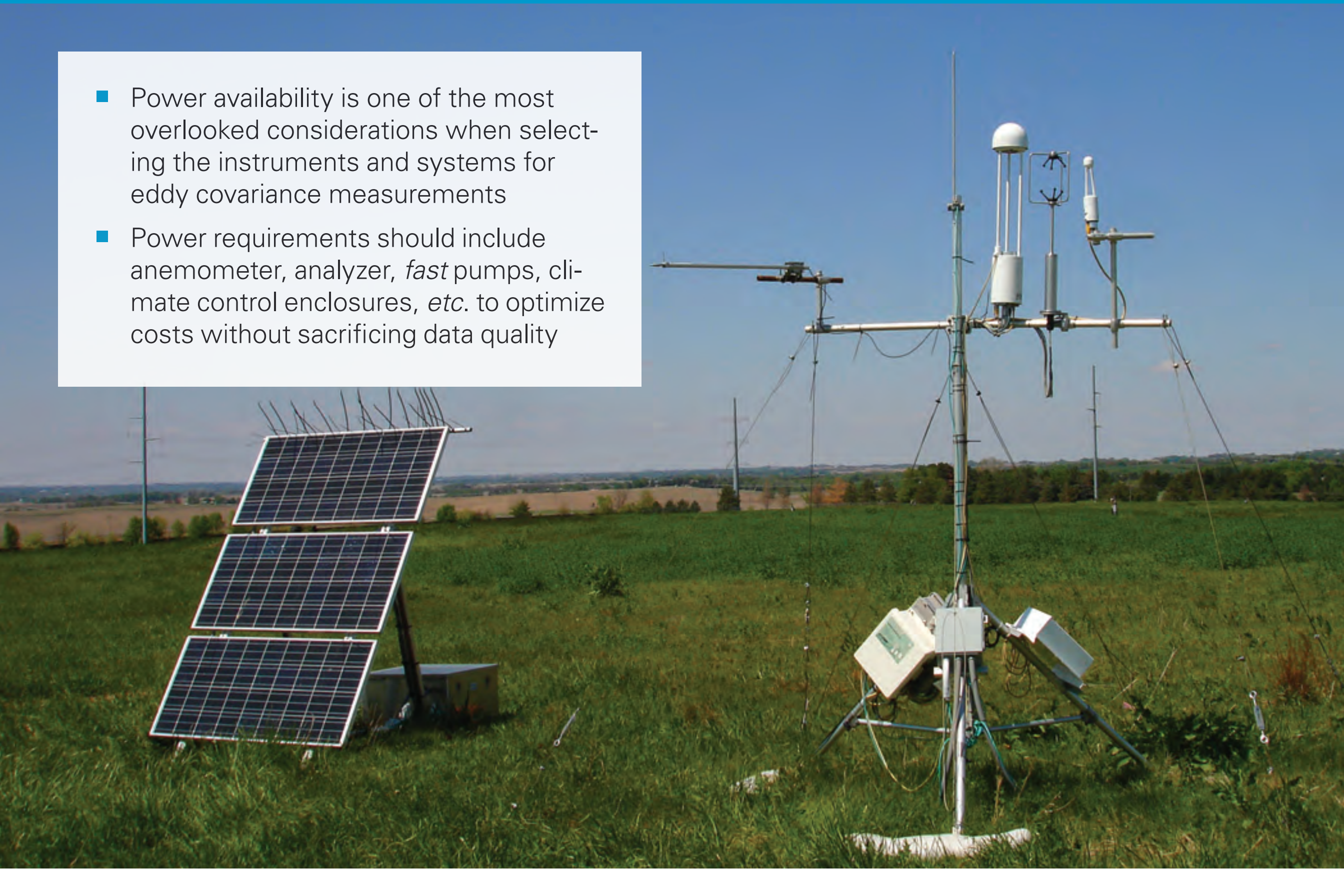
References

Frank, J., W. Massman, and B. Ewers, 2012. Underestimates of sensible heat flux due to vertical velocity measurement errors in non-orthogonal sonic anemometers. Agricultural and Forest Meteorology, *In press*

Kochendorfer, J., T. Meyers, J. Frank, W. Massman, and M. Heuer, 2012. How well can we measure the vertical wind speed? Implications for fluxes of energy and mass. Boundary-Layer Meteorology, 16 pp. DOI 10.1007/s10546-012-9738-1

Nakai, T., and K. Shimoyama, 2012. Ultrasonic anemometer angle of attack errors under turbulent conditions. Agricultural and Forest Meteorology, (162): 14–26

- Power availability is one of the most overlooked considerations when selecting the instruments and systems for eddy covariance measurements
- Power requirements should include anemometer, analyzer, *fast* pumps, climate control enclosures, *etc*. to optimize costs without sacrificing data quality



Power availability is one of the most overlooked considerations when selecting instruments and systems for eddy covariance measurements.

While many of the complex multi-ecosystem scientific applications and many of the industrial applications may have an electric line readily available at the site, most other applications may not have grid power.

One way around this issue is to locate the experiment at an area with an available grid line. This will alleviate the power issue, but may compromise the measurement itself, or make the measurements less relevant by poorly representing the area of interest.

Another approach is to bring grid power to the location deemed best for the particular measurements. This may be a reasonable option, but the expense of putting in the new power line and supporting it over time should be carefully accounted for, and weighed against the cost of a low-power system.

There are a number of actual cases where power requirements were not fully considered during the initial planning and instrument selection, and as a result, grid power had to be provided to the site at the cost of tens of thousands of dollars, and even over a million dollars. This is several times the cost for several complete low-power systems.

Low-power arrangements may include solar panels, wind or small fuel generators, or a combination of all of the above. These systems usually employ open-path or enclosed analyzers, because closed-path designs typically need high-power pumps to provide fast sampling flow and climate controlled enclosures to provide the optimal operating temperature range and weatherproofing.

Total power requirements of the site, including anemometer, analyzer, fast pumps (and especially, dry-scroll vacuum pumps), climate controlled enclosures for the analyzer and the pump, auxiliary measurements, data transmission *etc*. should all be computed when selecting the hardware, to optimize costs without sacrificing measurement quality.

- Measurements of CO_2 and other greenhouse gases can have a substantial carbon footprint themselves - this aspect may be important to consider during hardware selection
- Depending on the scope and focus of a particular study, some gas sensing technologies can lead to large CO_2 emissions, or equivalents, while other studies can remain nearly carbon-neutral
- For example, the carbon footprint of a study measuring fluxes of 3 gases (CO_2, H_2O and CH_4) over one year can differ by a factor of 30, depending on the gas sensing technology the measurements are based upon

Gas sensing technology	WMS/NDIR *(e.g., LI-7500A, LI-7700)*	WMS/NDIR *(e.g., LI-7200, LI-7700)*	CRDS	ICOS
Power Demand	≈ 20 W	≈ 39 W	≈ 600W	≈ 600W
Carbon Footprint	≈ 107 kg/yr	≈ 208 kg/yr	≈ 3200 kg/yr	≈ 3200 kg/yr
Power Cost	$19/yr	$38/yr	$574/yr	$574/yr

In recent years, more attention has been paid to the carbon footprint, defined as the total amount of greenhouse gas emissions "caused by an organization, event or product" (UK Carbon Trust). Carbon footprint is usually measured as the CO_2 equivalent, and describes how much of the greenhouse gas was emitted into the atmosphere as a result of direct emission (for example, using a power generator) or indirectly (as a result of general power consumption, travel, *etc*.). A number of organizations and individual groups have adopted a carbon-neutral approach by optimizing electrical demands, travel, and lifestyle.

Similarly, flux studies and projects may consider the carbon footprint resulting from how fluxes are being measured. This will depend on the scope and focus of the particular study, but also on the gas sensing technology being used.

Four leading gas sensing technologies presently employed in fast greenhouse gas measurements are Non-Dispersive Infrared (NDIR), Wavelength Modulation Spectroscopy (WMS), Integrated Cavity Output Spectroscopy (ICOS), and Cavity Ringdown Spectroscopy (CRDS). While being quite good in their respective applications and instruments, they are quite different in power consumption during long-term field deployments, resulting in substantial differences in their carbon footprint.

For example, the combination of NDIR and WMS gas sensing with a pump-free instrument design allows fast simultaneous measurements of CO_2, H_2O and CH_4 using about 20 Watts of power and causing 107 kg of CO_2 emissions per year during continuous studies. The ability to use solar panels with an NDIR/WMS combination can further offset this relatively small footprint and make this portion of the flux measurement process nearly carbon-neutral.

By contrast, current instruments that employ CRDS and ICOS gas sensing technologies require about 600 W of power or more (primarily due to high-powered vacuum pumps and demanding climate controls), and result in over 3200 kg of CO_2 emissions per year. The grid power requirements and associated construction may further increase this already substantial carbon footprint.

- Setup and maintenance are additional important considerations when selecting the instruments and systems for eddy covariance field deployment
- The following aspects should be considered:
  - Technical complexity of setup
  - Frequency, intensity and complexity of regular field maintenance
  - Risks and consequences of instrument or system failure
- The set of specific questions shown below helps to put these considerations into a practical perspective during the planning stage of the experiment

The additional important considerations when selecting the hardware are the setup and maintenance requirements. Particularly important are the technical complexity of setup; frequency, intensity, and complexity of regular field maintenance; and risk and consequences of instrument failure. These affect monetary and time/labor costs of setup and maintenance, data quality and percentage of coverage, and minimal qualifications of a field site operator.

Here are some examples of the questions to consider during instrument/system selection for the field deployment.

Technical complexity of setup:

(1) Can I set up the system in the location I want?

(2) What will it take to set it up in the location I want?

(3) What will it take to install it on the tower:

- Is it too heavy for the tower?
- Can it operate in cold/hot/rainy weather?
- Can it be housed in a box on the tower?
- Will building a hut be required?

Frequency, intensity, and complexity of maintenance:

(1) What will it take to maintain this instrument/system in the field:

- How expensive is the field maintenance?
- Can cell and windows be cleaned in the field?
- How often does one need to clean the cell?
- How often does one need to replace filters?

(2) How much memory does the system have:

- How often should one visit the site to download data?
- Is there data backup, Ethernet, wireless, *etc.*?

(3) Is this instrument/system simple enough:

- Could a local person be hired to do bi-weekly maintenance?
- Could this person hook a laptop to the system, check signals, clean cell, change filters and memory card?

Risks and consequences of failure:

(1) How robust is this instrument/system in the field?

(2) What happens if it is not regularly maintained:

- Will it gradually reduce data quality?
- Will it just stop collecting the data?
- Will it need factory cleaning and recalibration?
- Will it fail and need replacement?

Key instrument requirements:

- fast (actual response of about 10 Hz)
- high resolution at 10 Hz
- low flow distortion
- good at relevant specifications
- rugged, weatherproof
- low sensitivity to dirt, dust, *etc.*
- low sensitivity to water
- easy to use by non-technical user
- small/manageable size
- low power, few solar panels
- practical in the field

Air flow can be imagined as a horizontal flow of numerous rotating eddies of different sizes roughly distributed over the measurement height. Lower to the ground small eddies usually prevail, and they transfer most of the flux. Higher above the ground large eddies transfer most of the flux. Small eddies rotate at very high frequencies, and large eddies rotate slowly.

For these reasons, good instruments for eddy covariance need to be "universal". They need to sample fast enough to cover all required frequency ranges, but at the same time they need to be very sensitive to small changes in quantities.

Instruments should not distort the natural air flow moving into the sonic anemometer. They should not break large eddies with a bulky structure, so that they can measure accurately at great heights, and they should be aerodynamic enough to minimize the creation of many small eddies from the instrument structure, so that they can measure accurately at low heights. They should not average small eddies, and should be practical in terms of maintenance, power consumption and weight.

The next section will review major instrument types using LI-COR gas analyzer models as examples.

The selection of hardware has an overarching goal of satisfying the measurement purpose in the best possible manner. The foremost objective is simply to make sure that the hardware is capable of delivering high-frequency high-resolution data over the full range of gas concentrations. Only then should compromises be made on additional criteria to make the project less costly and more manageable.

References

Foken, T. and S. Oncley, 1995. Results of the workshop 'Instrumental and methodical problems of land surface flux measurements'. Bulletin of the American Meteorological Society, 76:1191-1193

Yamanoi, K., R. Hirata, K. Kitamura, T. Maeda, S. Matsuura, *et al.*, (Eds.), 2012. Practical Handbook of Tower Flux Observations. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp. (Electronic Edition in English)

Part Two:

Designing An Eddy Covariance Experiment

Section 2.4 Details for Some Specific Instrument Models

- Many manufacturers produce numerous models of anemometers to measure wind speed in various settings
- A relatively small number of specific models are suitable for eddy covariance flux measurements
- These models rely on sonic anemometry principles (see p. 47 for details); they are fast, have high resolution, and in most cases, can measure all three components of 3-D wind speed

Among numerous anemometer manufacturers and models, relatively few are suitable for eddy covariance measurements due to response rate limitations, directional abilities, geometric design, and signal resolution.

Modern commercially available models suitable for eddy covariance measurements are all based on the principles of sonic anemometry.

Cup and vane anemometers have difficulty measuring vertical wind speed, and are generally slow-response sensors.

Various hot wire anemometers can be very fast, but have difficulties distinguishing between wind components.

Laser anemometers are fast and work well with wind components, but most do not have adequate resolution of wind speed at high frequency.

Even among sonic anemometers, relatively few models can be successfully used for turbulent flux transport measurements. Only designs with paired transducers installed on the thin arms are suitable. Designs relying on two solid disks may distort too much flow.

Suitable models are fast high-resolution devices, overwhelmingly of 3-D design. The 1-D and 2-D type sonic anemometers can and have been used for eddy covariance measurements in the past, but data processing becomes quite challenging in such cases, and results may have higher uncertainty.

A list of key manufacturers and specific models suitable for eddy covariance measurements (as of 2012) are shown in the table on the next page.

Sections 2.2, 2.3 and 3.2 of this book provide more details on the principles of operation, selection criteria and installation of sonic anemometers of different design in the context of eddy covariance stations.

In brief, regardless of the model and design type, all anemometers require proper installation, leveling and maintenance. This includes selecting and installing the instrument to minimize flow distortion (details in pages 48 and 67-69), maintaining a constant orientation to minimize angle of attack errors, and keeping the transducers clean to minimize sonic errors.

- Examples of producers and key models of sonic anemometers frequently used in eddy covariance measurements

Manufacturer	Specific Models
Applied Technologies (ATI)	Vx, Sx, V, K
Campbell Scientific (CSI)	CSAT3
Gill Instruments	HS-100, HS-50, R3 and WindMaster series
Kaijo/Sonic Corporation	DA-500, 600, 700, and 900 series
Metek	uSonic-3 series
R.M. Young Company	81000VRE
Thies Clima	Ultrasonic Anemometer 3D

Instruments should be installed on a firm base facing prevailing wind directions; this is especially important for the c-clamp design. This design is not omni-directional, and while it may distort less flow from some angles, it is likely to distort a lot more flow from over ⅓ of backside wind directions. Further details of installation are provided in pages 150-155 of this book.

Small amounts of rain, dew, snow and frost on the sonic transducer may change the path length, and thus the estimate of speed of sound, and will usually lead to small errors in some models and to larger errors in others.

While each model may react differently to light rain events, none can produce reliable readings in heavy precipitation.

References

The key manufacturers of sonic/ultrasonic anemometers used in eddy covariance are:

ATI - http://www.apptech.com

CSI - http://www.campbellsci.com

Gill Instruments - http://www.gill.co.uk

Kaijo - http://www.u-sonic.co.jp

Metek - http://www.metek.de

R.M. Young - http://www.youngusa.com

Thies Clima http://www.thiesclima.com

A good source of information on sonic anemometry as applied to eddy covariance measurements is Chapter 2, pages 35-40 of: Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

A useful video demonstrating sonic anemometer operational principles can be accessed at:
http://www.gill.co.uk/products/anemometer/principleofoperation.htm

- The LI-7500A is a 2010 model for measurements of CO_2 and H_2O eddy fluxes and concentrations
- It is based on widely-used LI-7500 design, modified to produce substantially less heat and to consume less power during extremely cold conditions
- Includes fast logger for sonic anemometer, CO_2/H_2O analyzer, and open-path CH_4 analyzer
- Can create greenhouse gas (GHG) files for seamless processing with EddyPro® to produce final flux values
- Can integrate slow biometeorological files into GHG file
- Can communicate via multiple protocols including Ethernet for remote access via Internet
- Built for long-term, mobile and remote operations

The LI-7500A, an updated model of the older LI-7500, is an open-path, high speed, high precision, non-dispersive infrared gas analyzer for measuring fast densities of CO_2 and H_2O *in situ*.

It is designed specifically (*e.g.*, build, resolution, performance, *etc.*) for eddy covariance applications, but is often used for other gas measurement applications.

The LI-7500/LI-7500A is the most widely used open-path CO_2/H_2O analyzer in the world (as of 2012), deployed at several hundred eddy stations. Data from this analyzer have been used in many thousands of journal papers, and in tens of thousands of reports, technical, and conference publications across the globe.

The LI-7500A is a new model modified to produce substantially less heat and reduce power consumption during extremely cold conditions.

The new model also includes a logging system, the LI-7550, to collect data from a sonic anemometer alongside the CO_2 and H_2O data.

The LI-7550 accepts high-speed analog data from a fast 3-D anemometer, and can log complete GHG data sets to a removable USB storage device.

The LI-7550 is included with the LI-7500A, and has a weatherproof enclosure to house the control unit's high-speed electronics.

Ethernet and serial data are output at selectable speeds of up to 20 Hz. Direct PC logging of LI-7500A and sonic data is also possible.

The two selectable temperature settings available in the LI-7500A are: (i) a low temperature setting of +5 °C, and (ii) the default setting of +30 °C. The low temperature setting was added for studies in extremely cold climates to reduce energy usage and heat dissipation.

Both system power demand and external heat dissipation are reduced significantly when the +5 °C setting is activated in extreme cold. Please see section 4.6 (page 220) for details on the advantages of the +5 °C setting.

	CO_2	H_2O
Measures at 10 Hz or faster	up to 20 Hz	
High resolution at high frequency	0.11 ppm RMS@10 Hz	0.0047 ppt RMS@10 Hz
Wide gas concentration range	0-3000 ppm	0-60 ppt (mmol/mol)
typical ambient	*300-900 ppm*	*0.5-40 ppt (mmol/mol)*
Temperature range	(-40) -25 to +50 °C	
Pressure range	20-120 kPa	
Power	12 W nominal	
Size	6.5 x 30 cm (2.6" x 12") head on the tower near sonic 35 x 30 x 15 cm (13.8" x 12 x 6") interface/logging box below	
Weight	0.75 kg (1.65 lbs) head on the tower near sonic 4.4. kg (10 lbs) interface/logging box below	

- Ruggedness and weatherproofing – built for continuous year-round outdoor deployment without the need for shelter or climate control

The specifications for the LI-7500A are similar to the widely-used LI-7500 analyzer (key typical specifications are listed above). It is a fast high-resolution open-path device with wide operating temperature and pressure ranges designed to allow low-power deployment in any of the world's ecosystems.

Unique features:

- Two selectable settings help keep power dissipation to single Watts
- Optical sources and filters are temperature regulated to provide long term analyzer stability
- Includes a fast eddy covariance logging system with a wide range of memory capacities

Additional important specifications:

- Open-path design eliminates tube attenuation effects and related frequency response errors
- Flow distortion minimized by aerodynamic shape and ability to set up away from sonic anemometer
- No sample attenuation, distortion, or sorption by an intake tube
- Contamination is compensated for, but some data loss is expected due to precipitation, dew, fog and other window contaminants
- Communications include Ethernet, RS-232, SDM, DAC (6 outputs and 4 inputs)
- Logging memory ranges from 16 GB using internally powered USB flash drive to Terabytes using externally powered USB hard drive

References

A full list of specifications can be found here: http://www.licor.com/env/products/gas_analysis/LI-7500A/specifications.html

A full description of the design and features is located at: http://www.licor.com/7500A

Typical examples of installation of the LI-7500A gas analyzer on an eddy covariance tower near the 3-D sonic anemometer

The LI-7500A is designed for simple installation and low maintenance. Attention to these aspects is still required, so here are a few key considerations.

Installation. The illustration above shows typical examples of installation of the LI-7500A. The analyzer is usually installed 10-20 cm away from the sonic anemometer, or just below it. The best orientation is such that both anemometer and analyzer meet prevailing winds at the same time, and with the analyzer placed at the least frequent wind direction. Mounting at a slight angle (~10-15°) may help prevent droplets from remaining on the windows after precipitation, reducing the need for cleaning.

Cleaning. Spectrally neutral contamination is compensated for in the LI-7500A to a large degree using readings from a non-absorbing optical channel for CO_2 and H_2O. In addition, the exposed windows of the LI-7500A are usually kept sufficiently clean by rain. However, manual cleaning will sometimes be required, especially in highly dusty or salty environments, or excessive zero drift may be observed. The sapphire windows are extremely resistant to scratches, and can be cleaned with any mild detergent or glass cleaner.

Changing chemicals. The desiccant/scrub bottles should be changed every 12 months. For added security in humid tropical environments, marine applications, *etc.*, the frequency can be increased to about every 6-9 months.

Calibration. Factory calibration coefficients are usually stable for several years. Periodic checking of zero and span is recommended once per 6-12 months as a precaution.

Setting span and zero for an open-path analyzer on the tower is generally difficult due to possible leaks and wind-induced diffusion. Setting the H_2O span on the tower is extraordinarily difficult. If it is considered necessary, it is best to bring the instrument into a lab, and carefully follow calibration instructions.

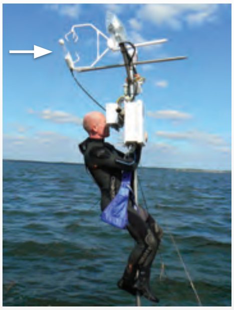
References

Further details are in the 7-step quick start guide: ftp://ftp.licor.com/perm/env/LI-7200/GHG_Quick_Start_Guide_print.pdf and in the manual: http://envsupport.licor.com/docs/LI-7500A_Manual_Rev3.pdf

Eddy Covariance


Land


Air


Water

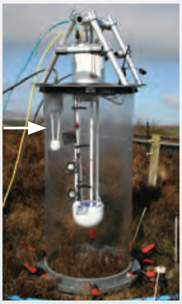
Other Applications:

Atmospheric monitoring

Mapping from moving platforms

Large soil and canopy chambers

etc.



The LI-7500A is used in a wide range of terrestrial flux applications over many environments, from natural and agricultural ecosystems, to urban and industrial areas. Fluxes and emission rates are typically measured from stationary or portable towers.

Although recommended and originally designed for placement on a stationary tower, in recent years the LI-7500A has been used more extensively for measurements from moving platforms on land, airborne, and shipborne applications. Less common uses include chamber, atmospheric monitoring, and other measurements.

Terrestrial stationary applications are usually not affected by vibration issues, but moving vehicle, airborne and shipborne installations can experience severe vibrations and some gyroscopic effects.

In these cases, installation of the LI-7500A will require a customized reinforcement to maintain structural integrity of the sensor head. The effects can also be minimized through appropriate compensating and mounting attachments.

In land-based installations, a potential source of vibrations can be a lightweight, tall tower with taut guy wires attached at the top. Vibration can be minimized by the use of more guy wires, including those attached at the middle of the tower.

A sensor head used in shipborne applications may also benefit from a customized coating, such as LPS3, to prevent splashing water from remaining on the windows.

It is important to note that the LI-7500A is vibration sensitive at frequencies of 152 Hz ± the bandwidth. Thus, if the bandwidth is 10Hz, the problematic frequency range will be 142 to 162 Hz (and upper harmonics). The instrument is nearly completely insensitive to vibrations slower than this, and only very slightly sensitive to vibrations higher than this.

References

Additional information on applications, design, updates and software is available at: http://www.licor.com/7500A

- The LI-7700 is a fast open-path CH_4 analyzer for stationary and mobile eddy flux measurements
- Extremely low power and lightweight; break-through technology reduced power requirements 30-100 times below other current technologies
- Can be deployed in virtually any remote or hard-to-reach location

The LI-7700 is a fast, high precision, laser-based gas analyzer that measures densities of CH_4 *in situ*.

Similar to the LI-7500A, the LI-7700 is designed specifically (*e.g.*, build, resolution, performance, *etc.*) for eddy covariance applications, but can be used for other gas measurement applications.

The LI-7700 uses Wavelength Modulation Spectroscopy, which employs a vertical-cavity surface-emitting laser for fast measurements of CH_4 with very low power consumption, 30-100 times below other currently available technologies, and with relatively light weight.

These design elements result in significant advantages for CH_4 flux and emission measurements:

- possibility of remote solar-powered deployments due to low power demand
- possibility of portable and mobile deployments due to light weight
- undisturbed *in situ* measurements due to open-path design and the absence of a chamber or a tube
- measurements can be done at the location of interest regardless of available infrastructure

The analyzer has four auxiliary input channels for a sonic anemometer or for any desired fast or slow sensors, and has an Ethernet output for logging and accessing with any Ethernet-enabled device.

The instrument can also be used with the LI-7550 interface to collect CH_4, CO_2, H_2O, and sonic anemometer data, and to log complete 3-gas GHG data sets to a removable USB storage device (as described for LI-7500A model).

References

McDermitt, D., G. Burba, L. Xu, T. Anderson, A. Komissarov, et al., 2011. A new low-power, open-path instrument for measuring methane flux by eddy covariance. Applied Physics B: Lasers and Optics, 102(2): 391-405

	CH_4
Measures gas density at 10 Hz or faster	up to 40 Hz
High resolution at high frequency	5 ppb RMS@10 Hz
Operates over ambient gas range	0-40 ppm
typical ambient	*1.5-5 ppm*
Temperature range	-25 to +50 °C
Pressure range	50-110 kPa
Power	8 W nominal
Size	14 x 83 cm (5.6" x 33")
Weight	5.2 kg (11.5 lb)

- Ruggedness and weatherproofing – built for continuous year-round outdoor deployment without the need for shelter or climate control

The LI-7700 is a fast high-resolution open-path device with wide operating temperature and pressure ranges designed to allow low-power deployment in a wide variety of the world's ecosystems. The key eddy covariance specifications are listed above.

Unique features:

- Extremely low power consumption, lightweight
- Unlike most other fast CH_4 analyzers, operates at normal atmospheric pressure and does not require a vacuum pump
- Four fast auxiliary input channels are available for sonic anemometer outputs
- Can log directly to PC, yet is compatible with fast eddy covariance logging system (LI-7550) with wide range of memory sizes which come as standard with CO_2/H_2O analyzers

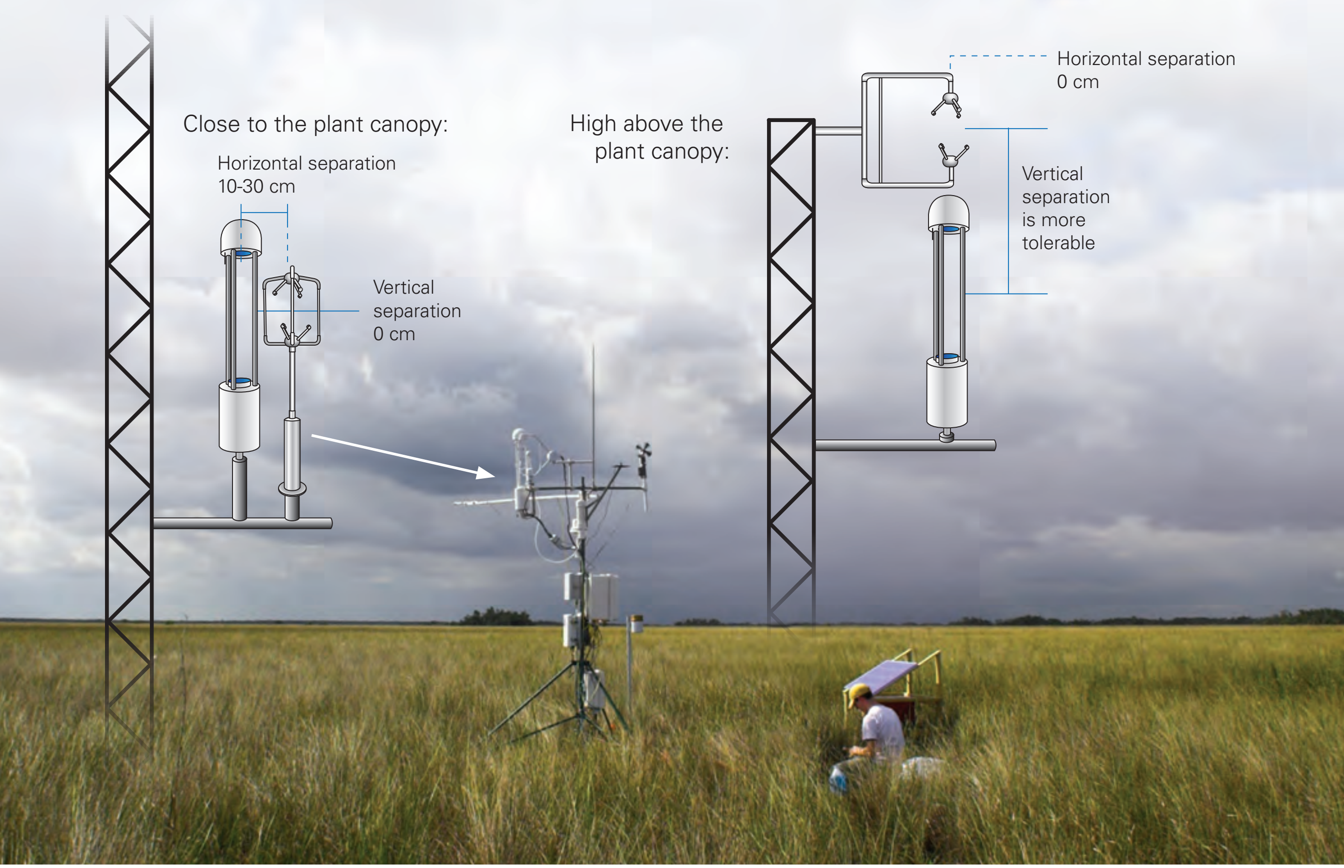
Additional important specifications:

- Open-path design eliminates tube attenuation effects and related frequency response errors
- Flow distortion is minimized by aerodynamic shape and ability to set up away from sonic anemometer
- No sample attenuation, distortion, or sorption by an intake tube
- Air temperature in the sampling path and fast atmospheric pressure are also measured
- Contamination is reduced by a self-cleaning system and compensation algorithms, but some data loss is expected due to precipitation, dew, fog and other window contaminants
- Communications include Ethernet output and DAC inputs; when used with LI-7550 additionally include RS-232, SDM, DAC (6 outputs; 4 inputs)

References

A full list of specifications can be found here: http://www.licor.com/env/products/gas_analysis/LI-7700/specifications.html

A full description of the design and features is located at: http://www.licor.com/7700



The LI-7700 is designed to easily fit into existing or new eddy covariance flux stations. There are, however, several factors to take into account when deploying it. Addressing these appropriately is important for minimizing frequency corrections.

The two key items are: instrument height above the canopy, and proximity to the sonic anemometer.

For most applications, the LI-7700, as with any other fast instrument, should never be within the canopy roughness sublayer, as this may violate the assumptions of the eddy covariance flux method. The minimum recommended height above the canopy is 1.5-2.0 m or more, but this will vary.

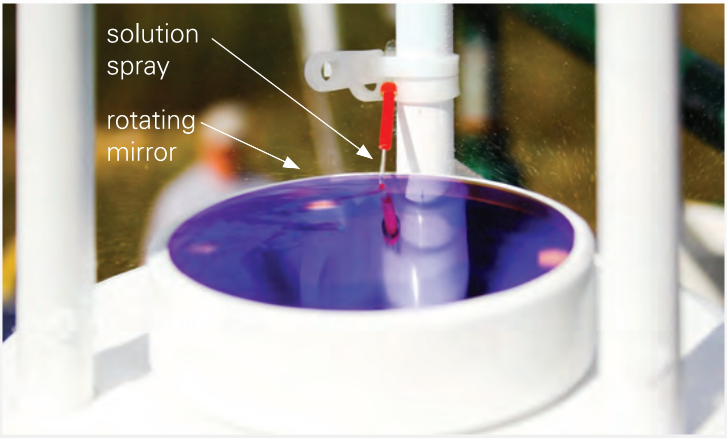
The lower the measurement height, the closer the instruments must be to each other to minimize frequency response corrections for sensor separation.

For near-surface deployments close to the canopy, the analyzer should be placed 10-30 cm horizontally from the anemometer, and they should have a minimal vertical separation.

The photo above illustrates an example of this type of setup. This solar-powered eddy station in the Florida Everglades is equipped with an LI-7700 and LI-7500 to measure fluxes of CH_4, CO_2, H_2O in the middle of the remote wetland.

For deployments high above the canopy, the analyzer should still be as close as is practical to the sonic anemometer; however, larger vertical separations are now acceptable (with the sonic anemometer above the LI-7700). For example, at a height of 40 meters above the canopy, the anemometer sample path can be entirely above the analyzer.

It is not recommended to put fast scalar measurements (*e.g.*, gas concentration, thermocouple temperature, humidity) above the vector measurements (*e.g.*, wind from sonic anemometer), as it may lead to errors and may require difficult to predict corrections.



- Field maintenance is reduced by a rotating lower mirror with an automated spray system to help keep it contamination-free
- Programmable heaters on both mirrors and radiation shield help to minimize condensation

Cleaning. Field maintenance is reduced by a fully-programmable self-cleaning mechanism for the lower mirror. Dew formation on both mirrors is avoided with fully programmable heaters. In addition, a removable radiation shield is provided to minimize condensation and power demands.

Manual cleaning will periodically be required, especially in highly dusty or salty environments. In rare cases, when dust becomes sticky when contacting liquid (for example, manure dust at cattle yards), custom-built air sprayers for both mirrors may be used instead of the default liquid sprayer.

The mirrors are scratch resistant, but when cleaning manually, they should be treated the same way as an expensive camera lens. Avoid applying strong pressure when cleaning a dry mirror; simply wipe with a soft, clean, moistened cloth. If this is not sufficient, a mild soap or a commercial glass cleaner such as Windex® can be used.

Calibration. Factory calibration coefficients are usually stable for several years. Periodic checking of the zero and span is recommended once every 6-12 months as a precaution.

As it is more difficult to find zero and span gas standards for CH_4 than for CO_2, make sure in advance to always use quality zero and span gases with CH_4 accuracy greater than 1%, and 0 ppm Volatile Organic Compounds (VOC free).

In remote locations occasional calibration checks can be done using small hand-carried gas tanks with a known CH_4 concentration and with CH_4-free air.

References

Further details on installation and field maintenance can be found in the LI-7700 manual: LI-COR Biosciences, 2010. LI-7700 Open-path CH_4 Analyzer Instruction Manual. Publication No.984-10751, 170 pp.

The custom-built air sprayer instructions are at: Ham J., C. Williams, and K. Shonkwiler, 2012. Automated Dust Blow-off System for the LI-7700 Methane Analyzer. Colorado State University, Fort Collins, CO, 6 pp., www.licor.com/Air_Blast_Cleaner

Eddy Covariance

Land

Water

Air

Other Applications:

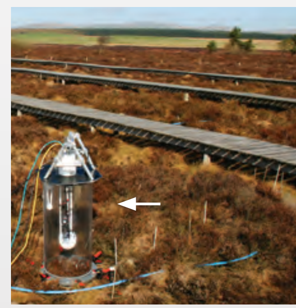
Many mobile applications

Mapping/moving platforms

Atmospheric monitoring

Large soil/canopy chambers

etc.



Like the LI-7500A for CO_2 and H_2O, the LI-7700 is used for measuring CH_4 in a wide range of terrestrial flux applications over many environments, from natural and agricultural ecosystems, to urban and industrial areas, including landfills and carbon capture and sequestration sites.

Fluxes, emission rates and high-precision gas concentrations are typically measured from stationary or portable towers.

Although recommended and originally designed for placement on a stationary tower, the LI-7700 is used quite frequently for measurements from moving platforms on land, as well as in airborne and shipborne applications, and sometimes, for chamber measurements.

Terrestrial stationary applications are not usually associated with vibration issues. Moving vehicle, airborne and shipborne installations, however, can experience vibrations and gyroscopic effects.

References

More on applications, design, and software is available at: http://www.licor.com/7700

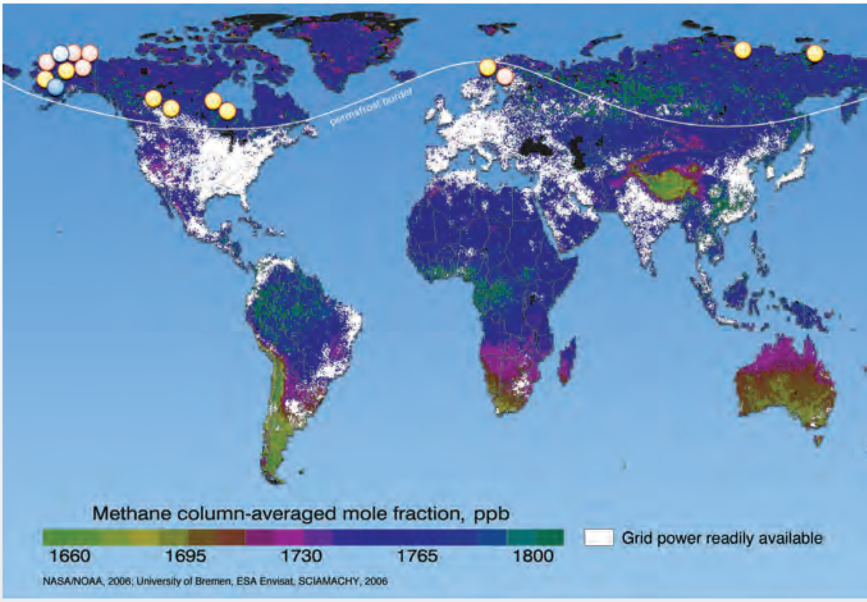
In these cases, installation of the LI-7700 will require a customized reinforcement to maintain structural integrity of the sensor head. The effects can also be minimized through appropriate custom-built compensating and mounting attachments.

Lightweight low-power CO_2/H_2O gas analyzers (*e.g.*, LI-7500/LI-7500A) have been around for over 10 years and are widely used for observation of CO_2 and H_2O eddy fluxes. By contrast, there were no low-power lightweight fast analyzers for CH_4 flux measurements until the introduction of the LI-7700 in 2010.

In the next two pages we will briefly describe the important scientific implications of low-power lightweight configurations for methane flux research.

When using the LI-7700 for eddy covariance flux calculations, make sure to use fast density output and not mole fraction output. The latter is provided for calibration, and may be used for some slow applications, but not for fast measurements.

Permafrost CH_4 flux stations utilizing low-power open-path measurements



Solar- and wind-powered
Large generator, or grid
Airborne, small airplane
Floating or ice-mounted

Methane is considered the most important greenhouse gas after H_2O and CO_2, and has a global warming potential about 23 times that of CO_2 over a 100-year cycle (Solomon *et al.*, 2007).

Prior measurements of CH_4 fluxes have mostly been made with chambers, and with the eddy covariance approach via closed-path analyzers.

Both chambers and closed-path analyzers have their advantages. However, chamber measurements are discrete in time and space, may disturb soil surface integrity and air pressure, and are often labor-intensive.

Current closed-path analyzers operate under significantly reduced pressures, and require powerful pumps and commercial grid power.

Power and labor demands may be reasons why CH_4 flux is often measured at locations with good infrastructure and grid power, and not necessarily with high CH_4 production.

At the same time, most of the natural CH_4 production occurs in remote areas with little infrastructure and no grid power.

The low power requirements and lightweight design of the LI-7700 make it fairly simple to measure eddy fluxes of CH_4 in the middle of the area of interest (wetland, rice paddy, forest, landfill, *etc.*) in the absence of grid power and roads.

This provides a new and unique opportunity for measuring natural, agricultural, industrial and other CH_4 production where it actually occurs, rather than measuring it where the power grid and roads are available.

It can also expand the measurement coverage, and possibly, significantly improve the budget estimates of world CH_4 emissions and budget.

The illustration above shows one example of such novel uses of low-power CH_4 measurements. Different types of automated remote low-power stations, indicated by dots, measure methane emission rates in cold regions using the LI-7700 and the eddy covariance technique.

A satellite map of light intensity at night (NASA, 2006) is used as a proxy for power grid distribution, and is overlaid on a satellite map of methane concentration in the atmosphere (SCIAMACHY, 2005), showing the lack of proximity of mains power to methane generating areas of the Earth. The dotted white line is an approximate permafrost border.

Another example is multi-year CH_4 measurements in the Florida Everglades. The power consumption by the entire open-path eddy covariance station was about 30 Watts, including the LI-7700 for CH_4, LI-7500 for CO_2/H_2O, sonic anemometer, air temperature/relative humidity sensors, and a barometer. The 12 lb. (5.5 kg) open-path methane analyzer was carried into the wetland by one person in a backpack, along with tools, other sensors, and a laptop.

Yet another example is a study in the middle of the municipal landfill in Lincoln, Nebraska. A solar powered eddy station equipped with the LI-7500A and LI-7700 measured emission rates of CH_4, CO_2, and H_2O year-round. Wireless communication was available to view the data and control the station in real time.

References

Recent literature with emerging research on CH_4 emission rates from various ecosystems and location using fast low-power open-path CH_4 gas analysis with LI-7700:

Billesbach D., M. Fischer, D. Cook, M. Torn, and C. Castanha, 2011. Establishment of a New, Cooperative ARM and AmeriFlux Site on the Alaskan North Slope. AGU Fall Meeting, San Francisco, California, 5-9 December

Burba, G., T. Anderson, A. Komissarov, L. Xu, D. McDermitt, et al., 2009. Open-path low-power solution for eddy covariance measurements of methane flux. AGU Fall Meeting, San Francisco, California, 14-18 December (*early prototype used*)

Burba, G., C. Sturtevant, P. Schreiber, O. Peltola, R. Zulueta, et al., 2012. Methane Emissions from Permafrost Regions using Low-Power Eddy Covariance Method. European Geosciences Union General Assembly, Vienna, Austria, 22-27 April

Dengel, S., P. Levy, J. Grace, S. Jones, and U. Skiba, 2011. Methane emissions from sheep pasture, measured with an open-path eddy covariance system. Global Change Biology, 17 (12): 3524-3533

Detto, M., J. Verfaillie, F. Anderson, L. Xu, and D. Baldocchi, 2011. Comparing laser-based open- and closed-path gas analyzers to measure methane fluxes using the eddy covariance method, Agricultural and Forest Meteorology, 151 (10): 1312-1324

McDermitt, D., G. Burba, L. Xu, T. Anderson, A. Komissarov, et al., 2011. A new low-power, open-path instrument for measuring methane flux by eddy covariance. Applied Physics B: Lasers and Optics, 102(2): 391-405

Peltola, O., 2011. Field intercomparison of four methane gas analyzers suitable for eddy covariance flux measurements. MS Thesis. University of Helsinki, 75 pp. (*early prototype used*)

Strohm, A., K. Walter-Anthony, F. Thalasso, A. Sepulveda-Jauregui, K. Martinez-Cruz, and K. Dove, 2011. Seasonal variation in methane emissions from an interior Alaska thermokarst lake. AGU Fall Meeting, San Francisco, California, 5-9 December

Sturtevant, C., and W. Oechel, 2011. Carbon Dioxide and Methane Fluxes along the Thaw Lake Cycle Chronosequence, Arctic Coastal Plain of Alaska. AGU Fall Meeting, San Francisco, California, 5-9 December

Xu, L., 2012. Impact of Changes in Barometric Pressure on Landfill Methane Emission. Global Waste Management Symposium, Phoenix, Arizona, 30 September - 3 October

Xu, L., J. Amen, X. Lin, and K. Welding, 2012. The Impact of Changes in Barometric Pressure on Landfill Methane Emission. 30th AMS Conference on Agricultural and Forest Meteorology, Boston, Massachusetts, 29 May - 1 June

Zona, D., W. Oechel, G. Burba, H. Ikawa, and C. Sturtevant, 2008. Methane emissions from the Arctic Coastal Plain in Alaska. 18th Conference on Atmospheric BioGeosciences, Orlando, Florida: 1.19 (*early prototype used*)

- The heart of the LI-7200 is a universal weatherproof sampling cell that can output both fast densities and fast dry mole fractions of CO_2 and H_2O
- Capable of versatile configurations: can be used in many different ways, from eddy covariance to lab measurements
- Combines advantages of open-path and closed-path designs
- Eliminates CO_2 and H_2O losses during rain, and any surface heating effects
- Includes fast logger for anemometer and gas analyzer data collection
- Optimized for remote and mobile flux measurements: can be configured as low power, and is relatively lightweight

The concept of an enclosed gas analyzer was developed for, and is introduced with the LI-7200 analyzer.

The heart of the LI-7200 is a universal, weatherproof, fast measuring sampling cell, which can output both densities and fast dry mole fractions of CO_2 and H_2O.

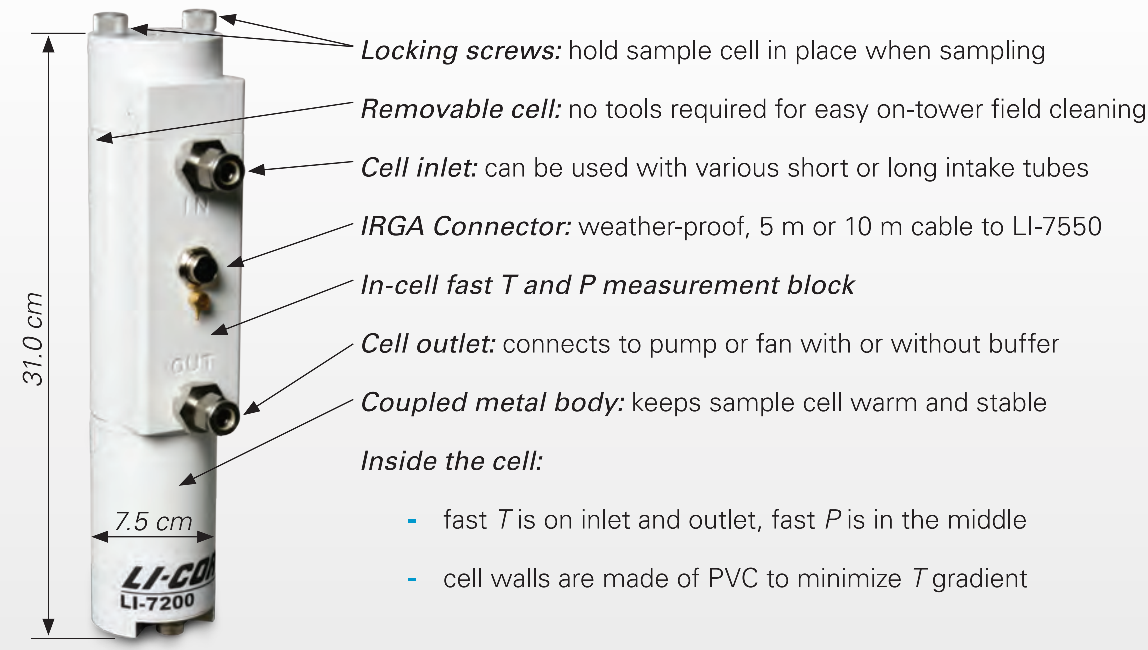
When used with a long intake tube, the analyzer behaves identically to traditional closed-path analyzers used for eddy flux, gradient flux, profile, mean concentration and many other measurements. Yet when used with a very short intake tube, the analyzer retains some features of open-path designs used mainly for eddy flux measurements. A brief description and advantages of this new approach is discussed in more detail in the next few pages and in Section 4.7.

When used in eddy covariance applications, the LI-7200 is a compact closed-path CO_2/H_2O analyzer enabled for operation with very short intake tubes. The intake tube can be as short as few centimeters or as long as many meters (similar to the LI-7000 and LI-6262), but the optimal length is about 0.5 m to 1 m.

The short-tube configuration is specifically designed for eddy covariance measurements, and is intended to maximize strengths and to minimize weaknesses of both traditional open-path and closed-path designs, but the instrument can still be used with any other flux measurement technique.

The LI-7200 is based on the absolute NDIR design of the LI-7500. However, it uses a closed-path sampling cell, similar to the LI-7000 and LI-6262. Unlike any previous closed-path instruments, the LI-7200 is weatherproof and can be mounted on the tower, and not at ground level.

Fast temperature and fast pressure of the gas stream are measured at the sampling cell. Fast temperature is measured in two places: just before gas entry into the cell and just after the gas exits from the cell. Fast pressure is measured in the middle of the sampling cell.



Special care was taken in the analyzer software to properly measure and align all inputs required to produce fast dry mole fraction from gas density (see details in pages 57-58 and Section 4.7). In particular, instantaneous air temperatures measured near the inlet and outlet of the sampling cell were weighted to compute cell air temperature in such a way that it properly reflects the fast temperature integrated over the entire cell volume. Furthermore, outlet air temperature is delayed in time in relation to inlet temperature to describe the same exact air parcel, and all other signals are delayed in relation to the temperature to compensate for the thermal inertia of thermocouples measuring inlet and outlet temperatures.

When used with a short intake tube, fast temperature and pressure measurements made inside the cell provide the strengths of both open-path and closed-path designs at the same time:

Similar to closed-path analyzers:

(1) minimal data loss due to precipitation and icing (similar to LI-7000 and LI-6262)

(2) no surface heating issues (similar to LI-7000 and LI-6262), because fast cell temperature is measured

(3) possibility of automated calibrations on tower (similar to LI-7000 and LI-6262) with additional custom hardware

(4) minimal-to-negligible thermal expansion density term in WPL correction

(5) system can be heated to prevent icing in extremely cold environments

Similar to open-path analyzers:

(1) frequency response is improved over traditional closed path design

(2) relatively small and correctable flux attenuation in short intake tube

(3) infrequent calibration requirements (similar to LI-7500A)

(4) reduced maintenance needs (similar to LI-7500A)

(5) tool-free cell cleaning on the tower (similar to LI-7500A)

(6) low power configuration when used with a short intake tube without fine-particle filter

(7) simplicity, small size, light weight, weatherproof

	CO_2	H_2O
Measures at 10 Hz or faster	up to 20 Hz	
High resolution at high frequency	0.11 ppm RMS@10 Hz	0.0047 ppt RMS@10 Hz
Wide gas concentration range	0-3000 ppm	0-60 ppt (mmol/mol)
typical ambient	*300-900 ppm*	*0.5-40 ppt (mmol/mol)*
Temperature range	(-40) -25 to +50 °C; can be heated in extreme cold	
Pressure range	20-120 kPa	
Power	12 W nominal + 16 W low-power flow module, or higher-power pump	
Size	7.5 x 31 cm (3" x 12") head on the tower near or below sonic 35 x 30 x 15 cm (13.8" x 12" x 6") interface/logging box below	
Weight	1.8 kg (3.95 lbs) head on the tower near or below sonic 4.4 kg (10 lbs) interface/logging box below	

- Outputs both fast density and fast dry mole fraction: important for eddy covariance; eliminates the need for density terms, including pressure term
- Rugged and weatherproof – built for continuous year-round outdoor deployment without the need for shelter or climate control

The technical specifications for the LI-7200 are generally similar to the open-path LI-7500 and the new LI-7500A analyzer. Key specifications for eddy covariance are listed above.

There are, however, several substantial differences between the enclosed LI-7200 and the open-path LI-7500/7500A related to instrument outputs and design, summarized on the previous page and in a table on page 58.

Unique features:

- A universal weatherproof fast measuring sampling cell that can output both densities and fast dry mole fractions (see pages 57-58, Sections 4.4 and 4.7)
- Can be used in numerous applications in addition to eddy covariance
- Substantially simplifies eddy flux calculations and reduces related methodological errors several times
- Uses intake tube, so virtually no data loss is expected due to precipitation, dew, fog, snow, icing, *etc.*
- Can be shielded or heated while on the tower to operate at extreme environments
- Comes with fast eddy covariance logging system
- When used without fine-particle filter, optional low-power flow module provides 15 lpm flow at 16 W of power for low-power deployments

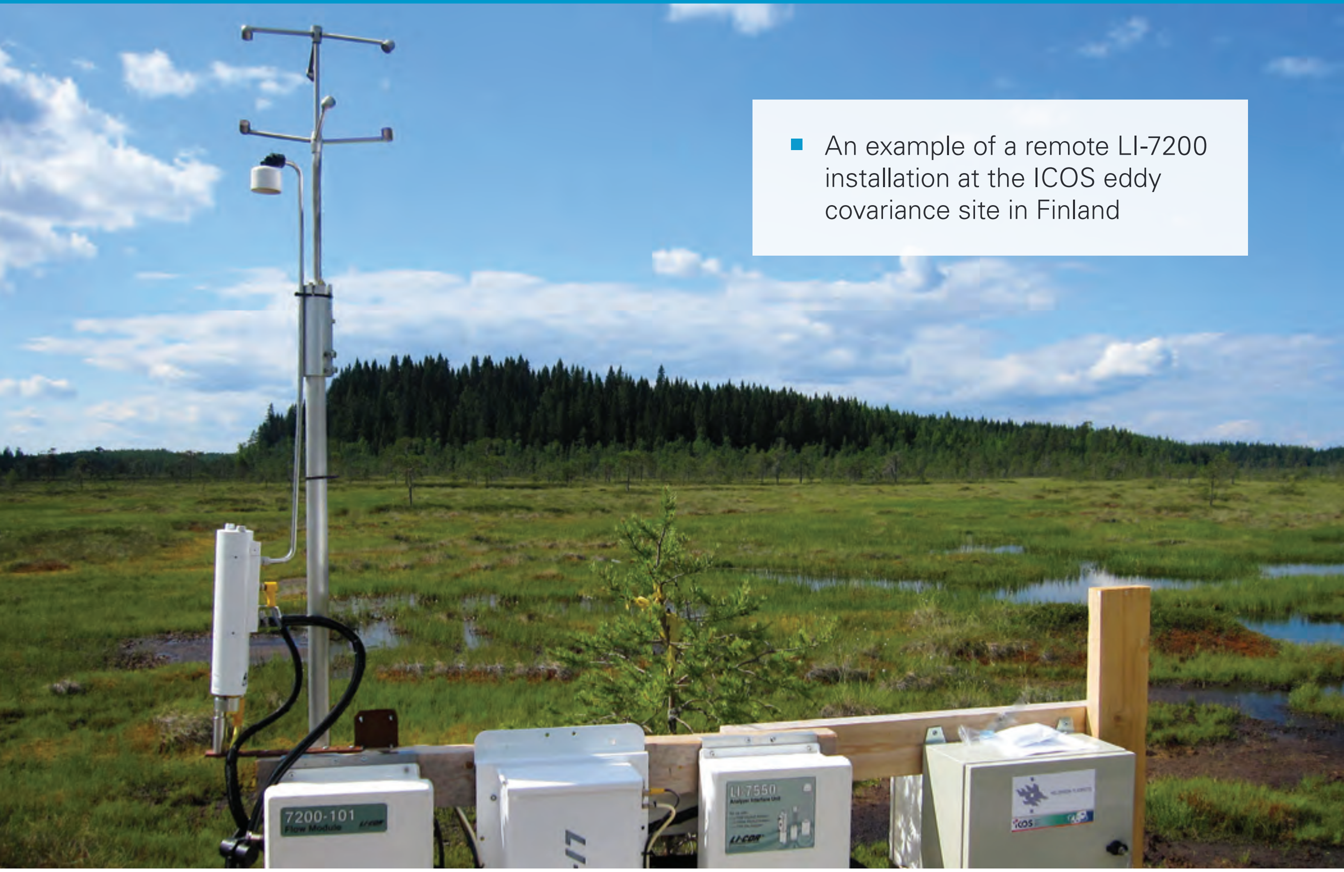
Additional important specifications:

- Flow distortion is minimal due to small size of tube
- Optical sources and filters are temperature regulated to provide long term analyzer stability
- Contamination is compensated for, but needs periodic cleaning when used without a fine-particle filter
- Communications include Ethernet, RS-232, SDM, DAC (6 outputs and 4 inputs)
- Logging memory capacity ranges from 16 GB using an internally powered USB flash drive, to terabytes using an externally powered USB hard drive

References

A full list of specifications can be found here: http://www.licor.com/env/products/gas_analysis/LI-7200/specifications.html

A full description of the design and features is located at: http://www.licor.com/env/products/gas_analysis/LI-7200



An example of a remote LI-7200 installation at the ICOS eddy covariance site in Finland

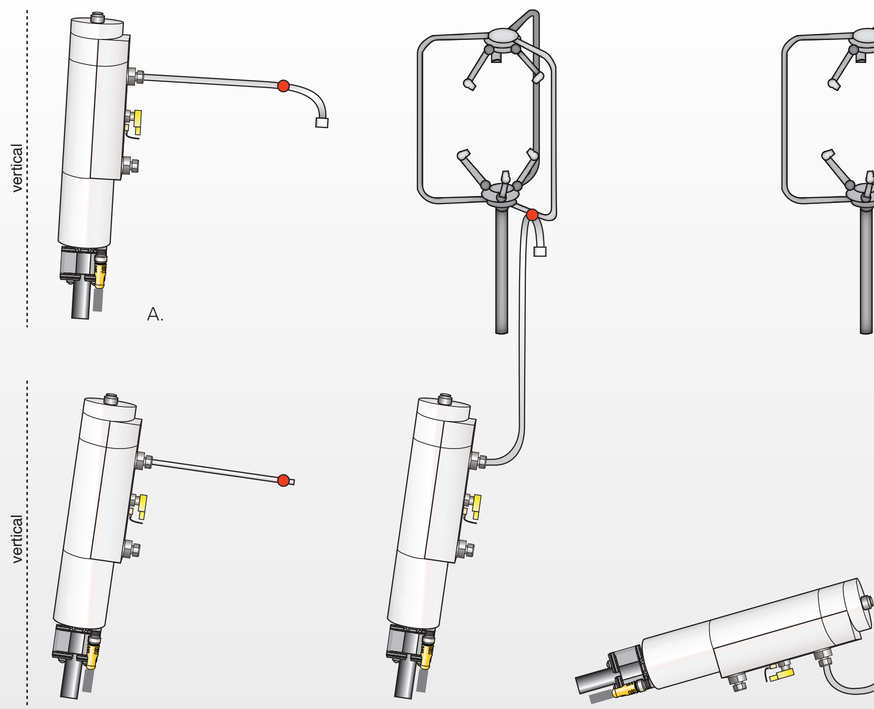
The LI-7200 is a fast measuring cell that can be easily installed in many different configurations, and used for many applications beyond eddy covariance. It can be used with intake tubes of various lengths, diameters and materials, depending on the application.

It can be used with long intakes (from 1.5 m to 40 m or more), like regular closed-path; the frequency response for CO_2 may be 3-5 Hz or less, depending on the tube length and flow rate. It can also be used with a short tube (0.4 m to 1.5 m), like enclosed-path analyzers; the frequency response for CO_2 may be 5-10 Hz depending on the tube length and flow rate. In addition, the LI-7200 can be used with an ultra-short tube (0.01 m to 0.4 m) and a very high flow rate; the frequency response for CO_2 may be 10-20 Hz, depending on the tube length and flow rate.

For convenience, a default 1 meter long 5.3 mm (¼") ID stainless steel intake tube is provided, with removable insulation under a white plastic sleeve, but any desired intake tube of different length, diameter and material suitable for the particular application can be used instead of the factory-provided default intake.

When used for eddy covariance measurements, the illustration above shows one example of a properly installed LI-7200 at the ICOS remote site in Finland. Please note several subtle but important details:

- A tube bender was used to modify the default steel intake without pinches and sharp turns
- Decabon/Synflex flexible tubing can also be used instead of the default intake tube
- Tube can be insulated and/or heated if desired
- Sensor head is slightly inclined forward to let water drain from the outlet port if it ever gets in, avoiding dust accumulation in the water pool
- Intake is fixed to a rigid element on the tower and sonic anemometer to avoid excessive torque on the head
- Area surrounding the sensor head is not crowded – easy to remove and clean the cell on the tower, without removing the sensor head or intake tube
- The result is a sturdy, low-maintenance, aerodynamic, omni-directional setup, and no data loss is expected when winds change direction



In most cases, the optimal position of the head is off-vertical, inclined forward, so that water that may have gotten into the cell during heavy rains does not pool inside the cell.

The sampling cell is waterproof and will not be damaged if water is present, but it will affect H_2O and CO_2 concentrations and fluxes, and may result in salt and dust accumulation on cell walls and windows, and in corrosion of the inlet and outlet thermocouples.

