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WHEN MEASUREMENTS MATTER

Campbell Scientific Flux Systems: Design Rationales and Performance Advantages

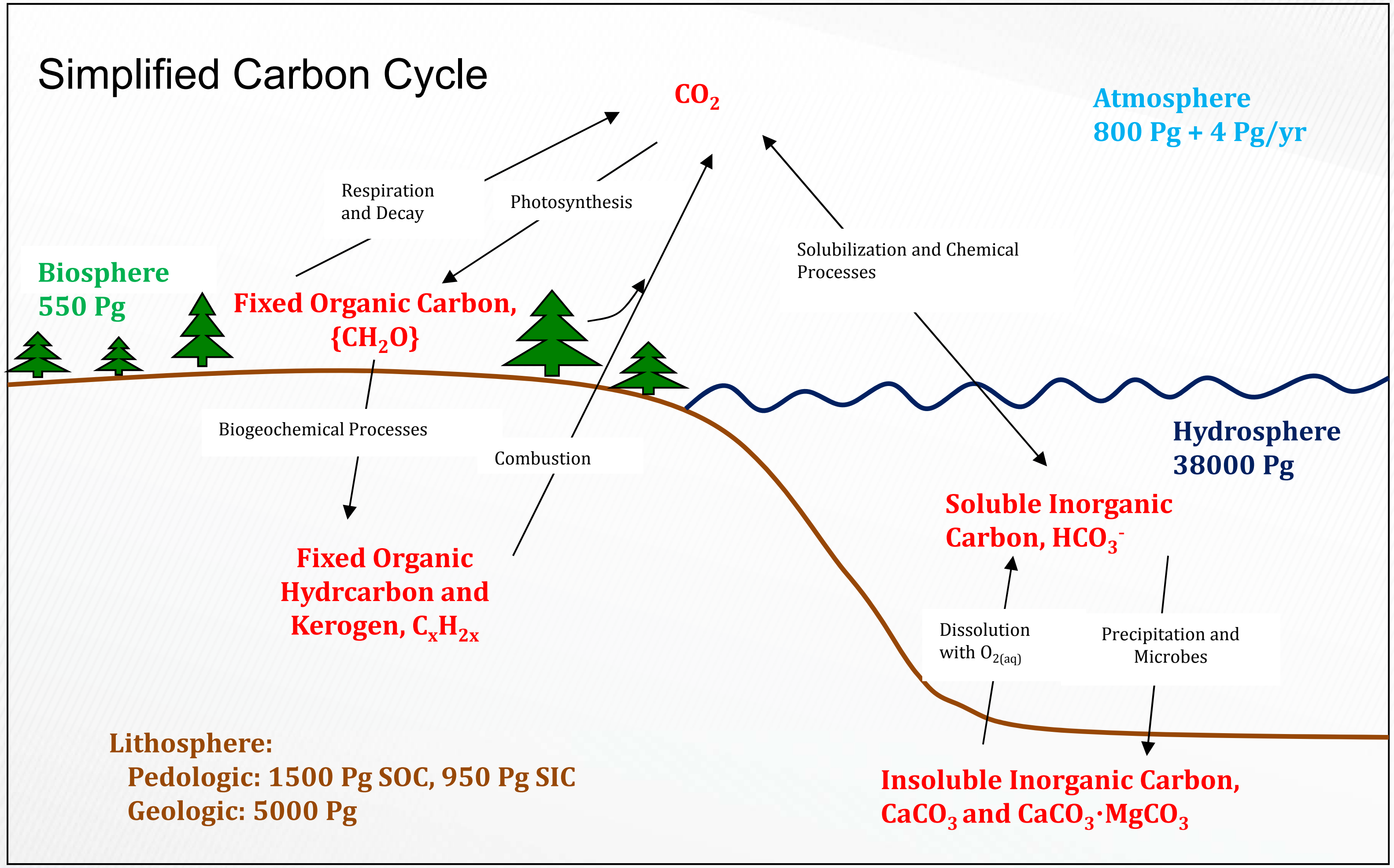
NUIST, China, 26 April 2014

Ryan Campbell

BASIC THEORY

- Introduction to Micrometeorology and Flux Measurements
- Eddy Covariance
- Storage
- Advection

Impetus: Better understand energy equilibrium and nutrient cycles and how humans are effecting these cycles



CAST Report 2011

We make measurements to help determine:

- Do we have all the CO_2 sources and sinks in the carbon cycle correctly identified and quantified and are they changing?

Terrestrial Ecosystems

CO_2 = ?

Hydrosphere

CO_2 = ?

Size of these sources/sinks and processes that govern them still have many unknowns.

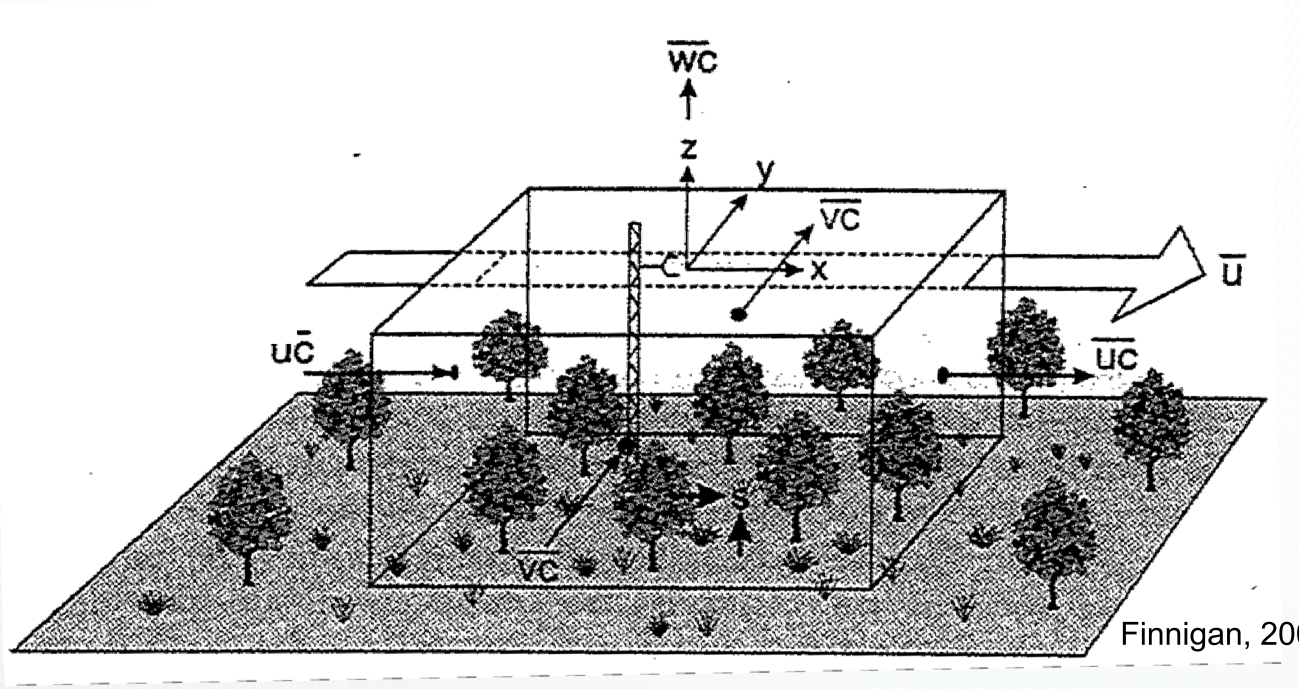
Measurement results have already illuminated our understanding of carbon cycle science:

- Fossil Fuel Burning
- Land Use Change
- Climate Change
  - Drought
  - Fires
  - Pine Beetles
- Ozone decreases NEP in trees and crops

What are common methods to measure flux?

- Chambers
- Micrometeorological Methods
  - Bowen Ratio
  - Gradient
  - Atmospheric Profile (e.g., AP200)
  - Mass Balance
  - Eddy Covariance
    - Open-Path and Closed-Path
    - Tower and Airborne
- Remote Sensing (i.e., satellite)

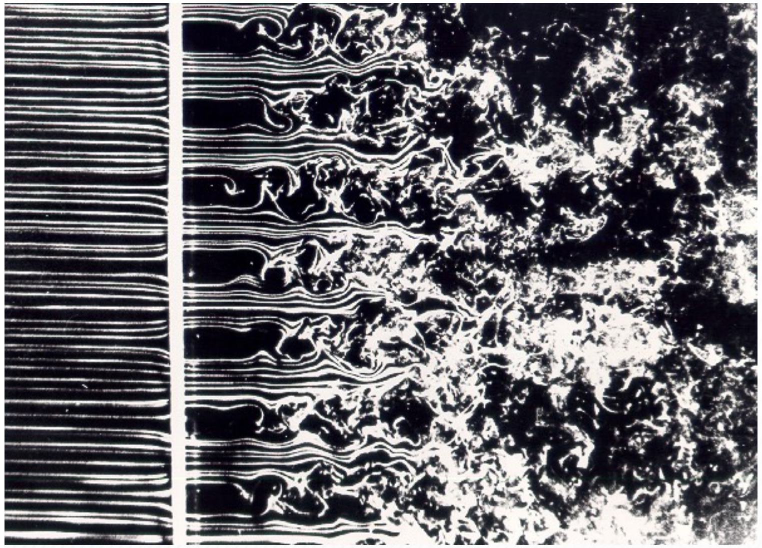
- So what method should be used to measure CO2 flux? IT DEPENDS!
- As CO2 is exchanged between the surface and atmosphere, it can either accumulate/be in deficit (storage) or be transported (advection and turbulence). Different methods are better suited to measure storage, advective transport, or turbulent transport.

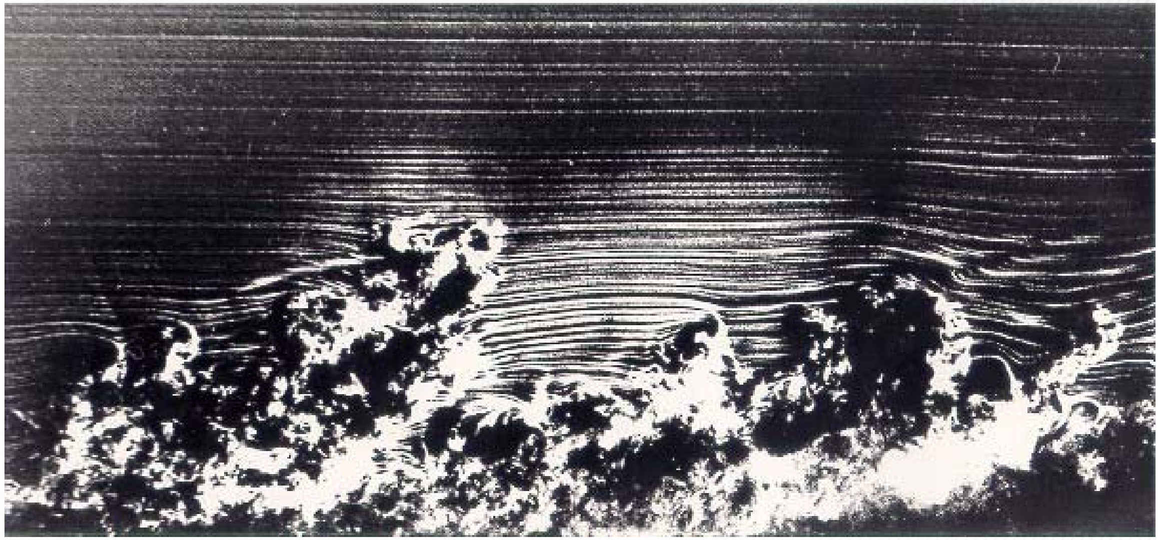


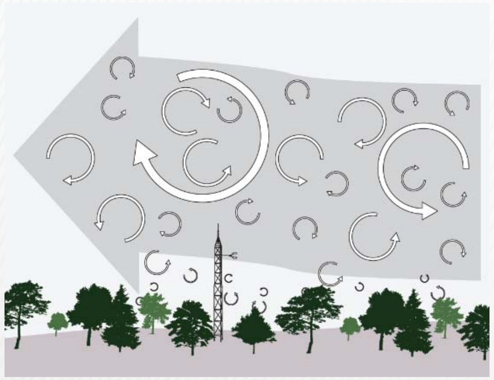
Finnigan, 2003

$$NEE = Storage + Transport_{Adv} + Transport_{Turb}$$

Turbulent Transport







Turbulence is quasi-chaotic motion of swirling parcels of air called eddies. Caused by surface forcings (solar heating, wind shears from frictional drag, and turbulent wakes from obstacles and uneven terrain).

If surface forcings are insufficient, flow will be laminar.

Turbulence is orders of magnitude more efficient at mixing than diffusion. (Stull, 1988)

http://fdrc.iit.edu/research/images/

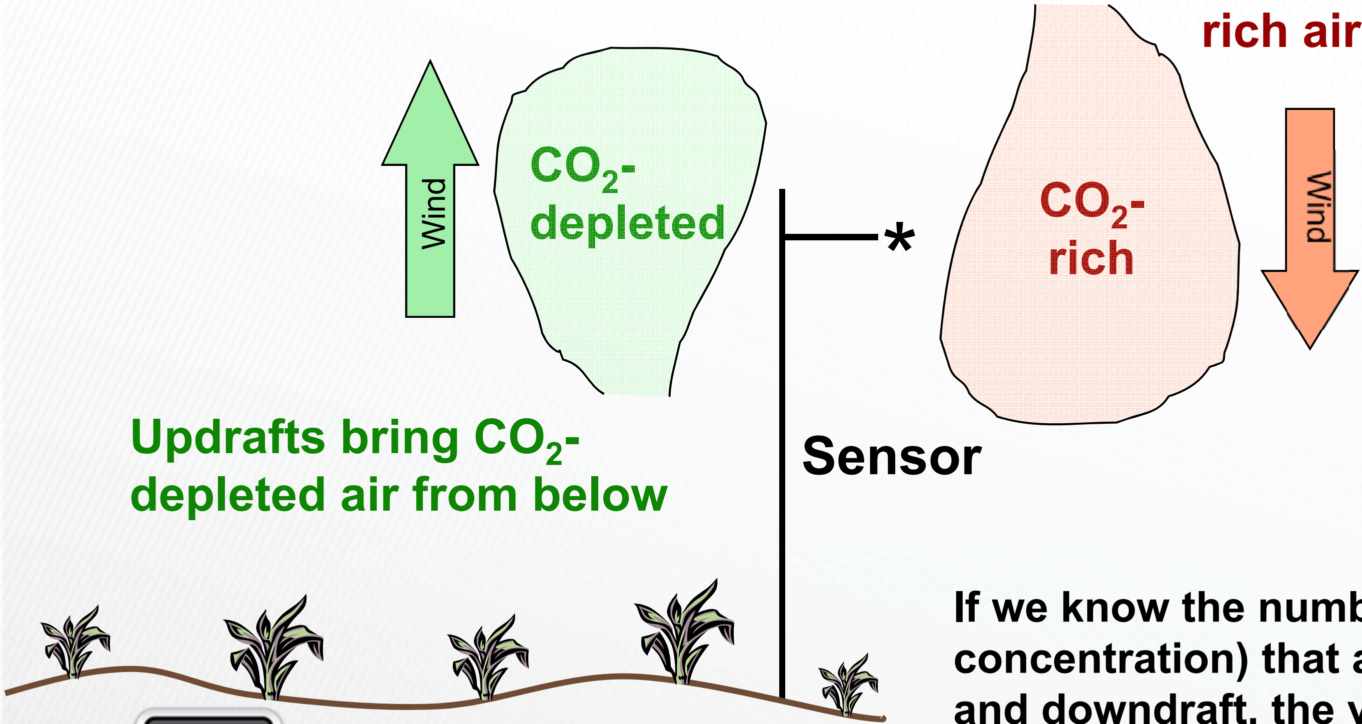
Eddy Covariance

Under unstable conditions, most of the flux is transported by turbulence and can be measured using eddy covariance (EC).

Correlation exists between vertical motions and atmospheric properties

Example: CO_2 Flux at a Photosynthetically-Active Surface Boundary Layer

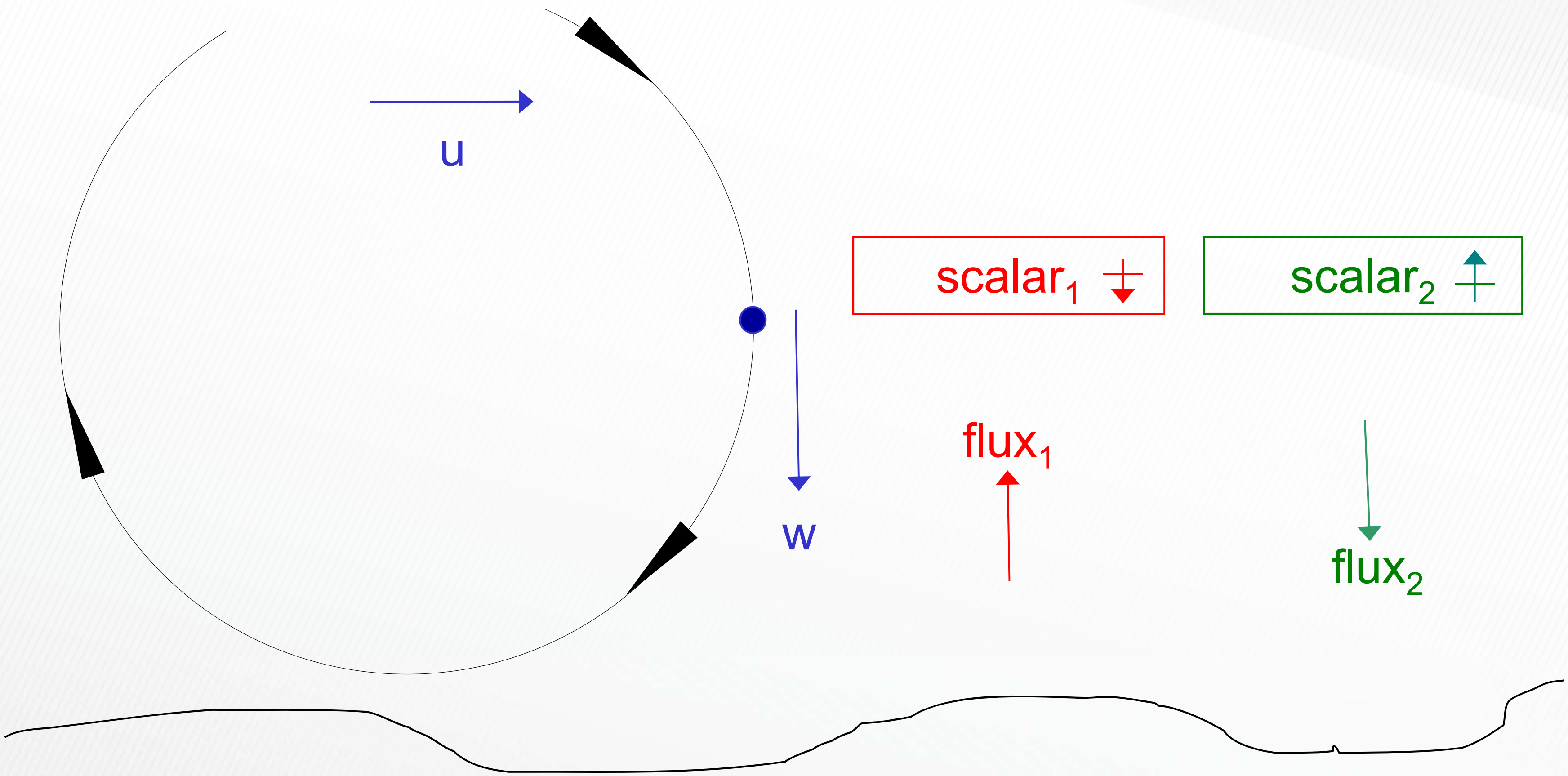
Downdrafts bring CO_2-rich air from above



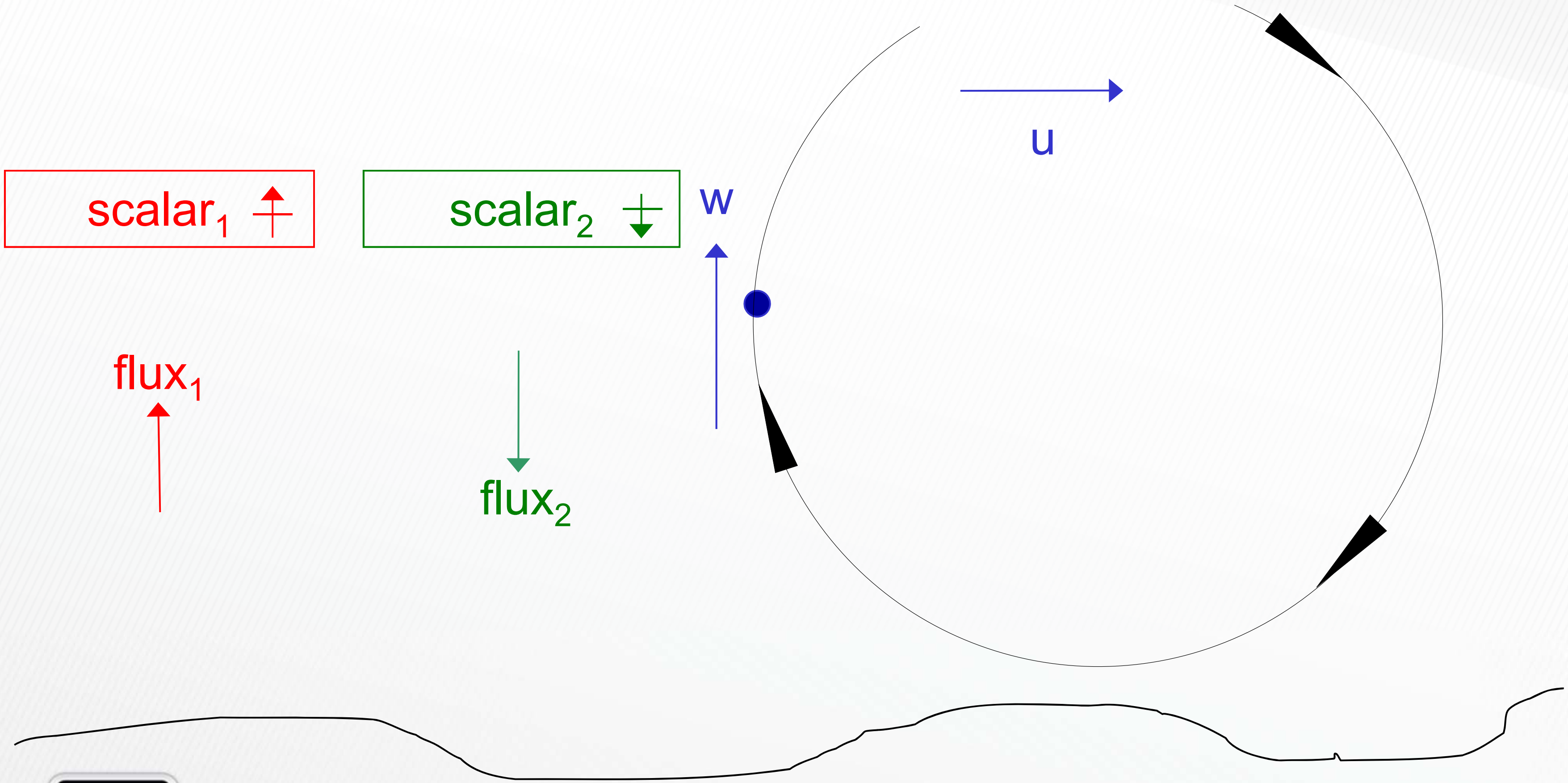
Updrafts bring CO_2-depleted air from below

If we know the number of molecules (i.e., concentration) that accompany each updraft and downdraft, the vertical flux of the gas can be calculated at that point over a certain time interval.

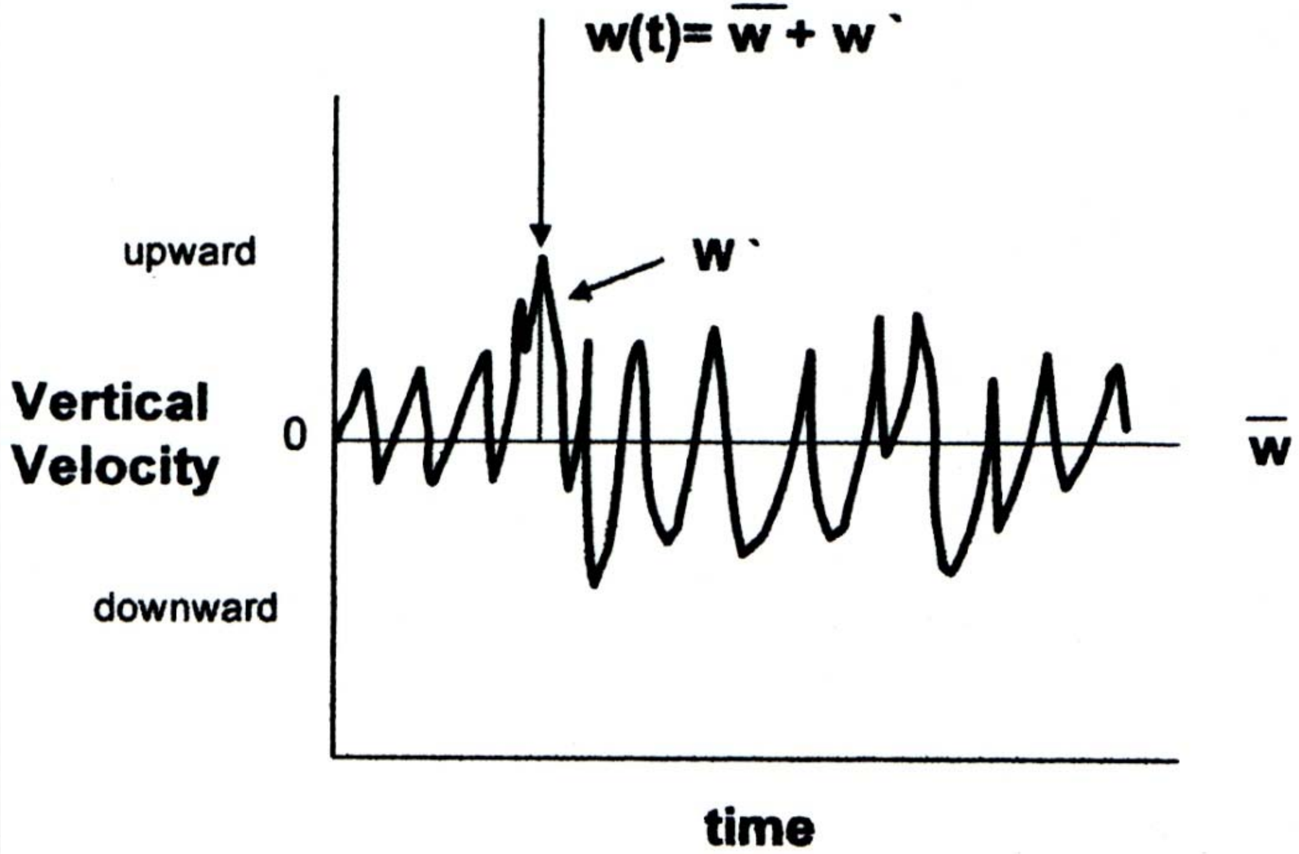
Eddy Covariance Measurement Principals



Eddy Covariance Measurement Principals



If turbulence is treated as a set of fluctuations about a mean value, which is called Reynolds Averaging, then the value of any variable at a given time is the sum of a temporal mean (defined over some suitable time period) plus an instantaneous deviation:



Turbulence (cont'd)

$$w(t) = \overline{w} + w'$$ **Vertical wind**

$$c(t) = \overline{c} + c'$$ **CO2 Density**

$$F_c = \overline{wc} = \overline{(\overline{w} + w')(\overline{c} + c')}$$

Reynolds Postulates

$\overline{w}$ tends to 0 over time

$$F_c = \cancel{\overline{w}\,\overline{c}} + \overline{w'c'}$$

$$F_c = \overline{w'c'}$$

What about horizontal turbulent fluxes???

