China Flux 2019 Eddy Covariance Instrumentation

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CAMPBELL SCIENTIFIC

China Flux 2019

Topic:
The fundamental working principals and major field applications of sonic anemometer, CO_2/H_2O/trace gas analyzer, and atmospheric profile system

Contents

a. How 3D sonic anemometer measures 3D wind
b. Definition and calculation of sonic temperature
c. Measurement working models of 3D wind speeds and sonic temperature
d. Frequency response of sonic anemometer
e. Optical principals of measuring CO_2, H_2O, and some trace gas species
f. Spectrum absorption of CO_2, H_2O, and some trace gas species
g. Beer-Bouguer Law
h. Measurement working models of gas analyzer
i. Frequency response of gas analyzer
j. Applications of sonic anemometer, infrared gas analyzers in OPEC, CPEC and AP systems.
k. Applications of laser trace gas analyzers in flux measurements.

The beginning in 2002: Changbaishan

Passion, Dedication and Commitment to Flux Measurements

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Passion, Dedication and Commitment to Flux Measurements

Acknowledgements for contributions from:

T. Foken, J. Wingard, M. Aubinet, J. Kaimal, J. Finnigan,

R. Leuning, T. Horst, G. Burba, A. Grelle, R. Vogt, S. Oncley

What is an eddy?

"Eddies within eddies from near and far…"

Eddy Covariance Tall Tower Installation

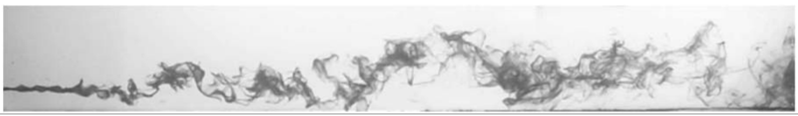
Eddy Covariance Measurement Principles

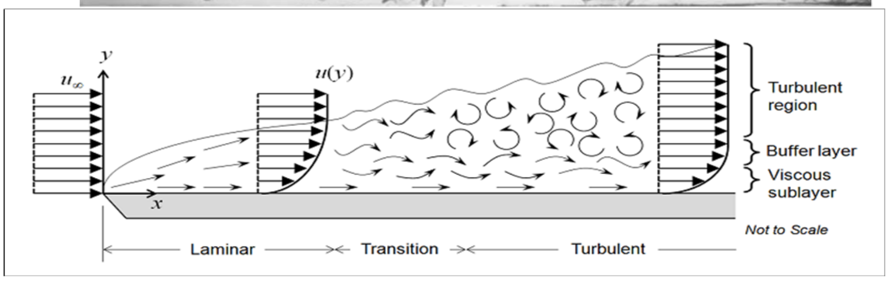
"Vortices swirl around each star,
Eddies within eddies from near and far…"

Vincent van Gogh "Starry Night" 1889

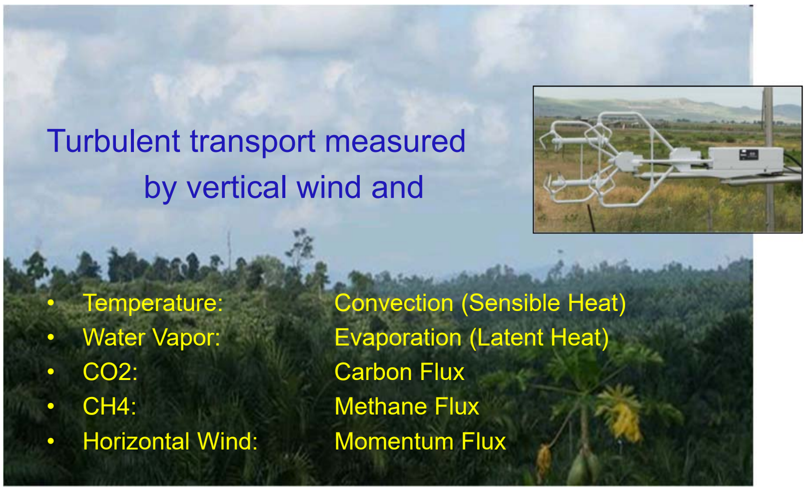
Google Art Project

Mechanism of Turbulence Transfer - Eddies

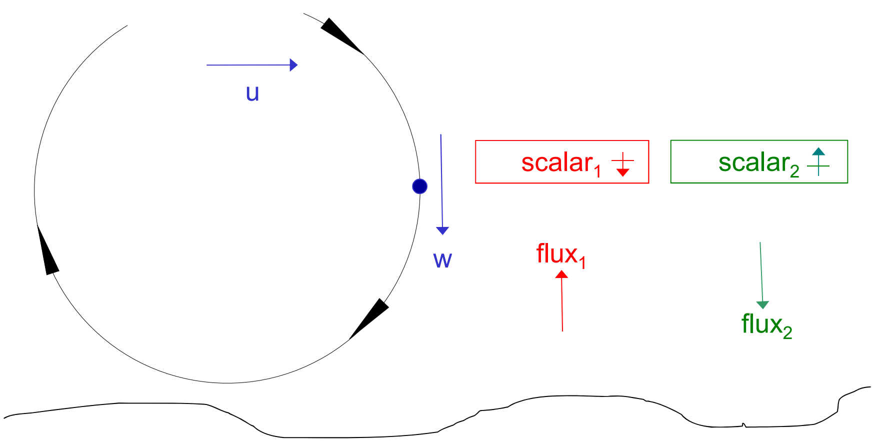




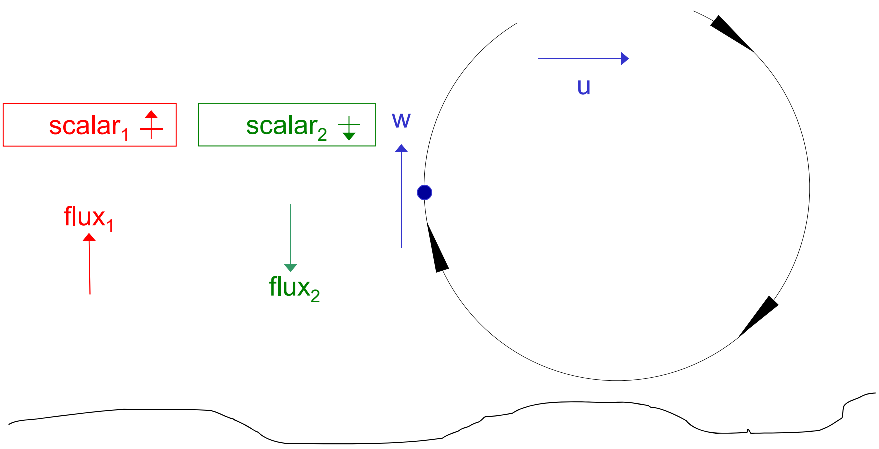
Mechanism of Turbulence Transfer Eddies and Scalars



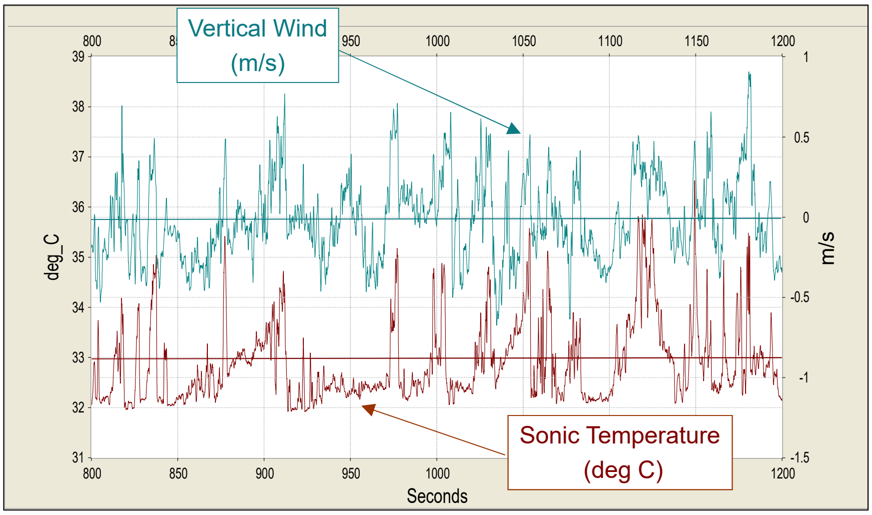
Eddy Covariance Measurement Principles



Eddy Covariance Measurement Principles



Eddy Covariance Time Series



Eddy Covariance Measurement Principles

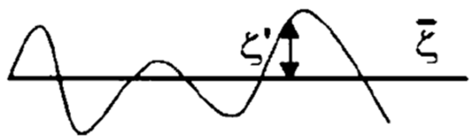
Reynolds decomposition of time series:

$$\zeta = \bar{\zeta} + \zeta' \qquad \bar{\zeta} = \frac{1}{T}\int_{t}^{t+T} \zeta(t)\,dt$$

Reynolds averaging rules:

$$I \quad \overline{\zeta'} = 0$$
$$II \quad \overline{\zeta\xi} = \bar{\zeta}\,\bar{\xi} + \overline{\zeta'\xi'}$$
$$III \quad \overline{\bar{\zeta}\xi} = \bar{\zeta}\,\bar{\xi}$$
$$IV \quad \overline{a\zeta} = a\bar{\zeta}$$
$$V \quad \overline{\zeta + \xi} = \bar{\zeta} + \bar{\xi}$$

Eddy Covariance Measurement Principles



Ensemble Averaging: averaging over many realizations under identical conditions

Ergodic Hypothesis: time averages are equivalent to ensemble averages when the fluctuations are **statistically stationary** during the averaging time

Eddy Covariance Measurement Principles

Eddy flux: $$F \approx \overline{\rho_a}\,\overline{w' s'}$$

where: ρ_a is the dry air density, *w* is the vertical wind and *s* is the scalar (mixing ratio, temperature, etc.) overbar denotes average and prime denotes fluctuations

Assumptions: no divergence/convergence, no storage or accumulation of mass, average fluctuations are zero

Eddy Covariance Measurement Principles

Scalar definition of intensity of a constituent:

(A) in terms of molar density (mole m^{-3})

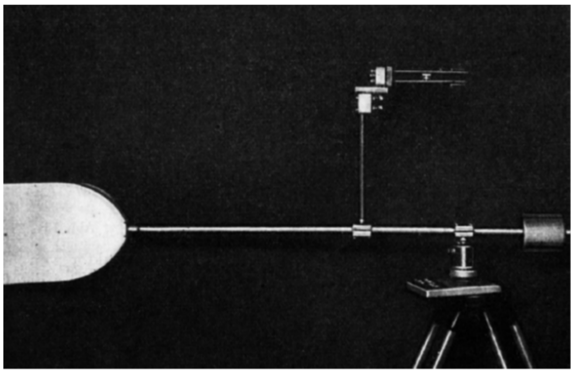
or mass density (kg m^{-3})

(B) in terms of mole fraction (mole $mole^{-1}$) constituents partial pressure to the total pressure

or mass mixing ratio (kg kg^{-1}) ratio of the mass of constituent to the mass of dry air

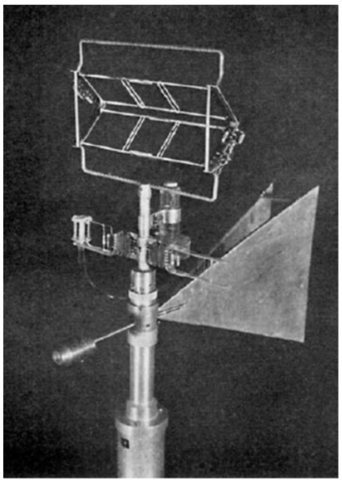
Only (B) are *conserved quantities* in the presence of changes in temperature, pressure and water vapor content

Early Instruments for Atmospheric Turbulence and Wind Measurements



Wind vane with two perpendicular hot wire sensors for measuring friction velocity (Obukhov, 1951)

Early Instruments for Eddy Covariance Measurements

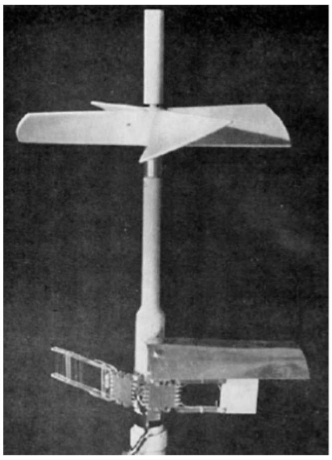


Evapotron

Hot wire anemometer and psychrometer

Dyer (1965)

Early Instruments for Eddy Covariance Measurements

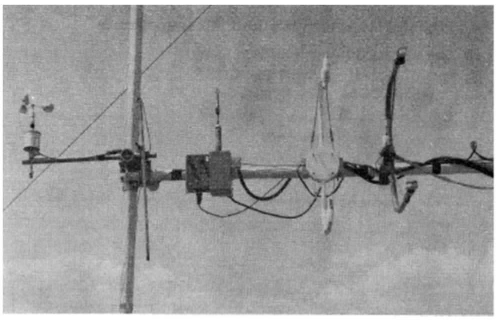


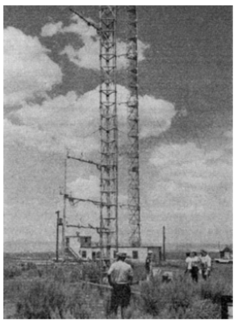
Fluxatron

Propeller anemometer with fine wire thermometer

Dyer (1967)

Early Sonic anemometers

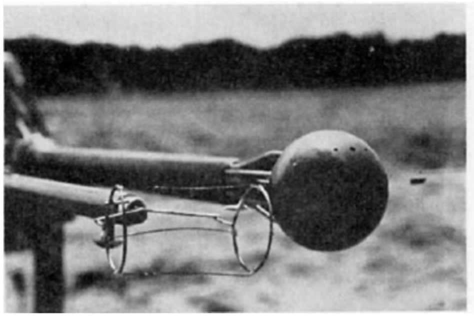


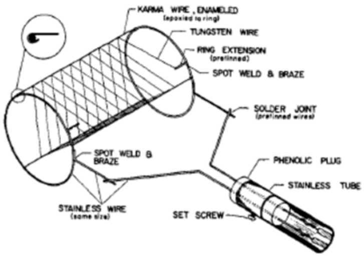


Businger (1969) University of Washington

Mitsuta & Hanafusa (1969) Kyoto University

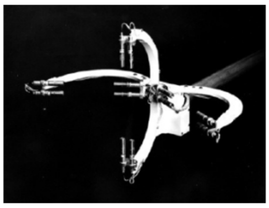
Early Instruments for Eddy Covariance Measurements

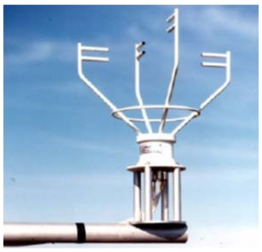




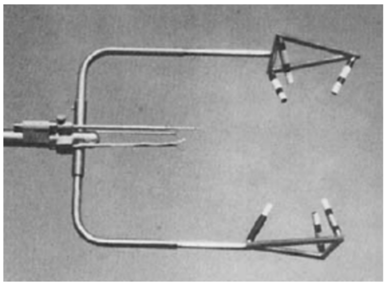
Fine wire PRT and spherical pressure probe for sensible heat flux measurements (Wesely 1970)

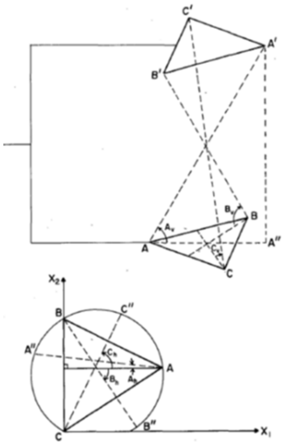
Early Sonic anemometers – orthogonal geometry





History of the CSAT3 Sonic Anemometer

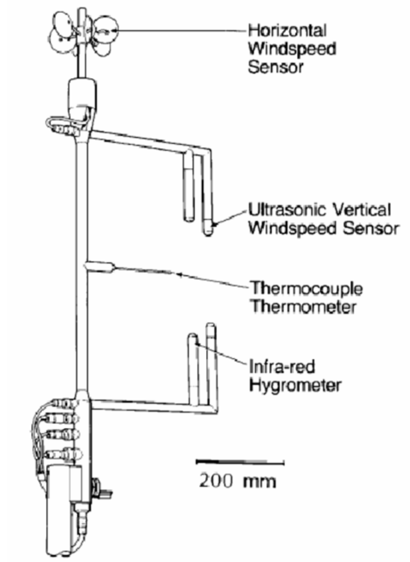




University of Washington
Non-orthogonal design

U.W. Sonic Anemometer (Zhang, Wyngaard, Businger and Oncley 1986)
Designed to reduce transducer shadowing for the horizontal wind components and increase the range of acceptable wind directions

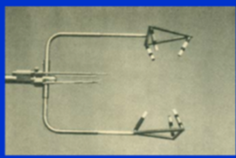
Early Eddy-covariance System Designs



Hydra II

History of the CSAT3 Sonic Anemometer

The Optimal Sonic Anemometer Type



Zhang, S. F., Wyngaard, J. C., Businger, J. A., and Oncley, S. P.: Response characteristics of the U.W. sonic anemometer, J. Atm. Oceanic Techn., 2, 548-558, 1986.