Below we describe several default configurations in addition to the one shown on the previous page that will work for most tower installations:

A. When using the rain guard and bug screen, the tube can be bent downward slightly to keep tube inlet below the level of the head inlet

B. If the rain guard and bug screen are not used, sensor head should be inclined even more, and the tube can be bent slightly downward

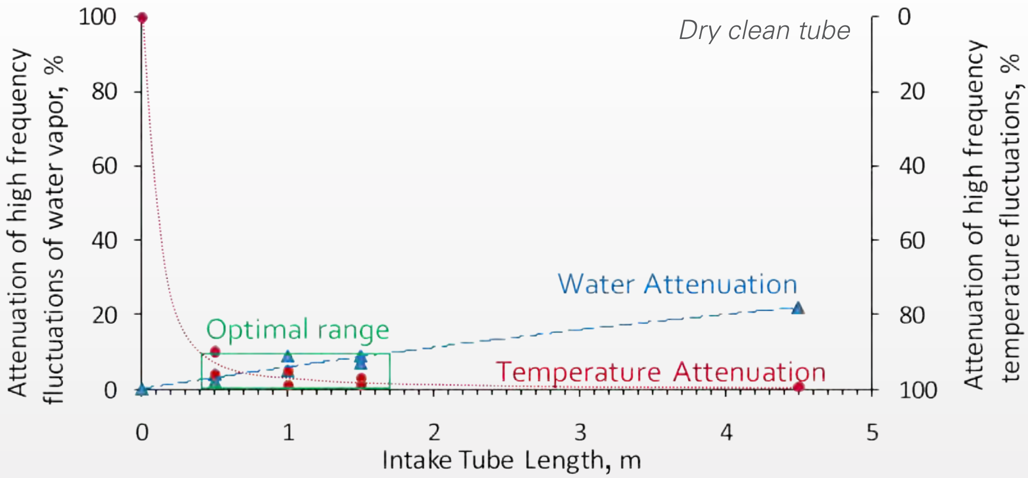
C. When a flexible, custom intake tube (*e.g.*, Decabon/Synflex) is used, it can be tied to the sonic anemometer to minimize flow distortion and sensor separation for omni-directional sampling

D. A more "waterproof" configuration can be used in rainy environments. The instrument head is inclined to near horizontal, and the intake is dropped down to prevent water from "climbing" up the tube.

When the intake tube is longer than 50 cm, it is best to install and secure the tube on the tower first, before attaching the analyzer head, to prevent excessive stress on the head inlet port.

When the intake tube is 50 cm or shorter, the tube can be attached to the LI-7200 head first, and then secured on the tower. Even then, it is recommended to secure the outer end of the tube to the anemometer or any other rigid element of the setup (red dots on the diagram above).

> Use a bug screen on the intake in all environments to prevent insects from getting pulled into the cell.
>
> Avoid sharp bends and tube pinches: flow must not be disturbed, and must have minimal flow restrictions.



- The intersection of two fitted lines suggests the best length of about 0.7 m
- H_2O-only studies may benefit from shorter intakes (0.4-1.0 m)
- CO_2-only studies may benefit from longer intakes (1.0-1.7 m)

The LI-7200 can be used with tubes of various lengths, diameters and materials, depending on the application, measurement method, and experimental setup.

The default intake is provided for convenience. It was chosen for simplicity, standard size and material compatible with various filters and valves. It can easily be cut to a desired length, or replaced with a different tube.

When used in eddy covariance applications, the intake tube can be adjusted to simultaneously maximize tube attenuation of instantaneous fluctuations of temperature, and to minimize the attenuation of instantaneous fluctuations of water vapor. This helps to significantly reduce the WPL term and associated uncertainties, without requiring excessive frequency response corrections for water vapor flux and its uncertainties.

The optimal length for the factory default intake suggested by experimental data for a dry, clean 5.3 mm ID tube ranges from about 0.4 m, attenuating 90% of high frequency temperature fluctuations and less than 5% of the water fluctuations, to about 1.7 m, attenuating 99% of the temperature fluctuations and less than 10% of the water fluctuations.

The intersection of the two fitted lines in the above figure suggests the best intake length is about 0.7 m. However, a single specified length is too restrictive to apply to all studies because each specific study may require a specific tube length.

For example, hydrological studies may benefit from shorter tubes (*e.g.*, 0.4-1.0 m, or less) of small diameter to reduce uncertainties associated with the tube effects on frequency dampening of water vapor fluctuations.

Meanwhile, research groups focused solely on ecosystem CO_2 exchange would benefit from using longer tubes (*e.g.*, 1.0-1.7 m, or more) to further reduce or eliminate temperature fluctuations and associated uncertainties. In such cases, especially with intake tubes longer than 1.7 m, the water attenuation can still be corrected by frequency response corrections, so no actual water vapor flux would be lost, but uncertainty will increase.

This uncertainty and attenuation can also increase with tube wall contamination, sharp turns or uneven joints in the intake tube, and at high relative humidity.

- Insulating the intake tube minimizes or prevents nighttime condensation inside the tube in humid environments, for any tube or any closed-path or enclosed analyzer
- Insulation is installed by default, but can be removed if desired
- In extremely cold environments (*e.g.*, winter measurements in arctic and alpine ecosystems, *etc.*) a heated wire may be placed under the tube's insulation to prevent icing on the inside of the intake tube
- Tube heating may also be helpful in high-humidity environments when water vapor flux is of particular interest
- If flow disturbance is a concern, part of the insulation can be removed or replaced with a heating wire or heating tape

When using any device with an intake tube, two phenomena are of particular concern: condensation of the water on tube walls, and attenuation of the high-frequency fluctuations, which especially affects sticky gases, such as H_2O, NH_3, *etc.* (see Tube Attenuation in Section 4.2 for details).

While these effects may be much smaller in short tubes of an enclosed analyzer when compared to multi-meter or longer tubes used with traditional closed-path analyzers, it is always a good strategy to try to minimize them.

The simplest first step is insulating or shielding the tube. This will prevent or significantly reduce condensation in most environments most of the time.

The second step is to decide whether or not to heat the tube. The following three strategies are typically considered:

(1) ***No tube heating.*** This is used by a vast majority of sites, which do not heat the tubes, but rather simply insulate them.

This is also typical for an enclosed LI-7200 when used with a short insulated tube.

(2) ***Heating a tube to prevent condensation.*** This requires heating by a fraction of a degree above ambient, or providing 1-2 Watts of continuous heat to keep condensation from forming.

This is sometimes used with long tubes, in humid sites, or at sites with rapidly changing temperature/humidity conditions, such as seashores, cities, small wetlands, lakes, *etc.*

(3) ***Heating a tube to keep relative humidity below 40-60%.*** This approach is aimed at reducing water vapor attenuation in the tube. It is used rarely, and requires custom-built electric circuitry for the tube heater.

Such a sophisticated heating solution may be useful in high humidity environments when small water fluxes are the main interest.

Growing evidence suggests that attenuation of water vapor flux can be significant during periods with very high relative humidity, in addition to other factors. Small fluxes are particularly affected because they tend to occur during periods of high relative humidity, with a small gradient driving the flux.

Adjusting relative humidity in the tube to below 40-60% seems to help reduce this attenuation. However, an attenuation correction may be used instead of heating to achieve the correct water vapor flux values.

The sensor head generally does not need to be insulated or shielded, as energy from the head's electronics is always larger than energy that can be radiated away at night by a "black" sky or borne away by wind convection.

There are two specific cases, however, when the analyzer head may benefit from shielding or insulation:

(i) Environments with extremely rapid advection of much warmer air, such as some locations within cities, warm ocean shores in the autumn, *etc*.

In these environments, the advection of much warmer air may happen very rapidly, and sampled air may be considerably warmer than the cell walls for one or two hours after the advection due to the thermal inertia of analyzer head. So, some minor condensation can theoretically occur, but it can be avoided if the head is insulated.

Insulating the head in warm environments, however, has an inherent risk of overheating the head above 50 °C, potentially reaching the "thermal runaway", and damaging the internal electronics.

(ii) In extremely hot environments, such as tropical deserts, it is theoretically possible for the analyzer head to get heated above 50 °C, even though we did not encounter this problem with the LI-7500 analyzer head during many years of use. Shielding the LI-7200 head in such cases may help.

As an alternative, a slightly longer tube may be used, and the analyzer head may be placed under the tower mounting plate, thus, naturally shielding the head from sunlight.

Heating of the head should not be required under most circumstances. Artificial heating (below 50 °C), however, will not adversely affect the measurements, since the air temperature in the cell is measured at a fast rate.

> In order to attenuate ambient temperature to negligible levels, the ratio of the intake tube length to its diameter should be about 1000:1 or more. So, when using short tubes for eddy flux measurements, the temperature of the sampled air stream has to be measured in the cell at a fast rate. This is required for fast dry mole fraction calculations, and for computing WPL thermal expansion term. Please make sure to use fast cell temperature, and not accidentally use slow block temperature when setting up custom processing codes. Further details on the importance of fast air temperature measurements in the enclosed cell are discussed in Sections 2.2 and 4.7.

References

The literature listed below provides further theoretical and experimental details on various aspects of tube attenuation, and its effects on flux calculations:

Aubinet, M., A. Grelle, A. Ibrom, U. Rannik, J. Moncrieff, et al., 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology. Advances of Ecological Research: 113-174

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, London, New York, 442 pp.

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Fratini G., A. Ibrom, N. Arriga, G. Burba, and D. Papale, 2012. Relative humidity effects on water vapour fluxes measured with closed-path eddy covariance systems with short sampling lines. Agricultural and Forest Meteorology, 165 (15): 53-63

Ibrom, A., E. Dellwik, H. Flyvbjerg, N. O. Jensen, and K. Pilegaard, 2007a. Strong low-pass filtering effects on water vapor flux measurements with closed-path eddy correlation systems, Agricultural and Forest Meteorology, 147: 140-156

Massman, W., 1991. The attenuation of concentration fluctuations in turbulent flow through a tube. Journal of Geophysical Research, 96 (D8): 15269-15273

Massman, W., and A. Ibrom, 2008. Attenuation of concentration fluctuations of water vapor and other trace gases in turbulent tube flow. Atmospheric Chemistry and Physics, 8(20): 6245-6259

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Runkle, B., C. Wille, M. Gažovič, and L. Kutzbach, 2012. Attenuation Correction Procedures for Water vapor Fluxes from Closed-Path Eddy-Covariance Systems. Boundary-Layer Meteorology, 142:1-23

- When needed, the LI-7200 sampling cell can be removed from the head and cleaned on the tower, without any tools, and without disconnecting the tubing or cables

Since the LI-7200 is a relatively new device, and is the first instrument with an enclosed design that can be used in multiple different configurations, here we will provide a more detailed description of field maintenance depending on how the instrument is set up and used.

Cleaning. The LI-7200 has a very similar optical design to the LI-7500A, and is similarly affected by dirt.

However, the LI-7200 optical cell is enclosed, so contamination can accumulate. Consequently, the windows should be kept clean either by regular manual cleaning or by using an intake filter, especially in dusty or salty environments.

The analyzer is also specifically designed to make it easy to remove and clean the cell on the tower without the use of tools.

The LI-7200 can be kept clean using any of the following three approaches:

1. With a low-power setup that includes the 7200-101 Flow Module and no intake filter, the windows should be cleaned about every 1-3 months, and less or more frequently, depending on the environment.
2. With the 7200-101 Flow Module and a 50+ micron intake filter, the frequency of cleaning may be extended depending on dust size and origin. It may also be possible to use a finer particle filter that has a low flow restriction.
3. With external grid power and a user-supplied external pump, a standard single micron filter (*e.g.*, Pall Gelman) can be used. The filter can then be changed as needed, usually every 1-6 months, depending on the environment.

When not using an intake filter in extreme environments (sea water splashes into intake tube, dust at cattle yards, soot near chemical factories, *etc.*), more frequent cleaning may be required.

If the optical windows become significantly contaminated with a material that is not spectrally neutral (*e.g.*, certain salts, chemicals, soot), it may become difficult to calibrate the analyzer, and excessive zero shifts may occur, leading to mean concentration changes of several percent or more.

These shifts generally do not affect flux calculations in a significant manner, but can still lead to changes in the span, and should be avoided by keeping the cell clean.

When cleaning manually, it is important to keep in mind that the LI-7200 has two surfaces that can be cleaned: the sapphire windows, and the PVC walls of the insert.

The sapphire windows are extremely resistant to scratches, and can be cleaned with any mild detergent or glass cleaner.

The PVC insert can be cleaned with mild soap and water, isopropyl alcohol, vinegar, or distilled/non-distilled water.

Do not use acetone, ammonia, chlorine, or wire brushes to clean the path, as irreparable damage to the PVC insert can occur.

After the cell is opened, cleaned, and closed again, checking the zero for CO_2 and H_2O is recommended, which can also be done while on the tower.

Resetting the zero after cell cleaning usually is not essential for eddy covariance flux measurements, but not doing so may cause an offset in mean concentration measurements, as cell conditions may have been modified by the user.

Changing chemicals. The desiccant/scrub bottles should be changed every 12 months. For added security in humid tropical environments, marine applications, *etc.*, the frequency can be increased to about every 6-9 months.

Unlike in the LI-7500A with two chemical bottles, the LI-7200 has three bottles located in two different places, and all three bottles should be replaced at the same time.

Calibration. When kept clean either by filtering or by periodic manual cleaning, the factory calibration coefficients are usually good for several years.

Periodic checking of zero and span is recommended once every 6-12 months as a precaution. These checks can be done relatively easily on the tower by stopping the sample flow, and flowing a calibration gas through an intake tube.

As with any closed-path instrument, an automated custom-built calibration system can be used for monthly, weekly, daily or even hourly calibration at the tower, depending on measurement technique and user preferences.

For open-path analyzers, setting zero and span on the tower is generally difficult, due to leaks and wind-induced diffusion, and setting the H_2O span is extraordinarily difficult.

With an enclosed design, or any closed-path design, the H_2O calibration process is easier, yet it is still important to carefully follow the calibration instructions provided in the instruction manual.

It is generally best to avoid trying to set the H_2O span on the tower for any analyzer design. This is because rapid changes in wind speed and sunlight can affect temperature of the walls of the calibration tube coming from the dew point generator into the analyzer, and can lead to substantial discrepancies between the generated humidity and the humidity reaching the analyzer sampling cell.

> Avoid putting long objects (*e.g.*, narrow tubing, screw drivers, *etc.*) into the inlet and outlet ports of the analyzer. Fine-wire thermocouples are stretched across the inlet and outlet ports of the sampling cell. Inserting long objects into the inlet and outlet ports may damage the thermocouples.

References

Further details on instrument installation can be found in a 7-step quick start guide: ftp://ftp.licor.com/perm/env/LI-7200/GHG_Quick_Start_Guide_print.pdf

A full description of cleaning, calibration and other maintenance items are provided in the LI-7200 manual: http://envsupport.licor.com/docs/LI-7200_Manual_Rev4.pdf

- Versatile sampling cell
- Very broad range of applications
- Eddy covariance
- Profile measurements
- Gradient flux measurements
- Canopy and soil chambers
- Airborne and shipborne
- Urban, high elevation (fast *P* measured)
- pCO_2
- Any ecosystem or area

Although the LI-7200 was designed for eddy covariance flux measurements, it can also be used for flux storage profile measurements, Relaxed Eddy Accumulation, gradient flux techniques, canopy and soil chamber measurements, airborne and shipborne measurements, pCO_2, and many other applications requiring fast or slow accurate measurements of CO_2 and H_2O indoors and outdoors.

Measurements can cover a wide range of environments, from natural and agricultural ecosystems, to urban, industrial and other areas, including volcanic environments, landfills, carbon capture and sequestration sites, *etc*.

Because the enclosed nature of LI-7200 allows it to operate equally well in all environmental conditions, from extremely cold to extremely hot, and from extremely humid to extremely dry, it can be placed in virtually any location over land or sea.

Another important feature of the LI-7200 is that it can be used in a solar-powered or small generator-powered arrangement with the 7200-101 Flow Module. The latter provides an efficient, integrated air-flow solution, and consumes about 16 Watts of power for 15 lpm of flow.

In this way, fast eddy covariance closed-path measurements are powered using solar panels, and the station can be placed in the middle of the area of interest without the need for grid power or infrastructure.

At the same time, tube attenuation, WPL correction, and precipitation data losses are greatly reduced or eliminated.

When the Flow Module is not used, a low-power pump may be used in slow applications and a higher-power pump may be used in fast applications with a fine-particle intake filter.

As with the LI-7500A and LI-7700, when using the LI-7200 on a moving platform, the vibration and gyroscopic effects should be minimized through appropriate compensating and mounting attachments. However, reinforcement to keep structural integrity of the head is no longer required.

References

Additional information on applications, design, updates and software is available at:

http://www.licor.com/env/products/gas_analysis/LI-7200

http://www.licor.com/env/products/gas_analysis/LI-7200/specifications.html

Useful literature related to LI-7200 design and applications:

Burba, G., D. McDermitt, D. Anderson, M. Furtaw, and R. Eckles, 2010. Novel design of an enclosed CO_2/H_2O gas analyzer for Eddy Covariance flux measurements. Tellus B: Chemical and Physical Meteorology, 62(5): 743-748

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, et al., 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399

Burba G., D. Anderson, M. Furtaw, R. Eckles, D. McDermitt, J. Welles, 2010. Gas Analyzer. Patent: US 8,130,379

Burba, G., M. Furtaw, D. McDermitt, and R. Eckles, 2009. Combining the strengths of open-path and closed-path designs into a single CO_2/H_2O gas analyzer. American Geophysical Union Fall Meeting, San Francisco, California, 14-18 December

Furtaw M., R. Eckles, G. Burba, D. McDermitt, J. Welles, 2008. Gas Analyzer. Patent: US 8,154,714

Furtaw M., R. Eckles, G. Burba, D. McDermitt, J. Welles, 2012. Gas Analyzer. Patent: US 8,300,218

LI-COR Biosciences, 2009. LI-7200 CO_2/H_2O Analyzer Instruction Manual. Publication No.984-10564, 141 pp.

Nakai T., H. Iwata, and Y. Harazono, 2011. Importance of mixing ratio for a long-term CO_2 flux measurement with a closed-path system. Tellus B, 63(3): 302-308

- The LI-7000 is a high-precision closed-path analyzer for fast and slow measurements of CO_2 and H_2O
- It is a differential analyzer with two cells: a sample cell with measured gas, and a reference cell with zero or known gas
- It is typically used for high-precision mean concentration measurements and long-term monitoring, but is also used for flux applications
- Built-in auxiliary pump can be used for slow measurements
- Has RS-232 and USB protocols for simple plug-and-play setup, operation, and data collection

The LI-7000 is a high performance, dual-cell, differential gas analyzer that uses a beam splitter and two separate detectors to measure infrared absorption by CO_2 and H_2O in the same gas stream.

It is designed for a wide range of applications that require high-precision gas measurements, but can be used for eddy covariance when used in a fast system configuration.

As with any conventional long-tube closed-path analyzer, the LI-7000 requires an external pump for fast operation, but also has a built-in pump for slow operation.

However, unlike most conventional closed-path gas analyzers, the LI-7000 has an optical bench that can be dismantled and cleaned by the user without the need for factory recalibration.

In addition to its normal operation, with a zero gas or a known gas in the reference cell, the LI-7000 can operate in Reference Estimation Mode (REM). In its normal mode, the sample cell value is updated based on a known reference cell concentration. In REM mode, the LI-7000 uses independently measured reference cell concentrations, in addition to computing the sampling cell concentration.

The theoretical advantage of REM is that one can make independent measurements of gas concentration in both cells, at least over the short term.

References

Further details on the LI-7000, its normal and REM modes, *etc.* can be found in the manual: ftp://ftp.licor.com/perm/env/LI-7000/Manual LI-7000Manual.pdf

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website: http://www.licor.com/7000

	CO_2	H_2O
Measures at 10 Hz or faster	up to 20 Hz	
High resolution at high frequency	0.078 ppm RMS@10 Hz	0.005 ppt RMS@10 Hz
Wide gas concentration range	0-3000 ppm	0-60 ppt (mmol/mol)
typical ambient	*300-900 ppm*	*0.5-40 ppt (mmol/mol)*
Temperature range	0 to +50 °C, but can be heated or climate-controlled	
Pressure range	20-120 kPa	
Power	15 W nominal after warm-up, without pump	
Size	37 x 13 x 25 cm	
Weight	8.8 kg (19.4 lbs)	

- Can be used in many other applications in addition to eddy covariance
- Uses a long intake tube, subject to all advantages and deficiencies of conventional closed-path analyzers

Key specifications applicable for eddy covariance are listed in the table above.

Unique features:

- Can be used in eddy covariance and many other applications
- Heat exchangers equilibrate incoming air to the cell temperature
- Built-in-pressure sensor with 0.1% accuracy, for automatic pressure compensation
- Can operate in Reference Estimation Mode (REM) in addition to normal operation
- Optical bench is cleanable in the field

Additional important specifications:

- Flow distortion to sonic anemometer is minimal due to small size of tube
- Optical sources and filters are temperature regulated to provide long term analyzer stability
- As with any long-tube closed-path device:
  - has relatively small frequency attenuation for CO_2, but significant tube attenuation for H_2O
  - must be climate controlled and filtered with fine particle filter
  - tube must be heated in most outdoor applications
  - virtually no data loss expected due to precipitation, dew, fog, snow, icing, *etc.*

References

A full list of specifications can be found at: http://www.licor.com/env/products/gas_analysis/LI-7000/specifications.html

A full description of the design and features is located at: http://www.licor.com/7000

- The LI-7000 requires an environmental enclosure to shelter the instrument from precipitation and dust
- Temperature control is highly advisable to minimize potential span drift with temperature, and to avoid overheating of the instrument, which is designed for temperatures ranging from 0 to +55°C
- All connections should be tested for leaks after instrument installation and before data collection

Installation. Since the LI-7000 is a traditional closed-path analyzer, an environmental enclosure is required to shelter the instrument from precipitation and dust. Temperature control is also highly advisable to minimize potential drift with temperature, and to avoid overheating of the instrument.

Intake Tube. Since traditional closed-path analyzers are usually located at the bottom of the tower, a long tube is required. As with the LI-7200, when using any device with an intake tube, two phenomena are of particular concern: condensation of the water on tube walls, and attenuation of the high-frequency fluctuations, which especially affects sticky gases, such as H_2O, NH_3, *etc.*

While these effects are relatively small in a short tube with an enclosed analyzer such as the LI-7200, they may become very pronounced in multi-meter tubes used with any conventional closed-path analyzers, including the LI-7000. Details on minimizing the tube effects are provided on pages 94-96.

References

Further details on the installation and calibration of LI-7000 in the field can be found in the LI-7000 manual:

ftp://ftp.licor.com/perm/env/LI-7000/Manual/LI-7000Manual.pdf

Cleaning. It is much more difficult to clean the bench of LI-7000 than the removable cell of LI-7200, so fine-particle filtering is required in field operation.

Changing chemicals. There are two small plastic scrubber/desiccant bottles near the detector housing, and two larger bottles near the chopper housing. These bottles should be changed annually.

Calibration. Factory determined polynomial calibration coefficients in a climate-controlled, clean system are usually stable for several years. However, periodically setting the zero and span is recommended to make sure the instrument performs correctly. The system can be custom-configured for automatic hourly, daily or weekly calibrations.

Leak tests should be provided for all instrument connections after the instrument is installed and before data collection. The simplest leak test can be done by breathing around the instrument connections and away from the intake, and making sure that the CO_2 signal does not increase.

Land

Air

Water

- The LI-7000, like its predecessors the LI-6262 and LI-6252, is used in a broad range of scientific, agricultural and industrial applications: eddy covariance, other flux measurements, high-precision mean concentrations, profiles, chambers, moving platforms, airborne and shipborne, *etc*.

The LI-7000 is a versatile instrument used in a variety of applications, from eddy covariance to small volume measurements.

The LI-7000 is suited for applications that demand high speed, high precision measurements, including plant gas exchange using chamber-based methods, atmospheric-surface flux eddy covariance and Bowen ratio techniques, vertical profiling, general atmospheric monitoring, and cross-sectional measurements of plumes from point sources such as volcanoes, geothermal degassing locations, or industrial sites.

The cleanable optics and software functions like integration and peak detection are useful for measuring dissolved CO_2 (pCO_2), and Total Organic Carbon (TOC) in aqueous samples.

Other applications include:

- Animal respiration
- Industrial monitoring
- Insect respiration
- Growth chamber applications
- Photosynthesis and transpiration studies
- Plant physiology

While most LI-7000 applications are land-based applications in flux networks, moving vehicles, airborne and shipborne installations are also common.

In land-based installations, performance is usually limited by sonic anemometer performance during rain and snow events. Airborne and oceanographic applications may require special mounting attachments to compensate for gyroscopic effects, such as wakes and heaving.

References

Additional information, updates and downloadable software can also be found at the LI-COR LI-7000 website: http://www.licor.com/7000

- Solar radiation, weather, soil, and canopy parameters can be valuable additions to eddy covariance measurements
- Leaf-level photosynthesis, green and total leaf area, and chamber soil flux measurements may be of interest for an even more comprehensive experiment

In addition to a sonic anemometer and gas analyzer, the eddy covariance technique may benefit from other meteorological, solar radiation, soil, and canopy sensors to help validate and interpret eddy flux data.

The main variables of interest include net radiation and soil heat flux to construct a full energy budget, shortwave radiation and PAR to quantify incoming light, and soil and weather data to assess the conditions at the site (soil temperature and moisture, relative humidity, air temperature, precipitation, *etc.*).

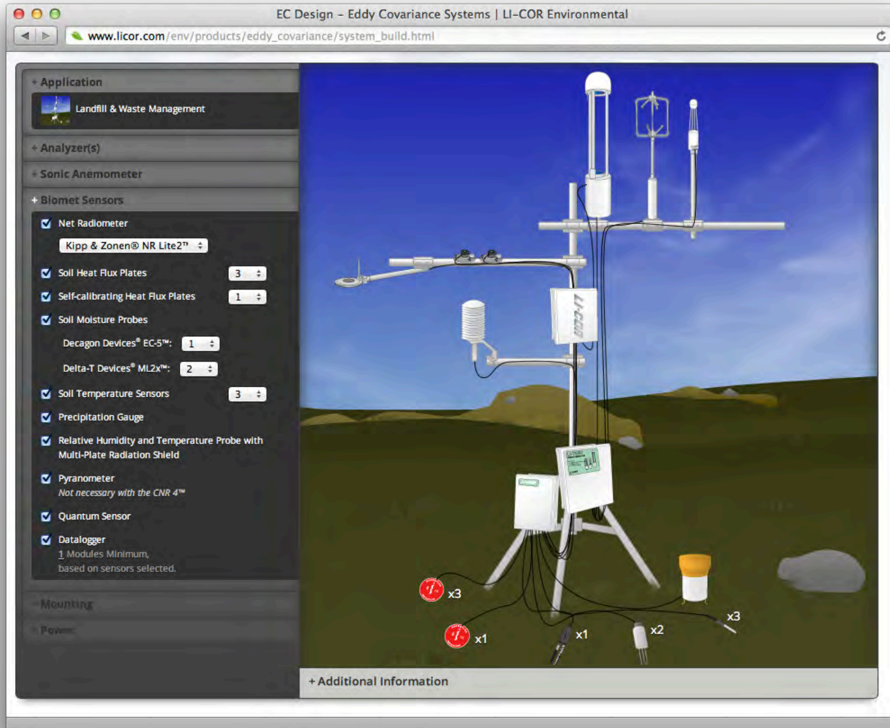
The station may range from minimally to fully equipped (details in page 34, Section 2.1). "Minimal" stations are used relatively infrequently, because data from these may be difficult to interpret in the absence of weather parameters and other supporting variables.

"Typical" stations are used more often, especially in non-scientific applications. Measured weather variables (*e.g.*, mean air temperature, relative humidity, wind speed, direction, and precipitation amounts, *etc.*) help interpret the flux data, and fill in the gaps.

"Full" eddy covariance stations include everything in "typical" stations, but in addition may also collect gas and water vapor concentration profiles below the flux measurement level, solar radiation data (*e.g.*, net radiation, incoming and outgoing shortwave and photosynthetically active radiation), and soil heat flux, temperature and moisture data.

For even more detailed experiments, leaf-level photosynthesis measurements help interpret eddy flux patterns; green and total leaf area measurements help quantify canopy development, condition and phenology; and chamber soil flux measurements help flux partitioning and attribution.

These measurement systems may include photosynthesis systems (*e.g.*, LI-6400/XT), soil CO_2/H_2O chamber flux systems (*e.g.*, LI-8100/A, LI-8150), or leaf area measurements (*e.g.*, LI-3000C, LAI-2200), *etc.*



To simplify the selection and integration of various instruments into an eddy covariance station, an interactive on-line web application is available to custom-design a specific station depending on the experimental goals.

This web application covers a wide range of measurements, from a minimal system for CO_2, H_2O, and energy flux, to an advanced system that includes CH_4 flux and additional biological and meteorological measurements.

Shown above is a screenshot of this application (http://www.licor.com/env/products/eddy_covariance/system_build.html). By clicking on a desired application, and then on a specific auxiliary sensor and quantity, one can quickly custom design the station and select main and auxiliary sensors on-line.

The application also provides an estimate of the power requirements to help size an optional solar power system.

There are two main components to these systems: fast eddy covariance, and slow auxiliary biometeorological components (*e.g.*, biomet).

The biomet system includes a slow datalogger and a pre-configured enclosure with mounting hardware. Components include circuit breakers, relay switches, terminal blocks, and grounding connections. The enclosure has an Ethernet connection for data transfer and collection on the LI-7550. Space is also available for adding network switches and/or cell modem communication devices.

To simplify setup and eliminate programming, the biomet system is provided with pre-configured programs for each of the available sensor packages.

Final fully processed fluxes are then computed using EddyPro software (see Section 2.5 for details) in a way that is now quite simple due to the integrated pre-set nature of the entire system.

References

The web application to design the station:
http://www.licor.com/env/products/eddy_covariance/system_build.html

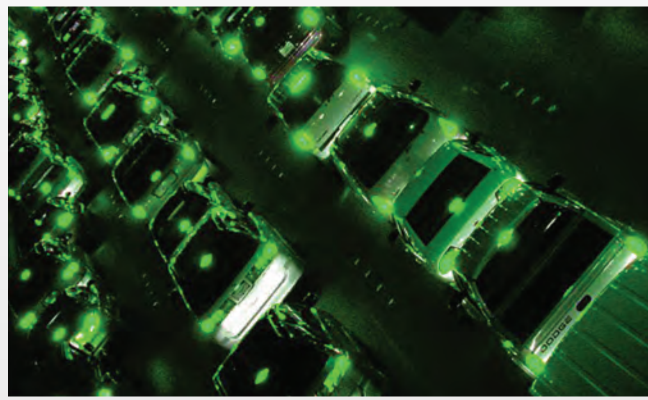
Biometeorological system components:
http://www.licor.com/env/products/eddy_covariance/system_components/biomet_system.html

Part Two:

Designing An Eddy Covariance Experiment

Section 2.5 Selecting Software

- Data collection
- Data processing
- Collection and processing
- It is imperative to keep and archive original high frequency raw data files



Until very recently, the majority of scientific groups used their own software that has been custom-written for their specific needs.

In last 3-5 years the situation started to change rapidly, and a number of comprehensive software packages became publicly available from flux networks, research groups and instrument manufacturers. These recent programs are sufficiently sophisticated, yet user-friendly, and can be of practical use to researchers outside the field of micrometeorology.

There are generally three types of software: data collection (without processing), data processing (after collection), and data collection with on-the-fly processing (simultaneously or within a few seconds after the data collection). Additional tools may include data gap filling, flux partitioning, specific data screening, *etc.*

Depending on the calibration schedule and expected failure rate of some instruments, data processed on-the-fly may need to be reprocessed after new calibration coefficients or other relevant new information has been incorporated into the old data, and after failed variables have been filled. For this and other reasons, fluxes calculated on-the-fly usually should not be considered as fully corrected fluxes, and should rather be treated as tentative estimates. Together with more specific diagnostics, on-the-fly fluxes can be useful for checking the status of the instruments and of the data acquisition system.

Throughout the entire sequence of data collection and processing steps it is imperative to keep the original raw data files. Raw data may be needed for many reasons, for example, for time delay re-calculation using a circular correlation technique, flux re-calculation with new calibration polynomials, recalculation using different averaging times or with different criteria of spiking, *etc.*

Original raw data files are large due to 10 or 20 Hz data collection, and may easily occupy 500 KB of memory for every half-hour. Provisions should be made to accommodate and archive these data.

It is extremely important to always keep and store original raw high-frequency data (10Hz, 20Hz, *etc.*), collected using the eddy covariance method. This way, data can be reprocessed at any time using, for example, new frequency response correction methods, or correct calibration coefficients. Some of the processing steps cannot be confidently recalculated without the original high-frequency data.

- Researchers often write their own software to process their specific data sets
- Recently, many comprehensive packages have become available from flux networks, research groups, and manufacturers; some examples are:

  AltEddy from Alterra Green World Research, the Netherlands
  BARFlux from Finnish Meteorological Institute, Finland
  ECO_2S from IMECC-EU and University of Tuscia, Italy
  ECPack from University of Wageningen, the Netherlands
  EC_Processor from University of Toledo, USA
  EddyMeas & EddySoft from MPI-BGC-Jena, Germany
  EddyPro from LI-COR Biosciences, Nebraska, USA
  Eddysol and *EdiRe* from University of Edinburgh, UK
  EddyUH from University of Helsinki, Finland
  Eth-flux from Swiss Federal Institute of Technology, Switzerland
  Flux Calculator and *Flux Analysis Tool* from JapanFlux, Japan
  HuskerFlux and *HuskerProc* from University of Nebraska, USA
  LundFlux from University of Lund, Sweden
  MASE from Marine Stratus Experiment, USA
  RCPM/SAS from Risø, Denmark
  TK3.0 from University of Bayreuth, Germany
  WinFlux from San Diego State University, USA

- Software and programming can be tested by processing "GOLD" data file on the Ameriflux web site to make sure that results match "GOLD" standard output

Modern programs process eddy covariance calculations using fast data, and output fluxes of water vapor, sensible heat, gases and momentum. These programs differ substantially in the level of complexity, flexibility, number of allowed instruments and variables, help systems and user support. In addition, some programs are open-source, while others are closed-source, proprietary, or commercial.

In all cases it is important to distinguish comprehensive software designed to obtain actual flux numbers from much simpler covariance calculators. The calculators compute the value of covariance between wind speed and gas concentration, often without proper coordinate rotation or time delay, and always without the entire suite of corrections and terms required for fully processed final flux values (see Part 4 for details).

Examples of comprehensive flux processing programs include free fully supported and documented open-source software such as EddyPro; free partially supported open-source programs such as ECO_2S, EddyUH, Flux Calculator from JapanFlux, and ECPack; free closed-source packages such as EdiRe, TK3, AltEddy, *etc.*; customized commercial packages; and many other programs.

Software outputs can be tested by processing the GOLD data files to make sure that results of data processing program match the GOLD standards.

References

AmeriFlux GOLD files location/downloads: http://public.ornl.gov/ameriflux/sop.shtml

Free open-source packages:

ECO_2S: http://gaia.agraria.unitus.it/eco2s

ECPack: http://www.met.wau.nl

EddyPro: http://www.licor.com/eddypro

EddyUH: http://www.atm.helsinki.fi/Eddy_Covariance/EddyUHsoftware.php

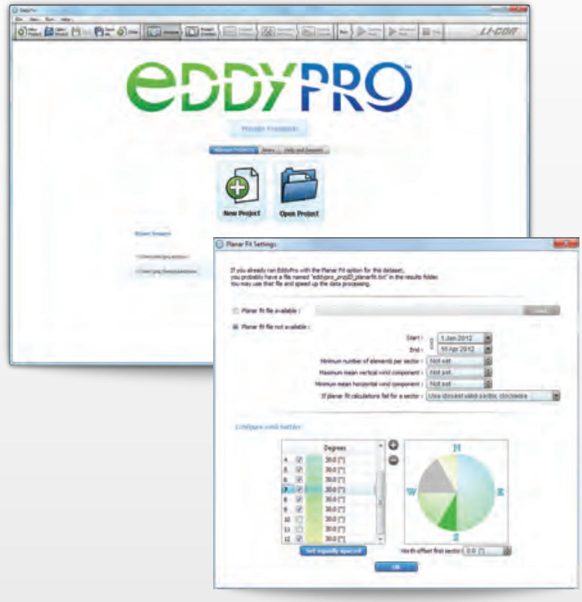
JapanFlux Flux Calculator and Flux Analysis Tool: http://www.japanflux.org/software_E.html

Intercomparison of eddy covariance software:

Mauder, M., T. Foken, R. Clement, J. Elbers, W. Eugster, *et al.*, 2008. Quality control of CarboEurope flux data – Part 2: Inter-comparison of eddy-covariance software. Biogeosciences, 5: 451-462

Comprehensive software designed specifically for a broad range of users with different levels of expertise – EddyPro®:

- Open-source and free
- Fully supported and documented
- Based on ECO_2S from IMECC
- Validated *vs.* EdiRe, ECO_2S, *etc.*
- Computes final fluxes, corrected for time delays, frequency, density, *etc.*
- Includes bio-meteorological data (*e.g.*, radiation, soil, weather, *etc.*)
- EddyPro in express mode is for non-micrometeorologists and beginners
- EddyPro in advanced mode is for micrometeorologists and advanced users



One of the latest comprehensive software packages specifically developed for eddy covariance data processing by users of different levels of familiarity with the method, from a novice to an expert, is EddyPro. It is open source software, fully documented, maintained, and supported by LI-COR Biosciences.

The processing and analysis engine is based on ECO_2S from IMECC-EU European project, which was carefully validated using six other eddy covariance programs (*e.g.*, EdiRe, EddySoft, *etc.*)

EddyPro computes fluxes of energy, momentum, carbon dioxide, water vapor, methane, and other trace gases, and also includes "biomet" data (*e.g.*, slow biometeorological data on incoming, outgoing and net solar radiation and PAR, soil temperature and moisture at different levels, weather parameters, *etc.*).

Two operational modes are available: express and advanced. In express mode, very minimal user configuration is required. The data are processed with just a few clicks using default settings, developed to provide reasonable and safe processing assumptions, but not custom-fit to the site conditions. This mode is useful for most standard sites and setups.

In advanced mode, a more experienced researcher can pre-configure the software, and fine-tune the entire processing workflow as desired.

Advanced mode is useful for non-standard sites and setups. It is also useful in situations when the researcher has particular preferences in data processing; for example, broadening criteria for despiking of fast gas concentration, adding angle-of-attack corrections, or using a planar fit rotation instead of double rotation, *etc.*

References

LI-COR Biosciences, 2012. EddyPro 4.1: Help and User's Guide. Lincoln, NE, 208 pp.

Papale, D., and G. Fratini, 2011 IMECC NA5 - Report Deliverable D_NA5.4: Software intercomparison. IMECC/University of Tuscia, Italy, 6 pp.

Key processing options in EddyPro, with express mode defaults in *italics*:

Coordinate rotation:
Double rotation
Triple rotation
2 sector-wise planar fits

Time delay:
Circular correlation-w/default
Circular correlation-no default
Time lag optimization
Constant
None

Detrending:
Block averaging
Linear detrending
Running mean
Exponential running mean

Frequency corrections:
High-pass filtering
Low-pass filtering
4 others

Density corrections:
Open-path
Closed-path
Use dry mole fraction
Surface heating
None

Other corrections:
Sonic temperature
Spectroscopic
Angle of attack

Flux footprint estimation:
Kljun et al. (2004)
Kormann & Meixner (2001)
Hsieh *et al.* (2000)

Available outputs:
Full (rich): fluxes, quality flags, etc.
Ameriflux format
GHG Europe format
Raw data statistics
Binned spectra and cospectra
Full length spectra & cospectra
Binned ogives
Details of turbulence tests
Raw data time series

EddyPro supports various types of raw input files containing fast data (*e.g.*, ASCII, binary, TOB1, and SLT for EddySoft and EdiSol). However, the most seamless format is a greenhouse gas (GHG) file that is created when logging using fast LI-COR analyzers.

The GHG format is a compressed tab-delimited text format containing two files: (i) the actual fast data file, and (ii) a metadata file with site setup information. Data and metadata files are also produced for slow biomet data files when available.

A metadata file is configured on LI-COR instruments when setting up the site or changing location or height. The file includes tower coordinates and elevation, measurement height, sensor separation, instrument models, and other parameters needed for automated data processing. When anything changes at the site, it can be registered in the metadata file and will be attached to each fast data file from the moment of change onward.

This approach allows the user to avoid numerous errors, which are common in eddy covariance data collection/processing schemes, especially at sites with multiple users, portable sites, and those with rapidly growing vegetation and related changes in measurement height. This is because each raw file now includes all the information needed to properly interpret raw data and to process fluxes, and each file can now be handled independently from the other files.

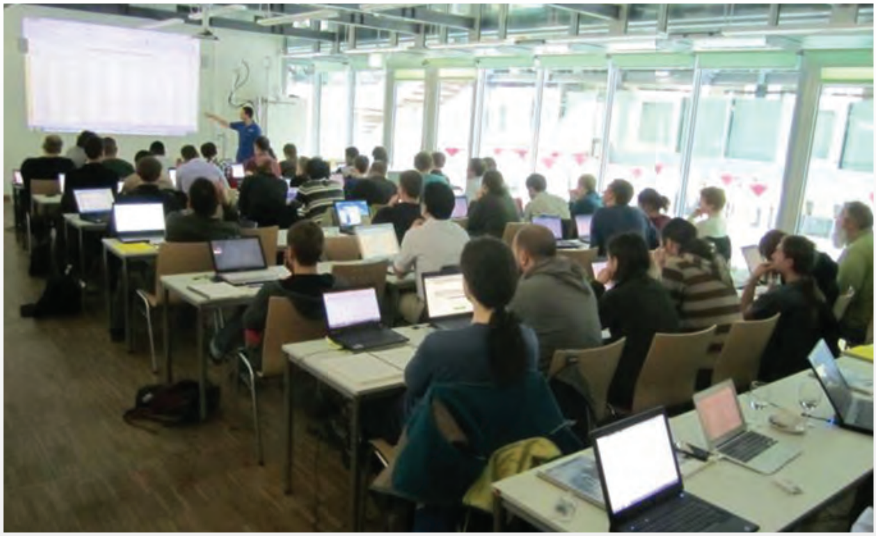
GHG files can be extracted and viewed in any text editor (*e.g.*, Notepad, WordPad, Excel, *etc.*), or using a specially created File Viewer program (ftp://ftp.licor.com/perm/env/LI-7500A/Software/fv7x00-1.0.1-install.exe), which allows viewing of multiple days of fast data instantly.

Whether using the automatically created GHG format or manually defining any other format, the data processing remains the same. The key processing options are shown in the illustration above.

References

Details of the standard steps used in general eddy covariance data processing are described in Part 4 of this book.

Details and options specific to EddyPro are provided in: LI-COR Biosciences, 2012. EddyPro 4.1: Help and User's Guide. Lincoln, NE, 208 pp.



- Since EddyPro software is fully supported and maintained, multiple resources and updates are provided to new EddyPro users
- Detailed manuals and quick start guides, webinars, video tutorials, an on-line forum, and hands-on trainings are available throughout the year

EddyPro in express mode is quite simple, and can be learned just by using and testing the program. The AmeriFlux GOLD file may be a good additional check to verify that the program runs correctly. A deeper understanding of this software can be gained via additional resources available from LI-COR:

EddyPro main web page:

- http://www.licor.com/eddypro

On-line help:

- http://envsupport.licor.com/help/EddyPro4/Default.htm

PDF Manual:

- ftp://ftp.licor.com/perm/env/EddyPro/Manual/EddyPro4_User_Guide.pdf

Webinars:

- EddyPro Data Processing Software http://www.licor.com/env/webinars/webinar_5-26-11.html
- EddyPro Data Processing with Advanced Settings http://www.licor.com/env/webinars/webinar_12-16-11.html
- Biomet Data Processing and Advanced Features http://www.licor.com/env/webinars/webinar_9-5-12.html

Video tutorials:

- http://envsupport.licor.com/help/EddyPro4/Video_Library.htm

EddyPro Forum for informal discussions:

- http://www.licor.com/env/forum

Eddy covariance training courses

- Cover all major aspects of the measurements, including EddyPro, and are taught many times per year around the globe: http://www.licor.com/env/products/eddy_covariance/training.html

Technical and scientific support:

- http://www.licor.com/env/products/eddy_covariance/support.html

- The main pitfalls of custom-written data collection and processing software are human errors in coding and configurations
- The main pitfall when using commercial software packages is not carefully checking fluxes and instantaneous data collected by such packages
- Other frequent pitfalls common to both custom and commercial approaches are:
  - not archiving original fast data
  - collecting fast data into different streams and files
  - configuring fast instruments to collect at different frequencies
  - configuring the data collection with insufficient decimals (*e.g.*, truncating)
  - not checking fluxes and instantaneous data periodically

When collecting and processing data using custom-written code, researchers are often forced to look at the data in order to verify and adjust the code.

On the one hand, custom code may introduce errors (*e.g.*, typos in the code, wrong units, *etc.*), but on the other hand, they help researchers to become familiar with the data, at least during the initial stages of data collection. Legacy custom code from past years often creates significant problems for new less experienced users, and may lead to serious collection and processing errors.

When using commercial packages for automated data collection and processing, there is always the danger of not adequately checking the data outputs. While modern software packages significantly simplify the complex process of eddy covariance data collection and processing, it is important to realize that these programs may compute some kind of flux numbers from instantaneous time series even when the time series are mislabeled or processing steps are misplaced.

It is important to carefully look at instantaneous time series to double-check that patterns look reasonable, units make sense, and diagnostic parameters for various instruments seem correct. It is also important to carefully look at computed flux products to make sure that they are physically possible and physiologically reasonable. Avoiding simply computing a number is perhaps the most important part of using modern eddy covariance software.

Other frequent pitfalls of eddy covariance data collection and processing include:

- ***not keeping original fast data*** - in case of processing errors, reprocessing may become difficult or impossible
- ***collecting fast data from anemometer and analyzer into two different streams/files*** - time mismatches may lead to flux loss, make processing complex and error-prone
- ***setting fast instruments to different collection frequencies*** (for example, 20 Hz for anemometer and 15 Hz for analyzer) - processing becomes cumbersome, error-prone
- ***configuring data collection with insufficient decimal places*** (*e.g.*, truncating) - fluxes may get lost because fast changes may occur in a truncated part of the variable, making for difficult or impossible data recovery
- ***not checking flux data at the initial collection stages*** to make sure they are reasonable - program can usually compute a number even if it is not a reasonable one
- ***not checking instantaneous data and diagnostics periodically*** to make sure system works - program will collect any data, and may not guarantee collection of good quality data

Part Two:

Designing An Eddy Covariance Experiment

Section 2.6 Selecting Location of the Study and Position of the Station

Many of the location requirements follow directly from the EC equations and are intended to satisfy the assumptions made during derivations

- Represent the ecosystem/area of interest
- Large enough: sufficient fetch/footprint
- Assumptions hold or are correctable
- Terrain is reasonably flat and uniform

Many of the location requirements follow directly from the eddy covariance equations described earlier in this book, and are intended to satisfy the assumptions made during derivation of these equations.

Most importantly, the location should represent the ecosystem or area of interest, and the plot size should be large enough to provide sufficient fetch/footprint, described in detail in Section 2.7.

Ideally the surface should be flat and uniform, or least manageable, so the assumptions would hold or be correctable.

Additionally, practical requirements such as power availability and site access should be considered when planning the site location and positioning the station.

The decision should be made as to whether the site will require a low-power arrangement, or if grid power will be provided. This may be a good time to assess the costs of such arrangements.

The site should also be reasonably accessible for maintenance in accordance with the maintenance plan.

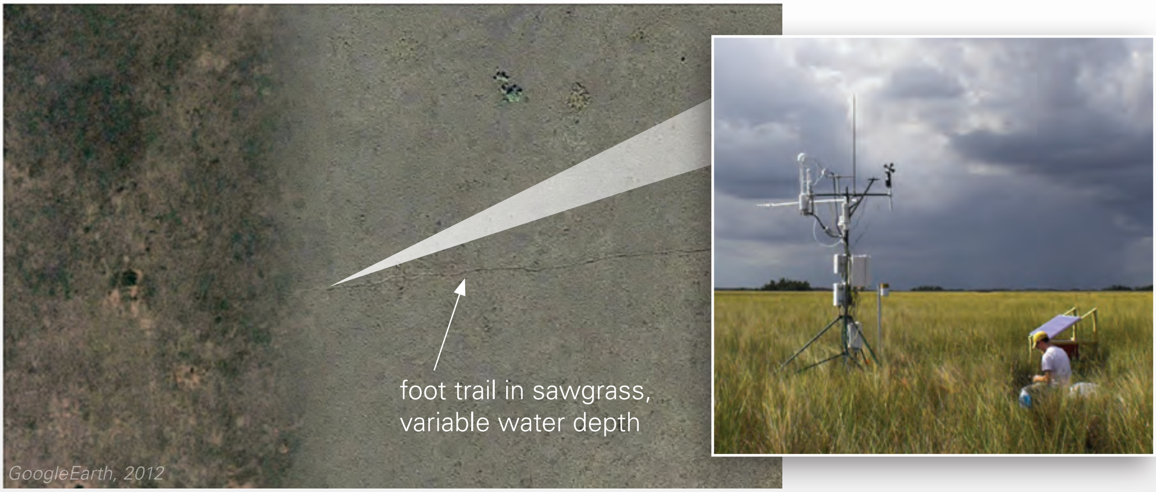
At this stage in the preparation of the experiment, the future location of the instruments on the tower and the respective tower height may also be considered, at least as a first approximation, in relation to atmospheric layers and the footprint of the station, as these may significantly affect the site selection and tower placement within the selected site.

Additional details are provided in Section 2.7 (Importance of Flux Footprint) and Part 3 (Implementing Eddy Covariance Experiment). Here are just a few important highlights to keep in mind during the planning.

References

Law, B., 2006. Flux Networks – Measurement and Analysis. http://dataportal.ucar.edu/CDAS/may02_workshop/presentations/C-DAS-Lawf.pdf

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228



- An eddy covariance station in the middle of a wetland in the Florida Everglades measured fluxes of CH_4, CO_2, and H_2O over a period of 3 years
- The flux tower consumed less than 30 Watts of power (LI-7700, LI-7500, sonic anemometer, weather data) and was hand-carried into the center of the wetland

Over the past few decades, flux measurements have been conducted in a relatively large number of major ecosystems, yet for a relatively small number of gas species. In recent years, these studies are moving further into new and lesser studied natural and agricultural ecosystems, industrial and municipal territories, and into new gas species. Some examples are methane flux measurements in remote Arctic wetlands, isotope flux measurements at high elevations, gas leak monitoring over carbon capture and sequestration sites, or constructing a greenhouse budget for a landfill or a city. Flux studies have also become longer in duration, and with less on-site presence for maintenance and data retrieval.

These tendencies make it especially important to consider the positioning of the tower within the ecosystem or other area of interest, with respect to power, installation, access and maintenance.

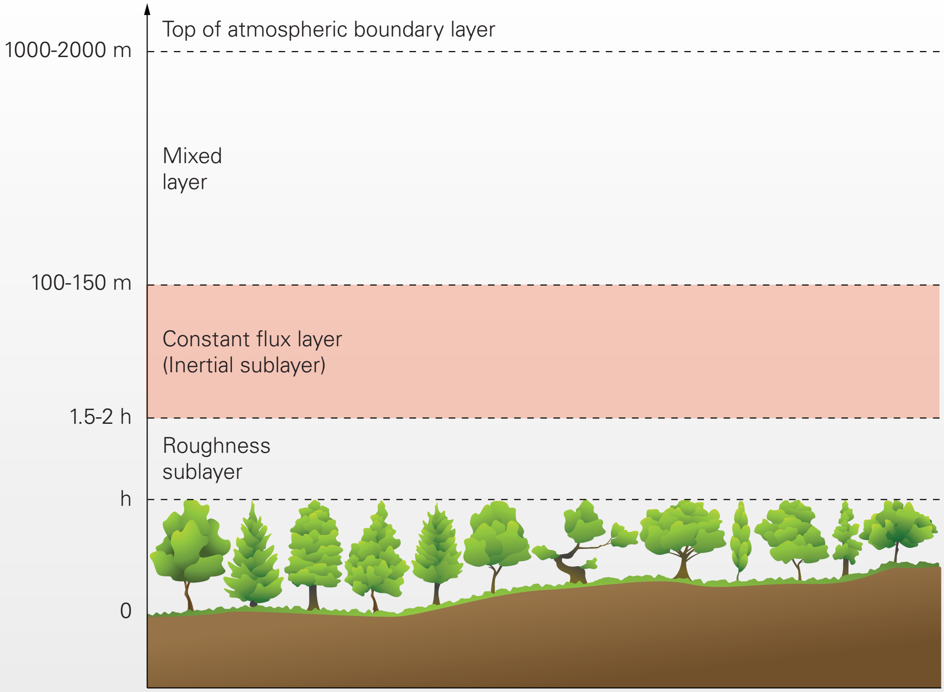
Many past studies were located near roads and commercial power lines, and the selection of the tower placement was determined by both scope of the study and practicality of the installation.

Recent low power and lightweight instrument developments allow placing remote unattended solar- or wind-powered flux towers in the middle of the study area without any consideration for the road infrastructure and grid power availability.

This reduces data loss due to bad wind directions, and enables novel experiments in little studied areas, but also has increased demands on experimental planning, instrument selection, site access and data retrieval. Often these arrangements must use open-path instruments, or enclosed instruments with no fine-particle filter, requiring that instruments have to be cleaned periodically, especially after dust storms, and during periods of heavy pollination or other natural or industrial contamination. Also, remote data access is not always available, and manual data retrieval may be required.

Similar maintenance schedules may also be needed even at grid-powered sites with enclosed or closed-path devices employing fine particle filters, in order to change filters after these type of events. Regular cleaning may also be required for sonic anemometers and auxiliary meteorological sensors, especially those used to measure light.

These items are usually resolved fairly easily at remote and low-power sites by hiring a responsible local person (*e.g.*, high-school student or hourly help) for a few hours per month for upkeep and data retrieval activities.



(layers are based on Stull, 1988; Denmead et al., 1996; and Oke, 2007)

An indirect, but important, factor when selecting the experiment location is the anticipated tower and instrument placement height above the surface. Generally, the best position for the eddy covariance instrumentation is in the constant flux layer, located approximately 1.5-2 canopy heights above the soil surface, but below the mixed layer (100-150 m above the soil surface).

Instruments located too close to the canopy, in the roughness sublayer, may not represent the turbulence adequately developed over the ecosystem of interest, but rather may characterize the local effects or disturbances by a single tree or a specific branch, for example. Instruments that are located too high, in the mixed layer, may be decoupled from the constant flux layer and may not represent the ecosystem of interest either.

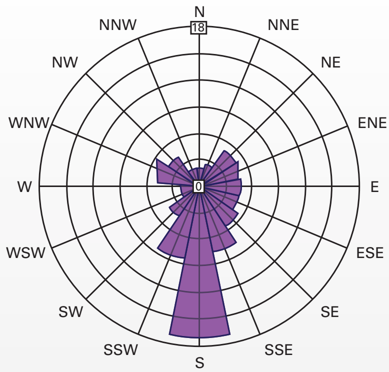
Within the constant flux layer, it is also desirable to position the instruments higher in order to minimize frequency response errors and related corrections. However, the uppermost height is usually restricted by the size of the study area via the flux footprint, described in detail in the Section 2.7.

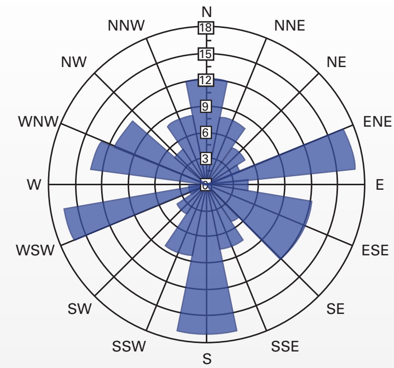
In general, the upwind distance represented by tower height can be determined by the 1:100 rule. For example, if the tower is 2 meters above the surface, the majority of measured flux will come from an oval-shaped area stretching from near the tower to 200 meters upwind.

Thus, when a location is selected, the study area should ideally be fairly large, so that the tower positioned in the center can provide adequate upwind distance in all wind directions.

Strictly speaking, the measurement height should be referenced for these purposes, not from the soil surface, but from zero plane displacement (*e.g.*, the height at which the logarithmic wind profile hypothetically goes to zero). This is usually about 2/3 of the canopy height, but depends heavily on the structure of the canopy and other factors.

The concept of zero plane displacement may be difficult for non-micrometeorologists, so below we provide two sets of rough rules-of-thumb, for short and for tall canopies, to avoid the need for in-depth studies of this concept.





Most winds come from the south:

- May place tower closer to the downwind (northern) edge of the site to gain upwind distance and increase measurement height
- May select smaller study area, but some data loss due to winds outside the area of study will occur

Winds come from various directions:

- Ideally, tower should be placed in the center of the area of study to access all wind directions and minimize data loss
- May select larger study area or lower tower; maximum instrument height will be restricted by upwind distances

For short canopies, (with heights below 2-3 meters), it is advisable to position the instruments at a height 2.0 times the canopy height from the soil surface, and at least 1.5-2.0 m above the top of the canopy. This also means that the site should be large enough to provide an upwind distance (*e.g.*, fetch) of several hundred meters.

For example, if the canopy is 0.5 meters tall, the instruments should ideally be located at least at 2.0 m (0.5 m + 1.5 m) above the soil surface. In this case, the site should provide a fetch of about 200 m.

In regions with winds from multiple directions, it would be ideal to find a site of at least 400x400 m, so that the tower can be placed in the center and can collect data from all directions, minimizing data loss. In regions with a single or only a few prevailing wind directions, the tower can be positioned on the downwind edge of the measured area, reducing the minimum size requirement to 200x200 m.

For tall canopies (with heights above 2-3 meters) it is desirable to position the instruments at a height of about 1.5 times the canopy height from the soil surface, or at least 2.0-3.0 m above the top of the canopy. For example, if the canopy is 5 meters tall, the instruments should ideally be located at least 7.5 m above the soil surface or higher.

Calculating the fetch and size requirements of sites with tall canopies is more involved due to large zero plane displacement. For a 5 m canopy, zero place displacement is about 3.3 m (2/3 x 5 m). Thus, the effective instrument height for a 7.5 m tower is about 4.2 m (=7.5-3.3) and ideally the site should be selected to provide a fetch of about 420 meters or more.

For areas with winds from multiple directions, the site should ideally be at least 840x840 m in size so that the tower can be placed in the center and collect data from all directions, minimizing data loss. For areas with a single or only a few prevailing wind directions, the tower can be positioned on the downwind edge or in the corner of the measurement area, reducing the minimum size requirement to 420 x 420 m.

> It is important to note that these "rules of thumb" are very approximate. If all other factors are equal, it is desirable to choose a larger site, and allow for taller towers and higher instrument positioning. If this is not possible, analyses of the wind rose (pictured above) and footprint (described in the next section) can be conducted for a specific site to evaluate the contributions from each wind direction, and to optimize the tower positioning within the site. It is, however, essential to avoid placing instruments outside of the constant flux layer.

Part Two:

Designing An Eddy Covariance Experiment

Section 2.7 Importance of Flux Footprint

Effect of measurement height

Effect of roughness

Effect of thermal stability

In the simplest terms, flux footprint is the area "seen" by the instrument on the tower. In other words, it is an area upwind from the tower, such that fluxes generated in this area are registered by the tower instruments. Another frequently used term, 'fetch', usually refers to the distance from the tower when describing the footprint.

Understanding the flux footprint concept is essential for proper planning and execution of an eddy covariance experiment. Therefore, the next 14 pages are dedicated exclusively to the concept of footprint, with detailed explanations and practical examples.

