Accuracy, Uncertainty, and Limitations of Eddy Covariance for Measuring Evapotranspiration

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OUTLINE

(1) What is Eddy Covariance (EC)

(2) What is the nature of the instrumentation

*Response time, Transfer function, Open- & Closed-Path Samplers

*Spectral attenuation and Spectral Corrections

(3) WPL Density "Terms" or "Corrections"

(4) How well do Eddy Covariance systems perform

*Surface Energy Balance

(5) Sonic Anemometers & Surface Energy Balance

(6) Soil Heat Flux & Surface Energy Balance

[1.0] What is Eddy Covariance

Eddy Covariance is a micrometeorological technique to measure the exchange rate of energy and mass between atmosphere and the earth's surface by sampling turbulent atmospheric motions and the associated fluctuations in mass concentration.

Or: Eddy Covariance measures the turbulent atmospheric fluxes of mass [$kg/m^2/s$] and energy [W/m^2] between the atmosphere and the biosphere (plants, soil, water bodies).

The benefit of Eddy Covariance is that it allows fairly strong inferences to be made about the state and the functioning of the biosphere; i.e., water and carbon cycles, soil water balance, water use efficiency and photosynthetic capacity of an ecosystem, soil respiration, impacts of ozone on vegetation, biospheric influences on climate.

For the present purposes I will focus on Eddy Covariance fluxes of water vapor. But much of what I have to say will apply more broadly to other trace gases as well.

Basic Assumptions are:

(a) "Well developed", stationary, and homogeneous atmospheric turbulence.
(b) Horizontally homogeneous surface conditions, particularly for about 1-3 km upwind of the instrumentation.

[1.1] What is Eddy Covariance?

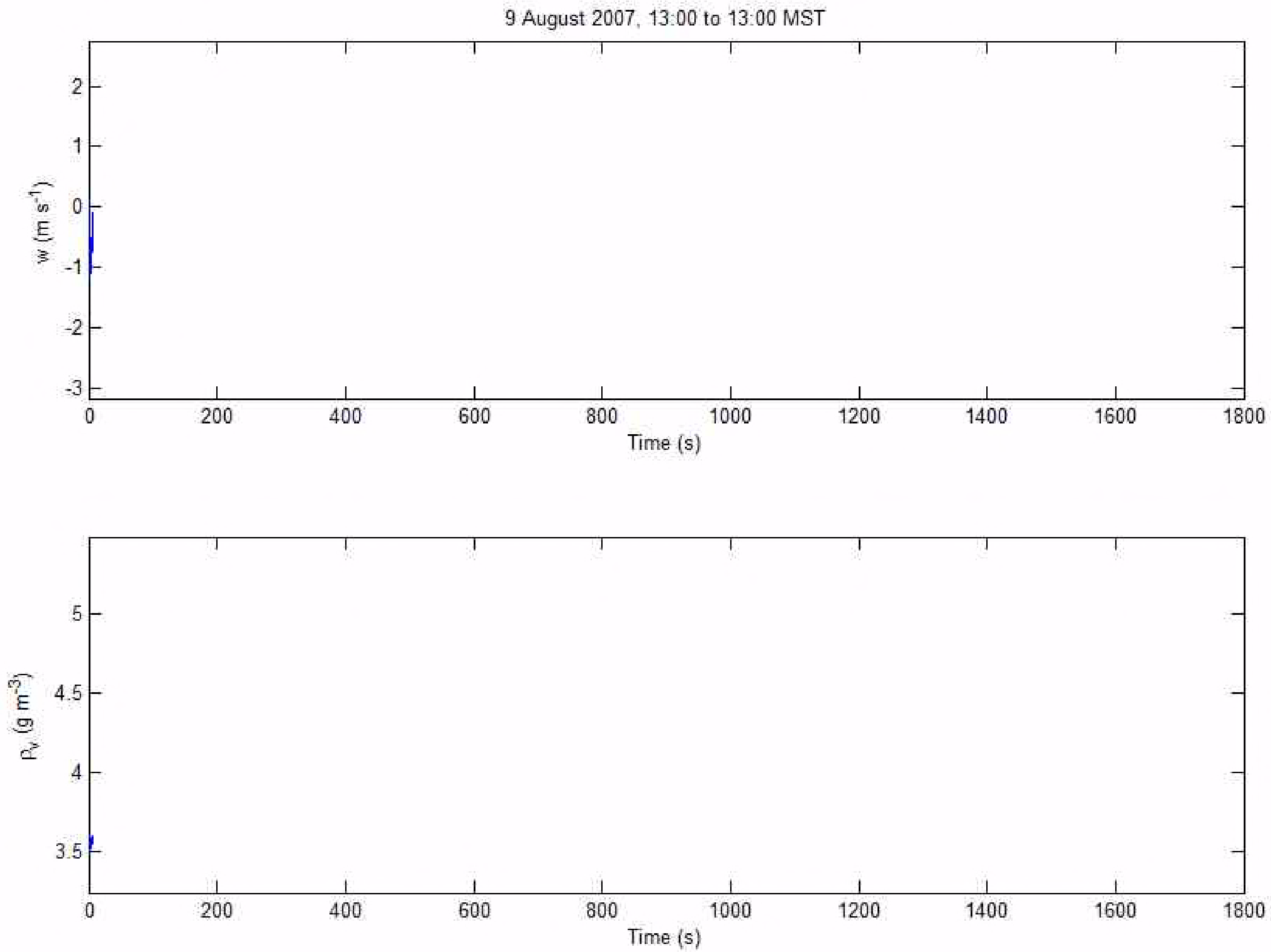
[1.2] What is Eddy Covariance?

Water Vapor Covariance is defined as:

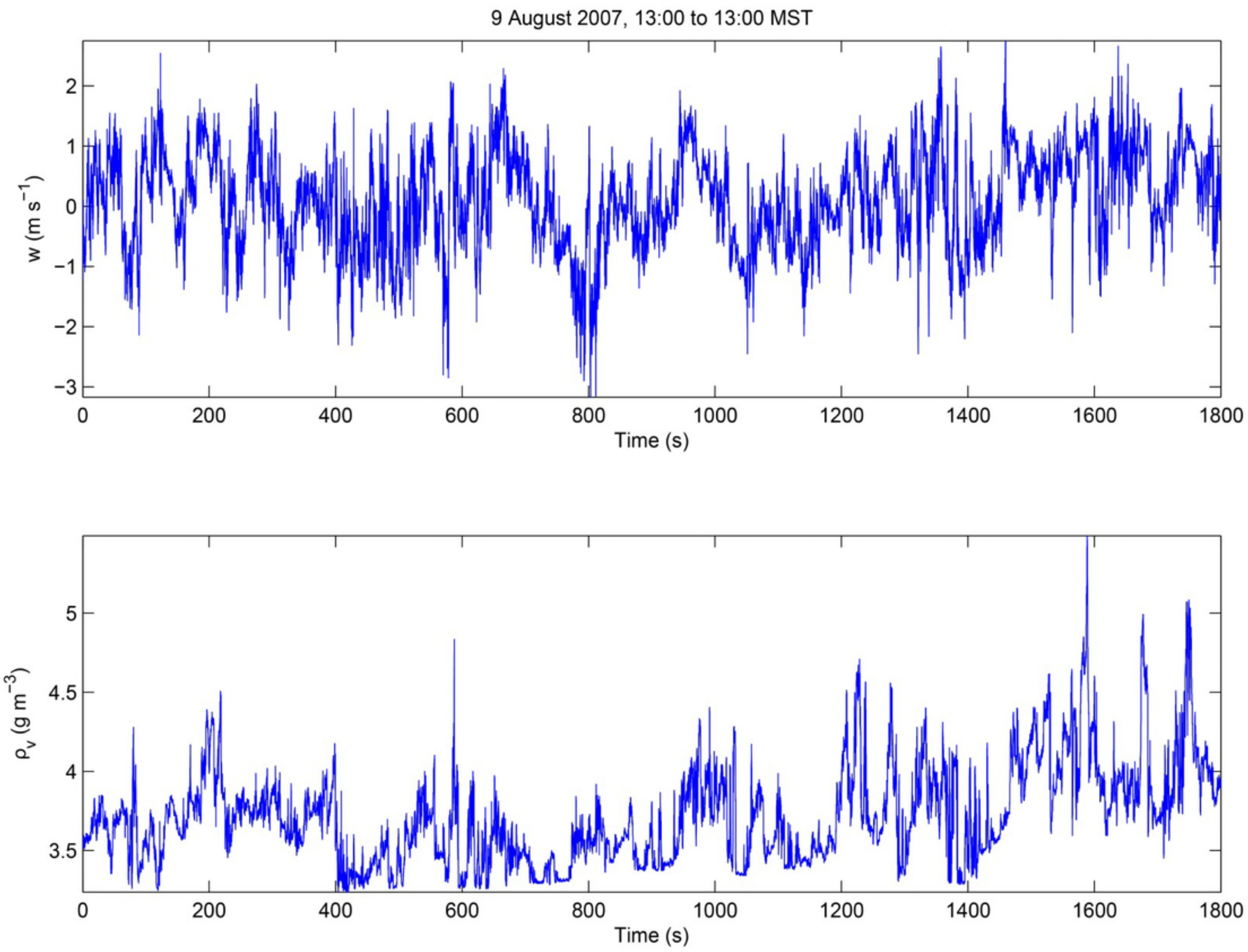
$$\overline{w'\rho'_v} = Cov(w, \rho_v) = \frac{1}{n}\sum_{i=1}^{n}\left(w_i - \overline{w}\right)\left(\rho_{v,i} - \overline{\rho_v}\right)$$

where w is the vertical wind speed and ρ_v is water vapor density. The same equation can be used for horizontal wind speed [u], temperature [T], and CO_2 [c].