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Printed in U.S.A.

Workshop on Instrumental and Methodical Problems of Land Surface Flux Measurements

Thomas Foken and Steven Oncley

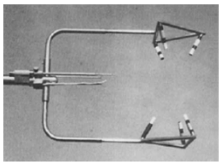
One year after an international workshop held in Grenoble in 1994, Campbell Sci. Inc. produced CSAT3

In memoriam
Dr. h.c. Bert Tanner

Slide by
T. Foken

21st Symposium on Boundary Layers and Turbulence
9-13 June 2014, Leeds, United Kingdom

Transformation Matrices

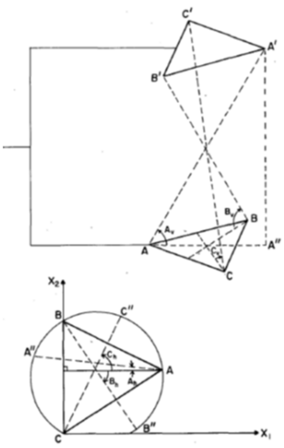


$$S_i = \sum_j a_{ij} U_j, \quad i, j = 1, 2, 3$$

$$a_{ij} = \begin{pmatrix} -\cos A_h \cos A_v & \sin A_h \cos A_v & \sin A_v \\ \cos B_h \cos B_v & -\sin B_h \cos B_v & \sin B_v \\ \cos C_h \cos C_v & \sin C_h \cos C_v & \sin C_v \end{pmatrix}$$

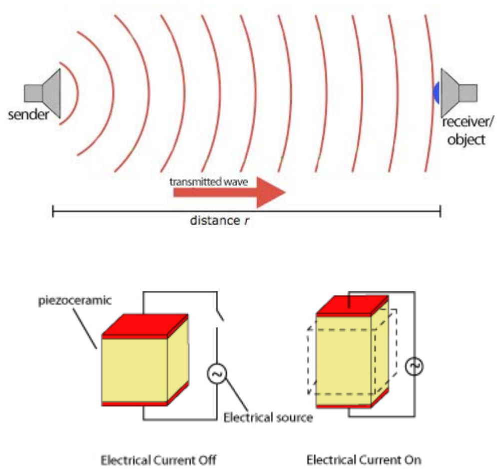
$$U_i = \sum_j b_{ij} S_j, \quad i, j = 1, 2, 3$$

$$b_{ij} = (a_{ij})^{-1}$$



Conversion from orthogonal to non-orthogonal coordinates

Sonic Anemometer Measurement Principles

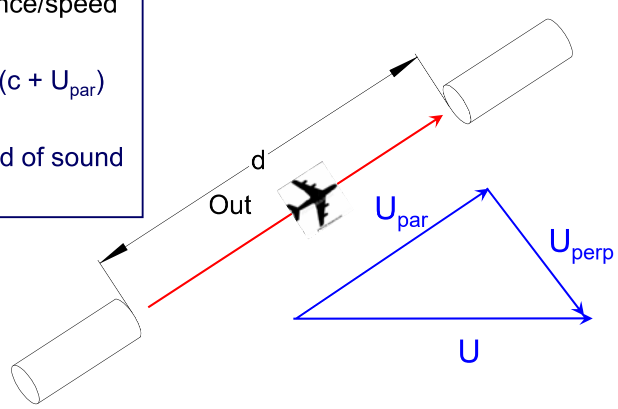


Sonic Anemometer Measurement Principles

t = distance/speed

$t_{out} = d/(c + U_{par})$

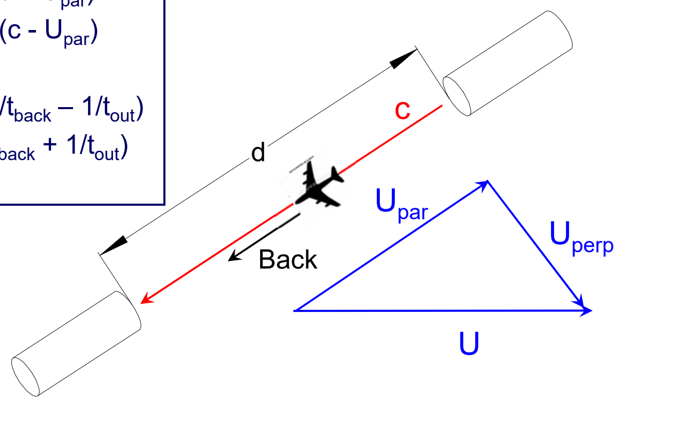
c is speed of sound



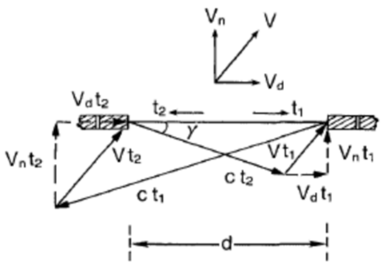
Sonic Anemometer Measurement Principles

$t_{out} = d/(c + U_{par})$
$t_{back} = d/(c - U_{par})$

$U_{par} = d/2\ (1/t_{back} – 1/t_{out})$
$c = d/2\ (1/t_{back} + 1/t_{out})$



Speed of Sound Measurement and Cross-Wind Correction



$$V_d = \frac{d}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \qquad \frac{1}{t_1} + \frac{1}{t_2} = \frac{2}{d} c\cos\gamma$$
$$= \frac{2}{d}(c^2 - V_n^2)^{1/2}$$

$$c^2 = \frac{d^2}{4}\left(\frac{1}{t_1} + \frac{1}{t_2}\right)^2 + V_n^2.$$

$$c^2 = 403\, T(1 + 0.32e/p),$$

e=0
dry air

$$T_v = \frac{d^2}{1612}\left(\frac{1}{t_1} + \frac{1}{t_2}\right)^2 + \frac{1}{403}V_n^2.$$

Implemented in the firmware of the CSAT3

$$c = \sqrt{\frac{1.4RT}{M}}$$

Acoustic Virtual Temperature is determined using Gas constant and Specific heat for **dry air**

Accuracy of Acoustic Temperature Measurement

$$T_v = \frac{d^2}{1612}\left(\frac{1}{t_1}+\frac{1}{t_2}\right)^2 + \frac{1}{403} V_n^2.$$

The distance (d) between the transducer faces needs to be measured accurately
A deviation of 0.1 mm (a thickness of a sheet of paper) will result in a temperature error of about 0.3K

Research grade anemometers can resolve 0.002K

Transducer delays need to be calibrated over the entire operating temperature range

Acoustic Virtual Temperature Measurement

$$c = \sqrt{\gamma_d R_d T \cdot \left(1 + \left(\frac{\gamma_v}{\gamma_d} - \frac{M_v}{M_d}\right) \cdot \frac{e}{p - \left(1 - \frac{M_v}{M_d}\right) \cdot e}\right)}$$

Speed of sound in **humid air**

$$T_{av} = T \cdot \left(1 + \left(\frac{\gamma_v}{\gamma_d} - \frac{M_v}{M_d}\right) \cdot \frac{e}{p - \left(1 - \frac{M_v}{M_d}\right) \cdot e}\right)$$

Acoustic Temperature depends on the humidity of the air
Acoustic Temperature>Air Temperature
Acoustic Temperature approximates virtual temperature

Acoustic Virtual Temperature Measurement

$$T_{av} = T \cdot \left(1 + \left(\frac{\gamma_v}{\gamma_d} - \frac{M_v}{M_d} \right) \cdot \frac{e}{p - \left(1 - \frac{M_v}{M_d} \right) \cdot e} \right)$$

The perfect instrument idea: all measurements are in the same volume
IRGASON can provide true air temperature because of the synchronized and co-located water valor measurement

$$T_s' = T' + 0.51 q' \overline{T}$$

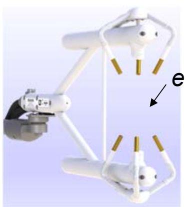
Standalone sonic anemometer are not able to measure true air temperature
The sonic virtual temperature spectrum is contaminated by water valor fluctuations scaled by absolute temperature
q – specific humidity [kg kg^{-1}] (moist air)

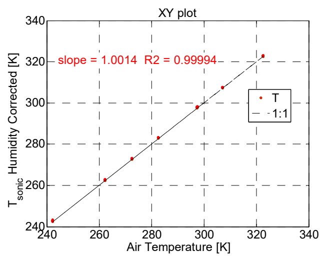
$$\overline{w' T_s'} = \overline{w' T'} + 0.51\, \overline{T}\, \overline{w' q'}$$

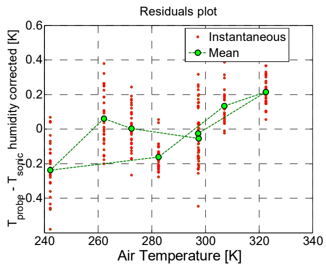
Sonic heat flux need a latent heat flux correction

Fast-response Acoustically derived Air Temperature Measurement

$$T_{av} = T \cdot \left(1 + \left(\frac{\gamma_v}{\gamma_d} - \frac{M_v}{M_d} \right) \cdot \frac{e}{p - \left(1 - \frac{M_v}{M_d} \right) \cdot e} \right)$$

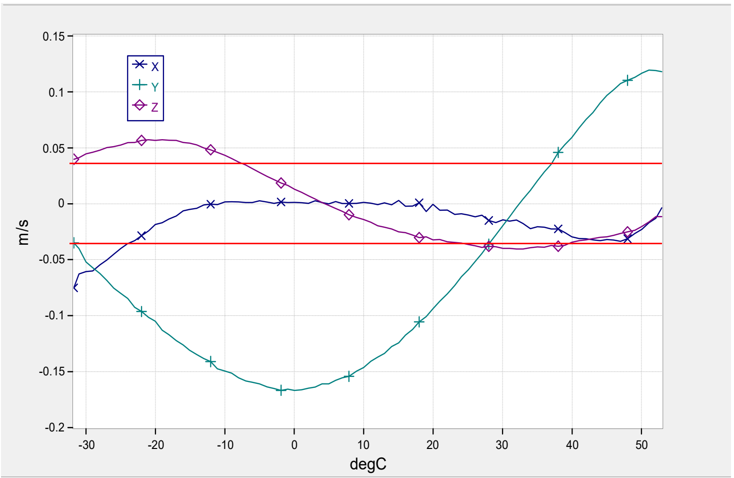






IRGASON can provide true air temperature because of the synchronized and co-located water vapor measurement

Sonic Anemometer Calibration



Wind Offset and Distance Calibration: Temperature range -30 to +50 deg. C

Piezoelectric transducers are resonant devices and have certain delay when excited. These delays are accounted during calibration in a zero-

Maximum Offset Error	< ±8.0 cm s^{-1} (u_x, u_y), < ±4.0 cm s^{-1} (u_z)

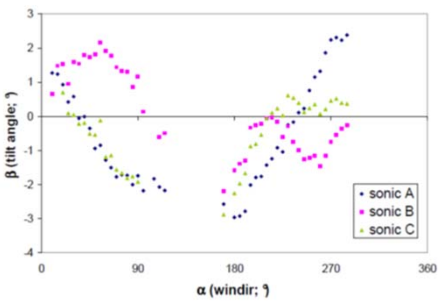
Sonic Anemometer Calibration

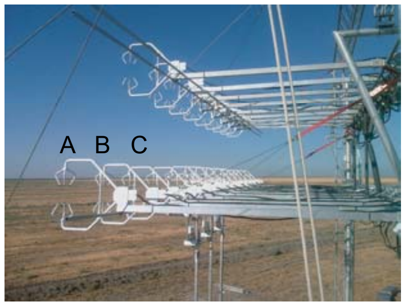
Zero-wind box with dry air

Wind Offset and Distance Calibration: Temperature range -30 to +50 deg. C

Maximum Offset Error	< ±8.0 cm s^{-1} (u_x, u_y), < ±4.0 cm s^{-1} (u_z)

Sonic Anemometer Coordinate Rotations



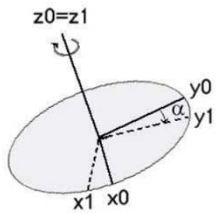


What is the frame of reference?
It is difficult (or impossible) to align the sonic coordinate system with an objective frame relative to the local flow field (not gravity)
If the sonic is not oriented with the stream flow there will be **cross-contamination between u' and w'**
z-axis should be perpendicular to the mean streamlines surface (and parallel to the scalar concentration gradient)

Sonic Anemometer Coordinate Rotations

Rotation around z-axis (yaw angle) aligns to mean (30 min) wind direction

$$\begin{pmatrix} \overline{u}_1 \\ \overline{v}_1 \\ \overline{w}_1 \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{R_{01}} \begin{pmatrix} \overline{u}_0 \\ \overline{v}_0 \\ \overline{w}_0 \end{pmatrix}$$

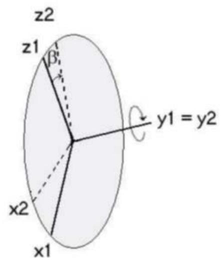


$$\alpha = \tan^{-1}\left(\frac{\overline{v}_0}{\overline{u}_0}\right)$$

Sonic Anemometer Coordinate Rotations

Rotation around new y-axis (pitch angle) nullifies mean vertical wind

$$\begin{pmatrix} \overline{u}_2 \\ \overline{v}_2 \\ \overline{w}_2 \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}}_{R_{12}} \begin{pmatrix} \overline{u}_1 \\ \overline{v}_1 \\ \overline{w}_1 \end{pmatrix}$$



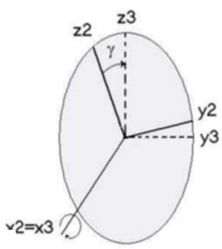
$$\beta = \tan^{-1}\left(\frac{\overline{w}_1}{\overline{u}_1}\right)$$

Sonic Anemometer Coordinate Rotations

Rotation around new x-axis (roll angle) nullifies w'v' NOT RECOMMENDED ANYMORE

Finnigan, J. J.: 2004, 'A re-evaluation of long-term flux measurement techniques Part II: Coordinates systems', *Boundary-Layer Meteorology*. **113**, 1-41

$$\begin{pmatrix} \overline{u}_3 \\ \overline{v}_3 \\ \overline{w}_3 \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & \sin\gamma \\ 0 & -\sin\gamma & \cos\gamma \end{pmatrix}}_{R_{23}} \begin{pmatrix} \overline{u}_2 \\ \overline{v}_2 \\ \overline{w}_2 \end{pmatrix}$$



$$\gamma = \frac{1}{2}\tan^{-1}\left(2\frac{\overline{v_2' w_2'}}{(\overline{v_2'^2} - \overline{w_2'^2})}\right)$$

Rotations are applied for each averaging period

Sonic Anemometer Coordinate Rotations

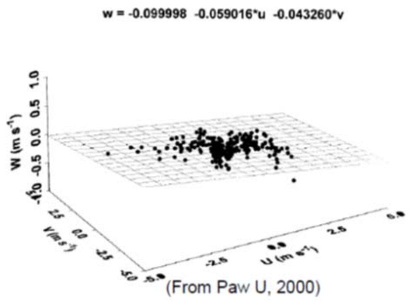
Long-term Planar Fit

Aligns the z-axis perpendicular to the long-term (weeks) mean streamline plane (**long data set** when the position of the sonic does not change.