We purposely select a site where we assume a horizontally homogeneous equilibrium layer, which implies (Finnigan, 2003):

Horizontal concentration gradients are negligible

Net horizontal flux is zero

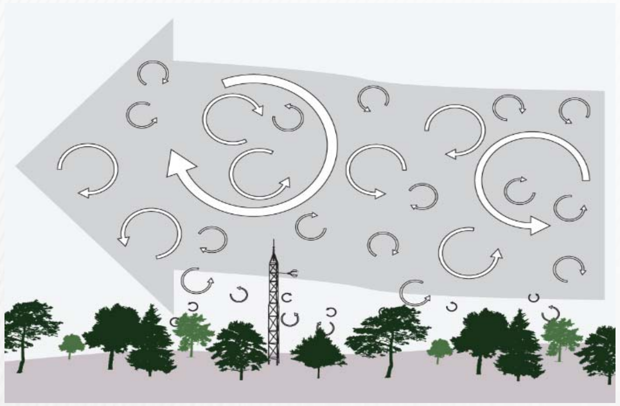
Measured vertical turbulent flux is representative of the total turbulent flux of the footprint area

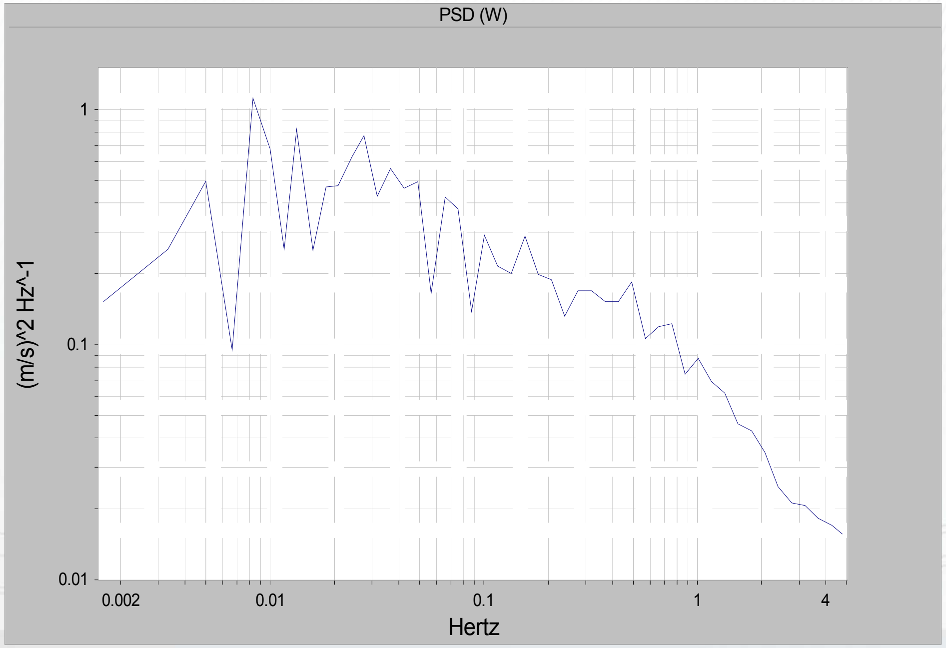
Eddies come and w and c vary at a spectrum of frequencies.

We must measure w and c often enough to capture the variance of the high frequencies (e.g. 10Hz).

10Hz sampling may include aliasing; however, aliasing is fine so long as there are enough samples to capture the amplitude of the variance of the high frequencies.

The 10Hz covariances are averaged over a long enough period to capture the signal from low frequencies (e.g., 30 min).



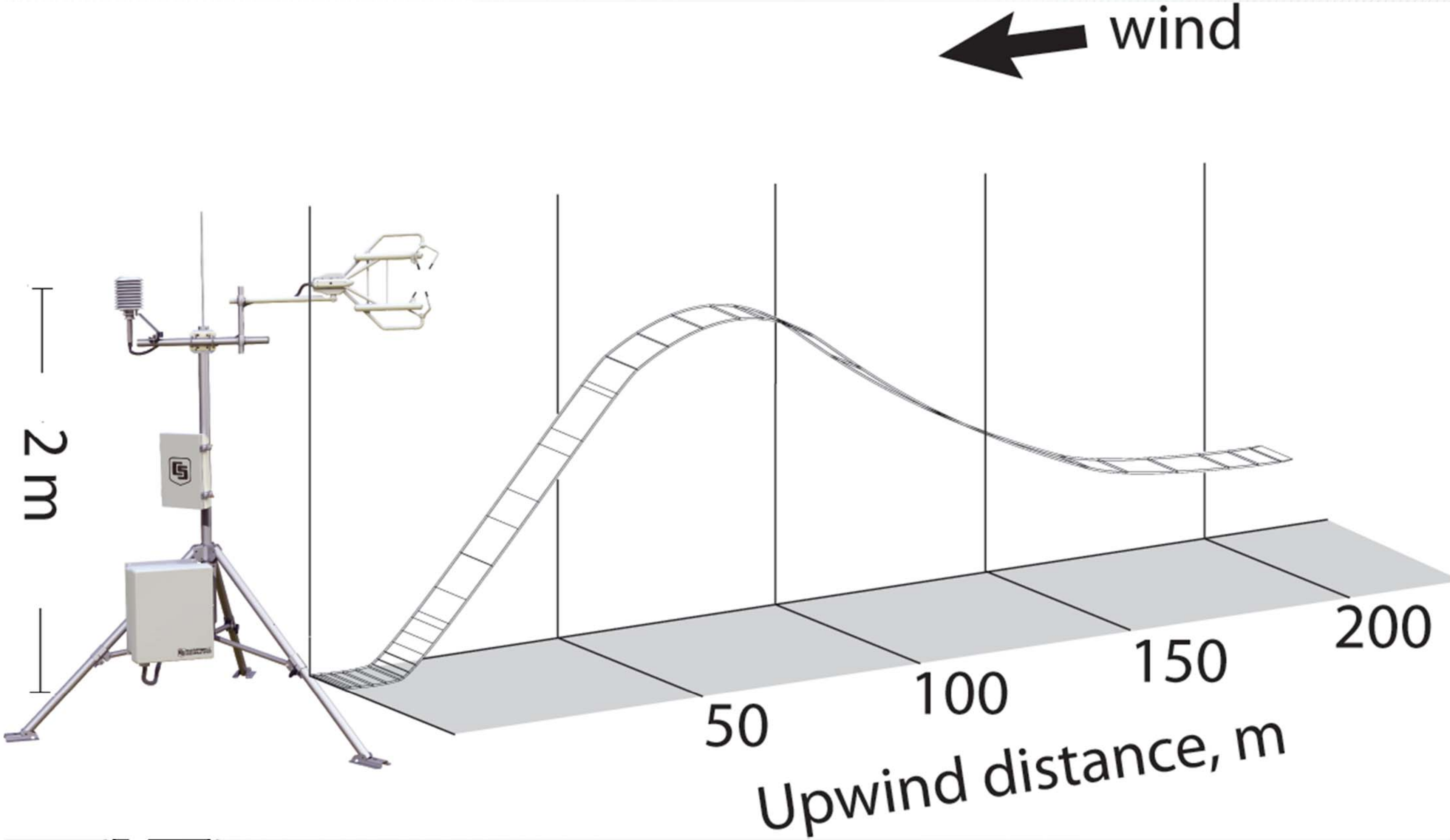


What is the footprint area or fetch?

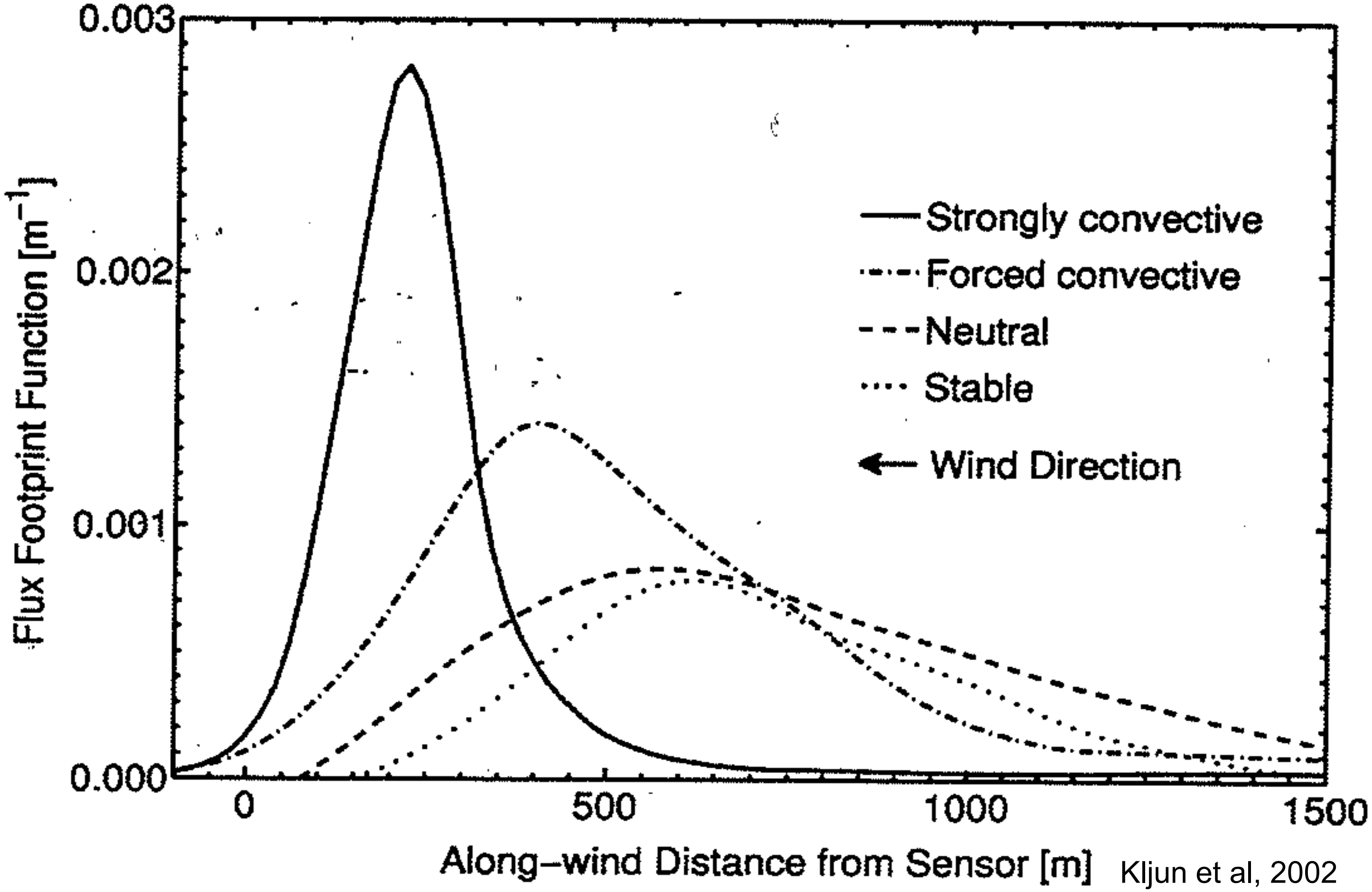
Because the wind is displacing or moving molecules, the sensors effectively “see” the vertical flux from an area upwind of the tower. This area is called the footprint or fetch.

The footprint depends on:

- Measurement height
- Surface roughness
- ABL stability


wind
2 m
50
100
150
200
Upwind distance, m

Flux Spatial Contribution for Various ABL Stabilities



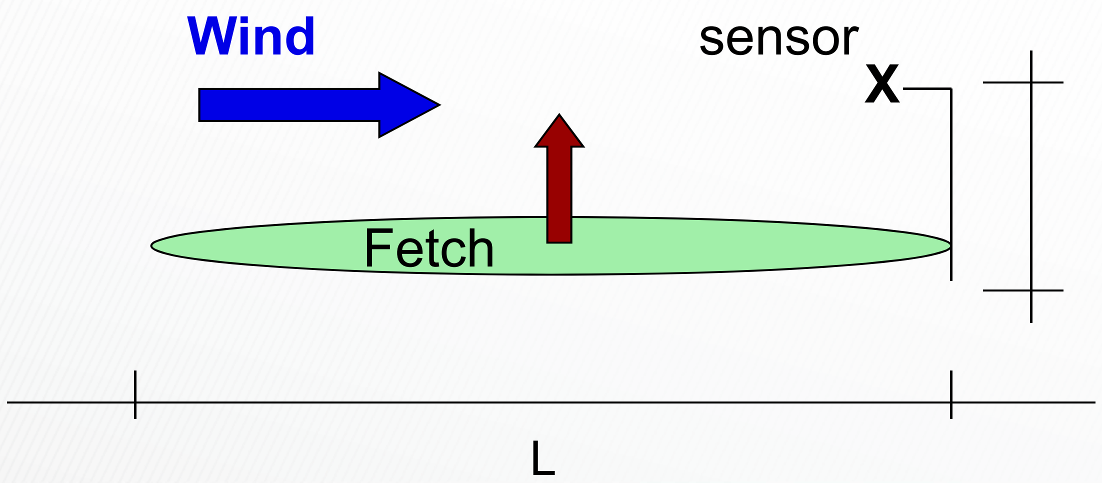
Kljun et al, 2002

Measurement height is 50m,

Roughness length is 0.05m

Fetch / Footprint

The local surface layer grows at a rate of approximately 1 vertical meter per 100 horizontal meters.



$$h_{ins} = \left[\frac{L}{100}\right]$$

The fetch should be homogenous and flat, and no abrupt changes in vegetation height should exist (Tanner, 1988)

Sensors height

The position of the EC instruments is restricted from the bottom and from the top

From the top: by the available upwind fetch of the area of interest

From the bottom: by the frequency response errors and corrections

Sensors located too high will cover an area larger than the area of interest

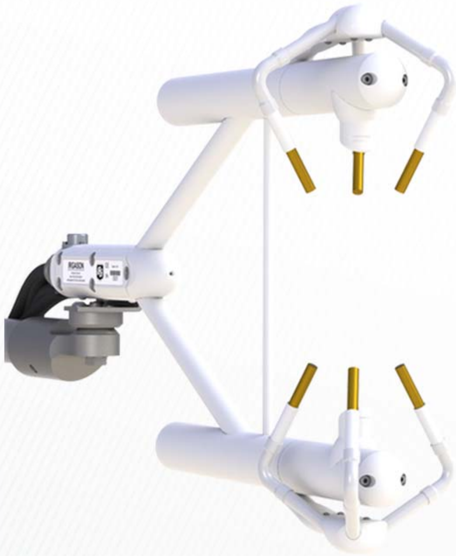
Sensors located above the boundary layer will catch the signals of flows unaffected by the land surface

Sensors located too low could pick up properties from the surface roughness sub layer and could average many small eddies

Q:How can we validate our EC system siting and setup?

A: Energy Balance, Spectral Analysis, Common Sense

Basic OPEC



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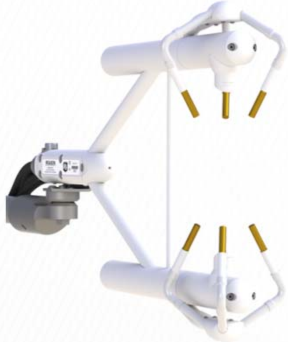
With these sensors, the system can measure carbon dioxide flux, latent heat flux, sonic sensible heat flux, momentum flux, temperature, humidity, horizontal wind speed, and wind direction.

EC System w/ Energy Balance



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Sensors added to a basic OPEC system to also measure radiation, soil heat flux, soil temperature, soil water content, and fast air temperature.

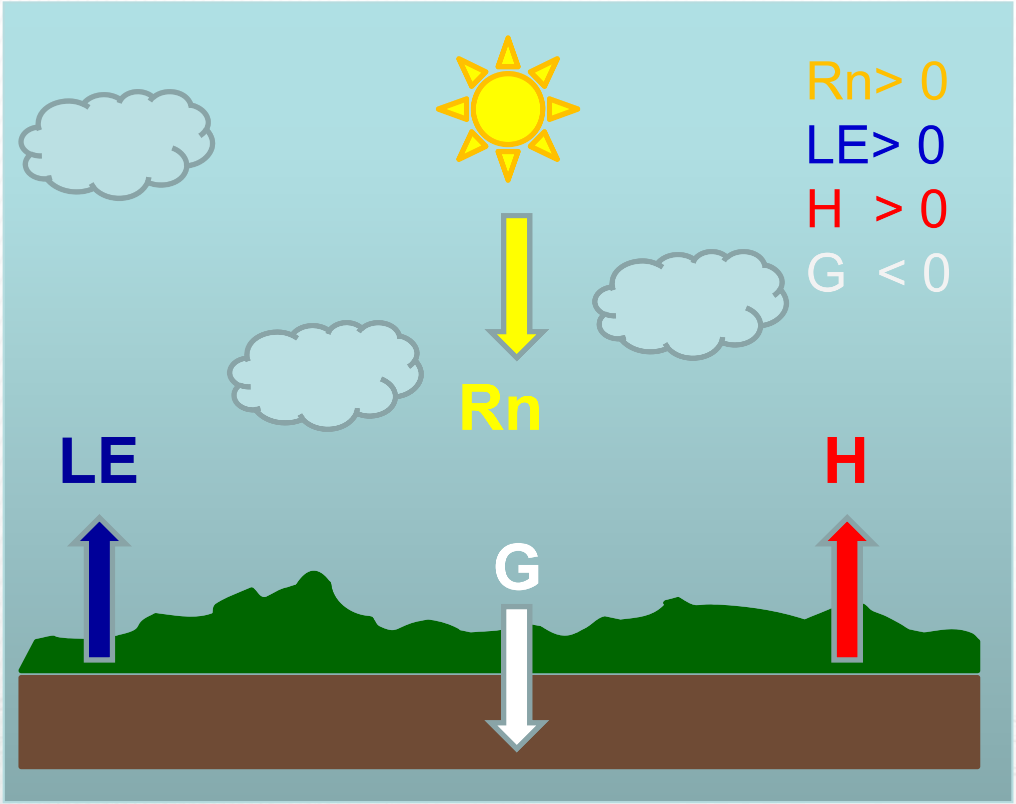
Why add energy balance sensors? To verify EC fluxes…

Latent Heat $$LE = L\,\overline{w'\rho_v'}$$

ρ_v = water vapor density
L = latent heat of vaporization

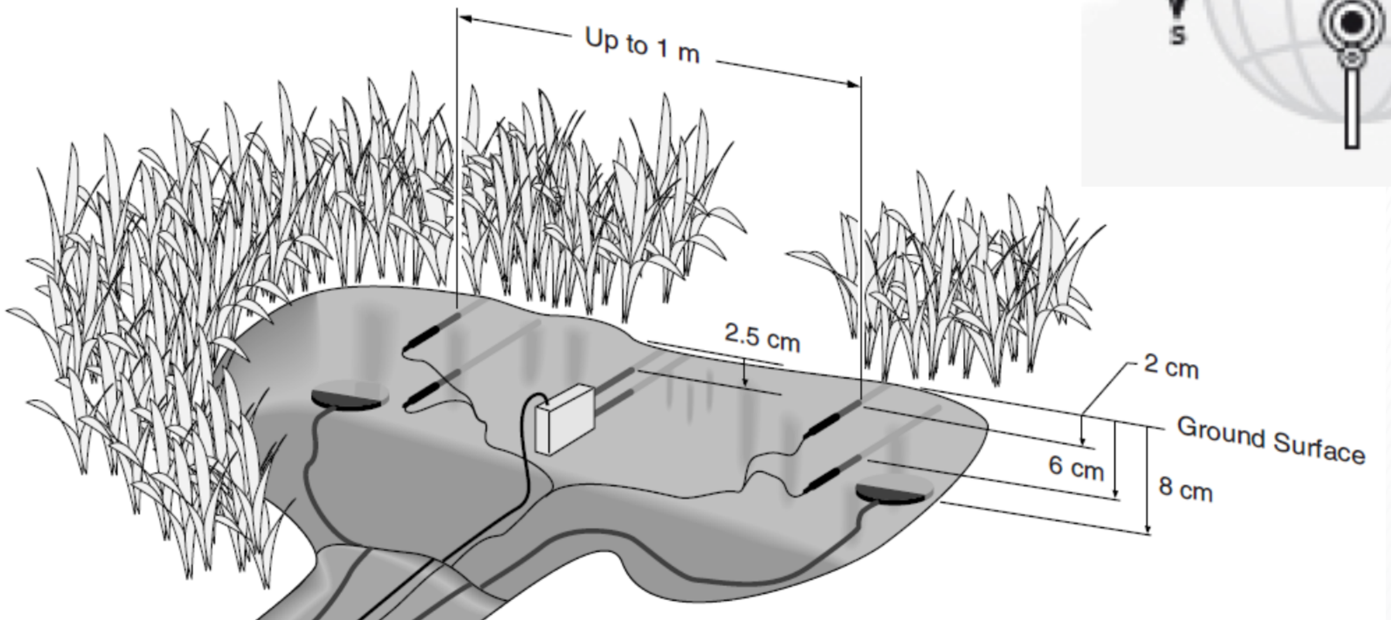
Sensible Heat $$H = \rho\, c_p\, \overline{w'T'}$$

ρ = air density
c_p = specific heat capacity of air



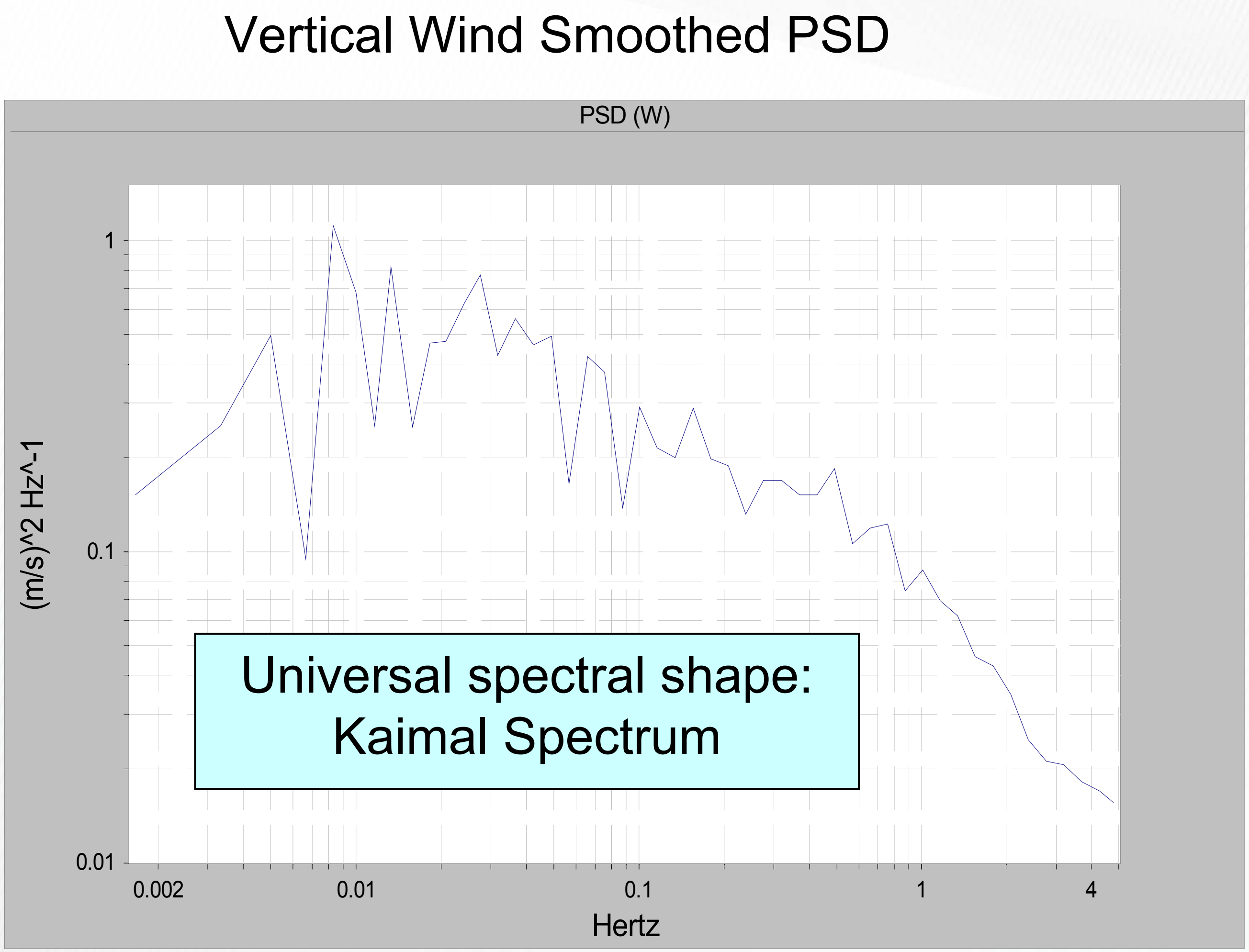
Rn + LE + H + G ≈ 0

- Properly install sensors
- Properly calculate G and Rn, realized there can be a phase lag as well as storage in biomass
- Use common sense!

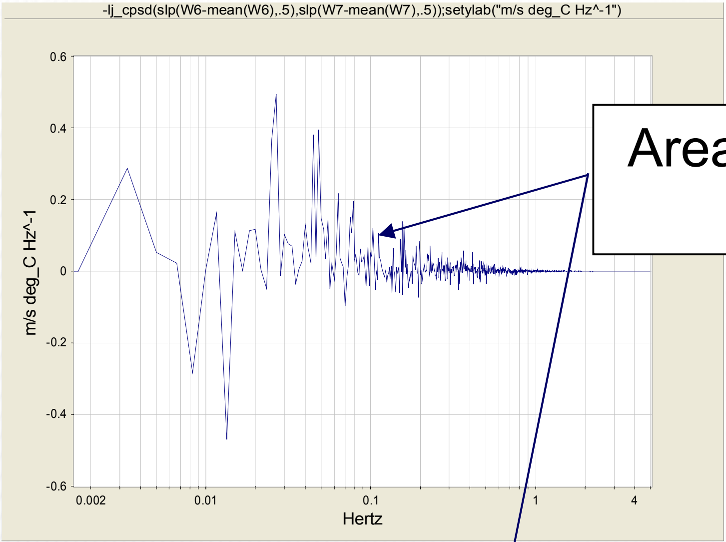


Partial emplacement of the HFP01 and the TCAV sensors is shown for illustration purposes. All sensors must be completely inserted into the soil face before the hole is backfilled.