[1.3] What is Eddy Covariance?



[1.4] What is Eddy Covariance?



[2.0] Eddy Covariance Instrumentation

[2.1] Instrumentation

Instrument characteristics are of two types: static and dynamic.

Static characteristics are synonymous with the calibration curve.
Dynamic characteristics are described by a response function or transfer function.

The simplest "model" of a physical instrument is a
first-order, linear, ordinary differential equation, such as

$$\tau\, dXo/dt + Xo = XI(t)$$

where τ is the time constant; X_0 is the output signal of the instrument; and $X_I(t)$ is the forcing or, in this case, the atmospheric signal we wish to detect.

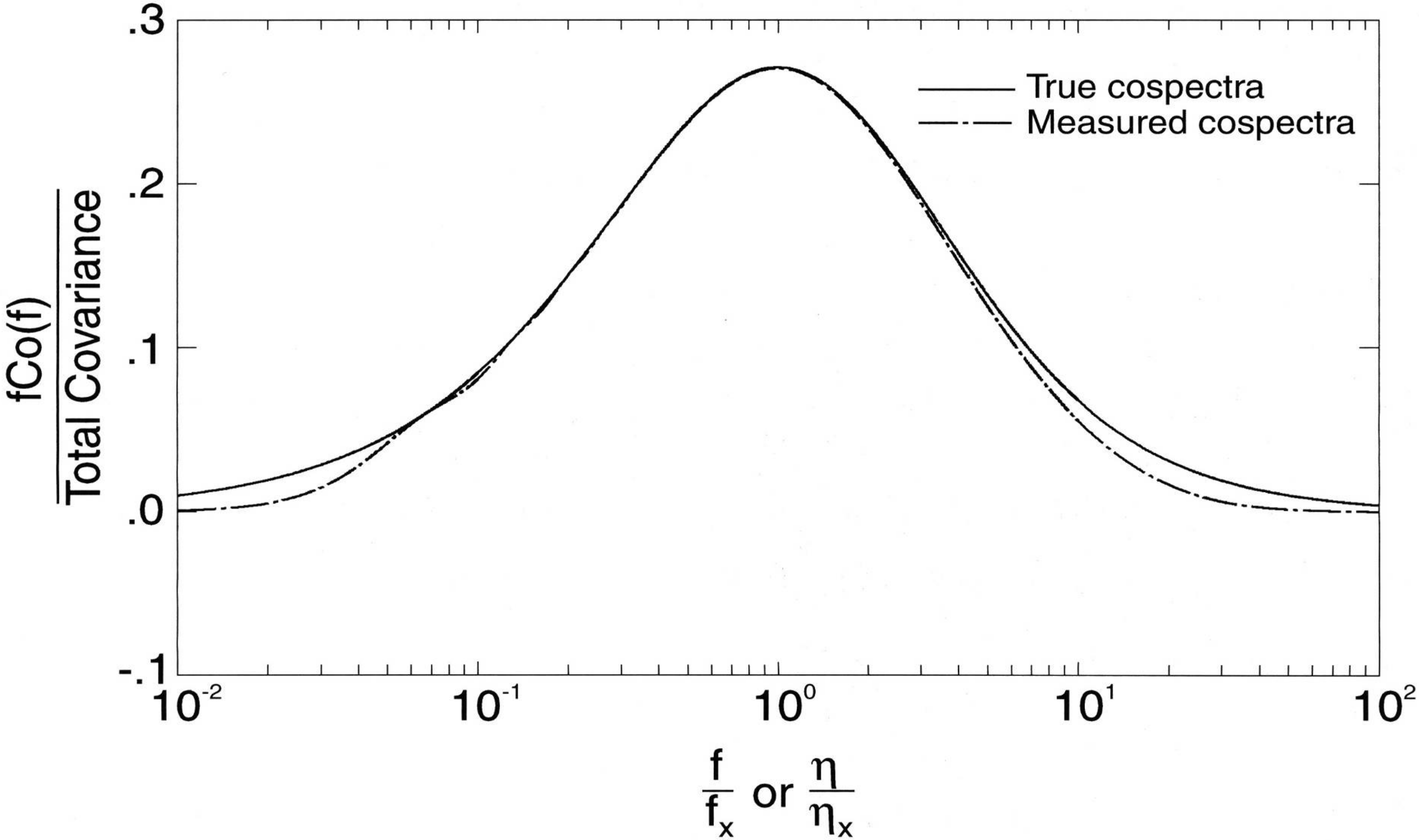
Assuming periodic input $XI(t) = Xin + A_I\, e^{-i\omega t}$, then the output signal $X_o(t)$ is

$$Xo(t) = Xin + AI/(1 - i\omega\tau)\, e^{-i\omega t} - AI/(1 - i\omega\tau)\, e^{-t/\tau}$$

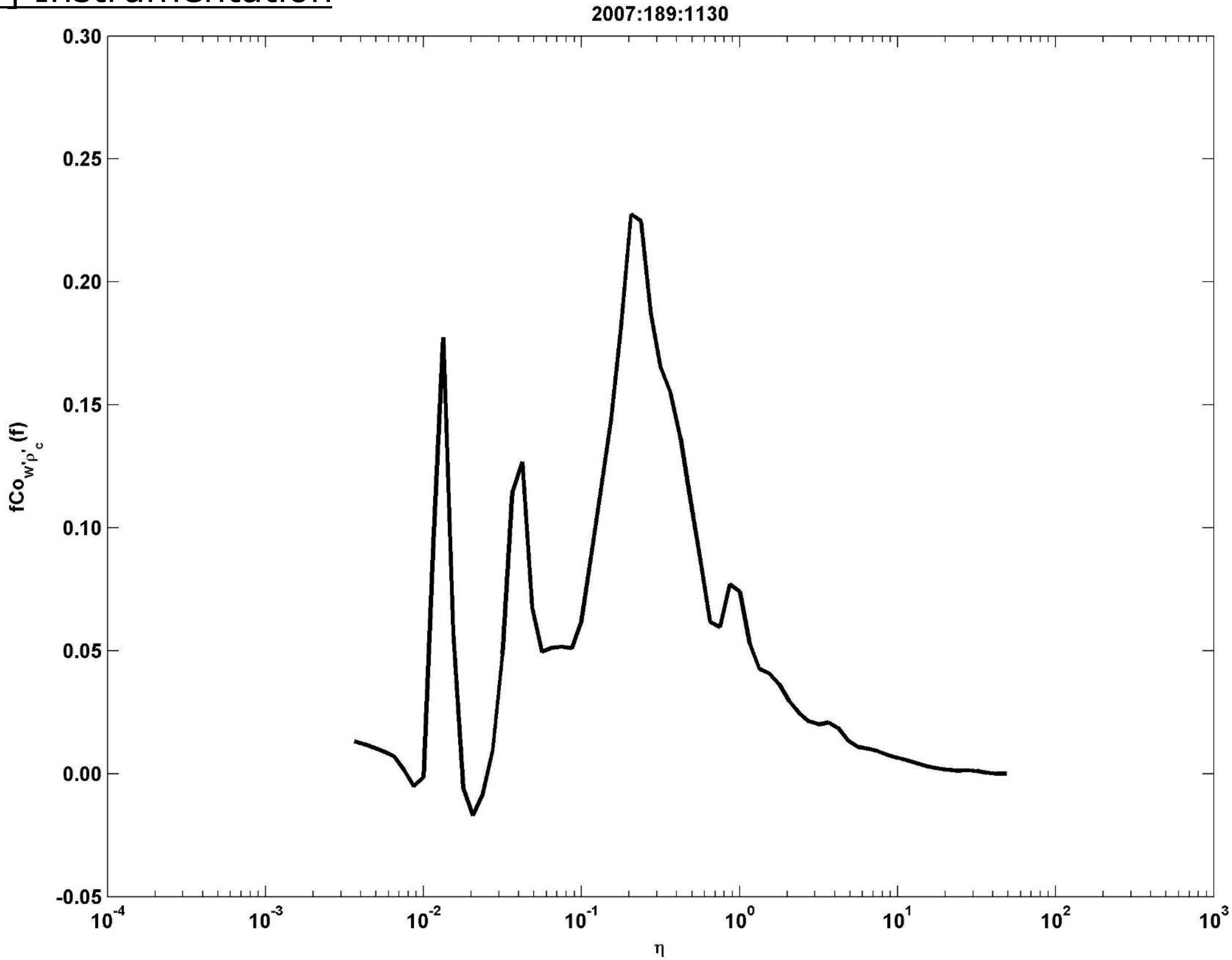
and the transfer function is

$$h(\omega,\tau;t) = \frac{X_o(t) - X_{in}}{X_I(t) - X_{in}} = \frac{1 - e^{-t/\tau} e^{-i\omega t}}{1 - i\omega\tau} \longrightarrow \frac{1}{1 - i\omega\tau}$$