Planar regression on wind components in the sonic coordinate system:

$$\overline{w}_0 = b_0 + b_1\overline{u}_0 + b_2\overline{v}_0$$

b_0 accounts for instrument offset
b_1 and b_2 define the orientation of the long-term streamline plane



(From Paw U, 2000)

Sonic Anemometer Coordinate Rotations

Long-term Planar Fit

R1: around z-axis, with α nullifies mean crosswind
R2: around y-axis with β_{PF}
R3: around x-axis with γ_{PF}

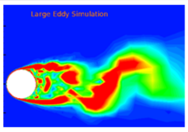
$$\alpha = \tan^{-1}\left(\frac{\overline{v}_0}{\overline{u}_0}\right)$$

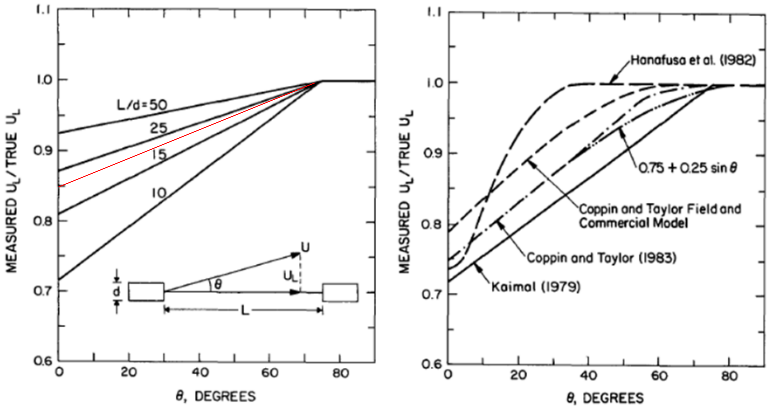
$$\overline{w}_0 = b_0 + b_1\overline{u}_0 + b_2\overline{v}_0$$

$$\beta_{PF} = \tan^{-1}(-b_1)$$
$$\gamma_{PF} = \tan^{-1}(b_2)$$

Mean long term vertical velocity =0 , but not short term (30 min)

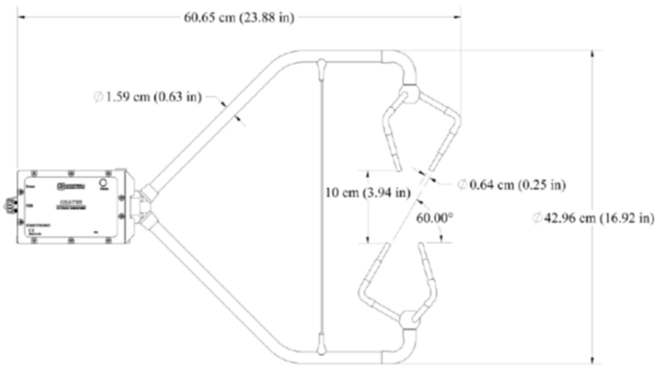
Transducer-Shadow Effects





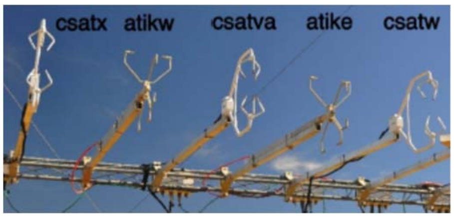
Difficult to characterize in turbulent conditions because there is no standard

Transducer-Shadow Effects



L/d ratio 17.2
Acoustic paths oriented at a zenith angle of 30 degrees while other designs the angle is 45 degrees with L/d ratio of 9

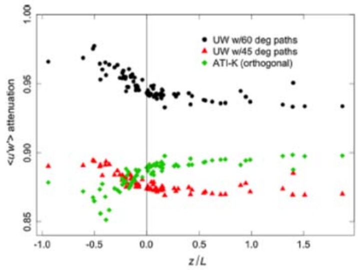
Experiment to Evaluate Transducer-Shadow Effects. What is the optimal geometry?

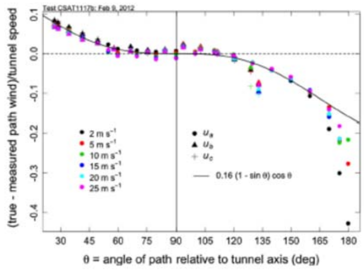


$$\hat{u}_a = u_a\,(0.84 + 0.16\,\sin\theta_a)$$

After Wyngaard and Zhang (1985)

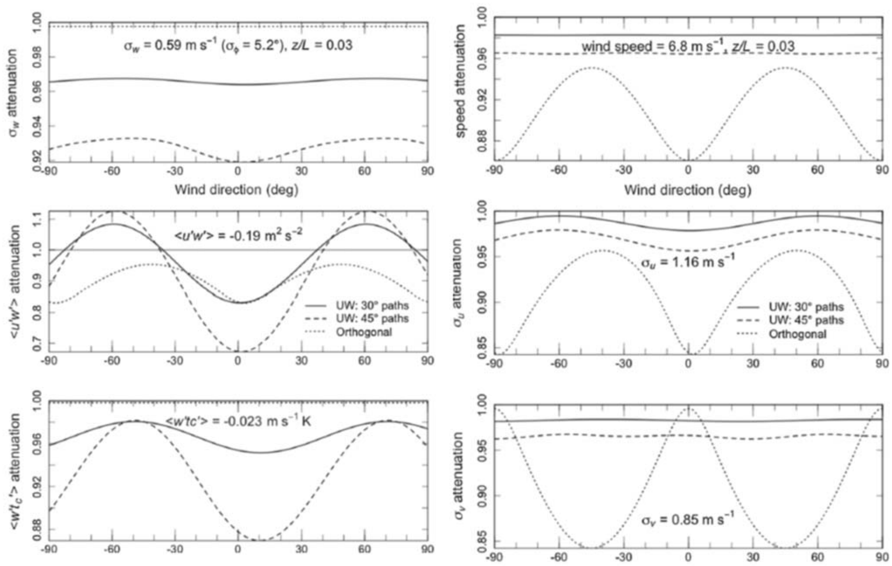
Correction derived in a wind tunnel under laminar flow conditions, but there is **no standard for turbulence.** All we can do is compare instruments or CFD





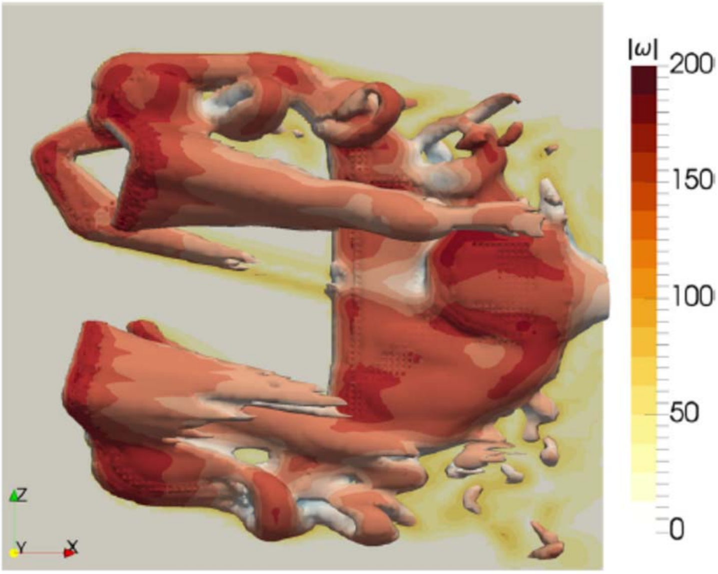
Transducer-Shadow Effects

After Horst (2015)

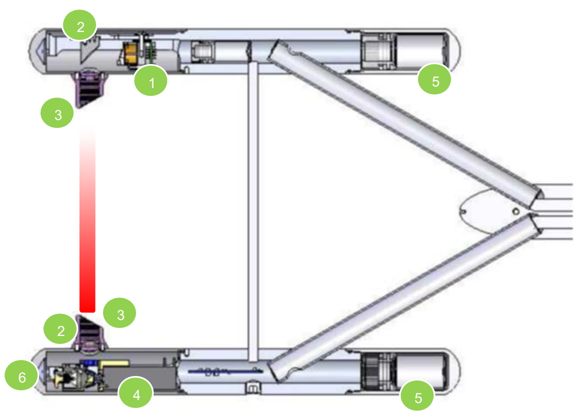


Transducer-Shadow Effects

After Huq et al. (2017)

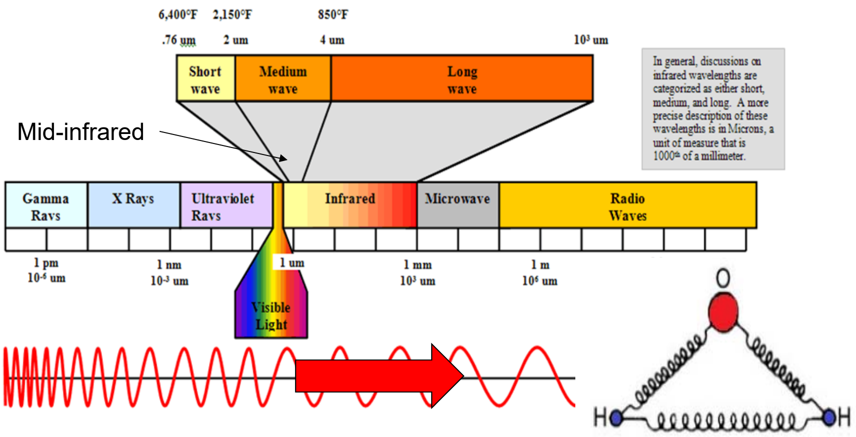


Gas Analyzer Measurement Principles



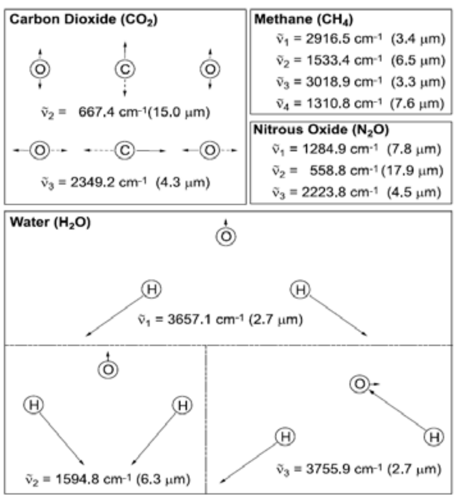
1. Temperature controlled detector
2. Precision optical components
3. Scratch resistant windows
4. Brushless chopper motor
5. CO_2 and H_2O scrubbers
6. Infrared source

CO_2 and H_2O Infrared Gas Analyzer Measurement Principles



Electromagnetic excitation of inter-atomic vibration
Electromagnetic energy is absorbed and converted to heat

Gas Analyzer Measurement Principles

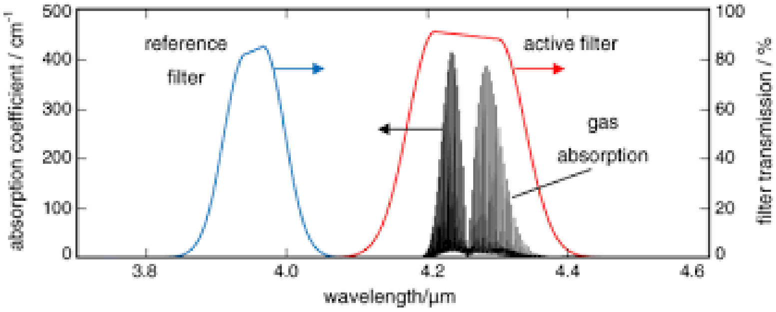


Different Vibration modes of some GHG with strong absorption coefficients

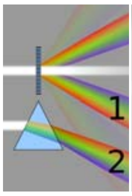
CO_2: asymmetrical stretching at 4.3 µm

H_2O: asymmetrical stretching at 2.7 µm

CO_2 Absorption Bands in the Infrared

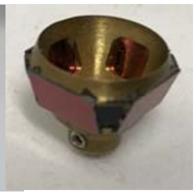


Dispersive



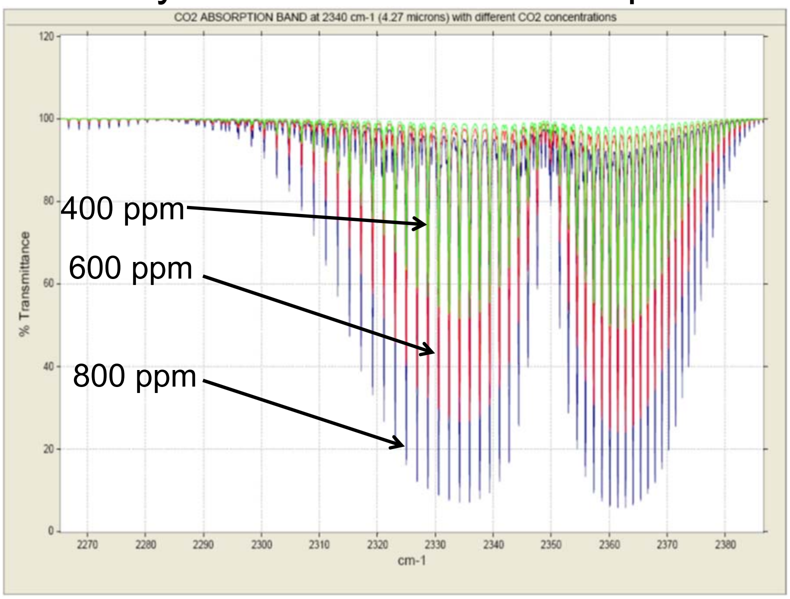
Non-dispersive

4 Positions Filter Wheel

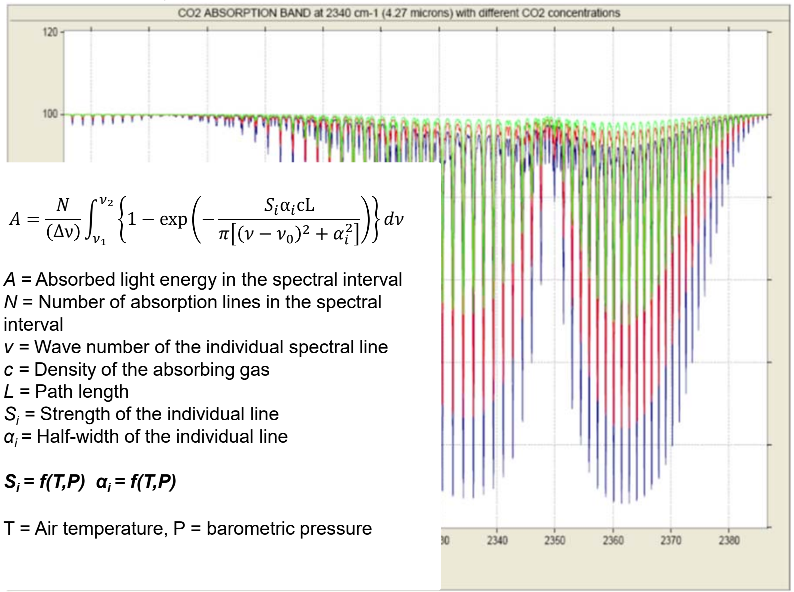


CO_2 active (absorbing)
CO_2 reference (non-absorbing)
H_2O: active (absorbing)
H_2O: reference (non-absorbing)

Gas Analyzer Measurement Principles



Gas Analyzer Measurement Principles



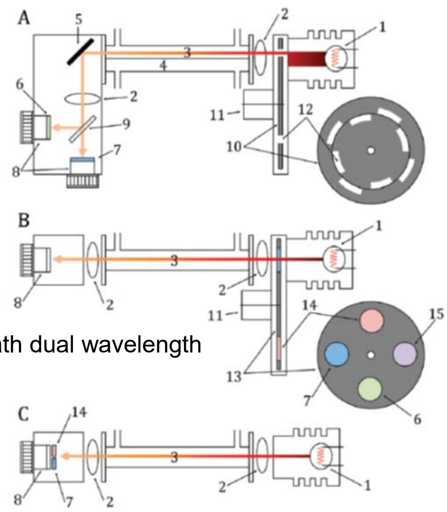
$$A = \frac{N}{(\Delta \nu)} \int_{\nu_1}^{\nu_2} \left\{ 1 - \exp\left(- \frac{S_i \alpha_i cL}{\pi \left[(\nu - \nu_0)^2 + \alpha_i^2 \right]} \right) \right\} d\nu$$