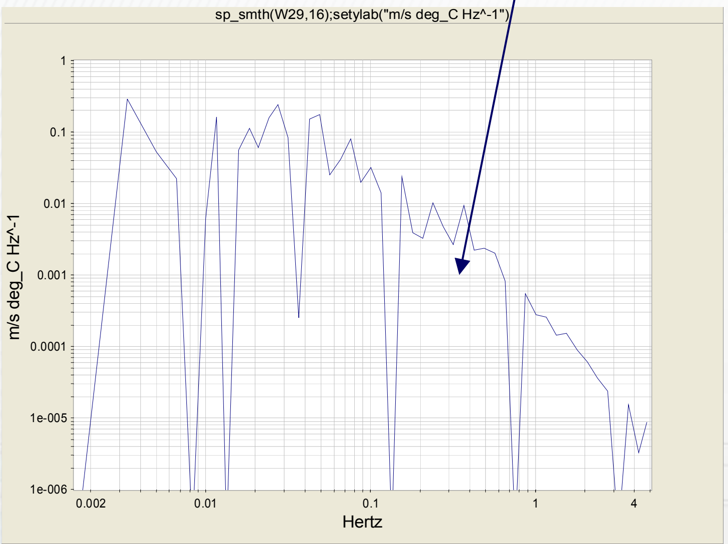
Check spectra for typical shapes

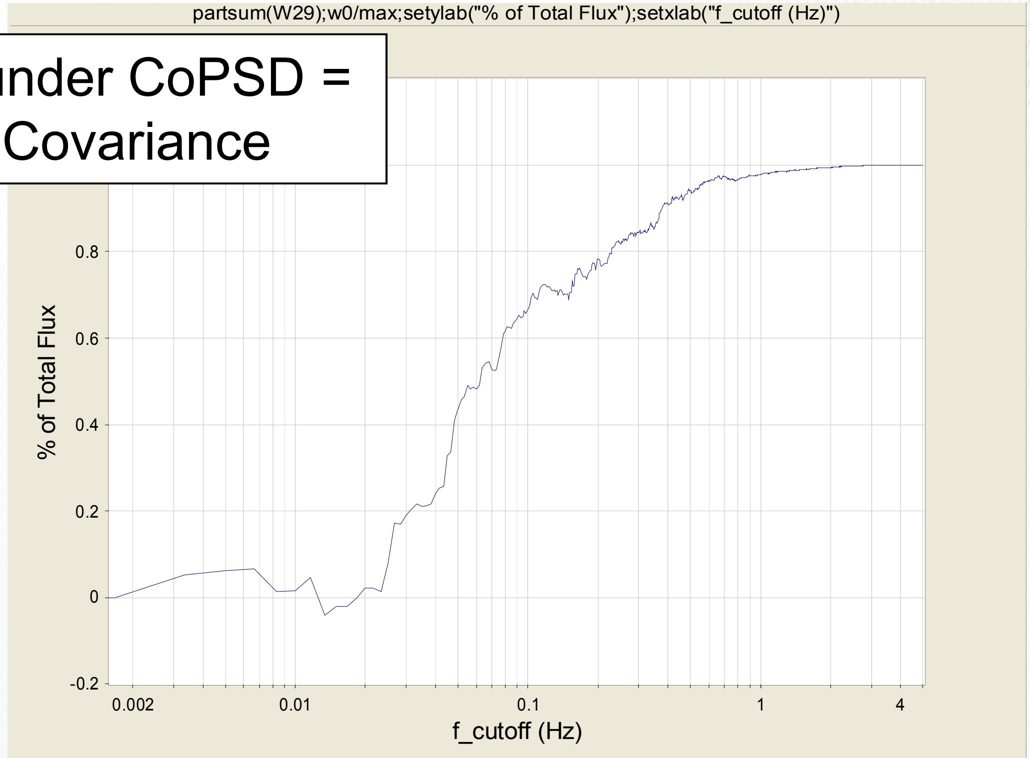


Evaluating Co-Power Spectral Density Plots



Area under CoPSD = Covariance





Integrated CoPSD

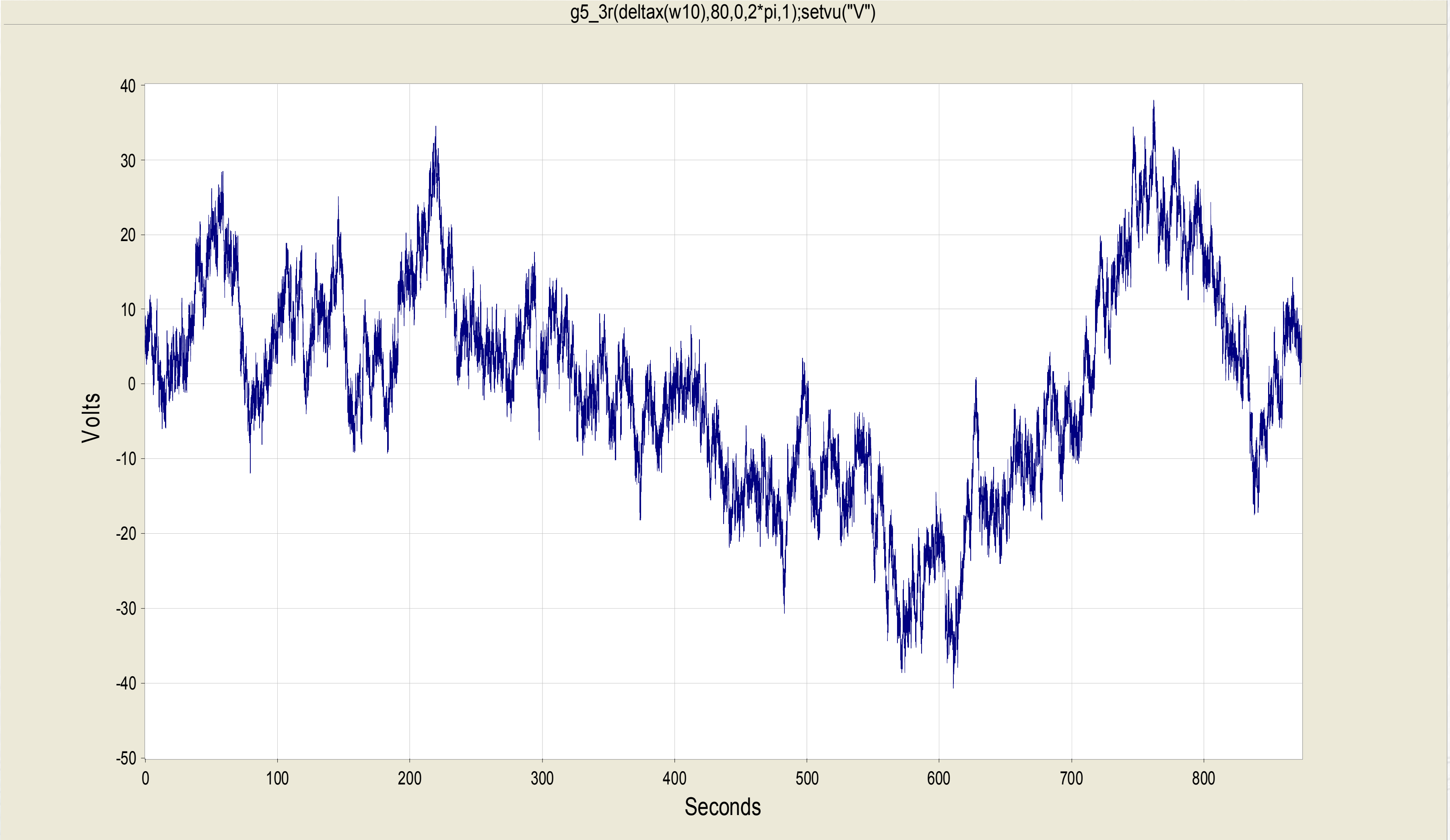
(Ogive function)

Spectral Analysis has some gotchas!

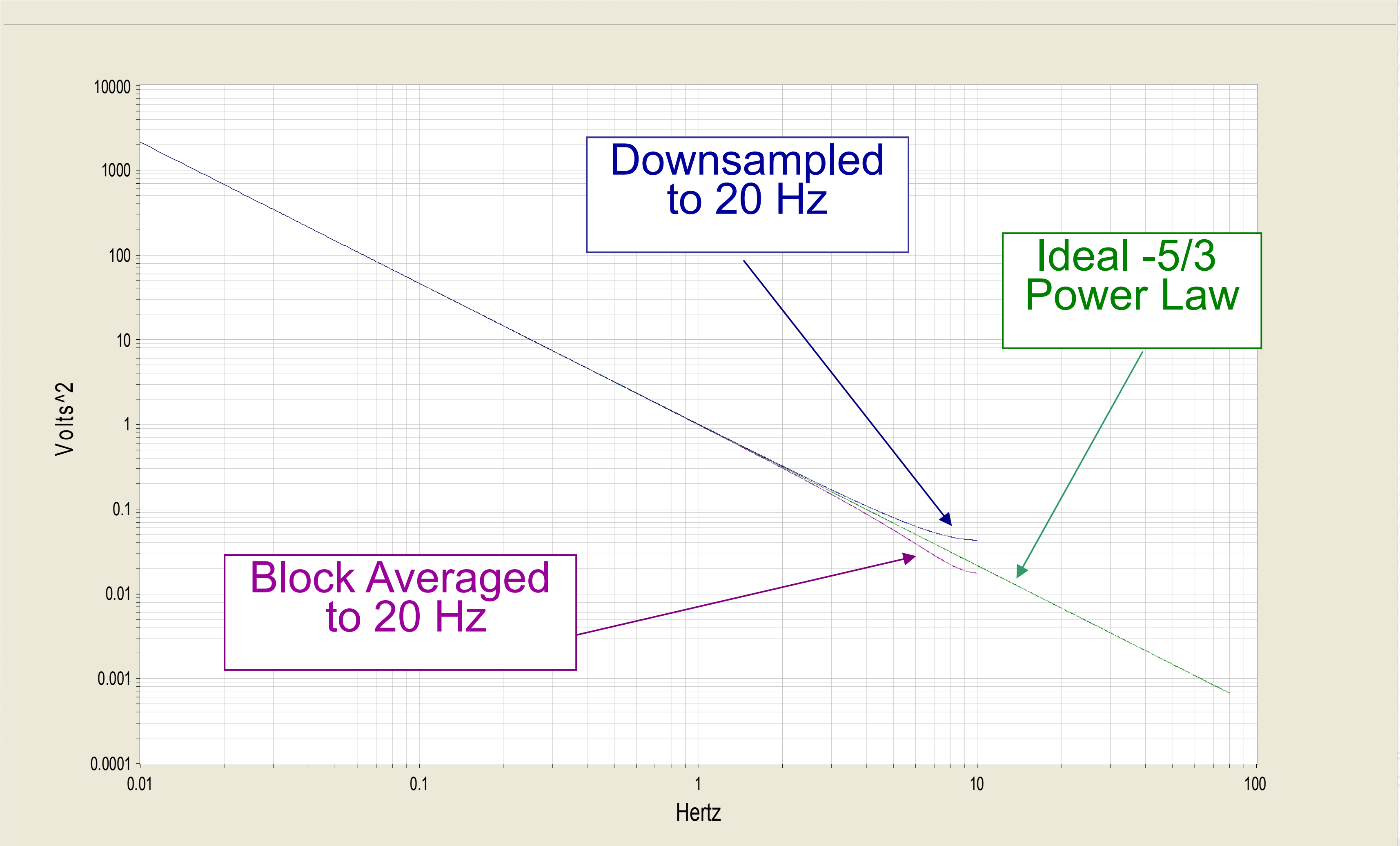
- Make sure EC100 bandwidth is set to half the datalogger scan rate! (Niquist Frequency)
- Except during spectral analysis, we recommend a default 20Hz bandwidth, especially at low measurement heights to capture all fluxes.
- A sample rate of 10Hz is fine even with 20Hz bandwidth because aliasing is okay since we’ve filtered out the high frequency noise above 20Hz.

Spectral Analysis Example

Synthesized Time Series with -5/3 Power Law

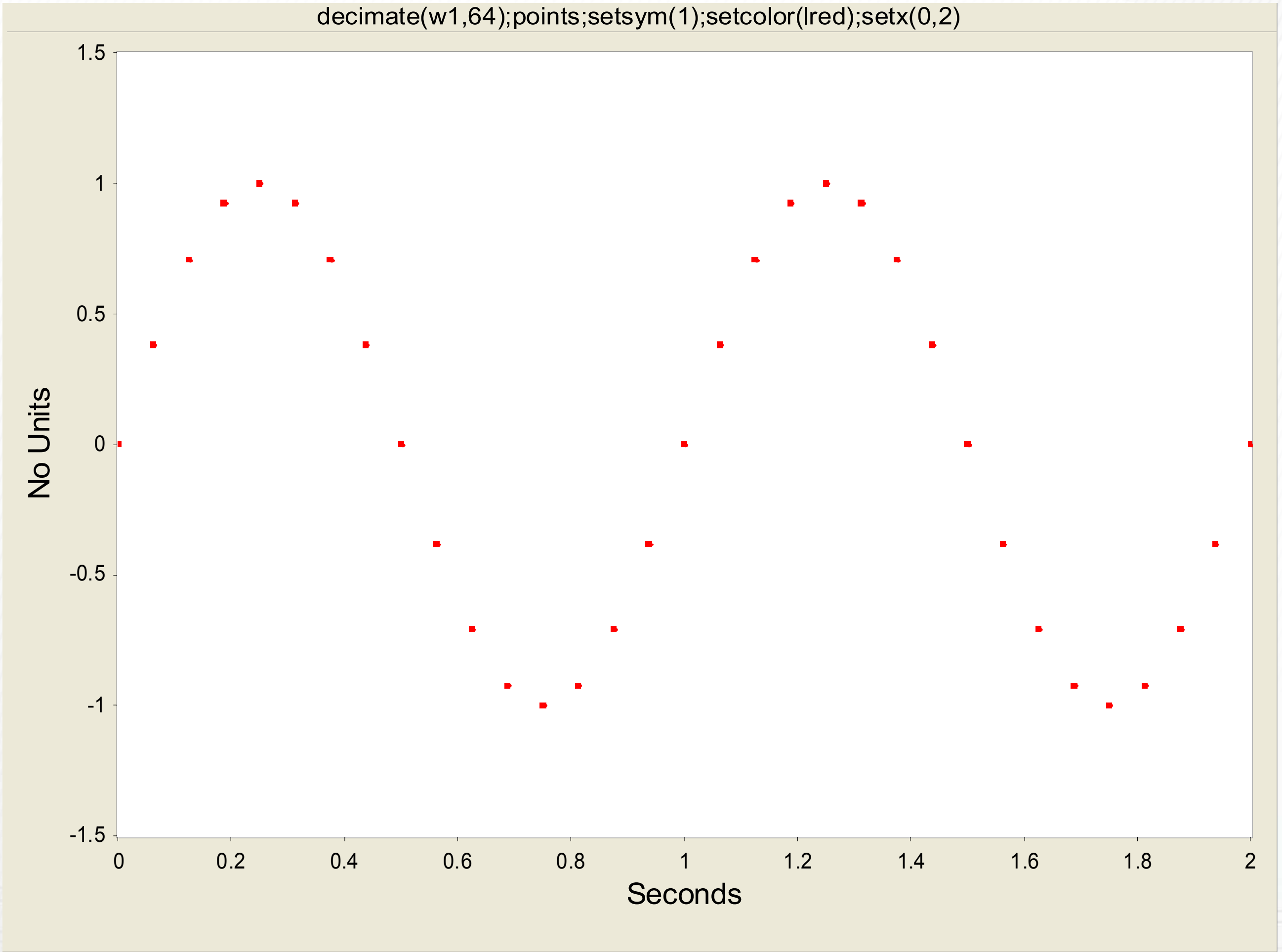


Downsampling will preserve high frequency fluxes through aliasing.

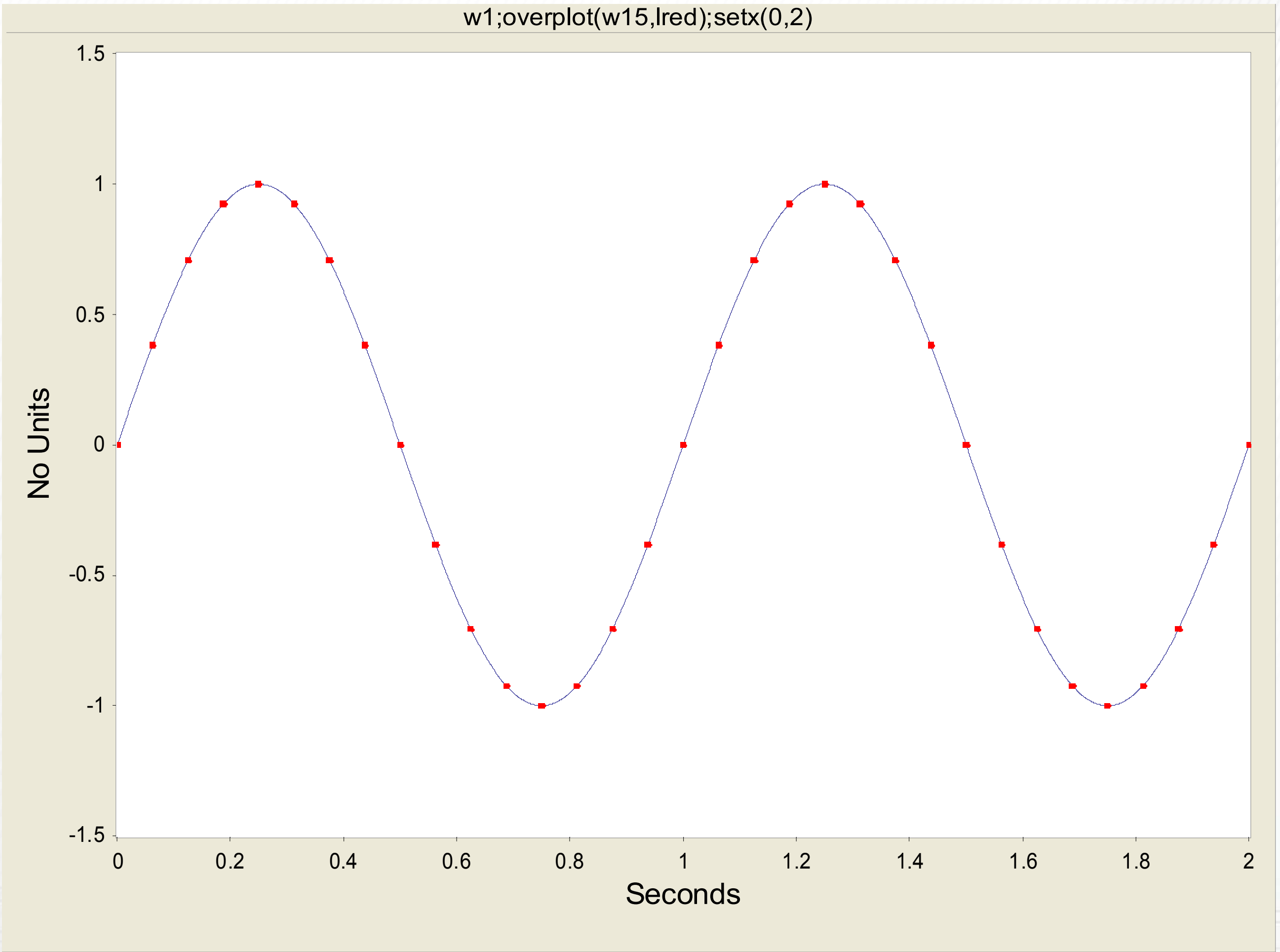


Aside: What is aliasing?

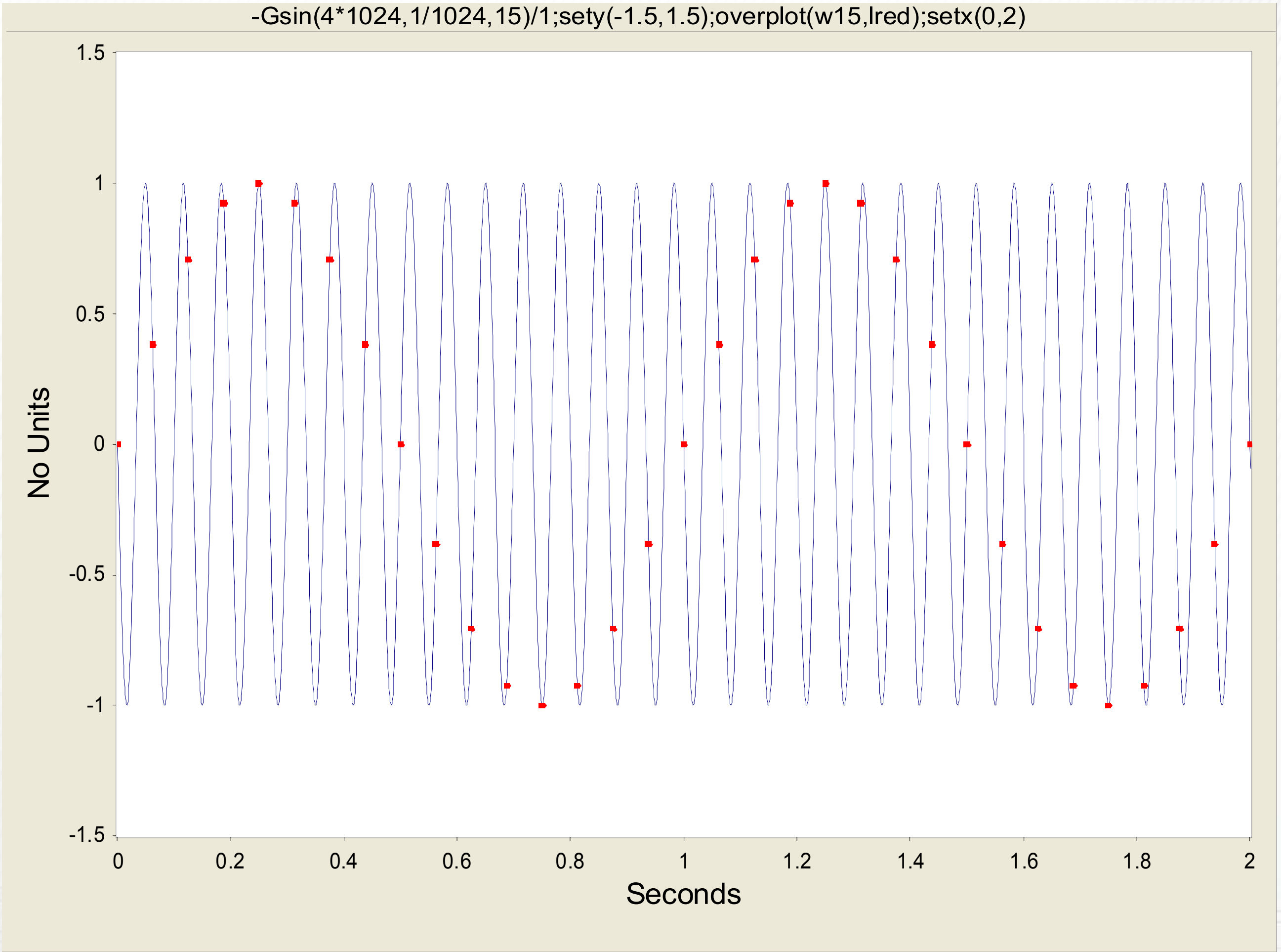
Example: Discrete-Time Sampled Signal



Original Signal(?)

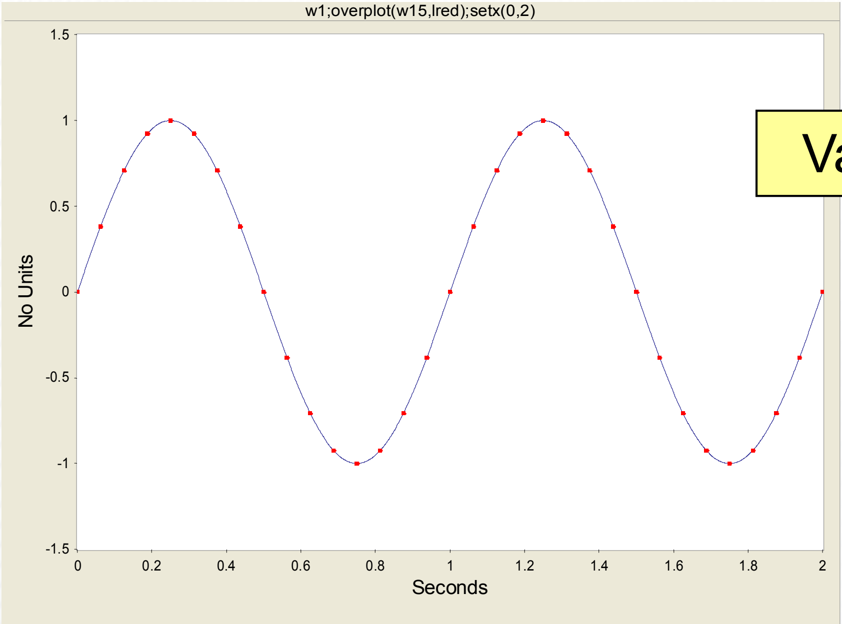


Or This?

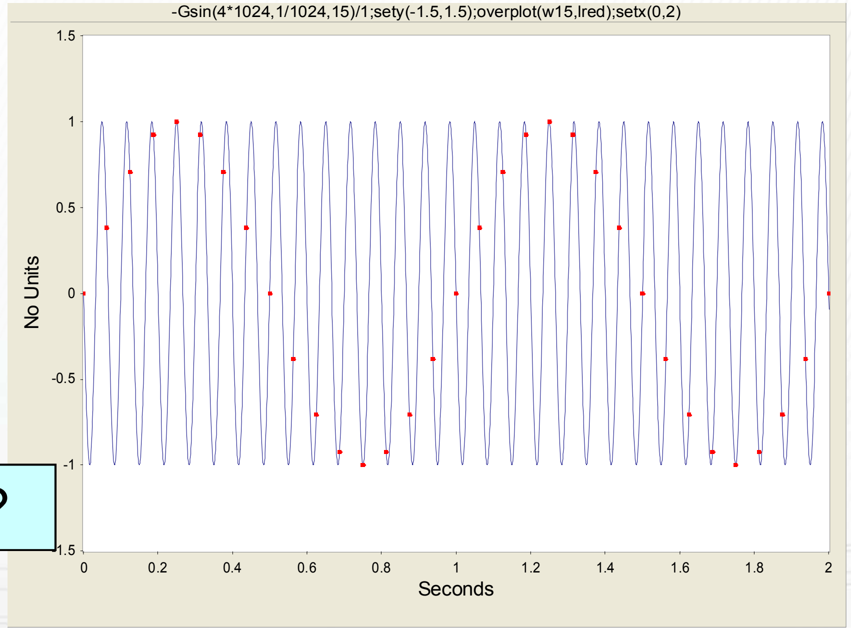

-Gsin(4*1024,1/1024,15)/1;sety(-1.5,1.5);overplot(w15,lred);setx(0,2)
1.5
1
0.5
0
-0.5
-1
-1.5
No Units
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Seconds

Statistical Descriptions of Aliased Signals

Bottom line: The flux is the same regardless of aliasing



Variance = ???