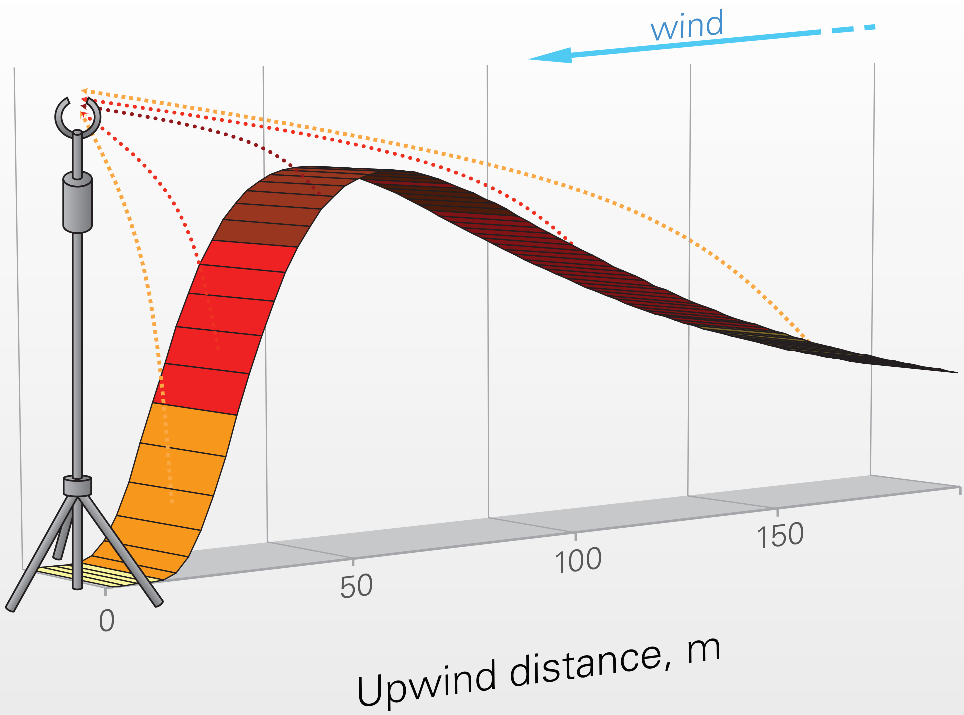
First, we will look at how the footprint is affected by measurement height. Then, we will look at how the roughness of the surface affects what the instrument can "see", and finally, how thermal stability affects the footprint.

Even more complex situations may exist when the footprint area is not homogeneous. See Schmid, HP, Lloyd, CR. 1999. Spatial representativeness and the location bias of flux footprints over inhomogeneous areas. Agricultural and Forest Meteorology, 93, 195-209

References

Kljun, N., P. Calanca, M. Rotach, and H. Schmid, 2004. A simple parameterization for flux footprint predictions. Boundary-Layer Meteorology, 112: 503-523

Burba, G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K. Hubbard and M. Sivakumar (Eds.). Automated Weather Stations for Applications in agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland: 77-87



The flux footprint is visualized above: the darker the red color – the larger the flux contribution that is coming from the area. Thus, most of the contribution usually comes not from underneath the tower and not from many kilometers away, but rather from somewhere in between.

To calculate actual distances and contributions, let us look at the main features of the dependence of the flux footprint on measurement height, surface roughness and thermal stability. We will use, as an example, an actual latent heat flux data (evapotranspiration, ET) from a tallgrass prairie site near Ponca City, OK.

To demonstrate the effect of measurement height and roughness in near-neutral conditions, two days were chosen from the 1999 growing season. One of the chosen days was a clear day shortly after a prescribed burn. With virtually no vegetation, the surface was smooth (with a roughness parameter of about 0.001 m). The thermal stability was near neutral, with z/L ranging from −0.003 to 0.05 for most of the day.

By contrast, another chosen day had a relatively large canopy height of 0.6 m, and a roughness parameter of about 0.08 m. It also had near-neutral conditions, with a stability parameter z/L ranging from -0.08 to 0.2 for most of the day.

References

Gash, J., 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorology, 35: 409-413

For near-neutral conditions:

$$CNF(x_L) = -\int_0^{x_L} \frac{U(z-d)}{u_* k x^2} e^{-\frac{U(z-d)}{u_* k x}} dx = e^{-\frac{U(z-d)}{u_* k x_L}}$$

CNF is Cumulative Normalized contribution to Flux measurement, %

x_L is distance from the station, m

U is mean integrated wind speed, m s^{-1}

z is measurement height, m

u_* is friction velocity, m s^{-1}

d is zero plain displacement, m

k is von Karman constant (0.4)

Schuepp, P.H., Leclerc, M.Y., Macpherson, J.I., and R.L. Desjardins, 1990.
Footprint prediction of scalar fluxes from analytical solution of the diffusion equation.

There are a number of models used to evaluate footprint contribution from any given distance. For near-neutral conditions, one of the simplest yet descriptive models is given by Schuepp *et al*. It estimates cumulative normalized contribution to flux measurement (CNF) computed from analytical solutions of the diffusion equation for near-neutral conditions.

The model inputs are: instrument height, canopy height, wind speed, desired distances from the tower, friction velocity, and zero-plane displacement. From these, the model computes how much of the measured flux comes from a particular distance.

References

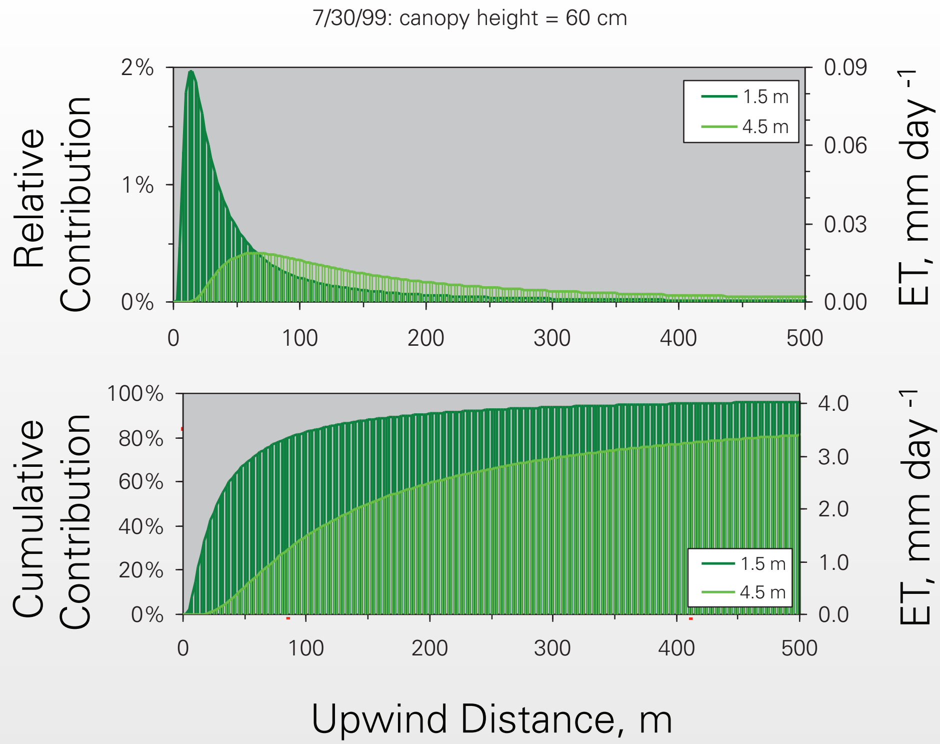
Schuepp, P., M. Leclerc, J. Macpherson, and R. Desjardins, 1990. Footprint Predictions of Scalar Fluxes from Analytical Solutions of the Diffusion Equation. Boundary-Layer Meteorology, 50: 355-373

Kljun, N., P. Calanca, M. Rotach, and H. Schmid, 2004. A simple parameterization for flux footprint predictions. Boundary-Layer Meteorology, 112: 503-523

Finn, D., B. Lamb, M. Leclerc, and T. Horst, 1996. Experimental evaluation of analytical and Lagrangian surface layer flux footprint models. Boundary-Layer Meteorology, 80: 283-308

Gash, J., 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorology, 35: 409-413

Horst, T., and J. Weil, 1992. Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorology, 59: 279-296



The values of latent heat flux contributed from the upwind distance are plotted in the figures above.

The top plot shows how much of the total flux comes from a particular upwind distance. The area under the curve integrated from zero to infinity, will give the total evapotranspiration rate from the site.

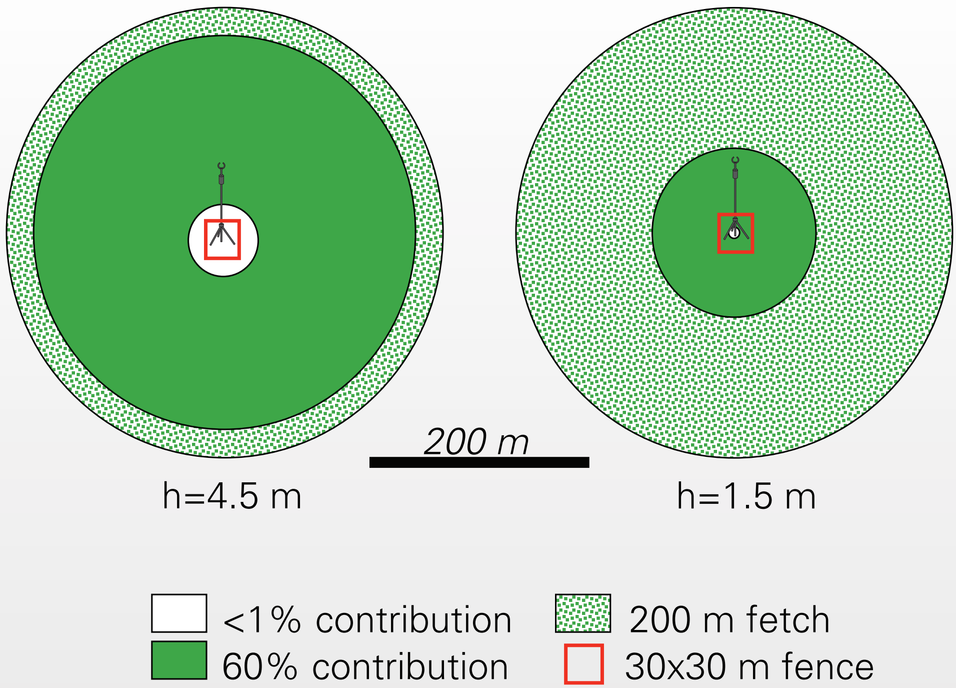
The bottom plot shows the same information as a cumulative contribution.

When measured at a height of 4.5 m, the peak contribution of the ET comes from the upwind distance of about 60-65 m, while an area within 20-30 m from the station did not contribute to any of the measured flux. In terms of cumulative contribution, 80% of the total daily flux came from an upwind distance of 20-450 m.

At a lower measurement height of 1.5 m a dramatic change in the contribution is observed. The peak contribution comes from a closer upwind distance of about 12-18 m. Over 80% of daily ET comes from an area within 80 m of the station (versus 20-450 m zone for the 4.5 m measurement height).

References

Burba, G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K. Hubbard, and M. Sivakumar (Eds.). Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland: 77-87



These are the same data as shown on the previous page, but are plotted as a view from above. They demonstrate the potential contribution of the footprint for 4.5 and 1.5 m towers from all wind directions. The tower is located in the center of each plot.

In the plot on the right, note how important it is to keep the area around the station undisturbed and representative of the overall site when the measurement height is low.

- Footprint strongly increases with measurement height:

  - at 1.5 m over 80% of the ET came from within 80 m upwind

  - at 4.5 m over 80% of the ET came from within 450 m upwind

- Footprint near the station may also be strongly affected:

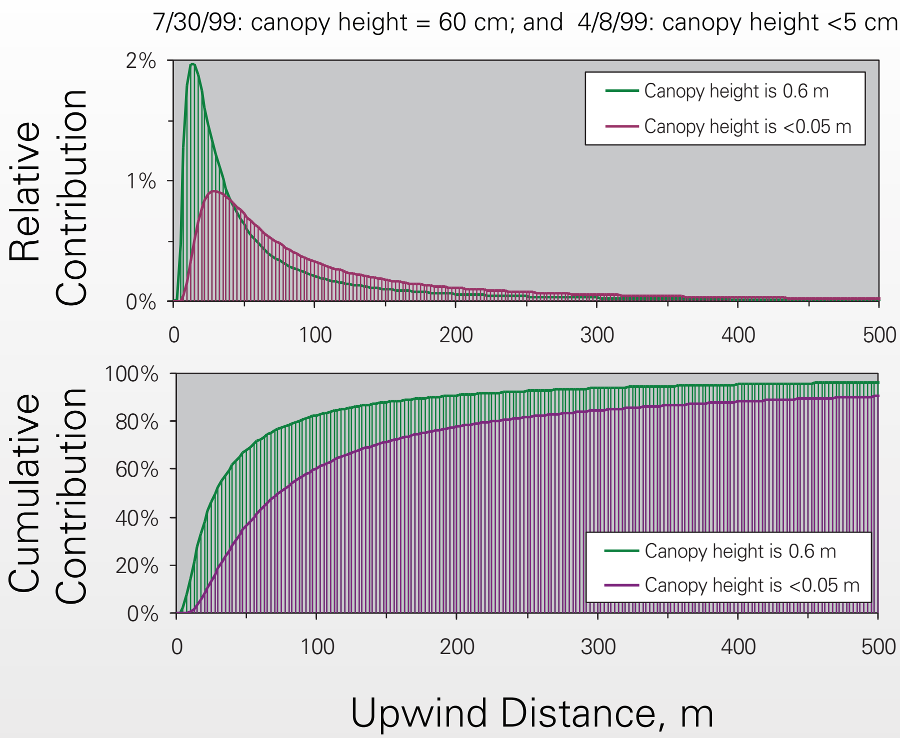
  - at 1.5 m, the area 5 m around the instrument did not affect ET

  - at 4.5 m, the area 32 m around the instrument did not affect ET

- Both sufficient fetch requirement and an undisturbed area around the instruments are important for proper footprint at any measurement height

Overall, with increased measurement height, the upwind distance to the peak contribution increased, while the magnitude of the peak contribution was reduced. The upwind distance covered by the station increased dramatically, as did a zone of "no contribution" around the station.

An important practical implication of the effect of the measurement height on flux footprint is that both sufficient fetch and an undisturbed area around the instrument are important for the proper footprint at any measurement height.



The effect of roughness on the flux station footprint is demonstrated in the figures above.

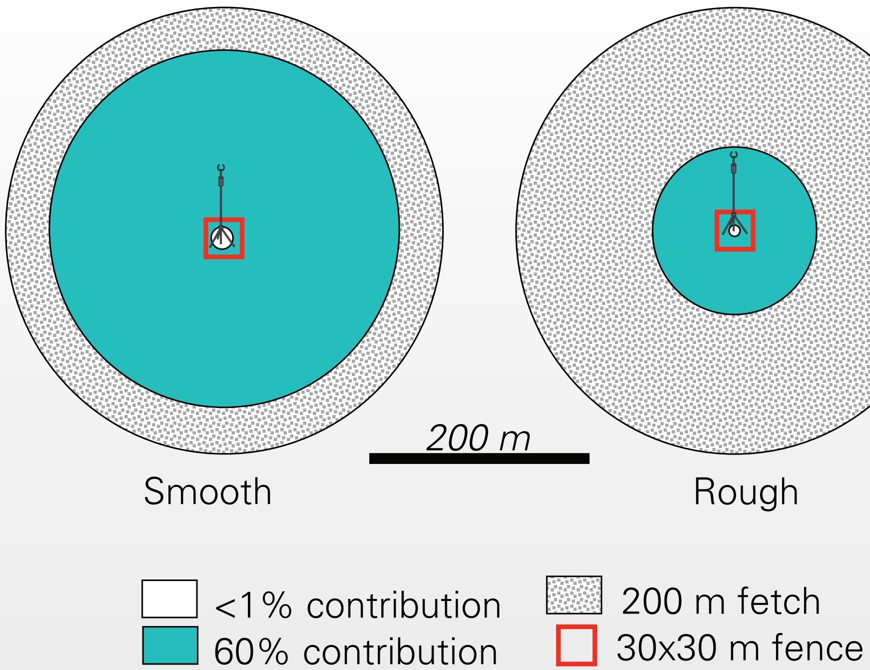
For the 1.5 m measurement height, the largest contribution came from 12-18 m (2% of ET) on a day with relatively high roughness (canopy height 60 cm).

For the same measurement height on a day with low roughness (canopy height <5 cm), the peak contribution shifted to about 30-35 m of the upwind distance, and was 2 times smaller (1% of ET).

In terms of cumulative contribution, over a rough surface, more than 80% of the ET came from within 80 m upwind. Over a smooth surface, the same contribution came from within 250 m.

References

Burba, G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K. Hubbard and M. Sivakumar (Eds.). Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland: 77-87



These are the same data as on the previous page, plotted as viewed from above. They demonstrate the potential contribution of the footprint for smooth and rough surfaces from all wind directions. The tower is located in the center of each plot.

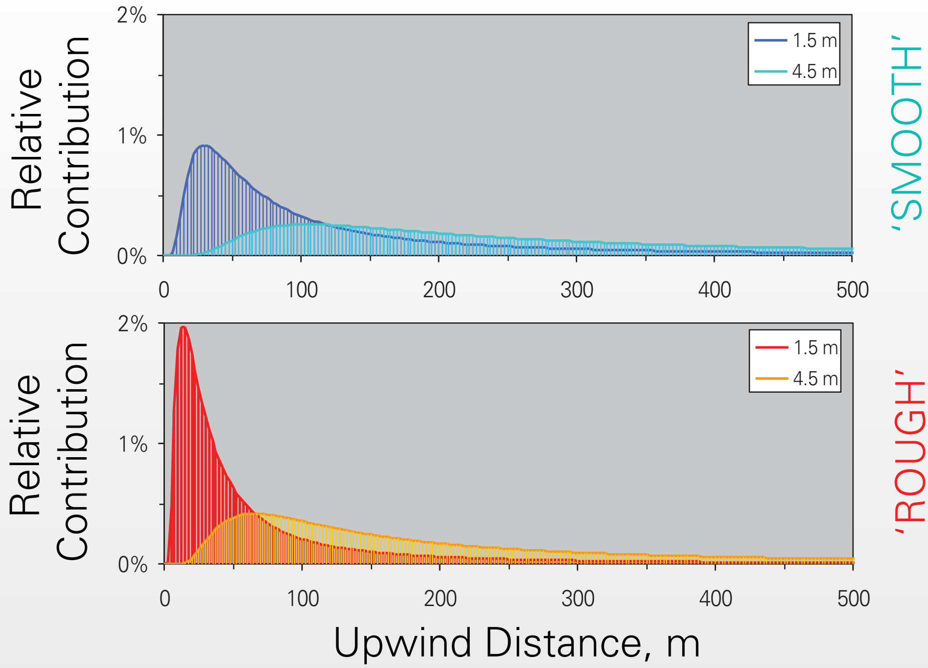
The “no contribution” zone was within 5 m around the station for the rough surface, and within 10 m for the smooth surface.

Please note again how important it is to keep the area around the station undisturbed under both roughness conditions.

- Footprint decreases with increased roughness:
  - at a sensor height of 1.5 m:
    - for rough surface over 80% of the ET came from within 80 m upwind
    - for smooth surface 80% of ET came from about 250 m upwind
- Footprint near the station is also affected by roughness:
  - for rough surface, area 5 m around the instrument did not affect ET
  - for smooth surface, area 10 m around the instrument did not affect ET
- Both sufficient fetch requirement and undisturbed area around instruments are important for proper footprint at any roughness

Overall, with increasing roughness, upwind distance to the peak contribution decreased, the magnitude of the peak contribution increased, while the upwind distance covered by the station and the zone of "no contribution" shrank in size, as compared to the "smooth" surface.

An important practical implication of the effect of the roughness on flux footprint is that both sufficient fetch and an undisturbed area around the instruments are important for the proper footprint at any roughness.

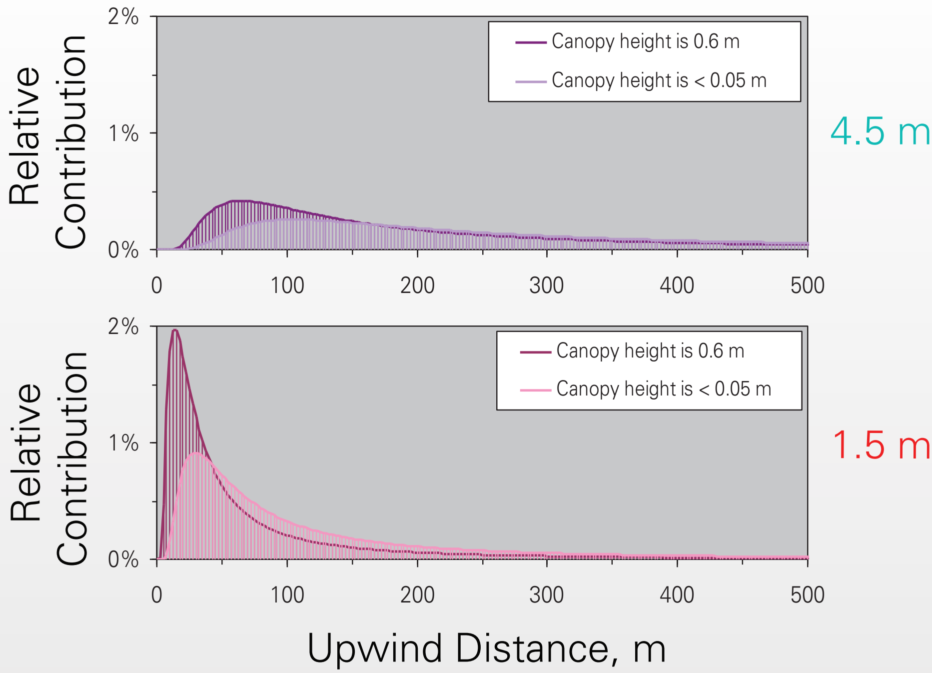


The contribution from the upwind distance for different measurement heights is shown above for a "smooth" surface in the top figure, and for a "rough" surface in the bottom figure.

For the "rough" surface, the measurement height had a more profound effect on footprint than for the "smooth" surface. While the peak contribution increased 3 times with an increase in measurement height for the smooth surface, the same increase in measurement height led to a peak contribution increase of 5 times for the rough surface.

References

Burba, G., 2001. Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness and Thermal Stability. In K. Hubbard and M. Sivakumar (Eds.). Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives. World Meteorological Organization publication No.1074. HPCS Lincoln, Nebraska – WMO Geneva, Switzerland: 77-87



The contribution from the upwind distance for different roughness levels is shown above for a 4.5 m measurement height in the top figure, and for a 1.5 m measurement height in the bottom figure.

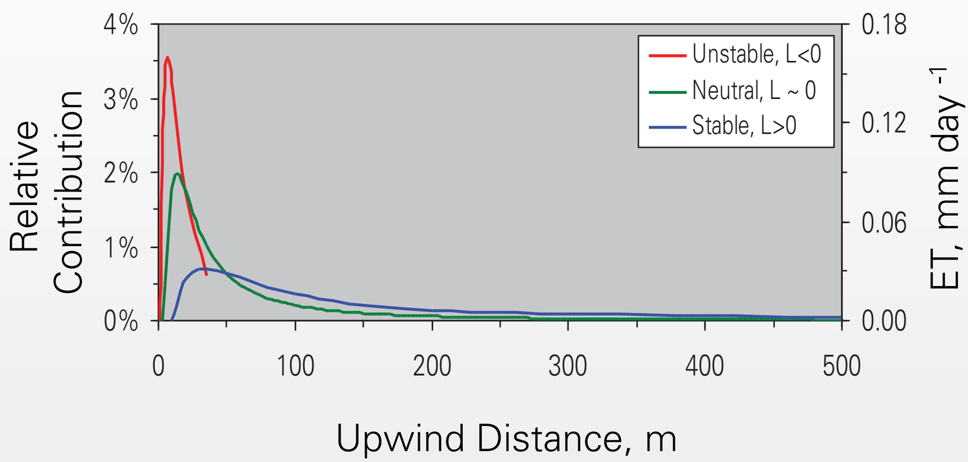
At the 4.5 m measurement height, the peak contribution increased 1.3 times in magnitude and shifted twice as close to the station with increased roughness. At the 1.5 m measurement height, the peak increased 2 times (from 1 to 2% of ET).

- The measurement height has a more profound effect on footprint over rough surfaces than over smooth surfaces
- At a lower measurement heights, the roughness has a more profound effect on footprint than it does at higher instrument heights
- Both factors should be included in the calculation of optimal instrument placement

Overall, the measurement height had a more profound effect on the footprint over rough surfaces than over smooth surfaces.

At lower measurement heights, roughness had a more profound effect on the footprint than it did at higher measurement heights.

Therefore, for practical purposes, both measurement height and surface roughness should be considered for optimal tower positioning and instrument placement.



Adopted from Leclerc and Thurtell (1990)

The effect of stability on the upwind distance contribution to latent heat flux is shown in the figure above (adopted from Leclerc and Thurtell, 1990).

For the same measurement height and roughness, changes in atmospheric stability can change the footprint size several times.

For a measurement height of 1.5 m and a canopy height of 0.6 m, very unstable conditions can lead to most of the flux footprint being within 50 m of the station.

In near-neutral conditions, most of the footprint is located between 5 and 250 m of the station.

And during very stable conditions, the area of flux contribution is located between 15 and 500 m upwind.

References

Leclerc, M., and G. Thurtell, 1990. Footprint prediction of scalar fluxes using a Markovian analysis. Boundary-Layer Meteorology, 52: 247-258

- For the same measurement height and roughness, atmospheric stability can increase the footprint size several times
- For a measurement height of 1.5 m and a canopy height of 0.6 m:

  - in very unstable conditions, most of the footprint is within 50 m

  - in neutral conditions, it is within 250 m

  - in very stable conditions, footprint is within 500 m
- Flux data at very stable conditions may need to be corrected or discarded due to insufficient fetch
- Flux data at very unstable conditions may need to be corrected or discarded due to the fact that a large portion of the flux may come from the disturbed area around the instrument tower

Some important practical implications of the effect of stability on the footprint for station positioning and data processing are as follows.

Flux data at very stable conditions may need to be corrected or discarded due to insufficient fetch. Flux data at very unstable conditions may need to be corrected or discarded due to the fact that a large portion of the flux comes from an area around the instrument, which is often disturbed to some degree by maintenance activity.

In some cases, when the specific microclimate of the site leads to a consistent prevalence of stable conditions, tower placement and measurement height may need to be adjusted to avoid large losses of data due to insufficient fetch.

Flux footprint depends on:

- Measurement height
- Surface roughness
- Thermal stability

Size of footprint increases with:

- Increased measurement height
- Decreased surface roughness
- Change in stability from unstable to stable

Area near instrument tower may contribute a lot if:

- Measurement height is low
- Surface roughness is high
- Conditions are very unstable

Flux footprint describes a contributing area upwind from the tower. This is the area that the instruments can "see".

Flux footprint mainly depends on measurement height, surface roughness, and atmospheric thermal stability. The size of the footprint increases with increased measurement height, with decreased surface roughness, and with changes in thermal stability from unstable to stable.

The area near the tower may contribute a lot to the flux footprint, if the measurement height is low, surface roughness is high, or if conditions are very unstable.

It is important to note that both the fetch requirement and conditions of the surface in the area immediately surrounding the flux station can and should be regarded for station placement, maintenance and data quality control.

References

Gash, J., 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorology, 35: 409-413

Rebmann, C., M. Göckede, T. Foken, M. Aubinet, M. Aurela, *et al.*, 2005. Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modeling. Theoretical and Applied Climatology, 80 (2-4): 121-141 DOI: 10.1007/s00704-004-0095-y

Schmid, H., 1994. Source areas for scalars and scalar fluxes. Boundary-Layer Meteorology, 67: 293-318

Stannard, D., 1997. A theoretically based determination of Bowen-ratio fetch requirements. Boundary-Layer Meteorology, 83: 375-406

Schuepp, P., M. Leclerc, J. Macpherson, and R. Desjardins, 1990. Footprint Predictions of Scalar Fluxes from Analytical Solutions of the Diffusion Equation. Boundary-Layer Meteorology, 50: 355-373

Part Two:

Designing An Eddy Covariance Experiment

Section 2.8 Planning Contingencies and Long-Term Maintenance

- Sensor cleaning
- Sensor replacement
- Sensor calibration
- Cable replacement
- System repair
- A maintenance plan is very important to avoid unnecessary data loss
- Individual maintenance items may be trivial, while interaction of all items gets complex: for example, 20 sensors calibrated yearly
- One or two spare sensors are desirable for each measurement

After defining the purpose and scope of the experiment, creating a list of variables, selecting hardware, software and the experiment location, but before actual setup, it is important to create a long-term maintenance plan.

Here maintenance can be defined rather broadly, as: (i) developing a regular instrument maintenance, cleaning and calibration schedule; (ii) periodically checking instantaneous raw data, instrument diagnostics, and flux products; and (iii) traveling to the site for maintenance based on such checking, and per instrument maintenance schedule.

At a minimum, the field portion of the maintenance plan includes: periodic instrument cleaning and replacement, calibration schedule, replacement of damaged cables, and other anticipated repairs to the instrument system.

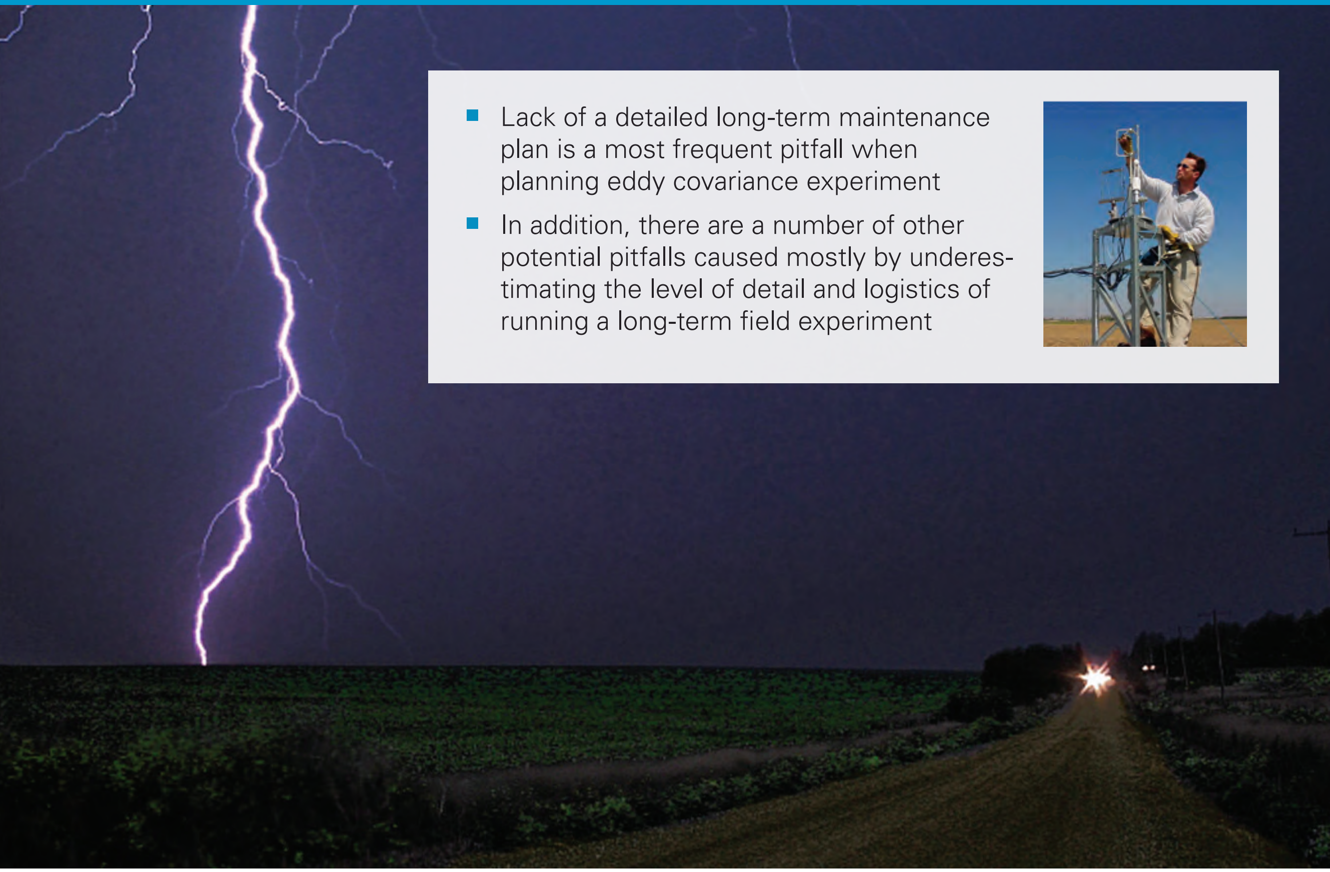
A well-designed maintenance plan is very important to avoid unnecessary loss of data in the future, during the data collection process. Each of the maintenance items may seem trivial, however, interaction of all these items gets complex fairly quickly.

For example, a yearly or 6-month recommended factory calibration of 20 different instruments becomes a serious logistical task, and requires optimization of the number of required back-up instruments, trips to the experimental site, and introduces a risk of data loss.

If a sensor requires factory service, it may take several weeks, so plans should be made beforehand for a replacement instrument.

In addition to routine maintenance, unforeseen circumstances may complicate the schedule further (fires, lightning strikes, storm damage, rodent damage, power failure, *etc.*). This is why one or two spare sensors for each variable, and a portable power backup for a few essential measurements are very desirable, especially at remote sites.

> The maintenance plan is one of the most overlooked items in the eddy covariance setup, especially for first-time users.
>
> Proper planning at this stage will help to avoid potentially large losses of data in the future, when running the experiment.



- Lack of a detailed long-term maintenance plan is a most frequent pitfall when planning eddy covariance experiment
- In addition, there are a number of other potential pitfalls caused mostly by underestimating the level of detail and logistics of running a long-term field experiment

In addition to not making a detailed long-term maintenance plan, other frequent pitfalls during the planning stage primarily come from underestimating the level of detail and logistics of running any long-term field experiment. Typical examples include the following:

- Purpose of the experiment is too narrowly defined, resulting in too short of a list of variables, and thus, in a lack of instrumentation for all the measurements which will actually be needed. This pitfall is particularly frequent in scientific applications with new users.
- Auxiliary measurements (*e.g.*, gas concentration profiles, solar radiation or PAR, soil moisture, soil heat flux, *etc.*) are either not deployed or not maintained. This is especially important in scientific applications, where interpretation of flux data relies on the weather and ecosystem data.
- Hardware is chosen not for the job, but for the cost, or selection is based on specifications irrelevant to eddy covariance measurements, or without regard for the vital specifications.
- Hardware is chosen without checking its compatibility with data collection and flux processing software.
- Hardware is chosen such that it would require grid power, while the site is chosen such that it is exceptionally difficult to build grid power access.
- No provision is made in the plan for full flux processing. Raw covariance products from the low-power loggers are used instead of actual flux from complete processing programs, resulting in missing terms and corrections, and in significant errors in flux results.
- No provision is made in the plan to record and archive raw 10 Hz or 20 Hz data.
- No provision is made for keeping a site log of visits and maintenance procedures.

- Location is chosen not for the required task, but for convenience. Tower is positioned in the middle of a plot that is too small, or the instruments are too close to the canopy.
- Wind rose, flux footprint, and shape of the site are not considered during the planning, resulting in incorrect site selection, and incorrect tower positioning. This could lead to significant data loss from non-negligible wind directions.
- Maintenance plan does not include regular calibrations or validations using known gases, when needed or recommended by the manufacturer.
- Maintenance plan does not include regular site inspections, including checking the data collection settings, which may reset from 10 Hz to 1 Hz or to some other default value, for example, due to computer malfunction.
- Maintenance plan does not include cleaning the instruments, intake tubes and sampling cells or changing fine-particle filters, resulting in unnecessary data degradation and flux loss.
- Maintenance plan does not include periodic check of real-time 10 or 20 Hz data, instrument diagnostics, flux calculations and overall data quality. This can be important in cases when the instrument may malfunction in terms of fast data and the resulting fluxes, but may look reasonable in real time on the software screen and in the settings.
- Provision is not made for some type of weather-resistant field enclosure to house tools, spare parts, regulators, electrical components, *etc*.

Although these and other planning and maintenance items may seem simple and obvious, the main challenge is to actually check all of them throughout the experiment, and if needed, be able to transfer the maintenance functions from one person or group to another to ensure continuity and data consistency. An additional challenge is to keep accurate records of maintenance procedures; why they were performed and when.

Part Two:

Designing An Eddy Covariance Experiment

Section 2.9 Summary of Experimental Design

- The design stage is an opportunity to avoid many future complications
- Main steps: purpose, variables, instruments, tower, location, maintenance
- Purpose will determine variables: include all needed for EC computations
- Variables will determine list of instruments, software needs, infrastructure
- Instruments: fast, sensitive to small changes, 'compact', and 'aerodynamic'
- Software is readily available; exotic instruments may need special coding

In summary, the experimental design stage is an opportunity to optimize the time and costs, to assure continuous and consistent collection of high-quality data, and to avoid numerous complications during implementation and execution of the experiment.

The key parts of the design include defining the purpose and variables, choosing appropriate instruments and other hardware and software, deciding on the experiment location, tower type and placement, and developing a detailed maintenance plan.

The purpose helps to determine a list of variables, including those needed for eddy covariance corrections.

Scientific applications are usually more demanding in terms of purpose, and may have a wide spectrum of goals within the same experiment. Industrial and agricultural applications have more focused goals, but may need additional parameters to interpret data. Regulatory applications are often specifically interested in quantifying the emission rates of a specific gas, and may have a very explicit, focused purpose.

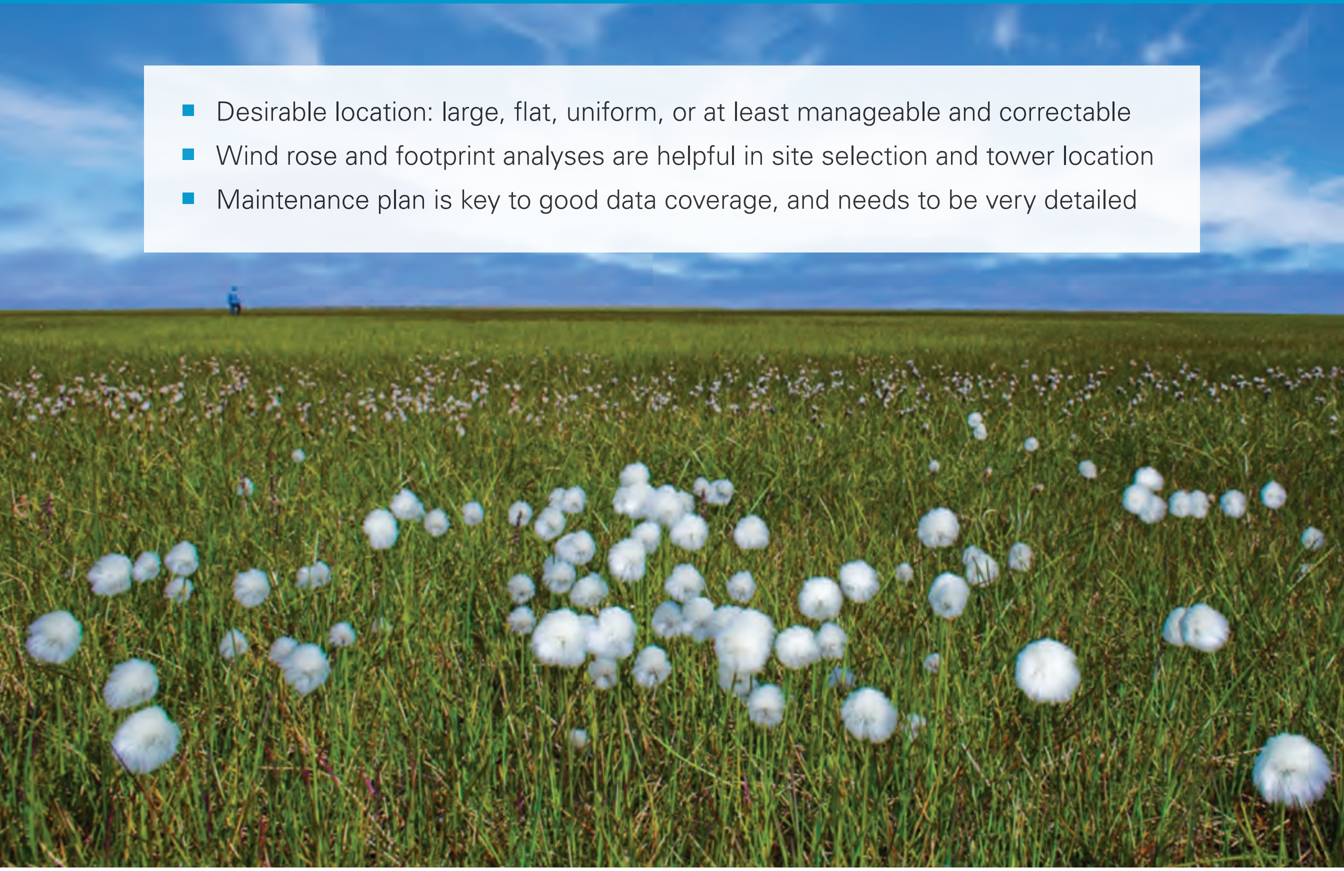
The list of variables in each application and project helps to determine the list of instruments and software needs, and overall infrastructure.

Scientific applications may use specialized, full or typical eddy covariance stations, while industrial and agricultural applications tend to use minimal and typical stations. Most regulatory applications would benefit from minimal eddy stations.

Regardless of the type of station, eddy covariance instruments should be fast, sensitive to small changes, compact in size, and aerodynamic. Ideally, they should also be designed to allow data collection from most or all wind directions, and should minimize flow distortion to the sonic anemometer.

Complete fully-supported software packages are readily available for eddy flux processing. When set up correctly, such software takes care of most of the complex steps (*e.g.*, spectral and cospectral analysis, footprint analysis, *etc.*) and corrections required for the flux processing, from raw covariance calculations all the way to final flux values.

- Desirable location: large, flat, uniform, or at least manageable and correctable
- Wind rose and footprint analyses are helpful in site selection and tower location
- Maintenance plan is key to good data coverage, and needs to be very detailed



Exotic instruments, such as custom-built or custom-ordered gas analyzers, may require additional processing codes for unit conversions and flux corrections.

Ideally, the site should be large in size to accommodate the desired tower height. It should be relatively uniform, or at least manageable. The analyses of the wind directions and flux footprint may be very helpful in selecting the site, and for tower positioning within the site. The tower should ideally be located in the center of the experimental site, collecting the flux data from all wind directions. For sites with strong prevailing winds from one direction, the tower may be positioned on the downwind edge of the area of interest.

Good maintenance planning is key to good data coverage. A well thought-out detailed maintenance plan will be the best insurance that the time invested in the experiment will produce accurate and meaningful data.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Yamanoi, K., R. Hirata, K. Kitamura, T. Maeda, S. Matsuura, *et al.*, (Eds.), 2012. Practical Handbook of Tower Flux Observations. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp.

Munger, B., and H. Loescher, 2008. AmeriFlux Guidelines for Making Eddy Covariance Flux Measurements. AmeriFlux: http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

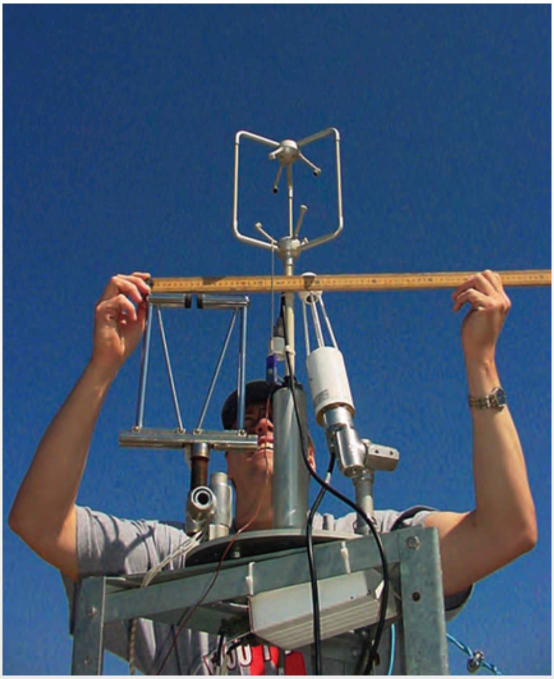
Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Part Three:

Implementing An Eddy Covariance Experiment

Section 3.1

Placing the Tower



- Tower placement
- Instrument placement
- Testing data collection
- Testing data retrieval
- Collecting data
- Checking initial results
- Maintenance upkeep

The experiment implementation stage comes after the field experiment has been carefully designed and planned.

The main parts of the experiment implementation are: placing the tower within the chosen experiment site, placing instruments on the tower, testing data collection and retrieval processes, collecting scientific data, processing the first few days' data to make sure the results make sense, and keeping up the maintenance throughout the experiment duration.

References

Some particularly good sources of information on tower and instrument setup are the following:

Munger, B., and H. Loescher, 2008. AmeriFlux Guidelines for Making Eddy Covariance Flux Measurements. AmeriFlux: http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

Yamanoi, K., R. Hirata, K. Kitamura, T. Maeda, S. Matsuura, *et al.*, (Eds.), 2012. Practical Handbook of Tower Flux Observations. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp. (Electronic Edition in English)

- Tower location is restricted by what it can 'see' upwind
- Location should be optimal to represent the area of interest for most wind directions
- At the very least, location should allow sampling of representative area of interest for prevailing wind directions

Tower location is restricted by what it can 'see' upwind. If possible, the location of the tower within the site should be optimized to represent the area of interest for most wind directions, but at the very least, its location should represent the area of interest for the prevailing wind directions.

The size of the area of study, canopy height, and topography may restrict fetch, instrument placement, and thus, affect tower placement criteria. The type of instrumentation used for the experiment may affect the placement of the tower as well.

The most problem-free approach to arranging the location of the eddy station is to use omni-directional instrumentation, in an omni-directional setup, on the top of the tower positioned in the center of a sufficiently large site.

This will assure that data from all wind directions, including infrequent ones, will be acceptable for flux calculations, data coverage will increase, and gap-related uncertainties will be minimized.

In some cases, such an ideal setup may not be possible. For example, the site may be too small to provide sufficient fetch in all wind directions, or the only instrumentation available is non-omni-directional, the tower has been already installed for other purposes (*e.g.*, TV or cell tower), or the tower may be massive or taller than the required measurement height, *etc*.

In these cases, optimization may be required during instrument placement in order to minimize flow distortion to the instruments from the prevailing wind directions, thus minimizing related data degradation and gaps.

For example, if non-omni-directional instrumentation is used, or if omni-directional instrumentation is used in a non-omni-directional setup (for example, set on the side of a massive tower), and at the same time the site is relatively small in size, then the tower may be located on the downwind edge of the site.

- Ideally, tower should be positioned in the center of the site, with omni-directional instrumentation installed at the top
- This will ensure that data from all wind directions, including infrequent ones, will be acceptable for flux calculations
- In some cases such an ideal setup may not be possible, so optimization may be required in order to minimize flow distortion to the instruments from the tower

The instrumentation should then be positioned on the boom and oriented into the prevailing winds, so that the tower is located to the side, or far downwind, from the instruments.

In this example, the data from the distorted wind directions should be excluded from flux calculations anyway, so positioning the tower at the downwind edge of a relatively small site may not lead to significant additional data gaps beyond those already caused by non-omni-directional instrumentation or setup.

Some additional details are given in the following pages, and in the references below.

References

Munger, B., and H. Loescher, 2008. AmeriFlux Guidelines for Making Eddy Covariance Flux Measurements. AmeriFlux: http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

Isaac., P., 2009. Thoughts on Flux Tower Design. OzFlux Presentation http://www.ozflux.org.au/meetings/feb2010/L13Flux-tower-design.pdf

Gash, J., 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorology, 35: 409-413

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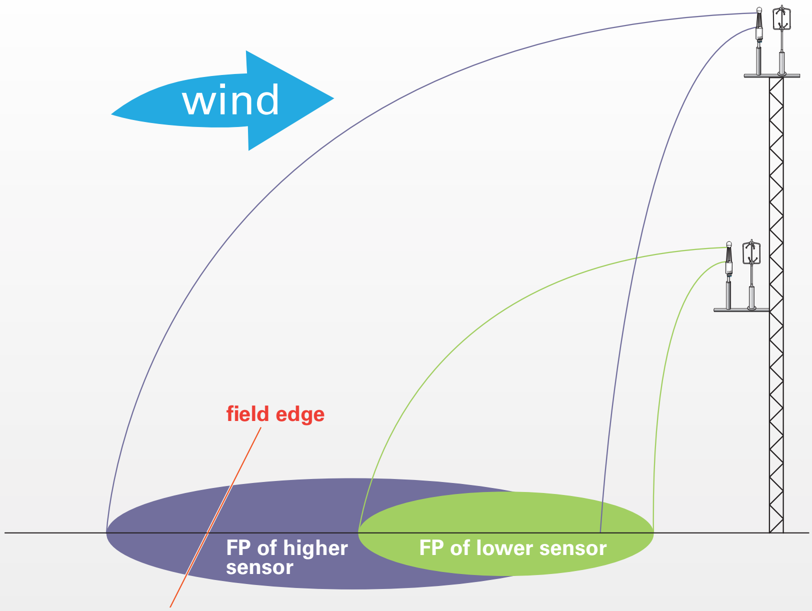
Part Three:

Implementing An Eddy Covariance Experiment

Section 3.2

Placing the Instrumentation



- Sensor placement height is usually restricted from the top by available upwind fetch for area of interest
- Sensors located too high may 'see' outside the area of interest

In addition to the top of the constant flux layer located about 100-150 m above the surface (see Section 2.6 for details), the instrument placement height is often restricted from the top by the available upwind fetch. For most measurement sites, the fetch is usually a more restrictive criterion than the top of the constant flux layer.

An instrument located very high, above the constant flux layer, will 'see' flows unaffected by the surface of interest. An instrument located too high within the constant flux layer may have a footprint stretching far beyond the area of interest, and 'see' some fluxes outside this area. The resulting measured flux may be a mixture of the fluxes from the territory of interest and fluxes from a completely different territory.

For example, an agricultural field may extend 400 meters upwind from the tower, and end with a large lake. Measurements located at a 10 meter height will "see" about 1000 m upwind, and a major portion of the fluxes measured at this height may come from the lake and not from the agricultural field. But if the measurement height is 4 meters, the fetch will be about 400 meters, and most fluxes will come from the field of interest.

Although the general rule of thumb is that the measurement height should be 100 times smaller than the desired fetch to avoid sampling outside the area of interest, during low winds and stable conditions at night, this ratio may grow from 1:100 to 1:500. In most cases such conditions provide low-quality data for eddy covariance measurements because of the underdeveloped turbulence, and should be excluded from the data anyway.

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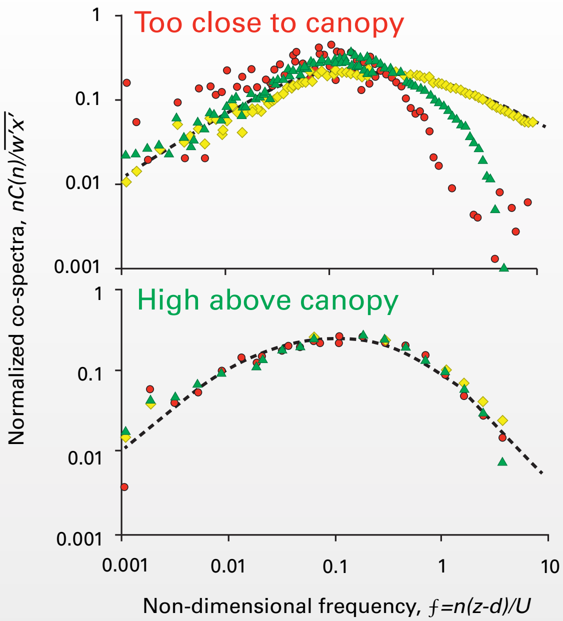


- Smaller eddies prevail
- A lot of contribution above 10 Hz
- Analyzers lose a lot of frequency above 1 Hz

- Larger eddies prevail
- Little contribution above 5 Hz
- Analyzers have good response at all relevant frequencies

- Sensor placement is restricted from the bottom by frequency response errors and corrections
- Sensors located too low may not register flux transport by small eddies

In addition to the height marking the boundary between the top of the roughness sublayer and the bottom of the constant flux layer (see Section 2.6 for details), the height of the instrument placement is also restricted from the bottom by the size of the frequency response errors and related corrections. Depending on canopy height and instrument size, the frequency response criterion may be more or less restrictive than the roughness sublayer criterion.

An instrument located too low may not register transport of the flux by small eddies occurring at very high frequencies. It may also see an area that is too small, and is not representative of the entire site.

The rule of thumb for the lowest placement height is that the instrument should be at least 1.5 m above the top of the canopy, *and* should ideally be at 1.5-2 times the canopy height, or higher. If the terrain is patchy, with scattered bushes or trees, the ratio may need to increase to 4-5 times the canopy height. In terms of instrument size, the measurements should preferably be located at a height 3-5 (or more) times the instrument path length.

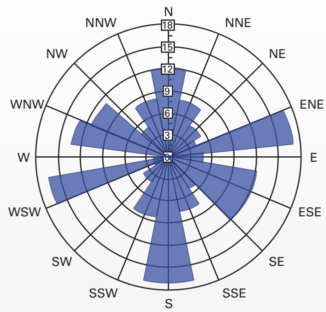
For example, the illustration above demonstrates the actual field-measured frequency response of two gas analyzers located too close to the canopy (0.75 m above the canopy top), and high above the canopy (5.0 m above the canopy top).

The plots show cospectra, the measure of flux transport at a given frequency (see Section 4.2 for details). The black line and yellow diamonds represent theoretical and sonic temperature cospectra respectively, most often used as a reference. The green triangles represent an open-path analyzer with a 12 cm path, and red circles represent an open-path analyzer with a 47 cm path.

When instruments were located too low, contributing eddies were generally small, both analyzers were noticeably affected, and both did not respond sufficiently well above a frequency of 1 Hz. The larger analyzer was affected more than the smaller one because it averaged more eddies in the longer path.

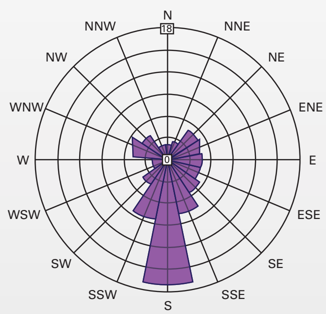
When measurements were located at a significant height above the canopy, both smaller and larger analyzers performed very well, had near-perfect frequency response and produced cospectra similar to the references.

The cospectral situation in most sites is typically somewhere in between those shown in the two plots above, and is generally closer to the lower of the two plots.



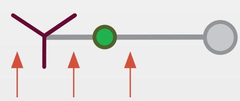
Variable Winds

omni-directional setup is usually the best
non-omni-directional setup will provide less data

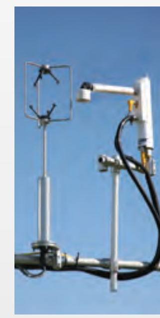


Prevailing Winds

omni-directional setup is still the best
non-omni-directional setup is also acceptable



Instruments meet winds at the same time



Tower or pole   Sonic anemometer   Gas analyzer or intake

The orientation of the gas analyzer and sonic anemometer in relation to each other, to the tower and to other instruments is an important step during instrument installation intended to minimize flow distortion. A simple and clean omni-directional setup is usually the most beneficial in the majority of situations, because it includes all wind directions, and as a result, leads to better data coverage.

This is especially important at sites with variable winds, as shown above in the top left wind rose. An omni-directional sonic anemometer may be installed at the top of the tower to minimize or avoid flow distortion from the tower itself. An omni-directional gas analyzer can then be installed near the anemometer, ideally in the least frequent wind direction, and with most of the "mass" located below the anemometer. The photo at top right shows an example of this type of setup. Flow distortion is minimized, yet sensor separation between the analyzer and anemometer is still small.

At sites with strong prevailing winds (bottom left example), it may still be best to use an omni-directional setup, but a non-omni-directional installation is also acceptable. In these cases, the instrument should ideally be located on the top of, or on the side of the tower or a boom, oriented perpendicular to the most prevailing winds. This way both analyzer and anemometer will "meet" the prevailing wind at the same time, minimizing time delay and allowing for small sensor separation between the instrument, without large distortion.

In cases when many other instruments are to be installed near the anemometer, or when the tower is bulky, or when there are other placement restrictions, the orientation should be designed to minimize flow distortion to the sonic anemometer from the prevailing wind direction first, and then if possible, to the fast gas analyzers. Longer booms and placement of bulky sensors sideways and away from the anemometer may be recommended.

Very large bulky objects (such as climate control boxes, solar panels, computer enclosures, *etc.*) should ideally be located well below and far away from the fast instrumentation. If possible, they should not be located behind the fast sensors, downwind of prevailing wind directions. The large objects can create pressure and flow fields, propagating upwind into fast sensor locations. If there is no good way to avoid having a large object at the site, it should be located on the ground, 3-5 measurement heights away from the tower, and preferably, in a direction perpendicular to the prevailing winds.

- Distance between gas analyzer inlet and sonic anemometer is restricted:

  on short side: by air flow distortion and interference
  on long side: by frequency response errors and corrections

- Sensors located too close to each other may mutually distort the air flow, and affect data in a significant and often unrecoverable fashion
- Sensors located too far from each other (horizontally or vertically) may "see" different footprints, may sample different eddies, and incur large frequency response corrections due to sensor separation
- Horizontal separation is generally less dangerous than vertical separation
- In all cases, however, it is recommended that the analyzer be positioned at or below sonic anemometer, and not above the anemometer

Distortion of natural air flow immediately next to the sonic anemometer's path is highly undesirable, and the distance between the gas analyzer head or inlet, and sonic anemometer, is restricted on the short side by this distortion. However, on the long side, the distance is also restricted by frequency response errors and related corrections which can result from sensor separation (Sec. 4.2)

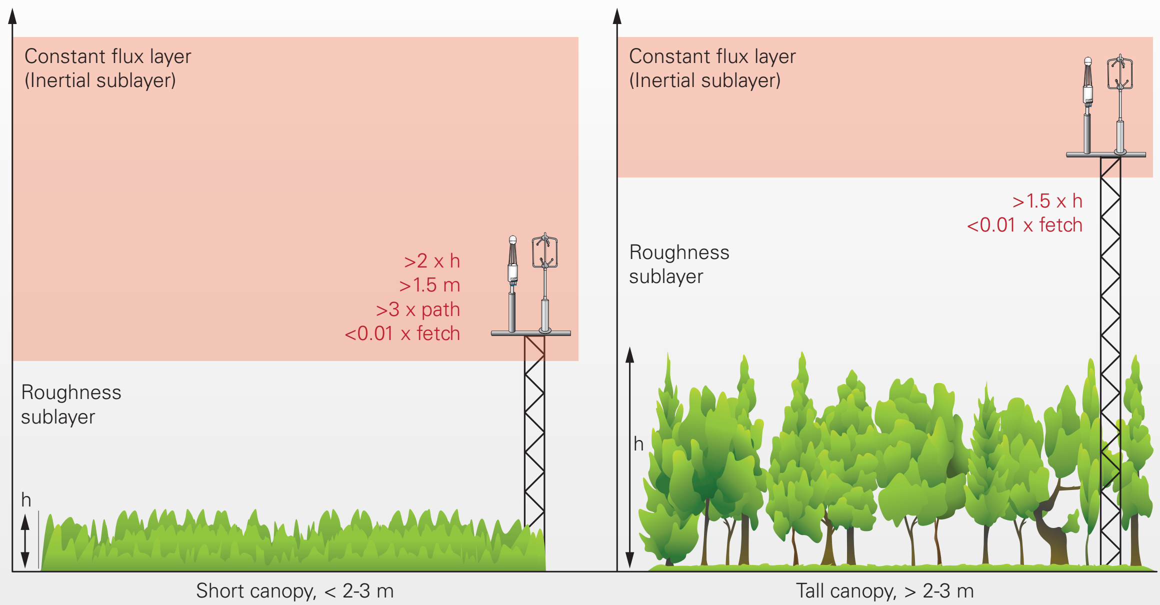
Sensors located too close to each other may mutually distort the air flow, and affect the data in a significant, and often unrecoverable, fashion. Sensors located too far from each other (horizontally or vertically) may "see" different footprints, may sample different eddies and incur large frequency response corrections. While horizontal separation is generally less critical than vertical separation, it is recommended that the analyzer is positioned at or below the sonic anemometer, and not above it. It is also important to note that the closer to the ground the instruments are located, the larger is the effect of sensor separation on the frequency response of the system.