A = Absorbed light energy in the spectral interval
N = Number of absorption lines in the spectral interval
v = Wave number of the individual spectral line
c = Density of the absorbing gas
L = Path length
S_i = Strength of the individual line
α_i = Half-width of the individual line

$S_i = f(T,P)$ $\alpha_i = f(T,P)$

T = Air temperature, P = barometric pressure

IRGA optical design schemes

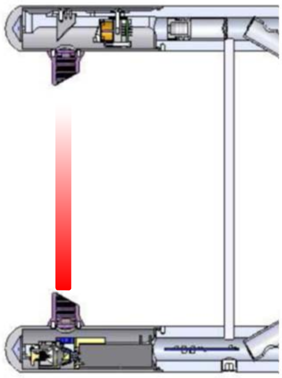


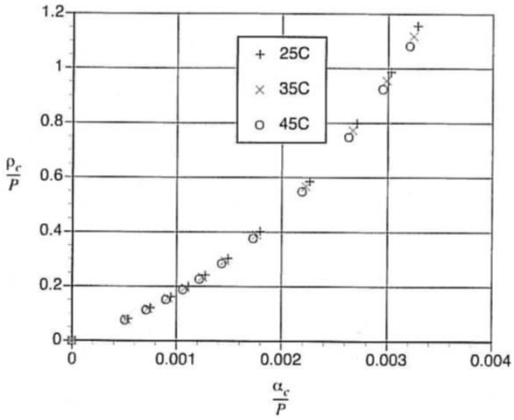
Single path dual wavelength

Gas Analyzer Measurement Principles

$$\frac{\alpha_c}{P\psi} = h\left(\frac{\rho_c L}{P\psi}\right)$$

Infrared spectroscopy measures density in mol m^{-3}, not the required mixing ratios





Eddy Covariance Measurement Principles

Need to convert from density to mixing ratio. Instantaneous pressure and temperature of the mixture in the sensing path are required, but are not available for traditional open-path sensors.

$$e = \frac{\rho_v RT}{M_v} \qquad \chi_c = \frac{\rho_c RT}{(P-e)M_c}$$

Point-by-point conversion of high frequency time series

$$F_c^{MR} = \frac{\overline{(P-e)} \cdot m_c}{R \cdot \overline{T}} \cdot \overline{w'\chi_c'}$$

Closed-path analyzers
IRGASON due to the co-location of the sonic

$$F_c^{WPL} = \overline{w'\rho_c'} + \left(\frac{m_d}{m_v}\frac{\overline{\rho_c}}{\overline{\rho_d}}\right)\overline{w'\rho_v'} + \left(1 + \frac{m_d}{m_v}\frac{\overline{\rho_v}}{\overline{\rho_d}}\right)\overline{\rho_c}\frac{\overline{w'T'}}{\overline{T}}$$

For open-path sensors density terms (WPL) on 30 min fluxes. Pressure is neglected

$$\overline{w'T'} = \overline{w'T_s'} - 0.51\overline{T}\,\overline{w'\chi'_v}$$

Correction of sonic temperature for humidity effects

Eddy Covariance Measurement Principles

Closed-path sensors: the air-temperature fluctuations are attenuated in the intake tubing. Temperature and pressure are measured in the sample cell

$$e = \frac{\rho_v RT}{M_v} \qquad \chi_c = \frac{\rho_c RT}{(P-e)M_c}$$

$$F_c^{MR} = \frac{\overline{(P-e)}\cdot m_c}{R\cdot\overline{T}}\cdot\overline{w'\chi_c'}$$

Point-by-point conversion of high frequency CO_2 density time series

All variables must be measured simultaneously

Must consider time lag and hi-frequency attenuation in the intake tubing

This approach can be used with the IRGASON due to the co-location of the sonic

Eddy Covariance Measurement Principles

Open-path sensors with co-located sonic anemometer: the air-temperature fluctuations in the sample volume can be measured correctly

$$e = \frac{\rho_v RT}{M_v} \qquad \chi_c = \frac{\rho_c RT}{(P-e)M_c} \qquad T_{av} = T\cdot\left(1+\left(\frac{\gamma_v}{\gamma_d}-\frac{M_v}{M_d}\right)\cdot\frac{e}{p-\left(1-\frac{M_v}{M_d}\right)\cdot e}\right)$$

$$F_c^{MR} = \frac{\overline{(P-e)}\cdot m_c}{R\cdot\overline{T}}\cdot\overline{w'\chi_c'}$$

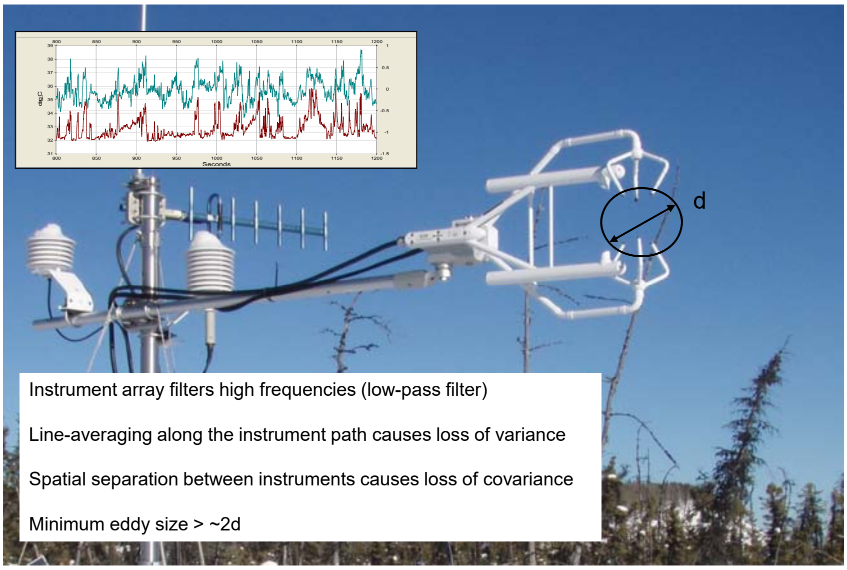
Point-by-point conversion of high frequency CO_2 density time series

Static Pressure probe

Common Electronics

u, v, w
Ts
H2O
CO2
P

Eddy Covariance Measurement Principles



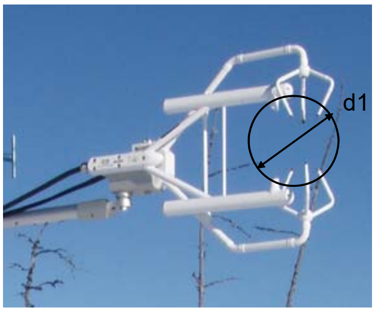
Instrument array filters high frequencies (low-pass filter)

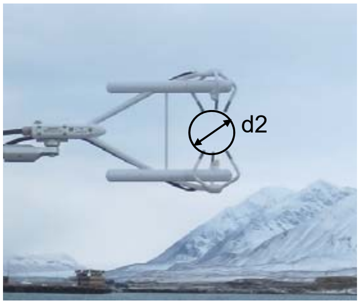
Line-averaging along the instrument path causes loss of variance

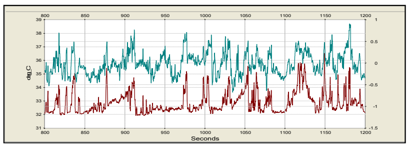
Spatial separation between instruments causes loss of covariance

Minimum eddy size > ~2d

Eddy Covariance Measurement Principles







Eddy Covariance Measurement Principles

Open-path sensors: subjected to the air-temperature fluctuations of the atmosphere. Fast-response air temperature is required: sonic BUT at a distance **d**

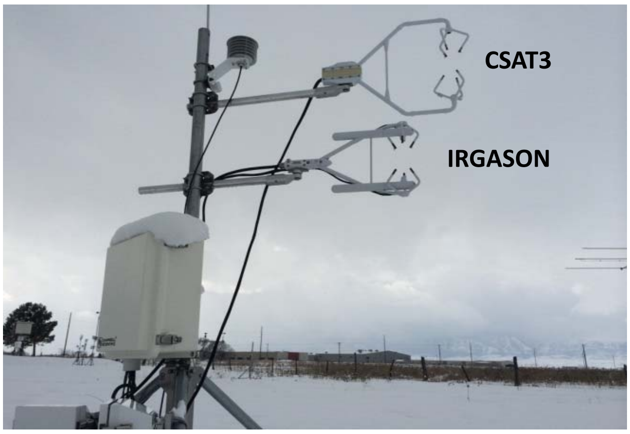
Separated by distance d
Low-pass filtered
Need spectral correction

In the same sampling volume and well synchronized

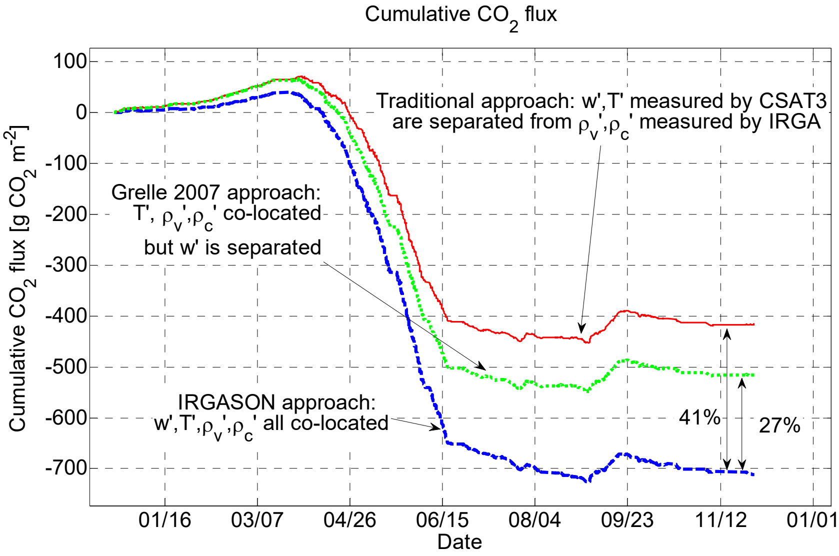
$$F_c^{WPL} = \overline{w'\rho_c'} + \left(\frac{m_d}{m_v}\frac{\overline{\rho_c}}{\overline{\rho_d}}\right)\overline{w'\rho_v'} + \left(1 + \frac{m_d}{m_v}\frac{\overline{\rho_v}}{\overline{\rho_d}}\right)\overline{\rho_c}\frac{\overline{w'T'}}{\overline{T}}$$

$$\overline{w'T'} = \overline{w'T_s'} - 0.51\overline{T}\,\overline{w'\chi'_v}$$

Eddy Covariance Sensor Separation: Case Study

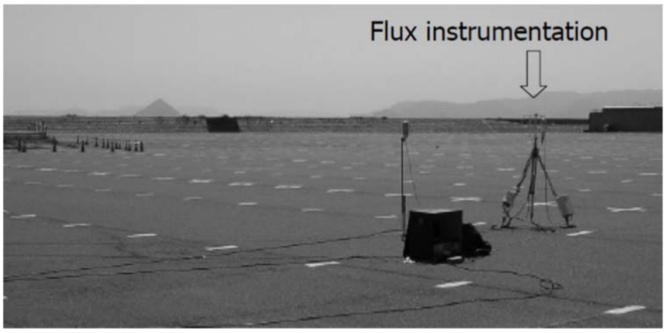


Eddy Covariance Sensor Separation



Eddy Covariance Experimental Verification

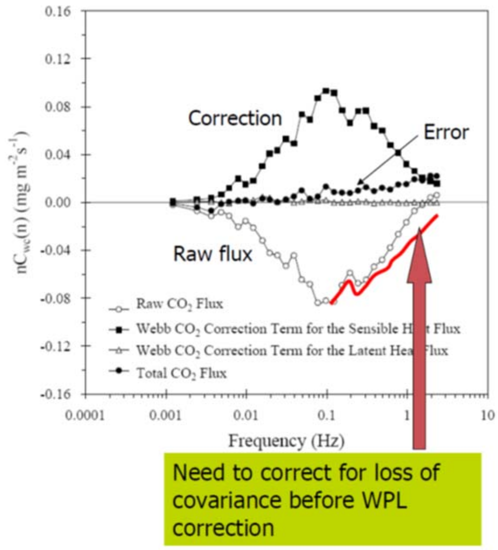
A case study- zero CO2 flux over asphalt . Kondo & Tsukamoto (2008)



Eddy Covariance Experimental Verification

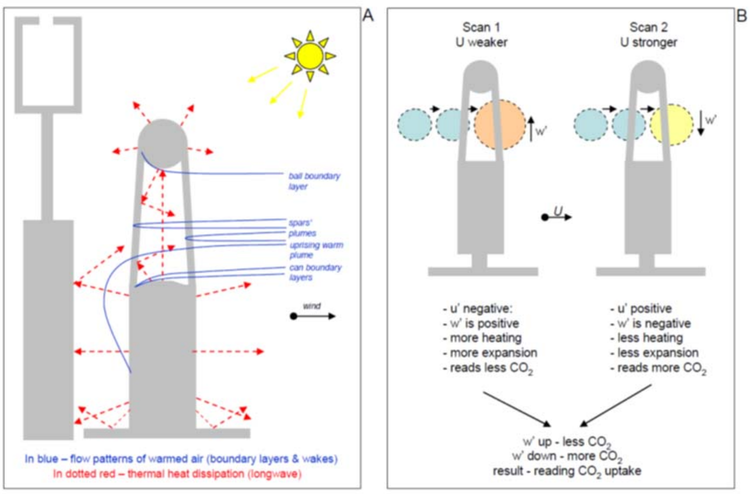
Measurements of heat, water vapor and CO2 fluxes must have the same spectral and co-spectral response

It is challenging when the corrections are large



Eddy Covariance Instrumentation Biases

Example: Instrument surface heating causing apparent CO2 uptake

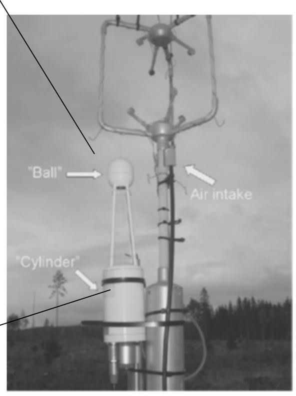


After Burba (2008)

Eddy Covariance Instrumentation Biases

$$H_{\mathrm{PRT}} = \rho c_p \overline{w' T'_{\mathrm{PRT}}} \ (\mathrm{W\ m^{-2}}).$$

Grelle and Burba (2007) installed a fine wire PRT in the sensing volume of the open-path analyzer to measure the extra heat generated by the lower cylinder

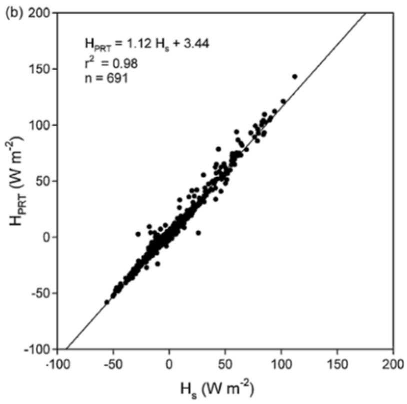


Eddy Covariance Instrumentation Biases

$$H_{\mathrm{PRT}} = \rho c_p \overline{w' T'_{\mathrm{PRT}}} \ (\mathrm{W\ m^{-2}}).$$

$$F_{\mathrm{cnew}} = F_{\mathrm{co}} + 1.6077 \frac{E_{\mathrm{new}}}{\rho_{\mathrm{d}}} \frac{\rho_{\mathrm{c}}}{1 + 1.6077(\rho_{\mathrm{v}}/\rho_{\mathrm{d}})} + \frac{H_{\mathrm{PRT}}}{\rho c_p} \frac{\rho_{\mathrm{c}}}{T_{\mathrm{a}}} \quad (1)$$

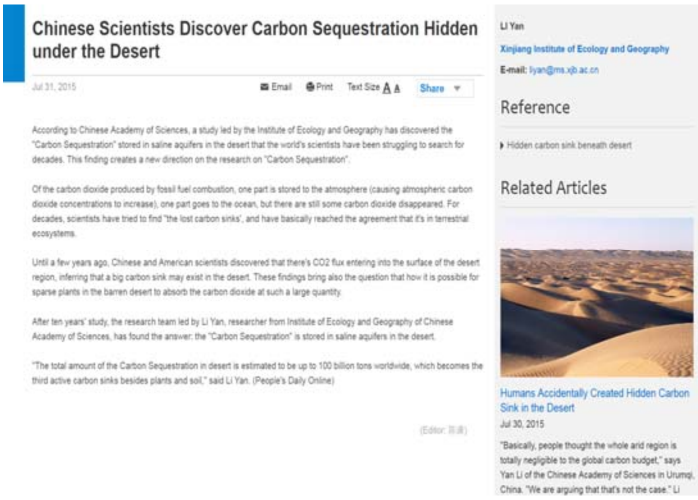
$$E_{\mathrm{new}} = \left(1 + 1.6077 \frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{d}}}\right) \left(E_{\mathrm{o}} + \frac{H_{\mathrm{PRT}}}{\rho c_p} \frac{\rho_{\mathrm{v}}}{T_{\mathrm{a}}}\right) \quad (2)$$



Grelle and Burba (2007)

Eddy Covariance Instrumentation Biases

Ma, J. et al. (2014). A downward CO_2 flux seems to have nowhere to go. *Biogeosciences*, **11**: 6251-6262.