Variance = ???

Even if siting is very good, corrections should be used.

Correction name	Affected fluxes	Effect	Correction range in %
Spike removal	all	increase or decrease flux	0-15
Frequency response corrections	all	increase flux	5-20
Coordinate rotation	all	increase or decrease flux	0-10
Webb-Pearman-Leuning correction	H_2O, CO_2, CH_4	increase or decrease flux	0-50
Sonic temperature correction	H	increase or decrease	0-10
Oxygen correction	H_2O	increase or decrease flux	0-10
Time delay	mostly for closed path	increase	5-15

In summary, for eddy covariance:

1. The fetch/footprint is horizontally homogeneous

2. The site is turbulent (measurements made inside the constant flux layer or lower portion of ABL)

3. There is no vertical movement of mass of the dry air over a suitable interval of time (mean vertical wind should be zero).

4. Measurements are made frequent enough to capture the variance of high frequency fluxes, and averaging periods are long enough to capture variance of low frequencies.

5. The sensors have been sited appropriately

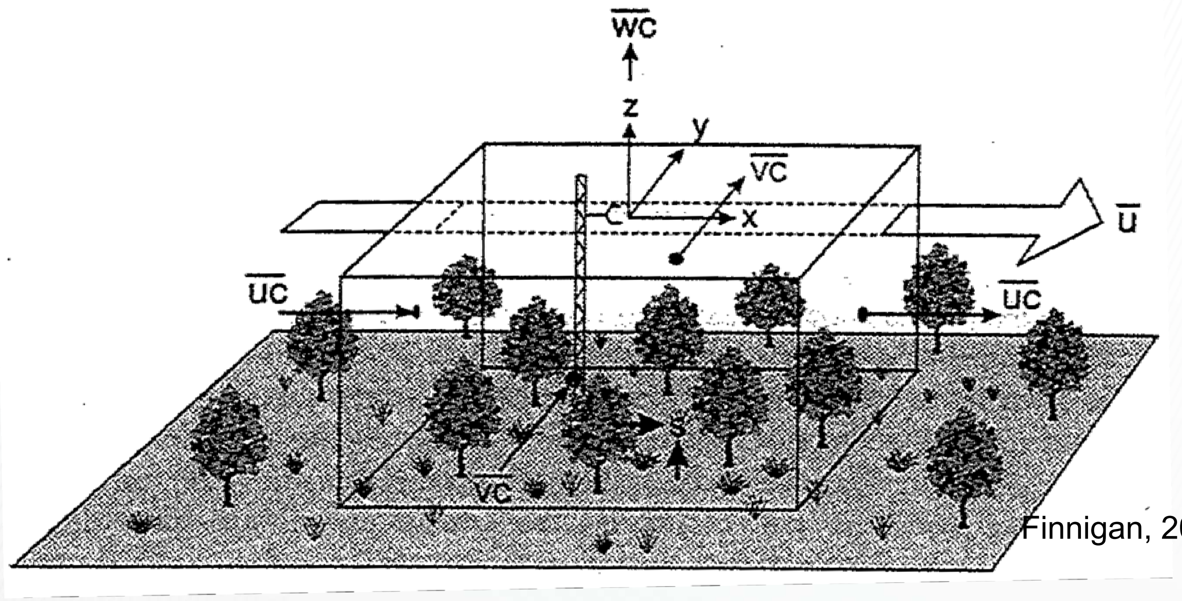
6. The setup can be validated through energy balance, spectral analysis, and common sense.

7. Corrections are applied for final flux results. (Our program applies some corrections to give a real-time estimate.)

Storage and Advection

- Consider a control volume with a source/sink of a substance X.
- X can either accumulate/be absorbed (storage) or be transported in/out (advection and turbulence)

change in storage = Σ(Flux in) – Σ(Flux out)



Finnigan, 2003

Think about mass balance.

$$NEE = Storage + Transport_{Adv} + Transport_{Turb}$$

- How significant is the storage term?
  - Depends on BL stability

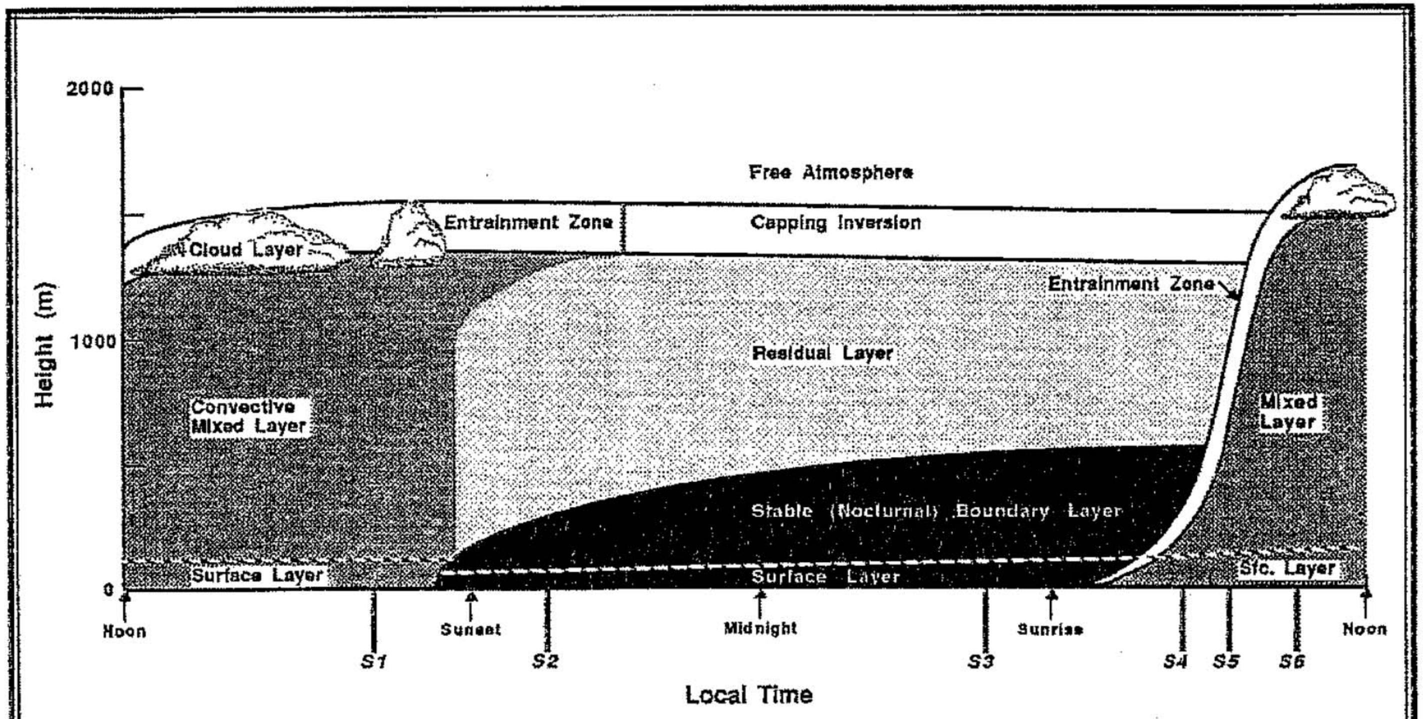


Fig. 1.7 The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer. Time markers indicated by S1-S6 will be used in Fig. 1.12.

Stull, 1988.

- If we integrate over the control volume, we can mathematically describe the net ecosystem exchange of X as:

$$\int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\overline{S_s}\,dzdydz = \int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\left[\underbrace{\overline{\rho_d}\frac{\partial\chi_s}{\partial t}}_{\text{Storage Term}} + \underbrace{\overline{\rho_d u}\frac{\partial\chi_s}{\partial x} + \overline{\rho_d v}\frac{\partial\chi_s}{\partial y} + \overline{\rho_d w}\frac{\partial\chi_s}{\partial z}}_{\text{Advection Transport}} + \underbrace{\frac{\partial\overline{\rho_d u'\chi_s'}}{\partial x} + \frac{\partial\overline{\rho_d v'\chi_s'}}{\partial y} + \frac{\partial\overline{\rho_d w'\chi_s'}}{\partial z}}_{\text{Turbulent Transport}}\right]dzdydz$$

Where,

h_m = Measurement height

L = Half the length

S_s = Rate of production/depletion

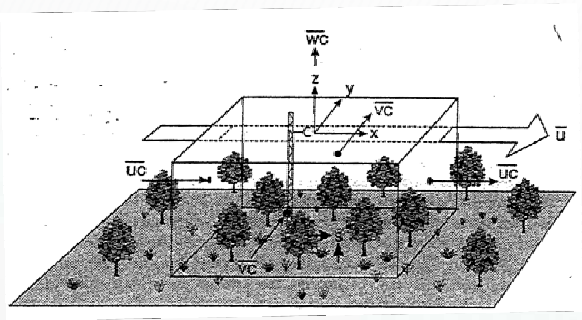
ρ_d = Density of dry air

χ_s = Mixing ratio

u, v, w = Respective x, y, z wind components

$'$= Fluctuation from the mean

$\overline{\ }$ = Average value of quantity



As discussed already, if we assume a horizontally homogeneous equilibrium layer, we can imply (Finnigan et al., 2003):

- Horizontal gradients are negligible
- Horizontal integration unnecessary
- Measured mixing ratios and turbulent fluxes are representative of the whole volume

Our equation becomes:

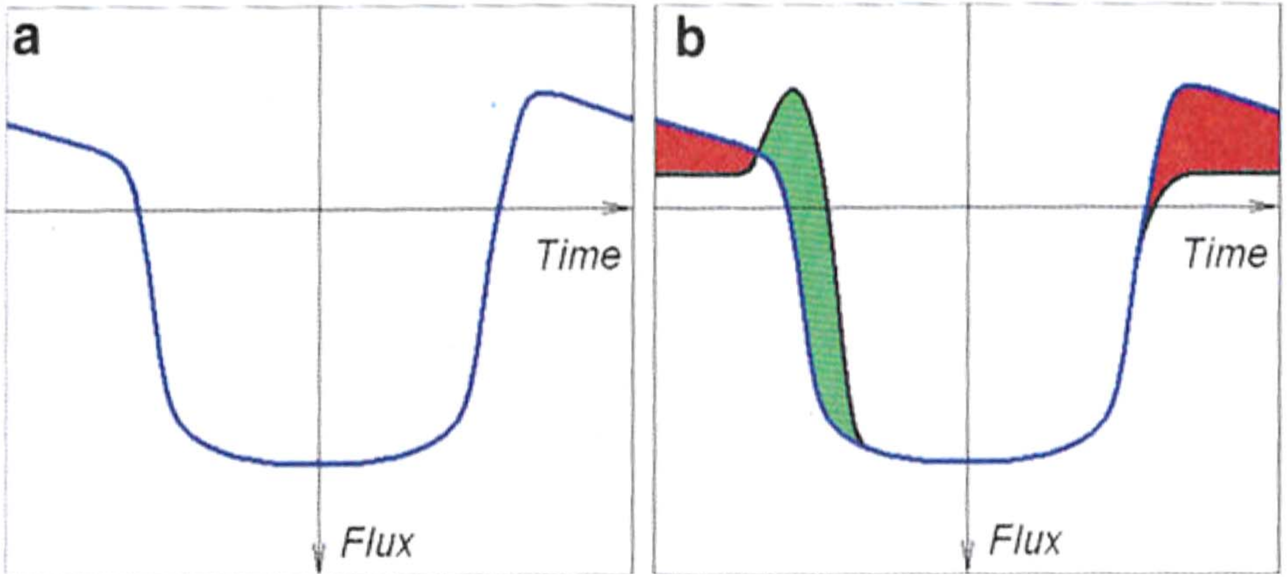
$\boxed{\text{Assume } \overline{w} = 0}$

Eddy Covariance!!!

$$NEE = \underbrace{\int_0^{h_m} \overline{\rho_d} \frac{\partial \overline{\chi_s}}{\partial t} dz}_{\text{Storage Term}} + \underbrace{\cancelto{0}{\int_0^{h_m} \overline{\rho_d}\, \overline{w} \frac{\partial \overline{\chi_s}}{\partial z} dz}}_{\text{Vertical Advection}} + \underbrace{\overline{\rho_d}\, \overline{w' \chi_s'} \Big|_{h_m}}_{\text{Turbulent Transport}}$$

Concentration profile measurement!!!

- As conditions become stable, the EC sensors don't "see" the flux.



Aubinet, 2012

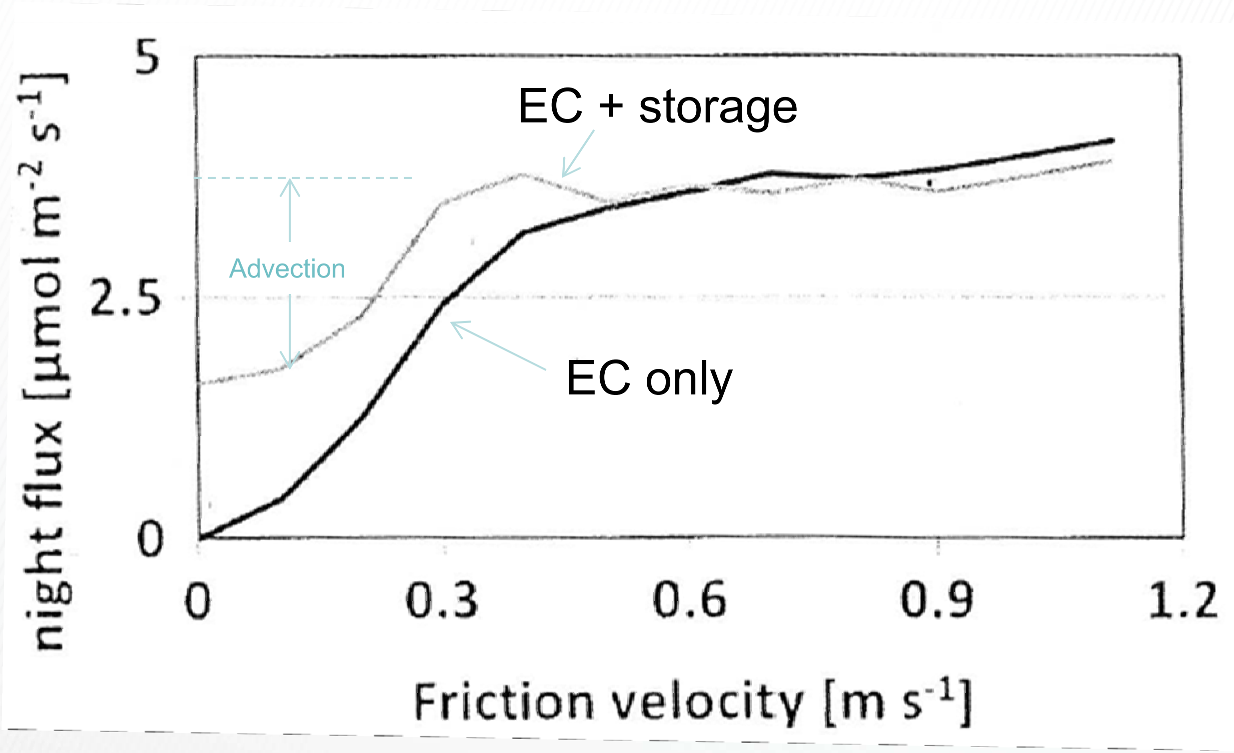
Blue Curve = Actual CO2 Flux, Black Curve = EC measured fluxes

Q: The red area and green area are equal. Does this mean over a 24-hr period EC fluxes will give us accurate net flux?

- A: Yes, in an ideal world, but in the real world, nighttime conditions may lead to:
  - Stratification that decouples surface and measurement system(s)
  - Growing footprint (perhaps into non-homogenous areas)
  - Horizontal gradients develop and advection becomes significant (especially nighttime flows)
  - Non-stationary conditions (sudden changes in concentration and velocity, e.g. nocturnal jets)

Advection is impractical to measure, so it is usually assumed negligible above u* threshold, and is estimated below u* threshold.

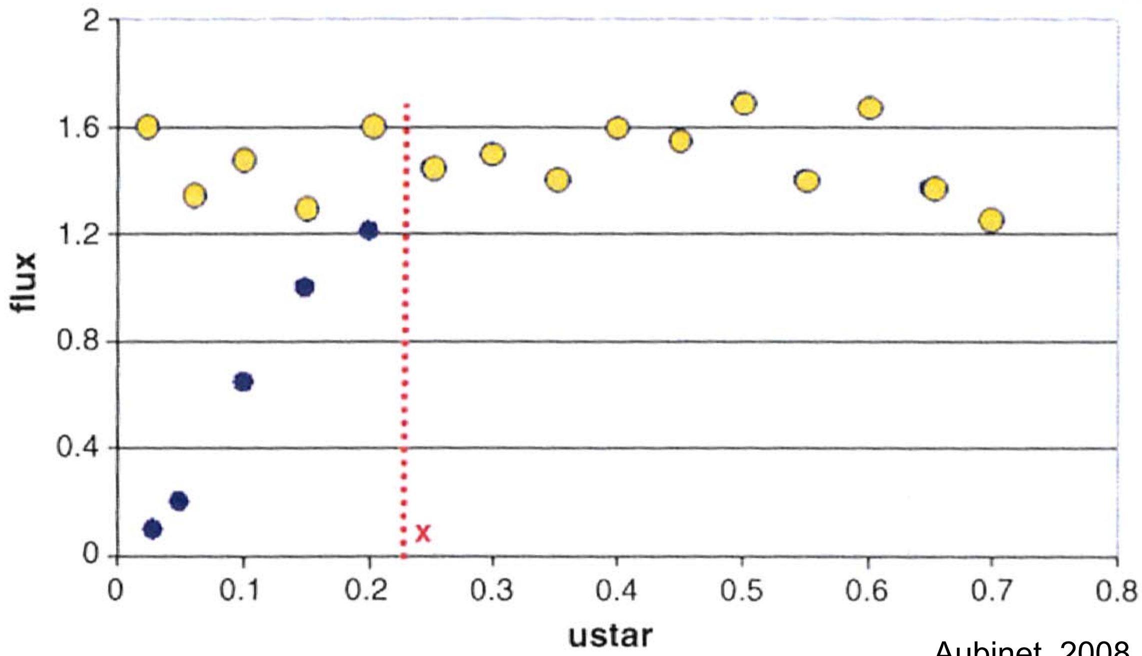
- Evidence of Advection



Aubinet et al., 2012

- We can filter data using a friction velocity threshold. Typical thresholds are 0.1 – 0.5 m/s, but should be determined experimentally.

$$\text{Recall that } u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{\frac{1}{4}}$$



Aubinet, 2008

Yellow Dots – Theoretical NEE
Blue Dots – Measured NEE (ECflux + storage)
x is u_* threshold.

More on u* filtering

- However, u* filtering to some standard value may not work. “Know thy site”.
- For sites with significant canopy, even high u* can have a significant storage term.
- “Any site with slope and a canopy needs profile measurements” – Ray Leuning, 2013 AsiaFlux Workshop.

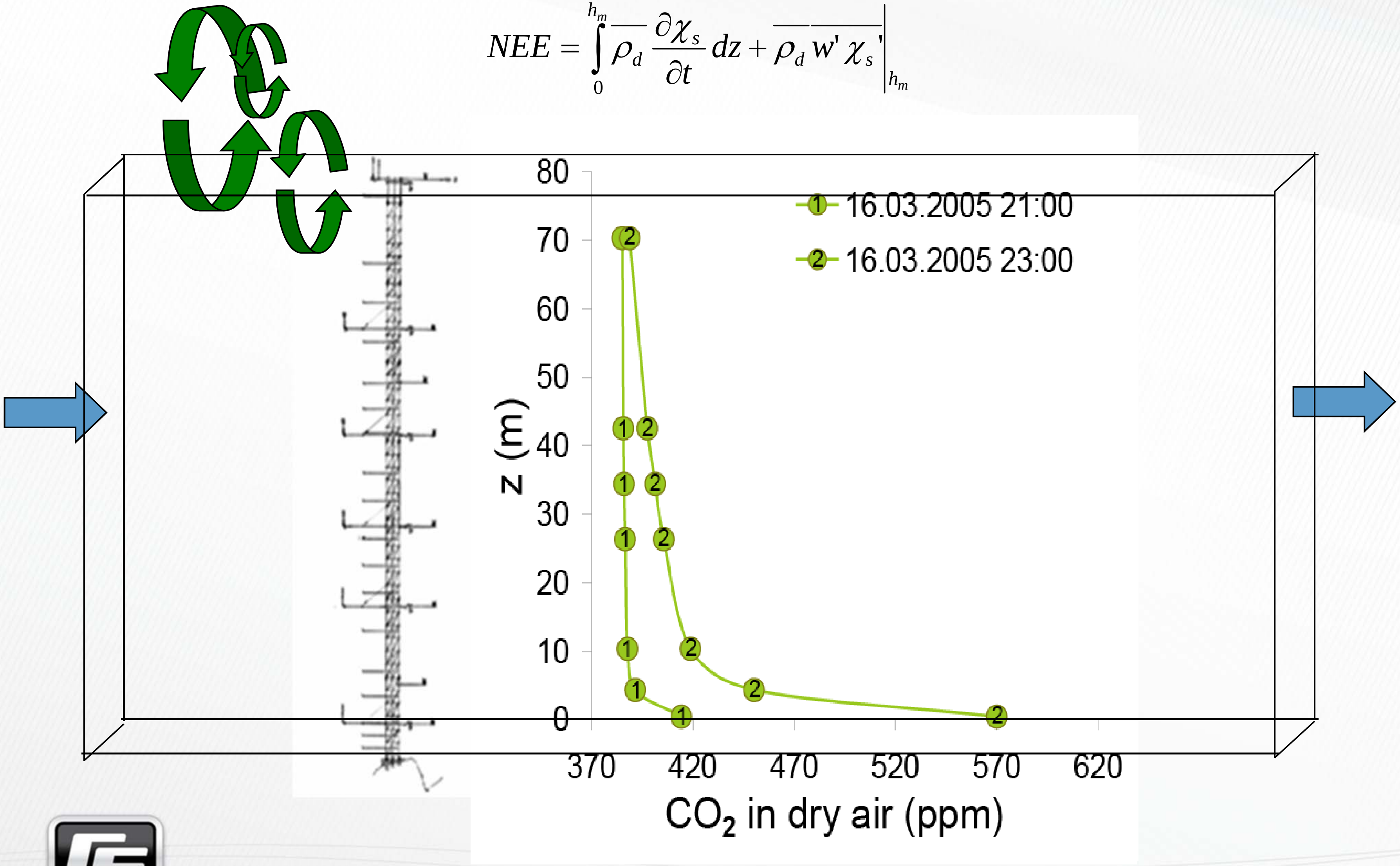
Intake Heights

- What heights should intakes be at?
  - Grasses & short crops
    - At least 4 intakes
    - Bottom intake within canopy
    - Remaining intakes are equidistant
  - Forests
    - Two intakes above canopy (top one in well mixed layer below EC sensors)
    - One intake at mean canopy height (region of highest LAI)
    - Rest of intakes should capture ecologically significant strata

Munger et al., 2012

Looking at the real world… An example site from Ray Leuning.

$$NEE = \int_0^{h_m} \overline{\rho_d} \frac{\partial \chi_s}{\partial t} dz + \overline{\rho_d} \, \overline{w' \chi_s'} \Big|_{h_m}$$



Slide courtesy of Ray Leuning.