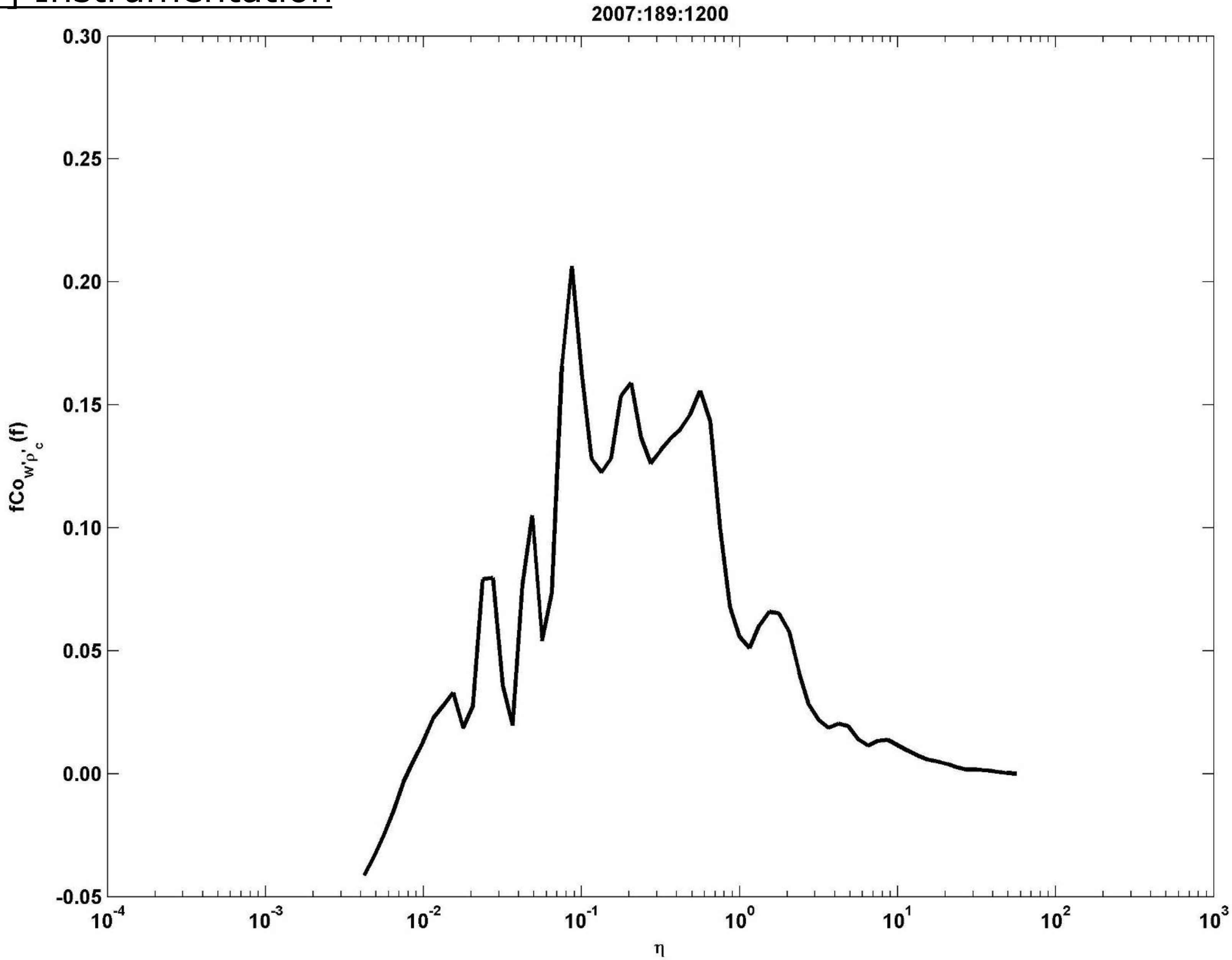
[2.2] Instrumentation



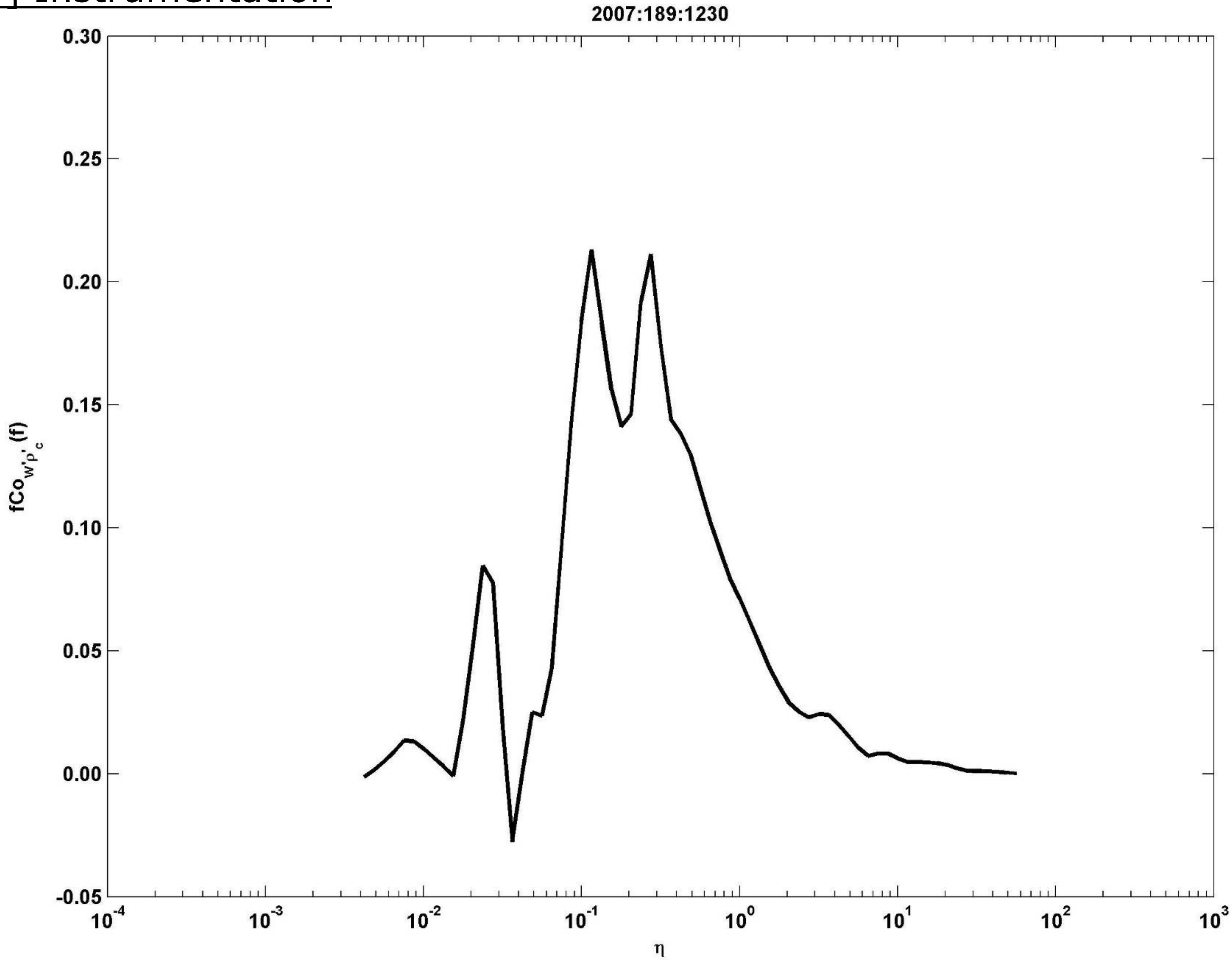
[2.3] Instrumentation



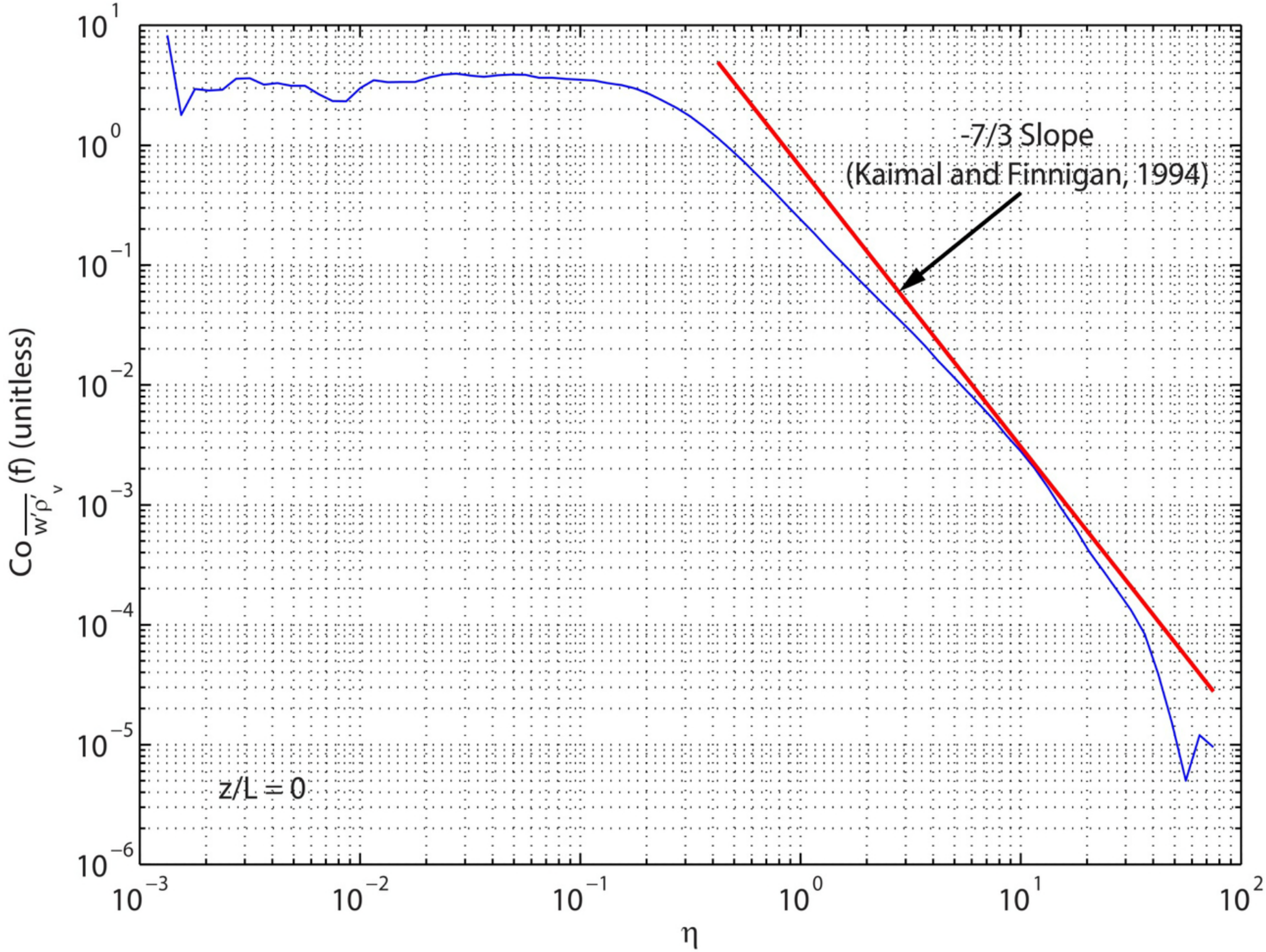
[2.4] Instrumentation



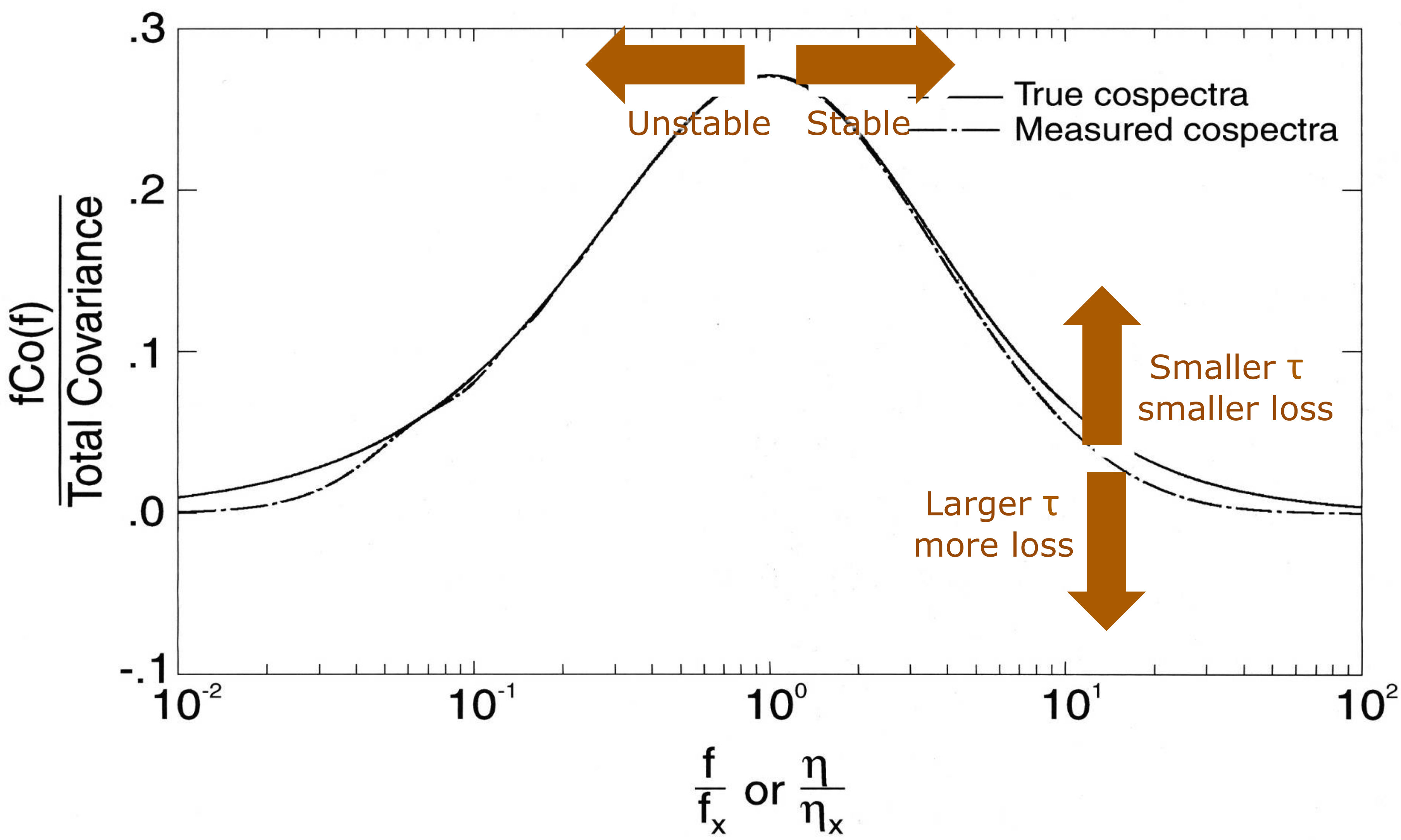
[2.5] Instrumentation



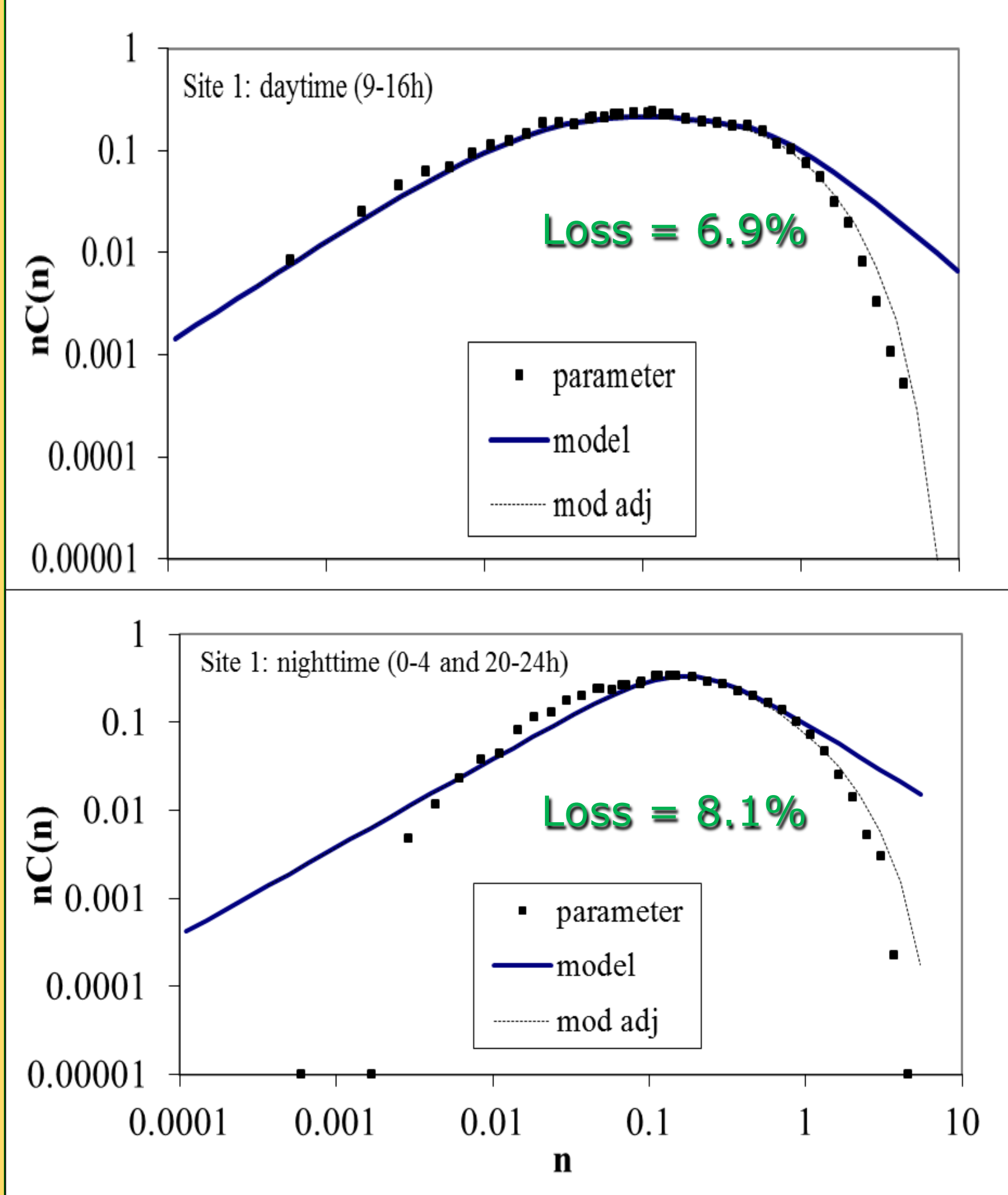
[2.6] Instrumentation



[2.7] Instrumentation



[2.8] Instrumentation Closed-Path Sensor



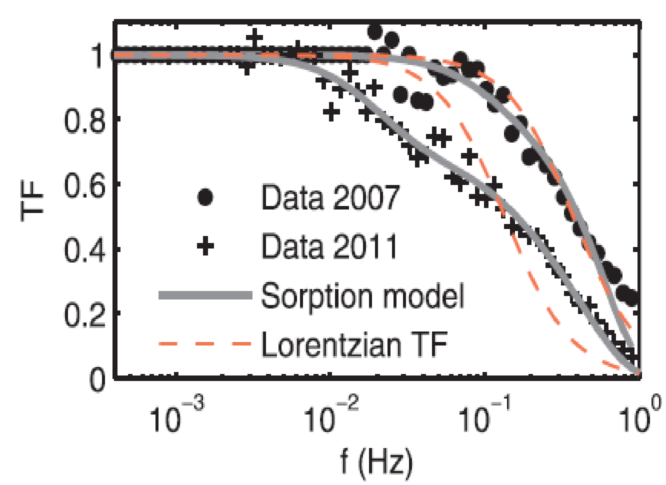