Chinese Scientists Discover Carbon Sequestration Hidden under the Desert

Jul 31, 2015 — Email — Print — Text Size A A — Share

According to Chinese Academy of Sciences, a study led by the Institute of Ecology and Geography has discovered the "Carbon Sequestration" stored in saline aquifers in the desert that the world's scientists have been struggling to search for decades. This finding creates a new direction on the research on "Carbon Sequestration".

Of the carbon dioxide produced by fossil fuel combustion, one part is stored to the atmosphere (causing atmospheric carbon dioxide concentrations to increase), one part goes to the ocean, but there are still some carbon dioxide disappeared. For decades, scientists have tried to find "the lost carbon sinks", and have basically reached the agreement that it's in terrestrial ecosystems.

Until a few years ago, Chinese and American scientists discovered that there's CO2 flux entering into the surface of the desert region, inferring that a big carbon sink may exist in the desert. These findings bring also the question that how it is possible for sparse plants in the barren desert to absorb the carbon dioxide at such a large quantity.

After ten years' study, the research team led by Li Yan, researcher from Institute of Ecology and Geography of Chinese Academy of Sciences, has found the answer: the "Carbon Sequestration" is stored in saline aquifers in the desert.

"The total amount of the Carbon Sequestration in desert is estimated to be up to 100 billion tons worldwide, which becomes the third active carbon sinks besides plants and soil," said Li Yan. (People's Daily Online)

(Editor: [illegible])

Li Yan
Xinjiang Institute of Ecology and Geography
E-mail: liyan@ms.xjb.ac.cn

Reference

- Hidden carbon sink beneath desert

Related Articles

Humans Accidentally Created Hidden Carbon Sink in the Desert
Jul 30, 2015
"Basically, people thought the whole arid region is totally negligible to the global carbon budget," says Yan Li of the Chinese Academy of Sciences in Urumqi, China. "We are arguing that that's not the case." Li

Eddy Covariance Instrumentation Biases?

Ma, J. et al. (2014). A downward CO_2 flux seems to have nowhere to go. *Biogeosciences*, **11**: 6251-6262. **The desert is a carbon sink**

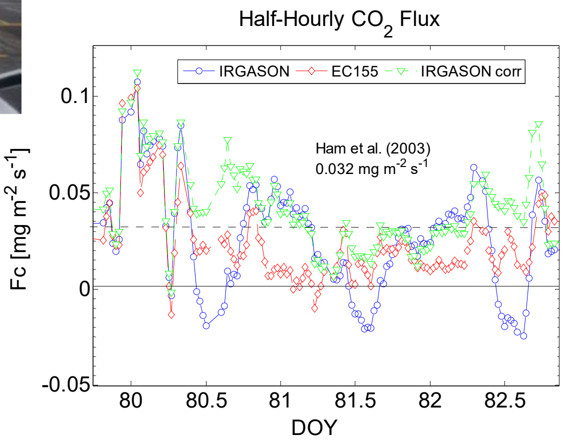
$$F_{cnew} = F_{co} + 1.6077\frac{E_{new}}{\rho_d}\frac{\rho_c}{1 + 1.6077(\rho_v/\rho_d)} + \frac{H_{PRT}}{\rho c_p}\frac{\rho_c}{T_a}$$

$$E_{new} = \left(1 + 1.6077\frac{\rho_v}{\rho_d}\right)\left(E_o + \frac{H_{PRT}}{\rho c_p}\frac{\rho_v}{T_a}\right)$$

Schlesinger, W. (2016). An evaluation of abiotic carbon sinks in deserts. *Global Change Biol.*, doi: 10.1111/gcb.13336 **We can't find the carbon?**

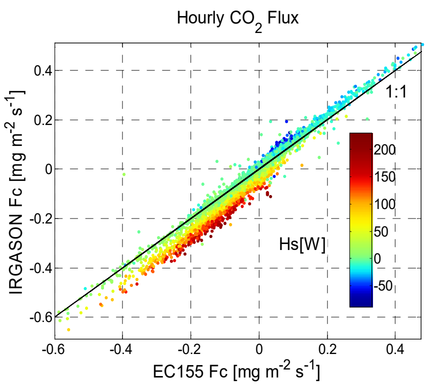
Eddy Covariance Instrumentation Biases

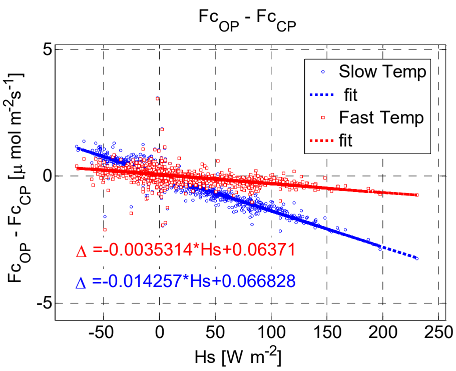
A parking lot experiment: Where is the carbon?



Eddy Covariance Instrumentation Biases

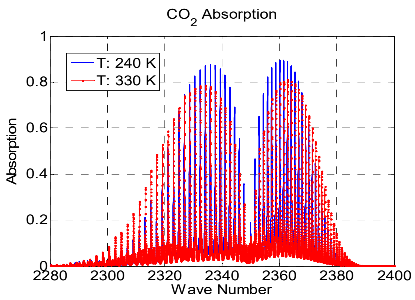
Open-path and closed-path comparison

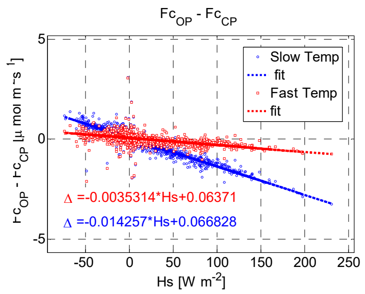




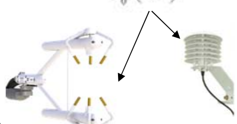
Eddy Covariance Instrumentation Biases

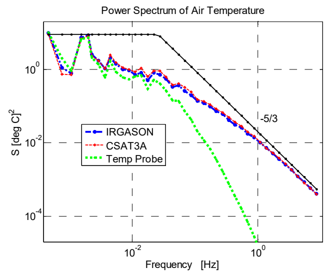
Spectroscopic bias in IRGASON





$$\alpha(P,T) = \alpha_0 \frac{P}{P_0}\left(\frac{T_0}{T}\right)^{1/2}$$



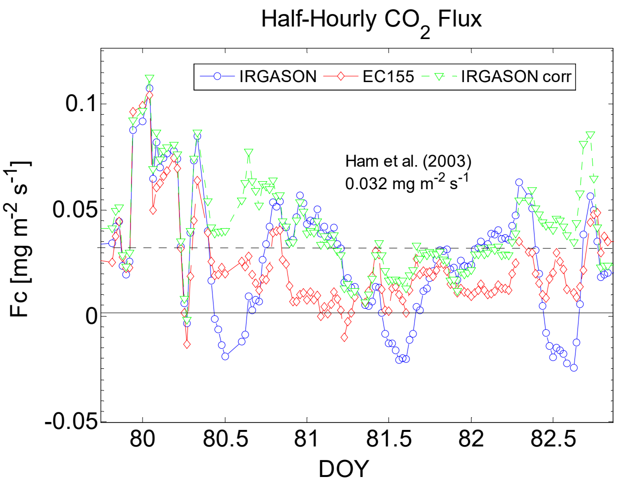


Fast-response

Slow-response

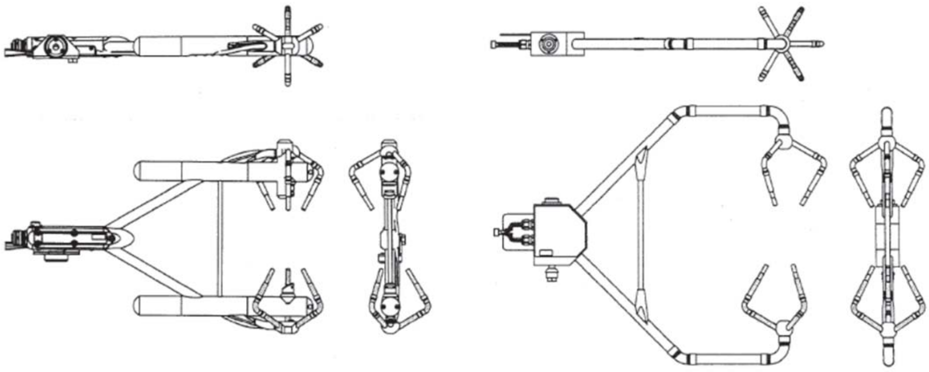
Eddy Covariance Instrumentation Biases

A parking lot is not a carbon sink



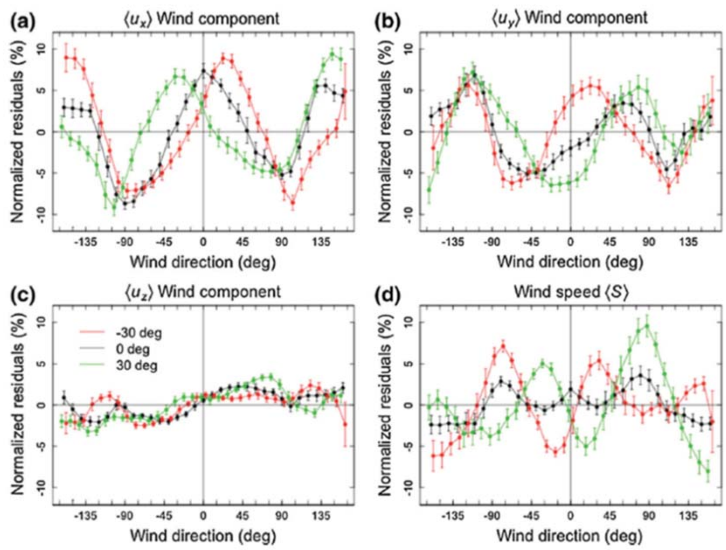
Eddy Covariance Instrumentation Biases

Example: Flow distortion causing artificial cross correlations between u' and v'

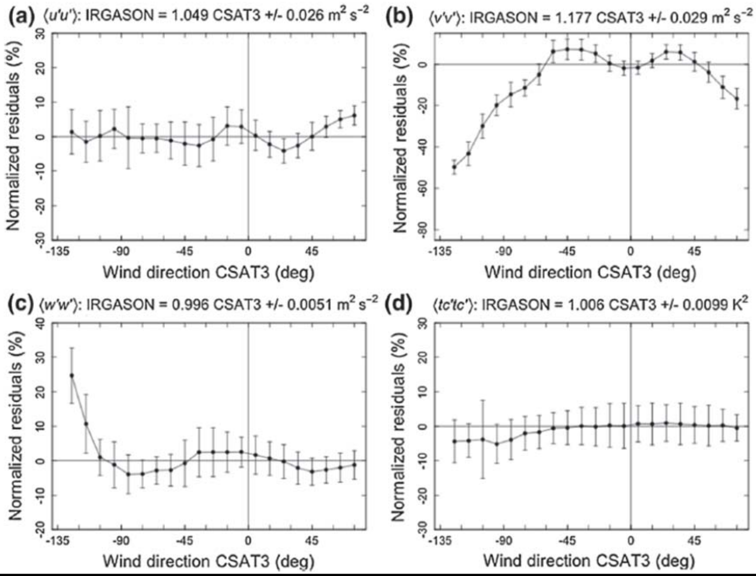


Eddy Covariance Instrumentation Biases

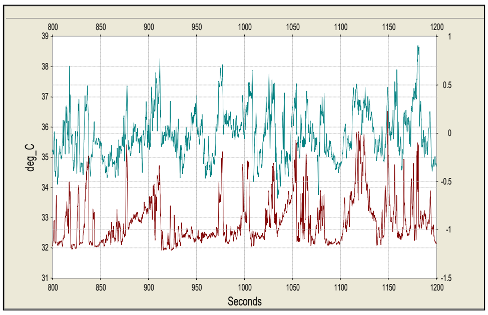
Example: Flow distortion errors



Eddy Covariance Instrumentation Biases



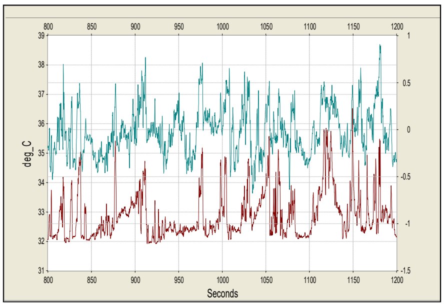
Instrument Requirements



Perfect instruments should:

- ❑ Be invisible (or very small) so that it does not affect the flow (create or destroy eddies) and not average small eddies in the sensing path
- ❑ Be fast-response to capture the rapid changes in the measured quantities
- ❑ Be sensitive to small changes in measured quantities
- ❑ Be highly accurate, stable, linear and unaffected by environmental factors (temperature, precipitation , dust, etc.)

Instrument Requirements



Perfect instruments should:

- ❑ Make all measurements simultaneously and in the same point in space (preserve covariance)
- ❑ Consume no power
- ❑ Operate forever with no maintenance or calibration under all conditions
- ❑ Easy to operate

Instrument Selection Guide and Tradeoffs

‘Know Thy Site’ ‘Know Thy Sensor’

Ray Leuning

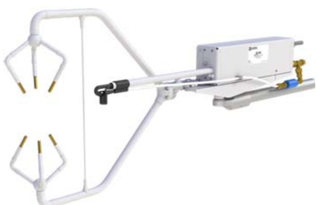
Most Flux Instruments are Very Good;
Pick the Instrument System that is Most Appropriate to Your Weather and Climate

And thy methods, tools, model assumptions and experiments!

Some instruments are better than others. Pick the instrument that is right for You.
Consider:

- Site conditions (rain, Hs, CO_2 flux, canopy…)
- Power budget
- Scientific objectives (uncertainties)
- Cost of operation, maintenance, calibration

Open- or Closed-Path System?