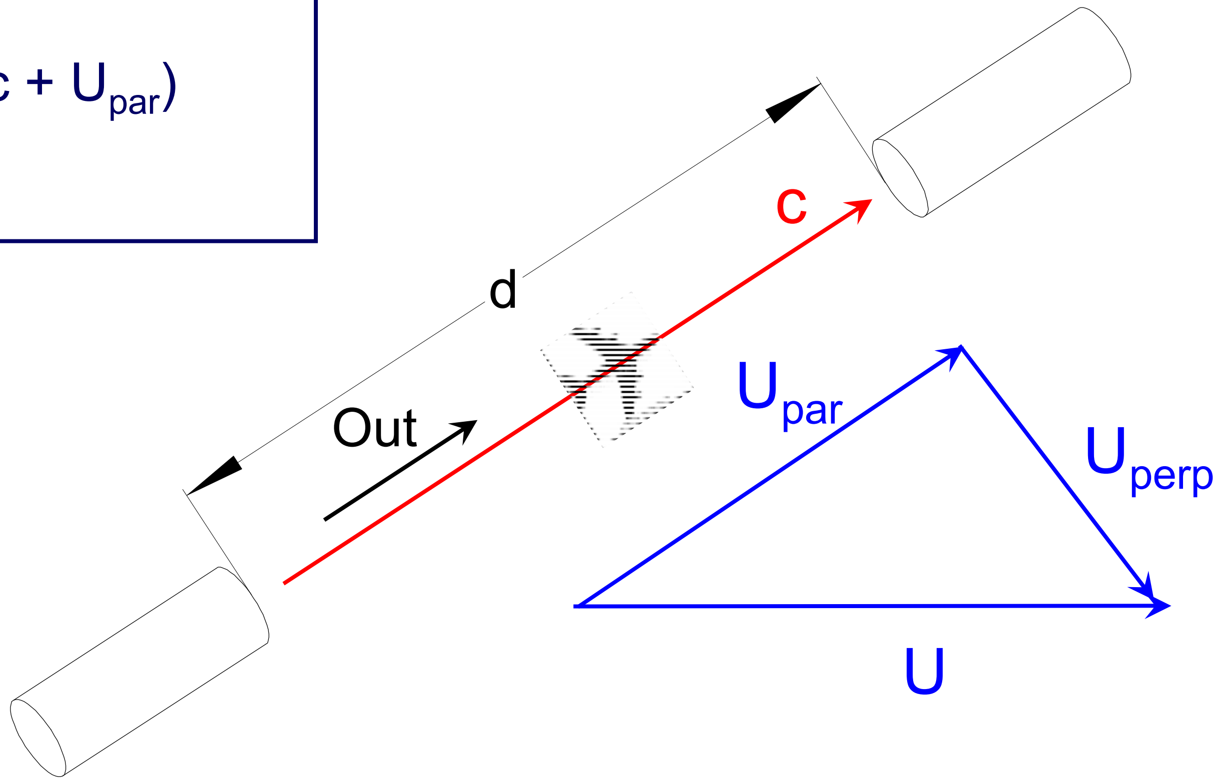
INSTRUMENTATION

- Measurement Principles
  - Sonic Anemometry
  - NDIR Gas Analysis
- Design Rationales for EC sensors
- Timeline of Micromet Systems at CSI
- Summary of Performance Advantages

Sonic Anemometer Measurement Principals

$t = d/rate$

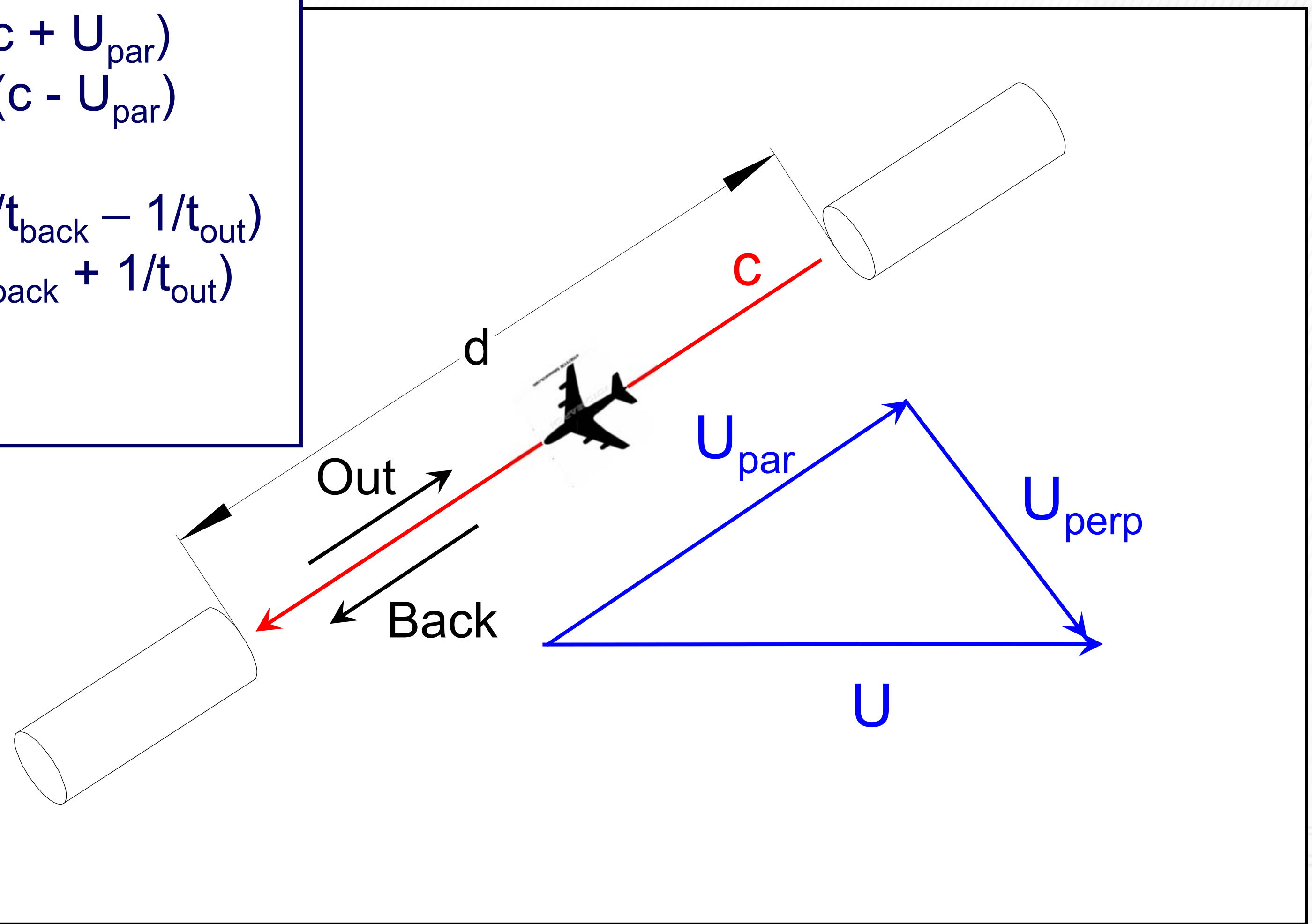
$t_{out} = d/(c + U_{par})$



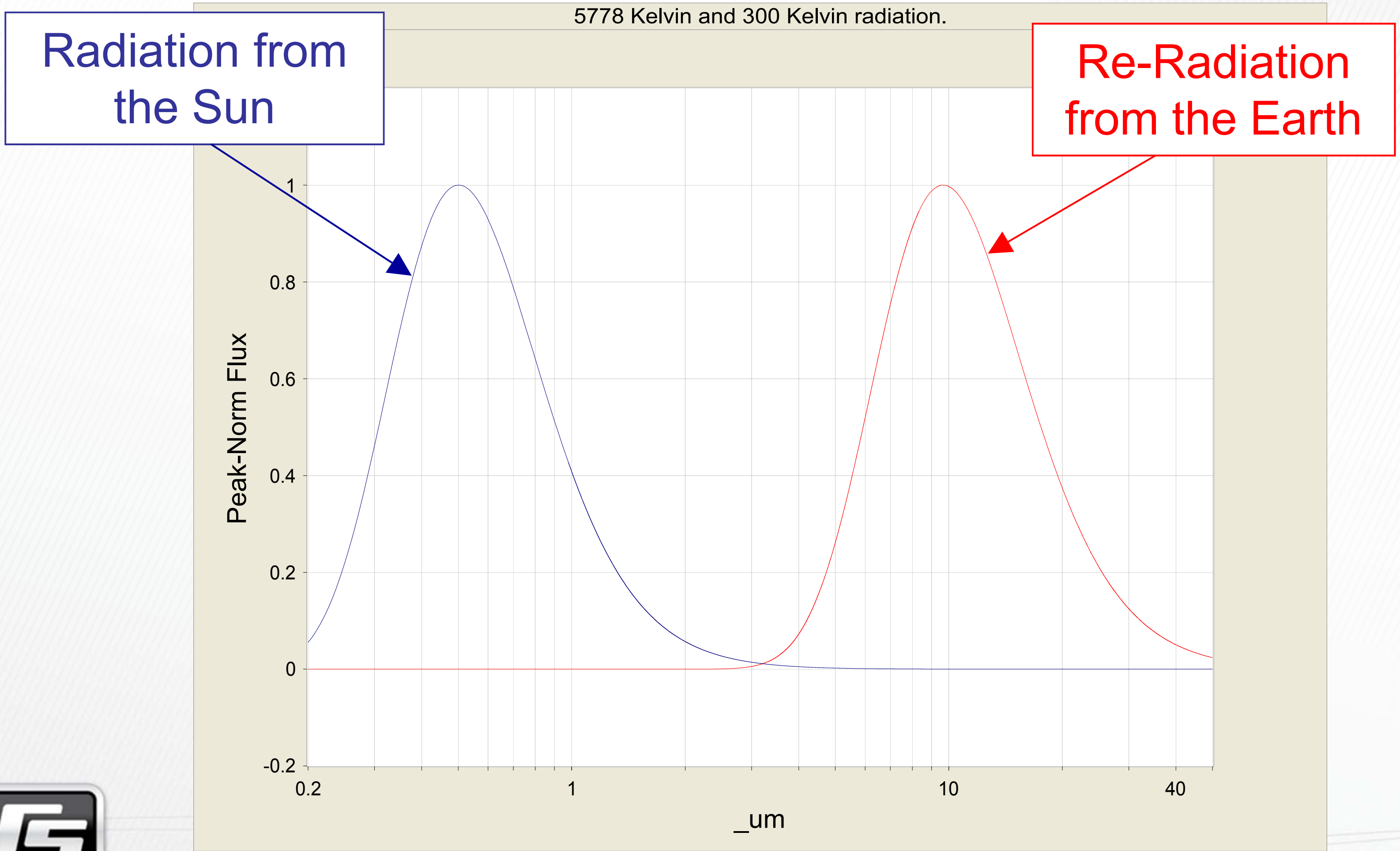
Sonic Anemometer Measurement Principals

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

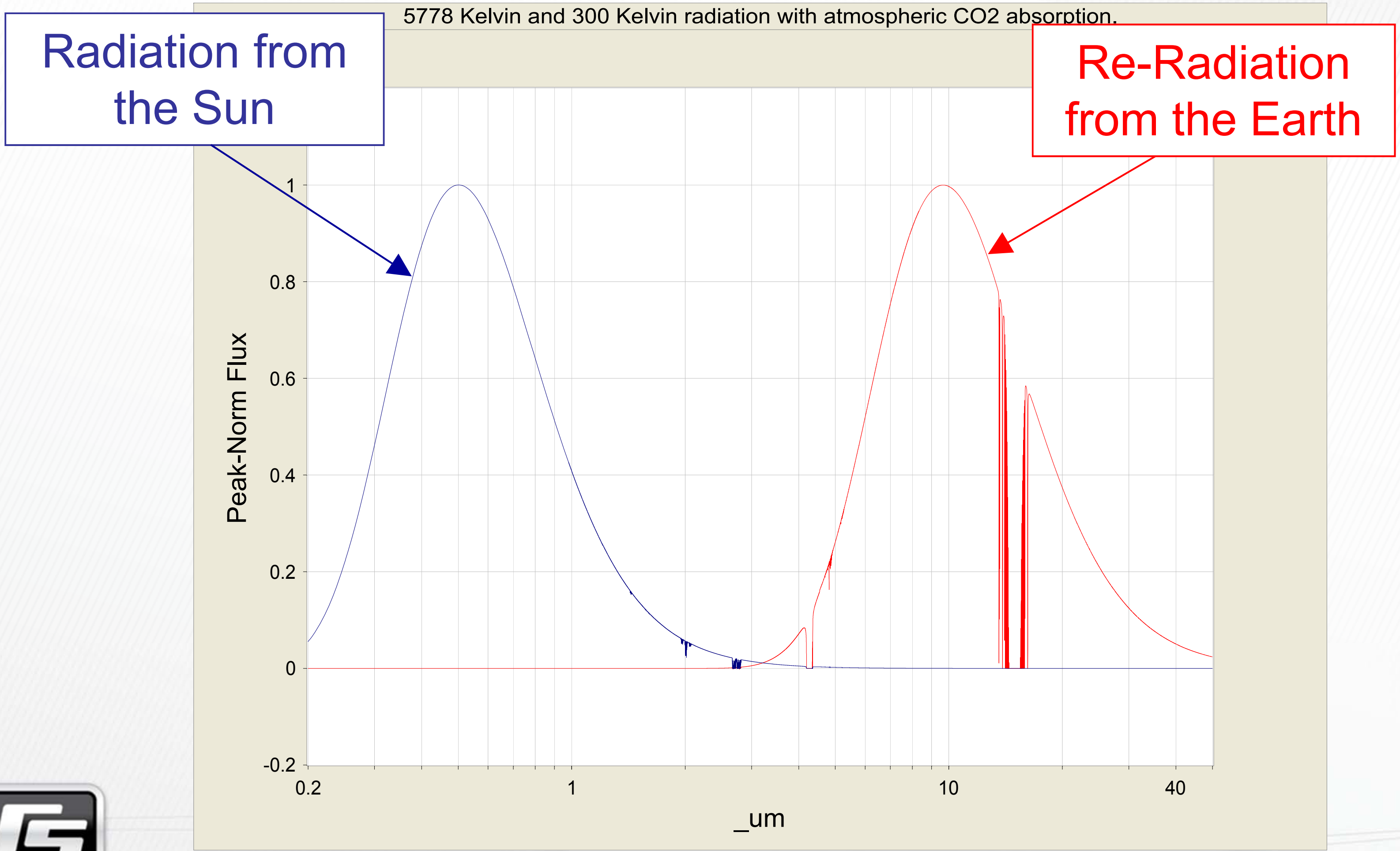
$$U_{par} = d/2\,(1/t_{back} - 1/t_{out})$$
$$c = d/2\,(1/t_{back} + 1/t_{out})$$



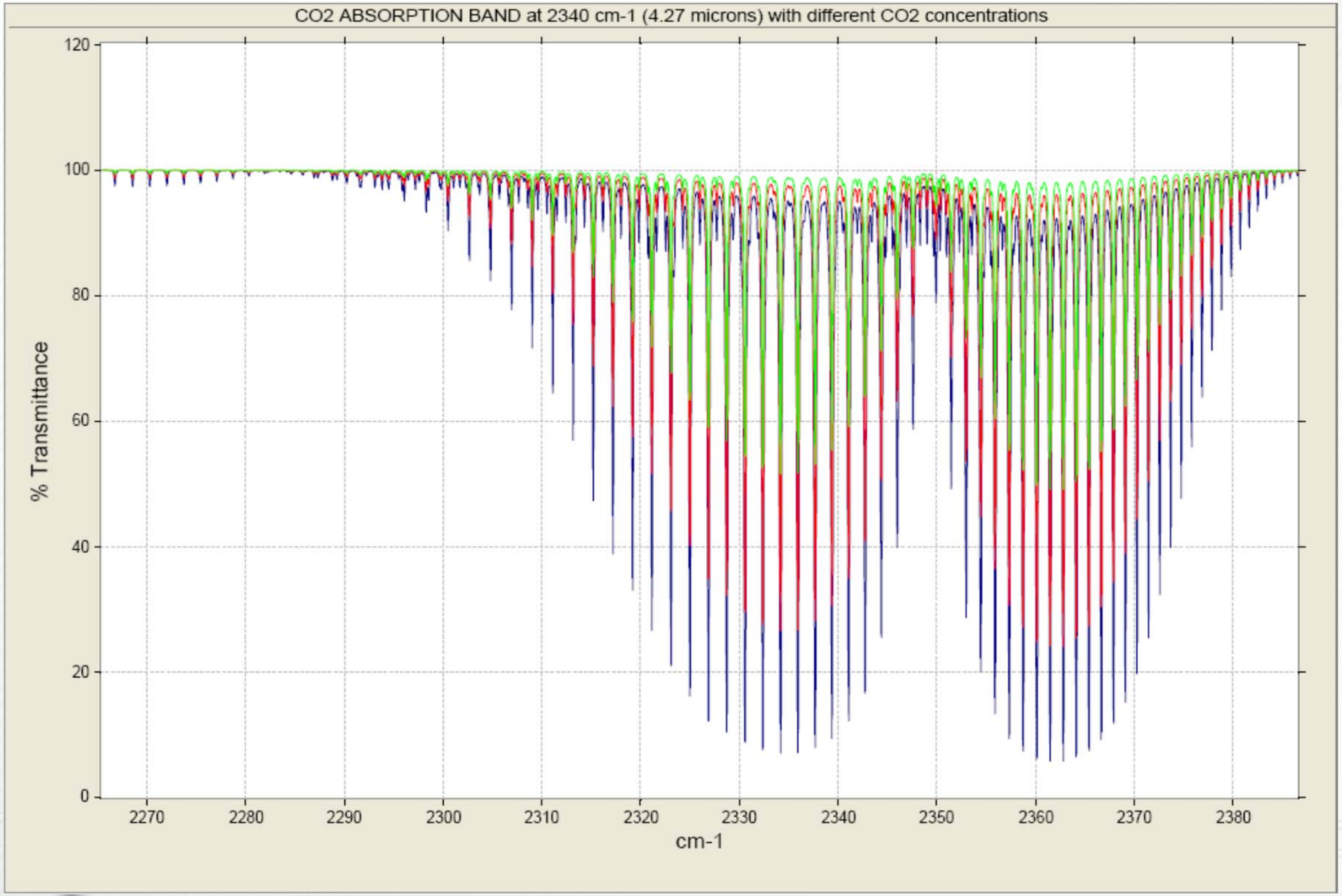
NDIR Measurement Principles
Sun and Earth Radiation

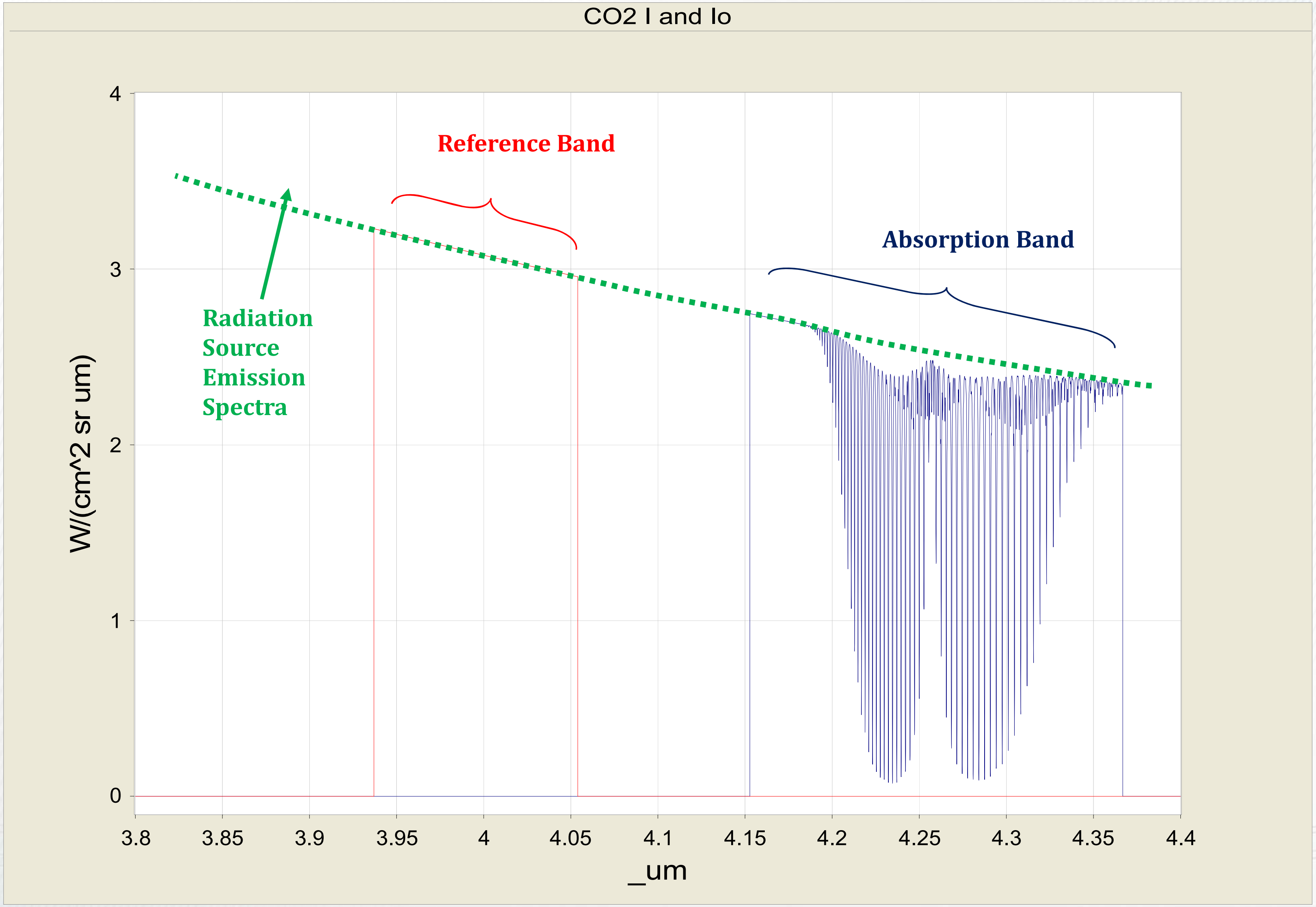


Sun and Earth Radiation with CO_2 Atmospheric Absorption

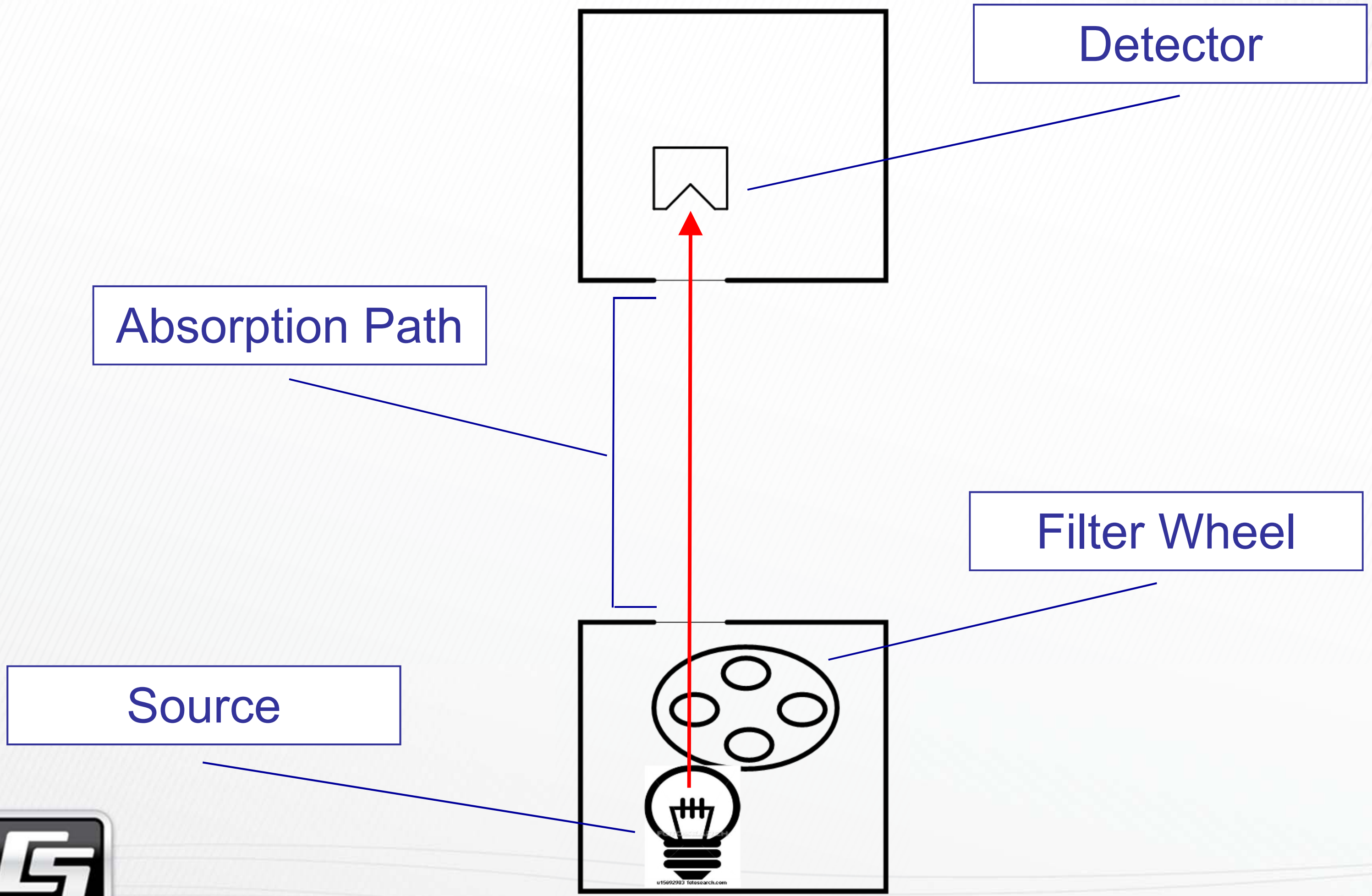


CO2 Asymmetric Stretch:

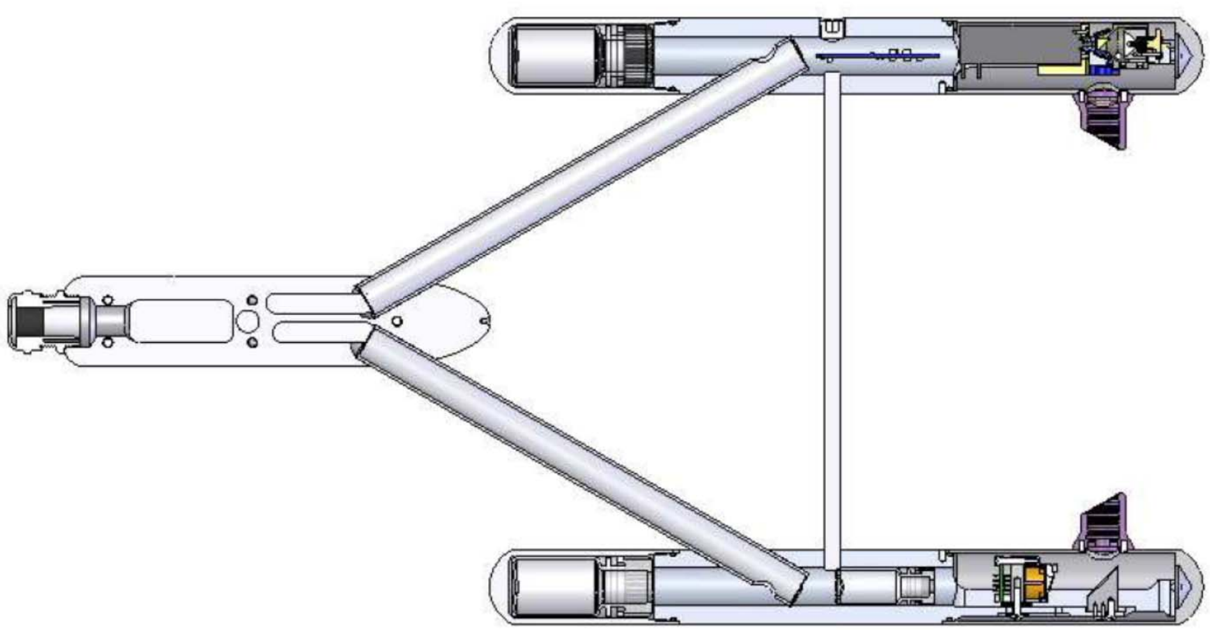



CO2 I and Io
Reference Band
Absorption Band
Radiation Source Emission Spectra
W/(cm^2 sr um)
_um
4
3
2
1
0
3.8
3.85
3.9
3.95
4
4.05
4.1
4.15
4.2
4.25
4.3
4.35
4.4