FIG. 5. Transfer functions (*TF*) as a function of frequency (*f*, [Hz]): Data from field measurements of turbulent fluctuations in water-vapor concentration in 2007 (black dots) and 2011 (black crosses), fits based on the proposed *TF* (Eq. (4)), and fits based on a Lorentzian *TF*. $RH = 58\%$ and $\mu = 0.024$ for both years. Fitting was made with $\lambda = 0.045$ and $\kappa = 0.64$ for 2007, and $\lambda = 0.16$ and $\kappa = 1.53$ for 2011.

$$TF = \left| \exp\left[\frac{1 - \sqrt{1 + 4\mu^2(i\omega + \lambda\sqrt{i\omega}\tanh(\kappa\sqrt{i\omega}))}}{2\mu^2} \right] \right|^2$$

[20] Nordbo, A, P Kekäläinen, E Siivola, R Lehto, T Vesala, and J Timonen (2013) Tube transport of water vapor with condensation and desorption. *Applied Physics Letters*, **102**, 194101, doi:10.1063/1.4804639.

[2.9] Instrumentation

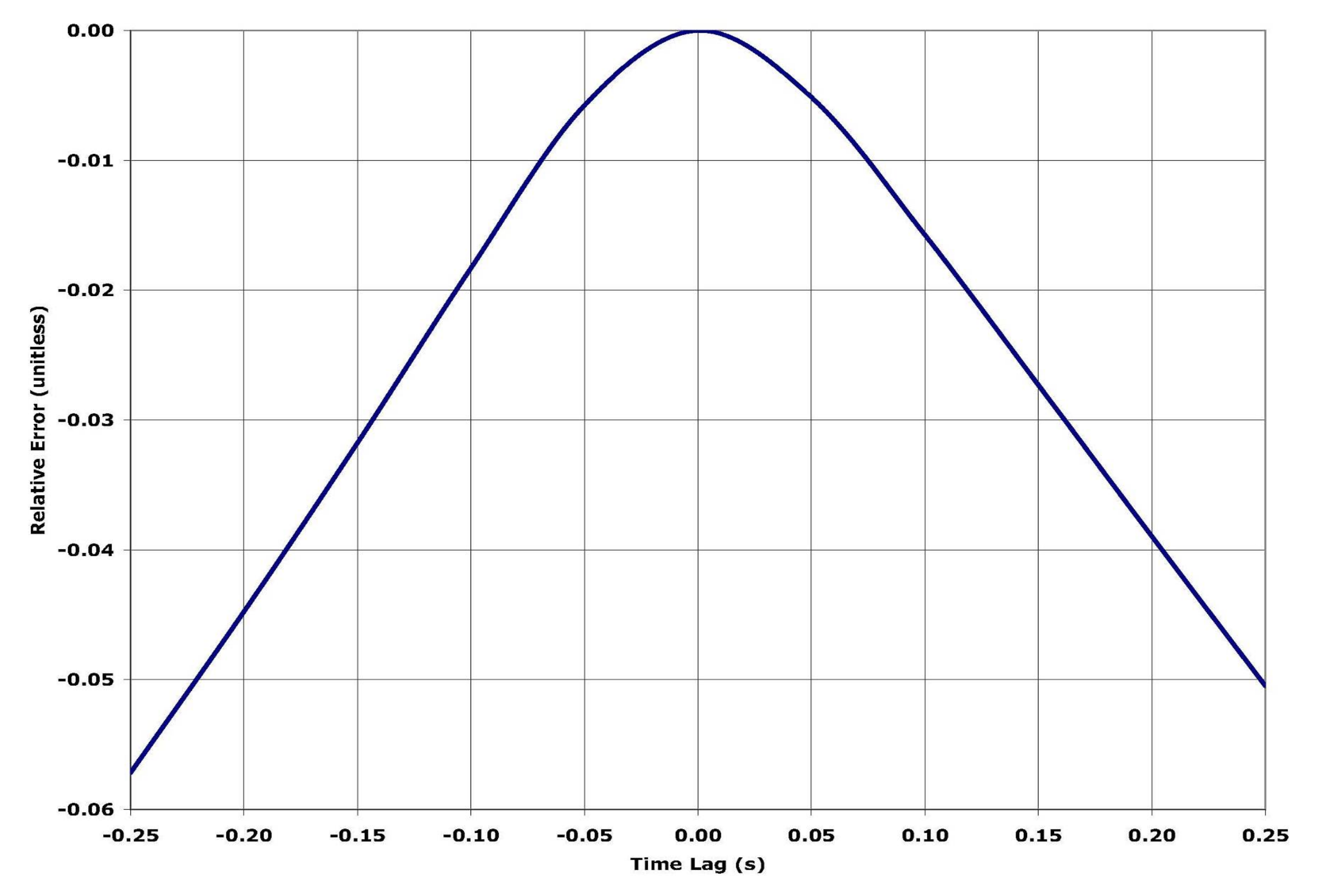
Sensor Displacement

Need to account for the time lag between the sonic anemometer and the EC H_2O/CO_2 sensor.