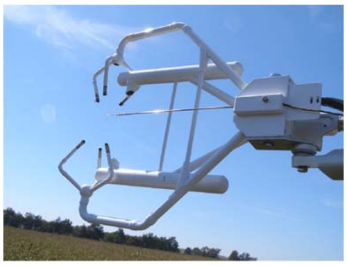


Open-path Systems

Sonic and gas analyzer separate

Or co-located

Open-path systems



Advantages:
- Excellent spectral response
- Low power consumption
- Less complex (no pumps, tubing and filters)
- Lower cost
- Low maintenance
- No tube delays and minimal time lag (scales with wind)

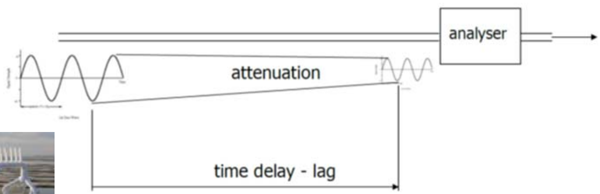
Disadvantages:
- Data loss due to precipitation, dust, birds, inscts (data spikes and drift)
- Larger density corrections
- No possibility for automated field calibrations

Closed-path Systems with Short Intake Tube

Advantages:

- Not affected by precipitation, dust, birds (less data spikes) But the sonic might be!
- Temperature fluctuations are attenuated in the intake tube - smaller density corrections
- Calculate mixing ratio in real time
- Possibility for automated field calibrations

Closed-path Systems with Short Intake Tube



High-frequency attenuation and time lag depend on flow rate, tube diameter and length, tube material, RH (becomes worse as dirt accumulates on the filter!)

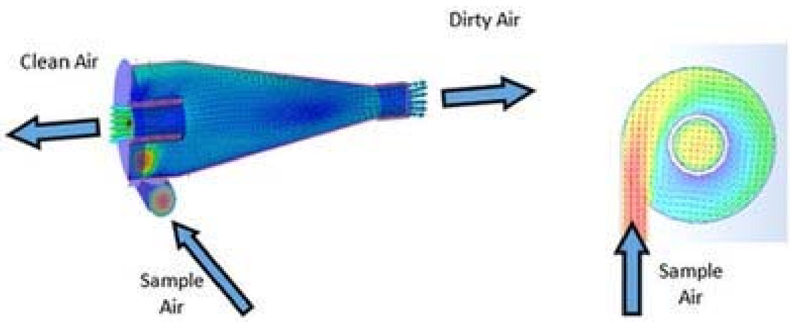
Different attenuation and lags for CO_2 and H_2O especially in at high RH regimes

Closed-path Systems with Short Intake Tube

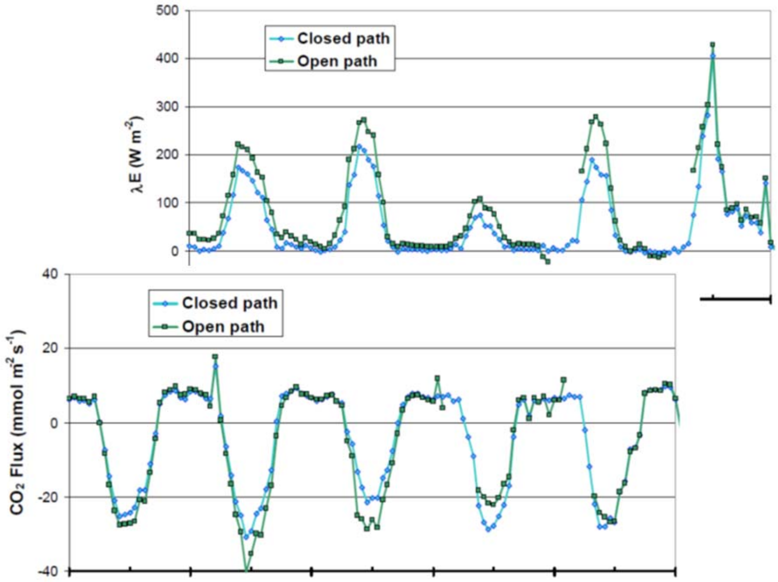
Disadvantages:
- Loss of frequency response due to tube attenuation and accumulation of particulates on the face of the filter (worse for water)
- Changing lag due to changes in flow
- Higher power requirements due to the pump
- Loss of synchronicity due to time variable lags
- Higher cost and increased maintenance (filters, pump, tubing)

Closed-path Gas Analyzer Vortex Intake

Particle separation based on size and mass
No accumulation of particulate mater
Constant flow conditions



Flux Time Series



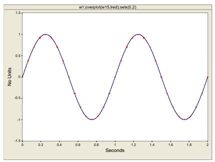
Math Tools and Concepts

- **Variance and Covariance**
- **Spectral Decomposition**: changing from time to frequency domain to identify instrumentation issues
- **Aliasing errors due to discrete sampling:** signals not measured at the correct frequency

Calculate Variation of a Signal or a Co-Variation Between Two Signals

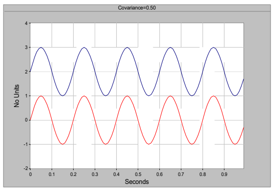
- **Variance:** A measure of how a signal varies about its mean

$$Var(x) = \frac{1}{N}\sum_{k=1}^{N}\left[x(k) - \bar{x}\right]^2$$

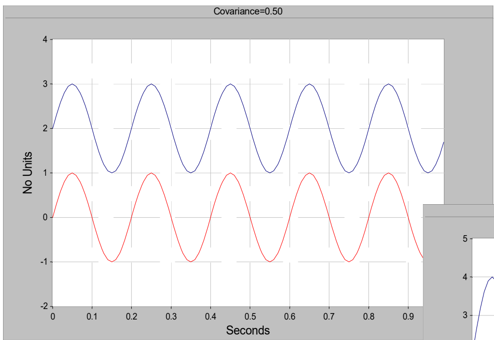


- **Covariance:** A measure of how two signals vary together about their means

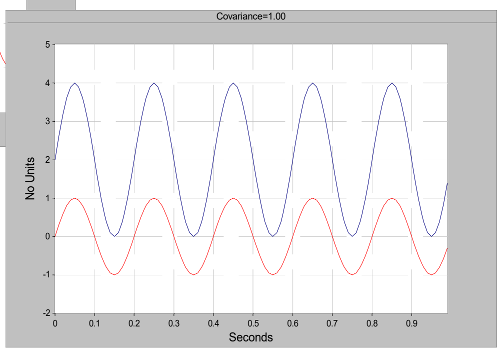
$$CoVar(x, y) = \frac{1}{N}\sum_{k=1}^{N}\left[x(k) - \bar{x}\right]\left[y(k) - \bar{y}\right]$$



Covariance - Amplitude Attenuation



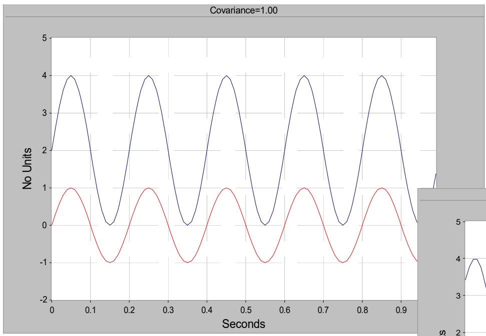
Covariance = 0.50



Double the variation of one signal

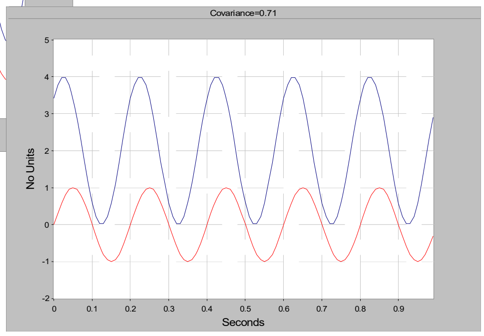
Covariance = 1.00

Covariance - Signal Time Delay



Two signals perfectly synchronized

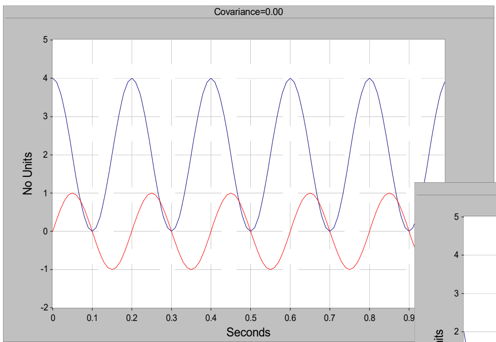
Covariance = 1.00



Time shift one signal by 1/8 of the period

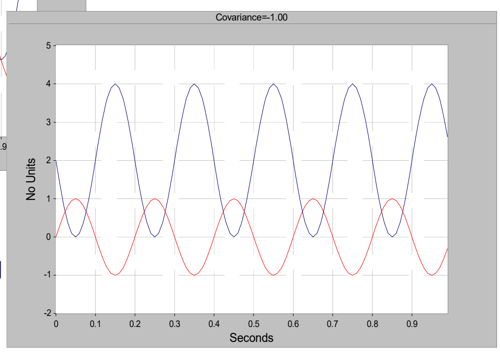
Covariance = 0.71

Covariance - Signal Time Delay



Time delay by 1/4 of a period

Covariance = 0.00



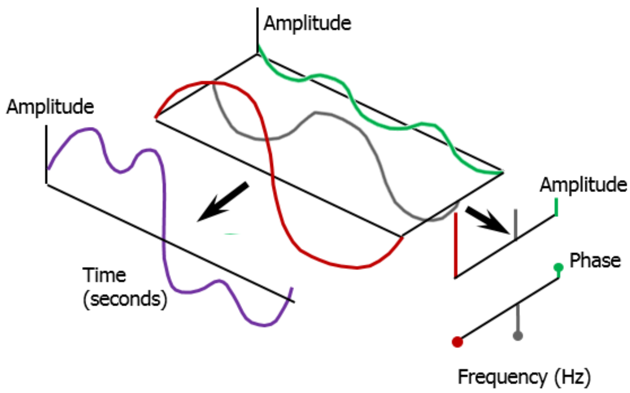
Time shift one signal by 1/2 of a period

Covariance = -1

Spatial separation is equivalent to a time delay

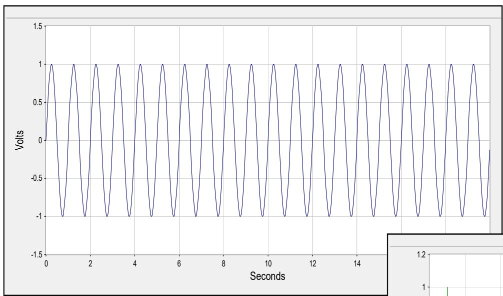
Spectral Decomposition of a Time Series

Fourier Transform

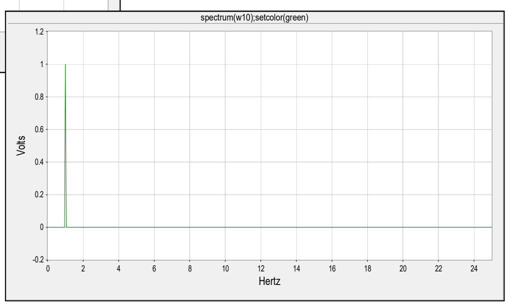


$$s_a(t) = k_a + A_{a_1}\cos(\omega_{a_1}t + \phi_{a_1}) + A_{a_2}\cos(\omega_{a_2}t + \phi_{a_2}) + A_{a_3}\cos(\omega_{a_3}t + \phi_{a_3}) + \ldots$$

Spectral Decomposition of a Sine Wave

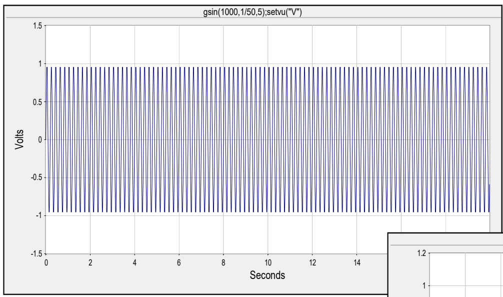


1-Hz Sine Wave as a function of time

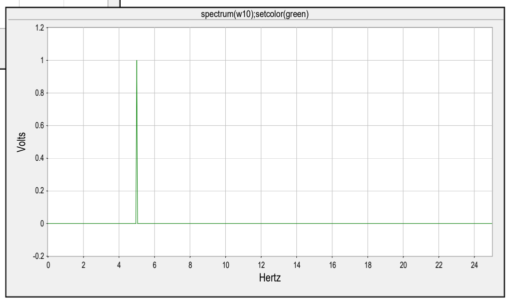


1-Hz Sine Wave as a function of frequency

Spectral Decomposition of a Sine Wave

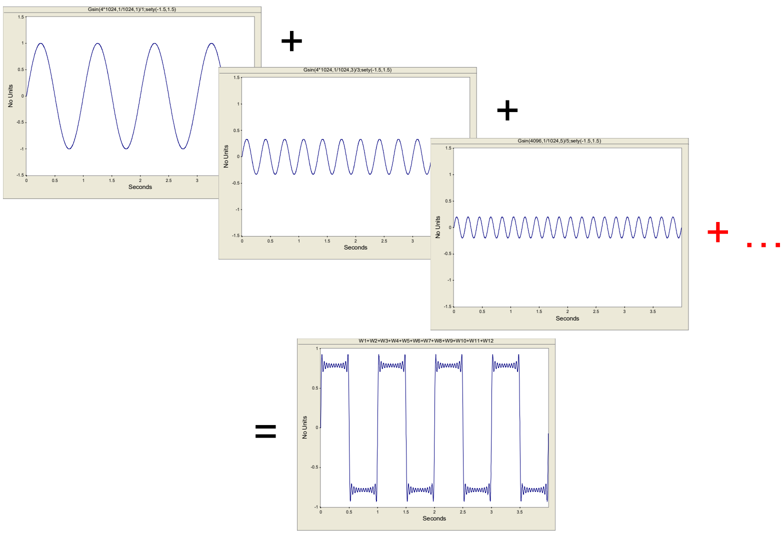


5-Hz Sine Wave as a function of time

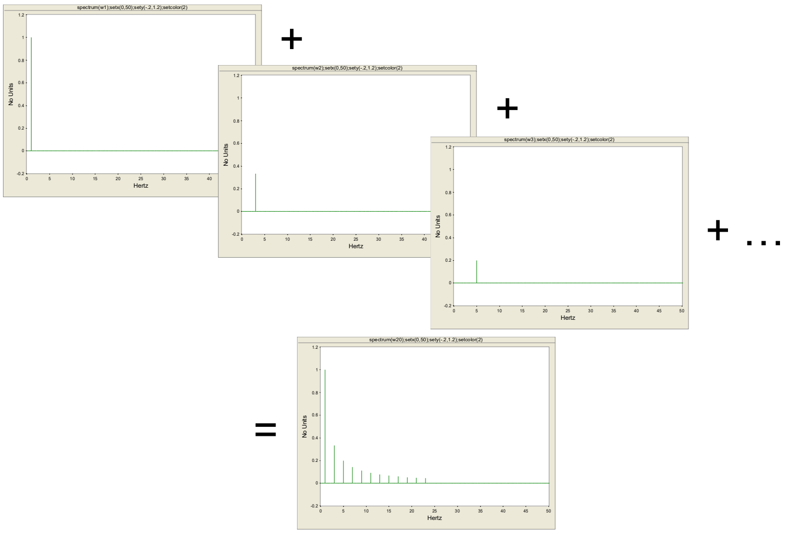


5-Hz Sine Wave as a function of frequency

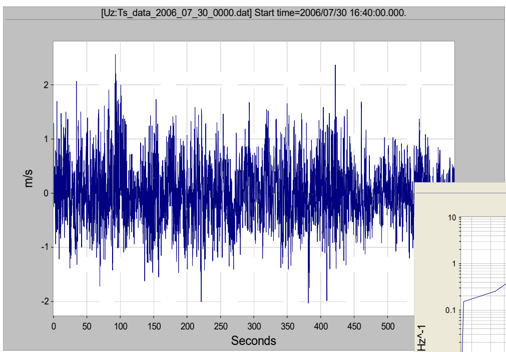
Spectral Decomposition of a Periodic Signal



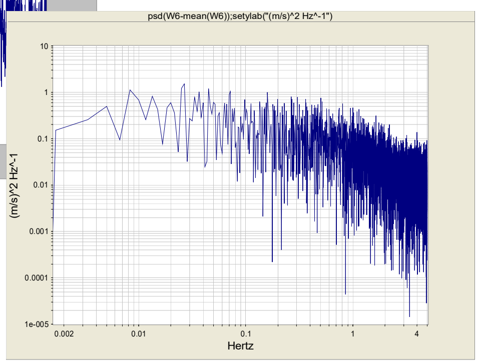
Spectral Decomposition of a Periodic Signal