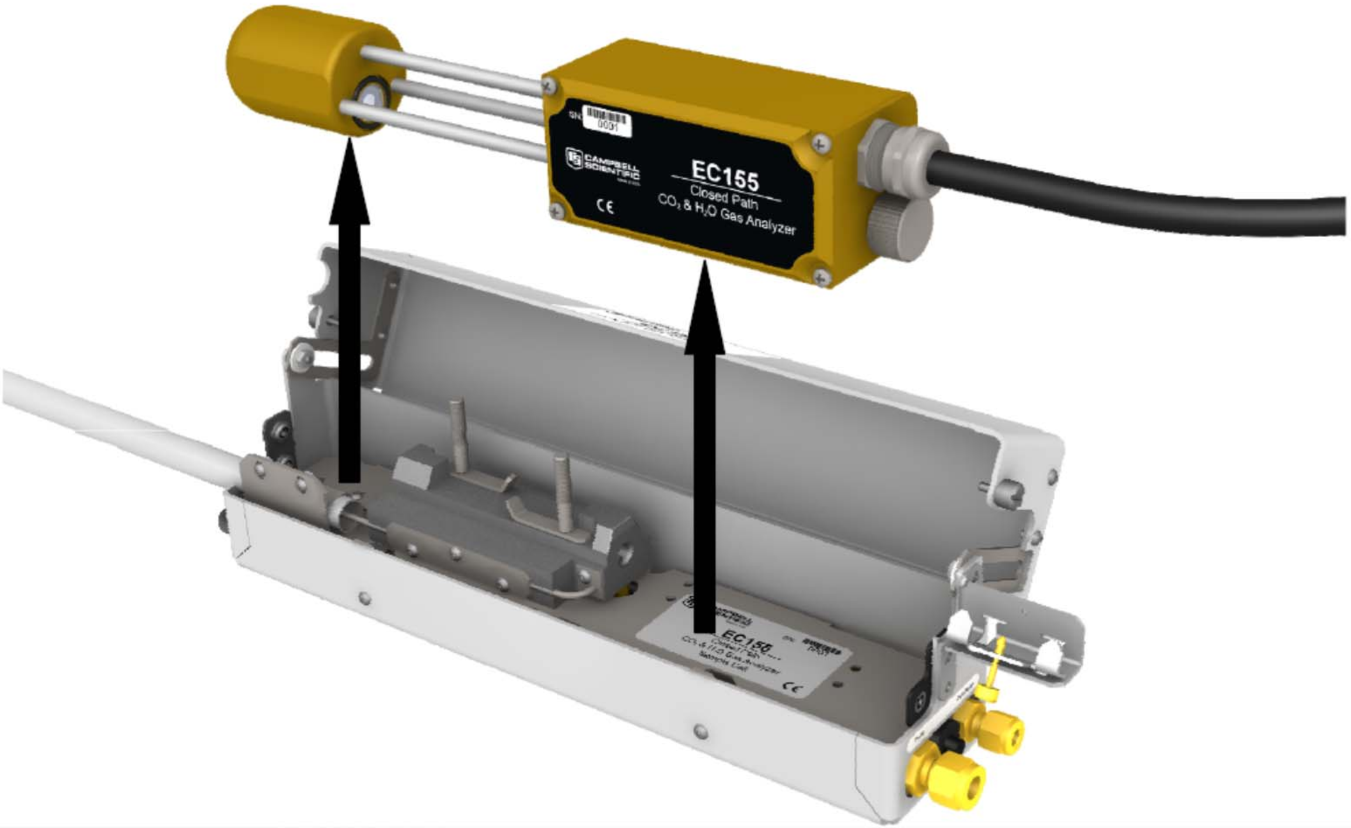
Non-Dispersive Infrared (IRGA) Gas Analyzer



Principle of Operation – Open Path EC 150



Principle of Operation – Closed Path EC 155



DESIGN RATIONALES

Instrumentation requirements:

- Preserve vertical wind and scalar correlation
  - Spatial Synchronicity (i.e. co-location)
  - Temporal Synchronicity

Spatial Synchronicity

- Sensor separation creates temporal asynchronicity

  t = d/r = d/u
- Sensor separation causes loss of spatial coherence

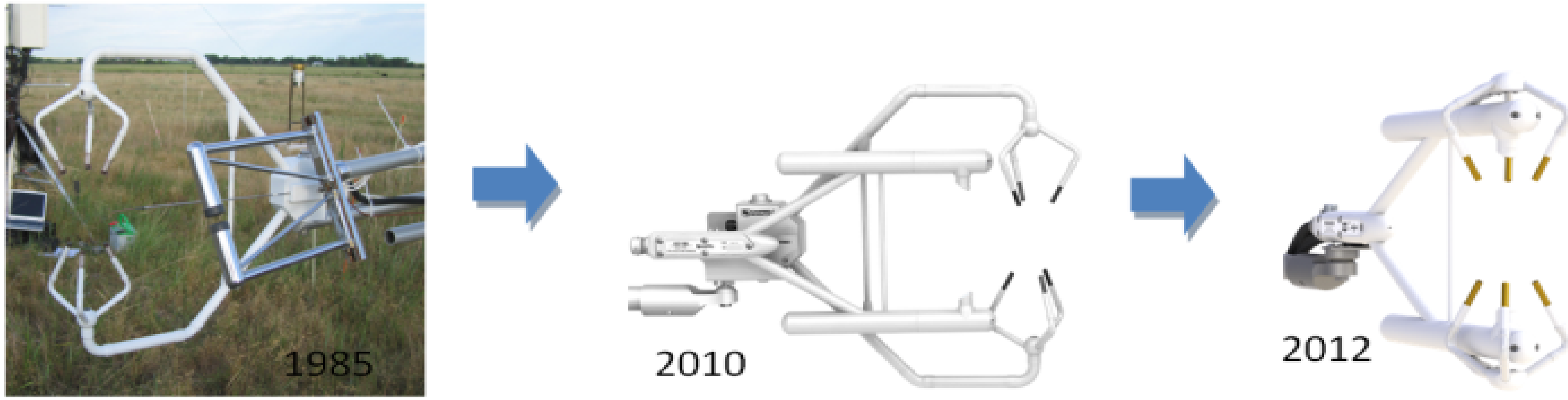
  Errors change with wind angle of attack
- Moving sensors closer together can be tricky

  Flow distortion on Sonic Anemometer:

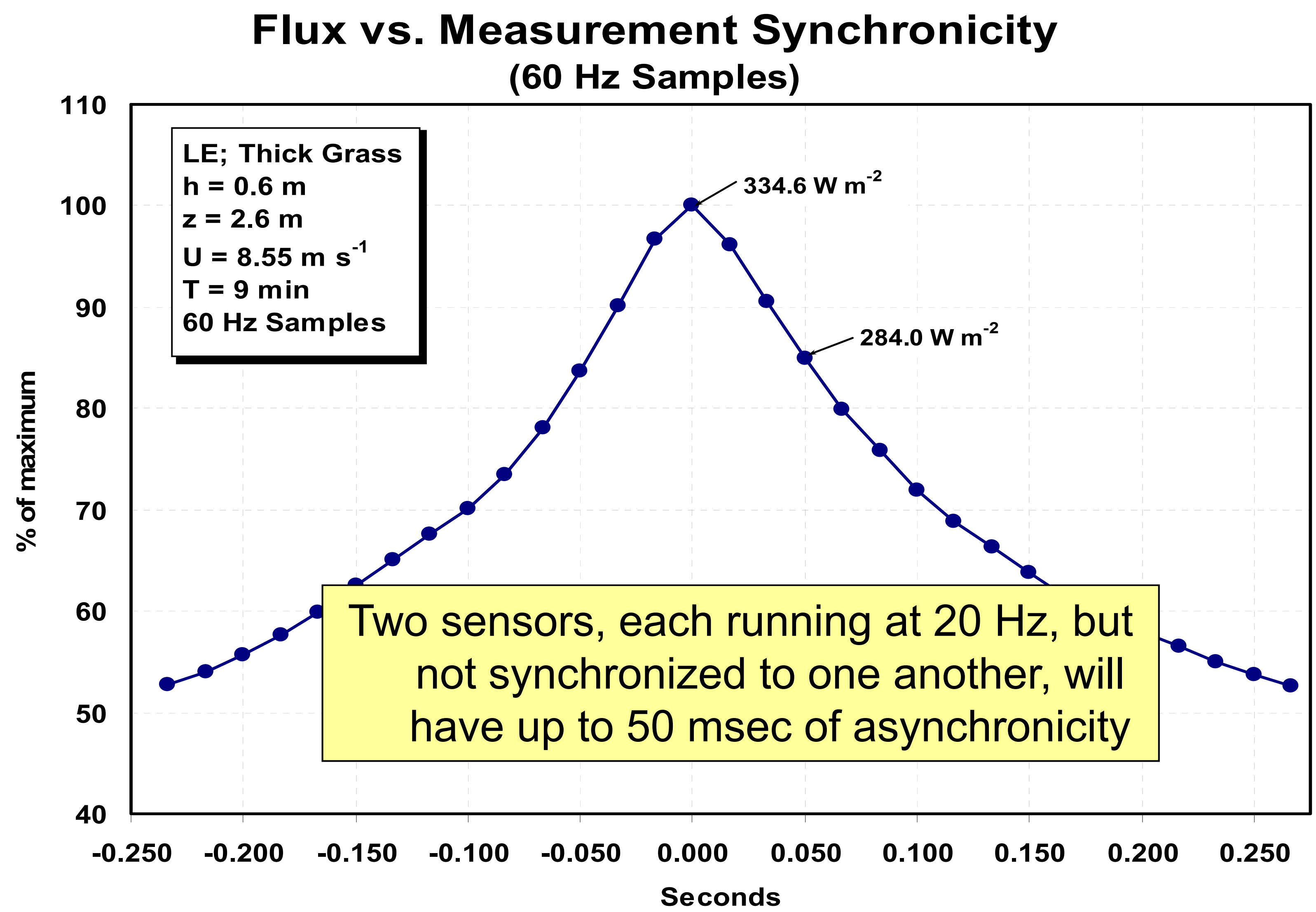
  Mean errors and turbulence errors

  Thus, aerodynamics very important!!!

Evolution of Campbell Colocated Design.

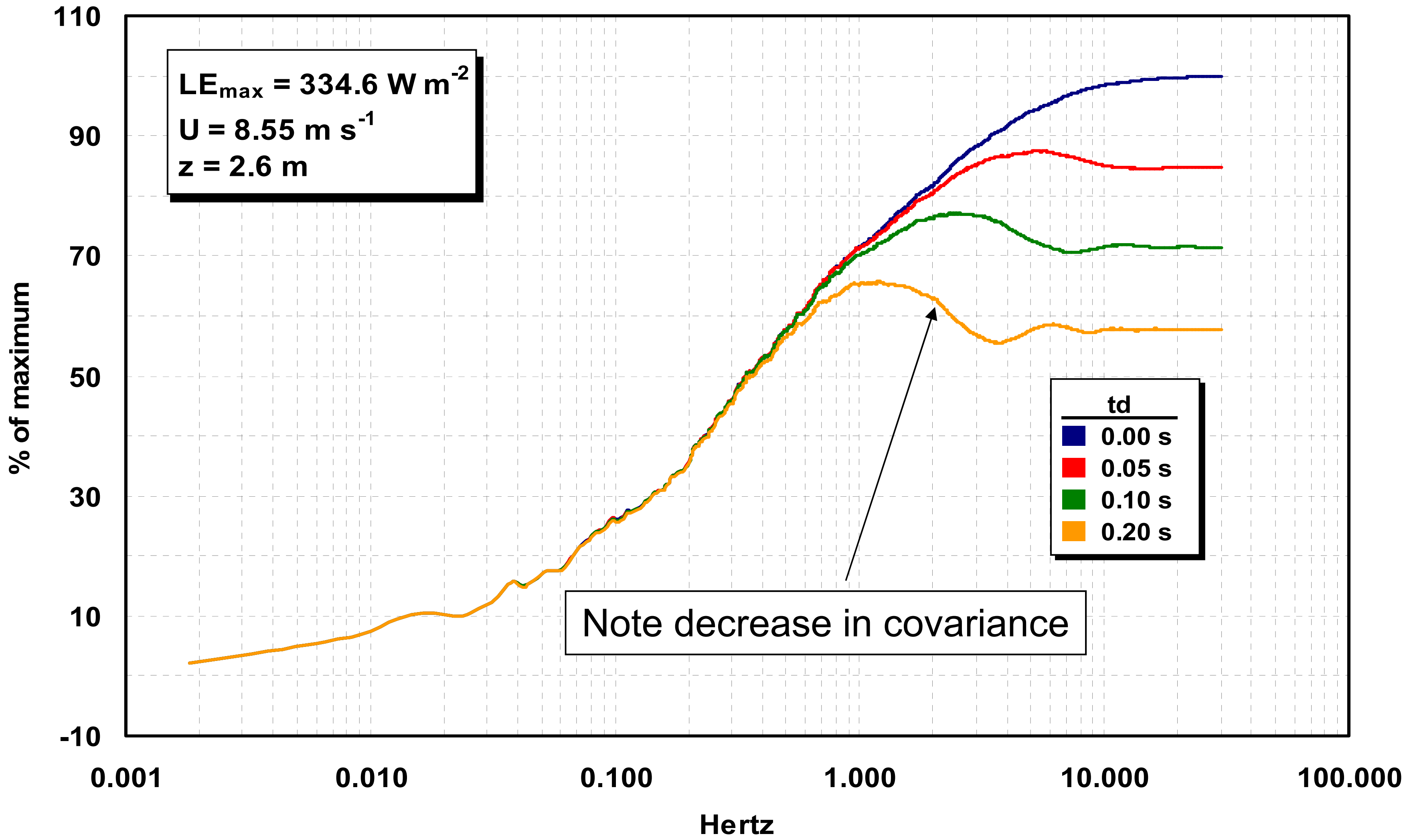


Temporal Synchronicity

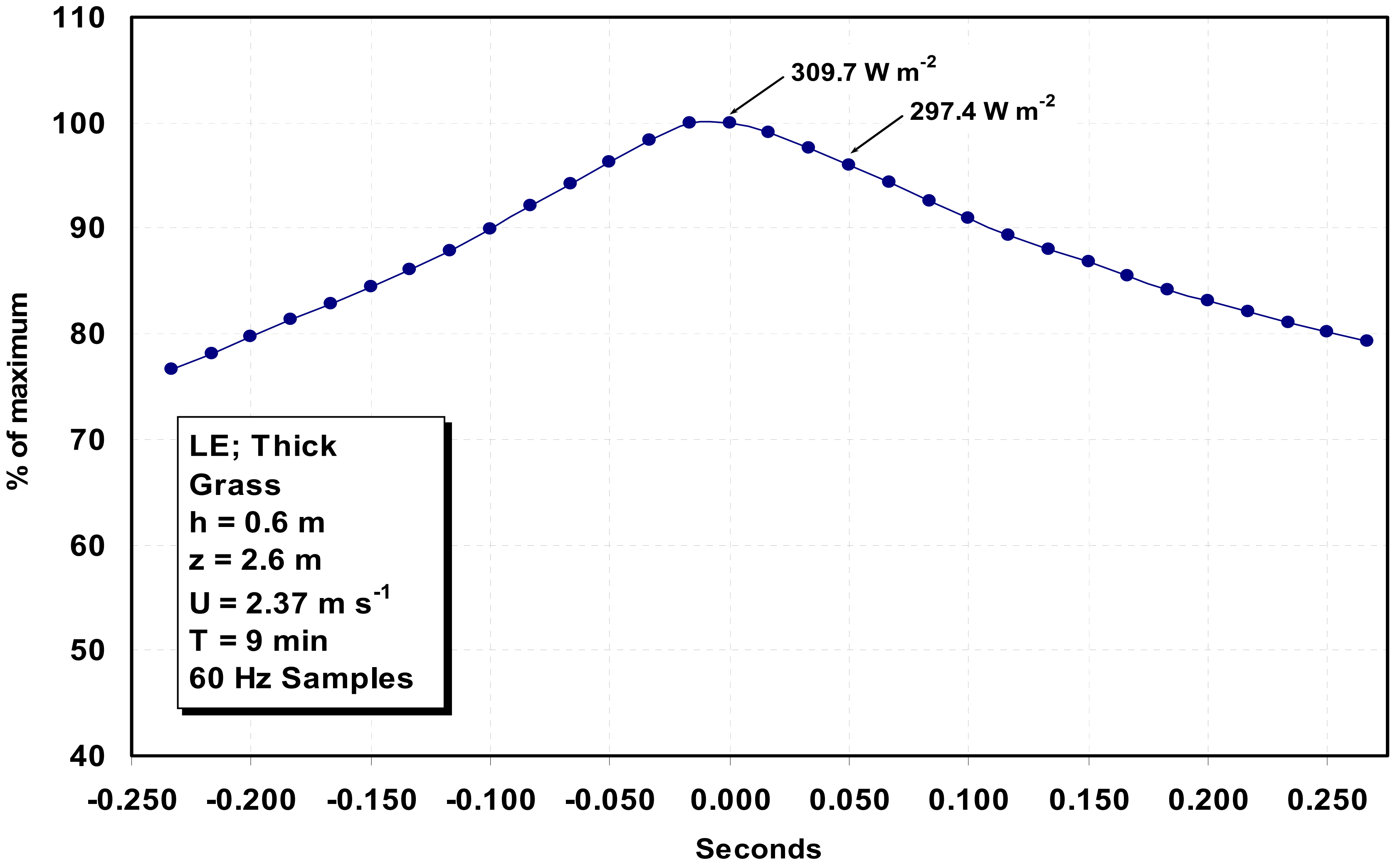


Two sensors, each running at 20 Hz, but not synchronized to one another, will have up to 50 msec of asynchronicity

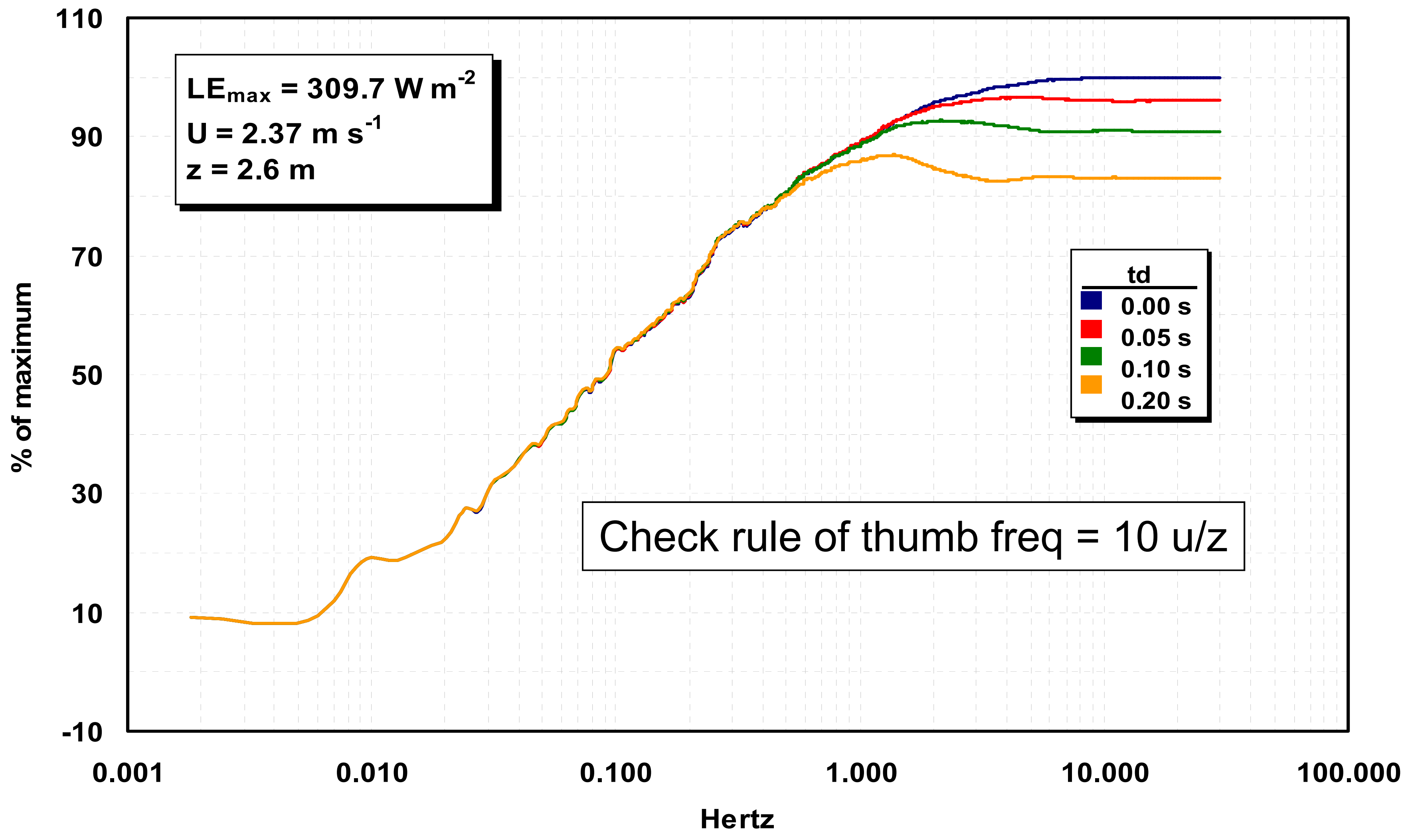
Flux vs. Covariance Cutoff Frequency
(60 Hz Samples)



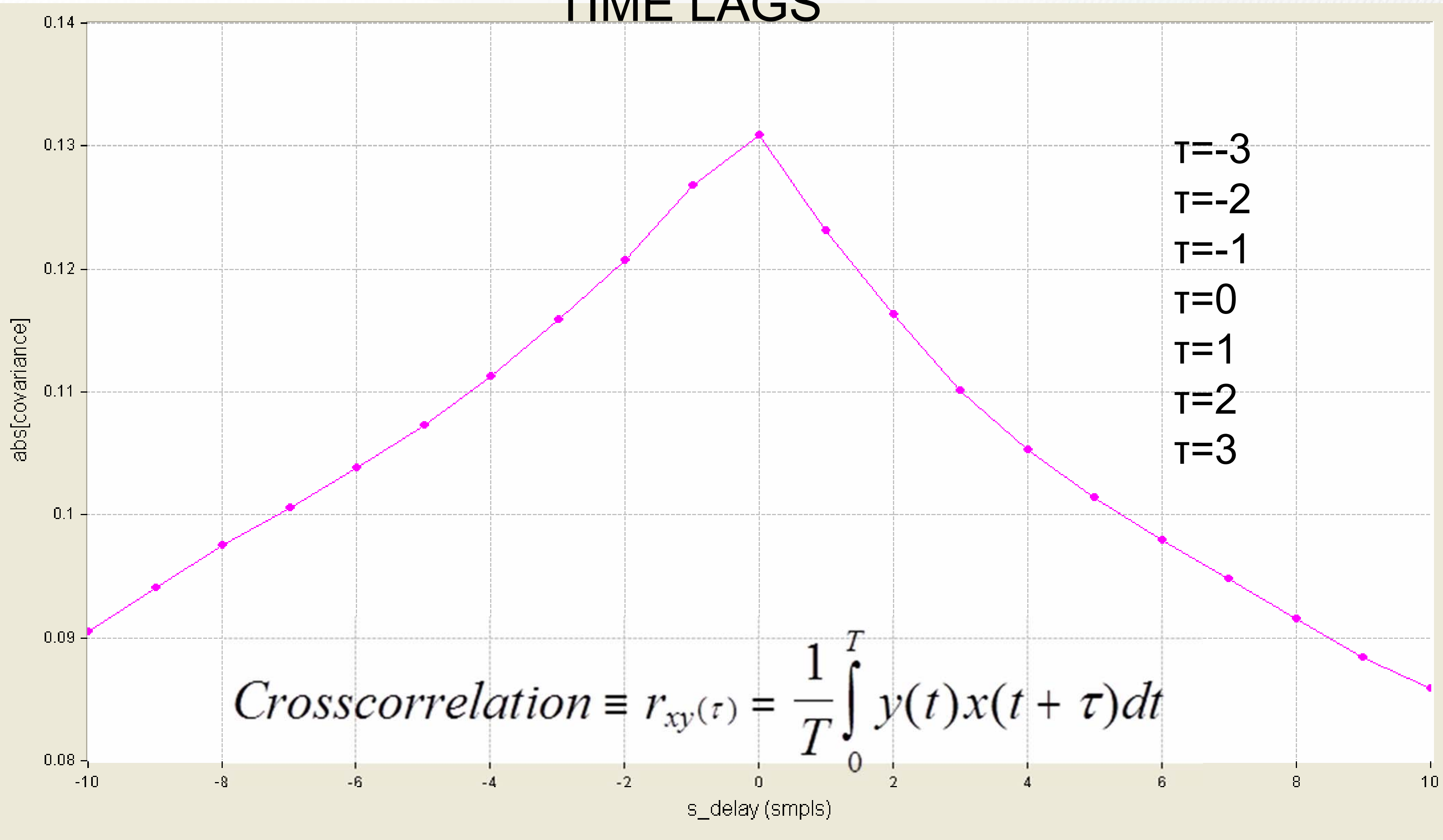
Flux vs. Measurement Synchronicity
(60 Hz Samples)



Flux vs. Covariance Cutoff Frequency
(60 Hz Samples)



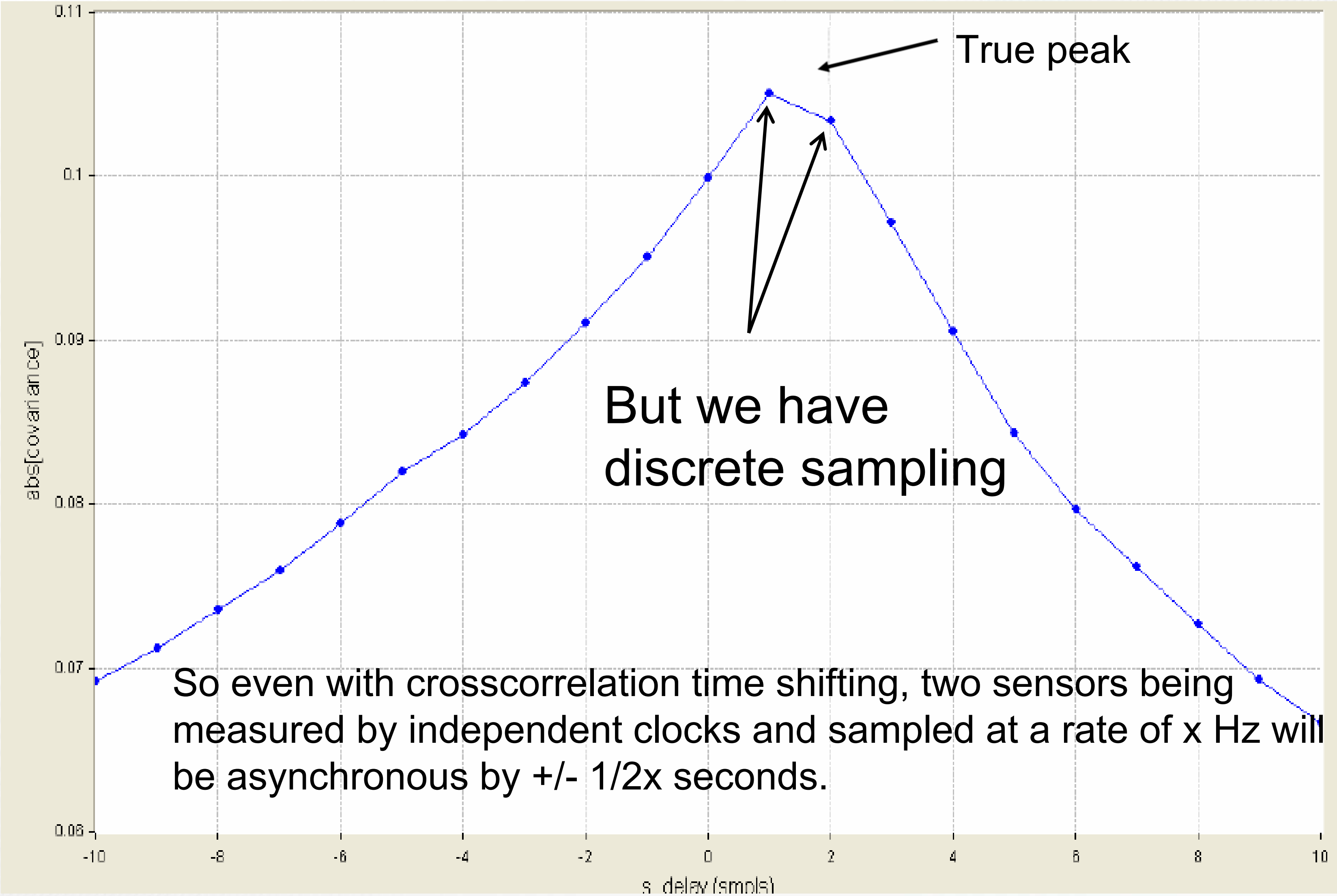
SYNCHRONIZATION OF TIME SERIES AND FINDING TIME LAGS



$$Crosscorrelation \equiv r_{xy}(\tau) = \frac{1}{T}\int_0^T y(t)x(t+\tau)dt$$

Performing the correlation for many different time shifts → crosscorrelation

Then find the maximum (or minimum if the flux is negative)

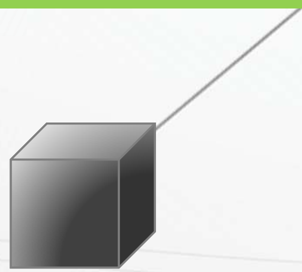

True peak
But we have discrete sampling
So even with crosscorrelation time shifting, two sensors being measured by independent clocks and sampled at a rate of x Hz will be asynchronous by +/- 1/2x seconds.
0.11
0.1
0.09
0.08
0.07
0.06
abs[covariance]
-10
-8
-6
-4
-2
0
2
4
6
8
10
s_delay (smpls)

Instrumentation requirements:

- High Precision
- Adequate frequency response

When requirements are not met, corrections must be applied to fluxes. The goal is to minimize corrections to minimize uncertainty.