The vertical wind speed and H_2O/CO_2 time series must be synchronized to ensure maximum covariance. There are several reasons why these two time series can be out of synch: different instrument processing times, sensor separation, etc.

The error from unsynchronized time series can be important ...

[2.10] Instrumentation   Sensor Displacement



[2.11] Instrumentation   Summary

(1) Underestimation of EC fluxes is inevitable due to imperfect sensors. For many applications (daytime) this should be < 8% and ‘correctable’.

(2) For heat flux (sonic thermometry) expect 1-3% loss.

(3) For vapor flux expect with 2-6% for an open-path sensor separated from the sonic by less than 30 cm.

(4) For closed-path vapor flux co-spectral loss can be > 10%, if the (water) vapor is adsorbing/desorbing on the tube walls. Characterizing this loss is more difficult with greater uncertainty.

(5) **BUT** for stable atmospheric conditions (nighttime) co-spectral attenuation can be significant (>20%) for any EC trace gas instrument and corresponding flux. Nevertheless, the spectral ‘corrections’ are robust and often reasonable; they do possess somewhat greater uncertainty.

(6) Low frequency loss (due to flux averaging time) remains uncertain.

[3.0] Webb-Pearman-Leuning (WPL 'Corrections')

So what exactly are we 'correcting' with these additional concerns?

We are **NOT** correcting the instrumentation, not in the sense of some failing or limitation on the instrument's part, as was just outlined in the previous section on sensor performance.

The WPL or density terms originate from atmospheric effects that influence the number of molecules (or mass density) of water vapor, CO_2, or any trace gas within the sensing path of an instrument that is designed to detect physical mass.

So above a transpiring surface we know that physical mass is being added to the atmosphere and can be detected by modern instrumentation. But the expansion and contraction of atmospheric volume elements during convection or mechanical mixing associated with environmental conditions also influence the density of the trace gas at the point of measurement.

[3.1] Webb-Pearman-Leuning (WPL 'Corrections')

The key point to remember about the WPL or density term is that the appropriate measurement of mass fluxes to and from a surface would be to measure the fluctuations in terms of mass mixing ratio relative to dry air, χ_v *[kg/kg or mol/mol],* rather than in terms of fluctuations in mass density, ρ_v *[kg/m^3]*. The mixing ratio automatically includes the effects of atmospheric density fluctuations caused by 'external' environmental fluctuations in temperature, pressure, and other atmospheric trace gases.

Equally important (at least to me) is to realize **(1)** that the WPL is **NOT** a consequence of a "mean vertical velocity", which is how WPL (1980) originally phrased this issue. It is rather a consequence of the conservation of mass of dry air. In addition, **(2)** introducing the conservation of mass into the derivation of the WPL terms yields the **Fundamental Equation of Eddy Covariance**, which allows further insights into the other physical processes that impact how we interpret eddy covariance fluxes.

But first, the original result from WPL (1980) is correct, although I may take exception to the introduction of WPL's "mean vertical velocity".

[3.2] Webb-Pearman-Leuning (WPL 'Corrections')

Water vapor

$$\overline{w'\rho'_v}^F = \left(1+\overline{\chi_v}\right)\overline{w'\rho'_v} + \overline{\rho_v}\left(1+\overline{\chi_v}\right)\left[\frac{\overline{w'T'_a}}{\overline{\overline{T_a}}} - \frac{\overline{w'p'_a}}{\overline{\overline{p_a}}}\right]$$

Carbon Dioxide

$$\overline{w'\rho'_c}^F = \overline{w'\rho'_c} + \overline{\rho_c}\left(1+\overline{\chi_v}\right)\left[\frac{\overline{w'T'_a}}{\overline{\overline{T_a}}} - \frac{\overline{w'p'_a}}{\overline{\overline{p_a}}}\right] + \overline{\omega_c}\mu_v\overline{w'\rho'_v}$$

These expressions derived originally by WPL (1980) assume horizontally homogeneous conditions, i.e., essentially a 1-D problem.

[3.3] Webb-Pearman-Leuning (WPL 'Corrections')

The benefit of Eddy Covariance
is made transparent by considering the relationship between the surface fluxes (including density effects) and the equation of mass conservation. Under the most ideal situation the equation of (mass continuity) yields:

$$\overline{w'\rho'_v}^F(z) = \int_0^z \overline{S_v}\,dz' + \overline{J_v}(0)$$

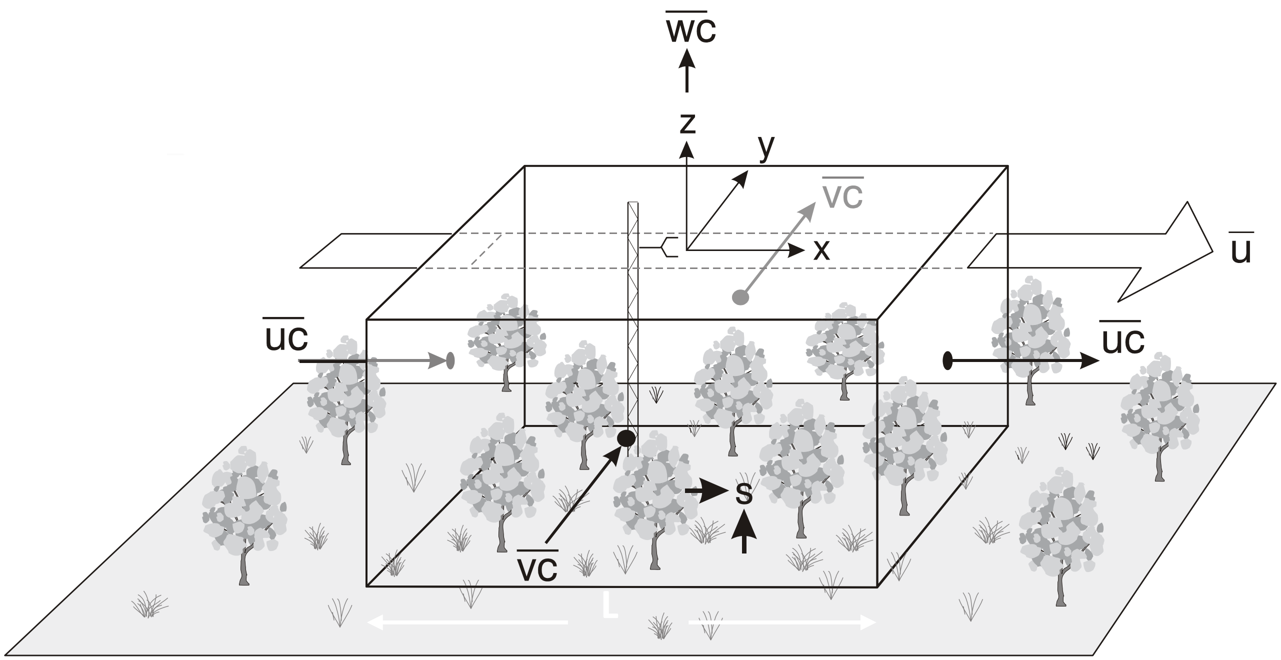
where z = measurement height; S_v = biological source (transpiration);
$J_v(0)$ = soil evaporation rate.

But what happens when conditions are not ideal?

The full 3-D Conservation of Mass yields:

[3.4] Webb-Pearman-Leuning (WPL 'Corrections')

Basics: mass/energy balance on a control volume, a 3-D problem



Combining the 3-D conservation of mass for water vapor (any trace gas) and dry air yields the Fundamental Equation of Eddy Covariance.

[3.5] Webb-Pearman-Leuning (WPL 'Corrections')

$$\left\{\int_0^z \overline{\frac{\partial \varrho_c}{\partial t}}\, dz' - \overline{\chi}_c(z) \int_0^z \overline{\frac{\partial \varrho_d}{\partial t}}\right\} +$$

$$\left\{\int_0^z \nabla_{\mathrm{H}} \bullet (\overline{\mathbf{u}\varrho_d}\,\overline{\chi}_c + \overline{\varrho}_d\,\overline{\mathbf{u}'\chi_c'})\, dz' - \overline{\chi}_c(z) \int_0^z \nabla_{\mathrm{H}} \bullet (\overline{\mathbf{u}\varrho_d})\, dz'\right\} + \overline{\varrho}_d(z)\,\overline{w'\chi_c'}(z) =$$

$$\left\{\int_0^z \frac{\overline{S}_c}{m_c}\, dz' + \overline{J}_c(0)\right\} - \overline{\chi}_c(z)\left\{\int_0^z \frac{\overline{S}_d}{m_d}\, dz' + \overline{J}_d(0)\right\} +$$

$$\overline{\varrho}_d(0)\,\overline{w'\chi_c'}(0) + \overline{w\varrho_d}(0)[\overline{\chi}_c(0) - \overline{\chi_c}(z)]$$

The terms of the last expression are easily identified. They are:

$\left\{\int_0^z \overline{\frac{\partial \varrho_c}{\partial t}}\, dz' - \overline{\chi}_c(z) \int_0^z \overline{\frac{\partial \varrho_d}{\partial t}}\right\}$ = 'Effective storage'.