Vertical Wind



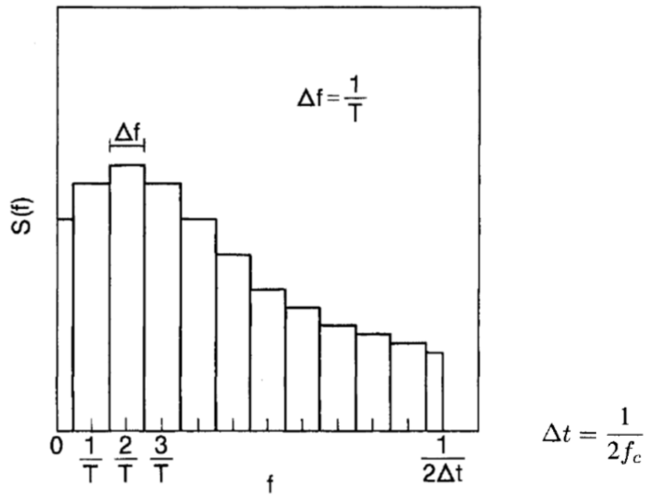
As a function of time



As a function of frequency

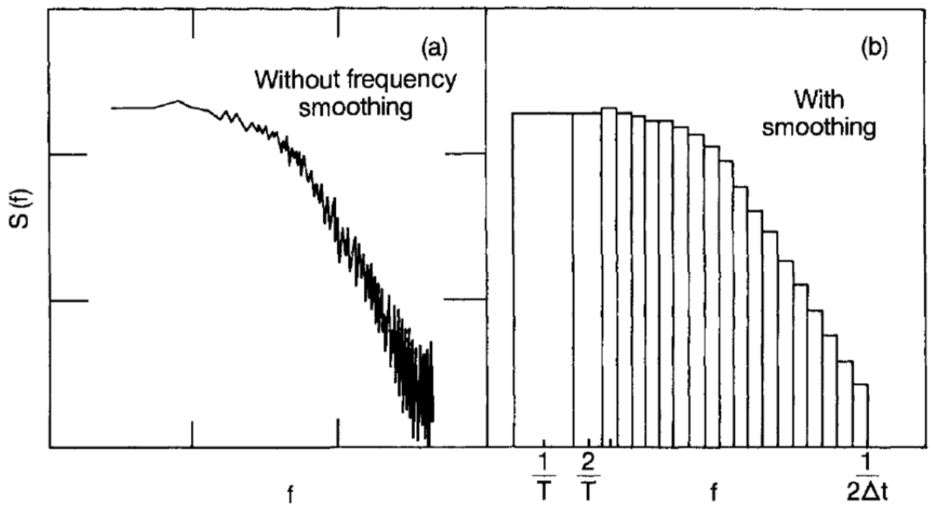
(phase not shown)

Spectral Resolution



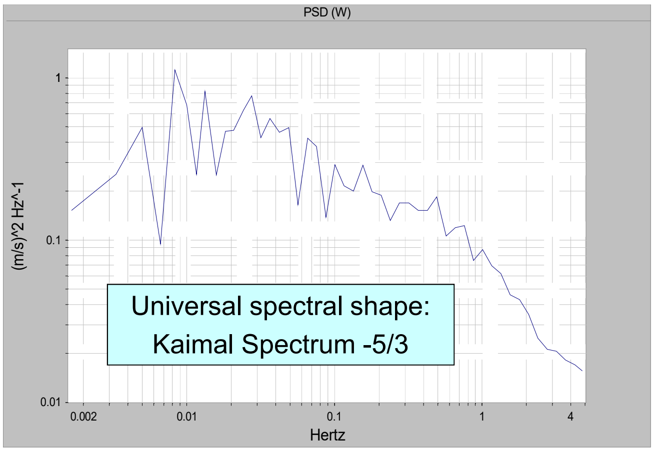
Length of the time series T determines the spectral resolution Δf and the sampling period Δt determines the maximum frequency

Spectral Smoothing of a "Raw" Spectrum



Scatter is reduced by averaging a frequency window that expands in width with frequency (log scales)

Spectral Smoothing of a "Raw" w Spectrum

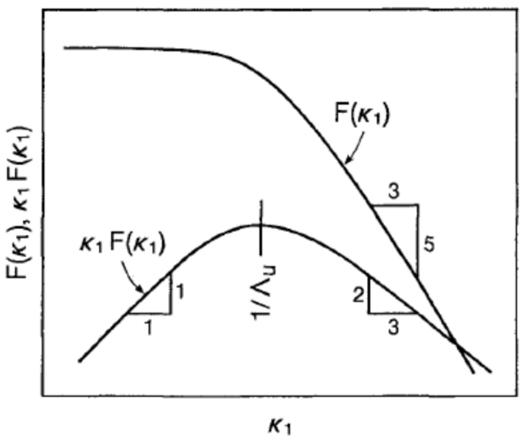


S(f) Spectral density $A^2/\Delta f$ (units of variance per Δf)

Area under the curve = variance

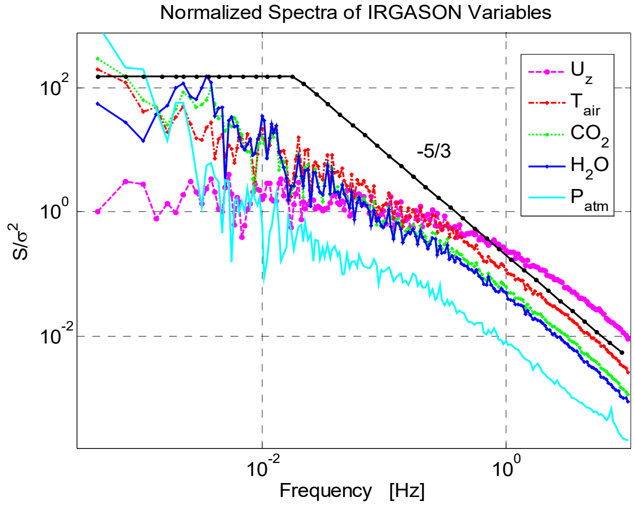
Sometimes frequency weighted spectrum is used fS(f) (units of variance)

Frequency Weighted Spectrum



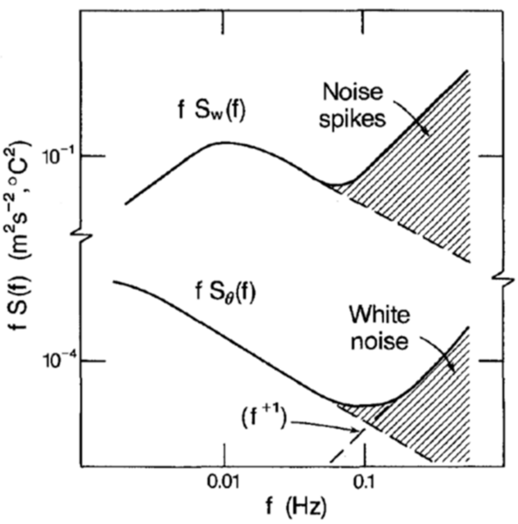
Frequency weighted spectrum is shows the spectral gap at the low frequency range

Spectral Similarity



Normalized spectra have similar shape for different variables (but not exactly the same)

High-frequency Distortion due to Instrumental Effects



Noise spikes in sonic w measurement (bug or precipitation)

Noise floor of PRT temperature measurement

Spectral Decomposition - Co-spectra

- **We can compute covariance in the time domain or the frequency domain.**

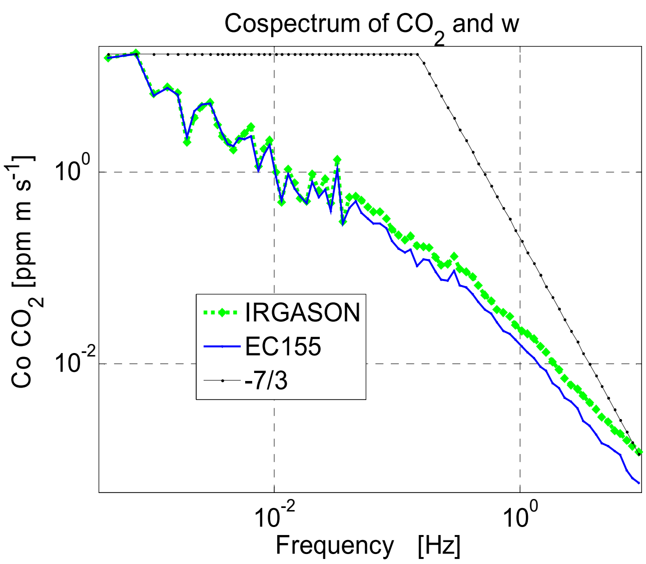
$$s_a(t) = k_a + A_{a_1}\cos(\omega_{a_1}t + \phi_{a_1}) + A_{a_2}\cos(\omega_{a_2}t + \phi_{a_2}) + A_{a_3}\cos(\omega_{a_3}t + \phi_{a_3}) + \ldots$$

$$s_b(t) = k_b + A_{b_1}\cos(\omega_{b_1}t + \phi_{b_1}) + A_{b_2}\cos(\omega_{b_2}t + \phi_{b_2}) + A_{b_3}\cos(\omega_{b_3}t + \phi_{b_3}) + \ldots$$

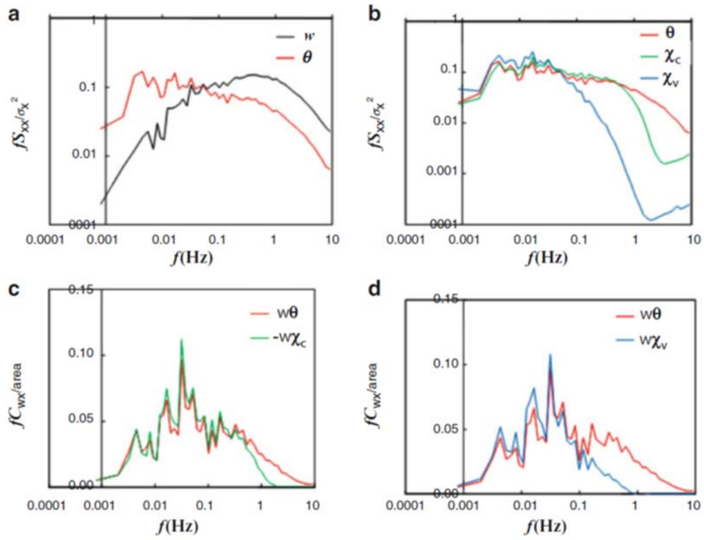
$$\mathrm{cov}(s_a, s_b) = \left[\frac{A_{a_1}A_{b_1}}{2}\cos(\phi_{a_1} - \phi_{b_1})\right]_{=0 if(\omega_{a1} \neq \omega_{b1})} + \left[\frac{A_{a_2}A_{b_2}}{2}\cos(\phi_{a_2} - \phi_{b_2})\right]_{=0 if(\omega_{a_2} \neq \omega_{b2})} + \left[\frac{A_{a_3}A_{b_3}}{2}\cos(\phi_{a_3} - \phi_{b_3})\right]_{=0 if(\omega_{a3} \neq \omega_{b3})} + \ldots$$

- **The covariance computed in the time domain equals the area under the curve of a Co-Power Spectral Density function (CoPSD).**

Co-Spectral Analysis



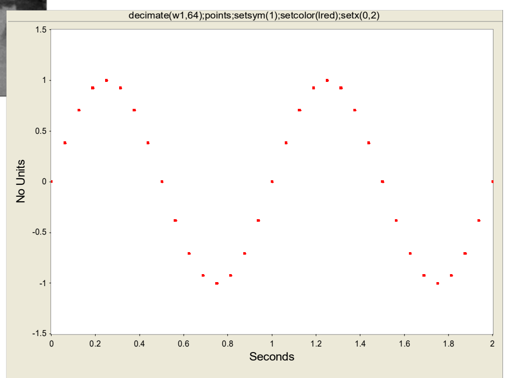
Frequency Weighted Co-Spectra



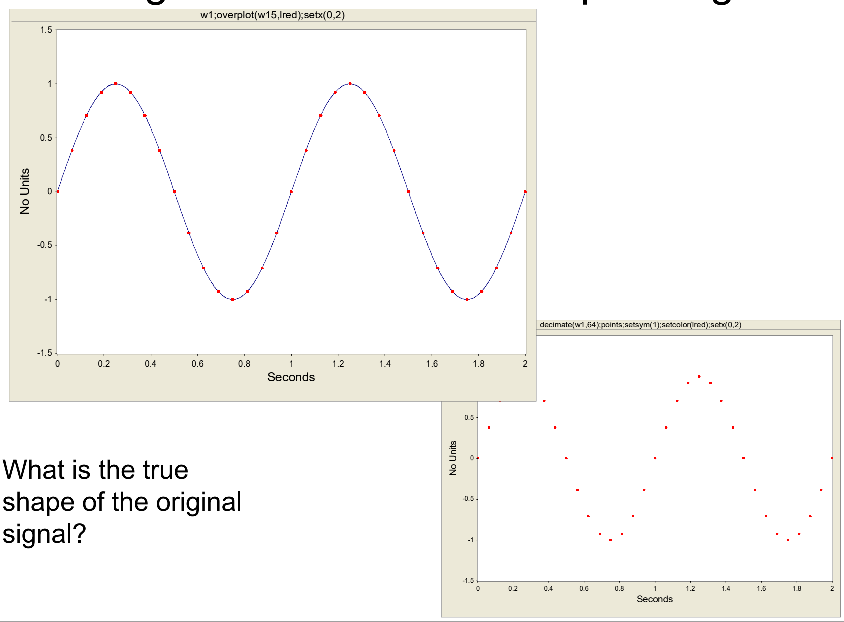
After Leuning

Aliasing – Discrete Time-Sampled Signal

What is the shape of the measured signal ?

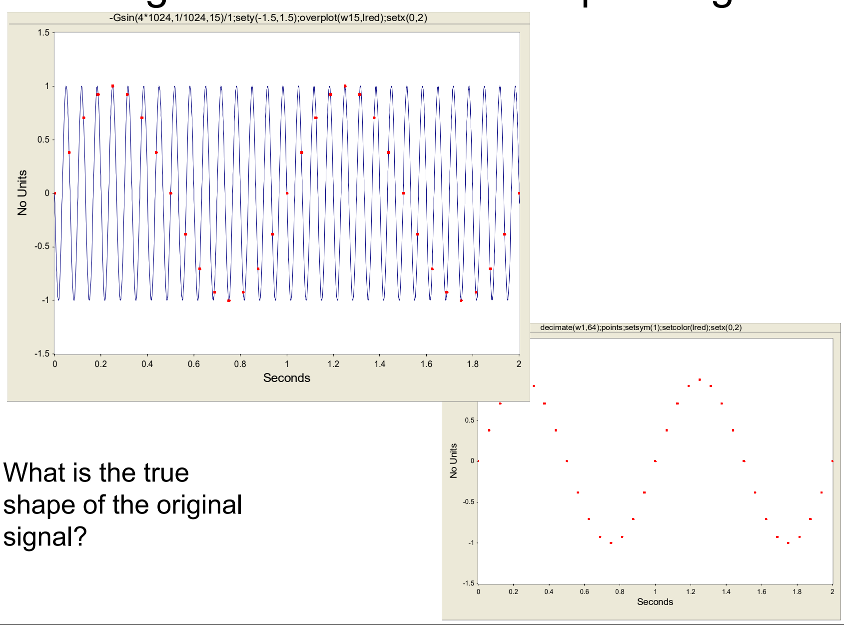


Aliasing – Discrete Time-Sampled Signal



What is the true shape of the original signal?

Aliasing – Discrete Time-Sampled Signal

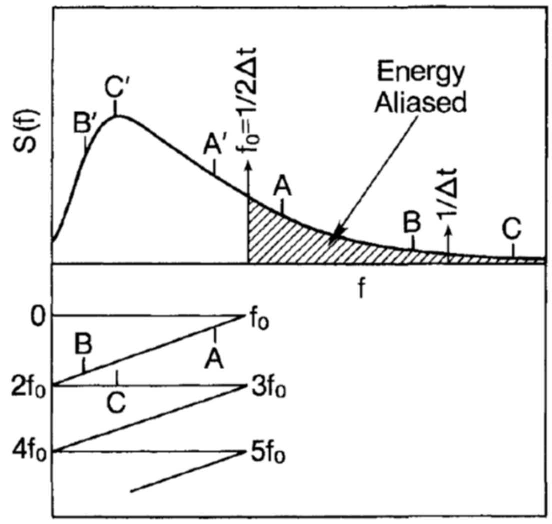


What is the true shape of the original signal?