In general terms, a typically-sized gas analyzer head (in case of the open-path design) or a sizeable intake (in case of the closed-path or enclosed designs) should be positioned at least 10-20 cm away from the anemometer in the horizontal direction, and with a vertical separation of 0-20 cm below the anemometer path.

Separation distances may be reduced significantly, to single centimeters, when the size of the analyzer head or the intake is very small (for example, a fine-wire thermocouple with a neck of a few mm in diameter, or an intake of an enclosed gas analyzer with a rain cup 2 cm x 3 cm in size), as shown in the photo on page 155. Separation distances may be increased on very tall towers (15 m or more above the canopy top), with horizontal and vertical sensor separation as large as 30-50 cm.

Please note that it is much more difficult to correct for flow distortion than for sensor separation. Flow distortion is unique to the instrument's shape, specific locations of other instruments, and changes in wind angles and direction. There is no established or verified way to correct for such installation-specific distortion effects, or to adjust established corrections for the particularly distorted flow. For example, angle-of-attack corrections, developed for a flow distorted by an anemometer itself, may change significantly if flow is distorted by co-located instruments.

On the other hand, correcting for the sensor separation, both in frequency response corrections and in finding time delay, has been well studied, established and verified via numerous experiments. It would be a more advisable and safer way to address the sensor positioning.



In summary, there are very general rules-of-thumb for determining the sensor placement. The rules shown above in the red font are all recommended, whichever is stricter, and imply "*and*" and not "or" operator.

For short canopies, the instrument height above the canopy top should be at least one additional canopy height, *and* desirably at least 1.5-2.0 m, *and* at least 3-5 times the largest sensor path. At the same time, the instrument height should be less than 100-150 meters, *and* desirably less than one hundredth of the upwind fetch.

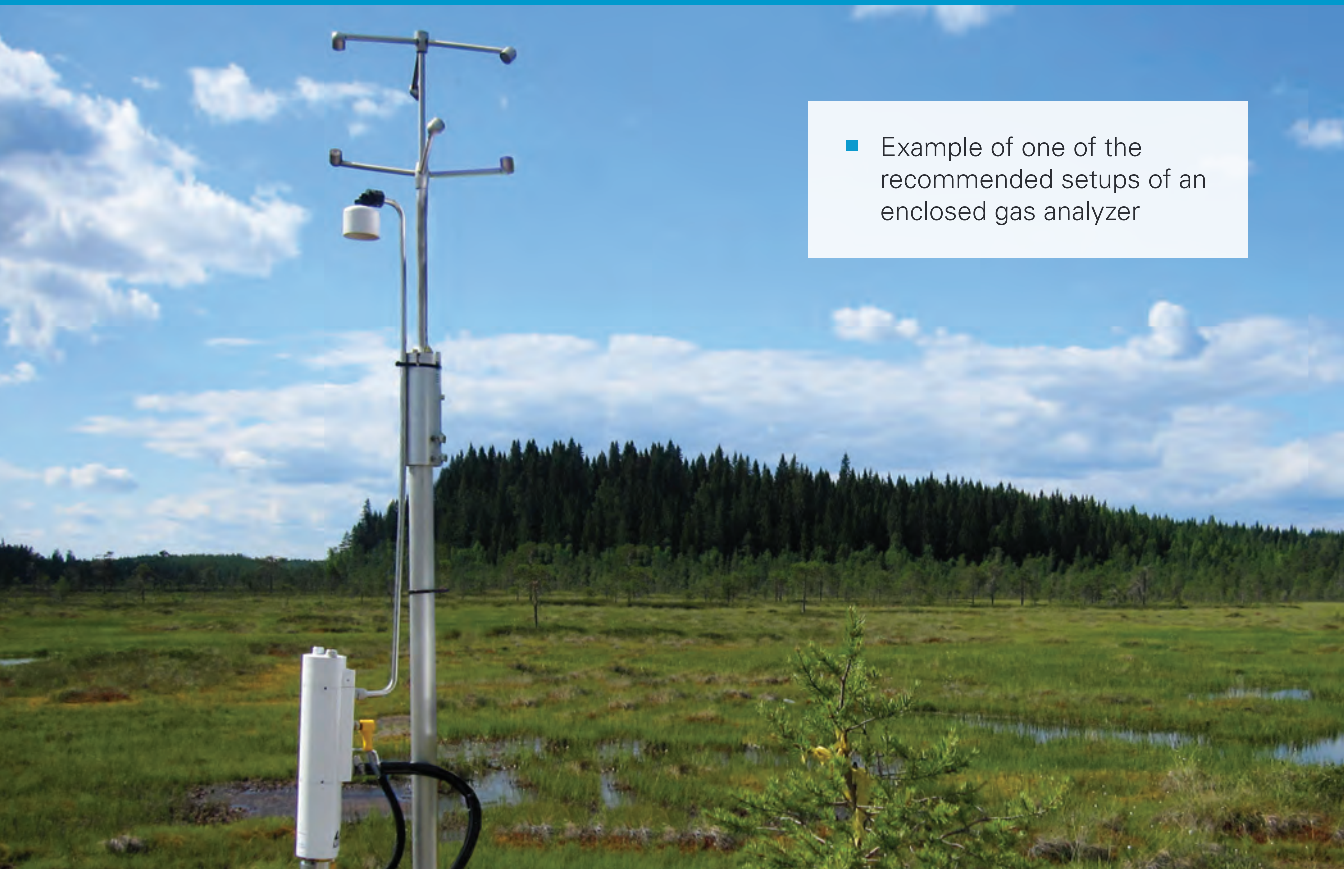
For tall canopies, the instrument height above the canopy top should be desirably at least one-half of an additional canopy height. At the same time, the instrument height should be less than 100-150 meters, *and* desirably less than one hundredth of the upwind fetch.

When working with short canopies, shown in the left picture above, the vegetation may only be 0.05 m; using the 2 x h rule would locate the sensors at 0.1 m above the ground. This is not acceptable because the sample path of the sensors (anemometers and analyzers) is too large to measure small eddies at such heights. At a minimum, then, even with no canopy, measurements should be at least 1.5 m above the ground, or 3-5 times the path length of the sensor above the ground.

When working with tall canopies, shown at above right, 1.5 x h usually works well. Placing the sensor higher is better, but one should consider if the higher placement still provides adequate 1:100 fetch.

Another important point to consider is placement in a fast-growing crop such as corn. One may have to move the sensor higher in the second half of the growing season.

It is also important to note that these rules of thumb are very approximate. In most cases, these rules can be "stretched", but at a cost of increased corrections and larger uncertainty in the final flux number.



Example of one of the recommended setups of an enclosed gas analyzer

Rules of thumb also exist for sensor separation. However, they are more difficult to apply universally, as relevant conditions and instrument sizes range widely.

A horizontal separation of 10-20 cm is generally recommended for average-sized analyzers and measurement heights. Smaller analyzers and intakes may be located closer to the anemometer. Taller towers can tolerate larger horizontal separations.

Vertical separation may be between zero centimeters (*e.g.*, centers of the sonic anemometer path and gas analyzer, or an intake, are at the same height above the ground) and 20 cm for small and medium towers, and may increase to 50 cm or more for tall towers.

Model-specific installation guidelines are often provided by the manufacturers of the instruments.

Overall, if all other factors are equal, it is usually most advisable to choose a higher instrument positioning, and an omni-directional configuration with smaller sensor separation.

If this is not possible, the wind rose and footprint analyses can be conducted for a specific site to evaluate the contributions from each wind direction, and to optimize the instrument placement height on the tower. It is, however, always essential to avoid placing the instruments outside of the constant flux layer.

Strictly speaking, the measurement height should be referenced for these purposes not from soil surface, but from zero plane displacement (*e.g.*, the height at which the logarithmic wind profile hypothetically goes to zero). This is usually about 2/3 of the canopy height, but depends heavily on the canopy and other factors.

The concept of zero plane displacement may be difficult for a non-micrometeorologist, so the two sets of approximate rules-of-thumb were provided on the previous page for short and for tall canopies to avoid in-depth discussion of this concept.

Part Three:

Implementing An Eddy Covariance Experiment

Section 3.3

Initial Testing of Data Collection and Retrieval

- Instrument interactions
- Data interruptions
- Power requirements
- Initial data inspection

Some of the key items to check, after the tower and instruments have been set up, are instrument interactions, data interruptions, and power conditions. Especially for eddy flux stations custom-built from a number of off-the-shelf instruments from different manufacturers, it is advisable to first make sure that there are no clock drifts, miscommunications, unexplained errors, lockups and other data interruptions when these instruments begin interacting.

For example, a digital-to-analog converter may need to be reconfigured in a specific way to accept the signal from a specific instrument. It is also advisable to assess potential data interruptions due to weather events, and determine how fast the system recovers after an event (rain, snow, dew, power interrupt during storm, *etc.*), and what can be done about minimizing the related data gaps.

Power grid variations, power backup and variations in power consumption are also important items to check, because power load on the tower may vary. Make sure that power requirements include the peaks of such variations to avoid blown fuses or deep discharge of backup batteries.

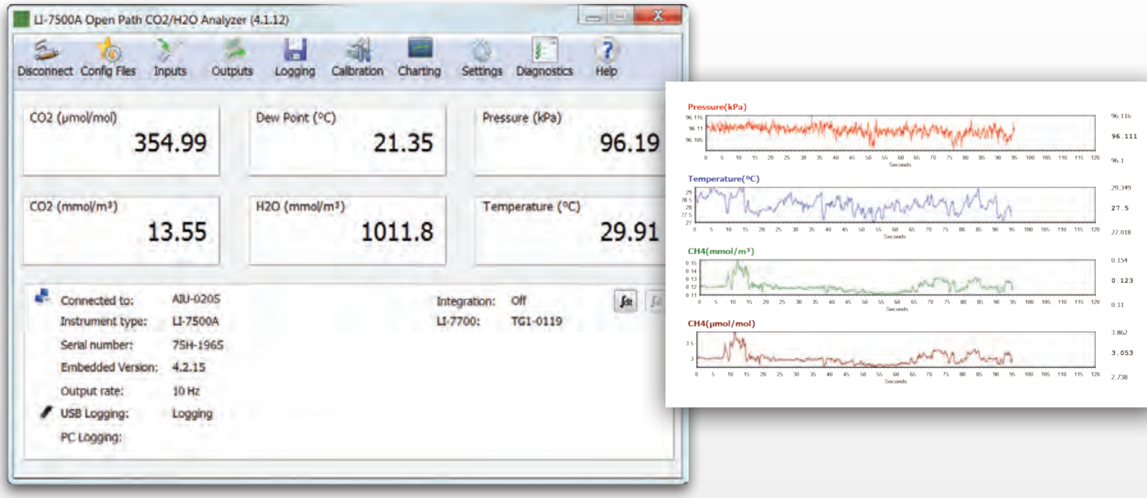
After these facility-related items have been checked, further inspections of the data collection can be done by looking at a few initial sets of data and comparing them to the expected reasonable physical ranges.

One of the easiest steps during initial data inspection is to check all mean weather, soil and canopy parameters, and instrument diagnostics, to make sure they look reasonable for a particular site, time of year, and canopy state.

For example, temperature readings in a mid-latitude summer may range from 5-10 °C at night to 30-40 °C at midday; CO_2 concentrations over a green canopy can be as high as 600-800 ppm on calm nights, and can drop to about 350-370 ppm during the day.

Such common-sense criteria may be established for a specific site using data from nearby automated weather stations, air quality stations, past research, *etc.*

Similarly, instrument diagnostics can be verified to make sure that diagnostic parameters adhere to the manufacturer's recommendations for each of the fast instruments.



- Make sure that all weather, soil and canopy parameters look reasonable, and instrument diagnostics are good
- Process fast data, and make sure that flux products look reasonable
- Repeat checks daily in the first few days, and weekly in the first few weeks

If mean data and diagnostics look reasonable, inspecting a few hours of midday fast 10 Hz data may help in finding potential spikes, cycling drifts, or other problems resulting from loose cables, ground loops, incorrect wiring, or instrument settings.

A bit more difficult, but quite important step, is to make sure that the final product of the eddy covariance station, the fluxes, look reasonable. One commonly used approach to achieve this is to look at the energy budget components (Section 4.10).

Net radiation describes the amount of energy coming from the sky minus the reflected portion, providing a basis for other energy fluxes in the study area. Typically, a mid-latitude summer may have 500-900 W m^{-2} of net radiation in the middle of a clear day. This energy is available for soil heat flux (heating the soil), sensible heat flux (heating the air), and latent heat flux (evapotranspiration of the water from the soil and canopy).

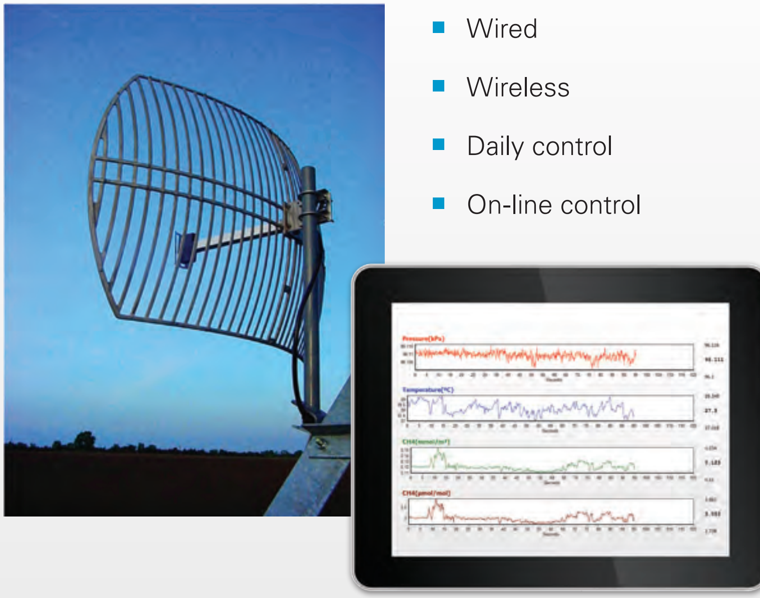
Other components may include heat energy stored in the plant matter, energy used for photosynthesis, *etc*. However, these are relatively small in magnitude, and may not be essential for the initial data inspection.

In most cases, midday summer soil flux is relatively small (below 50-200 W m^{-2}), especially in soils covered with dense, tall canopies. The midday summer sensible heat flux may be near zero in wet and cold environments, and 400-500 W m^{-2} in hot and dry environments. The latent heat flux may be near zero in a desert, and may exceed 600 W m^{-2} in irrigated crops. A comparison of energy budget components by energy budget closure (Section 4.10) is a useful tool for initial, and then overall, quality control of the flux station performance.

Gas fluxes (*e.g.*, CO_2, CH_4, *etc.*) may have large variability from one area or season to another, and from night to day. These can be assessed by comparing them to literature data from similar environments, and by techniques described in Section 4.10

> Ground loops during analog data collection, radio interference with unshielded cables, and positioning instruments in the path of the directional transmitter, or antennae, have been known to cause "unexplained" and "untraceable" errors, and peculiar noise patterns. These should be carefully checked in the field.

- Manually
- Wired
- Wireless
- Daily control
- On-line control



Data retrieval is another important process to test, whether data are retrieved manually by swapping out external memory devices, or delivered via the Ethernet, Internet, or other wireless communications. The better the connection to the site, the easier it is to do real-time on-line control, and full daily control of transmitted data.

Properly configured connections may also allow for remote setup of the instruments (changing calibration coefficients, voltage output ranges, *etc.*), remote reset of the instrument or PC after lockup, and other numerous useful tasks, saving time and money on travel to the site.

It is advisable to always collect data on some type of removable or built-in media in addition to remote data collection. This creates a backup, and also prevents data losses during any wireless failures.

When the site is not accessible remotely, it is important to remember to either keep a strict schedule of manual data retrieval or use a large memory device to accumulate data.

Data collection can usually be configured to fill the memory and then stop collection, or to continue collection and override the oldest data. This setting is important for the specific experiment schedule, and a conscious decision should be made on which setting is best.

Extremely remote low-power sites, with infrequent maintenance visits, sometimes use two different data collection streams. One stream collects a comprehensive set of fast data, and stores them in removable memory. A second stream collects infrequent sub-samples of the fast data, or mean half-hourly products, and sends them out wirelessly once a day, or once a week, for site diagnostics.

With minimal additional power, then, one can ensure that the site is running well on a daily basis, while complete data processing happens later, after manual retrieval of the removable memory containing the full data set. These arrangements need to be tested thoroughly to make sure the fast data stream that is not backed up is being properly collected to removable memory.

Part Three:

Implementing An Eddy Covariance Experiment

Section 3.4

Continuous Maintenance

- Keeping many instruments running properly over long periods of time is a challenge, which needs to be carefully planned, and then executed throughout the entire duration of the project

Maintenance is one of the most important parts of the execution of an eddy covariance field experiment, and it should be kept up continuously for the entire duration of the project, according to the maintenance plan developed during the planning stage (Section 2.8).

Depending on site complexity, instrumentation, and setup, typical visitation frequency can range anywhere between once every two weeks to once every three months. In rare instances at extremely remote sites that are custom-designed for low maintenance, visits may be done once every 3-6 months or based on instrument and data diagnostics.

Routine maintenance typically required at eddy covariance sites includes periodically checking instantaneous raw data, instrument diagnostics, and flux products; travelling to the site to maintain it based on such checks, and per maintenance schedule; manual data retrieval (swapping USB drives, *etc.*); cleaning of sonic anemometers and optical paths of open-path and enclosed gas analyzers, changing intake filters of closed-path analyzers, cleaning radiometers and solar panels, inspecting cables and backup batteries, and checking that electronics are powered and perform as expected. This maintenance is often accomplished by hiring a responsible local person (*e.g.*, high-school student or other hourly help) for a few hours per month. At the implementation stage, it is useful to have several maintenance rehearsals to make sure the maintenance plan is understood and executed correctly.

In addition to routine maintenance, events such as lightning, ice storms, wind gusts, and rodent damage are likely to happen several times a year during long-term deployment of instruments. If not planned for ahead of time, they may lead to large data gaps.

> Each data gap jeopardizes results and affects the final integrated number, so spare sensors and emergency protocols should be a part of routine planning and maintenance to help avoid data loss.

Part Three:

Implementing An Eddy Covariance Experiment

Section 3.5

Experiment Implementation Summary

- Tower placement: maximize useful footprint from all wind directions
- Instrument placement: at a maximum height that still allows useful footprint
- Testing collection and retrieval: test thoroughly to avoid data gaps
- Data collection: wireless, cabled, daily checks
- Maintenance: required throughout the project to avoid data gaps

In summary, experiment implementation requires proper tower and instrument placement, rigorous testing of data collection, retrieval, and remote communications with the site, and regular maintenance.

The tower should preferably be placed in the center of the area of study, in such a way that the useful footprint from all wind directions is maximized. If there is a single prevailing wind direction, the tower can be placed on the downwind edge of the area of interest to maximize the footprint.

Instruments should be placed at the maximum height that still allows for a useful footprint and service access. The instruments should be oriented in relation to the tower, prevailing winds, and each other so that flow distortion to the sonic anemometer (first) and gas analyzer (second) is minimized.

Data collection should be done by wireless, wired or some other method, preferably allowing for daily checks and real-time access, but parallel backup collection of all data using on-site removable memory is highly recommended.

Testing data collection and retrieval should be done thoroughly to avoid data gaps. Instrument diagnostics and data values should be checked daily for the first few days of the experiment, and weekly for the first few weeks of the experiment to make sure that all technical, weather and flux parameters are within reasonable ranges.

After successful implementation, further spot-check data inspections can be done bi-weekly or monthly, although automated daily summaries are useful and not difficult to implement at sites with remote access.

Maintenance should be kept up throughout the duration of the entire project, as per maintenance plan developed during the planning stage, to avoid collecting bad data over long periods, resulting in large gaps in the data.

Part Four:

Processing Eddy Covariance Data

Section 4.1

Pre-conditioning of Raw Data

Pre-conditioning

- convert units
- despike
- apply calibrations
- rotate
- correct for time delays
- de-trend
- average

Applying corrections

- frequency response
- sonic corrections
- WPL terms
- other corrections
- flux storage

Averaged data

- quality control
- fill-in
- integrate
- check
- analyze/publish

Different research groups may use slightly different methods for processing eddy covariance data to fit their specific needs, site-specific design, and sampling conditions. Here we will give one particular example of the generalized traditional way to process the data. The goal for this example will be to obtain flux calculations as close as possible to what is actually happening in the field.

The major steps in this process include: converting signals from voltages to physical units; despiking; applying calibration coefficients if needed; rotating coordinates; correcting for time delay; de-trending if needed; averaging fast data over 0.5 to 4 hour periods; applying frequency response, sonic, density and other corrections; conducting quality control; filling in missed periods and integrating long-term flux data. It is also recommended to double-check the entire process before analyzing and publishing the data.

Modern flux programs, such as EddyPro, will take care of most of the processing steps automatically for a standard eddy covariance experiment. For an especially elaborate or unusual setup, or for exotic instrumentation, some steps in the processing program may need to be customized to accommodate the unusual features. The major steps, however, will remain similar for most setups and configurations.

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- Check that all units for instantaneous inputs for flux calculations are appropriate and consistent to avoid errors in fluxes and corrections calculated on-line
- Double-check that auxiliary sensors use correct calibration coefficients to avoid errors in flux corrections, and in the mean data
- Be especially careful to avoid potential mixing of the fast inputs with the slow inputs when converting fast data units
- Some researchers may choose to convert gas density (per m^{-3}) into dry mole fraction (per moles of dry air) at this stage to avoid the need to apply Webb-Pearman-Leuning terms later

Unit conversion involves checking that all units for instantaneous (*e.g.*, “fast”) values are appropriate. Units need to be matched carefully to avoid errors in fluxes calculated on-line or in corrections applied later. It is also important to double-check that relevant auxiliary data use the correct calibration equations to avoid errors in flux corrections, or in mean data.

It is important to distinguish fast inputs from slow ones when converting fast units, especially when using custom codes and not the standard flux processing programs. For example, if converting fast density units into fast dry mole fraction units, the fast gas temperature, fast water content and fast gas pressure aligned with gas density are required. Using slow or delayed temperature and pressure may give correct mean mole fraction but may lead to significant errors in instantaneous mole fraction and the flux. Most instruments report a large number of units, some fast and some slow, so consulting specific instrument manuals is advised when writing custom conversion code for fast data.

Unit conversion is generally one of the first steps in processing the instantaneous data. Some, however, prefer to de-spike the data first, and then remove periods with outrageous values, and only then perform unit conversion and the rest of the processing. If done carefully, this sequence of steps should yield the same results as those presented below.

However, it is important to note that setting de-spiking criteria on voltages needs to account for non-linearity in some voltage-to-unit conversions. In other words, what may look like a spike in the raw voltage signal may not end up actually being a spike after conversion. The corollary is that an actual spike in the converted data may not look like a spike in the raw voltage signal. Therefore, the spike criteria may not always be the same for voltage and for converted units.

Some researchers may also choose to convert CO_2 and H_2O signals into dry mole fractions (mol mol^{-1} dry air) at this stage, to avoid the need to apply the Webb-Pearman-Leuning correction at a later stage. It is important to note, however, that point-by-point conversion of the signal to a mixing ratio for open-path instruments is associated with large potential uncertainties and errors. This is because vertical wind measurements and scalar measurements are not done in the same volume, and because sensor separation and related time delay may change with wind speed and direction within the same averaging period. One needs to be cautious when doing point-by-point corrections for open-path instruments, and may want to compare the results to those with traditional Webb-Pearman-Leuning corrections before finalizing the workflow.

- High frequency instantaneous data will have occasional spikes due to both electronic and physical noise
- Spikes should be removed and bad points should be replaced with running means to avoid errors in further calculations
- Despiking can be done on-line immediately after data collection, or later during post-processing
- Caution should be used to avoid removing too much data
- Each eddy covariance system will have slightly different spiking problems
- Researchers should examine instantaneous data periodically to make sure that spike removal is appropriate for the conditions

High frequency instantaneous data will have occasional spikes due to both electronic noise and physical reasons. After these spikes are removed, erroneous points can be replaced with running means or by some other method to avoid errors in further calculations. The procedure can be done on-line, after data collection, or during post-processing.

Each eddy covariance system will have slightly different spiking problems, and the researcher needs to look at instantaneous data periodically to make sure that spike removal criteria are appropriate for the conditions. Caution should be used to avoid setting the criteria too strict and removing too much data.

For example, the de-spike criterion can be set to remove signals that are more than 3-8 times the standard deviation for a given averaging period so that all outliers are considered spikes and are removed.

While too many spikes usually indicate an instrument or electronic problem, there are conditions, such as nighttime storage release, that may look like spikes, but are in fact natural phenomena.

Spike removal criteria in scientific applications over natural ecosystems may differ significantly from those in industrial or agricultural applications over areas saturated with the gas of interest (for example, in the case of methane stored in landfills and lagoons). Relatively small wind gusts in conjunction with changes in air pressure and topography may lead to very large excursions of the gas concentrations due to the release from the substrate. In such situations a much broader threshold for despiking (8 or more standard deviations) may be required.

References

LI-COR Biosciences,2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. (http://envsupport.licor.com/help/EddyPro4/Default.htm)

Vickers, D. and L. Mahrt, 1997. Quality control and flux sampling problems for tower and aircraft data. Journal of Atmospheric and Oceanic Technology, 14: 512-526

- Applying calibration coefficients is not a trivial matter in eddy covariance
- Many researchers choose to calibrate closed-path gas analyzers every night or even more frequently to assure highest data quality
- In these cases, calibration parameters may differ slightly each day, and software should be pre-set to incorporate these changes into the data
- For open-path or enclosed sensors, calibration coefficients are typically less involved, and with proper factory or lab calibrations, they can usually be set in the embedded instrument software

Applying calibration coefficients may not be a trivial matter in eddy covariance calculations, especially when using instruments that require frequent calibration.

Many researchers choose to calibrate closed-path instruments every night, or even more frequently, to assure the highest data quality.

In these cases calibration coefficients will differ slightly each day, and software should be set up (or written) to incorporate these changes into the data.

For open-path and enclosed sensors, calibration coefficients are usually less involved. With proper factory or laboratory calibrations, they can usually be set in the instrument software itself.

When manually calibrating in the field, it is often difficult to establish equilibrium, and avoid diffusion of outside air and other issues, especially when working with water vapor.

Such field calibrations may be treated as verification of the instrument performance, and if obtained values are close to those expected, manual field calibration may not need to be applied to the data.

It is also important to note that if changes in instrument calibration are related to cell contamination, it is usually a better strategy to keep the cell clean (with a filter, or via periodic cleaning) than to try to calibrate out the contamination.

This is because most of the contamination does not happen in a linear gradual manner, but rather happens as a large single event, or a series of medium-sized events.

With large variability in the natural parameters, it may not be clear from looking at the data when the contamination has occurred, and when new calibration coefficients should be applied.

- Sonic anemometer cannot be leveled perfectly, such that its *w*-axis is exactly perpendicular to the mean flow, or mean wind streamlines
- The *w* signal may be contaminated by the other two 3-D wind components
- Several ways to correct such situations:
    1. rotate coordinates so that mean *w*=0
    2. use planar fit method

A sonic anemometer cannot be leveled perfectly, such that its *w*-axis is always perpendicular to the mean flow/mean wind streamlines. As a result, the *w*-signal will likely be contaminated by the other two 3-D wind components.

There are traditional and new procedures to correct for such situations, commonly called "coordinate rotation" or "tilt correction". One well-established technique is to rotate the coordinates so that the mean *w* is equal to zero. Another newer popular way is to use a planar fit method.

When measuring over a complex terrain or from a moving platform, large eddy simulation modeling sometimes can be used to help determine the flow patterns and proper coordinate rotation.

Rotation of *w*, *u* and *v* at this early stage of data reprocessing may save time at later stages, because one would not need to rotate all the covariances (*e.g., u'w', w't', w'c', w'q', etc.*).

It is also important to note that some sonic anemometers may require a cross-wind correction before coordinate rotation is performed, while in other models this correction is done internally. This is not the same as coordinate rotation.

Please refer to pages 8-9 in the 'Documentation and Instruction Manual of the Eddy Covariance Software Package TK2' by Mauder and Foken for a list of the sonic anemometer models and other details for such corrections.

References

LI-COR Biosciences,2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. http://envsupport.licor.com/help/EddyPro4/Default.htm

Wilczak, J., S. Oncley, and S. Stage, 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorology, 99: 127-150

Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic, Dordrecht, The Netherlands: 33-64

CSI Inc., 2004-2006. Open Path Eddy Covariance System Operator's Manual. Logan, Utah, http://www.campbellsci.com/documents/manuals/opecsystem.pdf

- Rotating coordinates to mean *w*=0 can be done in several stages:

  1st stage: rotate to make *v*=0 (align *u* and *x*)

  2nd stage: rotate to make *w*=0 (align *w* and *z*)

  3rd stage: rotate to make *w'v'*=0 (align *z-y* plane)–rarely used

- Planar fit is a somewhat more complex rotation method
- After *u, v,* and *w* data have been collected over a long period, one can mathematically establish a 'hypothetical' plane, so 'true' vertical flux should be perpendicular to this plane
- This may be particularly useful when measurements are done over complex terrains (*e.g.*, hillsides, valleys)

Rotating coordinates to create a 'mean w=0' can be done in several stages: 1st rotation: turn to set *v*=0 (align *u* and *x*); 2nd rotation: turn to set *w*=0 (align *w* and *z*); 3rd rotation: turn to set *w'v'*=0 (align *z-y* plane –rarely used).

The planar fit is a somewhat more complex rotation method, but may be particularly useful when measurements are done over complex terrains (*e.g.*, hillsides, valleys).

In this method, after *u, v,* and *w* data have been collected over a long period, one can mathematically establish a 'hypothetical' plane, so that a 'true' vertical flux will be perpendicular to this plane. Unlike the rotational method, a planar fit requires long-term installations with instruments remaining undisturbed over long periods of time.

A somewhat different approach has been proposed by Wilczak, Oncley, and Stage, in a paper entitled "Sonic anemometer tilt correction algorithms." Boundary-Layer Meteorology, 1999, pages 127-150.

It is important to mention another anemometer correction, an angle of attack correction, which results from an uneven cosine response of most sonic anemometers to the horizontal wind angle. This correction is different from coordinate rotation or cross-wind correction, and is not applicable to all anemometers in the same manner.

The correction may also be fully or partially applied by manufacturers. Please refer to manufacturer manuals for details on the specific anemometer and model.

References

Nakai, T. and K. Shimoyama, 2012. Ultrasonic anemometer angle of attack errors under turbulent conditions. Agricultural and Forest Meteorology, 162: 14–26

van der Molen, M., J. Gash, and J. Elbers, 2004. Sonic anemometer (co)sine response and flux measurement: II. The effect of introducing an angle of attack dependent calibration. Agricultural and Forest Meteorology, 122: 95-109

Gash, J., and A. Dolman, 2003. Sonic anemometer (co)sine response and flux measurement. I. The potential for cosine error to affect sonic anemometer based flux measurements. Agricultural and Forest Meteorology, 119: 195–207

- Time delay adjustment compensates for delay in signal acquisition from different instruments
- Without correcting for this delay, fluctuations in *w'* will not fully correlate with fluctuations in gas concentration, and flux will be drastically underestimated
- Time delay is usually corrected in one of two ways, or in combination:
  1. theoretically, via flow rate, tube diameter, *etc.*
  2. empirically, by running circular correlation, shifting the delay scan-by-scan until maximum correlation (flux) is found

Matching the time series from a sonic anemometer and a gas analyzer requires compensating for time delay in the signal acquisition from these instruments.

This is especially important when using a closed-path instrument with a long intake tube, as air sampled by the sonic anemometer may arrive at the closed cell many seconds later than the *w*-signal. For enclosed-path and open-path analyzers the time delay is much smaller, but it also should be compensated for to avoid smaller flux losses.

Without correcting for the time delay, fluctuations in *w'* may not correlate well with fluctuations in gas concentration, and flux can be underestimated or even approach a value of zero.

Time delay is usually corrected in one of two ways, or in combination:

(1) Theoretically, via flow rate, tube diameter, *etc.*

(2) Empirically, by running a circular correlation, and shifting the delay scan-by-scan until a maximum correlation (flux) is found.

The theoretical approach may not always work well, especially at long-term sites, due to variable moisture and contamination of the tube walls changing the properties of the tube.

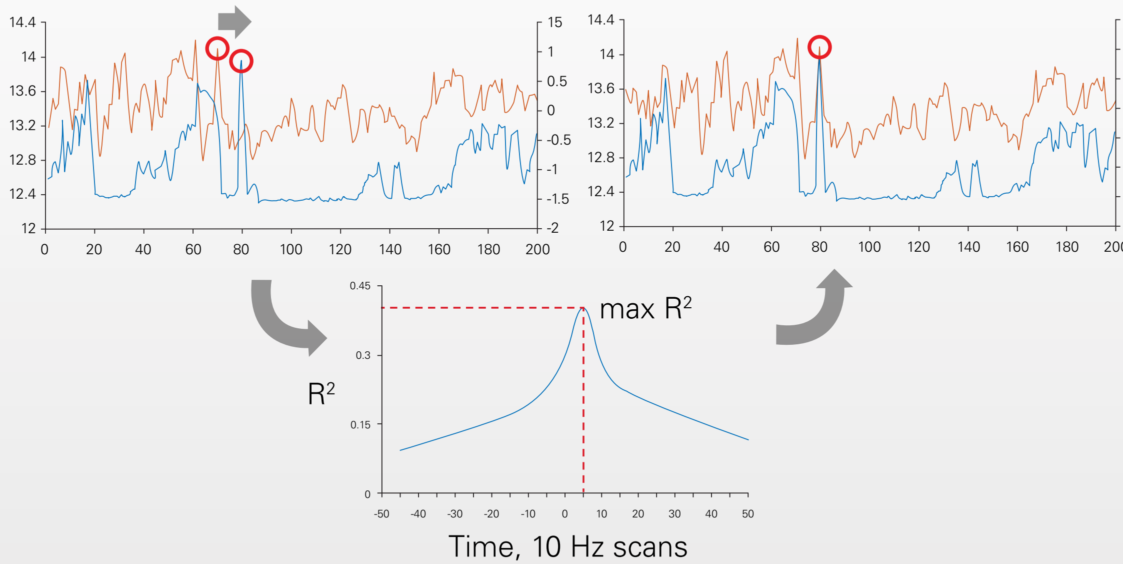
The empirical approach may not always work well, either, because it relies on the covariance value, which may be spurious or near-zero during periods with undeveloped turbulence (*e.g.*, night, U<1 m/s, u*<0.1, *etc.*) or small fluxes.

References

Mauder, M., and T. Foken, 2011. Documentation and Instruction Manual of the Eddy Covariance Software Package TK3. http://opus4.kobv.de/opus4-ubbayreuth/frontdoor/index/index/docId/681

LI-COR Biosciences,2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. http://envsupport.licor.com/help/EddyPro4/Default.htm

- Circular correlation (*e.g.*, cross-correlation, cross-covariance, covariance maximization) provides a reliable way to correct for time delay during periods with good flux values



The specific causes of time delay, and especially their relative contributions, are quite different for open-path, closed-path, and enclosed instruments.

In open-path devices, most of the delay is due to the separation distance between the analyzer and anemometer in relation to wind direction and speed, and from electronic, processing, and logging delays. The total delay in open-path systems is usually very small, on the order of a few 10 Hz scans (0.1-0.3 s).

The theoretical approach usually works works well for open-path devices, except during periods with low winds, or when electronic acquisition is unstable. The empirical approach may also be used instead of, or in addition to the theoretical approach, or simply as a verification.

In closed-path instruments, the largest delay is due to the time it takes for sampled air to travel through the intake tube, while other sources of delay (*e.g.*, sensor separation, electronics, logging, *etc.*) are relatively minor. The delay is usually quite large, often on the order of several seconds, and is dynamic, changing with moisture and dust.

In the enclosed design with a short, 0.5-1 m tube, the time delay is smaller, on the order of 0.2-0.5 s depending on flow rate. All causes of delay contribute comparable amounts: tube length, separation, electronics.

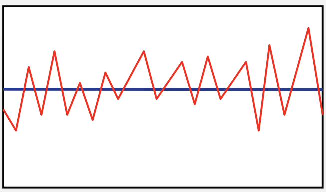
A combination of theoretical and empirical approaches during post-processing may be the safest. This is often achieved using the theoretical approach to establish reasonable defaults, which are then used during periods when the empirical approach is unreliable.

Special considerations are needed when computing defaults for H_2O and sticky gases (*e.g.*, NH_3), because delays for these gases is usually much larger than for CO_2, CH_4, *etc.*, and may change with the concentration of the sticky gas itself.

Time delay alignment will not help in the case of desynchronized sampling rates. The rate should be 10Hz on both instruments, and should not be 9.5 Hz on the anemometer and 10.5 Hz in the analyzer. Precision time protocol or other clock arrangements should be used to ensure the same sampling time intervals on all fast instruments.

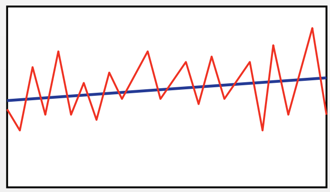
- Mean values are subtracted from instantaneous values to compute flux
- This requires establishing the mean for a given time series
- There are three main ways to look at it, and three respective techniques

Block averaging
(mean removal)



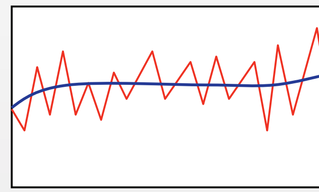
- Simplest situation
- Many prefer this method
- May gain artificial flux

Linear detrending
(linear trend removal)



- For example, sensor drifts
- Rapid diurnal changes
- May lose some flux

Non-linear filtering
(non-linear trend removal)



- Complex situation
- Same as high pass filter
- May lose a lot of flux

During de-trending, mean values are subtracted from instantaneous values to compute flux. This requires establishing the mean for a given time series. There are three main, traditional ways to look at it, along with three respective techniques: block averaging, linear de-trending, and non-linear filtering.

Each method may be appropriate for a specific situation. And although block averaging is the most popular way to de-trend (and sometimes viewed as no de-trending at all), complex terrains and rapid changes in concentration in some regions may require the use of linear and non-linear filtering. At the same time it is also important to not over-filter, because the flux contribution in the low frequency part of the cospectra will be lost as a result of over-filtering.

Generally, however, linear and non-linear de-trending is not recommended as it can leave spectral artifacts in the data and can mask improper averaging times.

Choosing a time constant recursive filter for de-trending, especially non-linear, (*e.g.*, removing a mean) is not the same as choosing an averaging period. However, most researchers just use block averaging de-trending over the same time as averaging period for computing fluxes.

References

More information on the best approach to filtering for specific situations can be found in Chapter 2 of the "Handbook of micrometeorology. A guide for surface flux measurement and analysis" and in Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Chapter 2 by Moncrieff, Clement, Finnigan and Meyers (pp. 7-30) of Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

- Averaging interval should not be too long - such that non-turbulent transfer could contribute, and diurnal cycle is not observed; or too short - such that high-pass filtering may lead to missed input from larger eddies, and to a reduction in flux
- Several methods exist to determine averaging time, for example:

  Mandatory - use standard time of 30 min or 1 hour – may not be best for all conditions

  Empirical - attempt different reasonable averaging times (*e.g.*, 10 min, 30 min, 1 hr, 2 hrs, 4 hrs); choose the one with the largest flux

  Ogives method – cumulative cospectra constructed over a range of frequencies; the point after which no flux is added being used as the averaging time

The averaging interval should not be too long. If it is too long, it may include slow, non-turbulent contributions to the turbulent flux. Also, the diurnal cycle of measured flux may be masked or eliminated by intervals of 5-6 hours or longer. The averaging interval must not be too short either. If it is too short it can lead to an effect similar to high pass filtering that will result in missed contributions from lower frequencies, and finally to underestimation of the measured flux.

There are several ways to choose an averaging time. The most widely used approaches are mandatory, empirical and ogives.

The mandatory approach simply uses standard averaging times of 30 min or 1 hour. It is easy to execute, and works well for many traditional settings, but may not be suitable for all conditions. The empirical approach analyzes the data with different (reasonable) averaging times (*e.g.*, 10 min, 30 min, 1 hr, 2 hrs, 4 hrs), and chooses the one with largest flux. The ogives method relies on cumulative cospectra constructed over a range of frequencies. As the accumulation period is lengthened, at some point no more flux is added. This then becomes the best averaging time. This is, perhaps, the most flexible and justified approach, but requires substantial data processing and analysis. The method is described in detail in pages 18-21 in Lee, Massman and Law's Handbook on Micrometeorology.

It is important to note that while they are usually done together, choosing an averaging period does not have to be the same as choosing a time constant recursive filter for de-trending, especially in non-linear cases.

References

Pages 7-30 of the Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Page 114 in Foken, T., 2008. Micrometeorology. Springer-Verlag, Berlin Heidelberg, Germany, 310 pp.

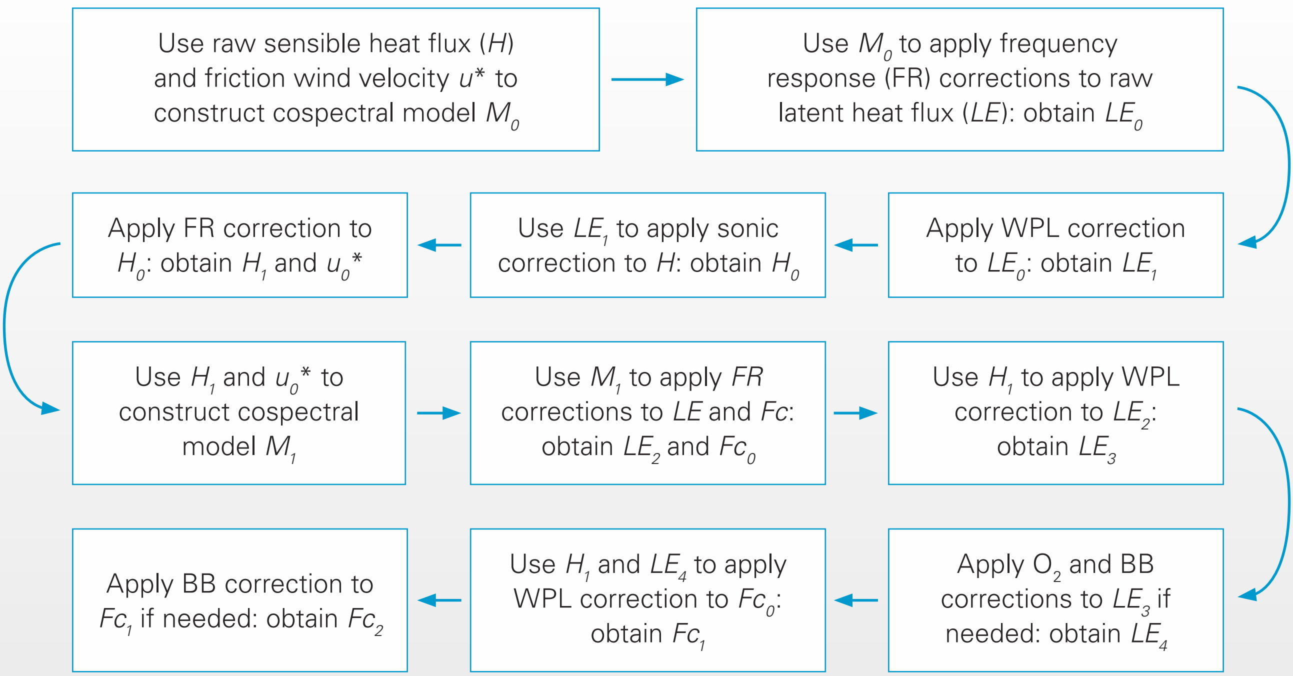
Finnigan, J., R. Clement, Y. Malhi, R. Leuning, and H. Cleugh, 2003. A Re-Evaluation of Long-Term Flux Measurement Techniques Part I: Averaging and Coordinate Rotation. Boundary Layer Meteorology, 107: 1-48

Part Four:

Processing Eddy Covariance Data

Section 4.2

Applying Frequency Response Corrections



After raw data have been pre-conditioned, corrections can be applied. Applying various corrections, including those for the system frequency response, can be a complicated and iterative process, especially if using one's own custom code. Following a fixed sequence of steps is very important. The diagram shown here gives an example of the workflow for applying the corrections. FR refers to frequency response corrections, WPL refers to the Webb-Pearman-Leuning density terms, O_2 stands for the oxygen correction, and BB stands for the band-broadening correction.

Fortunately, such lengthy sequences are usually done automatically by the processing software, and the user only needs to make sure that the order of steps is appropriate, and that no steps are missing. In the latest programs, such as EddyPro, even the sequence of the steps is usually set automatically.

Please note that some of the corrections may have been already applied by the instrument manufacturer, and be sure to consult the manuals on this matter.

It appears to be a general consensus that for open-path measurements, the frequency response corrections should be applied before the Webb-Pearman-Leuning terms. For more details refer to Chapter 7 in Lee *et al.* (2004) and Chapter 4 in Aubinet *et al.* (2012). We will discuss the details of these corrections in the following pages.

References

Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

LI-COR Biosciences, 2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. (envsupport.licor.com/help/EddyPro4/Default.htm)

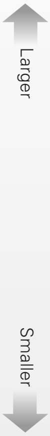
Fuehrer, P., and C. Friehe, 2002. Flux corrections revisited. Boundary-Layer Meteorology, 102: 415-457

Horst, T., 2012 (Accessed). Corrections to Sensible and Latent Heat Flux Measurements http://www.eol.ucar.edu/instrumentation/sounding/isfs/isff-support-center/how-tos/corrections-to-sensible-and-latent-heat-flux-measurements

- Frequency is lost for a number of reasons, all related to sensors and EC system frequency response

Key sources of frequency loss:

- Tube attenuation
- Scalar path averaging
- Sensor separation
- Sensor time response
- Sensor response mismatch
- Low pass filtering
- High pass filtering
- Digital sampling



- Frequency response corrections – a family of corrections that compensate for flux losses at different frequencies (eddy sizes)

Frequency response corrections are a family of corrections that compensate for flux losses at different frequencies of turbulent transport. There are a number of separate reasons for these losses, but all are related to sensor performance and the frequency response of the eddy covariance system.

The main frequency response corrections include the following: time response; tube attenuation; scalar/vector path averaging; sensor separation; sensor response mismatch; low pass filtering; high pass filtering; and digital sampling.

Before discussing each of the frequency response corrections, let us look at an extreme example illustrating the importance of the frequency response in general. Imagine that measurements are taken 30 cm from the ground with a bulky instrument, which has a 200 cm path and a sampling frequency of 5 Hz.

Most of the flux transport at this height would be done by very small eddies at very high frequencies. The instrument would average out most of the transport in the long path, would miss a good portion of the transport due to its slow 5 Hz sampling rate, and may generate a relatively large proportion of its own turbulence that is not representative of the environment of interest. As a result, fluxes may be greatly underestimated even after applying large corrections on the order of several hundred percent. Most real-life situations will likely be less extreme, but there can still be many factors responsible for missed flux at different frequencies.

One of the cornerstone papers on this subject is by C.J. Moore, entitled "Frequency response corrections for eddy correlation systems." Additional resources on frequency response corrections can be found below.

References

Moore, C., 1986. Frequency response corrections for eddy covariance systems. Boundary-Layer Meteorology, 37: 17-35

Chapter 4 by Massman, W. and R. Clement (pp. 67-101) in Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Mauder, M., and T. Foken, 2011. Documentation and Instruction Manual of the Eddy Covariance Software Package TK3. http://opus4.kobv.de/opus4-ubbayreuth/frontdoor/index/index/docId/681

- Open-path system frequency loss is usually very small, 5-10%
- Most frequency loss comes from:
  - path averaging
  - sensor separation
  - sensor time response
- In closed-path systems, frequency loss can be medium or large, up to 50% for H_2O and sticky gases
- Most frequency loss in closed-path systems comes from:
  - tube attenuation, the major source
  - path averaging, sensor separation, sensor time response also contribute

In open-path instruments, an intake tube is not used, so most frequency losses come from path averaging, sensor separation and sensor time response. Frequency losses for open-path instruments and resulting corrections are usually quite small, on the order of 5-10%.

Enclosed instruments use short tubes (less than 1 m), so their frequency loss is larger than in open-path instruments, but not by much. Shorter tubes will lead to smaller losses and longer tubes will result in larger losses and corrections. Sticky gases (*e.g.*, H_2O, NH_3, *etc.*) will have larger tube-related frequency losses than CO_2, CH_4, *etc.*

In closed-path instruments, intake tubes may be many meters long, and tube frequency attenuation is a major contributor to frequency loss. The respective correction can often exceed 25% or even 50%. Measuring sticky gases with very long tubes is generally not recommended due to the very large, uncertain magnitude of tube attenuation.

References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

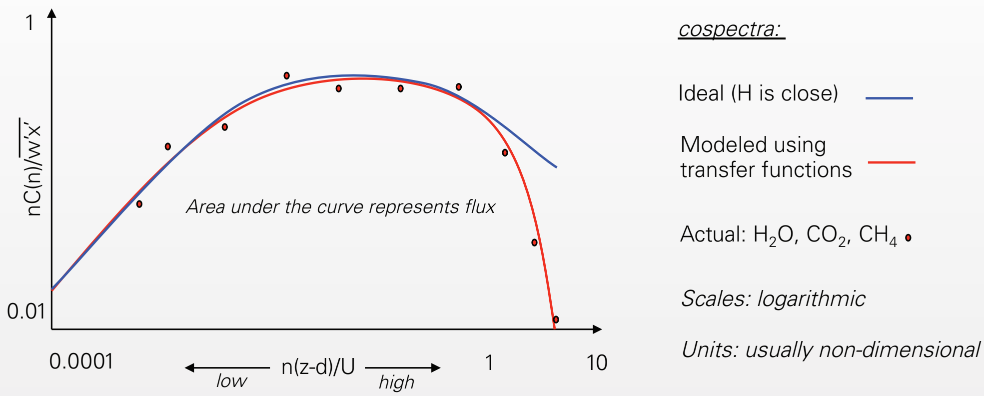
Foken, T., 2008. Micrometeorology. Springer-Verlag, Berlin Heidelberg, Germany, 310 pp.

Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Fuehrer, P., and C. Friehe, 2002. Flux corrections revisited. Boundary-Layer Meteorology, 102: 415-457

Horst, T., 2012 (Accessed). Corrections to Sensible and Latent Heat Flux Measurements http://www.eol.ucar.edu/instrumentation/sounding/isfs/isff-support-center/how-tos/corrections-to-sensible-and-latent-heat-flux-measurements

- Corrections for frequency loss are usually calculated from instantaneous data via cospectra, a distribution of flux transport by frequency



C(n) – cospectrum
$\overline{w'x'}$ – flux covariance
n – natural frequency
z – measurement height
d – zero-plane displacement
U – mean horizontal wind speed

As a first step in the frequency response correction process, let us look at a cospectrum, a distribution of flux by frequency. This is an important component of calculating frequency response corrections.

As described on page 12, turbulent air flow consists of a mix of eddies of different sizes and rotation velocities, so some flux transport is done at higher frequencies and some at lower ones, covering the whole range of frequencies: from large movements on the order of hours, to small ones on the order of 1/10 of a second.

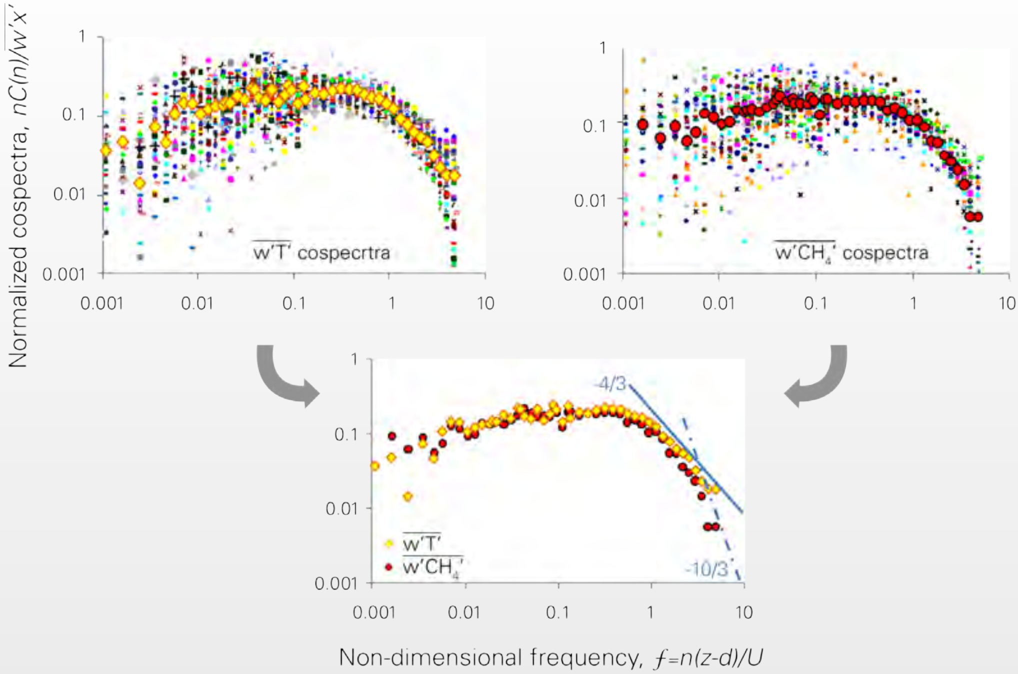
Cospectrum describes this situation in a mathematical form. It shows how much of the raw flux (covariance of the *w'* and gas density or other scalar) is transported at each frequency. This is achieved using a Fourier transform of the time series into the frequency domain. An integrated area under the ideal non-dimensional normalized cospectral curve equates to a value of 1, representing 100% of the flux.

The ideal cospectrum for a given height and conditions is usually modeled after Kaimal *et al.* (1972) or by other models, or by using fast readings from a sonic anemometer. The ideal cospectral curve is shown in the illustration above in blue.

Modern sonic anemometers are capable of very fast sampling with small errors over relatively short paths. In addition, the instantaneous temperature is derived from the same data as *w'*, and no sensor separation or time delay occurs between the two signals. As a result, cospectrum of sonic sensible heat flux *H* ($w'T_{sonic}'$) is often very close to the ideal cospectrum, especially in the middle of the day with good turbulent exchange high above the canopy.

The actual cospectral curve for gas fluxes (red dots and red fitted line above) is usually located below the ideal curve, especially at high frequencies. Such a position of the curve indicates flux losses related to deficiencies in frequency response when measuring covariances between *w'* and instantaneous gas fluctuations. The deficiencies are due to time response, tube attenuation (for closed path), sensor separation, path averaging, filtering, *etc*.

In very simple terms, the ratio of the area under the ideal cospectral curve (blue line) to the area under the actual curve (red line) represents the correction factor (*e.g.*, cospectral multiplier, cospectral correction, frequency response correction, *etc*.). The correction factor compensates for the non-ideal frequency response of a particular gas flux measurement system in specific conditions over a specific period of time.



Although modern flux programs will compute, apply, and even partially analyze the cospectral corrections, it is useful to have an occasional visual inspection of the specific cospectra at the specific site to ensure that they look reasonable.

Actual field cospectra computed over a single individual half-hour or an hour often look quite noisy, and may not be helpful in assessing system frequency response. Similarly, cospectra computed during periods with very small fluxes or undeveloped turbulence (for example, at night) may be near zero or erratic, because the co-variance on the y-axis may be close to zero.

Normalized ensemble-averaged hourly cospectra, binned by frequency, and computed for midday or daytime hours over many days, are typically used as an indicator of the system frequency response. These may be compared to an ideal Kaimal cospectra, or to sensible heat flux cospectra. Turbulent studies and methodological experiments may also look at nighttime cospectra after significant quality control, and after averaging over numerous hours to minimize noise.

The example in the top left corner in the illustration above describes individual hourly cospectra of sensible heat flux during daytime hours (small multi-colored symbols), and an ensemble-averaged cospectrum (large yellow diamonds). The leftmost portion of this plot describes flux contributions from the lower frequencies (0.001-0.01 Hz; larger slower eddies). The rightmost portion of the plot describes flux contributions from higher frequencies (1.0-10 Hz; smaller faster eddies). Such cospectra can be used as a measure of how the near-ideal system frequency response should appear at a given site.

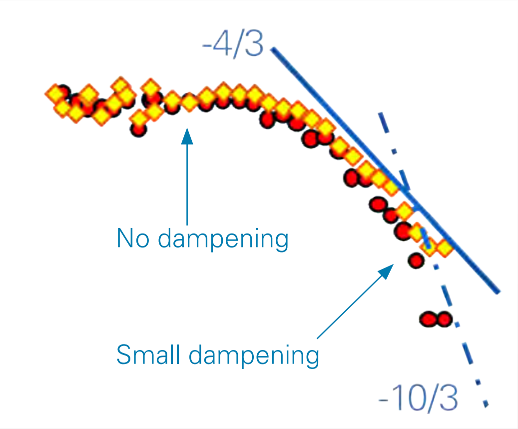
The example in the top right corner describes individual cospectra of methane flux during the same hours (small multi-colored symbols), and ensemble-averaged cospectrum (large red circles). The open-path analyzer used for this data set has a much larger path than the sonic anemometer, and some dampening at high frequencies is expected.

References

Cornerstone papers on spectra, cospectra and frequency response corrections:

Kaimal, J., J. Wyngaard, Y. Izumi, and O. Coté, 1972. Spectral characteristics of surface layer turbulence. Quarterly Journal of The Royal Meteorological Society, 98: 563-589

Moore, C., 1986. Frequency response corrections for eddy covariance systems. Boundary-Layer Meteorology, 37: 17-35



- Zoomed-in high-frequency portion of the cospectra from the previous page
- Small but non-negligible differences would not be visible without ensemble averaging of the cospectral data

Please note that without ensemble averaging of the cospectral data, one will not be able to see the difference between the topmost left and right plots on the previous page, and assess high-frequency dampening for the CH_4 flux measurements.

However, after ensemble averaging (bottom plot on previous page and in illustration above), the small but still noticeable difference in the high-frequency part of the cospectra is observed, as predicted for the larger analyzer. The differences between the ideal -4/3 slope and expected -10/3 slope show that the system works as expected.

By computing the ratio of an area under the near-ideal sensible heat flux cospectra and actual methane flux cospectra, one can construct a cospectral correction, compensating for the frequency response of a methane flux measurement system. In this example the correction would be quite small, on the order of 5-10%.

References

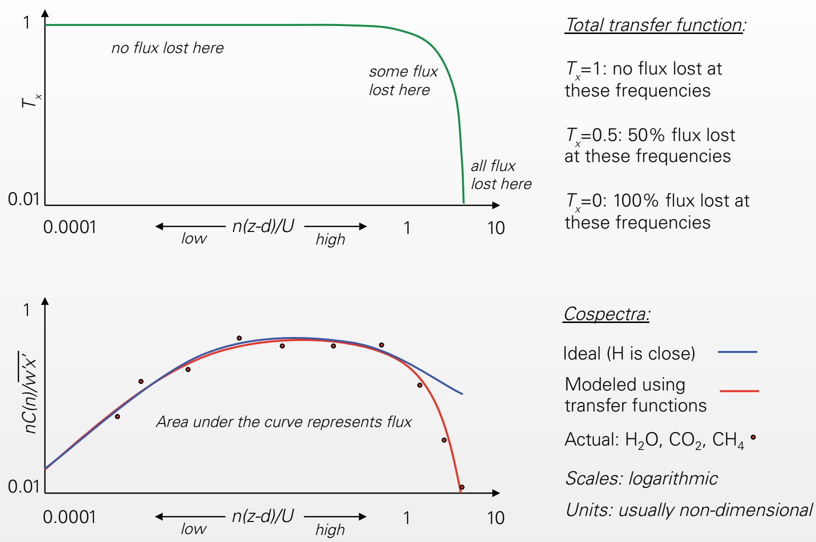
Moncrieff, J., J. Massheder, H. de Bruin, J. Ebers, T. Friborg, *et al.*, 1997. A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide. Journal of Hydrology, 188: 589-611

Moncrieff, J., R. Clement, J. Finnigan, and T. Meyers, 2004. Averaging, detrending and filtering of eddy covariance time series, in Handbook of micro-meteorology: a guide for surface flux measurements, Lee, X., W. Massman and B. Law (Eds.). Dordrecht, Kluwer Academic: 7-31

Horst, T., and D. Lenschow, 2009. Attenuation of scalar fluxes measured with spatially-displaced sensors. Boundary-Layer Meteorology, 130: 275-300

Su, H., H. Schmid, S. Grimmond, C. Vogel, and A. Oliphant, 2004. Spectral Characteristics and Correction of Long-Term Eddy-Covariance Measurements Over Two Mixed Hardwood Forests in Non-Flat Terrain. Boundary-Layer Meteorology, 110: 213-253

McDermitt, D., G. Burba, L. Xu, T. Anderson, A. Komissarov, *et al.*, 2011. A new low-power, open-path instrument for measuring methane flux by Eddy Covariance. Applied Physics B: Lasers and Optics, 102(2): 391-405



- Transfer functions describe how each sampling problem would affect the ideal cospectra at each frequency

Transfer functions describe how each of the factors affecting the system frequency response (*e.g.*, time response, tube attenuation, path averaging, sensor separation, filtering, *etc.*) will affect an ideal cospectra, and how much it will lower the cospectral curve below the ideal at each frequency.