$\left\{\int_0^z \nabla_{\mathrm{H}} \bullet (\overline{\mathbf{u}\varrho_d}\,\overline{\chi}_c + \overline{\varrho}_d\,\overline{\mathbf{u}'\chi_c'})\, dz' - \overline{\chi}_c(z) \int_0^z \nabla_{\mathrm{H}} \bullet (\overline{\mathbf{u}\varrho_d})\, dz'\right\}$ = 'Horizontal advection'.

$\overline{\varrho}_d(z)\,\overline{w'\chi_c'}(z)$ = 'Eddy covariance flux' or 'Turbulent surface exchange flux'.

$\left\{\int_0^z \frac{\overline{S}_c}{m_c}\, dz' + \overline{J}_c(0)\right\}$ = 'Net Ecosystem Exchange' or 'NEE' if CO_2 is the constituent.

$\overline{\chi}_c(z)\left\{\int_0^z \frac{\overline{S}_d}{m_d}\, dz' + \overline{J}_d(0)\right\}$ = 'Dry air source/sink term' or 'Dry air source correction term'.

$\overline{\varrho}_d(0)\,\overline{w'\chi_c'}(0)$ = 'Enhanced soil diffusion term' or 'Pressure pumping term'.

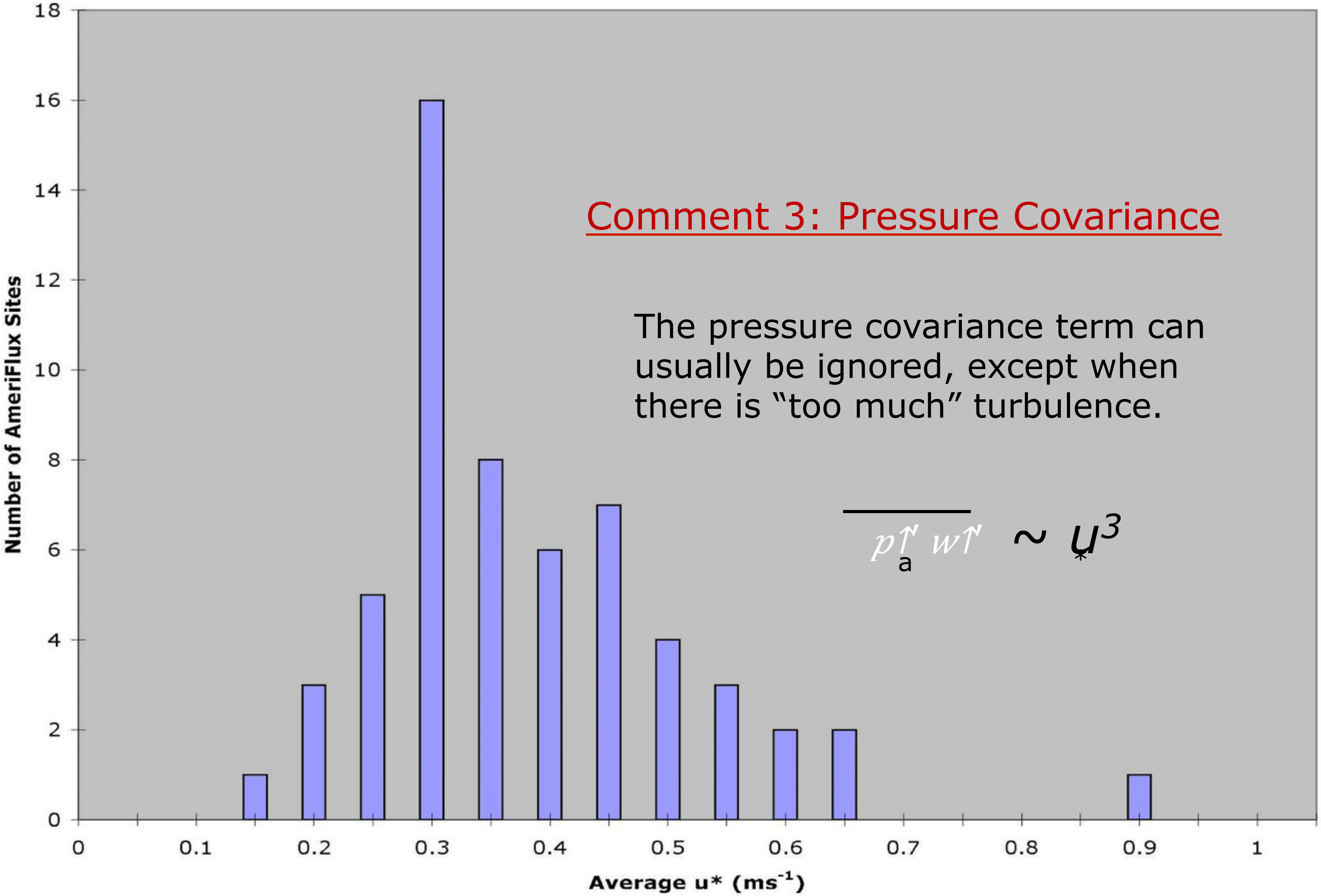
$\overline{w\varrho_d}(0)[\overline{\chi}_c(0) - \overline{\chi_c}(z)]$ = 'Dry air flux lower boundary condition'.

[3.6] Webb-Pearman-Leuning (WPL 'Corrections')

Comment 1: Infrared gas analyzers (open-path sensors) can have self heating issues that behave like WPL terms, because the sensor itself is a heat source. This is mainly a winter-time CO_2 flux problem. But it is important to be aware of this issue for ET fluxes.

Comment 2: Horizontal advection is nearly impossible to measure without several towers. It has the potential to be a big source of error and uncertainty in the flux data. But my own experience and the evidence suggests to me that it is more likely to be a problem with ET and trace gas (or mass) fluxes than with heat flux.

[3.7] Webb-Pearman-Leuning (WPL 'Corrections')



Comment 3: Pressure Covariance

The pressure covariance term can usually be ignored, except when there is "too much" turbulence.