Folding of Spectral Energy

Misrepresentation of the high frequency components

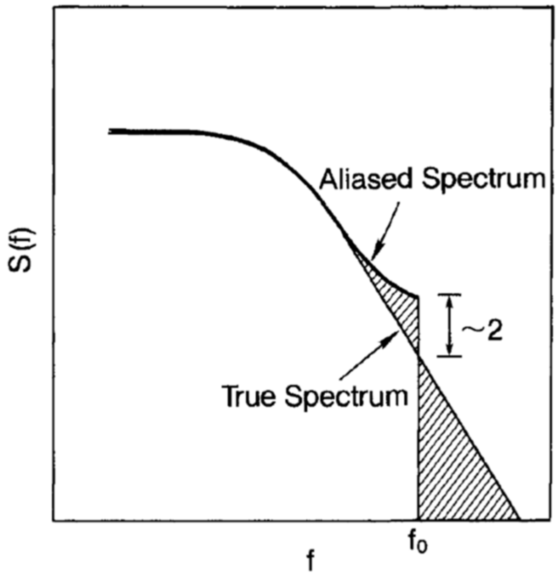
f_o –Nyquist frequency
$f_o=f_{sample}/2$
For proper frequency representation
$f_{sample}=2f_{max}$



Folding of Spectral Energy

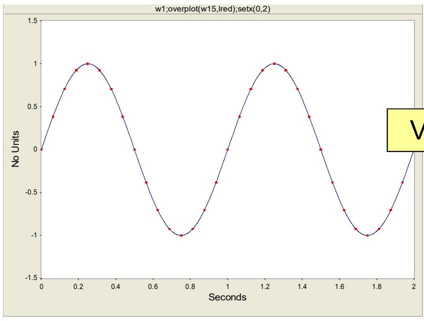
Misrepresentation of the high frequency components

The variation of the signal is preserved, so aliasing is not a problem for calculating fluxes

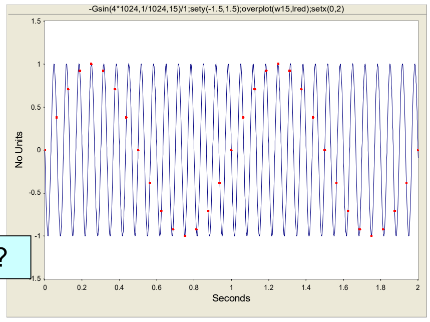


Folding of Spectral Energy

Misrepresentation of the rate at which the signals are changing



Variance = ???



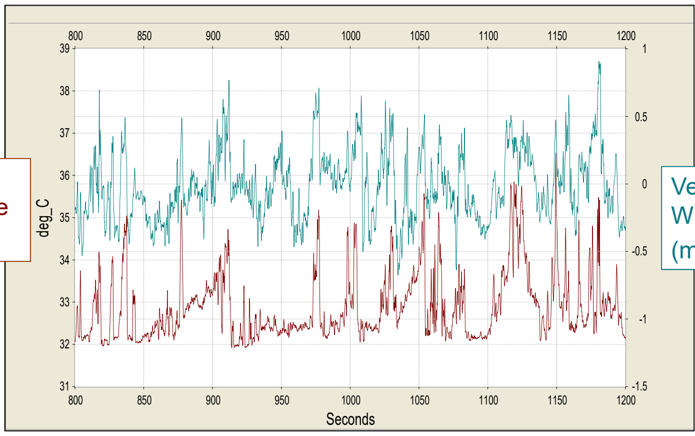
Variances and covariances are correct

Variance = ???

Eddy Covariance System Requirements

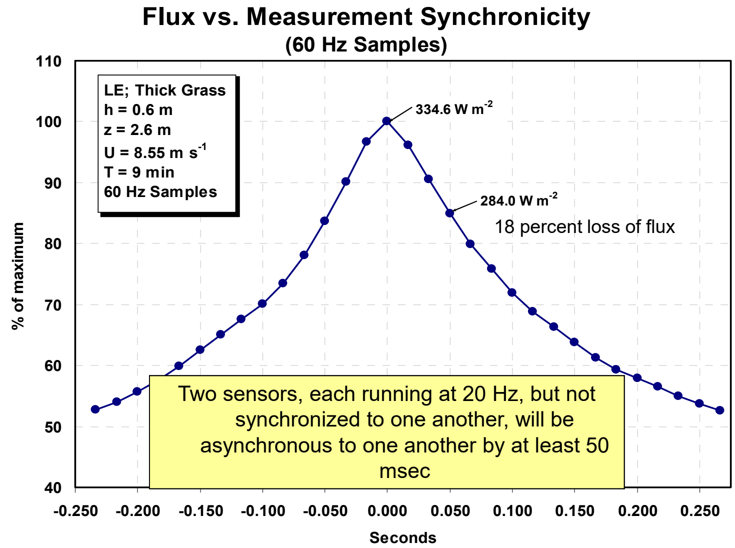
Adequate frequency response of the sensors (small d, high flow)
Preserve temporal and spatial correlation of vertical wind and scalar

Sonic Temperature (deg C)

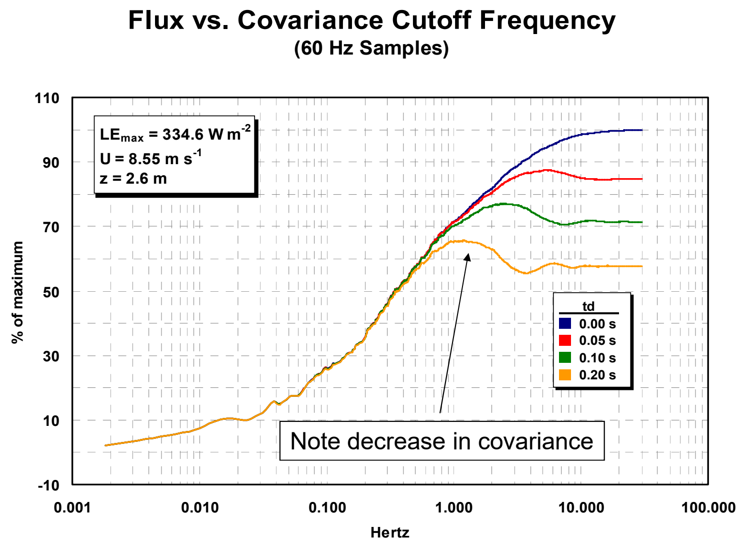


Vertical Wind (m/s)

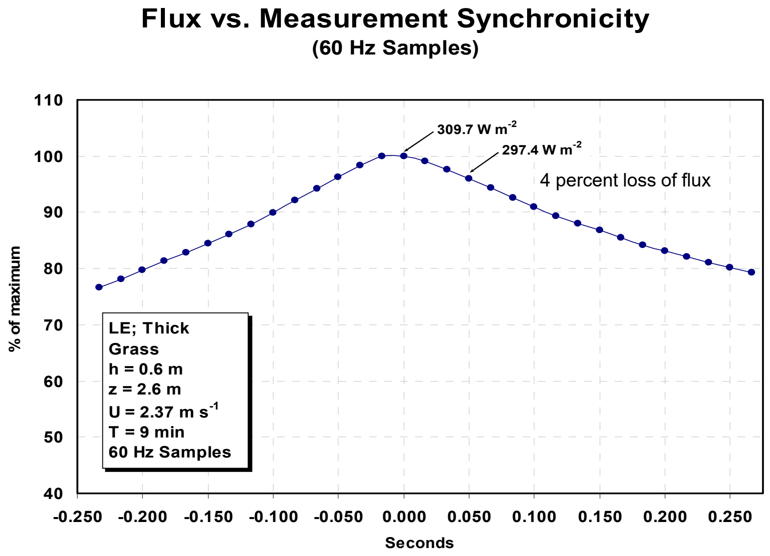
Eddy Covariance System Requirements



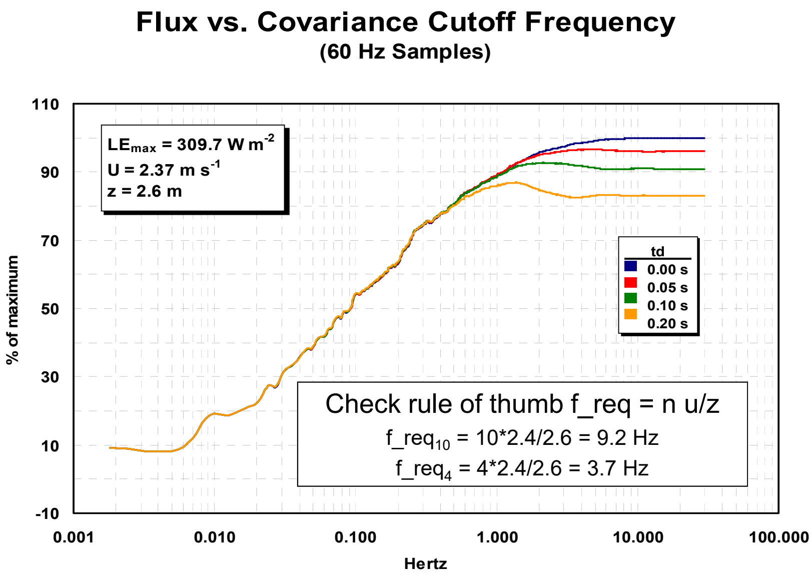
Eddy Covariance System Requirements



Eddy Covariance System Requirements



Eddy Covariance System Requirements



Summary

- Know the limitations and the assumptions of the method
- Know thy site (heterogeneity, advection, storage)
- Select instruments appropriate for your conditions and research goals (adequate frequency response, temporal and spatial synchronization)
- Know your instruments (test in lab conditions, intercompare, calibrate and maintain)
- QC your data (spectra, co-spectra, stationarity, advection, instrument effects)

Outlook after T. Foken:

The knowledge of the fathers of the eddy-covariance method is often forgotten and errors of the first days of the method are repeated

Four Problems of the Eddy-covariance Technique

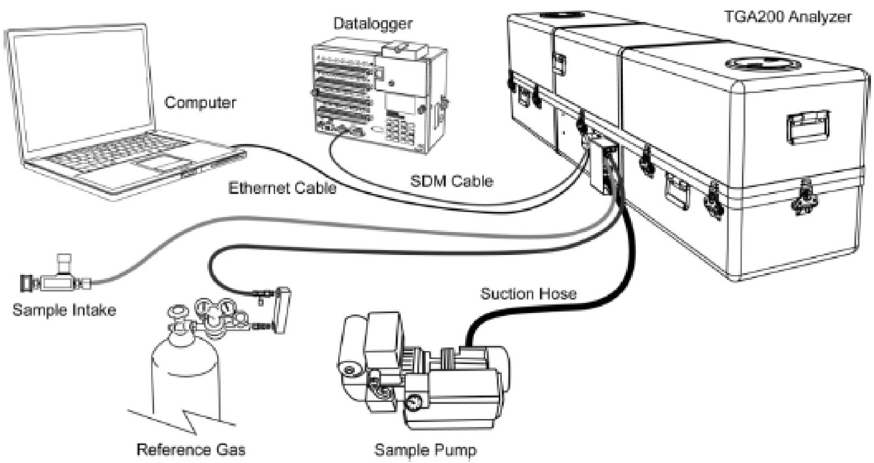
- Energy balance closure (not always an instrument problem)
- Night-time fluxes (sweeps systematic bias)
- Heterogeneous terrain (larger scales and secondary circulations)
- Accuracy of the method

Trace Gas Analyzer (TGA) for CH_4, N_2O and 13C Isotope Measurements

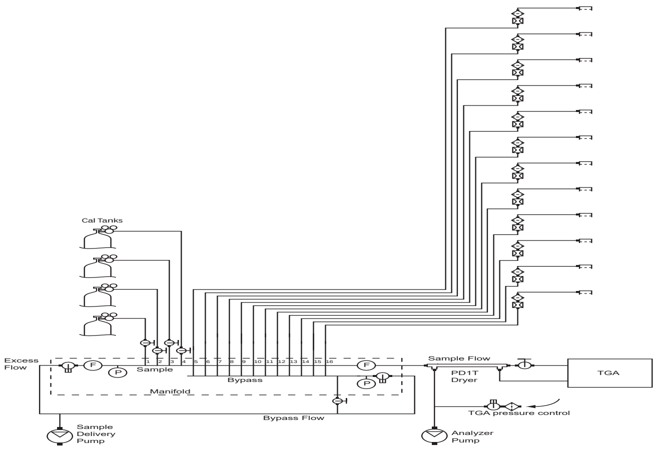
What is a TGA?

- CSI has been manufacturing TGA's since 1993
- TGA is a tunable diode laser absorption spectrometer (TDLAS), and new lasers are TE cooled
- They are rugged, portable, and designed for use in the lab or out in the field
- Uses a small sample cell volume for good frequency response no mater the application

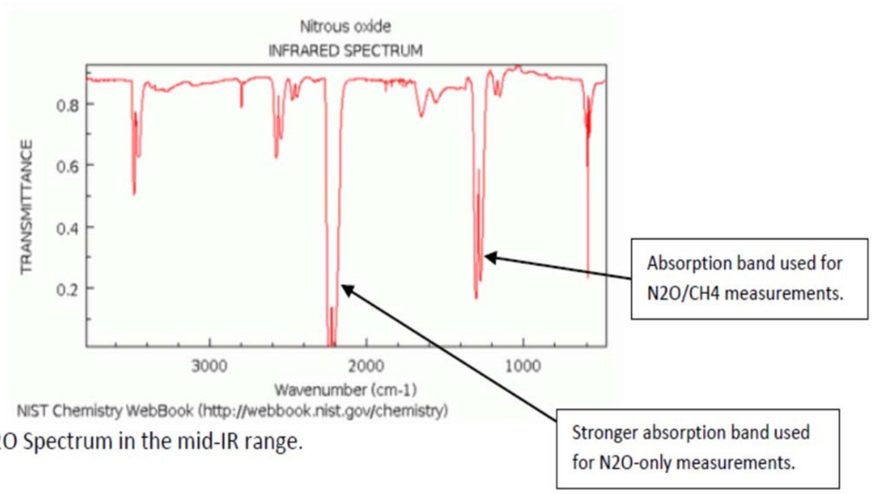
System Components for CH_4, N_2O and 13C Isotope Measurements



System Components for CH_4, N_2O and 13C Isotope Measurements from Multiple Inputs



Infrared Spectrum of CH_4, N_2O

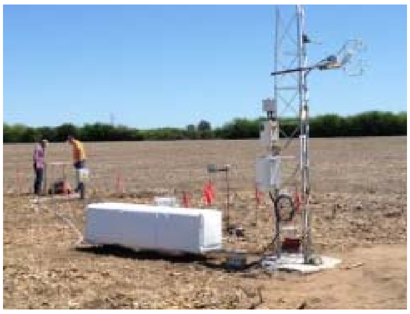


N2O Spectrum in the mid-IR range.

Example Configurations & Applications

- Argentina (N2O/CO2, Eddy Covariance)
- Australia (CO2 Isotopes, Leaf Chamber)
- Minnesota (Methane, Eddy Covariance)
- Brazil (N2O/CO2, Multi-Site Gradient)
- Example Pump Shelters

Example Configurations & Applications



LOCATION: NORTHEAST ARGENTINA
RESEARCH: UNDERSTAND NITROGEN AND CARBON CYCLES FOR CORN AND SOYBEAN ROTATIONS AND VARIOUS TILLAGE/FERTILIZER PRACTICES
MAJOR SYSTEM COMPONENTS: TGA200 ANALYZER, CSAT3 3D SONIC ANEMOMETER, FW05 FINEWIRE THERMOCOUPLE, LI-7500A, TIPPING RAIN BUCKET, NET RADIOMETER, SOIL MOISTURE PROBES, SOIL HEAT FLUX PLATES, SOIL TEMPERATURE PROBES

Example Configurations & Applications

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