Above is an example of how a transfer function predicts what would happen to the ideal cospectrum at given atmospheric conditions due to a diminished frequency response at high frequencies.

In this example, note how the actual and modeled cospectra decrease below the ideal cospectrum when the transfer function is reduced from 1.0 at high frequencies.

The total transfer function is a product of the different transfer functions, each of which describes flux loss at specific frequencies due to a specific reason.

If the effect (or the shape) of the transfer function is known, one can describe the shape of the actual cospectra and then relate it to the ideal cospectra, thus correcting the flux and increasing its magnitude.

References

Moore, C., 1986. Frequency response corrections for eddy covariance systems. Boundary-Layer Meteorology, 37: 17-35

Chapter 4 by Massman, W. and R. Clement (pp. 67-101) in Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Moncrieff, J., Y. Malhi, and R. Leuning, 1996. The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water. Global Change Biology, 2: 231-240

- Frequency response corrections can be applied via transfer functions to: (a) Kaimal-Moore's cospectral models, or (b) actual sensible heat flux cospectra
- Cospectral models use sets of equations for unstable, stable and neutral conditions
- Models use stability parameter (*z/L*), non-dimensional frequency (*f=n(z-d)/U*), measurement height (*z*), zero-plane displacement (*d*), and mean wind speed (*U*) to define the cospectral energy at each frequency (*C(n)*)
- Cospectral models are adjusted for the transfer functions at each frequency, and a correction factor is determined for the entire cospectrum
- Applying all frequency response corrections can increase fluxes by as much as 25% or more; corrections are often larger at night

Frequency response corrections can generally be applied via transfer functions either to Kaimal-Moore's cospectral models, or to actual sensible heat flux cospectra. Using cospectral models is somewhat safer, because they are independent of potential errors or instrument problems with sensible heat flux cospectra.

Cospectral models use sets of equations for unstable, stable and neutral conditions. They use parameters for: stability (*z/L*), non-dimensional frequency (*f=n(z-d)/U*), measurement height (*z*), zero-plane displacement (*d*), and mean wind speed (*U*), to come up with cospectral energy for each frequency (*C(n)*).

The cospectral model is adjusted for the transfer functions at each frequency, and a correction factor is determined for the entire cospectrum based on the integrated area under the actual cospectral curve in comparison with the ideal cospectra (a value of 1). Applying all frequency response corrections can increase fluxes by up to 25% or more, especially at night.

There are also alternative methods to compute frequency response corrections proposed in:

Nordbo A., and G. Katul, 2012. A Wavelet-Based Correction Method for Eddy-Covariance High-Frequency Losses in Scalar Concentration Measurements. Boundary Layer Meteorol., DOI: 10.1007/s10546-012-9759-9

Massman, W., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agric. and Forest Meteorol., 104: 185-198

References

Moore, C., 1986. Frequency response corrections for eddy covariance systems. Boundary-Layer Meteorology, 37: 17-35

Kaimal, J., J. Wyngaard, Y. Izumi, and O. Coté, 1972. Spectral characteristics of surface layer turbulence. Quarterly Journal of The Royal Meteorological Society, 98: 563-589

Moncrieff, J., J. Massheder, H. de Bruin, J. Ebers, T. Friborg, *et al.*, 1997. A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide. Journal of Hydrology, 188: 589-611

- Time response corrections compensate for the loss of flux due to inability of sensors to respond fast enough to small fluctuations that contribute to the flux
- Time response transfer function is applied to fluxes of H_2O, CO_2, CH_4, *etc.*

$$T_\tau(n) = \frac{1}{\sqrt{1+(2\pi n\tau)^2}}$$

T_τ – transfer function for time response

n - natural frequency

τ – dynamic time response of the sensor

Processing programs (*e.g.*, EddyPro, EdiRe, EddyUH, TK_4, *etc.*) automatically compute and apply frequency response corrections to flux data. It is still useful, however, to see how transfer functions appear mathematically, and what factors affect each major cause of the reduction in system frequency response.

In the next pages we will briefly cover the frequency response corrections and the associated transfer functions individually, and construct a total transfer function required for the correction factor described on the previous page.

The first one is a fundamental correction for time response. This correction compensates for the loss of flux due to the inability of an instrument to respond fast enough to small fluctuations contributing to the flux. The associated transfer function is generally applicable to gas and water fluxes. Theoretically, however, it is also required for sensible heat and momentum fluxes, when measurements are done very close to the ground, or when the time response of the instrument is insufficient.

For the time response correction, the key factor is dynamic time response of the instrument, as can be seen from the equation at the top of this page.

According to Horst (2000), the square root in the above function is not required when applying frequency corrections. This is still somewhat of an open question, with different groups using two different forms of this equation.

References

Moore, C., 1986. Frequency response corrections for eddy covariance systems. Boundary-Layer Meteorology, 37: 17-35

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Horst, T.W., 2000. On frequency response corrections for eddy covariance flux measurements. Boundary-Layer Meteorol. 94, 517–520

- Compensates for the loss of flux due to the fact that sampling air through the inlet tube attenuates (dampens) small fluctuations
- Required for closed-path and enclosed fluxes of H_2O, CO_2, CH_4, *etc.*

$$T_t(n) = e^{-4\pi^2 \Lambda a L n^2 / \bar{u}_t^2}$$

T_t – transfer function for tube attenuation

Λ – attenuation parameter for each gas

a – tube radius

L – tube length

u_t – mean tube flow velocity

Tube attenuation correction has been a persistent topic of discussion among eddy covariance method developers for more than 25 years.

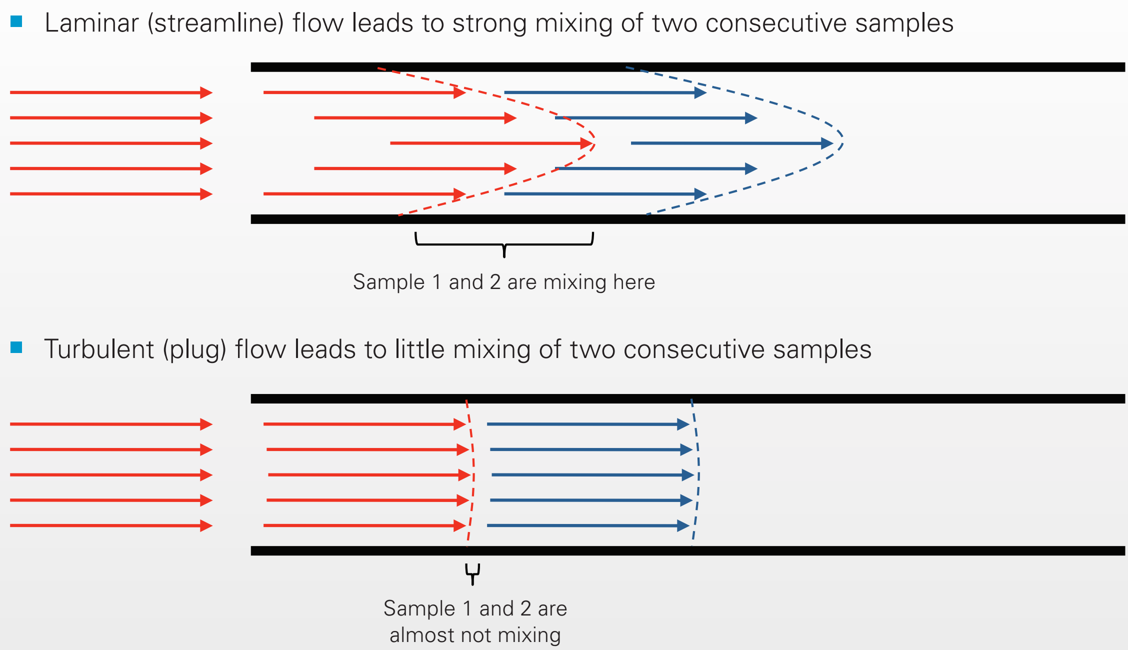
Variations in gas species, environmental conditions, tube material and length, tube wall contamination levels, flow rate, and numerous other physical parameters may affect the interaction between the sampled gas and the tube wall, and thus, may influence the respective transfer function.

With new instruments becoming available for flux measurements of various gas species, tube attenuation should be treated carefully, especially when using long intake tubes, when most of the total frequency response correction may be due to tube attenuation. Therefore, in this and in the next three pages we will examine the tube attenuation process in some detail, and provide important literature references on the topic.

A tube will always attenuate (or dampen) small fluctuations in the flow drawn through it. The tube attenuation correction compensates for the loss of flux that occurs due to such dampening. This correction is applied to gas and water vapor fluxes measured with closed-path and enclosed analyzers. It also can be used as a tool to determine what intake tube length is sufficient to attenuate most of the temperature fluctuations, so that the thermal expansion and contraction portion of the density corrections will become negligible.

There is growing evidence that attenuation of water vapor flux can be significantly affected by relative humidity, in addition to other factors. Thus, for fluxes of water vapor and other sticky gases, short small-diameter intake tubes may have significant benefits. Short intakes, however, will require fast temperature and pressure measurements in the sampling cell of the enclosed design, conducted at the same time as gas density.

The mean tube flow velocity in the formula above is the distance per time (*e.g.*, m s^{-1}) and not the flow rate in liters per minute (lpm). It can be computed as the rate (lpm) divided by the cross-sectional area of the tube.



The nature of the tube attenuation effect on eddy covariance flux can be envisioned, in a simplified manner, by examining two kinds of the air flow going through the tube.

Although the sampled air gets smeared to some degree with any tube, when the flow is laminar (*e.g.*, streamline flow) the smearing is quite heavy, leading to mixing of two consecutive 10 Hz samples, as indicated with red and blue color on the illustration above.

This type of mixing results in the inability to distinguish between consecutive samples describing rapid fluctuations of gas concentrations required for eddy covariance calculations. The covariance of rapid fluctuations in vertical wind and in gas concentration is diminished; wind still changes rapidly, but measured gas concentration will appear to change slowly, due to mixing of the 10 Hz samples in the tube.

If flow is turbulent (*e.g.*, plug flow) the smearing is much smaller, leading to little mixing of two consecutive 10 Hz samples. Very rapid fluctuations will still be attenuated, but 10 Hz samples may be easily distinguishable.

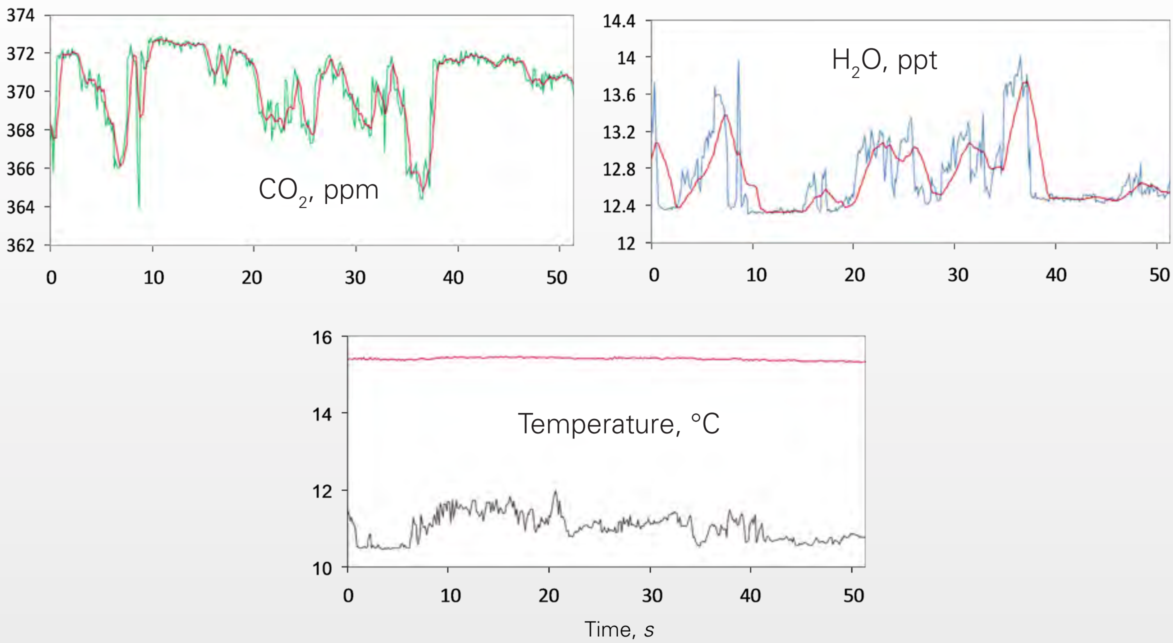
To provide a guide as to what flow rate should be chosen for the sampling for a particular instrument setup, the Reynolds number (*Re*) can be used. From the tube cross-sectional shape, diameter and flow rate, *Re* can help categorize the tube flow into laminar ($Re<2300$), transient ($2300<Re<4000$), or fully turbulent ($Re>4000$).

With short intake tubes used by enclosed gas analyzers, especially when measuring non-sticky gases and with tubes shorter than 0.5 m, the attenuation may be minimal even at transient flow rates. With long tubes and sticky gases, flow must be fast enough to stay turbulent.

Typically, for tubes with inner diameters of about 0.4-0.8 cm, turbulent flow may be achieved at rates ranging anywhere from 9 to 18 lpm, depending on the other parts of the intake system (such as particle filters, water traps, rain guards, *etc.*).

References

Reynolds, O., 1883. An experimental investigation of the circumstances, which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. Philosophical Transaction of the Royal Society, 174: 935–982



The plots above illustrate some typical examples of tube attenuation effects on actual 10 Hz field data for non-sticky gases, sticky gases, and temperature.

The green, blue and purple lines are actual fluctuations measured in open air. The red lines are their attenuated versions after passing through the sampling tube.

With fully turbulent flow and non-sticky gases, such as CO_2, small smearing leads to small dampening and a small time delay (red line in the top left plot).

With sticky gases such as H_2O, the dampening and time delay is larger (red line in the top right plot), so frequency loss will be larger, as well.

In the case of temperature, heat in the travelling air is rapidly exchanged with tube walls, and attenuation is very strong (red line in the bottom plot).

The latter is actually preferable, as it helps eliminate the sensible heat portion of density corrections, as explained later in Section 4.4.

As can be deduced from the plots above and from the mathematical form of the tube attenuation transfer function, shorter tubes and higher flow rates are highly desirable for flux measurements, especially in the case of sticky gases.

However, short tubes often cannot be used in current closed-path analyzers, because fast temperature and fast pressure are not measured in the cell simultaneously with gas density, and on-line high-speed conversion from instantaneous density to instantaneous dry mole fraction cannot be reliably achieved.

Outputting fast dry mole fraction implies that the instantaneous thermal and pressure-related expansion and water dilution of the sampled air have been accounted for.

Thus, density corrections would no longer be required to compute fluxes. This would significantly simplify the calculations and reduce uncertainty. This is possible with specially designed enclosed gas analyzers, and explained in more detail in Sections 2.2 and 4.7.

The literature listed below provides further theoretical and experimental details on various aspects of tube attenuation effects on flux calculations, such as:

- alternative transfer functions
- explanation of tube attenuation parameters
- effects of high relative humidity on tube attenuation and water vapor flux
- effects of tube heating on water sorption, attenuation and water flux
- *etc.*

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Massman, W., 1991. The attenuation of concentration fluctuations in turbulent flow through a tube. Journal of Geophysical Research, 96 (D8): 15269-15273

Aubinet, M., A. Grelle, A. Ibrom, U. Rannik, J. Moncrieff, *et al*., 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology. Advances of Ecological Research: 113-174

Ibrom, A., E. Dellwik, H. Flyvbjerg, N. O. Jensen, and K. Pilegaard, 2007. Strong low-pass filtering effects on water vapor flux measurements with closed-path eddy correlation systems, Agricultural and Forest Meteorology, 147: 140-156

Massman, W., and A. Ibrom, 2008. Attenuation of concentration fluctuations of water vapor and other trace gases in turbulent tube flow. Atmospheric Chemistry and Physics, 8(20): 6245-6259

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, London, New York, 442 pp.

Runkle, B., C. Wille, M. Gažovič, and L. Kutzbach, 2012. Attenuation Correction Procedures for Water vapor Fluxes from Closed-Path Eddy-Covariance Systems. Boundary-Layer Meteorology, 142:401-423

Fratini G., A. Ibrom, N. Arriga, G. Burba, and D. Papale, 2012. Relative humidity effects on water vapour fluxes measured with closed-path eddy covariance systems with short sampling lines. Agricultural and Forest Meteorology, 165 (15): 53-63

- Compensates for the loss of flux due to the fact that the transport by very small eddies is missed when averaged over a path (not a point)
- Applied to all scalar fluxes

$$T_{sp}(n) = \sqrt{\frac{3+\exp(-2\pi n\frac{p_s}{u}) - (\frac{4}{2\pi n\frac{p_s}{u}})(1-\exp(-2\pi n\frac{p_s}{u}))}{2\pi n\frac{p_s}{u}}}$$

T_{sp} – transfer function for scalar path averaging

p_s – scalar path length

u – mean wind velocity

- There is a similar correction for momentum, vector path averaging

Path or volume averaging corrections compensate for the loss of flux due to averaging of very small eddies.

The flux transport done by these eddies is missed when averaged over a path, and not sampled at just a single point.

This correction applies to all scalar fluxes, and has a special formulation (T_{vp}) for momentum flux that has a vector path average.

Laser-based gas analyzers may have enormous optical paths (from dozens of meters to many kilometers) folded into sampling cells of various physical sizes and shapes.

The p_s parameter in the formula above typically refers to the physical dimensions of the sampling cell length, and not to the optical path.

The formulation of p_s may get quite complex if the optical path, or cell, is arranged in an unusual geometric shape (such as a flat surface, ring, oval, *etc.*).

Consulting with the manufacturer when writing custom processing code, or using readily available full flux processing programs, may be useful in these cases.

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

LI-COR Biosciences,2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. envsupport.licor.com/help/EddyPro4/Default.htm

Mauder, M., and T. Foken, 2011. Documentation and Instruction Manual of the Eddy Covariance Software Package TK3. http://opus4.kobv.de/opus4-ubbayreuth/frontdoor/index/index/docId/681

- Compensates for the loss of flux due to the inability of the vertical wind speed and scalar sensors to sample in the same volume
- Usually applied to fluxes of H_2O, CO_2, CH_4, *etc.*
- Not for *H*: temperature is often sampled in same volume as *w* by sonic anemometer

$$T_s(n) = e^{-9.9(np_{xy}/\bar{u})^{1.5}}$$

T_s – transfer function for sensor separation

p_{xy} – sensor separation distance

u – mean wind velocity

The horizontal sensor separation correction compensates for the loss of flux due to the inability of the vertical wind speed and scalar sensors to be sampled in exactly the same volume. It is generally applied to gas and water fluxes, but not to sensible heat ($\sim w'T'$) and momentum ($\sim w'u'$) fluxes.

For momentum and sensible heat fluxes, the sonic anemometer samples vertical and horizontal wind speed and instantaneous temperature in the same volume at the same time, so the separation correction is not required.

There are a number of ways to apply this correction. It can be an integral part of the total frequency correction, or a separate step in data processing. It can also correct for only the horizontal separation, or for both horizontal and vertical separations.

When writing your own code, it is important to be careful to not confuse sensor separation corrections with time delay adjustments. In some methods time delay adjustment procedures may include sensor separation, but in others it will not.

References

The literature below shows several approaches to applying this correction:

LI-COR Biosciences, 2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. envsupport.licor.com/help/EddyPro4/Default.htm

Mauder, M., and T. Foken, 2011. Documentation and Instruction Manual of the Eddy Covariance Software Package TK3. http://opus4.kobv.de/opus4-ubbayreuth/frontdoor/index/index/docId/681

Moore, C., 1986. Frequency response corrections for eddy covariance systems. Boundary-Layer Meteorology, 37: 17-35

Horst, T., 2012 (Accessed). Corrections to Sensible and Latent Heat Flux Measurements http://www.eol.ucar.edu/instrumentation/sounding/isfs/isff-support-center/how-tos/corrections-to-sensible-and-latent-heat-flux-measurements

Horst, T., and D. Lenschow, 2009. Attenuation of scalar fluxes measured with spatially-displaced sensors. Boundary-Layer Meteorology, 130: 275-300

- Sometimes used in data processing programs to compensate for differences when slower-response and faster-response instruments are used together
- Often assumed to be negligible or may be partially incorporated as a part of the time delay correction when using circular correlation

$$T_m(n) = \frac{1+(2\pi n)^2 \tau_1 \tau_2}{\sqrt{(1+(2\pi n\tau_1)^2)+(1+(2\pi n\tau_2)^2)}}$$

T_m – transfer function for sensor response mismatch

τ_1 – dynamic time response of sensor 1

τ_2 – dynamic time response of sensor 2

Sensor response mismatch corrections are sometimes used in data processing programs to compensate for differences when both slower-response and faster-response instruments are used together.

This correction is often assumed negligible or may be partially incorporated as a part of time delay correction when using circular correlation.

This correction may not help when sampling rates from two fast instruments are severely desynchronized.

For example, the rate should be 10Hz on both instruments, and should not be 8.0 Hz on the anemometer and 12 Hz in the analyzer.

Precision time protocols or other modern readily available clock arrangements should be made to ensure the same sampling time intervals on all fast instruments.

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

- Compensates for the loss of flux in the high frequency part of cospectrum mainly due to use of anti-aliasing and other filtering
- Applies to all fluxes; example is a recursive low-pass filter

$$T_{lo}(n) = 1 - \frac{2\pi n \tau_f}{\sqrt{1 + \frac{\frac{(2\pi n \tau_f)^2}{1}}{(1 + \frac{1}{\tau_f n_c})}}}$$

T_{lo} – transfer function for low-pass filtering

τ_f – low-pass filter constant

n_c – cutoff frequency; ½ sampling frequency

Low-pass filtering corrections can sometimes be used to compensate for the loss of flux in the high frequency part of a cospectrum. These losses are due mainly to the use of anti-aliasing and other filters. The correction applies to all fluxes.

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

LI-COR Biosciences,2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. envsupport.licor.com/help/EddyPro4/Default.htm

- Compensates for loss of flux in the low frequency part of cospectrum due to time averaging, linear de-trending, or non-linear filtering
- Applies to all fluxes; example is a recursive high-pass filter

$$T_{hi}(n) = \frac{2\pi n\tau_f}{\sqrt{1 + \frac{(2\pi n\tau_f)^2}{\frac{1}{(1+\frac{1}{\tau_f n_c})}}}}$$

T_{hi} – transfer function for high pass filtering

τ_f – high pass filter constant

n_c – cutoff frequency; ½ sampling frequency

High-pass filtering corrections can sometimes be used to compensate for the loss of flux that occurs in the low frequency part of a cospectrum due to time averaging, linear de-trending, mean removal, non-linear filtering, *etc.* The correction applies to all fluxes.

The excessive use of filtering is typically not recommended in modern eddy covariance processing, as it is difficult to track and may lead to increased frequency loss.

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

LI-COR Biosciences,2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. envsupport.licor.com/help/EddyPro4/Default.htm

- Compensates for aliasing during digital sampling
- Applies to all fluxes
- Often assumed to be negligible

$$T_{ds}(n) = 1 + \left(\frac{n}{n_s - n}\right)^3 \text{ for } n \leqq n_s/2$$

T_{ds} – transfer function for digital sampling

n_s – sampling frequency (*e.g.*, 10 Hz)

A digital sample takes a 'snapshot' of the value being measured at one instant in time. Some unit of time passes (maybe only a fraction of a second) and then another 'snapshot' is taken.

Since the measurement is not continuous, there can be errors introduced into the final values. The digital sampling correction compensates for digital sampling errors, and applies to all fluxes.

These and other computations are done for the frequencies below the critical, or Nyquist, frequency ($n<=n_s/2$) to avoid aliasing in the rightmost part of the cospectra for frequencies above the Nyquist frequency ($>n_s/2$), as follows from Shannon's sampling theorem.

Digital sampling corrections are often assumed negligible for modern instruments. However, caution should be exercised when experimenting with novel or custom-made instruments, or non-standard settings and conditions.

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

time response for each of two individual signals

because filtering was done for each of 2 signals

$$T_{all}(n) = T_{\tau c}(n) T_{\tau w}(n) T_t(n) T_{ds}(n) T_s(n) T_{hi}^{\,2}(n) \sqrt{T_{sp}(n) T_{vp}(n)}$$

some researchers use square root of T_t depending on how they write their T_t function

because these functions were developed for the spectrum (loss in signal squared)

- Total transfer function is a product of individual transfer functions
- Important moment - to avoid double-correcting or under-correcting
- Depending on particular system - not all transfer functions may be required

The equation above is an example of the total transfer function, which is the product of several frequently applied individual transfer functions.

It is important to avoid double-correcting or under-correcting during this process, especially when flux processing routine is custom written.

For example, a sensor response mismatch may have already been fully or partially compensated by circular correlation to determine a time delay.

Depending on the particular system, not all transfer functions may be required. They can be removed from the total equation, or set to 1, which then would have no effect on flux loss or respective frequency response correction.

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

- Intended to compensate for flux losses at different frequencies due to diminished frequency response of the eddy covariance system
- Main corrections include: time response, tube attenuation, scalar and vector path averaging, sensor separation, sensor response mismatch, low and high pass filtering, and digital sampling
- Applied to cospectra via transfer functions describing losses at each frequency due to each individual cause
- Main pitfalls: not correcting, double-correcting, and under-correcting

In summary, frequency response corrections are intended to compensate for flux losses at different frequencies due to a diminished frequency response of the eddy covariance system.

Key corrections include: time response, tube attenuation, scalar and vector path averaging, and sensor separation. Low and high pass filtering, sensor response mismatch, and digital sampling may also be important under some conditions.

Frequency response corrections are usually applied to a cospectrum via transfer functions that describe losses at each frequency. The main pitfalls during this process are: not correcting, double-correcting, and under-correcting.

The majority of commercially available and free software programs take care of this step internally. In most cases, the researcher just needs to make sure to enter the correct parameters into the software.

References

Moore, C., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorology, 37: 17-35

Part Four:

Processing Eddy Covariance Data

Section 4.3

Applying Sonic Anemometer Corrections

- Sonic temperature is computed from speed of sound, c: $T_s = c^2 / y_d R_d - 273.15$
- Sonic temperature is different from air temperature, T: $T_s \approx T \times (1 + 0.51q)$
- Sonic temperature is different from virtual temperature, T_v: $T_v \approx T \times (1 + 0.61q)$
- Sonic temperature correction: $T \approx T_s / (1 + 0.51q)$

Temperature measured by a sonic anemometer (*e.g.*, sonic temperature) is actually computed from speed of sound, as described in the first equation above, where y_d is the ratio of specific heat of moist air at constant pressure to that at constant volume, and R_d is the gas constant for dry air.

Sonic temperature is different from the actual temperature due to the presence of water vapor (q stands for specific humidity), and it is also different from the virtual temperature. So a sonic temperature correction is required when one wants to obtain an actual air temperature or virtual air temperature from the sonic anemometer measurements.

Even after the sonic temperature correction, the absolute accuracy of the mean air temperature coming from a sonic anemometer is not nearly as accurate as that from a PRT, a properly configured thermocouple, or a thermistor.

Sonic temperature, however, is extremely useful for determining small and fast deviations from the mean, required for computing sensible heat flux via eddy covariance calculations.

So, fast temperature from the sonic anemometer is typically used for heat flux covariance computations and for cospectral analyses, while mean slow air temperature from an auxiliary temperature sensor is usually used in all other calculations.

References

van Dijk, A., A. Moene, and H. de Bruin, 2004. The principles of surface flux physics: Theory, practice and description of the ECPack library. Meteorology and Air Quality Group, Wageningen University, Wageningen, The Netherlands, 99 pp.

- Sonic sensible heat flux correction is different from sonic temperature correction
- Heat flux is corrected for humidity fluctuations and momentum flux, affecting the fast data from the anemometer
- Some instruments have the momentum fluctuations portion of the correction applied in their software

$$H = \overline{\rho} C_p \overline{w'T_s'} - \underbrace{\overline{\rho} C_p (0.51 \overline{T_s}\, \overline{w'q'})}_{\text{humidity fluctuations portion}} + \underbrace{\overline{\rho} C_p \frac{\overline{u}\,\overline{T}_s \overline{u'w'}}{63012.50}}_{\text{momentum fluctuations portion}}$$

The sonic sensible heat flux correction (*e.g.*, sonic correction) applies to sensible heat flux measured with sonic anemometers, and compensates for humidity fluctuations and momentum fluxes that affect sonic measurements.

A sonic correction is an additive correction, consisting of humidity fluctuations and momentum fluctuations, combined with sensible heat flux covariance, to produce the final corrected flux value, as shown in the equation above.

Before applying this correction, it is important to refer to the specific sonic anemometer user manual to make sure that the momentum portion of this correction was not previously applied by the manufacturer in the instrument software. The momentum fluctuations portion of the correction is instrument-specific and may not be identical to that shown in the example above.

> It is important to distinguish the sonic heat flux correction from the sonic temperature correction. A sonic temperature correction is a correction of the sonic temperature measurement and is not a flux correction.
>
> However, sonic temperature correction may still be important for flux calculations, especially if the mean air temperature used in the various calculations comes from the sonic measurements.

References

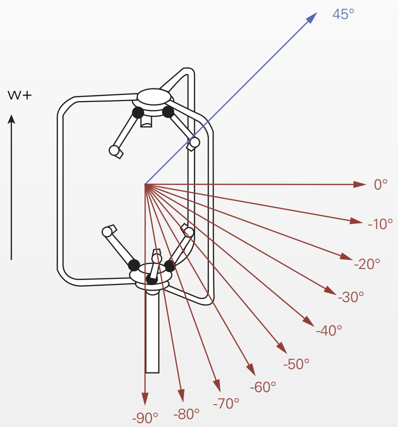
Pages B-1 – B-5 in: CSI Inc., 2004-2006. Open Path Eddy Covariance System Operator's Manual CSAT3, LI-7500, and KH_2O. Logan, Utah, http://www.campbellsci.com/documents/manuals/opecsystem.pdf

Schontanus, P., F. Nieuwstadt, and H. de Bruin, 1983. Temperature measurements with a sonic anemometer and its application to heat and moisture fluxes. Boundary-Layer Meteorology, 26: 81-93

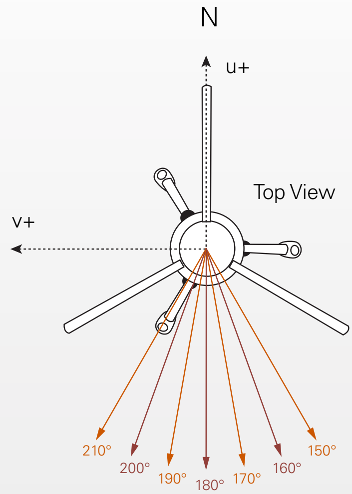
Horst, T., 2012 (Accessed). Corrections to Sensible and Latent Heat Flux Measurements http://www.eol.ucar.edu/instrumentation/sounding/isfs/isff-support-center/how-tos/corrections-to-sensible-and-latent-heat-flux-measurements

Mauder, M., and T. Foken, 2011. Documentation and Instruction Manual of the Eddy Covariance Software Package TK3. http://opus4.kobv.de/opus4-ubbayreuth/frontdoor/index/index/docId/681_

- Angle-of-attack correction compensates for the imperfect response of the anemometer when winds come at steep angles



From Nakai and Shimoyama, 2012



- This correction may be fully or partially applied in some anemometer models, and may also be called "head correction"

The angle-of-attack correction compensates for the imperfect response of an anemometer when winds come at the anemometer at a steep angle.

All sonic anemometer models experience this phenomenon to a varying degree, and may need different corrections.

Some parts of this correction may be applied by manufacturers, while the rest are being developed by the scientific community, and included in modern flux processing programs.

It is important to avoid overcorrecting for the angle of attack if, for example, the manufacturer's firmware correction was activated at the same time as the processing program's angle of attack routine for a specific anemometer model.

In these cases, it is usually best to turn off the manufacturer's correction, which may be partial, and apply a full correction during post processing using programs such as EddyPro.

References

van der Molen, M., J. Gash, and J. Elbers, 2004. Sonic anemometer (co)sine response and flux measurement: II. The effect of introducing an angle of attack dependent calibration. Agricultural and Forest Meteorology, 122: 95-109

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Nakai, T., M. van der Molen, J. Gash, and Y. Kodama, 2006. Correction of sonic anemometer angle of attack errors. Agricultural and Forest Meteorology, 136: 19-30

LI-COR Biosciences,2012. EddyPro 4.0: Help and User's Guide. Lincoln, NE, 208 pp. envsupport.licor.com/help/EddyPro4/Default.htm

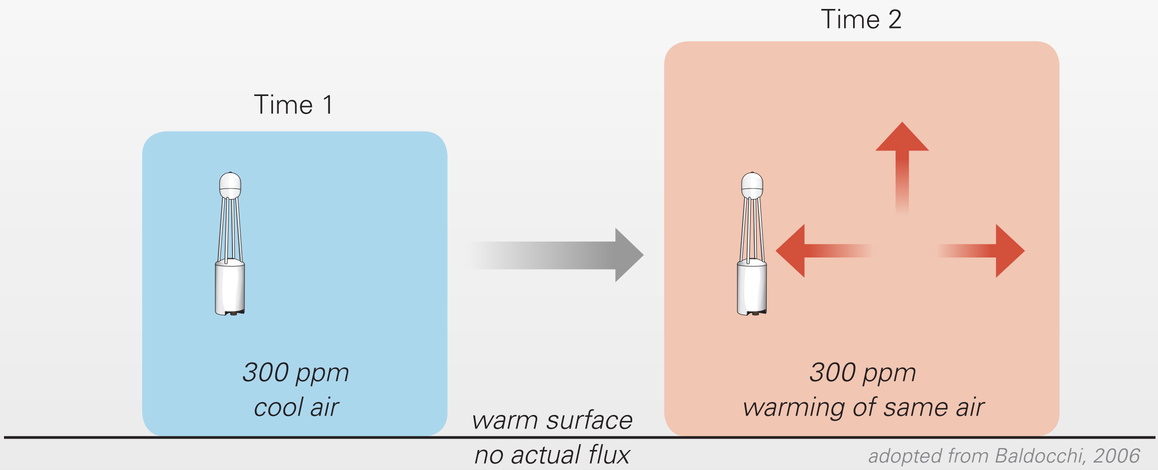
Part Four:

Processing Eddy Covariance Data

Section 4.4

Applying Webb-Pearman-Leuning Terms

- Compensates for the effects of fluctuations of temperature (thermal expansion) and water vapor (dilution) on measured fluctuations in densities of CO_2, H_2O, and other gases
- One way to understand this process is to imagine a surface with actual zero flux and with warming air of constant gas concentration
- As a result of the warming, the instrument measures flux due to volume expansion



The Webb-Pearman-Leuning terms (often referred to as WPL, or "density terms") are used to compensate for fluctuations in the density of CO_2, H_2O, and other gases resulting from fluctuations in gas temperature and water vapor content.

One simple way to visualize this process is to imagine a warm surface that has an actual zero flux and is covered by warming air of constant gas concentration. As a result of the warming, an instrument would measure a flux simply because of the volume expansion.

A more detailed way to visualize WPL is to imagine the process at a high frequency scale, *e.g.* 10 Hz. If a CO_2-inert surface is warm and wet, then high-frequency updrafts in the vertical wind speed, w', would be a little warmer and a little wetter than downdrafts, because of the transport of the heat and water up from the surface into the atmosphere.

For CO_2, then, updrafts would be slightly more thermally expanded and diluted than downdrafts, and as a result, would have a slightly lower CO_2 density than downdrafts. This high-frequency process of lower density updrafts and higher density downdrafts would create an appearance of CO_2 uptake, when there is no actual CO_2 flux, simply because the surface is warm or wet, or both.

Since eddy covariance flux measurements rely on the covariance of changes in vertical wind speed with changes in gas density resulting solely from the ecosystem adding or removing gas from and into the air flow above it (see Part 1, pages 14-15), we want to correct out all other changes in gas density which do not come from these additions or removals. Thus, the thermal and pressure expansions and contractions, and water dilution of the gas of interest have to be corrected.

> It is also important to keep in mind that the WPL correction does not actually correct for any kind of instrument or measurement error, but rather compensates for normal and expected physical processes of thermal expansion and water dilution. Therefore a more appropriate name for the WPL correction is probably WPL terms.

References

Webb, E., G. Pearman, and R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water vapor transfer, Quarterly Journal of Royal Meteorological Society, 106: 85-100

Lee, X., and W. Massman, 2011. A Perspective on Thirty Years of the Webb, Pearman and Leuning Density Corrections. Boundary-Layer Meteorology, 139(1):37-59

$$F_c = \overbrace{\overline{\rho_d}\,\overline{w's'}}^{\substack{\textit{when instrument outputs}\\ \underline{\textit{true}}\textit{ fast dry mole fraction}}} = \overbrace{\underbrace{\underbrace{\overline{w'q_c'}}_{\substack{\text{Covariance}\\ \text{with fast density}}}}_{\text{raw flux}} + \underbrace{\underbrace{\mu \frac{\overline{E}}{\overline{\rho_d}} \frac{\overline{q_c}}{1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}}}_{\substack{\text{Water}\\ \text{dilution term}}} + \underbrace{\frac{H}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}}}_{\substack{\text{Thermal}\\ \text{expansion term}}}}_{\text{WPL density terms}} - \underbrace{\left(1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}\right) \frac{\overline{w'P'}}{\overline{P}}\,\overline{q_c}}_{\substack{\text{Pressure expansion term}\\ \text{(usually neglected)}}}}^{\substack{\textit{when instrument outputs fast density}\\ \textit{(typical open-path case)}}}$$

F_c – final corrected flux
E – evapotranspiration
H – sensible heat flux
P – air pressure

q_c – mean CO_2 density
ρ_d – dry air density
ρ_v – water vapor density
ρ – total air density

C_p – air specific heat
T_a – air temperature in K
μ – ratio of mol. masses of air to water, μ=1.6077

Optical gas analyzers fundamentally measure the amount of gas in a known volume (*e.g.*, density), as discussed in Section 2.2. Typically these instruments output fast density values for flux computation, and slow mole fraction values for calibration purposes (converting density to mole fraction using slow temperature and pressure), or in some cases, slow dry mole fraction values (converting density to dry mole fraction using fast water vapor, and slow temperature and pressure).

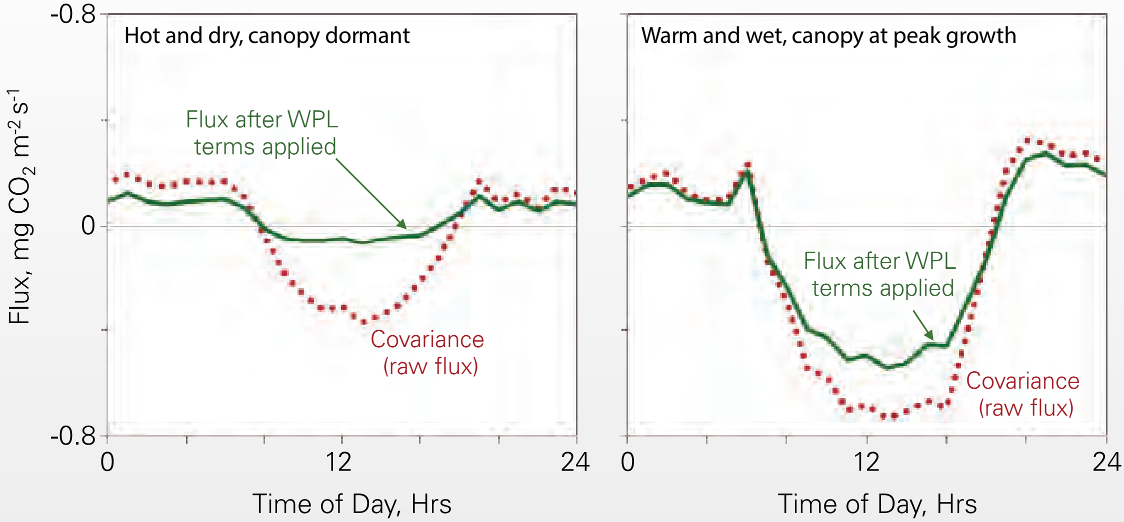
Some newer instruments (*e.g.*, LI-7200) can also output fast dry mole fraction using fast temperature, pressure and water vapor content of the gas, and convert native gas density to dry mole fraction at a fast rate in real time. The form of the equation used for the flux computation depends heavily on the outputs provided by the specific instrument, and is discussed later in this section.

The classical form of the WPL equation, often referred to as WPL-80 (Webb, Pearman and Leuning, 1980) consists of two main terms; a temperature-related expansion and contraction term, and a water dilution term. Sometimes a pressure-related expansion and contraction term, neglected in WPL-80, can also be computed, but is often assumed negligible, especially for hourly fluxes. Although the pressure effect is routinely ignored in the classical formulation, it is, on average, a one-way process that can introduce a small bias. This effect may become significant during high winds, at high elevations, in complex terrains, and over long integration periods in ecosystems or areas with very small flux rates.

The WPL terms apply to CO_2, H_2O, CH_4 or any other trace gas flux when computed using fast density output from a gas analyzer.

For instruments than can output fast dry mole fraction, the fundamental flux equation can be used, and WPL density terms are not required.

However, it is important to note that fast dry mole fraction calculations in these instruments have to be truly fast, and have to utilize fast temperature, pressure and water vapor of the sampled gas synchronously with the gas density.



- WPL terms are quite important for calculating correct final flux values in nearly all situations, and must be coded and applied correctly

The relative importance of WPL terms in relation to the raw flux changes from ecosystem to ecosystem, and throughout the year.

The two examples above show actual field data for CO_2 flux measured over ryegrass. On a hot and dry day in early spring, with a dormant canopy, sensible heat flux was large and positive, and CO_2 flux was very small, near zero.

Thus, the raw CO_2 flux was dominated by the thermal expansion-contraction term and was implying strong photosynthesis at midday (negative flux). However, after applying WPL terms, CO_2 flux neared zero.

Nighttime soil and canopy respiration calculations were also affected by WPL terms, primarily due to small negative sensible heat fluxes.

On a warm and wet day in summer, with a rapidly growing canopy, photosynthesis was strong and CO_2 flux was large. Thus, raw CO_2 flux was not dominated by WPL terms, which were still important, yet not overwhelming.

These are typical examples for canopy-covered terrains. The WPL terms are relatively smaller during the growing season with large raw fluxes, and relatively larger during the off-season, when fluxes are small and density terms can reach values several times the actual flux.

In all cases, WPL terms are important and must be applied correctly. If writing your own code for applying WPL terms, please note the important differences between equations 24 and 44 in the original paper on WPL (Webb *et al.*, 1980). The first equation is used for covariances, while the latter is used for the fluxes.

References

Webb, E., G. Pearman, and R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. Quarterly Journal of Royal Meteorological Society, 106: 85-100

$$F_c = \overline{\rho_d}\,\overline{w's'} = \overline{w'q_c'} + \mu \frac{E}{\overline{\rho_d}} \frac{\overline{q_c}}{1+\mu \dfrac{\overline{\rho_v}}{\overline{\rho_d}}} + \frac{H}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}} - \overbrace{\cancel{\left(1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}\right) \frac{\overline{w'P'}}{\overline{P}}\, \overline{q_c}}}^{\substack{\textit{usually neglected;} \\ \textit{very difficult to measure} \\ \textit{in the open air flow}}}$$

$$F_c = \overline{w'q_c'} + \mu \frac{E}{\overline{\rho_d}} \frac{\overline{q_c}}{1+\mu \dfrac{\overline{\rho_v}}{\overline{\rho_d}}} + \frac{H}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}}$$

- Typical WPL equation for open-path analyzer: *H* comes from the sonic anemometer

Open-path analyzers usually output gas density, and require WPL terms to obtain correct final flux values.

Some instruments have fast water vapor measurements in addition to the gas of interest, and can correct gas density for water dilution in real time. In these cases, fluxes will no longer require a water dilution term (middle term in the last equation above), but the instrument still would not have fast temperature integrated over the measurement path, and fluxes will have to use the thermal expansion-contraction term.

Fast pressure is extraordinarily difficult to measure in open air because flow distortion from the measurement itself significantly affects the balance between static and dynamic pressure components. Thus, considering the typically small contribution of the pressure term to the flux, this term is usually assumed negligible.

References

Webb, E., G. Pearman, and R. Leuning, 1980. Correction of flux measurements for density effects due to heat and water vapor transfer, Quart Journal of Royal Met Society, 106: 85-100

Lee, X., and W. Massman, 2011. A Perspective on Thirty Years of the Webb, Pearman and Leuning Density Corrections. Boundary-Layer Meteorology, 139(1): 37-59

Leuning and Massman in Chapters 6 and 7 (pp. 119-158) of the Lee, X., W. Massman, and B. Law (Eds.), 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, The Netherlands, 252 pp.

Ham, J. and J. Heilman, 2003. Experimental Test of Density and Energy-Balance Corrections on Carbon Dioxide Flux as Measured Using Open-Path Eddy Covariance. Agronomy Journal, 95(6): 1393-1403

Zhang, J., X. Lee, G. Songa, and S. Hana, 2011. Pressure correction to the long-term measurement of carbon dioxide flux. Agricultural and Forest Meteorology, 151: 70–77

$$F_c = \overline{\rho_d}\,\overline{w's'} = \overline{w'q_c'} + \mu\frac{E}{\overline{\rho_d}}\frac{\overline{q_c}}{1+\mu\frac{\overline{\rho_v}}{\overline{\rho_d}}} + \overbrace{\cancel{\frac{H}{\overline{\rho C_p}}\frac{\overline{q_c}}{\overline{T_a}}}}^{\substack{\text{usually neglected;}\\ \text{assumed unimportant}\\ \text{after long tube}}} \overbrace{\cancel{-\left(1+\mu\frac{\overline{\rho_v}}{\overline{\rho_d}}\right)\frac{\overline{w'P'}}{\overline{P}}\overline{q_c}}}^{\substack{\text{usually neglected;}\\ \text{pressure-controlled or}\\ \text{assumed unimportant}}}$$

$$\Downarrow$$

$$\boxed{F_c = \overline{w'q_c'} + \mu\frac{E}{\overline{\rho_d}}\frac{\overline{q_c}}{1+\mu\frac{\overline{\rho_v}}{\overline{\rho_d}}}}$$

- Typical WPL equation for closed-path analyzer with long intake tube when water vapor measurements are not used to convert gas density into mole fraction

Closed-path measurements use long intake tubes, which attenuate a significant amount of the fast fluctuations of air temperature affecting measured gas density. At the same time, slow temperature of the cell block is usually measured and can approximate mean gas temperature in the cell. Therefore, the thermal expansion-contraction term is typically not required.

Many closed-path instruments output fast water vapor measurements in addition to the gas density. If these measurements can be used to correct the gas density for dilution on-the-fly, the water dilution term is no longer needed (right term in the last equation above). When such on-the-fly conversion is not done, the classical equation without the thermal expansion-contraction term can be used, as shown in the last equation above.

The pressure term may or may not be important in closed-path analyzers, depending on the pressure control and pressure measurements made in the cell. With a multitude of closed-path analyzers available for gas flux measurements, handling the pressure term is instrument-specific.

If the instrument system controls cell pressure in terms of both mean magnitude and fast fluctuations, the pressure term is not required for flux calculations. If the instrument does not control the pressure but rather measures it at a fast rate, gas density output may be corrected on-the-fly, or the pressure term may be computed during post-processing. If the instrument neither controls nor measures fast pressure, the contribution is usually assumed negligible.

A special case exists for instruments that do not measure fast water vapor in the closed cell. In these cases, fast gas density is still diluted due to fast water vapor fluctuations, but there is no measure of this process inside the cell. One approach to solve this is to dry the air with a Nafion-type dryer. This will reduce system frequency response, but will remove most of the water vapor from the sampled gas.

> When computing density terms for closed-path flux measurements, parameters for the WPL equation (*e.g.*, e' or ρ_v' for E, T' for H, P', *etc.*) should come from within the closed sampling cell.
>
> If a closed-path instrument works at significantly reduced pressure or at temperatures (in K) significantly different from ambient, and when density outputs were not brought to mean ambient temperature and pressure, or were not converted to dry mole fraction, further normalization may be required using $(P_{ambient}/P_{cell})x(T_{cell}/T_{ambient})$ as a multiplier for F_c following Leuning and Moncrieff (1990).

$$\boxed{F_c = \overbrace{\overline{\rho_d}\,\overline{w's'}}^{\text{analyzer can output true fast dry mole fraction; no density terms needed}} = \overbrace{\overline{w'q_c'} + \mu \frac{E}{\overline{\rho_d}} \frac{\overline{q_c}}{1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}} + \frac{H}{\overline{\rho} C_p} \frac{\overline{q_c}}{\overline{T_a}} - \left(1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}\right) \frac{\overline{w'P'}}{\overline{P}} \overline{q_c}}^{\text{no longer needed}}}$$

$$\boxed{F_c = \overline{\rho_d}\,\overline{w's'}}$$

- Typical equation for enclosed analyzer with fast temperature, water vapor and pressure measurements in the cell, synchronized with fast gas density
- Also will work for a closed-path analyzer with long intake tube and fast water vapor and pressure measurements in the cell, synchronized with fast gas density

WPL density terms are not required in some instruments, such as the LI-7200, that are capable of outputting true dry mole fractions at high speed.

When these output units are used for computing gas flux, thermal expansion and contraction, water dilution and pressure-related expansion and contraction of the sampled air have already been accounted for in the fast conversion from density to dry mole fraction, and related assumptions are no longer required.

In addition, long intake tubes are no longer needed to attenuate fast temperature fluctuations, which allows one to take advantage of short tubes and increased system frequency response.

However, in such an approach it is critical that the instrument design allows temperature, water vapor and pressure to be measured at the exact same time as gas density. Section 4.7 covers these types of measurements and their requirements in greater detail.

References

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399

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Furtaw M., R. Eckles, G. Burba, D. McDermitt, J. Welles, 2012. Gas Analyzer. Patent: US 8,154,714

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Part Four:

Processing Eddy Covariance Data

Section 4.5

WPL and Spectroscopic Corrections

- When eddy covariance flux is computed, fast changes in gas density are correlated with fast changes in vertical wind speed
- Changes in gas density occur due to the gas flux itself, due to thermal and pressure-related expansion and contraction of the air, and due to water vapor dilution
- These processes are described by the Ideal Gas Law and by the Law of Partial Pressures, are often called *density effects*, and are corrected using WPL terms
- When gas density is measured by laser spectroscopy, there are also *spectroscopic effects* affecting measured gas density
- Spectroscopic effects are related to changes in the shape of the absorption line due to the changes in gas temperature, pressure and water vapor
- These effects are different from the Ideal Gas Law effects, and from the effects of the Law of Partial Pressures

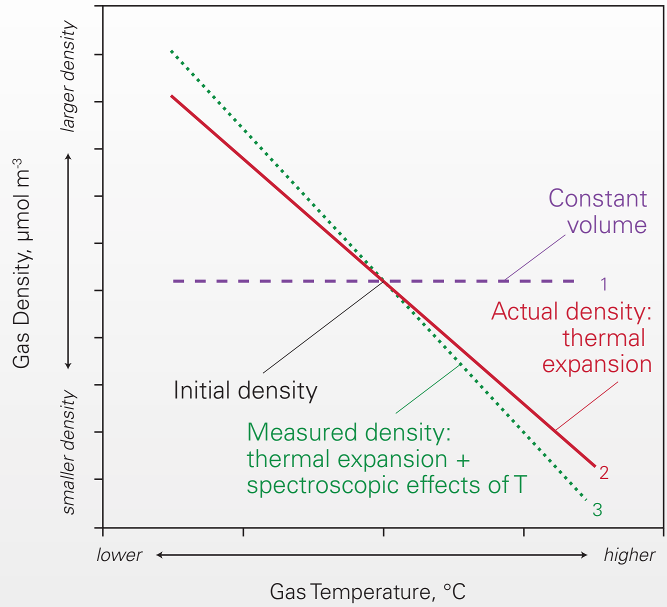
In recent years, the use of laser technologies for fast gas measurements has led to the development of a number of laser-based gas analyzers for eddy covariance flux measurements. Depending on the specific design and technology, some of these devices may need an additional flux correction due to the effects of temperature, pressure and water vapor on the narrow absorption band, or a single absorption line, used for gas sensing in such devices. The key aspects of these relatively new and uncommon flux corrections are briefly described on the following few pages.

As discussed earlier, when eddy covariance flux is computed, fast changes in gas density are correlated with fast changes in vertical wind speed. Measured changes in gas density occur due to the gas flux itself, thermal expansion and contraction of the air, water vapor dilution, and pressure-related expansion and contraction.

These processes are described by the Ideal Gas Law and by the Law of Partial Pressures, and are often called density effects. The gas flux is usually corrected for density effects using widely accepted Webb-Pearman-Leuning terms.

When gas density is measured by laser spectroscopy (*e.g.*, narrow-band or single line laser instruments, using WMS, ICOS, CRDS, and other technologies), there are also spectroscopic effects affecting measured values of gas density, in addition to the density effects.

Spectroscopic effects are related to changes in the shape of the absorption line of the gas resulting from the changes in gas temperature, water vapor content, and pressure. These effects are individual for each specific absorption line, known from spectroscopy laws and via verification *vs.* HITRAN database. These spectroscopic effects are different from the Ideal Gas Law effects, such as temperature and pressure expansion-contraction, and different from the effects of the Law of Partial Pressures, such as water dilution.



- Concept: the spectroscopic effect of change in temperature adds to the thermal expansion effect of change in temperature, when gas is measured by a laser

In a laser-based device, fluctuations in sampled gas temperature, water vapor content, and pressure can lead to changes in measured gas density due to:

(1) gas density effects as per Ideal Gas Law and Law of Partial Pressures;

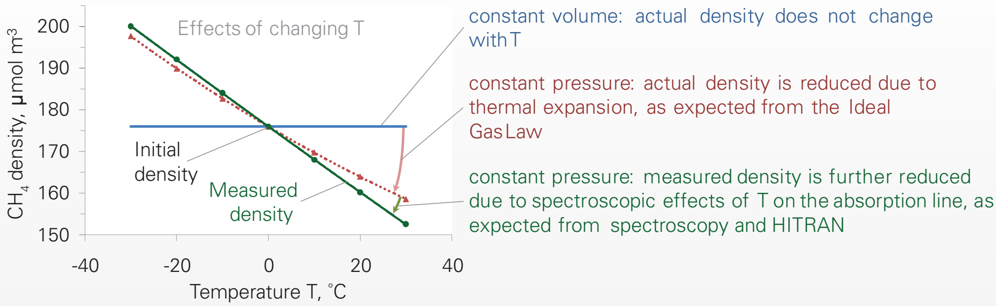
(2) spectroscopic effects as per spectroscopy laws.

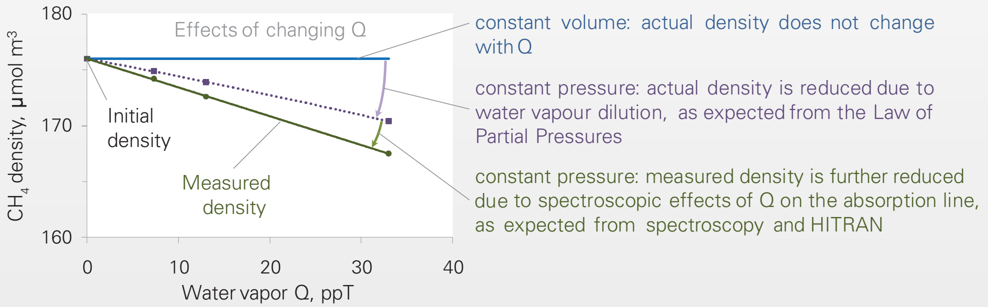
In any open-path, closed-path or enclosed laser-based instrument where sample temperature is not fully attenuated, and pressure and water content are not controlled, the spectroscopic effect is important for obtaining correct measurements of gas density and gas flux.

For closed-path gas analyzers, the majority of the density effects and spectroscopic effects can be reduced or eliminated, when: (i) intake tube is sufficiently long, (ii) air sample is dry, and (iii) pressure fluctuations are negligible. This way the fast fluctuations in temperature are strongly attenuated, fast fluctuations in water vapor are removed, and pressure fluctuations are neglected. Rather than drying the air sample, water vapor can also be measured at high speed inside the cell, and can be used to correct for both dilution and spectroscopic effects of water vapor.

With measurements of gas density taken at slow rates, the spectroscopic effects can be corrected in real time using measurements of mean temperature, water vapor and pressure in or near the sampling cell.

However, when gas density is measured at a fast rate, especially with an open-path instrument, it may be difficult to correct for spectroscopic effects in real time, as it requires accurate and precise measurements of fast gas temperature, pressure, and water content integrated over the entire sampling cell volume, and recorded at the exact moment when the absorption is measured.





In these cases, there is still a way to reliably relate spectroscopic effects to density effects, and then to use the WPL concept to apply both spectroscopic and density effects to flux data based on half-hourly, hourly, or other averaged products.

This relation is possible because the spectroscopic effects are known from theory and are verifiable in laboratory experiments, although they are specific to each absorption line of each gas and to specific execution of a particular measurement technique.

The shape and strength of these effects can be deduced from fundamental spectroscopic information using HITRAN database tables (Rothman *et al.*, 2009), and verified using calibration of a specific laser-based device over a range of temperatures, sample pressures and water vapor contents.

With this knowledge, one can establish a reliable relationship between density effects (dotted red and purple lines in plots above) and spectroscopic effects (solid green lines in plots above) of changes in gas temperature, water vapor content, and pressure respectively, and can then use this relationship to incorporate the spectroscopic effects into the WPL equation.

Spectroscopic corrections to eddy covariance fluxes are quite recent, so it is useful to look at a specific example of how the spectroscopic effects can be incorporated into flux processing.

A fast open-path laser-based CH_4 gas analyzer, the LI-7700, is used here as an example. The illustrations above present actual laboratory data from this instrument.

References

Rothman, L., I. Gordon, A. Barbe, D. Benner, P. Bernath, *et al.*, 2009. The HITRAN 2008 molecular spectroscopic database. Journal of Quantitative Spectroscopy & Radiative Transfer, 110: 533–572

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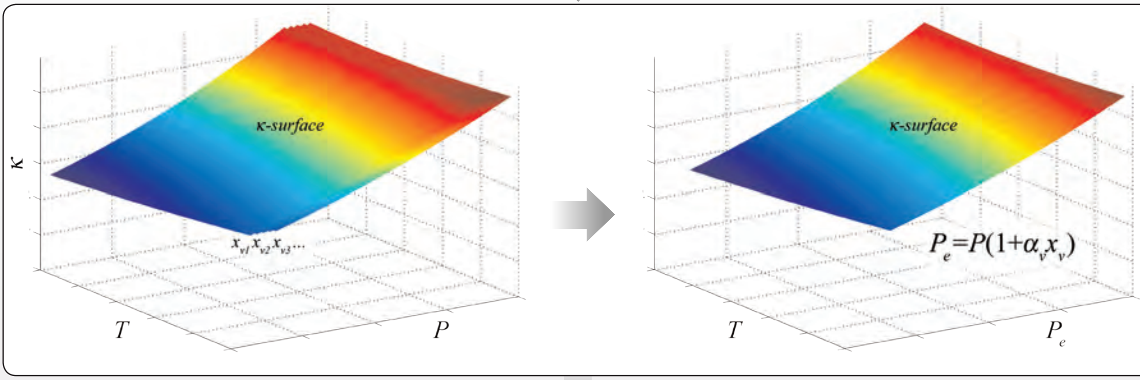
Burba G., D. McDermitt, A. Komissarov, L. Xu, and B. Riensche, 2010. Method and Apparatus for Determining Gas Flux. Patent: US 7,953,558

$$q_c = q_{cm}\kappa$$



$$\kappa \approx \bar{\kappa}(\bar{T}, \bar{P_e}) + \kappa_T T' + \kappa_{P_e} P_e' + \ldots$$

In simple terms, if it is known that at a given temperature the spectroscopic effect of the change in temperature is 30% of the density effect of the change in temperature (*e.g.*, thermal expansion-contraction), then one can correct for both effects by multiplying the thermal expansion term in the WPL equation by 1.3.