$$\overline{p'_a w'} \sim u_*^3$$

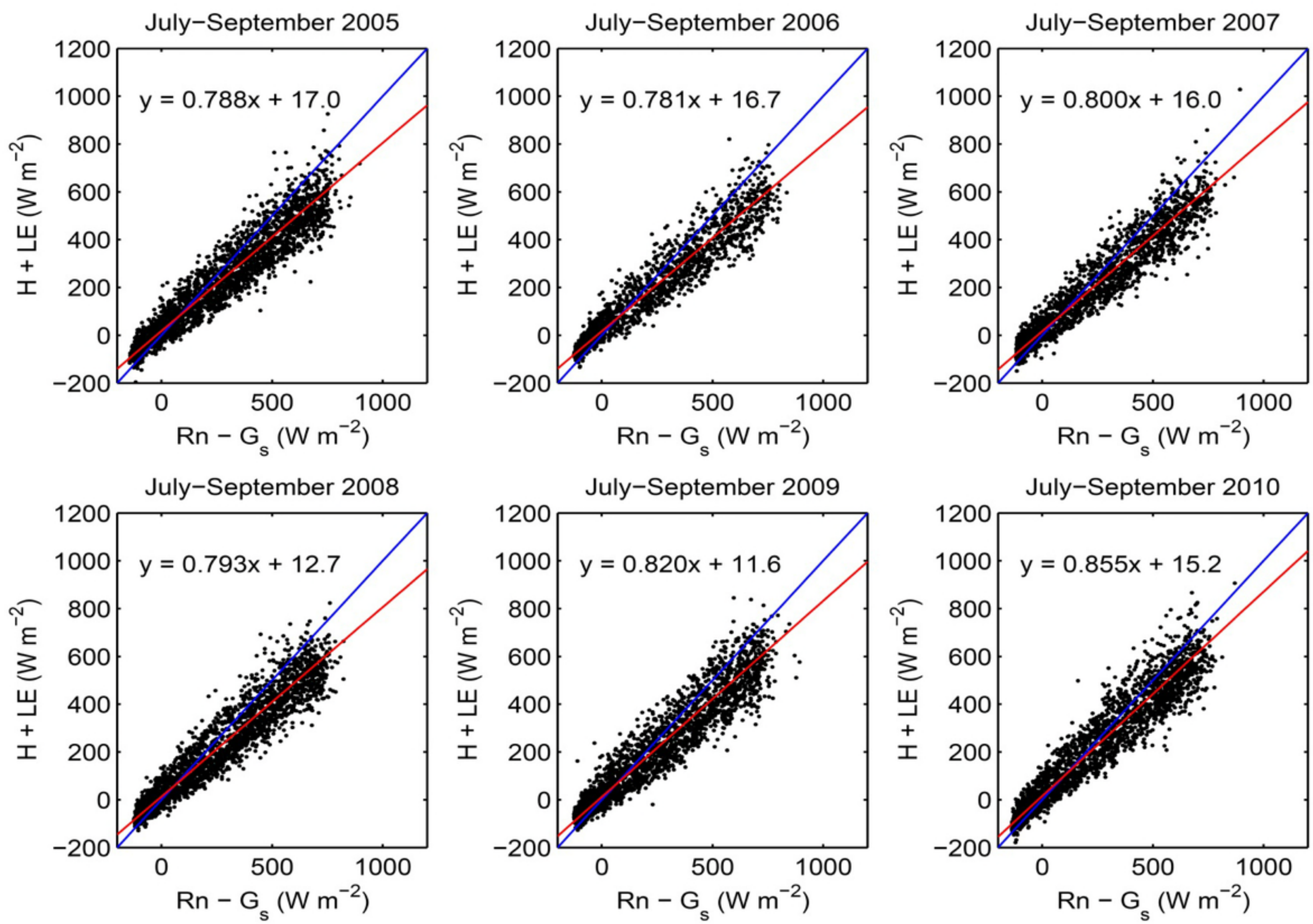
[4.0] EC and Energy Balance Closure

So how well does all of this stuff really work?

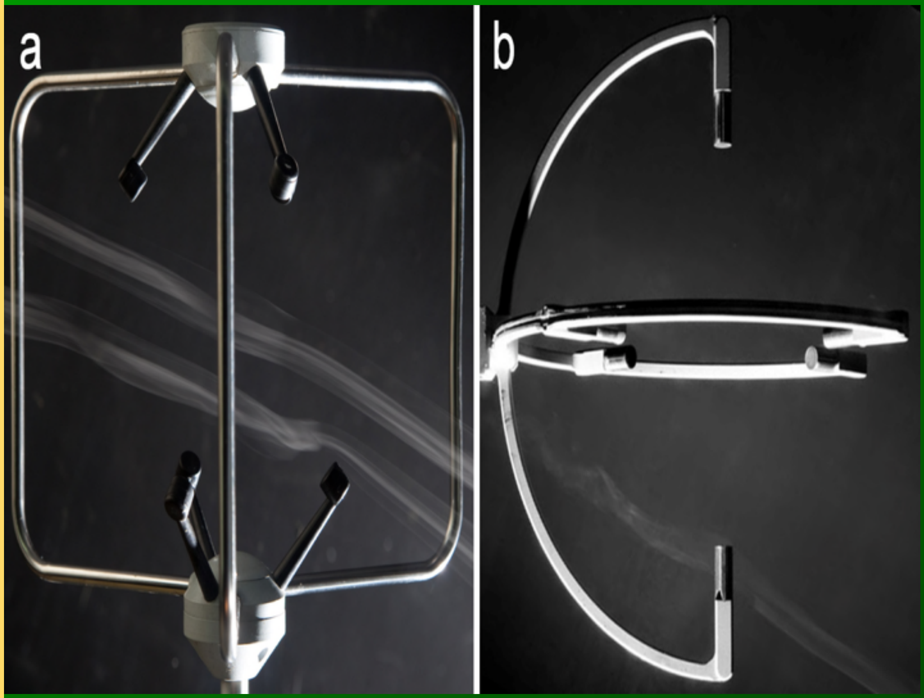
Closing the Surface Energy Balance: The acid test ?

$$R_n = H + LE + G_s$$

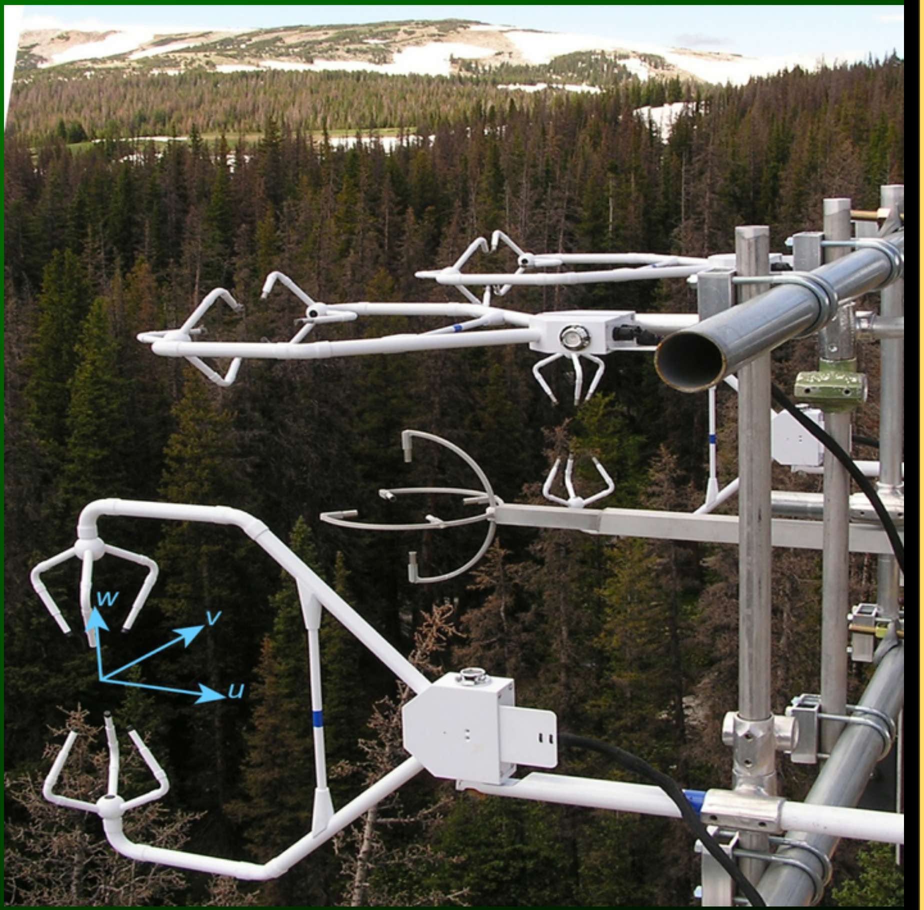
[4.1] EC and Energy Balance Closure



[5.0] Sonic Anemometers and Energy Balance



Kochendorfer et al (2012; 2013)
Boundary-Layer Meteorology **145**: 383-398;
Boundary-Layer Meteorology **147**: 337-345.



Frank et al (2013)
Agricultural & Forest Meteorology **171-172**: 72-81.

[5.1] Sonic Anemometers and Energy Balance

These two papers report that non-orthogonal sonic anemometers appear to underestimate the vertical velocity fluctuation, *w′*, by about 10%, which then translates into a 10% reduction in the fluxes.

Clearly this is an unexpected finding, but if further confirmed can account for a significant portion of the lack of energy balance closure.

[5.2] Sonic Anemometers and Energy Balance

So our (Frank & Massman) most recent sonic inter-comparison experiment is focused on different non-orthogonal sonic designs.

Stay tuned for results!

[6.0] Soil Heat Flux & Energy Balance

Often soil heat flux and heat storage terms are mentioned as potential causes for at least some of the failure to close the surface energy budget.

In general, it is often important but usually not the ultimate cause of systematic failure so often observed.

But given the importance of soil heat flux, soil temperature, and soil evaporation to agriculture I have included some key papers on these matters in my reference list. But in truth this is really the subject of a separate talk.

(7.0) Energy Balance Summary

Conclusions from Leuning *et al*. (2012)

(a) Half-hourly averages of [$H + LE$] systematically underestimate [$R_n - G_s$] at most flux sites.

(b) Advective flux divergences cannot explain imbalance because they require unrealistically large and systematically positive horizontal temperature gradients and vertical velocities.

(c) Imbalance partially explained by:

* Phase lags due to incorrect estimates of energy storage in soils, air & biomass below the measurement height, but 24-hr averages can remove much of this bias.
* Incorrect coordinate rotation: $u'T'$ contamination of $w'T'$.
* Carefully implemented eddy flux systems on horizontally homogeneous sites can measure fluxes accurately.

+ Flow distortion associated with non-orthogonal sonics.

(7.1) Energy Balance Summary

Recommendations from Leuning *et al*. (2012)

(a) Do not adjust/scale time-averaged values of [$H + LE$] to = [$R_n - G_s$].

(b) Do not adjust other scalar (CO_2) fluxes either.

Thank You