Q: What limits frequency response in a sonic anemometer or gas analyzer?



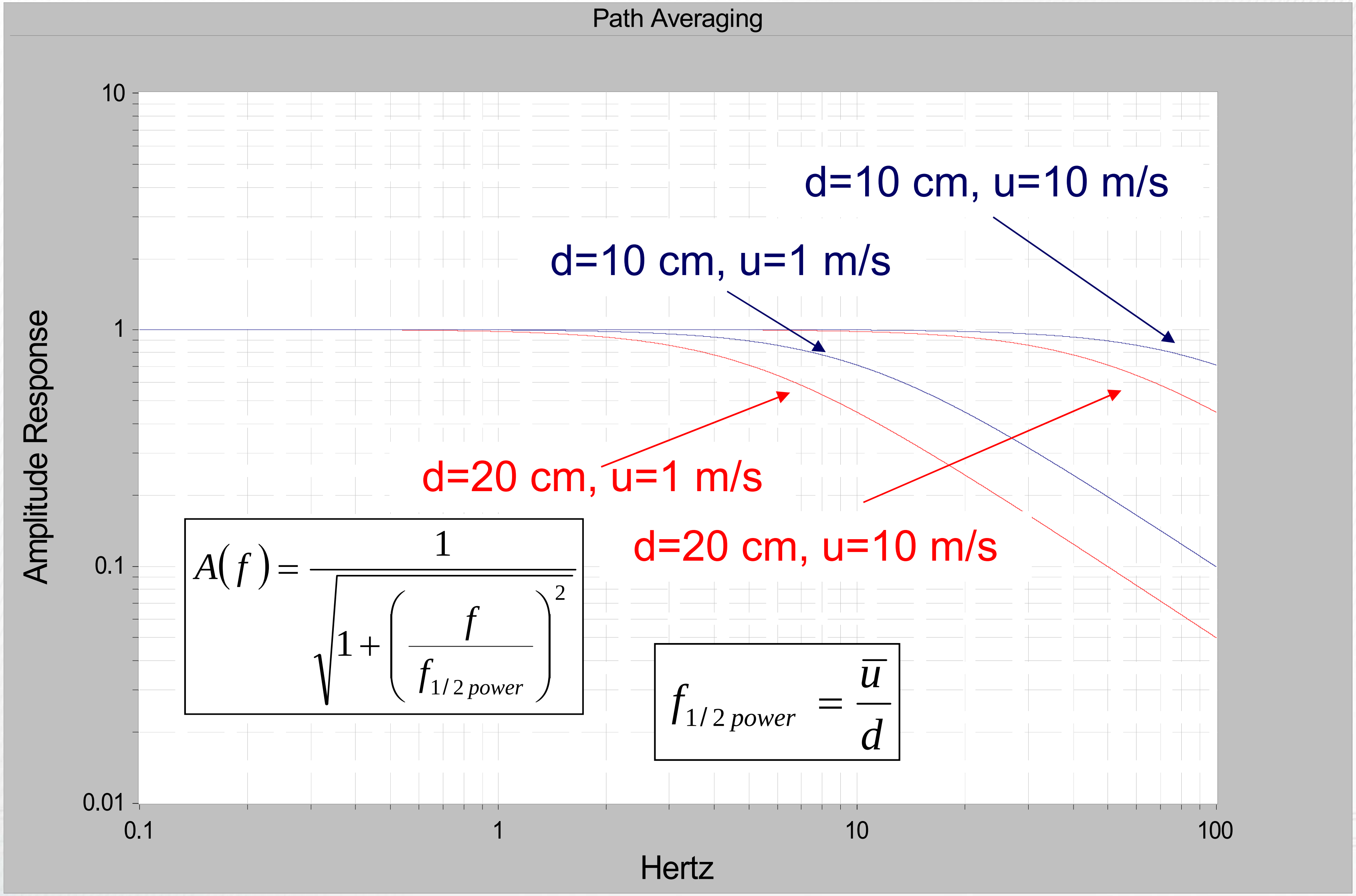
10Hz Scan Rate

A: Frequency-Response Limitations:

- Path (and volume) averaging
- Non-instantaneous measurements
- Signal-processing filters
- Other (e.g. thermometer time constants)
- Closed-path gas analyzer unique issues

Vertical Path Averaging

Frequency Response Improves with Wind Speed



$$A(f) = \frac{1}{\sqrt{1+\left(\frac{f}{f_{1/2\,power}}\right)^2}}$$

$$f_{1/2\,power} = \frac{\bar{u}}{d}$$

Vertical Path Averaging

$f_{req} \geq 10\ \bar{u}/z$

$\bar{u}$ is mean wind speed

z is measurement height

$f_{½\ power} = \bar{u}/d$

d is path length

$\bar{u}/d \geq 10\ \bar{u}/z$

$z \geq 10\ d$

- z impacts fetch requirements

A: Frequency-Response Limitations:

- Path (and volume) averaging
- Non-instantaneous measurements
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A: Frequency-Response Limitations:

- Path (and volume) averaging
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- Signal-processing filters
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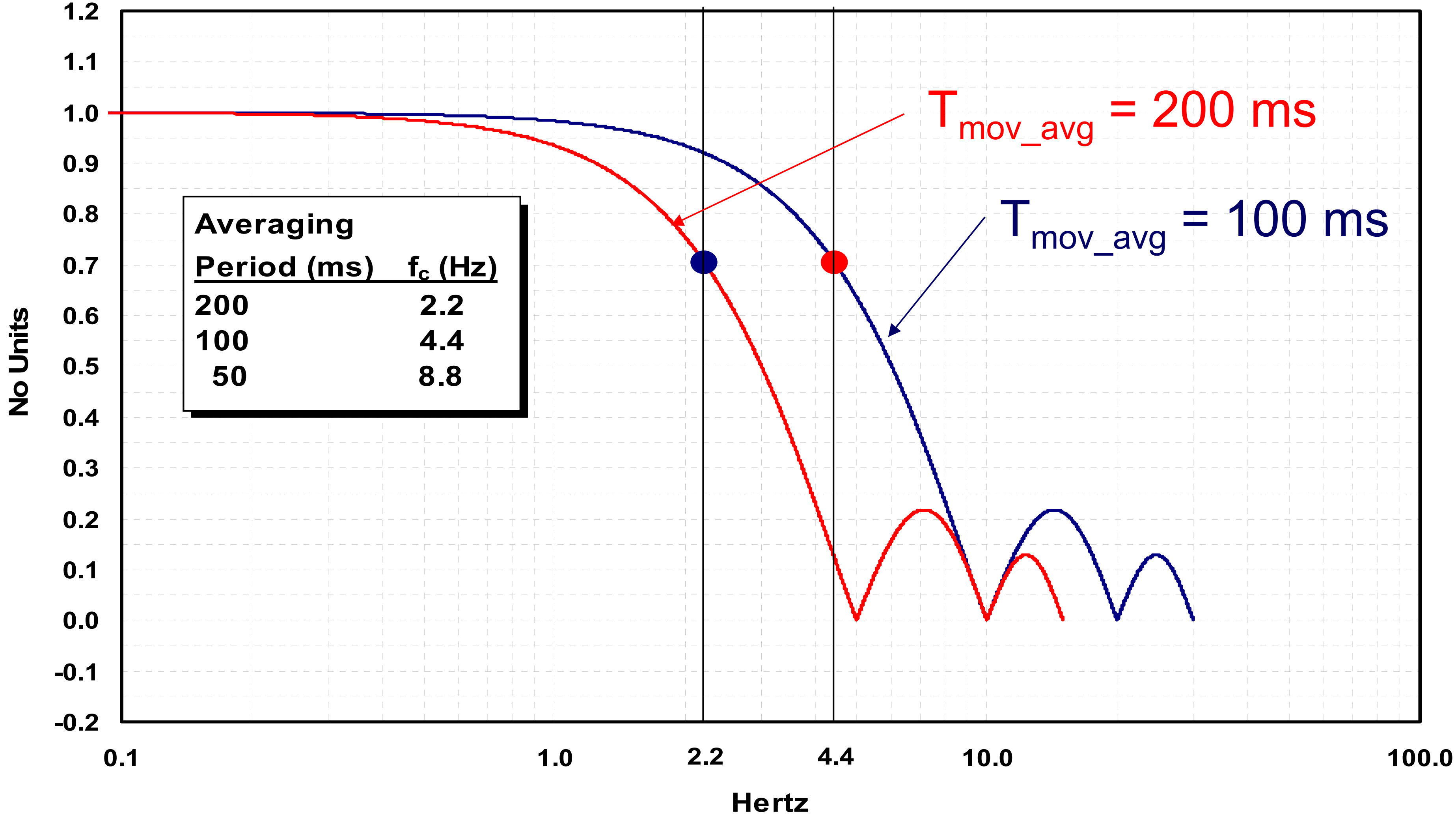
The detector is initially oversampled, so a filter is used to reduce to a reasonable dataset that preserves spectral covariance but attenuates noise.

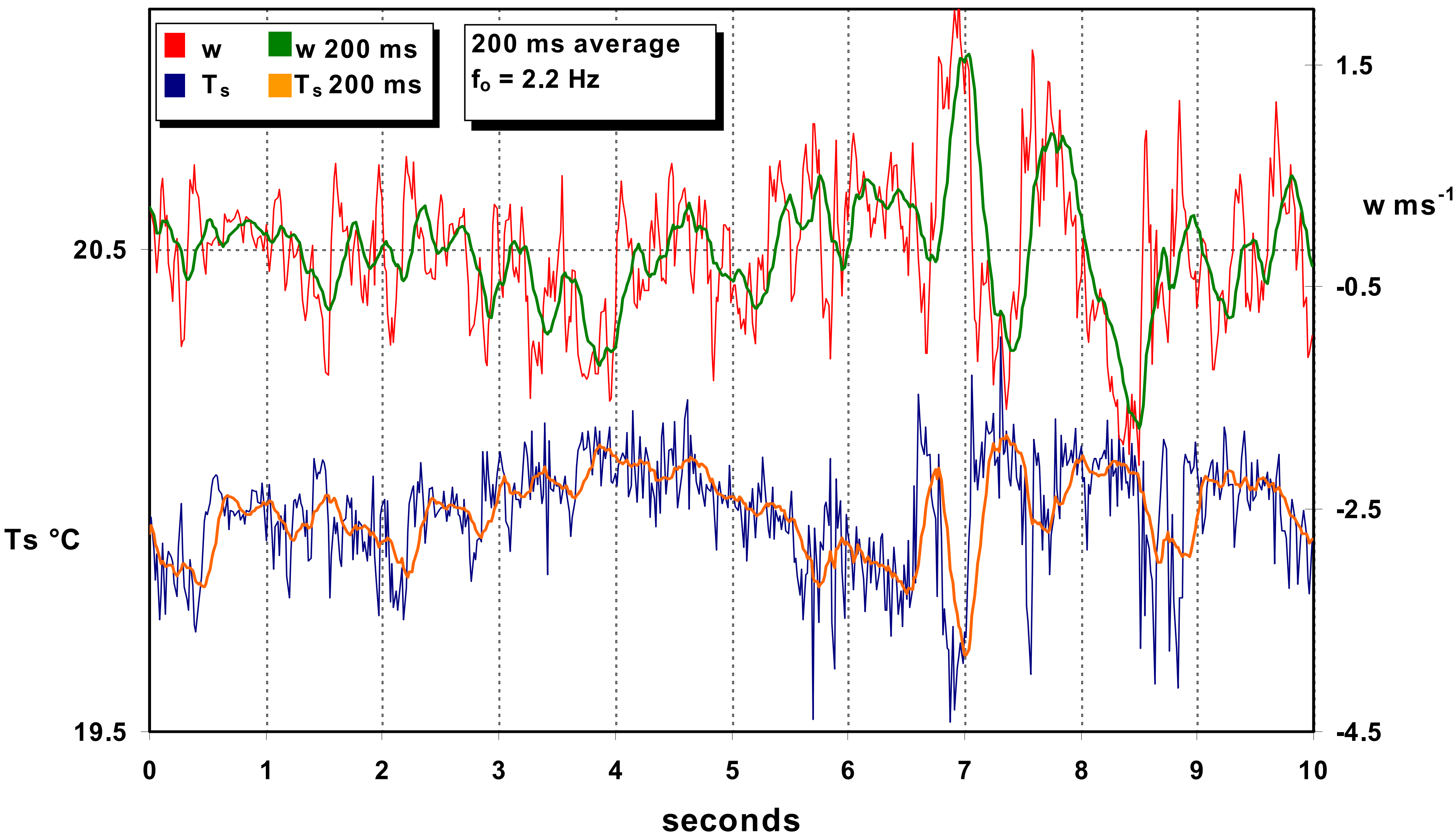
Some types of filters:

- Moving Average (low-pass filter)
- Down-sample (decimation)
- Block average (decimated moving average)
- Custom filter

Amplitude Frequency Response of Moving Averages

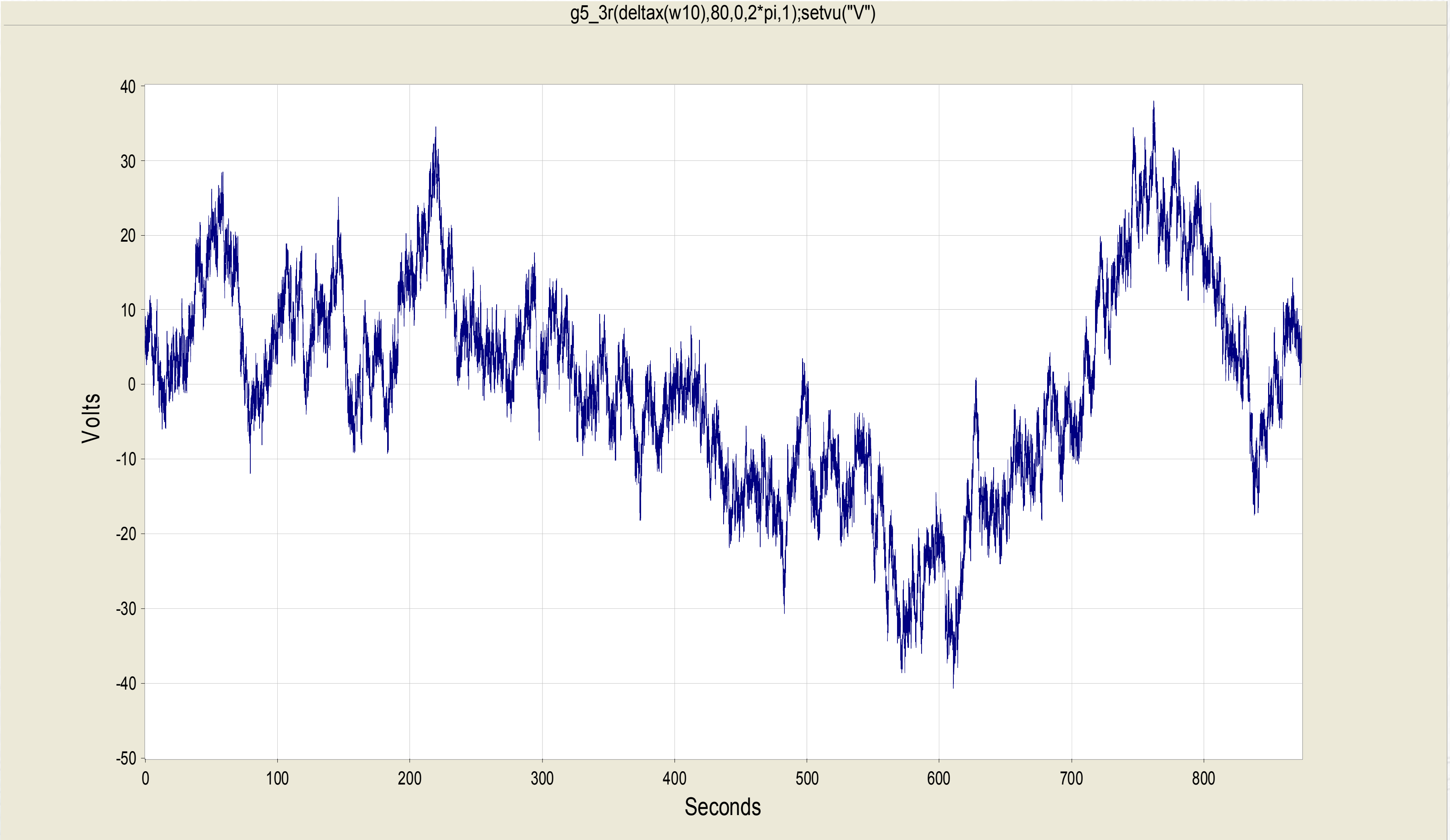


w and T_s with Attenuated Response - 60 Hz



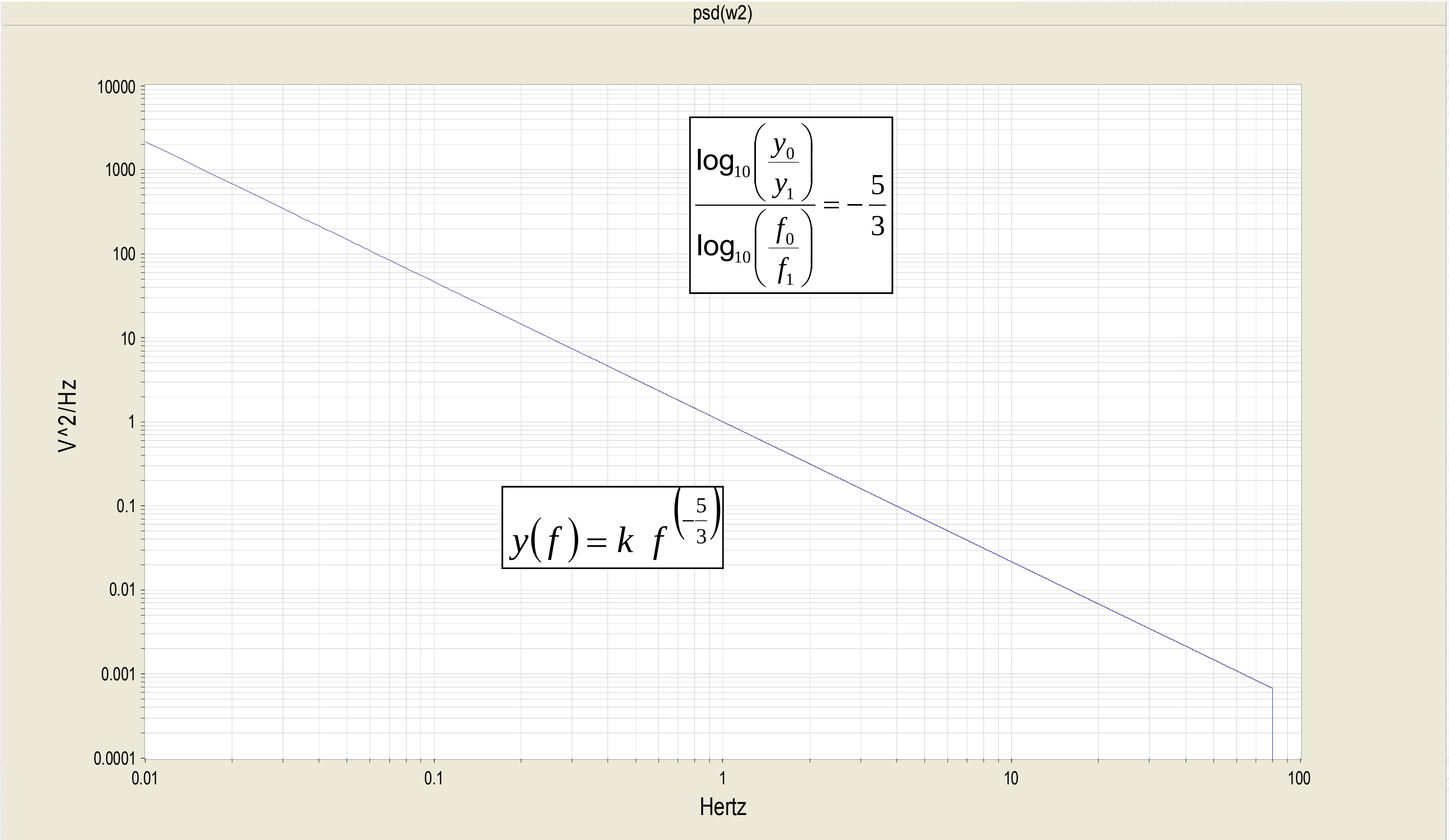
What will applying a moving average filter do to a dataset?