Similarly, if it is known that the spectroscopic effect of water vapor is 40% of the density effect of water vapor (*e.g.*, dilution), one can correct for both effects by multiplying the dilution term in the WPL equation by 1.4.

The approach looks uncomplicated, and in principle it is. However, over a wide range of environmental conditions the mathematical relationship between spectroscopic and density effects is neither linear nor simple, and at each point this relationship depends on interrelated effects of temperature, water vapor, and pressure.

To address this complexity, a function κ can be used to describe the relationship between actual gas density (q_c) and gas density measured with a laser device (q_{cm}) such that $q_c=q_{cm}\ \kappa$. Over the entire range of environmental conditions, the κ value can be represented by a set of 3-D surfaces, with each surface depending on temperature (T) and pressure (P) at each water vapor content ($x_{v1}, x_{v2}, x_{v3}, \ldots$), as shown in the leftmost plot above.

It is difficult to work with such a family of surfaces, and to simplify the situation, the concept of equivalent pressure can be used to combine water vapor effects (expressed as an equivalent pressure by water vapor) with air pressure effects into a pressure parameter (P_e). Then a single, more manageable 3-D surface is formed where κ depends on T and P_e, as shown in the rightmost illustration above.

The κ value is now a function of T and P_e, and can be incorporated into the WPL equation using $q_{cm}\kappa$ instead of q_c.

References

LI-COR Biosciences, 2010. LI-7700 Open-path CH_4 Analyzer Instruction Manual. Publication No.984-10751, 170 pp.

$$F_c = \overline{w'q_c'} + \mu \frac{E}{\overline{\rho_d}} \frac{\overline{q_c}}{1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}} + \frac{H}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}}$$

$$F_c = A\left(\overline{w'q_{cm}'} + B\mu \frac{E}{\overline{\rho_d}} \frac{\overline{q_{cm}}}{1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}} + C\frac{H}{\overline{\rho C_p}} \frac{\overline{q_{cm}}}{\overline{T_a}}\right)$$

where $A = \overline{\kappa}$ $\quad B = \left[1+(1-1.46\overline{x_v})\alpha_v \overline{P_e}\frac{\kappa_{P_e}}{\overline{\kappa}}\right]$ $\quad C = \left[1+(1-\overline{x_v})\overline{T}\frac{\kappa_T}{\overline{\kappa}} + \overline{x_v}(B-1)\right]$

In this fashion the relationship is established between spectroscopic and density effects over a wide range of conditions (*e.g.*, *κ-surface*), and is used to correct for both spectroscopic and density effects via the WPL approach.

The derivation itself is mathematically complicated and presented in detail in the references below, but the results are quite simple: the WPL equation is modified with three multipliers to incorporate the spectroscopic effects of temperature, water vapor, and pressure on the final flux value, in addition to the density effects.

These multipliers depend on the form of the function κ at a given temperature, water vapor and pressure, and can be determined from look-up tables or closely approximated by a polynomial.

For an LI-7700 at normal conditions, typical values for A range from 0.96 to 0.99, B ranges from 1.41 to 1.43, and C ranges from 1.32 to 1.34. These may be quite different for other instruments and technologies.

Please note that no empiricism was needed in establishing the function κ (except the broadening value of 1.46), and in its propagation through further computations. The form of κ was established using HITRAN and verified in lab experiments.

References

LI-COR Biosciences, 2010. LI-7700 Open-path CH_4 Analyzer Instruction Manual. Publication No.984-10751, 170 pp.

Burba G., D. McDermitt, A. Komissarov, L. Xu, and B. Rienche, 2010. Method and Apparatus for Determining Gas Flux. Patent: US 7,953,558

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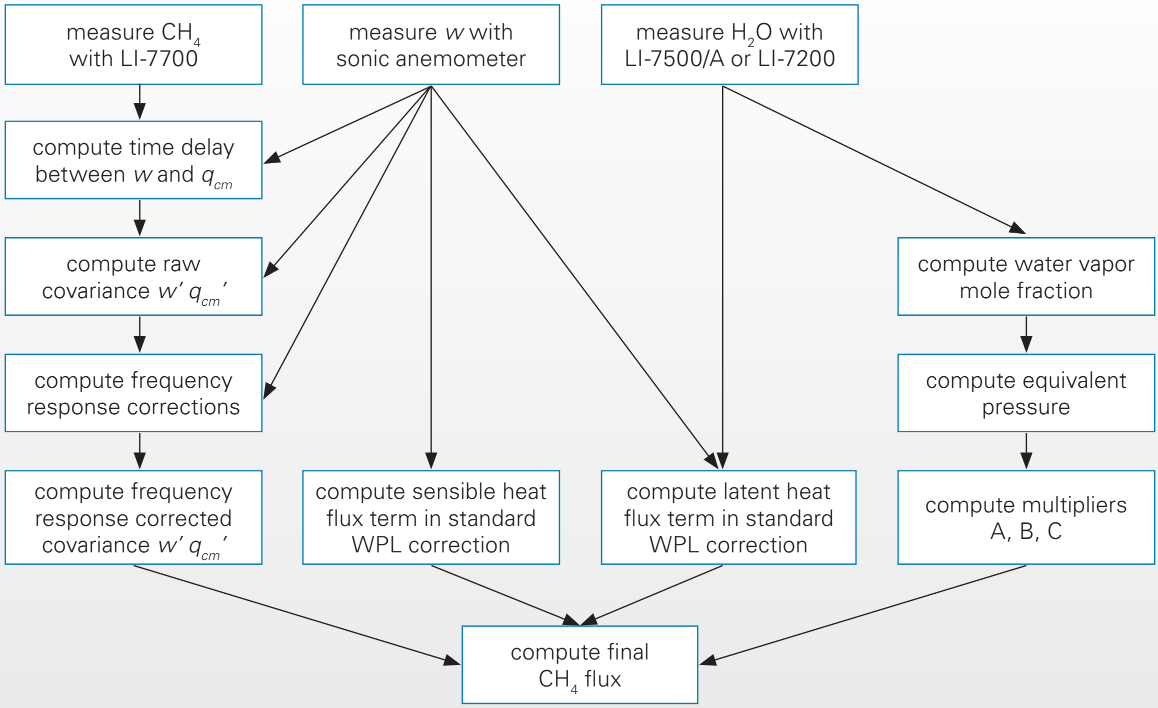
Burba G., D. McDermitt, A. Komissarov, L. Xu, B. Riensche, 2012. Method and Apparatus for Determining Gas Flux. Patent pending



Modern flux processing programs recently started to incorporate spectroscopic corrections into their menu items and processing routines, so special effort may not be required when using these programs.

If writing your own code, it is advisable to program the correction into the custom code, then verify the coding by hand-calculations for one or two periods, and then use this code in all further computations of final CH_4 fluxes.

The complex sequence of steps then becomes part of the flux processing code, and additional efforts or time investments are not required.

The example above presents an algorithm for programming the spectroscopic correction for the LI-7700 open-path CH_4 gas analyzer.

It is also important to note that fast CH_4 density in this example is affected by fast changes in water vapor flux (E) and sensible heat flux (*H*) as though water vapor and temperature were measured in the same path with CH_4.

So some adjustment may be needed for attenuation of E and *H* if they were measured by instruments with significantly different sampling paths, or if the intake tube was used to measure water vapor flux.

When using NDIR technology, the spectroscopic corrections are not applied to WPL terms during flux calculations, because related effects (*e.g.*, line broadening) are usually corrected on-board the instruments.

Part Four:

Processing Eddy Covariance Data

Section 4.6

WPL and Open-path Instrument Surface Heating

- Instrument surface heating correction compensates for the effects of temperature differences between the open cell surfaces and ambient air
- This correction is sometimes applied to data from older open-path instrument models when data were collected in cold conditions, and when fluxes were small
- In some new open-path instruments, steps are taken to significantly reduce and eliminate surface heating contribution to the measured fluxes

The instrument surface heating correction compensates the computed flux (or measured fast density) for the effects of temperature differences that may occur between a cell surface of an open-path instrument and ambient air, under certain conditions.

This correction is sometimes applied to data from older open-path instruments (for example, LI-7500 CO_2/H_2O analyzer, *etc.*), when data were collected in cold conditions, and when fluxes were small. Certain optical components in such instruments were controlled at a warm temperature setpoints (about +30 °C or more), so in cold environments, temperature gradients could develop between the instrument surfaces and the air, causing small hourly biases in heat and gas fluxes.

While heating or cooling of the surfaces around a sampling cell will occur in any instrument, closed-path and enclosed designs do not require such corrections, because gas temperature in the cell is generally known. Fast temperature fluctuations of the air entering the cell are either attenuated in long intake tubes or measured at a fast rate.

In newer open-path instruments, steps are taken to prevent surface heating in cold environments from contributing to the flux beyond negligible levels. For example, the effect of surface heating was substantially reduced or eliminated in two newer open-path designs (*e.g.*, LI-7500A and LI-7700). In the LI-7500A CO_2/H_2O analyzer, 5-20 times reduction in surface heating was achieved by using a lower component temperature setpoint that can be activated in cold environments. In the LI-7700 CH_4 analyzer, the size and geometric design of the instrument, as well as the position of temperature controlled components, prevented instrument surfaces from contributing detectable amounts of heat into the measurement path even when mirrors were heated by 17 °C above ambient (McDermitt *et al.*, 2011).

In the next few pages, a brief review of the factors affecting open-path surface heating will be provided, along with fundamental and practical equations that account for it. Suggested reading and references are also provided to describe a choice of methods available to correct old data, or new data collected with older models.

Detailed step-by-step methodology for deciding if the heating correction is needed and what method is best for a given dataset is beyond the scope of this textbook. Please consult the provided references or contact LI-COR Scientific and Technical Support (envsupport@licor.com) for detailed documentation on this subject.

Regular open-path WPL equation

$$F_c = \overline{w'q'_c} + \mu \frac{\boxed{E_{ambient}}}{\overline{\rho_d}} \frac{\overline{q_c}}{1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}} + \frac{\boxed{H_{ambient}}}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}}$$

Fundamental equation for surface heating

$$F_c = \overline{w'q'_c} + \underbrace{\mu \frac{\boxed{E_{inpath}}}{\overline{\rho_d}} \frac{\overline{q_c}}{1+\mu \frac{\overline{\rho_v}}{\overline{\rho_d}}}}_{\text{water dilution term inside the heated or cooled open path}} + \underbrace{\frac{\boxed{H_{inpath}}}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}}}_{\text{thermal expansion term inside the heated or cooled open path } (H_{inpath} = H_{ambient} + H_{added})}$$

In all gas analyzers with the open-path design, fast air temperature fluctuations are not attenuated, and have a strong effect on the measured fast gas density as per the Ideal Gas Law. Similarly, fast water vapor fluctuations have a significant dilution effect on the measured fast gas density as per the Law of Partial Pressures. Therefore, fluxes measured with open-path instruments must include WPL density terms that account for thermal expansion and water vapor dilution (Section 4.4).

Traditionally, the sensible heat flux (H) used in the open-path thermal expansion term is measured outside the path of the gas analyzer by sonic anemometry-thermometry, or with a fine-wire thermocouple installed near the sonic anemometer path.

In cold conditions, warm instrument surfaces around the gas analyzer open path may heat the air in the path. Then there may be non-negligible differences (H_{added}) between sensible heat fluxes measured inside the open path of the analyzer (H_{inpath}) and that measured in the ambient air by a sonic anemometer ($H_{ambient}$).

In such cases, the sensible heat flux inside the optical path ($H_{inpath} = H_{ambient} + H_{added}$) is the one affecting measured gas and water vapor density, and should be used in both WPL density terms instead of that measured in ambient air by the sonic anemometer. This leads to a very simple fundamental equation for instrument surface heating, as shown in the second equation above.

Thus, the general physical basis of the surface heating concept is the following: if the instrument surface temperature is substantially different from ambient temperature, it can lead to temperatures and sensible heat fluxes inside the path being different from those in the ambient air, affecting CO_2, H_2O, and other gas densities measured in the path.

References

More details are provided in pages 137-159 of: Burba, G., and D. Anderson, 2010. A Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and Workflow Examples for Scientific and Industrial Applications. LI-COR, Lincoln, USA, 211 pp.

- When H_{inpath} is not available, H_{added} can be used to assess the heating effect, and the fundamental equation can be rewritten as follows:

$$F_{cnew} = \overline{w'q_c'} + \mu \frac{E_{inpath}}{\rho_d} \frac{\overline{q_c}}{1 + \mu \frac{\overline{\rho_v}}{\overline{\rho_d}}} + \frac{H_{ambient} + H_{added}}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}}$$

$$E_{inpath} = (1 + \mu \frac{\overline{\rho_v}}{\overline{\rho_d}})E + (1 + \mu \frac{\overline{\rho_v}}{\overline{\rho_d}}) \frac{H_{ambient} + H_{added}}{\overline{\rho C_p}} \frac{\overline{\rho_v}}{\overline{T_a}}$$

$$F_{cnew} = \underbrace{F_{ct}}_{\textit{Traditionally corrected flux}} + \underbrace{\frac{H_{added}}{\overline{\rho C_p}} \frac{\overline{q_c}}{\overline{T_a}} (1 + \mu \frac{\overline{\rho_v}}{\overline{\rho_d}})}_{\textit{Correction due to added surface heating}}$$

When a data set in question does not have sensible heat flux measured directly in (and integrated over) the open path of the gas analyzer, H_{inpath}, but rather has it measured by a sonic anemometer, $H_{ambient}$, then the added heat, H_{added}, can be estimated and added to the WPL density terms. This is, of course, only if there is reason to believe that H_{inpath} is substantially different from $H_{ambient}$.

In such cases, traditionally computed gas flux, F_{ct}, can be recalculated into a new flux, F_{cnew}, corrected for instrument surface heating, using the equation shown above. This correction adjusts the sensible heat flux portion of the WPL density terms for the small amount of heat added into the open path by instrument surfaces.

When the heating correction is deemed necessary, knowing H_{inpath} for a fundamental equation, or H_{added} for the supplementary equation above, is required.

In other words, in the equations above we have separated the flux calculation into a term computed with the traditional WPL formulation (F_{ct}) and a term involving H_{added}. The correction can proceed by either measuring H_{inpath}, as on the previous page, or estimating H_{added}. Methods for measuring or estimating H_{inpath} and H_{added} are discussed below.

References

Burba, G., D. McDermitt, A. Grelle, D. Anderson, and L. Xu, 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology, 14(8): 1854-1876

Grelle, A., and G. Burba, 2007. Fine-wire thermometer to correct CO_2 fluxes by open-path analyzers for artificial density fluctuations. Agricultural and Forest Meteorology, 147: 48–57

Jarvi, L., I. Mammarella, W. Eugster, A. Ibrom, E. Siivola, *et al.*, 2009. Comparison of net CO_2 fluxes measured with open- and closed-path infrared gas analyzers in an urban complex environment. Boreal Environment Research, ISSN 1239-6095 (14): 14 pp.

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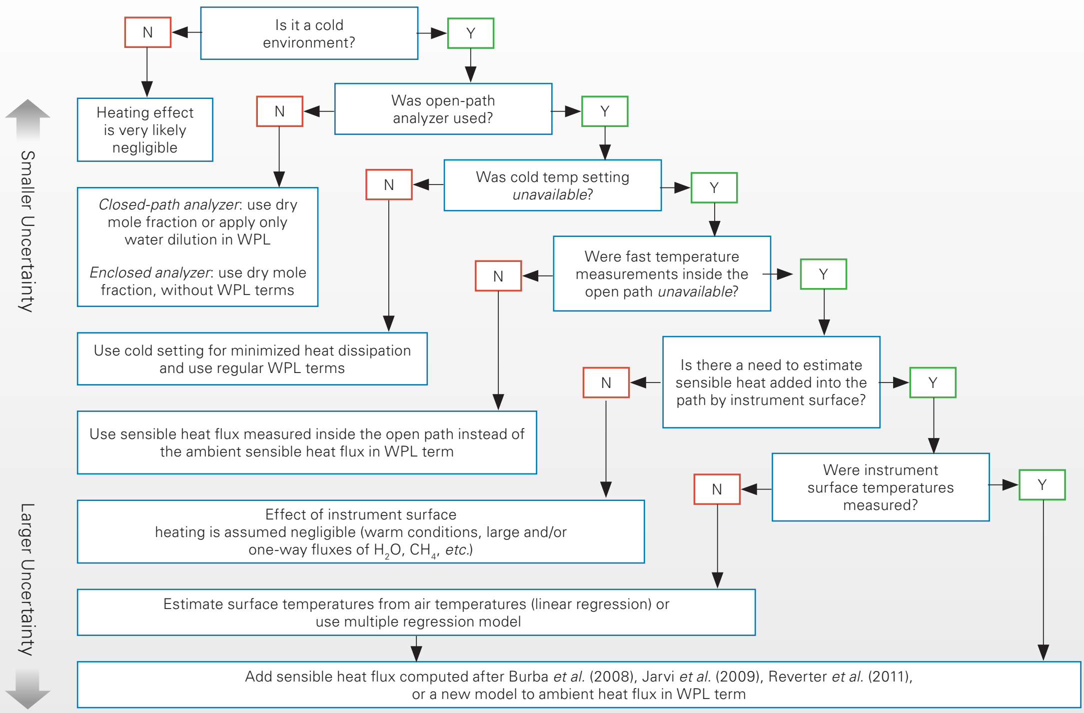


The diagram above is a decision tree to help determine if the correction is needed, and what would be the best method to correct a specific set of open-path CO_2 flux data based on the auxiliary measurements available. It is important to note that the hourly surface heating correction is quite small, even in cold environments (typically, an order of magnitude smaller than the WPL correction, and on the same order as the open-path frequency response correction), and is usually negligible in warmer conditions. So, it should not be confused with other important contributing factors and corrections.

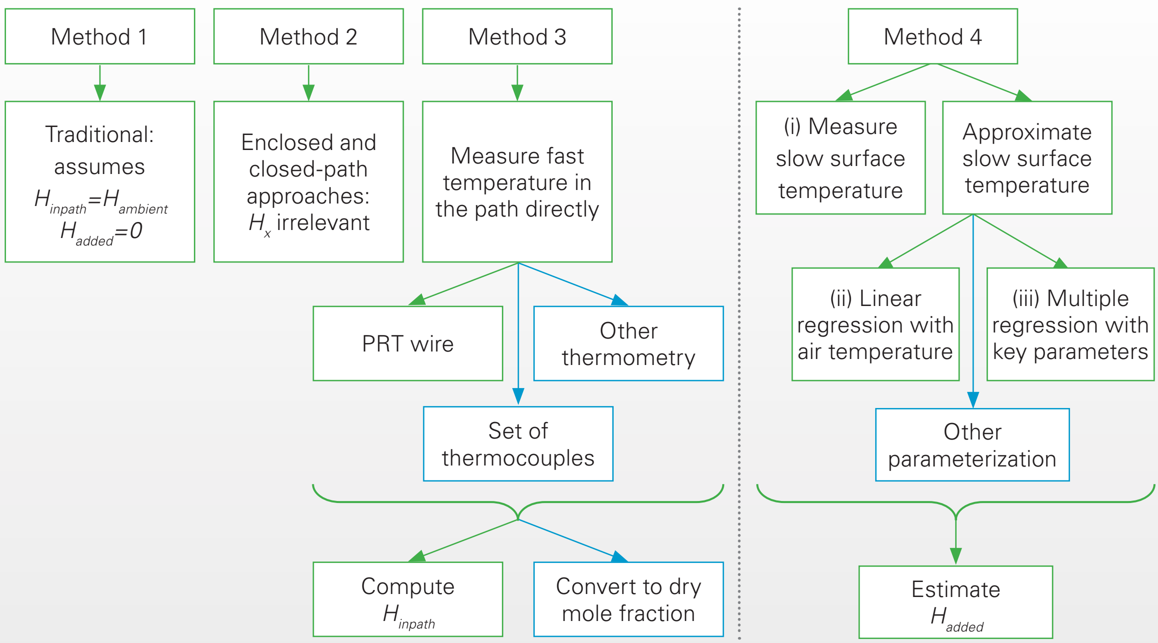
Direct measurements of surface heating in the open path of an older model LI-7500 gas analyzer (Grelle and Burba, 2007; Massman and Frank, 2009) obtained H_{added} of about 15-20 W m^{-2} in cold conditions, suggesting a fairly small added heat correction term, on the order of 0.03-0.04 mg CO_2 m^{-2} s^{-1} or less. Field measurements of differences between open-path and closed-path CO_2 fluxes were on average also on the order of 0.03 mg m^{-2} s^{-1} or less, corroborating the H_{added} measurement results (Burba *et al.*, 2008).

The 24-hour averaged heating effects are expected to be on the order of 0.01 mg CO_2 m^{-2} s^{-1} or less at 40 °C, and 0.05 mg CO_2 m^{-2} s^{-1} or less at -40 °C. These small biases may not be noticeable on hourly or 24-hour time scales but may combine to become important when a CO_2 budget is constructed over long periods of cold conditions, or over a season when the integrated annual CO_2 budget may be near zero.

Unlike the CO_2 exchange, the exchanges of H_2O, CH_4, and other gases do not usually have a chronological sequence of emissions and uptakes of similar magnitudes and opposite signs, that lead to integrated sums near zero. Therefore, the percentage-error in long-term water or methane budgets is typically similar to the percentage-error incurred during hourly measurements of water vapor or methane flux. This is a small number and is usually within the error bars of the measurements.

Exceptions may be areas with extremely low, near-zero fluxes. In these cases, any bias can appreciably affect the cumulative results, as discussed in the example of water vapor flux in Reverter *et al.* (2010), and should be corrected.

> If the anticipated heating correction must exceed 0.03-0.04 CO_2 m^{-2} s^{-1} to reconcile a specific dataset, it may be caused by entirely different factors, such as errors in calibration, processing code, time delay, WPL terms, frequency response corrections, *etc.* These need to be carefully examined to determine what is causing the error, how the error can be corrected, and whether the data during the problematic period need to be removed from the final dataset.



* *Green color indicates methods proposed in GCB paper (2008)*

** *Blue color indicated later modifications and alternatives proposed in 2009-2012*

If it was determined that for a particular dataset the heating correction should be applied, there are many possible ways to measure H_{inpath}, and to measure or estimate H_{added} for the heating equations. Four broad methods proposed for correcting the fluxes for instrument surface heating in Burba *et al.*, (2008) are summarized above. These are sometimes erroneously combined, and may benefit from a brief clarification.

Method 1 is basically a traditional approach that assumes heating to be negligible, such that $H_{inpath}=H_{ambient}$, $H_{added}=0$. $H_{ambient}$ is then used in the WPL equation.

This method generally performs well in moderate or warm environments, and with large gas fluxes overwhelming the WPL terms and surface heating effect. However, it may not perform well in cold environments or during cold periods with small fluxes, when added heat comprises a non-negligible portion of the WPL terms and the total flux magnitude.

Method 2 relies on using enclosed or closed-path designs, so that the entire surface heating effect is avoided. This method performs well in all environments, and is perhaps the most direct and robust solution for instrument surface heating.

Method 3 relies on measurements of fast temperature fluctuations integrated over the open path. H_{inpath} can be computed directly from T' measured using a fine-wire PRT and w' from a sonic anemometer. Massman and Frank (2009) have also successfully used a set of fine-wire thermocouples distributed over the open path of a gas analyzer, instead of a PRT wire, to measure T' in the path and compute H_{inpath}.

Method 4 is the only method suitable for correcting previously collected data, when in-path fast temperature was not available. This method does not provide direct measurements of H_{inpath} or H_{added}, but rather allows estimation of H_{added}. There are three versions of Method 4. All three versions (i, ii, and iii) have a similar principle: they use estimates of differences between instrument surface temperatures and air temperature to estimate H_{added}. These differences can either be measured with thermocouples or estimated in various ways by regression methods based on air temperature.

Overall, for *past* open-path data, the surface heating correction should be treated like other corrections such as frequency response corrections and WPL terms:

(1) Study and understand the effect

(2) Evaluate its magnitude

(3 Make appropriate corrections (some can be applied automatically by programs such as EddyPro)

The corrections can be applied by developing a site-specific open-path/closed-path relationship (Jarvi, *et al.*, 2009; Reverter, *et al.*, 2011), using semi-empirical relationships (Burba, *et al.*, 2008), or by deriving a new relationship based on the concept of surface heating.

For *future* data, a number of robust approaches are available:

(1) In extremely cold weather, use enclosed gas analyzers, or a closed-path design (power and error tolerance permitting), or use newer open-path analyzers with low heat dissipation at cold temperature setting

(2) Measure surface heating using a fine-wire thermometer (Grelle and Burba, 2007), or a set of fine-wire thermocouples (Massman and Frank, 2009)

(3) Use a site-specific open-path/closed-path relationship following Jarvi, *et al.* (2009) or Reverter *et al.* (2011)

Please contact the authors of respective papers or LI-COR (envsupport@licor.com) for full texts of papers and other detailed documentation.

Modern flux processing programs (such as EddyPro) include a surface heating correction as an option. Method 4 (versions ii or iii) is usually available.

Special care should be used when opting for automated application of the surface heating correction by Method 4 (all three versions). This method was developed for an older pre-2010 gas analyzer model that was positioned vertically. Newer open-path sensors may or may not need a surface heating correction, depending on their design and settings. Sensors angled away from vertical may need parameterization or adjustment.

Due to the novelty of the correction and the intricate nature of the heating effect, LI-COR has an informational package available to help deal with past data. It was written based on questions generated by the community in 2005-2012, and contains additional explanations, an Excel worksheet that computes the correction for vertical sensors, and relevant papers on the topic. Please e-mail george.burba@licor.com for this information.

References

Reverter, B., A. Carrara, A. Fernández, C. Gimeno, M. Sanz; *et al.*, 2011. Adjustments of annual NEE and ET for the open-path IRGA self-heating correction: magnitude and approximation over a climate range. Agricultural and Forest Meteorology, 151 (12): 1856-1861

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Part Four:

Processing Eddy Covariance Data

Section 4.7

Calculating Flux From Dry Mole Fraction without WPL Terms

- Optical gas analyzers measure how known light is transformed by gas molecules in a known volume, so they essentially measure density
- The classical eddy covariance flux equation is based on dry mole fraction
- Dry mole fraction s (per mole of dry air) is different from density q_c (per m^3), due to just 3 variables: water vapor mole fraction X_w, temperature T, and pressure P:

$$\boxed{s = q_c \frac{RT}{P(1 - X_w)}} \rightarrow \boxed{F_c = \overline{\rho_d}\,\overline{w's'}}$$

- If an instrument can output fast dry mole fraction, the classical flux equation can be used, and WPL density terms are no longer required

Optical gas analyzers measure how known light is transformed by gas molecules in a known volume, so they essentially measure density. The classical eddy flux equation, however, is based on the dry mole fraction (see Part 1 and Section 4.4 for details).

Dry mole fraction of a gas, sometimes called mixing ratio in micrometeorology, is different from gas density due to water vapor mole fraction X_w, temperature T and pressure P of the gas.

If the instrument can output fast dry mole fraction, the flux processing is significantly simplified and WPL density terms are no longer required. This is because use of instantaneous dry mole fraction implies that the instantaneous thermal and pressure-related expansion, and water dilution of the sampled gas have been accounted for.

The flux can then be computed in a very simple way, by multiplying raw covariance by a frequency response correction.

This approach can resolve two key theoretical challenges of computing flux from gas density: (i) uncertainty in H and LE affecting respective WPL terms; (ii) uncertainty in approximating instantaneous behavior with hourly behavior. Both of these are quite difficult to measure and verify.

However, computing flux from dry mole fraction has two engineering challenges: (i) matching time of fast CO_2 and H_2O measurements with fast T and P measurements of the sampled air; (ii) specifications of T and P sensors.

Both of these challenges are easy to measure and verify, but they must be resolved prior to using dry mole fraction in flux calculations.

> It is important to use consistent units (moles, grams, *etc.*) throughout the flux equation above for s', ρ_d and F_c. Mixing moles, micromoles, grams, kilograms and others in the same equation can easily result in a large error in the flux calculations.

References

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must be measured fast in the cell

must be measured fast in the cell, integrated over the entire path, and aligned with q_c at fast rate

$$s = q_c \frac{RT}{P(1 - X_w)}$$

can be successfully used for flux calculations

must be measured fast in the cell, and aligned with q_c at fast rate

must be measured fast in the cell, and aligned with q_c at fast rate

Using fast dry mole fraction for flux calculations reframes difficult-to-verify theoretical problems into easily verifiable engineering tasks (*e.g.*, measure *T*, *P*, CO_2 and H_2O content of sampled air fast, well, and at the same time), but it requires special care in instrument design.

For instruments using an open-path design, this method is difficult to use because of complexities with maintaining reliable fast temperature measurements integrated over the entire open path, and also because of extraordinary challenges with accurate measurements of fast pressure in the open air flow.

For instruments utilizing a traditional long-tube closed-path design, this method can be used when instantaneous fluctuations in the air temperature of the sample are attenuated by the tube, instantaneous pressure fluctuations are regulated (or can be assumed negligible), and water vapor is measured simultaneously with gas, or the sample is dried.

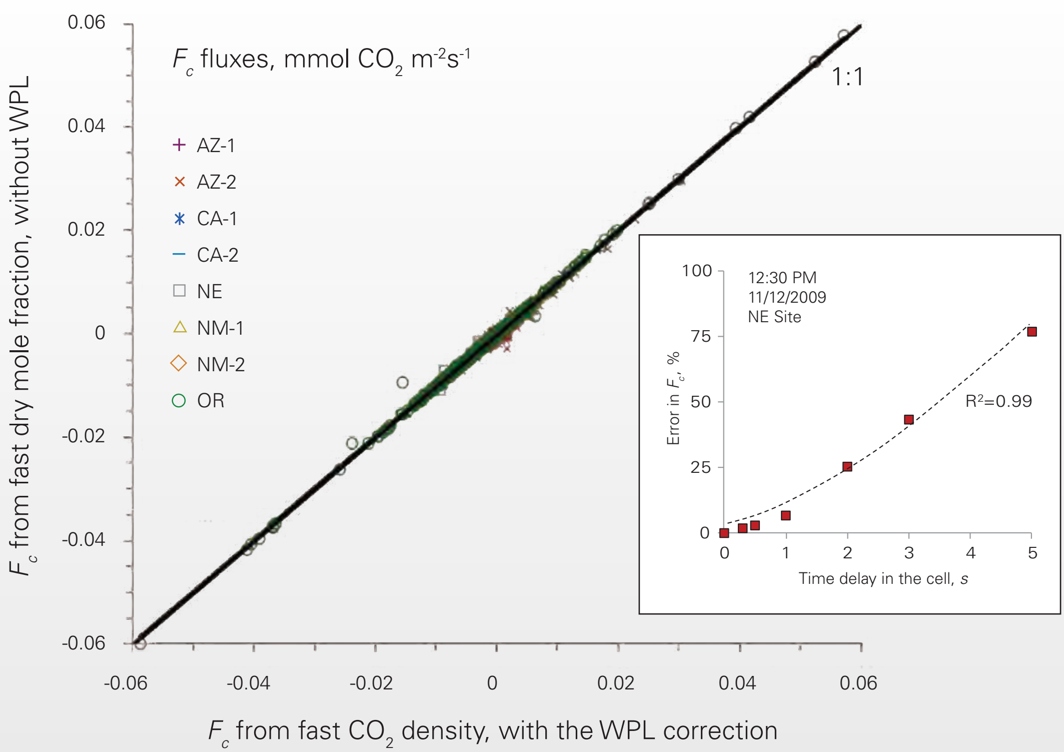
For instruments with a short-tube enclosed design, most but not all of the instantaneous temperature fluctuations are attenuated, so calculating fluxes using fast dry mole fraction output requires fast temperature measurements of the air stream inside the cell.

In both closed-path and enclosed analyzers, precise time matching between q_c, *T*, *P* and X_w is extremely important for computing the correct instantaneous dry mole fraction, because temperature- and pressure-related expansion and contraction, and water vapor dilution are instantaneous processes affecting gas density and its conversion to dry mole fraction.

Therefore, special steps should be taken in the gas analyzer electronics and firmware to properly measure, weigh, delay and align all inputs required for conversion from native density measurements to dry mole fraction.

References

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399



The larger plot above gives an example of the level of performance that can be achieved when the instrument is specifically designed to properly compute fast dry mole fraction. Dry mole fraction-based CO_2 fluxes without WPL terms are plotted *vs.* traditional density-based fluxes with WPL terms for nine different deployments over a wide range of environments using enclosed LI-7200 analyzers. The dry mole fraction-based approach performs well for hourly fluxes across all sites collectively, and for nearly each hour at each site.

To obtain these results, fast temperatures were measured in the sampled air stream near the cell inlet and outlet, and were weighted 1:4 to provide a temperature properly integrated over the entire cell volume. Outlet air temperature was delayed in time in relation to inlet cell temperature to describe the same exact air parcel, and all other signals were delayed in relation to the temperatures to compensate for the thermal inertia of the thermocouples.

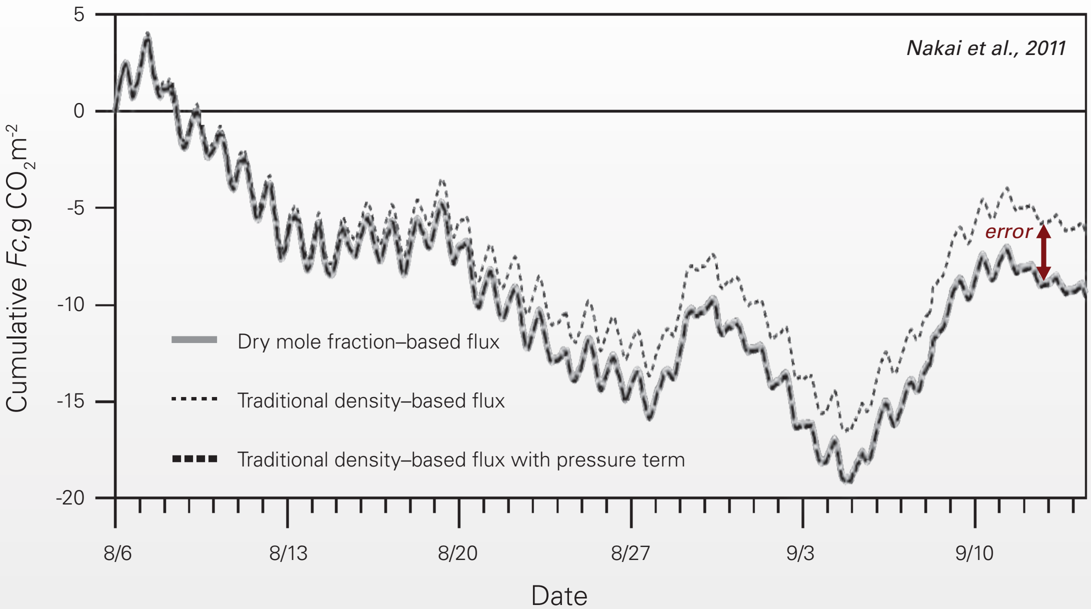
Let us look at an example of what would happen if the parameters were misaligned. Using the traditional density-based approach, *H* and *E* for WPL terms are computed during post-processing, and proper delays are determined using circular correlation or other similar means. Thus, if the relevant time series (*e.g.*, q_c, *T*, *P* and X_w) were to be misaligned in relation to each other, the post-processing routine would re-align them, leading to correct results. When using fast dry mole fraction, there is no opportunity for on-the-fly post-processing to realign the misaligned time series.

The smaller plot above illustrates a hypothetical situation, where instantaneous cell *T* is intentionally misaligned. The error in the CO_2 fluxes rapidly increased with the delay. The daytime CO_2 uptake increases as if it was under-corrected by the H-term in WPL. Sub-second delays caused errors of a few percent, and multi-second delays caused flux errors as high as 25% to 75%.

When the inputs are properly aligned, as computed by the instrument firmware in real time, the dry mole fraction-based fluxes matched density-based hourly fluxes, as expected from the theory.

References

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399



- Errors in traditional density-based flux calculations due to neglected pressure effects can be avoided when using dry-mole fraction to compute gas fluxes

On the previous page, properly measured dry mole fraction was shown to provide reliable hourly fluxes without the need for WPL density terms. There is also another advantage to using the dry mole fraction-based approach, related to pressure effects.

The effects of fast fluctuations in gas pressure are often neglected when computing hourly or daily gas fluxes. However, the pressure effect is additive and primarily in one direction, and can potentially cause a bias over the long term.

When using open-path devices or unregulated closed-path devices, pressure effects are assumed negligible, often are not measured at a fast rate, and thus, are not part of the flux calculations.

When using enclosed analyzers or closed-path devices with fast pressure measured in the cell, the role of pressure effects can be examined by comparing three ways of computing flux:

(i) traditional way based on fast density with no pressure term in WPL equation (see Section 4.4);

(ii) same approach with pressure term;

(iii) computations based on fast dry mole fraction, with fast pressure incorporated into the calculations.

Such a study was conducted by Nakai *et al.* in 2011, demonstrating strong evidence that:

(i) Pressure term is important for gas budgets, and can account for 25-30% of the budget over 6 weeks;

(ii) Pressure effects are measured well when fluxes are computed using fast dry mole fraction.

These findings are important not only for windy sites with rapidly fluctuation pressure, but are also significant for any site or period with small fluxes, and potentially for nearly all long-term studies.

References

Nakai T., H. Iwata, and Y. Harazono, 2011. Importance of mixing ratio for a long-term CO_2 flux measurement with a closed-path system. Tellus B, 63(3): 302-308

- To obtain correct fast dry mole fraction of a gas, fast measurements of gas temperature, water content and pressure must be integrated over the same sampling volume, and done at the same time as gas density
- Computing fluxes from such fast dry mole fraction may be more beneficial than computing them traditionally from fast density:
  - Long-standing methodological issues are reframed into a set of fairly simple engineering and instrument tasks
  - Flux processing is simplified significantly, and flux data quality and temporal resolution are likely to increase, while size of uncertainty and minimum detectable flux are likely to decrease

Gas flux calculations based on dry mole fraction (converted from density using fast gas temperature, water vapor content and pressure measured in the sampling cell) may offer benefits over the traditional density-based approach:

- Fairly complex theoretical and methodological problems are reframed into a set of simple engineering tasks (*e.g.*, measure T, P, X_w and q_c together, fast and well)
- Flux processing simplified to: (i) running time delay between w' and s' to obtain maximum covariance, and (ii) applying frequency response corrections to obtain the final flux
- Flux data quality and temporal resolution are likely to increase, while the size of uncertainty and minimum detectable flux is likely to decrease, because errors in WPL terms coming from eddy covariance (+/-10% to +/-20%) are replaced with errors from H_2O, T and P measurements in the cell (less than a few percentage points)
- Pressure effects are measured and incorporated into dry mole fraction, so pressure effects do not have to be neglected, benefiting long-term flux integrations

References

Additional aspects and details on this topic for closed-path and enclosed analyzers are covered in the following recent studies:

Leuning, R., 2007. The correct form of the Webb, Pearman and Leuning equation for eddy fluxes of trace gases in steady and non-steady state, horizontally homogeneous flows. Boundary-Layer Meteorology, 123: 263-267

Ibrom A., E. Dellwik, S. Larsen, and K. Pilegaard, 2007b. On the use of the Webb–Pearman–Leuning theory for closed-path eddy correlation measurements. Tellus B, 59: 937-946

Kowalski A, and P. Serrano-Ortiz, 2007. On the relationship between the eddy covariance, the turbulent flux, and surface exchange for a trace gas such as CO_2. Boundary-Layer Meteorology, 124: 129-141

Nakai T., H. Iwata, and Y. Harazono, 2011. Importance of mixing ratio for a long-term CO_2 flux measurement with a closed-path system. Tellus B, 63(3): 302-308

Burba, G., A. Schmidt, R. Scott, T. Nakai, J. Kathilankal, *et al.*, 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399

Part Four:

Processing Eddy Covariance Data

Section 4.8

Other Corrections and Flux Storage

- *Oxygen correction:*
  - Compensates for krypton hygrometer sensitivity to oxygen
  - Applies to krypton hygrometer's H_2O flux
- *Foreign gas (band broadening) correction in NDIR measurements:*
  - Compensates for the broadening of CO_2 IR absorption band due to the presence of other gases in the sampling volume
  - Applies to CO_2, may apply to other gases depending on instrument
  - See LI-COR application note for details

There are other less common instrument-specific corrections, for example, oxygen correction for UV-based measurements, or band broadening corrections for NDIR-based measurements.

An oxygen correction compensates for sensitivity to oxygen for a specific instrument (*e.g.*, a krypton hygrometer), and is applied to the measured latent heat flux. More information on the oxygen correction can be found in the literature listed below.

The band broadening correction for NDIR instruments is most often used to compensate for the broadening of the CO_2 infrared absorption band due to the presence of water molecules in the sampled gas. It applies primarily to CO_2 flux measured with infrared gas analyzers, but may apply to other gases as well, depending on the instrument. Similar band-broadening effects of oxygen and other abundant gases are usually assumed negligible, since their concentrations are not as variable as water vapor.

Newer gas analyzers (*e.g.*, LI-7000, LI-7200 and LI-7500A) apply this correction automatically in the instrument software. Older instruments or instruments by other manufacturers may require applying this correction manually. Please refer to specific instrument manuals for details. The principles of band broadening and related practical applications can be further studied in the references listed below.

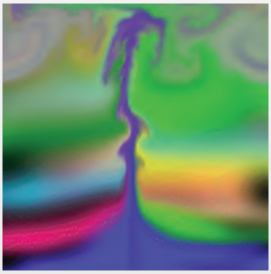
References

McDermitt, D., J. Welles, and R. Eckles, 1993. Effects of Temperature, Pressure, and Water Vapor on Gas Phase Infrared Absorption by CO_2. LI-COR, Lincoln, Nebraska, 6 pp.

Chen, W, T. Black, P. Yang, A. Barr, H. Neumann, *et al.*, 1999. Effects of climatic variability on the annual carbon sequestration by a boreal aspen forest. Global Change Biology, 5: 41-53

Tanner, B., E. Swiatek, and J. Greene, 1993. Density fluctuations and use of the krypton hygrometer in surface flux measurements. In: Allen R. (Ed.), Management of irrigation and drainage systems: integrated perspectives. American Society of Civil Engineers, New York: 945-952

van Dijk, A., W. Kohsiek, and H. de Bruin, 2003. Oxygen sensitivity of krypton and Lyman-alpha hygrometers. Journal of Atmospheric and Oceanic Technology, 20: 143-151



- Eddy covariance instruments record flux at a certain measurement height
- Below this measurement height, concentration can build up or decrease, especially during calm periods (for example, on a calm night)
- Gusts of wind can move this buildup sideways or upward very quickly, so this flux may be either undetected or only partially detected
- Gas concentration profile measurements help detect and account for most of such buildups

Eddy covariance instruments record flux at a certain measurement height. Below this height, gas can build up or become depleted, especially during calm periods, or within a tall canopy (for example, CO_2 buildup on a calm night or CO_2 depletion on a calm day).

Depending on canopy and terrain, wind gusts can move such buildups sideways below the tower, or upward next to the tower very rapidly, so this flux is either undetected or only partially detected, especially in tall canopies or in complex terrains.

On flat uniform terrains with short canopies and with good turbulent mixing, these processes are either small or eventually balance themselves out over the long term, but they still may significantly affect hourly data.

Gas concentration profile measurements allow detection of the majority of these buildups by providing data for computing a gas flux storage term below the measurement height.

References

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Heilman, J., K. McInnes, and M. Owens, 2003. Net Carbon Dioxide Exchange in Live Oak-Ashe Juniper Savanna and C_4 Grassland Ecosystems on the Edwards Plateau, Texas: Effects of Seasonal and Interannual Changes in Climate and Phenology. http://www.nigec.tulane.edu/heilman.htm

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

- A storage term can be calculated from temporal changes in gas concentration profiles, and can be incorporated into the final flux as follows:

$$F_{ecosys} = F_c + F_{storage} = \underbrace{F_c}_{\text{flux from eddy covariance}} + \underbrace{\int_0^{z_m} \rho_d \frac{\partial s}{\partial t} dz}_{\text{flux storage term}}$$

- Storage calculations are especially important during conditions with low wind, stable stratification, in high canopies, or in any cases when air mixing is significantly reduced and/or atmosphere and surface are decoupled

The storage term is usually calculated from the temporal changes in the integrated gas concentration profile, and is added to the eddy covariance flux to arrive at the final flux value.

The gas concentration profile is typically measured at a slow rate at several heights (z) above the soil surface, and below the height of the eddy covariance instrumentation (z_m).

The flux storage is computed from this profile over some time interval (t), usually a half-hour or an hour.

Storage calculations are especially important during conditions with: low wind, stable stratification, high canopies, in cases when air mixing is significantly reduced, or when the atmosphere and surface are decoupled from each other.

Storage calculations are not measurements of turbulent fluxes, but they are important for the final flux values, especially when net ecosystem exchange is the focus of the study.

> It is important to distinguish between "gas flux storage", the amount of gas building up under the tower, from "energy storage". Energy storage (or heat storage) is part of the ecosystem energy budget, and describes the heat energy stored in the soil, liquid water, canopy, or mulch layer. The soil portion of the heat storage is a part of soil heat flux, and is often called "soil heat storage", or sometimes, may be called "soil heat flux storage".

References

A good discussion of the flux storage and its role for hourly fluxes is provided in Chapter 5 (pages 135-139, and Figure 5.2) of Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Finnigan, J., 2006. The storage term in eddy flux calculations. Agricultural and Forest Meteorology, 136 (3): 108-113

Part Four:

Processing Eddy Covariance Data

Section 4.9

Summary of Corrections

Procedure	Affected fluxes	Effect	Range
Spike removal	all	depends	0-15%
Coordinate rotation	all	depends	0-25%
Angle of attack correction	all	depends	0-25%
Time delay adjustment	mostly closed path	increases flux	0-50%
Frequency response corrections	all	increases flux	0-50%
Sonic heat flux correction	sensible heat flux	depends	0-10%
Webb-Pearman-Leuning terms	any gas	depends	0-50%
Spectroscopic effects for LASERs	any gas	depends	0-25%
Band-broadening correction for NDIR	mostly CO_2	depends	0-5%
Oxygen correction	some H_2O	depends	0-10%
Gas flux storage term	any gas	increases flux	0-5%

Since flux measurements are imperfect due to assumptions, instrument problems, physical phenomena, and specifics of the particular terrain, there are a number of corrections that must be applied to the raw flux value.

The impact of the corrections is strongly dependent upon the instrument design, system setup, environmental conditions, and the size of the raw uncorrected flux. The table above shows the most common corrections, affected fluxes, and very approximate mid-day warm-season ranges of these corrections in relation to the flux in an unstressed mid-latitude green vegetative ecosystem.

Please note that even though the size of a correction is shown as a percentage of the flux for illustrative purposes, some of the corrections are multiplicative, while others are additive.

Modern flux programs will automatically apply most of the corrections as a part of the standard flux processing sequence. For an unusual setup or custom-built instrumentation, some steps in the processing program may need to be customized accordingly.

Key considerations:

- Spike removal is applied to all fluxes, and usually affects no more than fifteen percent of the flux. Good instrument maintenance may help to minimize the effect of data spikes.

- Coordinate rotation corrects for an unleveled sonic anemometer in relation to mean flow, and affects all fluxes due to contamination of the vertical wind speed with a horizontal component.

  This correction can reach 25% or more of the raw flux, depending on the leveling of the sonic anemometer. A cosine response correction, and/or angle-of-attack correction can also be considered at this stage for some sonic anemometer models.

  It is important to note that the anemometer correction listed above will not correct for flow distortion caused by an overly cluttered setup, or bulky objects located near the anemometer path.

  It is best to avoid flow distortion during instrument selection and system setup rather than try to correct for it during data processing.

- A time delay adjustment corrects the delay in the correlated time series, and is especially crucial for closed-path systems. The result of the adjustment may typically range between five and fifteen percent of the raw flux, and can be applied by shifting two time series in such a way that the covariance between them is maximized, or can be computed as a theoretical time delay from the known flow rate and tube diameter.

  For sticky gases, such as H_2O, NH_3, *etc.*, the tube delays may become very large when long tubes are used. In these cases the resulting adjustment of the time delay may be 50% or more of the measured flux.

- Frequency response corrections compensate for flux losses at different turbulent transport frequencies. They consist of a number of individual corrections (*e.g.*, time response, tube attenuation, scalar/vector path averaging, sensor separation, sensor response mismatch, low pass filtering, high pass filtering, and digital sampling) combined into one final transfer function. They are applied to all fluxes, usually range between five and twenty five percent of the flux, and can be minimized to some extent by proper experimental setup.

  Like the time delay adjustment, attenuation of sticky gases, such as H_2O, NH_3, *etc.*, in the long tubes of closed-path analyzers may become very large. In these cases the frequency correction for the attenuation may be 50% or more of the measured flux.

- Sonic heat flux correction compensates for humidity fluctuations and momentum flux, affecting sonic temperature measurements and usually affecting no more than ten percent of sensible heat flux.

- The Webb-Pearman-Leuning density terms affect gas and water fluxes. The size and direction of these additive terms varies greatly, from several hundred percent of the flux in winter, to only a few percent in summer.

  Open-path analyzers have a large WPL impact due to a typically large thermal expansion-contraction term. Closed-path devices have a much smaller WPL impact due to temperature attenuation in long intake tubes. Enclosed devices that can output dry mole fraction at a fast rate do not need WPL terms in flux calculations, and also account for the pressure effects traditionally neglected in open-path and closed-path measurements.

- Spectroscopic effects for laser-based technologies may affect fast concentrations and fluxes. The impact is generally specific to the technology, and should be treated with caution. Corrections exist for specific instrument models.

- The band-broadening correction affecting gas fluxes measured by NDIR greatly depends on the instrument used. The correction is usually on the order of zero to five percent, and is either applied in the instrument's software, or described by the manufacturer in the instrument manual.

- Oxygen correction compensates for oxygen in the path of a krypton hygrometer, and is usually no more than ten percent of the raw flux.

- The gas flux storage term accounts for a build-up of the gas below the height of eddy covariance measurements under low winds, stable conditions or within tall canopies. On flat uniform terrains with short canopies and with good turbulent mixing these processes are either small, or negligible, or even themselves out over the long term, but they can still significantly affect hourly data.

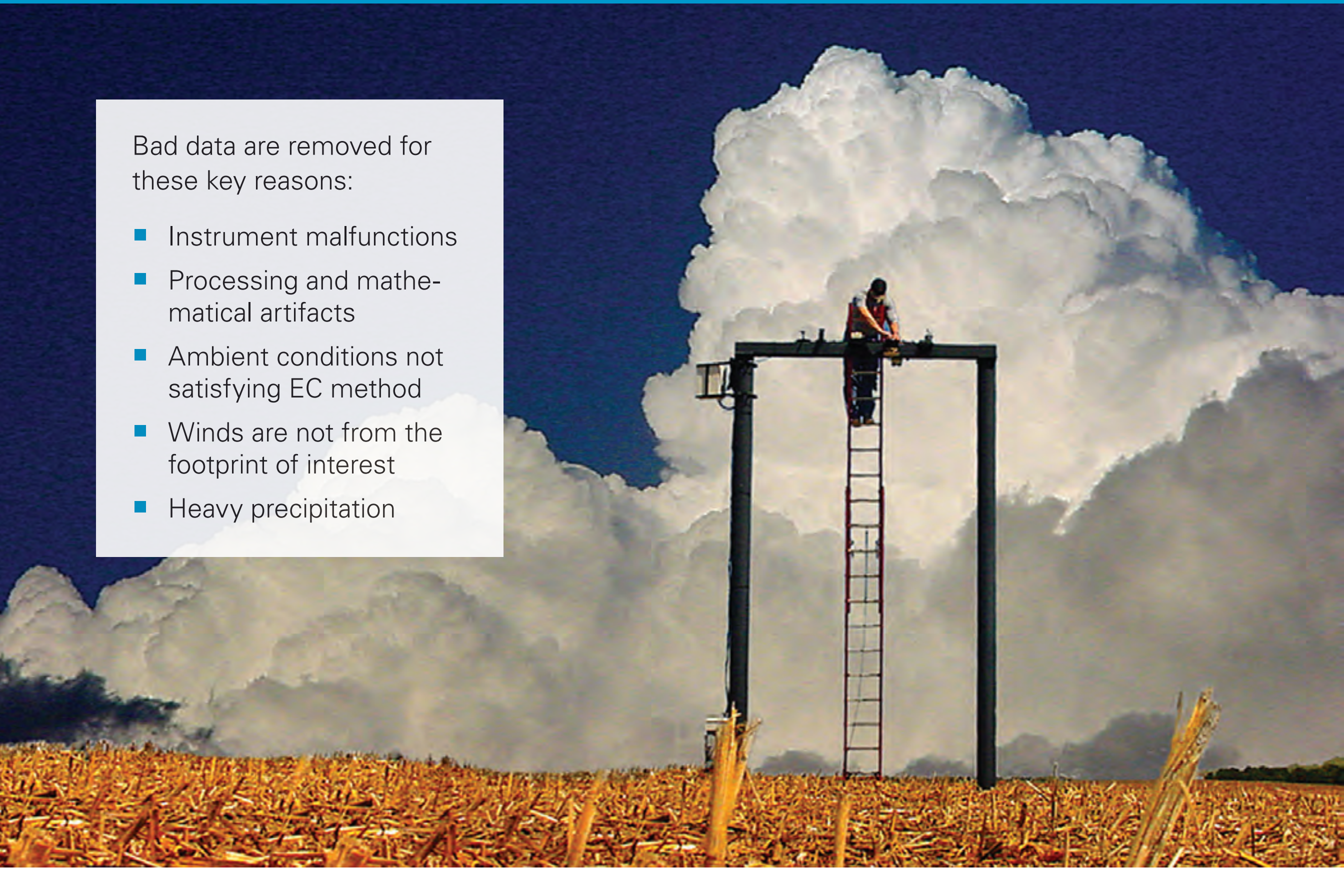
Finally, please note that none of these corrections, adjustments and terms are negligible. Combined, they can easily sum to over one hundred percent of the initial flux value, especially for small fluxes and for yearly integrations. This illustrates how important it is to minimize potential errors during experiment planning and setup, and correct the remaining errors during data processing.

Part Four:

Processing Eddy Covariance Data

Section 4.10

Quality Control of Eddy Covariance Flux Data



Data quality control and gap filling are not directly related to the methodology of eddy covariance flux measurements, but are an important part of arriving at the final result describing the amount of gas produced or consumed by an ecosystem or other territory per unit area per unit time.

Some of the available flux processing programs (*e.g.*, EddyPro, ECO_2S, TK3, FluxUH) can perform a lot of the necessary quality control tests and data flagging as part of standard data processing. When writing your own code or using programs such as EdiRe, EddySol, *etc.*, it is useful to know the key steps of cleaning the eddy covariance data.

The most important parts of quality control and gap filling procedures are described below, and refer the reader to more detailed literature sources.

Removing bad data is the first important step in the data quality control process. It ensures that results do not have a bias or errors due to several obvious reasons.

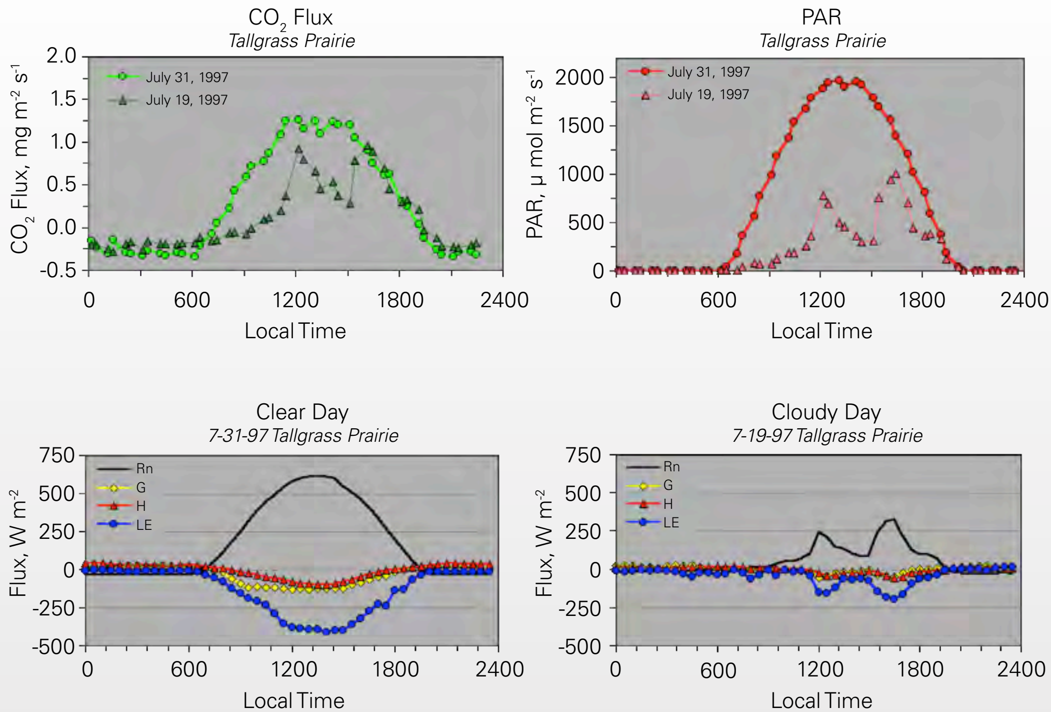
Bad data are usually removed due to one of the following reasons: instrument malfunctions, processing/mathematical artifacts, ambient conditions not satisfying the eddy covariance method, winds are not from the footprint of interest, and heavy precipitation.

Among these, ambient conditions not satisfying the eddy covariance method include: conditions when turbulent transfer does not prevail, non-stationary conditions, periods with significant convergence or divergence, *etc.*

References

Munger, B., and H. Loescher, 2008. AmeriFlux Guidelines for Making Eddy Covariance Flux Measurements. AmeriFlux: http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

Mauder, M., T. Foken, R. Clement, J. Elbers, W. Eugster, *et al.*, 2008. Quality control of CarboEurope flux data – Part 2: Inter-comparison of eddy-covariance software. Biogeosciences, 5: 451-462



The most important elements of flux quality control are basic logic and common sense. Simply spot-checking flux values along with mean radiation and weather data helps to immediately point out serious problems. Also, if fluxes appear erroneous, it is helpful to check fast raw data for the time period when the flux appeared unreasonable, and evaluate if there were irregularities in these original data leading to incorrectly computed covariance and flux.

For example, latent heat flux (*e.g.*, evapotranspiration rate) may be observed to remain near zero over an irrigated field in the middle of the day. This is very unlikely, as there is plenty of moisture in the soil and plenty of energy in the ecosystem to drive the evapotranspiration process.

Inspection of 10 Hz data for one midday hour with near zero latent heat flux may yield the following explanation: while vertical wind speed time series exhibit the expected rapid up-and-down changes (see examples in Part 1 and Section 4.1), the fast water vapor signal appears smooth. Again, this is unlikely, as turbulent motions captured in the vertical wind speed also carry water vapor that should have led to fast upward and downward changes in the water signal.

Further inspection at the field site might determine that the flow rate for the gas analyzer was reduced from the required 15 liters per minute to just 1 liter per minute due to a broken diaphragm in the pump. Observing the data periodically throughout the measurement period may help catch and fix such problems early, minimizing overall data loss.

However, it is also important to note that a lot of natural processes can change rapidly due to changing weather and sunlight conditions. Fluxes may appear to be incorrect while in fact perfectly normal given the conditions. The example above illustrates this point. The CO_2 flux on July 19, 1997, may appear erroneous if inspected by itself, or in comparison with the CO_2 flux on July 31. However, by observing sunlight conditions (photosynthetically active radiation, PAR) it becomes clear that CO_2 flux simply follows PAR. This is expected, as PAR is used during the process of photosynthesis, driving the daytime CO_2 uptake (positive number on these plots). In addition, the overall amount of sunlight that drives PAR also drives temperature, energy fluxes, and many other ecosystem processes.

The marked difference in the net solar radiation (*Rn*), soil heat flux (*G*), sensible heat flux (*H*) and latent heat flux (*LE*) can be easily observed between a clear day on July 31 and an overcast day on July 19, 1997, in the two lowermost plots.

Now, when looking at the CO_2 flux on July 19 from this perspective, it becomes apparent that the flux values are reasonable, and are not indicative of any problems at the site.

- The variety of algorithms and protocols used by different groups/networks (*e.g.*, Carboeurope, FluxNet-Canada, AmeriFlux) have these features in common:
  - Ranges of tolerance established for each variable
  - Data outside tolerance ranges removed or flagged
  - Precipitation events flagged
  - U, u*, stationarity, higher moment and integral turbulent intensity tests done
  - Low-turbulence and non-stationary periods removed or flagged
  - Data validated via energy budget closure, cospectral models, *etc.*
  - Data gaps filled with backup instruments, regressions, models
  - Data integrated, uncertainties computed
- Quality control is very much a site- and instrument-specific activity

Various algorithms and protocols are used by different groups and networks (*e.g.*, AmeriFlux, AsiaFlux, CarboEurope, Fluxnet-Canada, ICOS, NEON, *etc.*) to automate data quality control and bad data removal procedures. These protocols are somewhat different from each other, but they have a number of common steps.

In general, the quality control procedure is very much a site-specific and instrument-specific activity, except for these common steps. Therefore, it is important not to overdo bad data removal at one study site based on past experiences at a different study site.

For example, the tolerance thresholds for sensible heat flux data will differ greatly between open-water flux measurements over a lake (which will generally have small sensible heat fluxes), and a desert environment that has high heat fluxes.

Thus, applying criteria developed for open water fluxes would probably eliminate many 'good' data points if applied to measurements over the desert. This is why it is recommended to collect a sufficient amount of data and establish a baseline for a specific site before the removal criteria are established and applied to the original data.

References

Sec 4.3 of Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, 442 pp.

Vickers, D. and L. Mahrt, 1997. Quality control and flux sampling problems for tower and aircraft data. Journal of Atmospheric and Oceanic Technology, 14: 512-526

Foken, T., and B. Wichura, 1995. Tools for quality assessment of surface-based flux measurements, Agricultural and Forest Meteorology, 78: 83-105

Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., *et al.*, 2008. Quality control of CarboEurope flux data – Part 1: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems, Biogeosciences, 5: 433-445

Gash, J., 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorology, 35: 409-413

- Fluxes are small
- Winds may be low, cospectra bad
- Conditions may be stable
- Turbulence may not prevail
- Storage may be significant
- Advection of the flux, drainage flows
- Divergence, convergence

Nighttime is usually a specific case for quality control. Special care is required at night, because the winds are usually low, stratification is stable, and turbulence may not be fully developed.

With slow winds and temperature inversions, flow may become non-stationary and advection, drainage, flow convergence and divergence may become dominant.

The footprint may also increase dramatically due to stable conditions. With a larger footprint, the tower instrumentation could measure some of the fluxes outside the area of interest.

As a result, data loss usually increases at night, especially during calm nights and over tall canopies.

A stationarity test is one of the more reliable tests for cleaning nighttime data. This test sets criteria for the behavior of air flow in such a way that non-stationary periods can be flagged and removed.

Chapter 5 in Aubinet *et al.* (2012) contains an excellent discussion of the nighttime quality control steps. Other literature referenced below has protocols for nighttime quality control implementation.

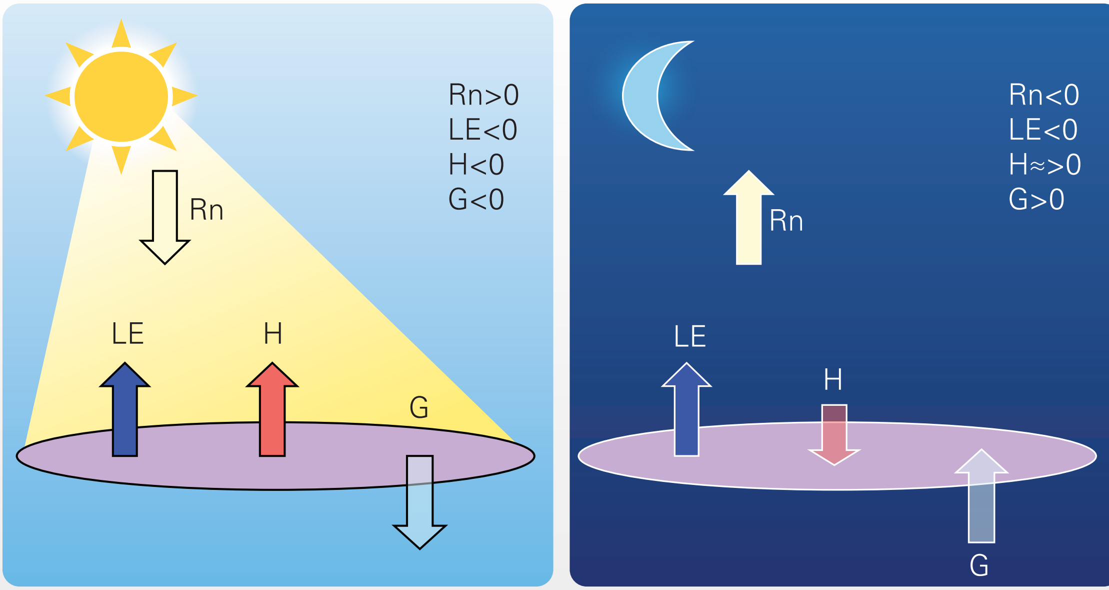
References

Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, Dordrecht, Heidelberg, London, New York, 442 pp.

Mauder, M. and T. Foken, 2006. Impact of post-field data processing on eddy covariance flux estimates and energy balance closure. Meteorologische Zeitschrift, 15: 597-609

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228

Aubinet, M., C. Feigenwinter, C. Bernhofer, *et al.*, 2010. Advection is not the solution to the nighttime CO_2 closure problem – evidence from three inherently different forests. Agric and Forest Met, 150 (5): 655-664



Short Equation: $Rn+H+LE+G\approx 0$

One way to validate fluxes measured with the eddy covariance method is to construct an energy budget for the study site. Two traditional examples (daytime and nighttime) with key components of the energy budget are shown above. *Rn* is net radiation; *LE* is latent heat flux; *H* is sensible heat flux, and *G* is the sum of soil heat flux and soil heat storage.

These examples illustrate a short, four-component equation for an energy budget, where net radiation is usually measured with a net radiometer, or with other radiation sensor, soil heat flux is usually calculated from heat flux plates and soil temperature, and latent and sensible heat fluxes come from eddy covariance measurements.

The idea of validating an energy budget is simply the following: if all of the key components sum up to zero as required by conservation of energy, then all energy transfers have been successfully accounted for, and sensible and latent heat fluxes were measured correctly. Since the latter was measured correctly by eddy covariance, the CO_2 and other trace gas fluxes were most likely to have been measured correctly as well.

A challenge in using the energy budget to validate closure is that a good measurement of latent heat flux does not necessarily mean a good measurement of the trace gas, because transfer for water and for the gas of interest may differ, especially if gases are reactive (such as volatile organic compounds) or have significantly different sources and sinks as compared to water vapor.

Another challenge in using the energy budget is often related to the difficulty in measuring soil heat flux, especially in soils with relatively rapid changes in water content, and also in non-uniform and patchy soils or terrains.

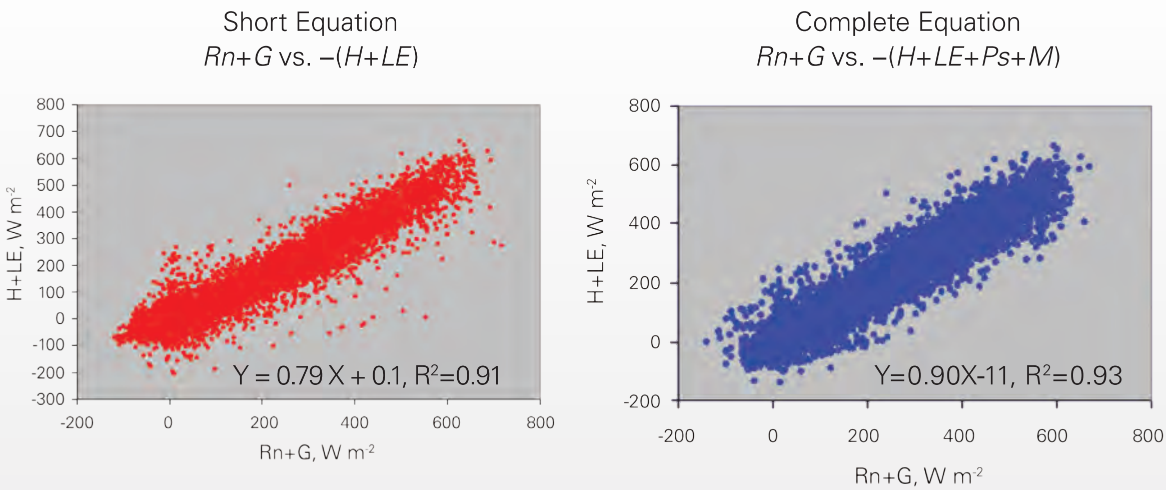
In spite of these difficulties, and with proper precautions, surface energy budget remains one of the most convincing ways to assess the quality of eddy covariance results, and is widely used in the flux community.

> It is important to note, however, that a good (closed) energy budget will not necessarily indicate good measurements of the trace gas flux, while a "non-closing" energy budget will almost certainly indicate a problem when measuring the flux.

References

Wilson, K., A. Goldstein, E. Falge, M. Aubinet, D. Baldocchi, *et al.*, 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology, 113(1-4): 223-243

Rosset, M., M. Riedo, A. Grub, M. Geissmann, and J. Fuhrer, 1997. Seasonal variations in radiation and energy balances of permanent pastures at different altitudes. Agricultural and Forest Meteorology, 86: 245-258



- Ideal closure (Y=X) is rarely achieved by eddy covariance method
- Including all members of energy budget substantially improves closure
- Good closure is not necessarily a validation, but bad closure is a definite problem

Another caveat in energy budget validation of eddy covariance fluxes is that minor components may be missed in the short energy budget equation shown on the previous page, even if all four key components were measured properly.

Constructing a complete equation is more difficult, but may also be more beneficial for quality control or validation of the eddy covariance data. The complete equation might include components such as energy spent on photosynthesis by plants (Ps), and miscellaneous terms (M) such as heat stored in the canopy, mulch, soil water, *etc*. Ideal closure, when ($Rn + G$) is equal to -($H + LE$), is rarely achieved due to a number of reasons that have been described earlier. However, including all components into an energy budget can significantly improve closure and help avoid unnecessary data removal or unneeded corrections of the eddy covariance data.

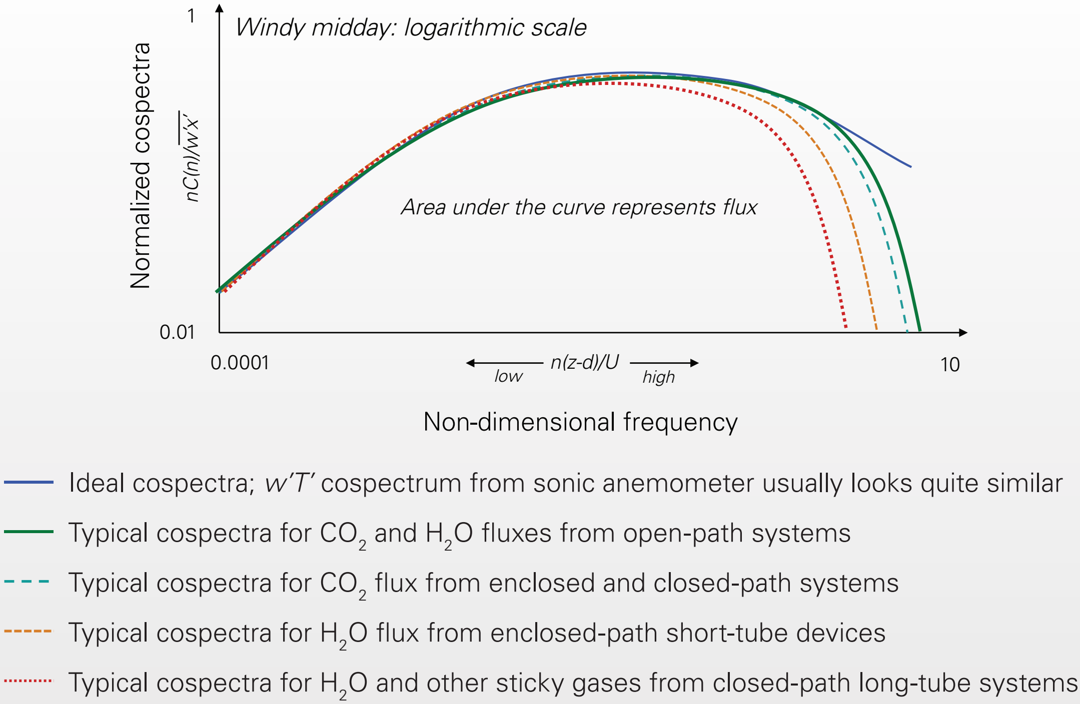
To illustrate this point, two plots with actual field data collected over maize in Nebraska over an entire year are shown above. The ideal closure on these plots would be indicated by a regression slope of 1 (or 100%) and an offset of zero. With the short equation, there is only 79% closure. That means that 21% of the energy is missing. Using a more complete equation leads to a closure of 90%, which is better than most typical values for eddy covariance study sites observed in the past.

> Recent studies by Frank and Massman (2011), Frank *et al.* (2012), Kochendorfer *et al.* (2012), and Nakai and Shimoyama *et al.* (2012) indicate that about 10% of the reduction in fluxes measured with eddy covariance may come from flow distortion by sonic anemometer models, which do not have an orthogonal arrangement and a vertical path for *w*. This can substantially affect energy budget closure because two of its four main components are measured using eddy covariance. The choice of sonic anemometer and angle-of-attack correction may help improve the budget closure due to this specific reason alone.

References

Wilson, K., A. Goldstein, E. Falge, M. Aubinet, D. Baldocchi, *et al.*, 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology, 113(1-4): 223-243

Kim, J., and S. Verma, 1990. Components of surface energy balance in a temperate grassland ecosystem. Boundary-Layer Meteorology, 51: 401-417



The quality and shape of daytime gas flux cospectra in comparison with sensible heat flux cospectra, or with ideal Kaimal-Moore cospectra, help us understand at what frequencies gas flux may be missed or measured incorrectly.

This is a powerful, but somewhat advanced, tool for quality control of instrument and system performance, turbulent conditions, and flux magnitudes.

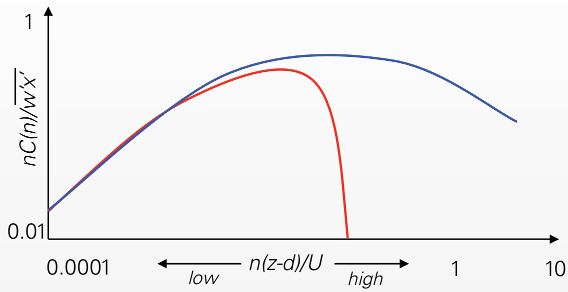
Modern programs compute cospectra of relevant parameters, but will not be able to analyze them. Thus, cospectral analysis must be conducted by the researcher.

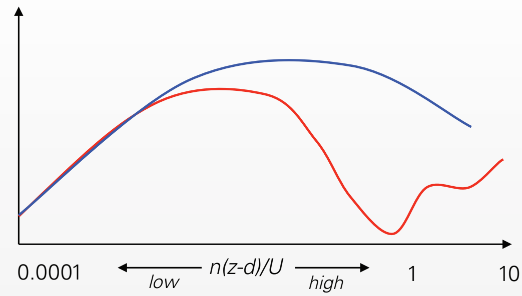
Actual field cospectra computed over a single individual half-hour or an hour often look quite noisy (see examples on page 182, Section 4.2), and may not be particularly helpful in quality control. Similarly, cospectra computed during periods with very small fluxes or undeveloped turbulence (for example, at night) may be near-zero or erratic, because the covariance on the y-axis may be close to zero.

Normalized ensemble-averaged hourly cospectra, binned by frequency, and computed for midday or daytime hours over many days, is perhaps the easiest way to approach the cospectral analysis.

There are many issues that can be diagnosed by looking at cospectral shapes. For example, shipborne and airborne eddy covariance studies may find unusual cospectral shapes for gas fluxes at the frequencies of ship heave and airplane vibration, and may need to counter these interferences with a different arrangement of instruments.

There are also a number of other less exotic issues that can be diagnosed by looking at cospectra. Some typical shapes of good cospectra are shown in the illustration above, while examples of problematic cospectra with a list of likely causes are shown on the following pages.





- Instrument may be too slow
- Instrument settings are too slow
- Data collection is too slow
- Flow rate is too slow
- Instrument is too close to canopy
- Data are truncated

- Instrument is too slow and noisy
- Instrument is too slow and aliased
- Noise may be partially correlated with w', T', ρ_v', P'
- Flow rate is too slow
- Instrument is too close to canopy

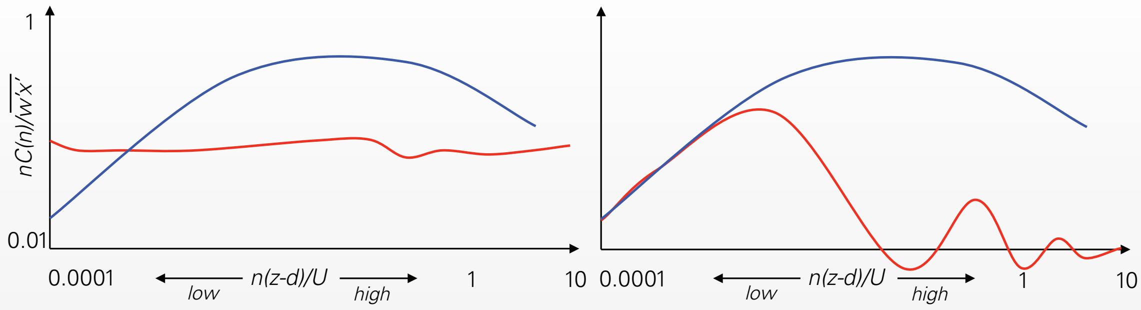
One of the most frequently occurring issues is a slow response of the entire system, shown in the leftmost plot above. Flux cospectrum drops off very rapidly, starting at low or medium frequencies, and stays at or near zero.

Several things can cause such an issue. Instrument or system frequency response may simply be too slow for 10 Hz data collection. For example, an instrument that takes 1 minute to detect instantaneous change may display this type of cospectra when installed on the tower. Another cause may be related to instrument or data collection settings. For example, a fast instrument, capable of detecting changes at 10 Hz, may be set to collect data at 0.1 Hz, or the data collection system on the computer may be accidentally set to 0.1 Hz. The computer or other data collection device may not have a strong enough processor to handle incoming data, and may default to a slow data collection rate.

For closed-path and enclosed systems, such cospectra may also be caused by an insufficient flow rate. For example, instead of exchanging the air sample in the cell 10 times per second or more, the flow rate may be such that only 1 exchange happens per second. This can be due to pump issues, plugged filters, pinched intake tube, insufficient power at the site, pump settings, *etc*.

Cospectra such as these may also be observed when measurements are conducted close to the ground or close to the canopy top, so that even 10 Hz or 20 Hz data collection is not sufficient to adequately capture turbulent transport. Since both axes on the plot are normalized, the low positioning may not be easily observed in the cospectral peak in these cases. There are also other possible reasons for this cospectral shape, but they are typically quite unusual and infrequent.

The top right plot above shows a cospectrum that drops down at low or medium frequencies, and then appears to come back at higher frequencies in a noisy or a wavy fashion. This is often a subset of the first case, but with added aliasing, noise, radio interference due to unshielded cables, or due to the fast effects of temperature, water vapor, or pressure noises on the density-based gas flux cospectra at higher frequency ranges.



- Data miscalculated
- Wrong column used for *w′* or scalar
- Electric noise overwhelms signal
- Wrong column plotted

- Data aliased
- Nyquist frequency cutoff ignored in instrument or in the data collection settings

Examples of less frequently occurring issues are shown above. The leftmost figure describes a cospectrum that does not follow turbulent transport, suggesting that equal amounts of turbulent transport are happening at all frequencies.

Since this turbulent transport is neither physically realistic nor supported by the sonic *w'T'* cospectra (blue), the situation is likely caused by miscalculations in the data, wrong columns used, or overwhelming electric noise. In addition, it may simply be a near-zero cospectra at all frequencies normalized by a near-zero covariance, and as a result, manifesting itself as a flat non-zero cospectral form.

The rightmost plot is a classic example of data aliasing. This can occur when data collection and bandwidth settings are the same (for example, 10 Hz data collection at a 10 Hz bandwidth), so that the Nyquist frequency/ Shannon's theorem are ignored. The aliasing may not be noticeable in actual data as vividly as that shown above, due to averaging of multiple cospectra, and due to natural noise in the measurements.

When conducting a cospectral analysis, it is usually quite easy to determine if the system performs correctly or not. However, there can be cases when the reason for poor system performance is difficult to track.

In these cases, it is important to keep in mind that the cospectral shape of the scalar flux may incorporate and combine many different causes, affecting system frequency response in comparison with sonic anemometer cospectra, or ideal modeled cospectra.

Thus, when having difficulties analyzing unusual cospectra and finding the cause of the problem, it is advisable to study the specific measurement system using transfer functions. Transfer functions can be used to construct expected cospectra by bringing down the sonic cospectra based on tube length, sensor separation, instrument time response, sensor path averaging, *etc*.

Comparing the actual measured cospectra to the expected one may help diagnose difficult-to-track problems much faster than comparing to an ideal or sonic cospectra. Furthermore, especially in difficult cases, it may be helpful to also conduct spectral analysis and examine a spectrum of a particular single variable, rather than covariance of two variables.

- There are many other ways to validate eddy covariance flux:
  - Similarity theory models (*vs. z/L*)
  - Verification with biological data (NEP)
  - Upscaling from leaf level (leaf chamber measurements)
  - Upscaling from soil level (soil chamber measurements)
- None of these methods can guarantee correct data, but when combined, they can help identify problems or help defend the flux data

There are many other ways to validate eddy covariance flux.

Similarity theory models involving the Monin-Obukhov stability parameter may help to assess if flux covariances or momentum characteristics behave in a predictable way and fit established meteorological models.

Verification of tower data with data collected by other techniques (for example, net ecosystem production computations from biomass data, leaf chamber measurements or soil chamber data) can help all of the intercompared techniques reveal inconsistencies and suggest the causes of differences.

None of these methods alone will guarantee correct data, but all of them combined can help find hidden problems or defend the flux data.

Automated quality controls can also be pre-programmed in processing code. These are available in many modern flux processing programs (such as TK4, EddyPro, *etc.*) via a system of quality control flags describing the timing and causes of problematic data periods.

References

Mauder, M. and T. Foken, 2006. Impact of post-field data processing on eddy covariance flux estimates and energy balance closure. Meteorologische Zeitschrift, 15: 597-609

Section 4.3 of Aubinet, M., T. Vesala, and D. Papale (Eds.), 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer, New York, 442 pp.

After bad data have been removed, data gap inventory and data filling need to be performed

- Inventory is important for getting an idea of the quality of results and may be useful for computing uncertainties of integrated values
- Filling in the data is not a trivial process in the eddy covariance method – there is always a danger of bias
- Some of more established strategies to fill-in missing data are:
  - Regressions with backup instruments
  - Regressions with nearby sites (when appropriate)
  - Physical restrictions (energy budget, mass budget, *etc.*)
  - Lookup tables and AmeriFlux gap filling strategies
  - CO_2 daytime – light response curves for different GFAI
  - CO_2 nighttime – temperature, moisture, for different GFAI, Q_{10}
  - Combination of several methods
  - More sophisticated approaches, such as neural networks, *etc.*

After bad data have been removed, one should perform data gap inventory and fill in the missing periods in order to construct a seasonal or yearly picture of ecosystem exchange.

An inventory of bad data is important for getting an idea of the quality of results, and may also be useful for computing uncertainties of integrated values.

Filling in the data is not a trivial process in the eddy covariance method – there is always a danger of adding bias to the data.

Some of the established strategies for "filling in" missing data are: regressions with backup instruments; regressions with nearby sites; physical restrictions (energy budget, mass budget, *etc.*); lookup tables and AmeriFlux gap filling strategies; CO_2 daytime (light response curves for different green leaf area index, GFAI); CO_2 nighttime (temperature, moisture, respiration-temperature dependence, Q_{10} for different green leaf area index); *etc.*

It is important to note that nighttime data often need to be filled in separately from the daytime data for physiological reasons (for example, a different set of processes is responsible for CO_2 release/uptake during the day than that during the night), and because of turbulent exchange problems (see page 245 of this book).

References

Moffat, A., D. Papale, M. Reichstein, D. Hollinger, A. Richardson, *et al.*, 2007. Comprehensive comparison of gap filling techniques for net carbon fluxes. Agricultural and Forest Meteorology, 147: 209–232

Falge, E., D. Baldocchi, R. Olson, P. Anthoni, M. Aubinet, *et al.*, 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107(1): 43-69

Falge, E., D. Baldocchi, R. Olson, P. Anthoni, M. Aubinet, *et al.*, 2001. Gap filling strategies for long term energy flux data sets. Agricultural and Forest Meteorology, 107(1): 71-77

- Integration should be done after the data have been processed, corrected, quality controlled, validated, and storage term has been added to eddy flux
- Yearly CO_2 integrations are especially unforgiving, because two similar quantities (photosynthesis/uptake and respiration/release) are subtracted from each other
- Result is a relatively small number with relatively large uncertainties related to instrument performance, eddy covariance methodology, and gap filling
- Error analysis should be conducted to estimate uncertainties, and results should be presented as a range, or as a set of points with error bars

Integration should be done after data have been processed, corrected, quality controlled, validated, and a storage term has been added in cases when it is non-negligible.

Yearly CO_2 integrations are especially unforgiving, because two large, similar quantities (photosynthesis/uptake and respiration/release) are subtracted from each other. As a result, uncertainties due to instrument performance, eddy covariance methodology, quality control and gap filling, which appeared small or negligible in comparison with large hourly fluxes, now become relatively large in comparison with the small integrated seasonal flux number.

Error analysis is highly advisable at this stage, and can help to quantitatively estimate the impact of these uncertainties, and present the resulting integrated flux as a realistic range rather than as a single number.

References

Falge, E., D. Baldocchi, R. Olson, P. Anthoni, M. Aubinet, *et al.*, 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107(1): 43-69

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Billesbach, D., 2011. Estimating uncertainties in individual eddy covariance flux measurements: a comparison of methods and a proposed new method. Agricultural and Forest Meteorology, 151: 394–405

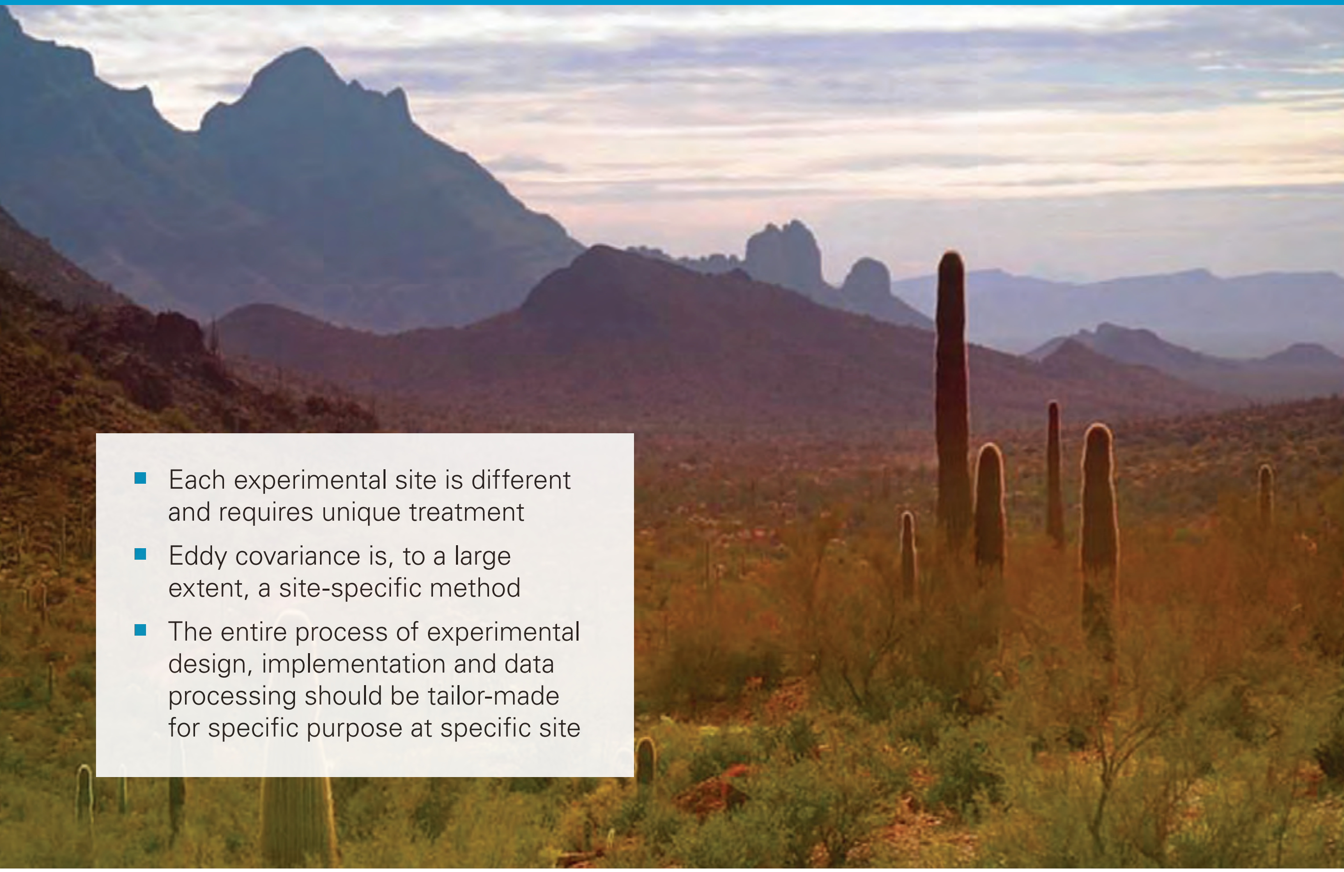
Ueyama, M., R. Hirata, M. Mano, K. Hamotani, Y. Harazono, *et al.*, 2012. Influences of various calculation options on heat, water and carbon fluxes determined by open- and closed-path eddy covariance methods. Tellus B, 64: 19048, 26 pp.

Part Four:

Processing Eddy Covariance Data

Section 4.11

Summary of Eddy Covariance Workflow



- Each experimental site is different and requires unique treatment
- Eddy covariance is, to a large extent, a site-specific method
- The entire process of experimental design, implementation and data processing should be tailor-made for specific purpose at specific site

The eddy covariance method provides measurements of gas emission and consumption rates, and also allows measurements of momentum, sensible heat, and latent heat fluxes integrated over areas of various sizes.

Eddy covariance is a statistical method to compute turbulent fluxes, and can be used for a variety of purposes. The specific applications of the eddy covariance method are numerous, and may require specific mathematical approaches and processing workflows.

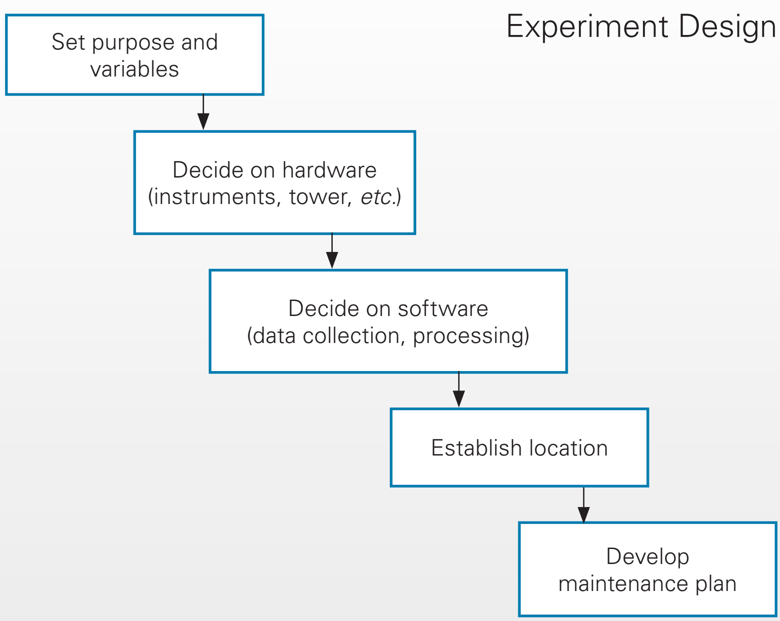
Because of this, there is no single 'recipe' to using the eddy covariance method. The need for individualized, customized approaches to each experiment is perhaps the most important feature of the eddy covariance approach. It is, to a large extent, a purpose-specific and site-specific method.

These purpose-specific and site-specific features also provide great built-in flexibility. In conjunction with user knowledge and understanding of the method and the study site, eddy covariance allows confident custom-fit measurements in multiple environments.

The eddy covariance workflow helps the researcher to take advantage of the flexibility and navigate through the entire complex process.

Proceeding step-by-step through the stages of the workflow will allow a researcher to properly design and implement the experiment, to correctly process, validate and analyze the data, and to provide reliable results satisfying the specific purpose.

More details on the workflow can be found in Parts 2-4 of this book, while a brief summary of the main parts follows.



The first part of the eddy covariance workflow is the experiment design stage. This stage consists of establishing the purpose, variables, instruments, software, location, and developing a maintenance plan. This stage is an opportunity to optimize time and costs, ensure continuous and consistent collection of high-quality data, and avoid numerous complications during the implementation and execution of the experiment.

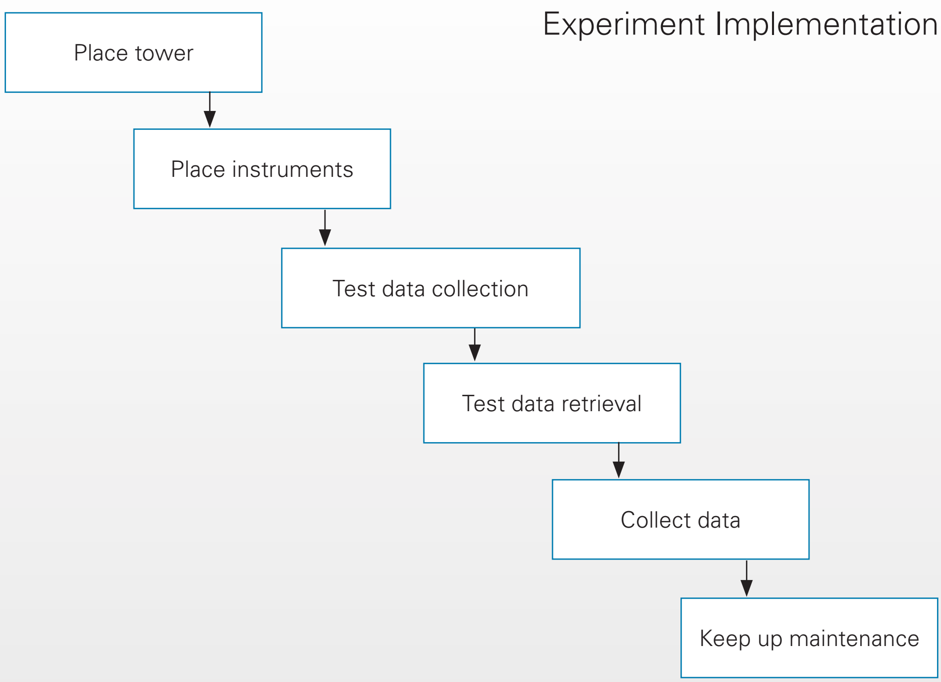
Experimental purposes can vary greatly, from scientific applications (multiple or single ecosystem studies, ocean studies, *etc.*) to industrial, agricultural and regulatory applications. The complexity of design, number of required variables, and instruments will also vary significantly depending on the purpose and application.

The experiment may be as complex as a comprehensive multi-layer ecosystem network tied into satellite observations and global modeling, or can be as simple as a small tripod with one sonic anemometer and one fast gas analyzer in the middle of a landfill.

Establishing the purpose will prompt a list of required variables and location, and will then lead to the selection of specific instruments and software.

Regardless of the type of the station, eddy covariance instruments should be fast, sensitive to small changes, and 'aerodynamic'. They should ideally be omni-directional and minimize flow distortion to sonic anemometer. The site should ideally be sufficiently large in size, and uniform.

A maintenance plan will also be required. Without well-planned and coordinated data checking and site visitations, data loss can significantly impair the results. The majority of sites may need bi-weekly or monthly visits to inspect the site and clean the instruments. Sites equipped with remote access can plan on checking instrument diagnostics and data quality remotely on a daily, weekly or bi-weekly basis, and reduce site visitation to an as-needed basis. Extremely remote sites can be designed to reduce visitations to monthly or bi-monthly, but this requires substantial investments in planning time and instrument selection.



Implementation involves placing the tower and instruments, testing data collection and retrieval, testing the processing program, and keeping up regular maintenance throughout the experiment. Establishing remote communications with the site will be of great benefit at this stage.

The tower should be preferably placed in the center of the study area, in such a way that the useful footprint from all wind directions is maximized. If there is one prevailing wind direction, the tower can be placed on the downwind edge of the area of interest to maximize the footprint.

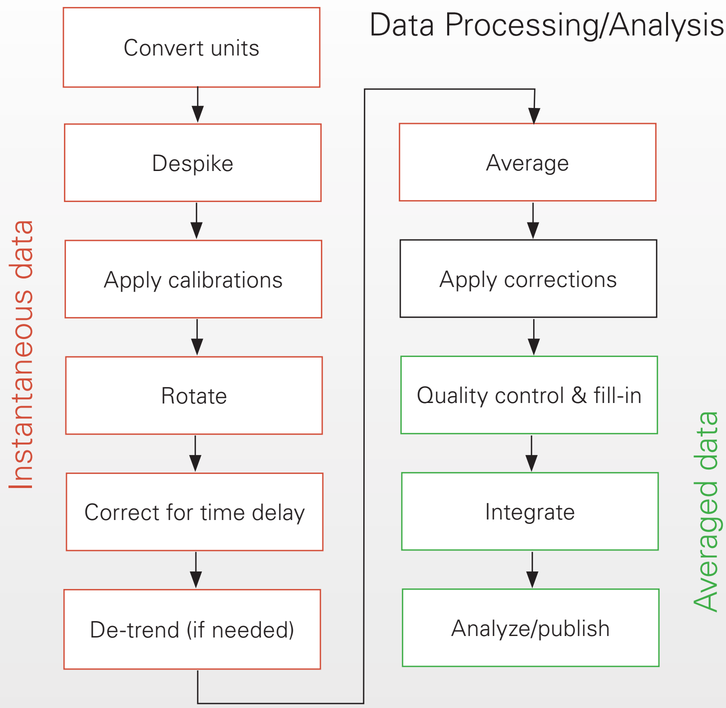
Instruments should ideally be placed at the maximum height that still allows for a useful footprint. The instruments should be oriented in relation to the tower, prevailing winds, and each other so that flow distortion to the sonic anemometer and gas analyzers is minimized.

Data collection should ideally allow for remote daily checks and real-time access and logging, but parallel backup collection of all data using removable on-site memory is highly recommended.

Testing data collection and retrieval should be thorough, to avoid data gaps. Instrument diagnostics and data values should be checked daily for the first few days of the experiment, and weekly for the first few weeks of the experiment to make sure all technical, weather and flux parameters are within reasonable ranges.

After successful implementation, further spot-check data inspections can be done bi-weekly or monthly, although automated daily summaries are useful and easy to implement at sites with remote fast access.

Regular maintenance should be kept up throughout the duration of the entire project, as scheduled during the planning stage, to avoid collecting bad data over long periods. Lack of properly scheduled verification of data and diagnostics, regular site visits and instrument maintenance are some of the most common pitfalls at this stage of the workflow.



The main parts of the data processing stage of the eddy covariance experiment are pre-conditioning of the raw instantaneous data, applying corrections and terms, conducting data quality control and gap filling, and validating the data.

Processing of instantaneous data involves unit conversion, despiking, applying calibration coefficients, rotating the sonic coordinates to obtain correct vertical wind speed, computing the time delay between vertical wind speed and scalar of interest, detrending gas concentration time series (if needed), choosing the best average time for flux data calculations, and averaging the instantaneous data.

Further processing includes frequency response and other corrections and terms, conducting quality control and gap filling, computing storage terms, and integrating long-term data.

Data validation can be done in a number of different ways, including: energy budget closure, cospectral analysis, results from back-up instruments, alternative flux methods, biomass data, light-response curves, *etc*. Initial data analysis involves careful verification of data, especially during nighttime, calm, and advection periods, and calculating uncertainties for integrated flux numbers.

While modern software packages significantly simplify the complex and iterative steps of eddy covariance data processing, it is important to realize that these programs may be able to compute flux numbers from instantaneous time series even in cases when the time series are mislabeled and processing steps are misplaced.

It is important to carefully look at instantaneous time series and double-check that patterns look reasonable and units seem correct. It is also important to carefully look at computed flux products to make sure that they are physically and physiologically reasonable.

Avoiding simply computing a number is an important part of using modern tools for automated flux data processing.

Part Five:

Overview of Alternative Flux Methods

- Environmental conditions may prevent using the eddy covariance method
- Instrument system is not fast enough for certain gases (*e.g.*, NH_3, VOC, *etc.*)
- Information is required other than that from eddy covariance (for example, soil respiration)
- Complimentary methods to add value, validation, and backup to eddy covariance

There are a number of situations where the eddy covariance method either cannot be used to measure fluxes, or is not the best method to do so.

These include environmental conditions with a very small area of study, predominantly low winds, complex terrain, single point flux sources, *etc*. For some gases, such as ammonia and volatile compounds, the available instrument systems may not be sensitive or fast enough to measure small changes at a fast rate.

The focus of the experiment itself may prevent the researcher from using the eddy covariance method; for example, when the focus is specific to only one of the components of the flux, such as soil respiration, or canopy transpiration.

In these situations, other methods become more useful scientific tools. They can also be used as complementary methods to add value, validation or backup to the eddy covariance method.

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Denmead, O., and M. Raupach, 1993. Methods for measuring atmospheric gas transport in agricultural and forest systems. In: Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. American Society of Agronomy

Burden, F., I. McKelvie, U. Forstner, and A. Guenther, 2002. Environmental Monitoring Handbook. McGraw-Hill Professional, 1100 pp.

Turbulence-based Methods

- **Eddy accumulation**
- **Relaxed eddy accumulation**
- Disjunct eddy covariance
- Relaxed eddy accumulation with injections
- *etc.*

Other Direct Tower Methods

- **Bowen ratio**
- **Aerodynamic**
- **Resistance**
- Surface renewal method
- Integrated horizontal flux
- Control volume
- *etc.*

Non-tower Methods

- **Chamber measurements**
  - soil
  - leaf
  - canopy
- Lysimeter
- Biological and soil sampling
- *etc.*

Some examples of the most frequently used alternative methods are listed in the illustration above. The following pages contain a quick overview of some of these methods; further details can be found in the literature sources listed throughout this section.

In addition to those listed above, there are also a number of other "direct" measurement methods to quantify fluxes, including modifications of established approaches and completely new methods.

Furthermore, there are a number of less direct approaches where models are combined with some field observations for tuning and verification. These include tall-tower top-down approaches, Lagrangian methods, fence-line monitoring, plume tracer methods, boundary layer and virtual towers, *etc.*

Finally, there are new and developing methods that are not widely used at present but show promise, such as new modifications of mass-balance techniques for small plots, scintillometry for H_2O fluxes, long-beam open-path devices, LIDARs, and RADARs.

References

A nice overview of various methods is provided in Denmead, O., 2008. Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere. Plant and Soil, 309 (1-2): 5-24

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Yamanoi, K., R. Hirata, K. Kitamura, T. Maeda, S. Matsuura, *et al.*, (Eds.), 2012. Practical Handbook of Tower Flux Observa-tions. Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo, Japan, 196 pp.

- Updrafts ($w'>0$) are physically sampled separately from downdrafts ($w'<0$)
- Sampling is proportional to the strength of updraft and downdraft
- After data have been accumulated over time, one is subtracted from the other
- Result is a net flux at the sampling level
- Difficult to sample proportionally
- Difficult to sample small changes
- Does not require fast gas analyzer
- Theoretically as accurate as eddy covariance

Similar to the eddy covariance method, the eddy accumulation method is based on measuring the turbulent transport of gases.

Unlike eddy covariance, however, eddy accumulation samples updrafts and downdrafts separately. This sampling is proportional to the strength of the updrafts and downdrafts, and after data have been accumulated over time, the updraft average concentration is subtracted from the downdraft average concentration. As a result, a net flux at the sampling level is obtained.

The main challenge for the eddy accumulation method is to make sure that sampling is actually proportional to the strength of the updrafts and downdrafts, and that small changes in concentration are measured adequately.

More information on this method is available in the literature listed below.

References

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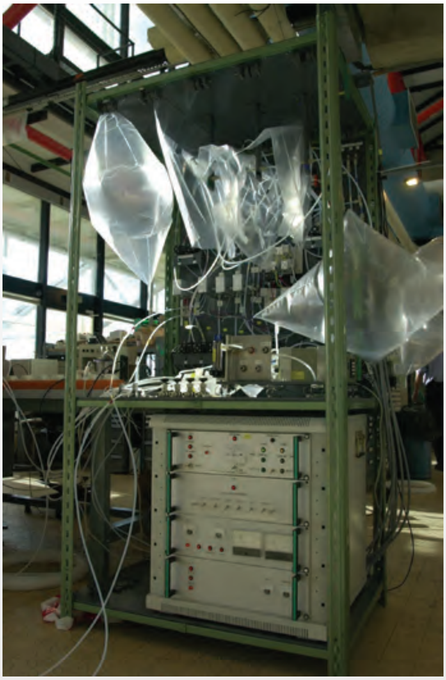
Katul G., P. Finkelstein, J. Clarke, and T. Ellestad, 1996. An investigation of the conditional sampling method used to estimate fluxes of active, reactive, and passive scalars. Journal of Applied Meteorology, 35: 1835-1845

Baldocchi, D., 2012. Advanced Topics in Biometeorology and Micrometeorology. Department of Environmental Science, UC-Berkeley, California: http://nature.berkeley.edu/biometlab/espm228



- Updrafts (w'>0) are physically sampled separately from downdrafts (w'<0)
- Sampling is not proportional to the strength of updraft and downdraft
- Sampling is done at a constant flow rate
- After data have been accumulated over time, one is subtracted from another
- Result is a net flux at the sampling level
- Difficult to correctly evaluate empirical coefficient required for calculations
- Number of corrections required; difficult to measure small changes

A modification of the eddy accumulation method is the relaxed eddy accumulation method. Like eddy accumulation, updrafts are sampled separately from downdrafts. This sampling, however, is not proportional to the strength of the updrafts and downdrafts, and is done at a constant flow rate. After data have been accumulated over time, the updraft average concentration is subtracted from the downdraft. As a result, a net flux at the sampling level is obtained.

The main challenge for the relaxed eddy accumulation method is to make sure that empirical coefficients are evaluated correctly, that corrections are properly applied, and that small changes are sampled adequately.

Both eddy accumulation and relaxed eddy accumulation methods, as well as the disjunct eddy covariance method, have some significant commonalities with eddy covariance. They rely on the theory of turbulent transport, and need a fast anemometer to measure wind at 10 Hz or faster. They also require a high-resolution gas analyzer that includes H_2O measurements (or drying of the sample gas). They require fast collection of large volumes of data, preferably need to be positioned in the middle of the site, and are quite expensive to execute.

However, these methods have two significant differences from eddy covariance. Firstly, they are not as widely used and accepted as the well-established eddy covariance approach. Secondly, they do not require a fast gas analyzer. The latter is perhaps the most important difference, especially when exotic gases with little available instrumentation are of interest.

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- Latent heat flux is computed from surface energy budget components and the Bowen ratio (ratio of sensible to latent heat fluxes)
- Turbulent exchange coefficients for heat & water assumed similar
- Turbulent exchange coefficient for gas assumed similar to water
- Actually, turbulent exchange coefficients are rarely similar
- Difficult to measure gradients without biases
- Bowen ratio may not hold in evenings and mornings (division by zero)
- Results rely heavily on soil heat flux and storage data: difficult to measure accurately
- There are several recent promising modifications of the method

The Bowen ratio method is a relatively old and well-established technique, initiated in the 1920s.

Water or gas fluxes are computed from surface energy budget components, and from a Bowen ratio (that is, the ratio of sensible and latent heat fluxes, which is assumed to be proportional to the ratio of temperature and humidity gradients between two measurement levels). The Bowen ratio method usually assumes that the turbulent exchange coefficients for heat/water/gases are similar, or are easily predictable.

The method was widespread in agricultural and flux studies for many years, and accumulated both positive and negative reviews. The method is easy to implement in the field, data processing is relatively simple, and equipment is not expensive, yet the method has a number of significant challenges.

One of the main challenges of the Bowen ratio method is related to the fact that the exchange coefficients are often dissimilar between temperature, water vapor and other gases, may be rather gas-specific and change dynamically. Another challenge is that it is difficult to measure gradients without biases. To minimize errors, the method often requires physical exchange of the two sensors between two levels. Computations may not hold in evenings and mornings, when the humidity gradient is near-zero (leading to a division by zero), or at any time of the day when temperature or humidity profiles are not consistent and have kinks. Additionally, results of the method rely heavily on soil heat storage data, which is difficult to measure correctly over a large flux footprint.

> To avoid confusion please note that what has been described thus far is the classic Bowen ratio method and not the more recent modified Bowen ratio method. The modified method is a combination of eddy covariance and traditional Bowen ratio methods. This technique is explained well in Liu, H. and T. Foken, 2001 (A modified Bowen ratio method to determine sensible and latent heat fluxes. Meteorologische Zeitschrift, Vol. 10, No. 1, 71-80).

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The original source for the classic Bowen ratio method is Bowen, I., 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Physics Review, 27: 779-787

Rosenberg, N., B. Blad, and S. Verma, 1983. Micro-climate: The Biological Environment. Wiley-Interscience Publishers: 255-257

- Flux is computed from wind profile and gas concentration profile
- Turbulent exchange coefficients for momentum and gas are assumed similar
- Alternatively, turbulent exchange coefficients must be known or modeled
- Difficult to determine turbulent exchange coefficient for momentum
- Turbulent exchange coefficients rarely similar, especially for rare gases
- Atmospheric stability significantly affects calculations

In the aerodynamic method, or family of methods, flux is computed from vertical profiles of wind speed and gas concentration. Turbulent exchange coefficients for momentum and the gas of interest are either assumed to be similar, are measured, or modeled.

The main challenges are related to difficulties in determining the turbulent exchange coefficient for momentum, and the fact that the turbulent exchange coefficients between momentum and gases are not always similar, and may in fact, be gas-specific.

Atmospheric stability can also significantly affect the flux calculated using the aerodynamic method.

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- Can be considered a version of aerodynamic method
- Computes flux from gradient and resistances to transport
- Must know aerodynamic and stomatal resistances
- May need to know soil surface resistance
- Resistances are difficult to measure

The resistance approach is considered, by some, to be a version of the aerodynamic method. Fluxes in the resistance approach are computed from gradients and resistances to transport.

Both aerodynamic and stomatal resistances are usually required to measure fluxes over live canopies. The soil surface resistance is often required as well, especially in sparse canopies.

With well-developed and tested models (such as Shuttleworth-Wallace and Penman-Monteith) and a good understanding of the exchange processes, the main challenge in using the traditional resistance approach is the great difficulties encountered while attempting to accurately measure the resistances.

Bowen ratio, aerodynamic and resistance methods have a lot in common. They rely on the theory of flux-gradient transport, require gas measurements at least at two levels, and preferably need to be positioned in the middle of the study site. They use high resolution gas analyzers, but do not require a fast sonic anemometer or fast gas analyzer. They are considerably less expensive when compared to turbulence methods.

Out of the three, the Bowen ratio was widely used in the 1970s-1990s, and is still probably the second-most popular method after eddy covariance, but it is much less utilized at the present time. Aerodynamic and resistance approaches are rarely used, although they remain theoretically sound in many environmental conditions.

References

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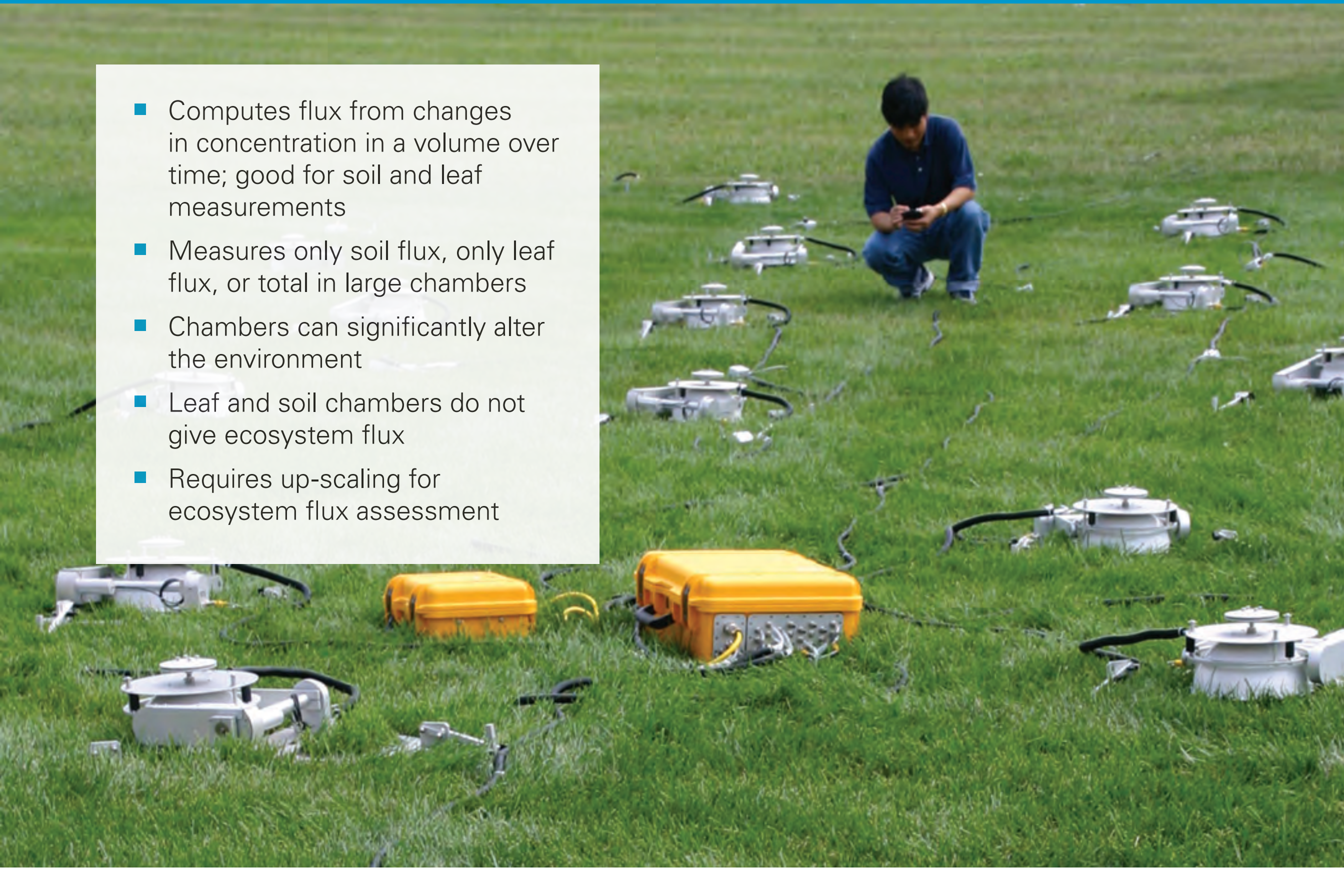
Monteith, J., 1963. Gas exchange in plant communities. Environmental control of plant growth. Evans L. (Ed.), Academic Press: 95-112

- Computes flux from changes in concentration in a volume over time; good for soil and leaf measurements
- Measures only soil flux, only leaf flux, or total in large chambers
- Chambers can significantly alter the environment
- Leaf and soil chambers do not give ecosystem flux
- Requires up-scaling for ecosystem flux assessment



Even though the chamber method is not a tower measurement, it is an important and widely used technique to measure fluxes over relatively small areas.

The classic chamber method computes flux from changes in concentration in a known volume over time, and is a good tool to measure soil flux, leaf-level and canopy fluxes.

Unlike tower flux measurement methods, the chamber method allows measurement of soil flux separately from canopy or leaf fluxes.

Large chambers can also include both soil and canopy, but they alter the environment significantly, and are used less often than small chambers.

While leaf and soil chambers do not measure ecosystem flux, they allow process-level analysis of the sources and sinks at different time and areal scales.

These measurements are useful for a deeper understanding and modeling of the factors governing the ecosystem gas exchange.

Comparison of chamber-based and tower-based fluxes requires the chamber fluxes to be up-scaled to the ecosystem level.

Successful up-scaling depends on the ecosystem variability, number of chambers used, and their placement within the ecosystem.

References

For more details please see Chapter 12 by Rochette and Hutchinson (pages 247-286) in Hatfield, J., and J. Baker (Eds.), 2005. Micrometeorology in Agricultural Systems. ASA-CSSA-SSSA, Madison, Wisconsin, 588 pp.

Elíoa, J., M. Ortegab, E. Chacónb, L. Mazadiegob, and F. Grandiac, 2012. Sampling strategies using the “accumulation chamber” for monitoring geological storage of CO_2. International Journal of Greenhouse Gas Control, 9: 303-311

Part Six:

Future Developments

- Scientific disciplines
- New applications
- Gas species
- Terrains
- Scale expansion

The eddy covariance method has been used in the field of micrometeorology for more than 30 years, and until recently, was practiced primarily by trained micrometeorologists, atmospheric physicists, physical engineers, *etc.*

In the early 2000s, important developments in instrument technology and pivotal efforts by FluxNet organizations led to significant progress in standardizing the eddy covariance method.

Eddy covariance became widely used by ecologists, climate scientists and other natural science professionals to study climate change, various aspects of ecosystem dynamics and gas exchange in natural, agricultural and urban ecosystems, including oceanographic and hydrological applications, and especially in carbon flux and trace gas studies. The number of tower sites increases every year, and new experiments are planned.

Industrial, agricultural, and regulatory institutions are also becoming more familiar with the advantages of direct gas emission measurements integrated over an area, as offered by the eddy covariance method.

In the following pages we will briefly look at some examples of near-term prospects for the method:

- ongoing expansion into scientific disciplines beyond micrometeorology
- expansion into industrial, agricultural and environmental monitoring and management fields
- expansion to many gas species beyond CO_2, to dust and aerosols
- measuring at difficult terrains (hillsides, mountains, urban, *etc.*)
- expansion into multiple geographic scales of measurements

- In the recent past, the use of eddy covariance method was often restricted by complexities with non-uniform terminology and by the lack of user-friendly, comprehensive, standardized software to provide the non-expert user a choice of settings and parameters to properly handle eddy flux data
- Now, disciplines such as ecology, entomology, biology, hydrology, ecosystem science, *etc*. are benefiting greatly from the use of modern standardized methodology, field procedures, equipment, and software

The use of the eddy covariance method was often restricted in the past by complexities with non-uniform terminology and the lack of user-friendly, all-inclusive software that would provide the non-expert user a choice of settings and parameters to properly handle the eddy flux data.

As these challenges are being successfully resolved by flux networks, scientific and educational institutions, disciplines such as ecology, entomology, biology, ecosystem science, hydrology, oceanography *etc*., benefit greatly from using the eddy covariance method for their specific applications.

These applications can range widely, from studies of cicada life cycles and related soil aeration to incorporating gas exchange into GIS modeling, or remote sensing validation of dissipation of methane through ocean waters and into the atmosphere.

It remains important for the researcher to understand the basic principles of turbulent flux transport measurements, the significance of well-planned station setup and regular maintenance, and to appreciate the intricacies of data processing.

However, multi-year specialization in the field of micrometeorology is no longer a prerequisite for successful use of the eddy covariance method in many scientific disciplines.

Further details and examples of scientific applications of the eddy covariance method can be found in Section 2.1.1.

- The eddy covariance methodology is now poised to become a valuable tool for applications outside of scientific studies: it is a direct, defensible, practical and repeatable method
- It can be quite useful for industrial, agricultural, and environmental monitoring and management, regulatory applications, carbon capture and sequestration, landfill management, carbon credit system, *etc.*

As the eddy covariance method becomes more uniform and accessible outside the scientific disciplines, it may be valuable for a number of industrial, agricultural and environmental monitoring and regulatory applications, and may become an important part of a future carbon credit system.

Some of the relevant advantages of the eddy covariance method are:

- Direct measurement
- Reliability and repeatability of the results
- Defensible measured value
- High temporal resolution
- Integrated over an area
- Many gas species can be covered
- Backed by scientific community
- Can be low-power, unattended, continuous

While there are a lot of potential non-scientific applications that can benefit from the eddy covariance method, some obvious examples are:

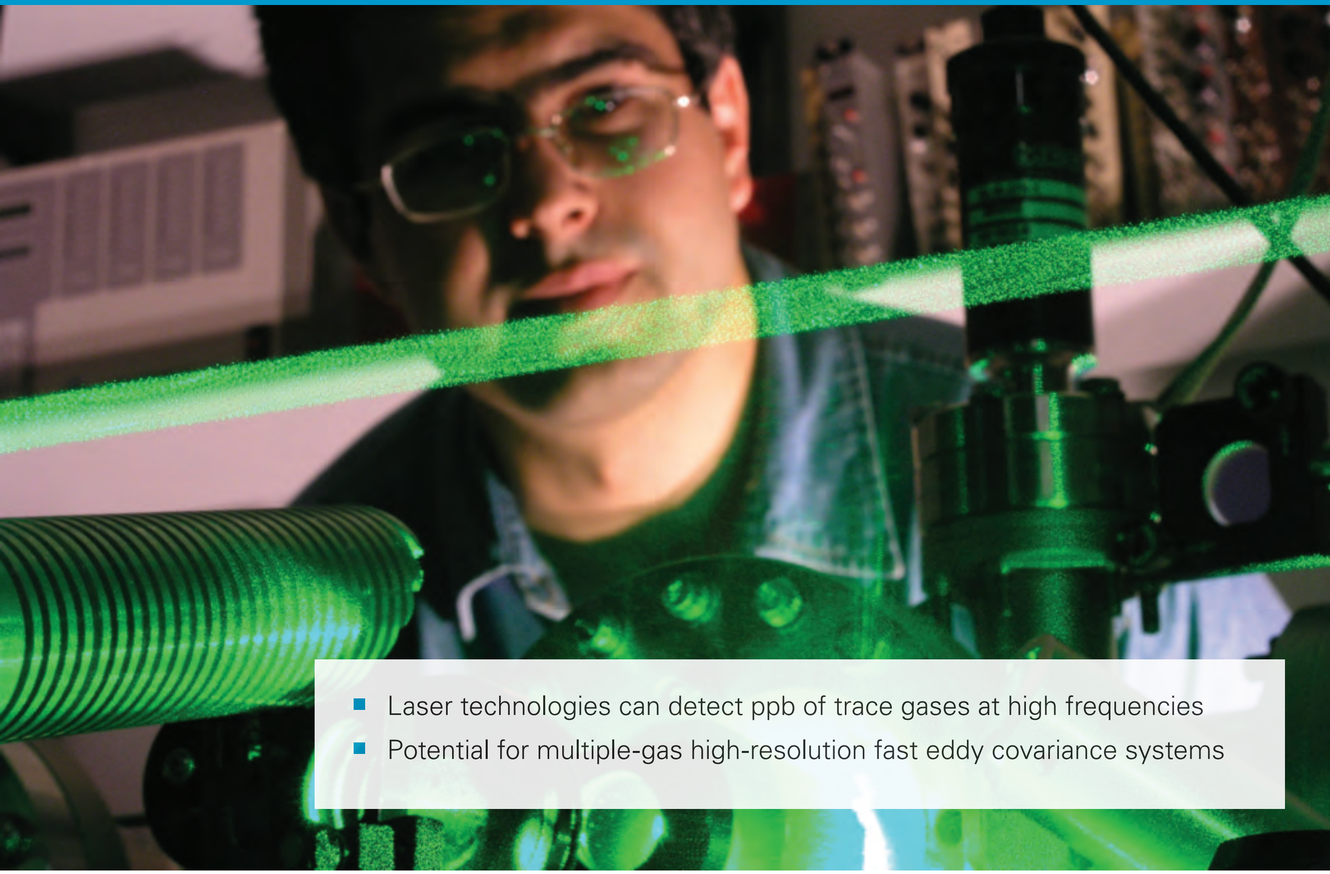
- Carbon capture and sequestration
- Emissions from industries, landfills, *etc.*
- Line efficiencies and leak detection
- Oil and gas industry applications
- Agricultural carbon sequestration
- Precision agriculture
- Irrigation and water use efficiencies
- Environmental emission monitoring
- Regulatory applications at city and state levels
- Carbon credits and budgets at city/state levels
- Emission verification by NGOs
- *etc.*

Additional examples of non-scientific applications of the eddy covariance method can be found in Sections 2.1.2 -2.1.4.

It is important to keep in mind that monitoring of mean gas concentrations is not the same as measuring the rates of gas emission. This distinction becomes quite important when results are used for business or regulatory decisions.

References

NETL's Carbon Sequestration Program - http://www.netl.doe.gov/technologies/carbon_seq



- Laser technologies can detect ppb of trace gases at high frequencies
- Potential for multiple-gas high-resolution fast eddy covariance systems

Fluxes of momentum, heat, carbon dioxide and water were the primary focus of eddy covariance until the mid-1990s. With advances in technological development, such as improvements in NDIR (non-dispersive infrared) approaches, adaptation of recent laser technologies (Wavelength Modulation Spectroscopy, *etc.*) to field gas measurements, and increased ability of fast digital processing and wireless low-power solutions, instruments are now able to rapidly detect several parts per billion concentration at high frequencies for many more gas species, with better accuracy, and with less power.

As a result, the eddy covariance method is positioned to compute fluxes from rare or multiple gas species in low-power open-path and enclosed systems, and shed more light on the processes affecting fluxes of such gases as methane, nitrous oxide, ozone, VOCs, carbon and water isotopes, *etc.*

The majority of modern instruments for non-CO_2 eddy covariance measurements still remain fundamental laboratory instruments adapted for outdoor use. However, this dynamic is rapidly changing as more instrument manufacturers realize the scale and importance of gas monitoring and flux measurements for scientific, industrial, agricultural and regulatory applications.

References

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**Photo CarboEurope*

- Further understand the complex flows
- Measure convergence and divergence
- Measure drainage flux, advection, and storage
- Use control volumes, multiplexed towers, transects, large eddy simulations, *etc.*

The latest scientific developments have enabled eddy covariance to be used in complex terrains (on hills, in cities, and under various flow obstructions).

In these difficult environments, eddy covariance studies rely on a deeper understanding of the complex flow, measurements of flow convergence and divergence, drainage flows, advection, and storage, as well as the use of control volumes, multiplexers, and other instrument-intensive techniques.

These developments are especially important for understanding and quantifying fluxes in ever-expanding urban territories and in sparsely studied mountainous regions. Both of these areas are vast, and have a very large impact on global fluxes of carbon, water, and aerosols.

Success of these applications is growing. For example, over 60 urban flux stations were deployed as of 2012 for both scientific and regulatory purposes (http://www.geog.ubc.ca/urbanflux). At least 25 additional stations operate in complex mountainous terrains across the globe.

References

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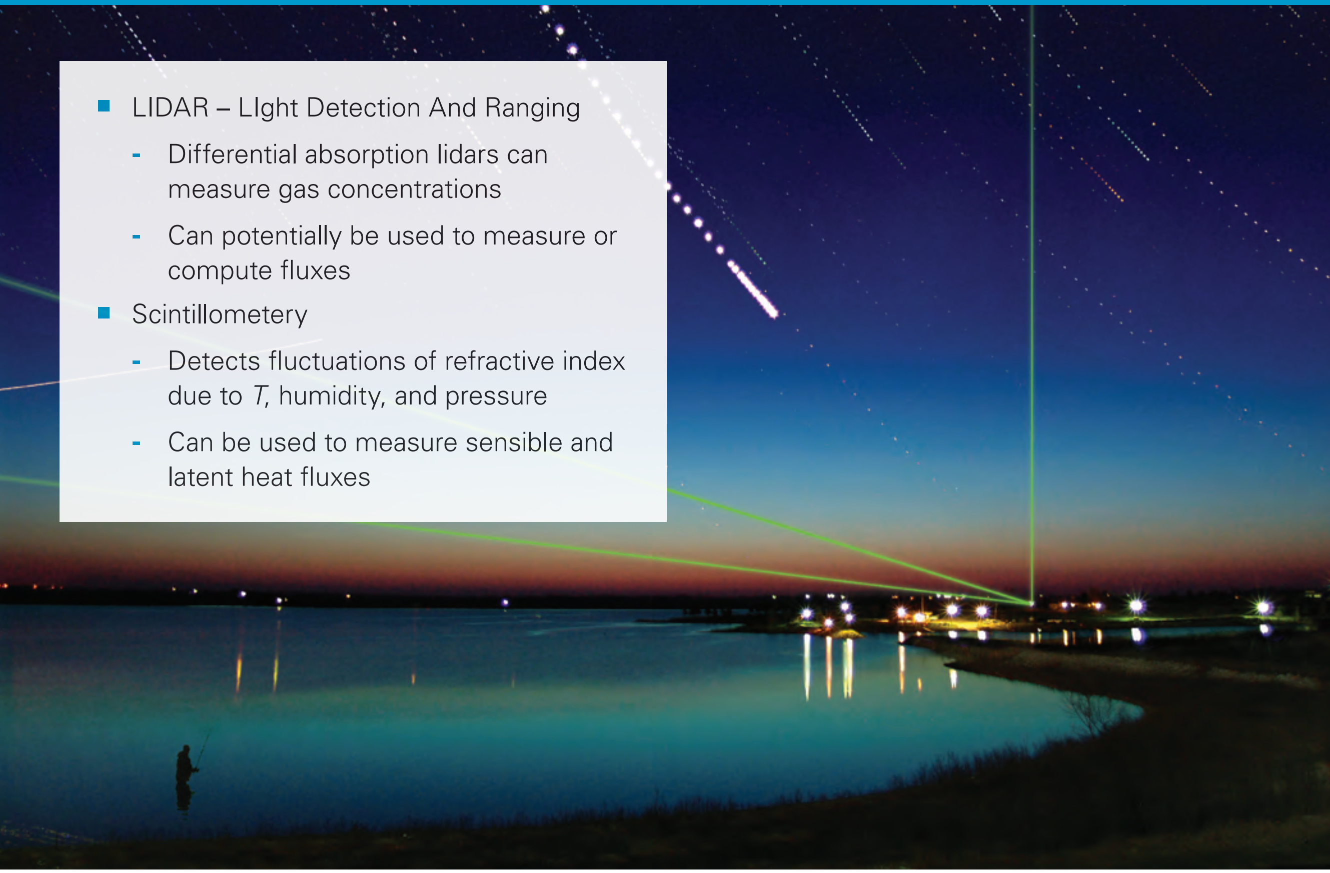


Classic tower flux measurements cover upwind footprints on the order of thousands of square meters or single square kilometers.

New technologies, such as LIDAR, scintillometers, and long-distance FTIR instruments can potentially be used to measure and compute gas fluxes from areas of many square kilometers, and from all wind directions.

Based on established eddy covariance principles and these emerging technologies, new methods can potentially be developed to be both fast and accurate, similar to eddy covariance, and have large spatial averaging independent of wind speed and direction, similar to LIDAR or Scintillometry.

LIDAR is an abbreviation for LIght Detection And Ranging, alternatively called 'laser radar'. The main types of LIDAR are:

- range finders – measure distances
- differential absorption – gas concentrations
- dopplers – measure velocity of a target

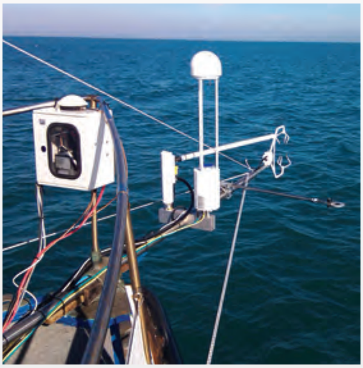
In addition to flux measurement potential, LIDAR can also be used to measure average concentration of the entity of interest in a vertical column in the lower atmosphere, and can measure average concentrations over two-dimensional planes above the surface.

Scintillometers have recently been used for detecting sensible heat flux over large territories, with reasonable success, and for detection of water vapor flux, with some limited success.

These and other long-range methods currently require a substantial amount of modeling, empirical calibration and adjustment of the calculations, but they have good future potential, when directness and resolution challenges can be successfully addressed through technology.

Airborne

Shipborne



Vehicle-mounted

Flux measurements conducted using airplanes, helicopters, drones, ships, land vehicles (both stationary and moving), *etc*. are expanding their scope and frequency, and may cover areas of hundreds to thousands of square kilometers.

Fluxes, concentration gradients and transects can all be measured by mobile platforms with modern instrumentation. High-precision mapping of the fluxes and mass flows may be possible when using fast-response systems in conjunction with fast-response GPS devices, in addition to more traditional concentration mapping typically performed using slow systems.

Special networks are being formed, such as NAERS, the Network of Airborne Environmental Research Scientists (http://www.naers.org/) to advance new types of environmental research.

In conjunction with newly developed instrumentation and data from tower networks, mobile measurements can also help tower measurements be scaled up to a regional level.

References

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Mahrt, L., 1998. Flux sampling errors for aircraft and towers. Journal of Atmospheric & Oceanic Technology, 15(2): 416-429

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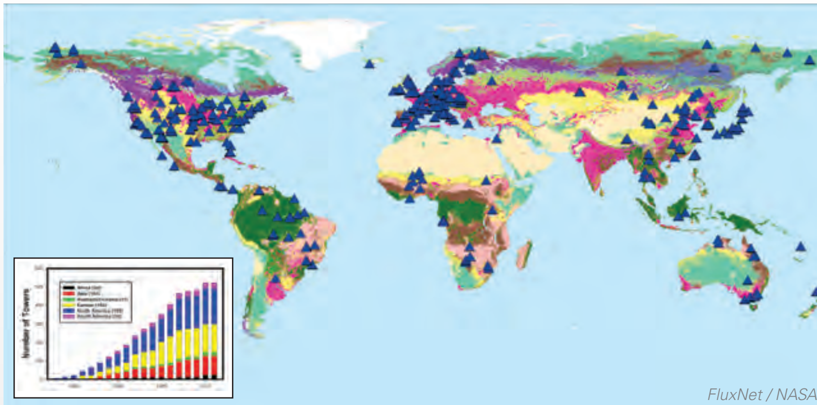
Vickers, D. and L. Mahrt, 1997. Quality control and flux sampling problems for tower and aircraft data. Journal of Atmospheric and Oceanic Technology, 14: 512-526



- Need for spatial resolution at all scales
- Local: multiplexed systems for soil, multiple towers, remote field sensing
- Regional: regional networks (ICOS, NEON, AmeriFlux, AsiaFlux, *etc.*)
- Global: global network (iLEAPs/FLUXNET), standardized databases, modeling
- Earth observations intranet

Flux networks unite eddy covariance research with varied spatial resolution and coverage. Data from many sites are collected in a single archive. They are collected with uniform collection and reduction methods, and are stored and maintained with consistent formats. These data are invaluable for carbon cycle and global climate modeling, and may have multiple uses in other disciplines.

Network archives cover ecosystem flux and related parameters on a variety of scales, from field scale (*e.g.*, short tower data, multiplexed systems for soil, field-size remote sensing) to regional scale, with networks such as ICOS, NEON, InGOS, AmeriFlux, FluxNet-Canada, *etc.*, and finally globally, with networks like iLEAPs and FluxNet. The websites of global and regional flux networks listed below help access general network descriptions, recent publications, field data sets, and other useful information.

References

FluxNet - http://fluxnet.ornl.gov
AmeriFlux - http://public.ornl.gov/ameriflux
AsiaFlux - http://www.asiaflux.net
Carbo-Africa - http://www.carboafrica.net
CarboEurope IP - http://www.carboeurope.org
Carbomont - http://www.uibk.ac.at/carbomont
ChinaFlux - http://www.chinaflux.org/en/index
FluxNet-Canada - http://fluxnet.ccrp.ec.gc.ca
ICOS - http://www.icos-infrastructure.eu
IMECC - http://imecc.ipsl.jussieu.fr
InGOS - http://www.ingos-infrastructure.eu
JapanFlux - http://www.japanflux.org/link_E.html
KiwiFlux by WaiBER - http://waiber.com
KoFlux - http://adsabs.harvard.edu/abs/2002AGUFM.B71C..08K
LaThuile Data Set - http://www.fluxdata.org
NEON - http://www.neoninc.org
NitroEurope - http://www.nitroeurope.eu
NordFlux - http://www.nateko.lu.se/nordflux
OzFlux - http://www.ozflux.org.au
Stable Isotope Network - http://basin.yolasite.com
Swiss FluxNet - http://www.swissfluxnet.ch/
ThaiFlux - http://compete.center.ku.ac.th/HomeFlux.htm
Urban Flux - http://www.geog.ubc.ca/urbanflux

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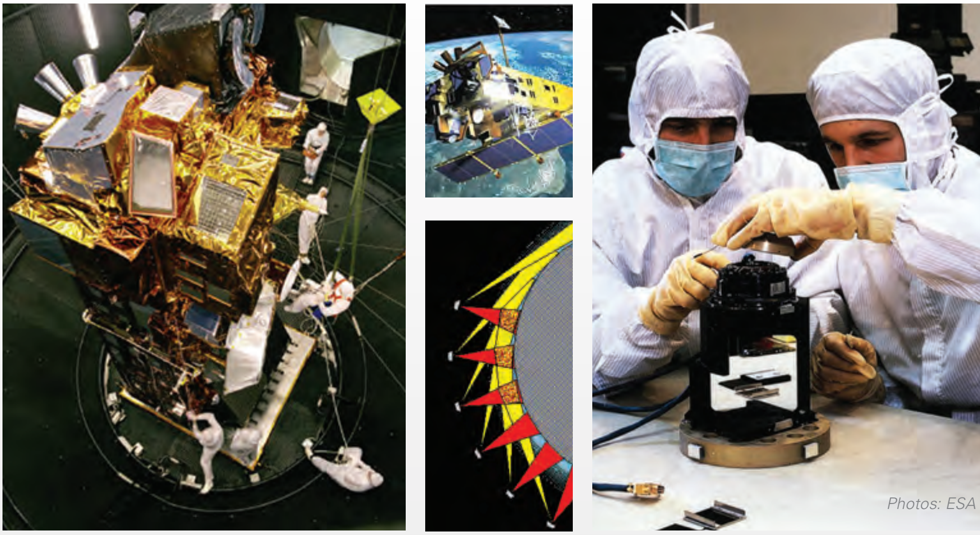

Photos: ESA

- Spectral measurements from space could potentially observe dynamic content of entire atmosphere – the ultimate goal of tower networks
- The working example is SCIAMACHY – orbital imaging spectrometer

Spectral measurements from space can potentially observe dynamic content of the entire atmosphere – the ultimate goal of tower networks.

Future satellite measurements require development and testing of instruments and data collection systems on the ground, which later could be used for remote sensing.

Comparison of field and satellite data, called ground truthing, is very important for developing this approach. In time, satellite instrument systems could reliably determine the dynamics of gases, aerosol and dust for the planet as a whole.

One pioneering example of a system such as this is the orbital imaging spectrometer SCIAMACHY – Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY.

Although they do not use eddy covariance, such observations and measurements can be used in combination with tower measurements to compute fluxes at both high temporal resolution (from eddy covariance) and broad spatial coverage (satellite data) at the same time.

References

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Part Seven:

Summary of Eddy Covariance Method

- Eddy covariance is a micrometeorological technique to measure vertical turbulent fluxes in the atmospheric boundary layer: nearly-direct, theoretically solid and proven, very flexible in applications, verifiable by other techniques
- Widely used in micrometeorology to measure H_2O, CO_2, CH_4, heat, momentum, increasingly being used to measure N_2O, NO_x, NH_3, O_3, isotopes, bVOCs and other gases
- Requires a number of assumptions and corrections, demands careful design, instrument selection, execution and processing custom-fitted to the specific purpose at the specific experimental site
- Continuously develops on conceptual and instrument levels to allow wider applications in more environments

In this book we put together simple guidelines to help the non-expert understand general principles, requirements, applications, key steps in experimental design, and data processing of the eddy covariance method.

The goal of this book is to promote further understanding of the method via more advanced sources, such as other micrometeorology textbooks, journal papers *etc*., and to help the reader develop an observational platform for their specific needs in the areas of science, industry, agriculture, environment and regulatory monitoring.

In summary, eddy covariance is a micro-meteorological technique to measure vertical turbulent fluxes in the atmospheric boundary layer. It is nearly-direct, theoretically solid, proven over time, very flexible in applications, and verifiable by other techniques.

The eddy covariance method provides measurements of gas emission and consumption rates, and allows measurements of momentum, sensible heat, and latent heat (*e.g.*, evapotranspiration, evaporative water loss, *etc*.) fluxes integrated over areas of various sizes.

Fluxes of H_2O, CO_2, CH_4, N_2O and other gases are characterized above soil and water surfaces, plant canopies, and urban or industrial areas, from a single-point measurement using permanent or mobile stations.

The method requires a number of assumptions, corrections, and terms. It demands careful experimental design, instrument selection, execution and processing fit to a specific purpose for the specific experimental site.

Eddy covariance continues to develop on conceptual and instrument levels. It is expanding in application scope, and is being used in numerous diverse environments.

- Eddy covariance is of great use to many non-meteorological sciences, industry, agriculture, environmental management and regulatory monitoring, when energy, water or gas exchanges and balances are of interest
- Major flux measurement networks already exist to provide global synthesis, and allow interpretation of one particular site in the context of world-wide observations, thus providing a new and invaluable scientific tool

Eddy covariance is potentially of great use to many non-meteorological sciences, industrial monitoring, agricultural research, carbon storage and sequestration, landfill and environmental management, and any type of regulatory or other monitoring of actual emission rates when energy, water or gas exchanges and balances are of interest.

Major flux measurement networks already provide open access to uniform experimental data from hundreds of tower sites to a variety of natural sciences. These network observations are an invaluable global scientific tool, which did not exist 20 years ago.

Today, they provide modelers and field researchers with a wide range of opportunities, from interpretation of a particular eddy covariance experiment in the context of world-wide observations to a global synthesis of local and regional flux processes.

The guides and protocols from such networks are based on multiple years of experience in numerous locations. In conjunction with modern software programs, these can help a non-expert user navigate through the eddy covariance method relatively easily.

However, it remains critical for the researcher to understand the basic principles of turbulent flux transport, to appreciate the crucial importance of detailed experimental planning, instrument selection and regular maintenance, and to be aware of the intricacies of data processing.

This book provides many key details of the method's workflow, as well as simple explanations of its most important theoretical aspects and practical steps. The author, editors, and reviewers of the book hope to have made the eddy covariance method accessible and useful to non-micrometeorologists without oversimplifying its complex mathematical and physical nature.

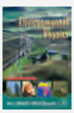
We intend to keep the content of this book current, so please do not hesitate to write with any questions, updates and suggestions to 'george.burba@licor.com' with the subject '2013 EC Book'.

Part Eight:
Useful Resources

Eddy Covariance: A Practical Guide to Measurement and Data Analysis, 2012. By M. Aubinet; T. Vesala; and D. Papale (Eds.). Springer-Verlag

Micrometeorology, 2008. By T. Foken. Springer-Verlag

Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, 2008. By X. Lee; W. Massman; B. Law (Eds.). Springer-Verlag



Principles of Environmental Physics, 2007. By J. Monteith and M. Unsworth. Academic Press

Microclimate: The Biological Environment. 1983. By N. Rosenberg, B. Blad, S. Verma. Wiley Publishers

Introduction to Micrometeorology (International Geophysics Series). 2001. By S. Pal Arya. Academic Press

References

Additional useful books and dissertations on the topics of eddy covariance methodology and underlying principles include:

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http://nature.berkeley.edu/biometlab/espm228

AmeriFlux Guidelines For Making Eddy Covariance Flux Measurements, by W. Munger and H. Loescher, AmeriFlux
http://public.ornl.gov/ameriflux/measurement_standards_020209.doc

FluxNet-Canada Measurement Protocols
http://research.eeescience.utoledo.edu/lees/papers_PDF/FluxnetCANADA_Protocols.pdf

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http://www2.ffpri.affrc.go.jp/labs/flux/manual_e.html

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The following are also instructive:

Corrections to Sensible and Latent Heat Flux Measurements, 2012. By T. Horst.
http://www.eol.ucar.edu/instrumentation/sounding/isfs/isff-support-center/how-tos/corrections-to-sensible-and-latent-heat-flux-measurements

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http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe

Open Path Eddy Covariance System Operator's Manual CSAT3, LI-7500, and KH20, 2004-2006. By CSI Inc.
http://www.campbellsci.com/documents/manuals/opecsystem.pdf

Summary and Synthesis of Recommendations of the AmeriFlux Workshop on Standardization of Flux Analysis and Diagnostics, 2002. By B. Massman, J. Finnigan, and D. Billesbach: http://public.ornl.gov/ameriflux/workshops/workshop-20020827-CorvallisOR-summary.doc

FLUXNET - http://fluxnet.ornl.gov

GCP - http://www.globalcarbonproject.org

ICOS - http://www.icos-infrastructure.eu

iLEAPs - http://www.ileaps.org

InGos - http://www.ingos-infrastructure.eu

NEON - http://www.neoninc.org

References

In addition to the global and large-scale efforts shown above, a recently compiled list of regional flux networks and specialized ecosystem study networks involving eddy covariance flux measurements is given below:

AmeriFlux - http://public.ornl.gov/ameriflux

AsiaFlux - http://www.asiaflux.net

Carbo-Africa - http://www.carboafrica.net

CarboEurope IP - http://www.carboeurope.org

Carbomont - http://www.uibk.ac.at/carbomont

ChinaFlux - http://www.chinaflux.org/en/index

FluxNet-Canada - http://fluxnet.ccrp.ec.gc.ca

IMECC - http://imecc.ipsl.jussieu.fr

JapanFlux - http://www.japanflux.org/link_E.html

KiwiFlux - http://www.ozflux.org.au/meetings/july2012/Thursday/1_JohannesLaubach.pdf

LaThuile Data Set - http://www.fluxdata.org

NitroEurope - http://www.nitroeurope.eu

NordFlux - http://www.nateko.lu.se/nordflux

OzFlux - http://www.ozflux.org.au

Stable Isotope Network - http://basin.yolasite.com

Swiss FluxNet - http://www.swissfluxnet.ch/

Thai-Flux - http://compete.center.ku.ac.th/HomeFlux.htm

Urban Flux - http://www.geog.ubc.ca/urbanflux

- Over the past 40+ years LI-COR has developed significant expertise and resources related to eddy covariance measurements in the form of teaching and training, knowledge base, and technical and scientific support
- Teaching and training resources include intensive eddy covariance courses taught throughout the year, sets of on-line webinars available at any time, ongoing technical tips, and tours of LI-COR Experimental Research Station

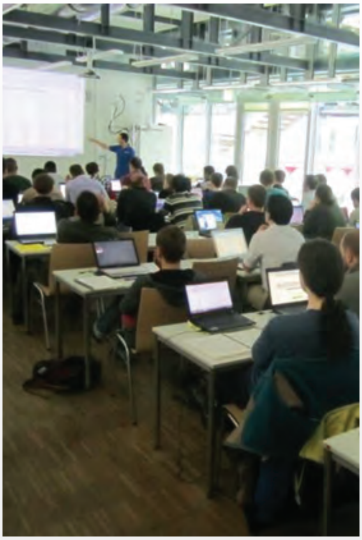
LI-COR has specialized in various kinds of flux and gas emission measurements for over 40 years. The Science & Technology and Technical Support staff includes many post-graduate experts in flux measurements, with significant field experience in eddy covariance.

This experience is embodied in the substantial resources available at LI-COR on eddy covariance measurements in the form of teaching, knowledge base, and support.

Teaching and training

- *Eddy covariance training courses*. Intensive multiday courses cover all major aspects of the measurements, from theory and experimental planning to supporting measurements and data processing. The courses are taught multiple times throughout the year across the globe. The schedule of upcoming courses and a registration form can be found at:
  - www.licor.com/ec-training (global)
  - www.licor.com/europe-training (Europe only)
- *Eddy covariance webinars*. Webinars are available on-line on multiple specific, narrow focused aspects of gas flux and emission measurements. The eddy covariance method is described in the webinars listed at the following site:
  - www.licor.com/ec-webinars

  Other gas flux measurements are covered in these webinars:
  - www.licor.com/env/webinars
- *Technical tips* on Facebook and the LI-COR website cover frequently asked questions, specifics of instrument handling, and unusual applications:
  - www.facebook.com/LICORenv
  - www.licor.com/env/newsline/category/tech-tips



- Knowledge base includes white papers, application notes and brochures available on-line, conference presentations from LI-COR authors, and lists of recent journal and conference papers on specific topics, and recent case studies and applications

- *Guided tours of LI-COR Experimental Research Station* (LERS) show a fully equipped continuously running eddy covariance station used for development and testing of new instrumentation and methods.

  Tours are available to groups and individuals visiting the LI-COR headquarters in Lincoln, Nebraska, for eddy covariance or photosynthesis classes, or by individual arrangement. Please see Appendix 1 in this book for details on LERS.

Knowledge base

- *White papers, application notes, and brochures* are available on specific topics of gas emission measurements on-line. Some recent examples are in the following webpages:
  - www.licor.com/ec-brochures
  - www.licor.com/ec-notes

- *Conference presentations by LI-COR* with the latest instrument developments, theoretical and methodological findings. Over 90 conference presentations on various aspects of eddy covariance are available from LI-COR authors as of 2012; some examples can be found here:
  - www.licor.com/ec-posters
  - www.licor.com/7200-posters
  - www.licor.com/7700-posters
  - www.licor.com/7500-posters

- *Journal and conference papers.* Over 9000 journal papers cite LI-COR instrumentation using the eddy covariance method. A few recent examples for a particular instrument or a method can be found on the following websites:
  - www.licor.com/ec-pubs
  - www.licor.com/7200-references
  - www.licor.com/7500-references
  - www.licor.com/7700-references

- Technical and scientific support includes direct assistance by phone, e-mail and on-line, environmental forum, on-line eddy covariance station interactive "design-your-own-system", comprehensive EddyPro flux processing website, and presence and availability of staff at all major environmental conferences

- *Case studies* and examples of recent application across the globe can be found at:
  - www.licor.com/ec-map

Technical and scientific support

- *Technical and scientific support by phone or e-mail*, as well as manuals and current software can be accessed at:
  - www.licor.com/ec-support
- *LI-COR Environmental Forum* is available for informal discussions on various aspects of flux measurements for flux researchers and LI-COR staff:
  - www.licor.com/env/forum
- *Design-You-Own Station* is an online interactive tool to help devise a customized eddy covariance station depending on particular research application and related specific needs for supporting biometeorological data:
  - www.licor.com/ec-design
- *EddyPro webpage* is a resource to use for eddy covariance flux processing. It is equipped with programs, help, manuals and examples:
  - www.licor.com/eddypro
- *Presence at all major scientific conferences*, related to gas flux measurements, with experts available for informal communication.

Appendix 1:

Example of Eddy Covariance Site

Overview of LI-COR Experimental Research Station

- LI-COR Experimental Research Station (LERS) is a multi-purpose experimental site
- Review of LERS provides a useful practical example of the three main stages of the eddy covariance experiment: design, implementation and data processing

The LI-COR Experimental Research Station (LERS) is a multi-purpose outdoor research facility, designed to accommodate engineering and scientific experiments and tests, technical support training and exercises, LI-COR multi-day courses on eddy covariance and photosynthesis, *etc.*

LERS collects continuous year-round CH_4, CO_2, and H_2O data, heat and momentum fluxes from open-path and enclosed gas analyzers, fast and slow air temperatures and humidity, atmospheric pressure, 3-D wind speed and direction, turbulence parameters, supporting biometeorological data, *etc*. There are 16 resources available to reserve (*e.g.*, towers, booms, plots, *etc.*), 8 buried gas calibration lines, 32 power ports and 16 Ethernet access points. Resources at LERS can be reserved using the same on-line reservation system used for other equipment.

The eddy covariance station is an important part of the total facility, and looking at the actual design and implementation of the station within a much larger structure may be helpful in developing a feel for the intricacies of the station design. It may also help to better understand the scope of efforts needed during planning and long-term deployment.

I. Design

- Purpose and variables
- Selection of hardware
- Selection of software
- Establishing location
- Maintenance plan

II. Implementation

- Tower placement
- Instrument placement
- Testing data collection
- Testing data retrieval
- Collection of data
- Continuous usage and maintenance

III. Data processing, display and use

The core of the LERS flux station is similar to a Full Eddy Station (described in Section 2.1), although there are many more instruments, towers and experimental plots at LERS than would be at a typical Full Eddy Station.

The specific purpose of the core eddy station at LERS is *to provide reference CH_4, CO_2, and H_2O fluxes and concentrations using established instrumentation for the tests of new instruments and methods*. However, since the facility is used by many people for many different purposes, the specific design, implementation and rules of use become quite important in assuring continuous high quality data collection.

References

For detailed protocols of a much more complex facility, please refer to the National Ecological Observatory Network (NEON) available at: http://www.neoninc.org/documents/all

Products	**Variables**
Primary products and variables - used as references for all the tests	
Open-path CH_4 flux	Fast and mean CH_4 densities, fast vertical wind, sensible heat flux, open-path H_2O flux, mean air temperature, mean air humidity
Open-path CO_2 flux	Fast and mean CO_2 densities, fast vertical wind, sensible heat flux, open-path H_2O flux, mean air temperature, mean air humidity
Open-path H_2O flux	Fast and mean H_2O densities, fast vertical wind, sensible heat flux, mean air temperature, mean air humidity
Enclosed CO_2 flux	Fast dry mole fraction for CO_2, fast vertical wind speed, fast cell air temperature, fast cell air pressure, flow rate
Enclosed H_2O flux	Fast mole fraction for H_2O, fast vertical wind speed, fast cell air temperature, fast cell air pressure, flow rate
	Mean CH_4 density
	Mean CH_4 dry mole fraction
	Mean CO_2 density
	Mean CO_2 dry mole fraction
	Mean H_2O density
	Mean H_2O mole fraction
Secondary products and variables - needed to compute or correct primary products	
Sensible heat flux	Fast and mean ambient air temperature, fast vertical wind speed, mean horizontal wind speed, mean air humidity
Momentum flux	Fast and mean vertical and horizontal wind speeds
	Multiple instrument diagnostics
	Mean wind speed
	Mean wind direction
	Mean air temperature
	Mean air humidity
	Mean atmospheric pressure
Auxiliary variables - to help explain behavior of primary and secondary products	
	Incoming global radiation
	Net radiation
	PAR
	Soil heat flux
	Soil temperature
	Soil moisture
	Precipitation

Variables	Instruments
Fast vertical wind, sensible heat flux, momentum flux, fast and mean air temperature, mean wind speed and direction	3-D Sonic Anemometer, Gill R3-50
Open-path CH_4 flux, fast and mean CH_4 densities, mean CH_4 mole fraction, mean atmospheric pressure	Open-path CH_4 gas analyzer, LI-7700
Open-path CO_2 flux, fast and mean CO_2 density, mean atmospheric pressure	Open-path CO_2/H_2O fast gas analyzer, LI-7500A
Open-path H_2O flux, fast and mean H_2O density, humidity	
Enclosed CO_2 flux, fast and mean dry mole fraction of CO_2, fast cell air temperature, fast cell air pressure, flow rate	Enclosed CO_2/H_2O fast gas analyzer, LI-7200
Enclosed H_2O flux, fast and mean mole fraction of H_2O, fast cell air temperature, fast cell air pressure, flow rate	
Multiple instrument diagnostics	All of the above
Incoming global radiation	Pyranometer, LI-200
Net radiation	Net Radiometer, NR-Lite
PAR	Quantum sensor, LI-190
Soil heat flux	Soil heat flux plates, Hukseflux-HFP01
Soil temperature	Soil temperature probes, 7900-180
Soil moisture	Theta probes, ML2X
Precipitation	Precipitation bucket, TR-525 USW
Logging the data	All data integrated into a GHG file on LI-7550 logger
Transferring the data	All data are transferred hourly to a PC via Ethernet
Processing the data	All data processed automatically with EddyPro

In order to satisfy the main purpose of the experiment, the core station should provide a number of primary products and variables (*e.g.*, fluxes and concentrations) that will be used as established references for newly developed instruments and methods.

These products consist of open-path CH_4, CO_2 and H_2O fluxes, enclosed CO_2 and H_2O fluxes, as well as a number of variables including mean gas densities and mole fractions (see top portion of the table on the preceding page).

However, full computation of gas flux also requires sonic corrections, frequency response and density corrections. Each of the corrections requires additional inputs beyond raw fluxes and gas concentrations.

Sonic correction requires knowledge of mean air temperature and humidity, and mean horizontal wind speed.

Webb-Pearman-Leuning density terms require a knowledge of sensible heat fluxes, water vapor fluxes, and concentrations and temperature means.

Frequency response corrections and closely-related cospectral analysis require knowledge of momentum flux and fast components of the wind speed.

Multiple instrument diagnostics are also required to make sure that core reference instruments operate properly.

All of these suggest a list of secondary products and variables needed to compute and correct the primary products.

Additional variables may be needed to help explain the behavior of primary and secondary products and variables, as well as to satisfy other non-eddy covariance applications of LERS.

The most important products and variables for the core eddy station at LERS are listed in the table on page 296.

Note however, that we do not presently measure gas concentration profiles at our site, because measurement heights are relatively low (2-4 meters), canopy height is very low (5-15 cm), and local weather is generally quite windy. These conditions usually lead to negligible flux storage at the site.

Temporary concentration profile measurements conducted at this site confirmed that gas flux storage here is almost always zero.

- Close-up of the core fast instrumentation, and booms for additional test instruments
- Prevailing winds at the site are North-South and booms are oriented East-West

In addition, we do not measure canopy characteristics (such as canopy surface temperature, leaf area, leaf wetness, canopy light interception and absorption, *etc*.), because main purpose of our experiment does not require these variables. The profiles and canopy measurements can be implemented if needed for a specific test, but are not part of the core permanent data collection system.

After the list of products and variable was created to suit the purpose of the experiment, the choice of hardware was fairly easy.

Since LI-COR provides complete integrated eddy covariance stations at different levels of complexity (from minimal to full stations; see Section 2.1 for details), we simply chose the open-path 3-gas system with standard biometeorological package. This system was augmented with an enclosed gas analyzer.

In this system the fast data are collected by the LI-7550 fast logger, and slow biomet data are initially collected by a Sutron 9210XLite logger and then transferred to the LI-7550, so that all fast and slow data are integrated into a single GHG package.

The GHG file package that includes both flux and biomet data is then transferred from the tower to the remote computer via Ethernet. The backups of the data files are also kept at the tower on removable USB memory for added safety.

Software selection was also quite straightforward, since LI-COR developed the EddyPro flux processing package. EddyPro is used at LERS to process fast and slow data, and to produce final fully corrected fluxes, diagnostics, weather, and soil parameters.

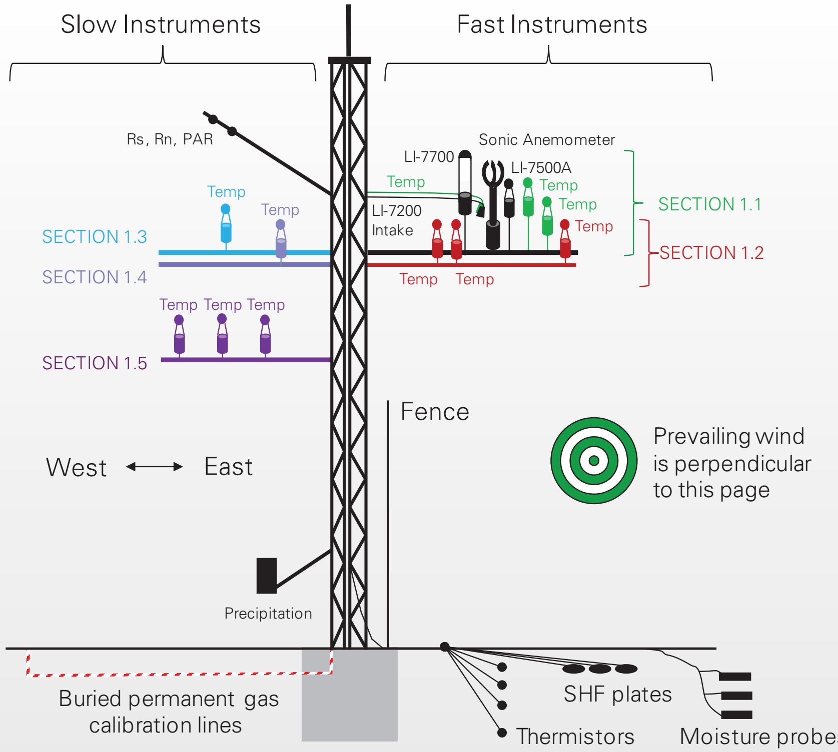
References

An on-line application to help design a custom eddy covariance station dependent upon a specific application, ranging from ecosystem gas exchange, through feedlots, wetlands and forests, and to land management can be found here: http://www.licor.com/ec-design

Eddy covariance system design and implementation webinar: http://www.licor.com/env/webinars/webinar_4-21-11.html

Webinar on biometeorological sensor selection for eddy station: http://www.licor.com/env/webinars/webinar_8-15-12.html

Technical note on biometeorological sensor selection for eddy station: http://envsupport.licor.com/docs/Flux_Station_Sensors_Rev1.1.pdf



A unique feature of LERS is a very large amount of instrumentation expected at the tower when new instruments or methods are to be tested against the core reference station. Careful planning of instrument arrangement was required to properly accommodate multiple short-term projects in the vicinity of the core instrumentation.

The figure above shows the plan of instrument installation on the tower. The black color indicates the core continuously running reference instruments. Site section 1.1 in green indicates placeholders for temporary fast instruments located next to the core instruments. Site section 1.2 in red indicates placeholders for temporary fast instruments located a bit further away, on a boom parallel to the core boom.

Site sections 1.3-1.5 in blue and purple are located on the other side of the tower, away from the fast instrumentation, and are intended for testing of slow instruments. This positioning was specifically planned to avoid overcrowding the booms with fast instrumentation, and to reduce related flow distortion.

The fast permanent instrumentation was planned to be positioned on booms extending over the fence, and oriented perpendicular to the prevailing wind directions:

(1) Gill sonic anemometer outputting three wind components, sonic air temperature, *etc.*

(2) LI-7700 outputting CH_4 density, diagnostics, *etc.*

(3) LI-7500A, outputting CO_2, H_2O concentrations, diagnostics, atmospheric pressure and air temperature, *etc.*

(4) LI-7200, outputting CO_2, H_2O mole fractions, diagnostics, cell pressure and temperature, *etc.*

The slow permanent instrumentation was planned to be positioned inside the fenced plot:

(1) LI-200, incoming global radiation

(2) LI-190, incoming PAR

(3) NR-Lite, net radiation

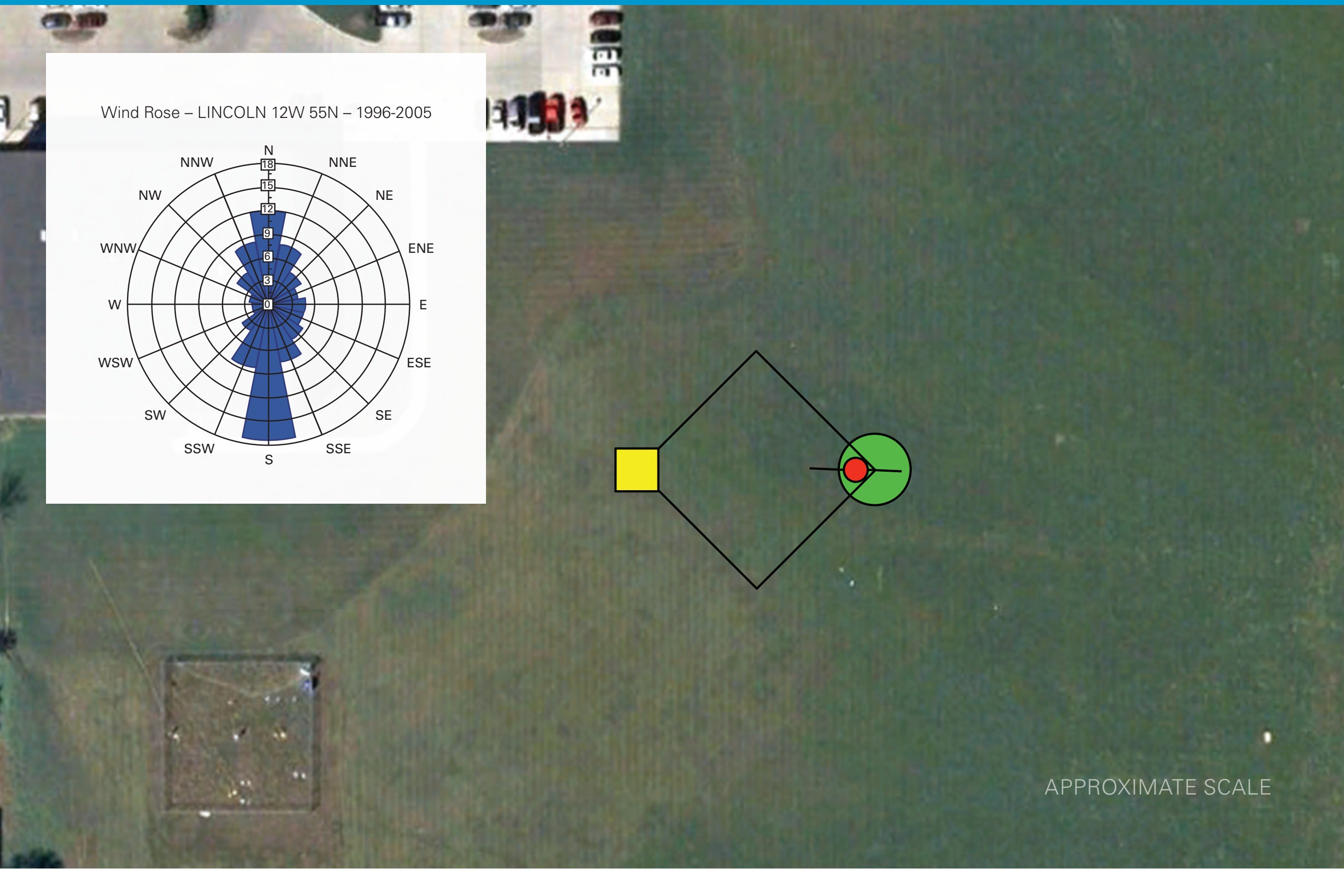
(4) HMP-155, air temperature/relative humidity

(5) 7900-180, soil temperature in 3 locations

(6) HFP-01, soil heat flux in 3 locations

(7) ML2X, soil moisture in 3 locations

(8) TR-525 USW, precipitation



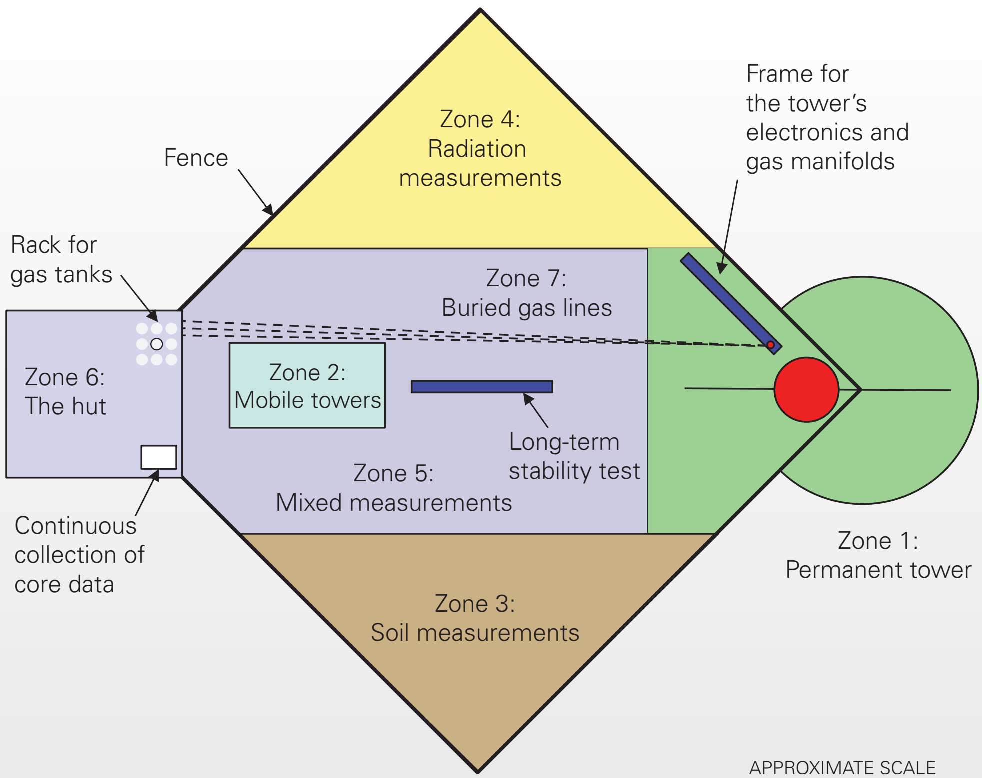
Choice of the site locations for LERS was restricted by the available plot, and the positioning within the location was dictated by the prevailing winds.

The prevailing winds at the site are north in winter and south in summer, so the site perimeter (black diamond) and the permanent tower (red dot) were planned to be positioned in such a way that provided maximum north-south fetch with minimum flow distortion to the eddy covariance flux measurements made on the tower.

Most of the hardware, fencing, other experiment plots, hut (yellow square), and other structures were placed far to the west of the tower, into the least frequent wind direction, in order to minimize flow distortion, wind and sun shading, and other effects.

A disturbance-free zone was also established around the permanent tower (green circle) to minimize disturbance to the tower data from any non-tower experiments.

The aerial view photo above is from Google Earth, and pre-dates the actual construction of the LERS site.



At least four different groups were expected to use LERS for a large number of eddy covariance and other experiments. With so many people and equipment at the station, it was important to plan usage so that new experiments would not disturb or diminish the value of ongoing experiments.

Such coordination is important at eddy covariance sites used by multiple groups, because seemingly trivial overcrowding can lead to serious consequences.

For example, the absence of an Ethernet port for a new experiment can result in the loss of several hours during setup. Flow distortion to eddy instrumentation caused by non-eddy covariance tests can reduce flux data quality, *etc*. These and other related issues can cumulatively cause significant time delay in the tests, and lead to the extension of the tests in order to re-measure distorted data.

Thus, in case of LERS, not only was the eddy tower divided into reserved sections, but the whole site was divided into reserved zones (shown above). A system was developed so that reserving a resource by one group does not preclude the use of the same resource by another group. Instead, it is a mechanism to alert the ongoing experiment owners that someone else is adding instruments to the same area of LERS.

In this way new and ongoing experiments can be properly coordinated and accommodated by their respective owners. This also helps prevent overcrowding certain areas by planning new experiments with the reservation information readily available.

To optimize time and efforts, the following rules were established for use and sharing of LERS facility:

- Plan several weeks ahead of actual experiment
- Reserve zone or section via reservation system
- Coordinate with ongoing experiment owners to accommodate new tests
- Log each visit into the LERS field log
- Keep experiment setup clean and simple
- Keep ground level cables and tubes in conduits
- Clean area after experiment is done
- Put tools back into toolbox
- Lock the hut and gate

A maintenance plan was also developed for core measurements, with daily-to-weekly quality control and bi-weekly site visits.

After detailed planning, the tower and instrument placement were straightforward. The tower was placed at the eastern corner of the fenced plot. The eddy covariance instruments were placed on the boom as far to the east as possible, extending over the fence to minimize flow distortion from the fence, and to maximize prevailing north-south wind directions.

Fast instruments were positioned next to each other so that they face prevailing north-south winds at the same time with minimal flow distortion.

Signs were placed to indicate no-disturbance zones for the tower, and all other zones and objects were labeled.

Eight permanent buried gas lines were constructed between the equipment hut and the permanent tower, ending at a weatherproof termination box. These can be used by experiment owners to set zero and span, and to check their instruments.

Eight Ethernet-and-power ports were constructed alongside the perimeter of the fence. Each port contains 2 high-speed Ethernet connectors and 4 power connectors. An additional port was added at the center of the site.

Security cameras and access codes were also implemented.

The illustration above shows an aerial view of the actual LERS site (Google Earth). The aerial photos are oriented with north at the top. The rightmost photo shows the entrance to Zone 1 and the eddy covariance tower, looking from West to East.

The photos on pages 294 and 298 illustrate the placement of the fast instruments. The view is from the North looking South. Permanent eddy covariance instrumentation was installed exactly as planned. Slow instrumentation was not yet installed in these photos.

Collect *Process* *Plot*

- Data collection and processing at LERS are done automatically using GHG file formats and EddyPro
- Final fully processed flux numbers, biometeorological data and diagnostics are computed, updated and plotted every hour
- Plots and data, as well as instrument software and settings, are accessible remotely via Ethernet and Internet

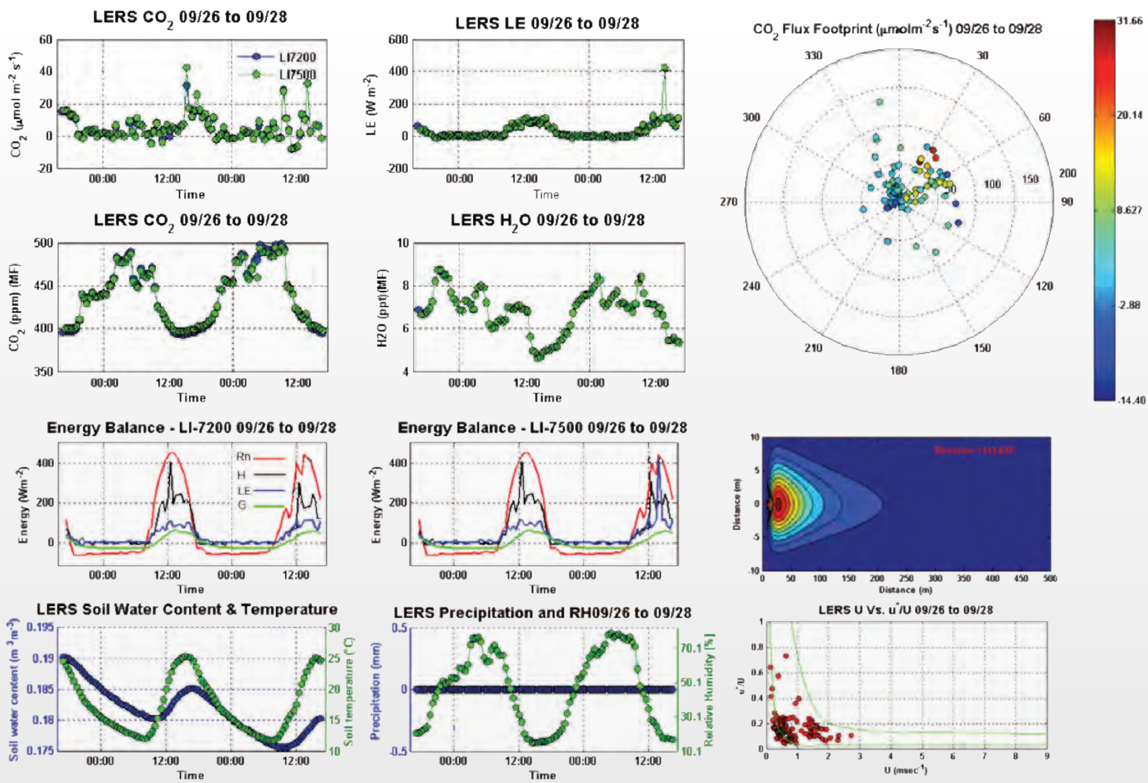
Initial data collection and retrieval were thoroughly tested for several weeks after installation by daily monitoring of diagnostics and mean data ranges, and processing and checking flux values.

Data collection continuity was assured by doing daily-to-weekly quality control and bi-weekly site visits. Proper use and continuous maintenance of the site were promoted by a Site Manual placed at the hut and sent to all users.

Fast and slow data are continuously collected by the LI-7550 logger and backed up onto removable USB storage. Data are also streamed via Ethernet into the PC at the equipment hut. GHG file format is used.

Data processing is done automatically, and final flux values are computed by the PC every hour. This is achieved using a script to activate EddyPro every hour to process new fast and slow GHG data.

All data are plotted with hourly updates for easy visual inspection, and are accessible remotely via Ethernet and Internet.



A subset of plots with flux, biomet and diagnostic data observed at LERS is shown above. Half-hourly values are plotted for the last two days and are updated automatically every half hour. The top two plots (left and center) are CO_2 and H_2O fluxes at LERS from an open-path LI-7500A gas analyzer (green circles) and from an enclosed LI-7200 gas analyzer (blue circles). These are final fully processed fluxes, with all corrections and terms added. The following two plots are CO_2 and H_2O concentrations at LERS from an open-path LI-7500A gas analyzer (green circles) and from enclosed LI-7200 analyzers (blue circles).

The two plots below these are the four main components of the energy budget at the site: net radiation (*Rn*, red), sensible heat flux (*H*, black), latent heat flux (*LE*, blue) and soil heat flux (*G*, green). The leftmost plot uses *LE* from an enclosed LI-7200 and the rightmost plot uses *LE* from an open-path LI-7500A. The bottom left plot shows soil temperature (green) and soil water content (blue). The bottom center plot shows relative humidity (green) and precipitation amounts (blue).

The bottom right plot shows mean hourly turbulence conditions (u^*/U vs. U) at the site with red circles plotted each hour. The red circles are bounded by green borders that indicate turbulence development acceptable for eddy covariance flux computations. All hourly data (red circles) inside the two green borders are under well-developed turbulence. Circles outside the borders are under weak turbulence and may be questionable (usually late night or pre-dawn hours). The rightmost top and center plots describe the flux footprint. The circular plot shows the direction and distance from the tower to the peak contribution for CO_2 flux for the last 48 hours. The blue rectangular plot shows the actual 2-D footprint from the last half-hour. This latter plot is the only one not directly coming from the EddyPro data.

This plot panel allows very rapid site assessment. For example, one can immediately see that open-path and enclosed fluxes, and concentrations, match very well. The exception is data from one hour for open-path fluxes (easily seen on the top center *LE* plot at about 1 PM), likely due to an insect or other contaminant temporarily residing on the window. One can also immediately see that the energy budget at the site looks reasonable, and most of the fluxes come from the area of interest.

Since these types of plots can be viewed remotely, a few seconds spent looking at the data can help keep the site running smoothly, continuously producing high quality data.

References and Further Reading

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Sections 2.2 and 2.4 use some information from technical documentation written by Thad Miller and Ron Nelson, LI-COR. The remaining references are listed throughout the text, and in the list of references accordingly.

Eddy Covariance Method

for Scientific, Industrial, Agricultural and Regulatory Applications

A Field Book on Measuring
Ecosystem Gas Exchange and
Areal Emission Rates

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The "Eddy Covariance Method for Scientific, Industrial, Agricultural and Regulatory Applications: A Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates" book has been created to familiarize the reader with the general theoretical principles, requirements, applications, and planning and processing steps of the eddy covariance method. It is intended to assist readers in furthering their understanding of the method, and provide references such as micrometeorology textbooks, networking guidelines and journal papers. In particular, it is designed to help scientific, industrial, agricultural, and regulatory research projects and monitoring programs with field deployment of the eddy covariance method in applications beyond micrometeorology.

Some of the topics covered in "Eddy Covariance Method for Scientific, Industrial, Agricultural and Regulatory Applications" include:

- Overview of eddy covariance principles
- Planning and design of an eddy covariance experiment
- Implementation of an eddy covariance experiment
- Processing eddy covariance data
- Alternative flux methods
- Useful resources, training and knowledge base
- Example of planning, design and implementation of a complete eddy covariance station

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