Synthesized Time Series with -5/3 Power Law



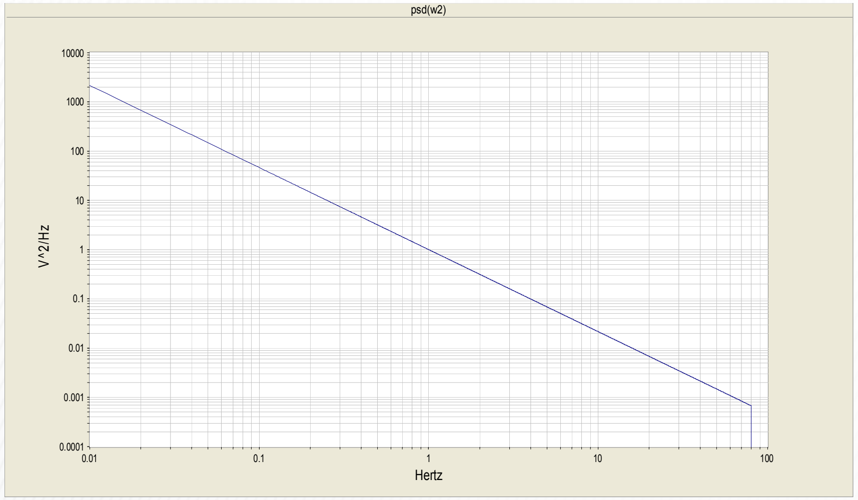
Show dataset in frequency domain (spectrum)

PSD of Synthesized Time Series with -5/3 Power Law

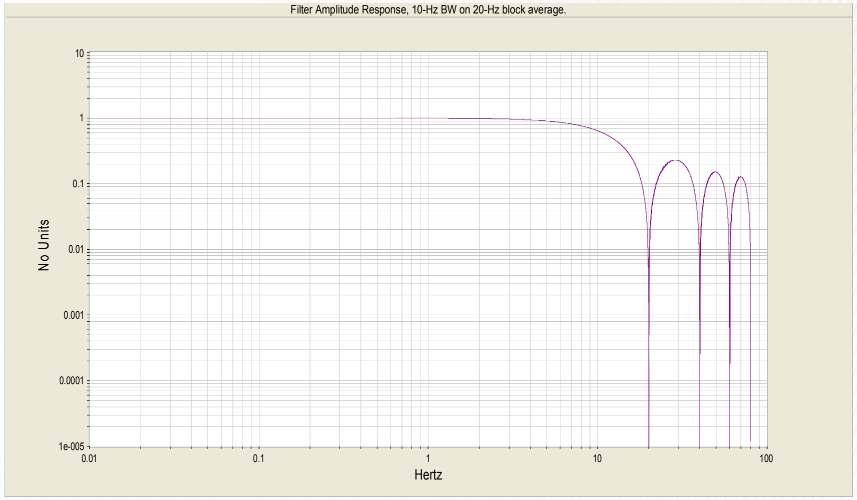


Moving Average and Spectra

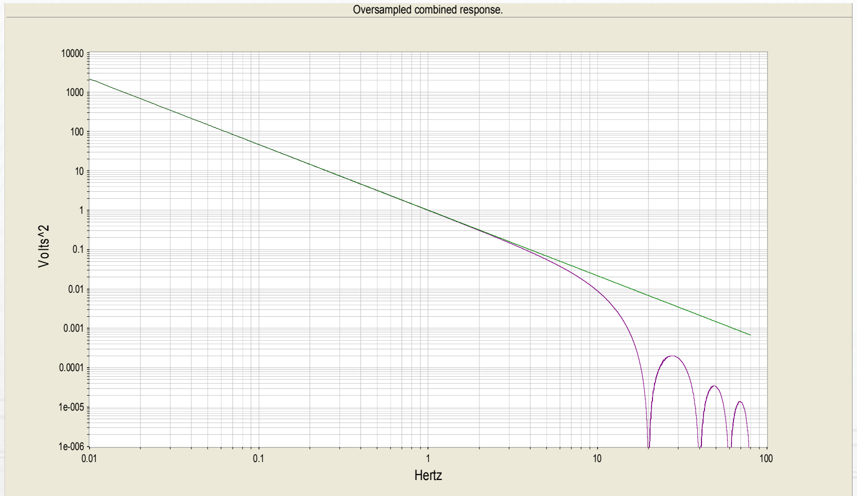
Apply Moving Average Low-Pass Filter



X

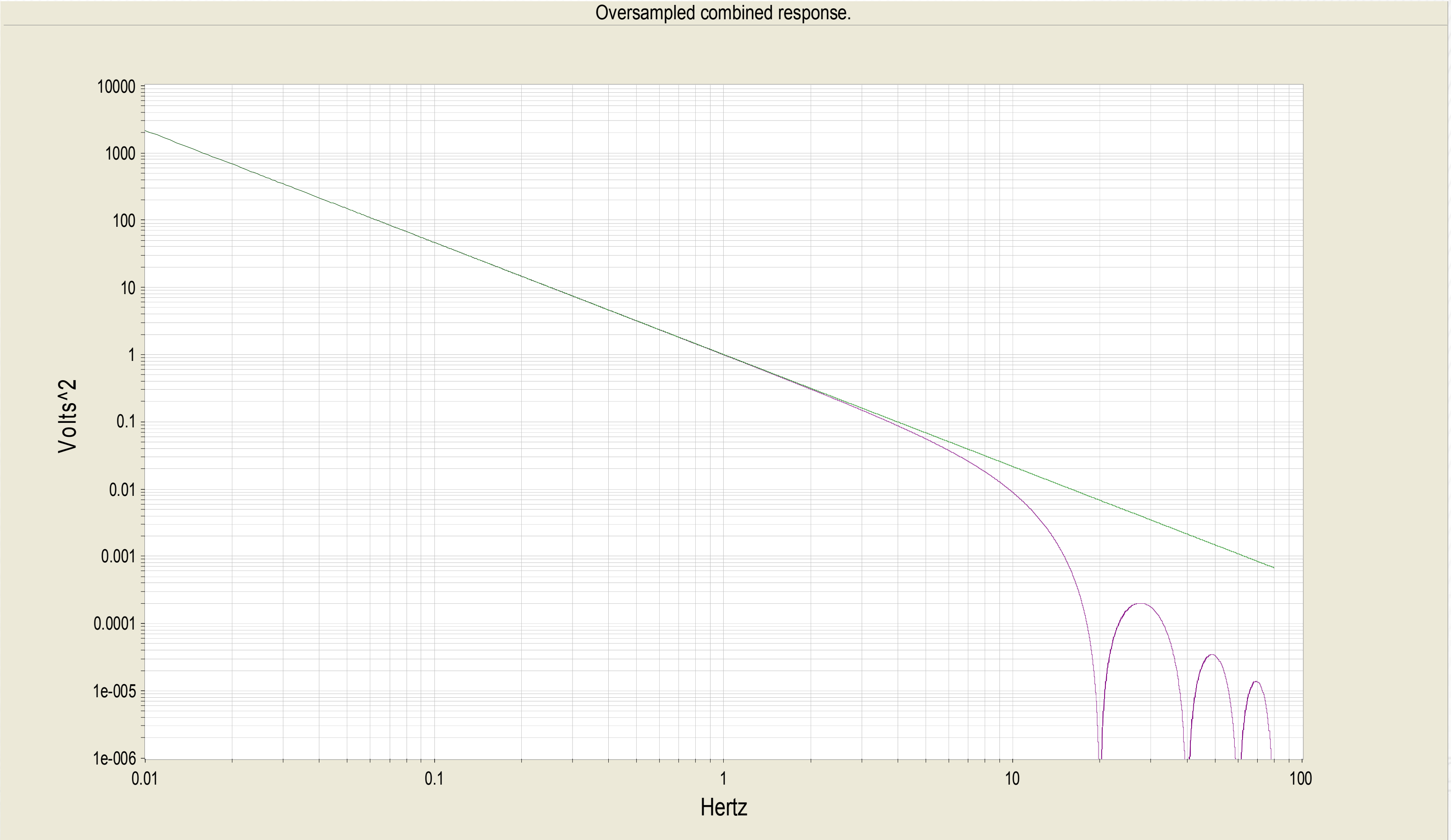


=



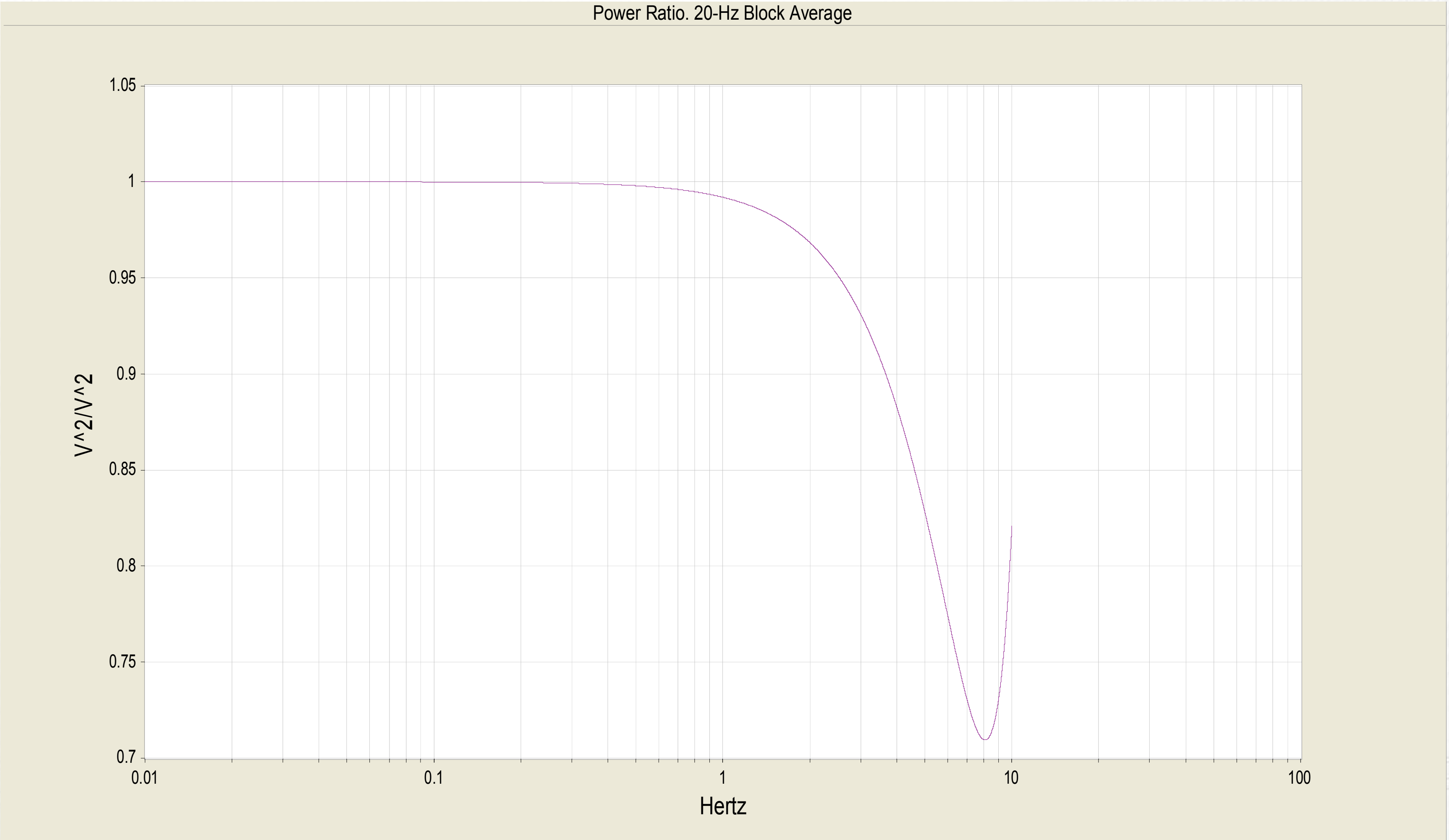
Moving Average and Spectra

Result of 50-msec Moving Average



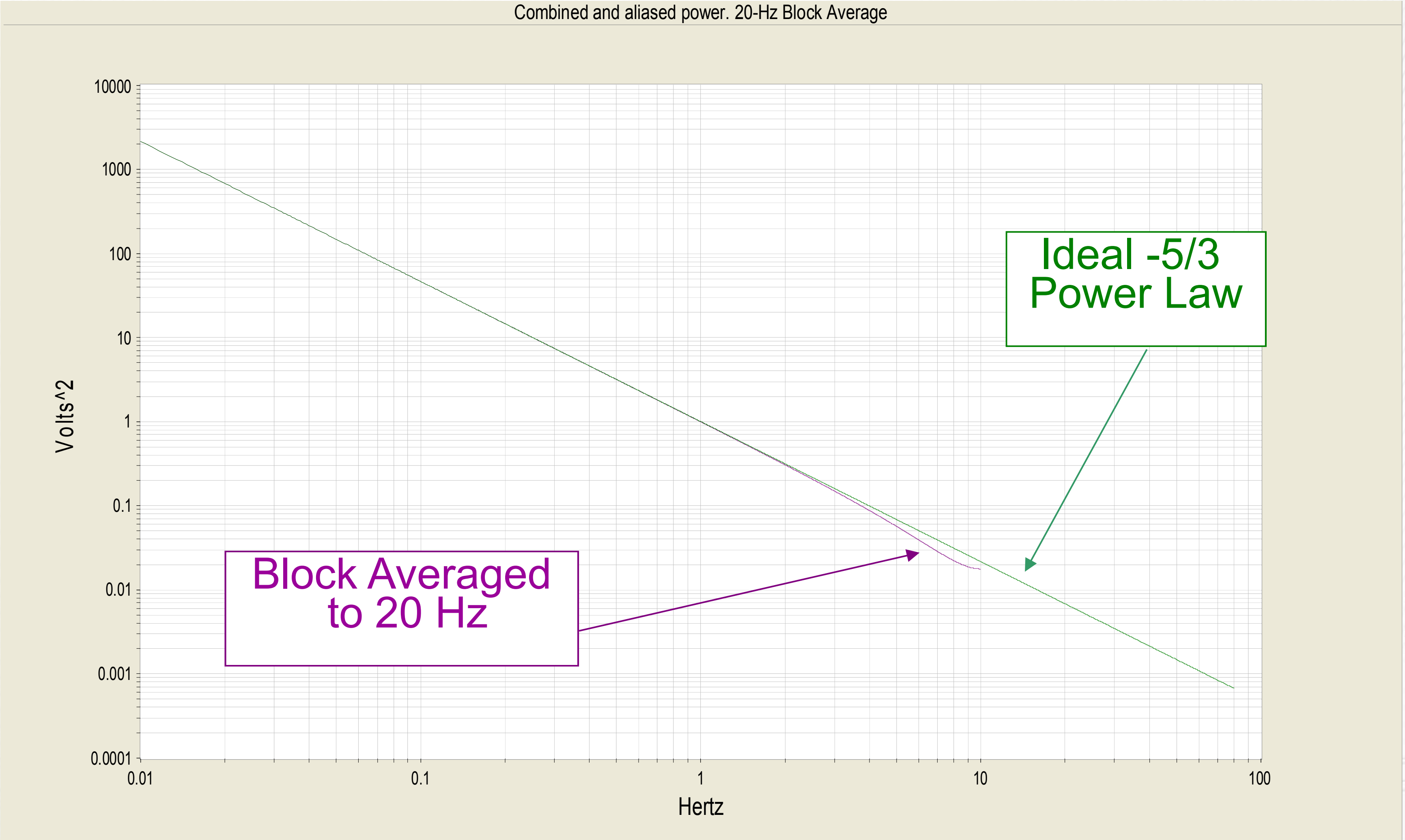
Amplitude Frequency Response of Block Average

Normalized by -5/3 Power Law

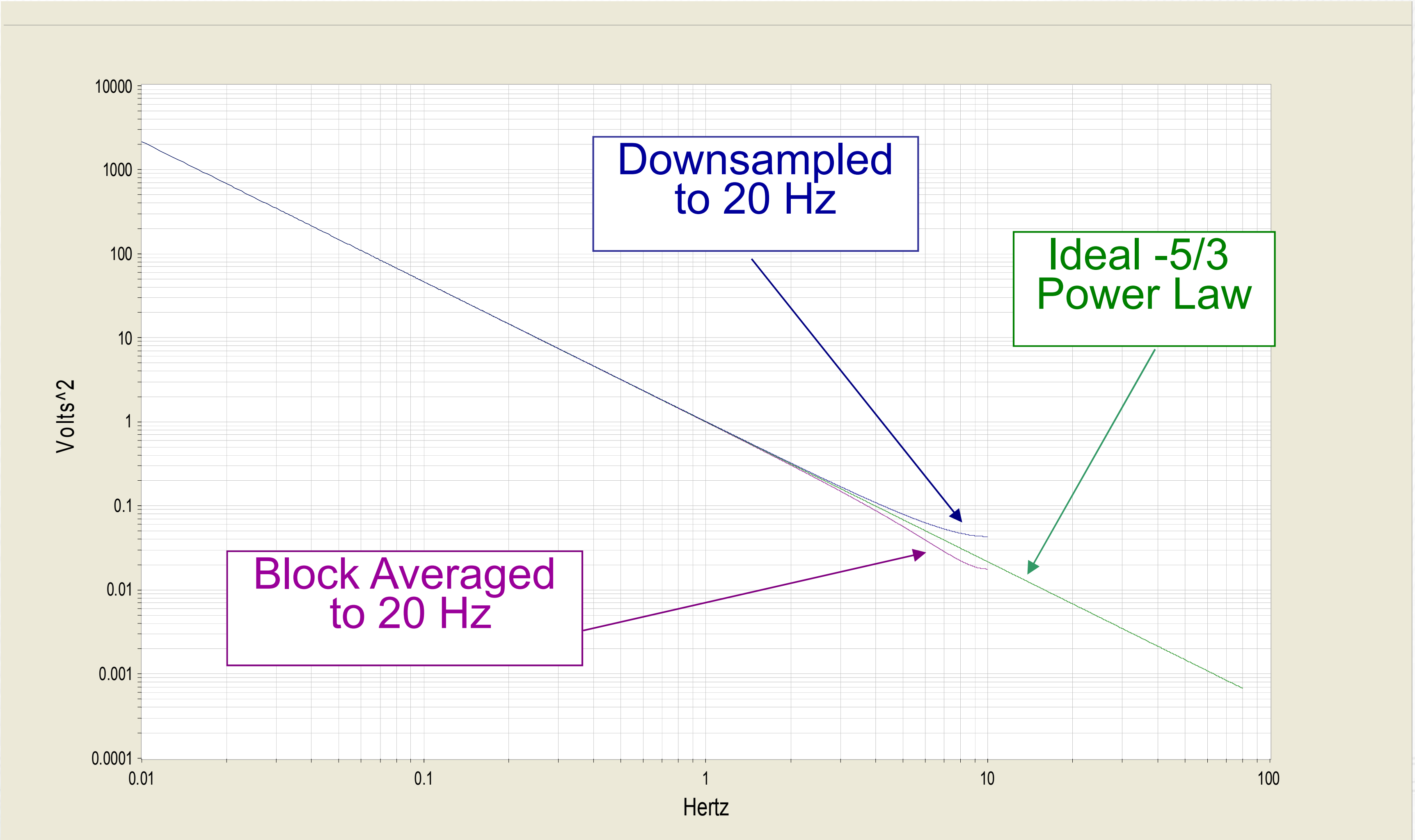


Block Average and Spectra

Next: Down Sample to 20 Hz – Alias above 10 Hz

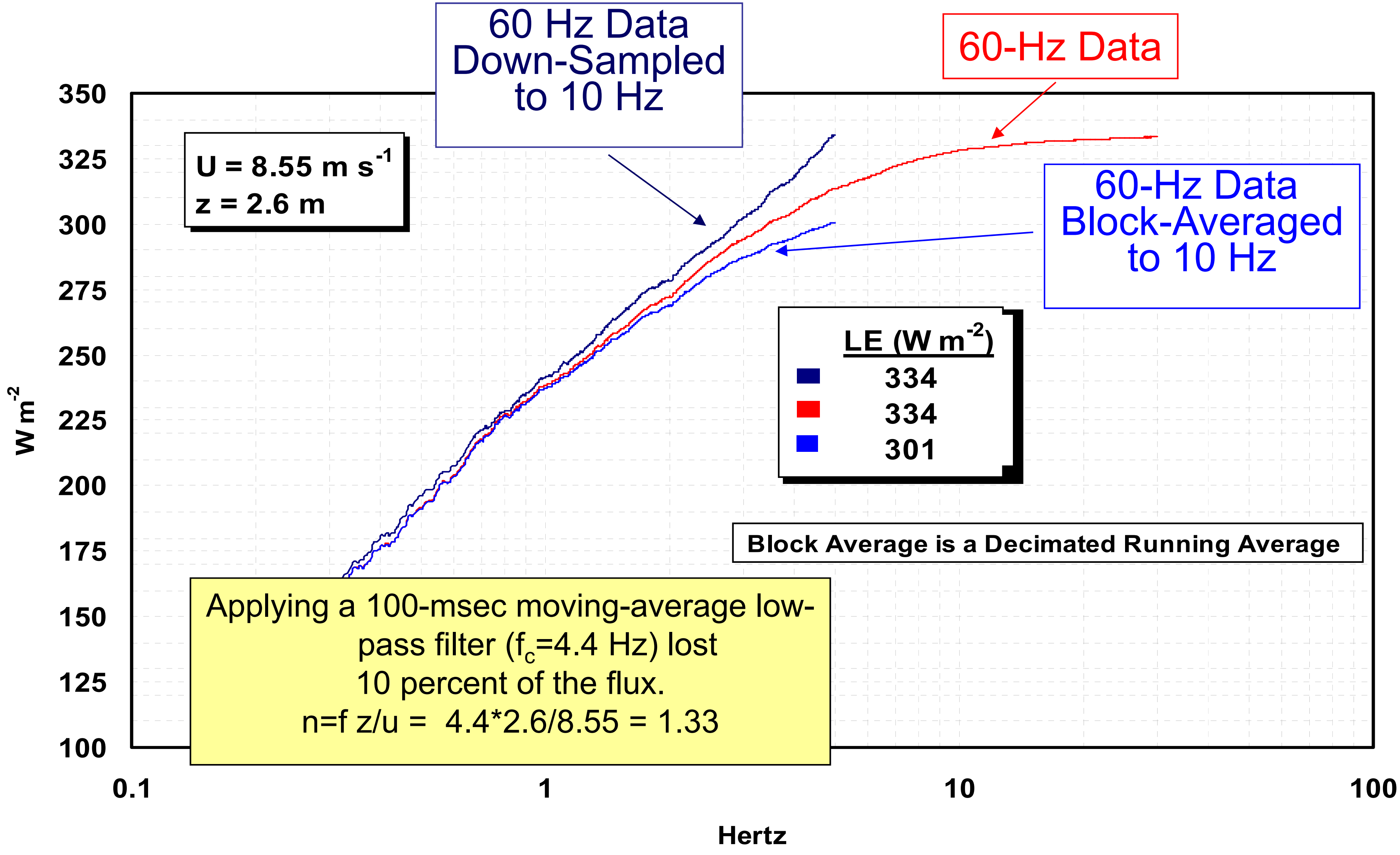


Downsampled Spectrum
Alias above 10 Hz

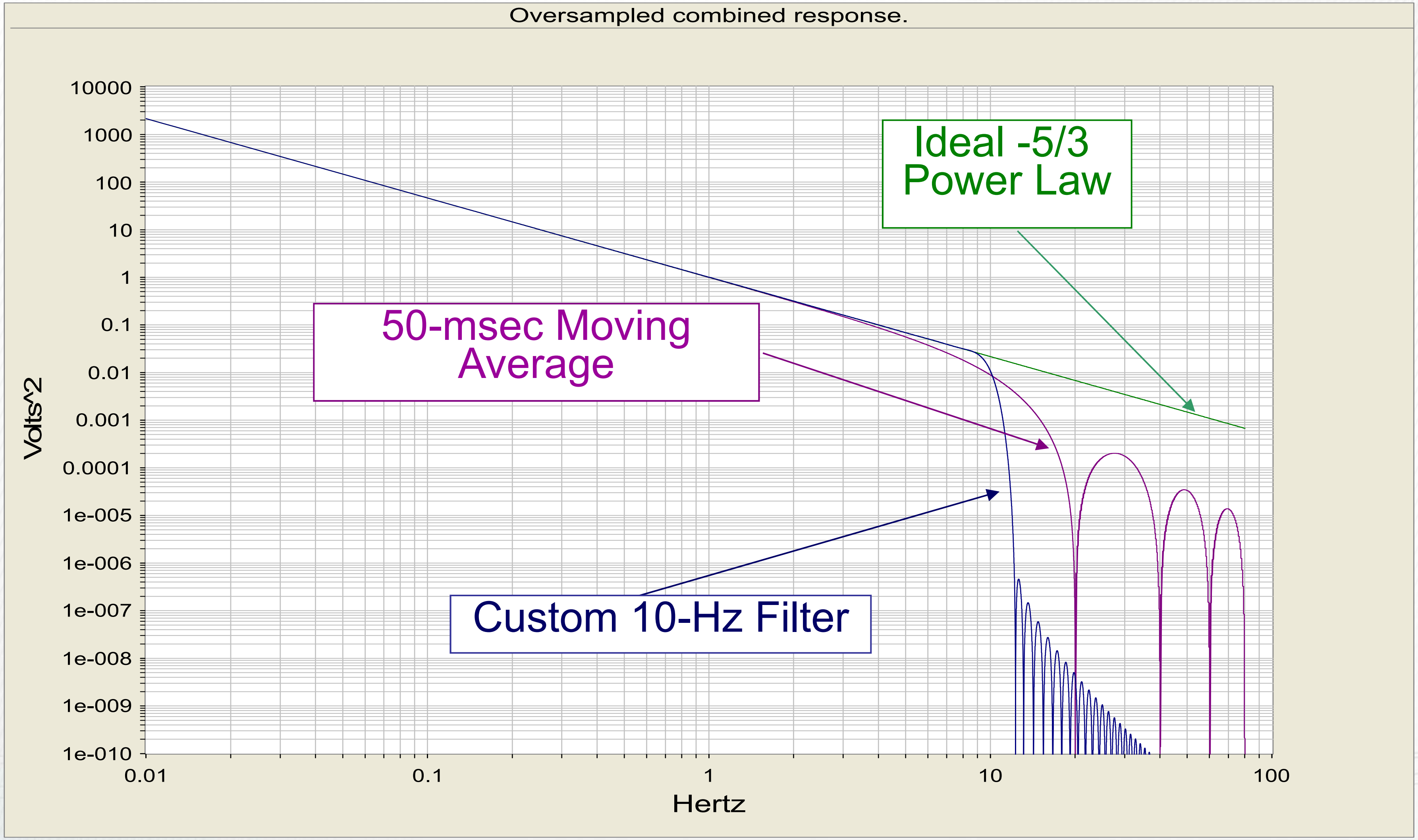


Integrated CoPSDs

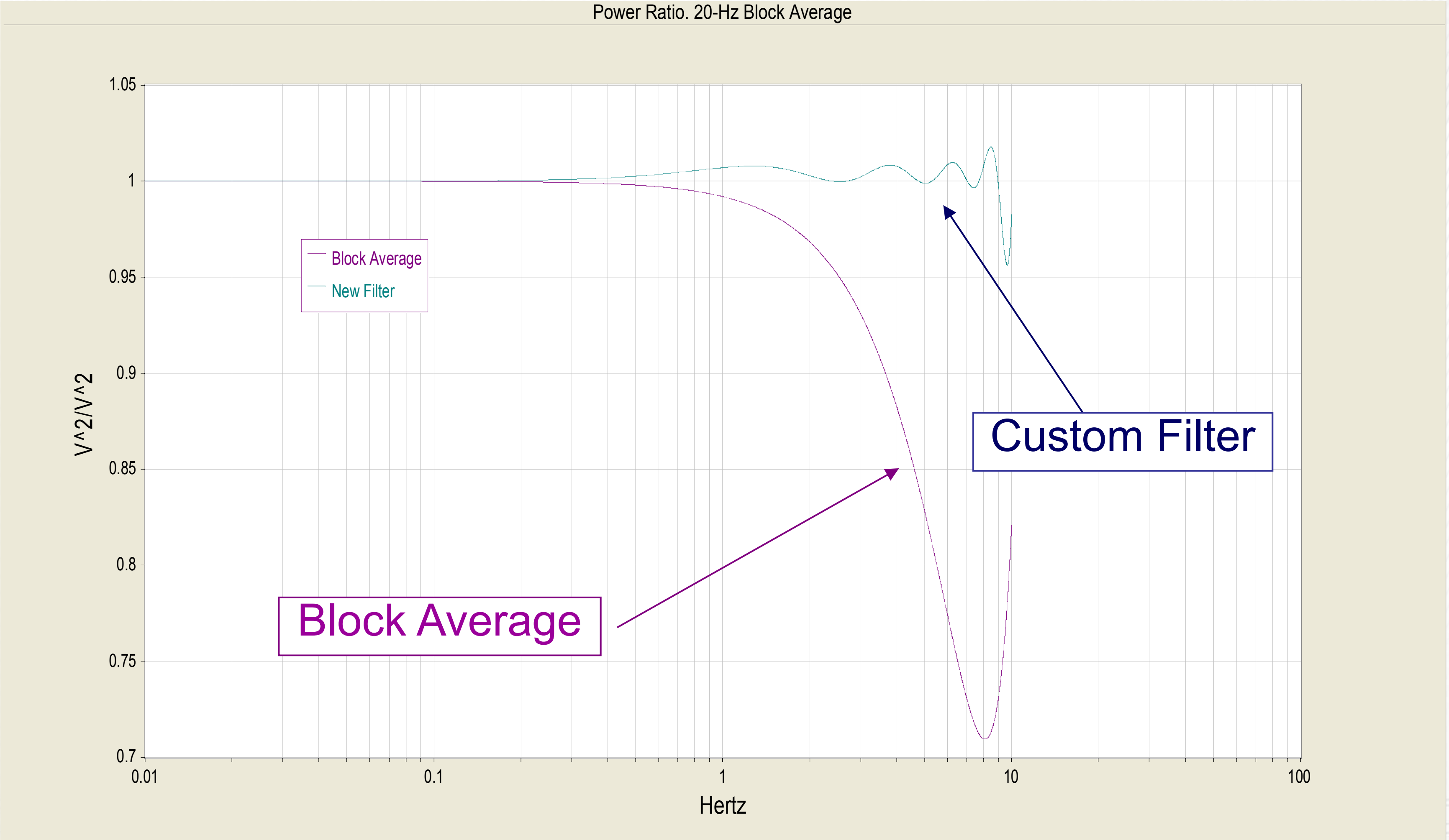
with Different Signal Processing



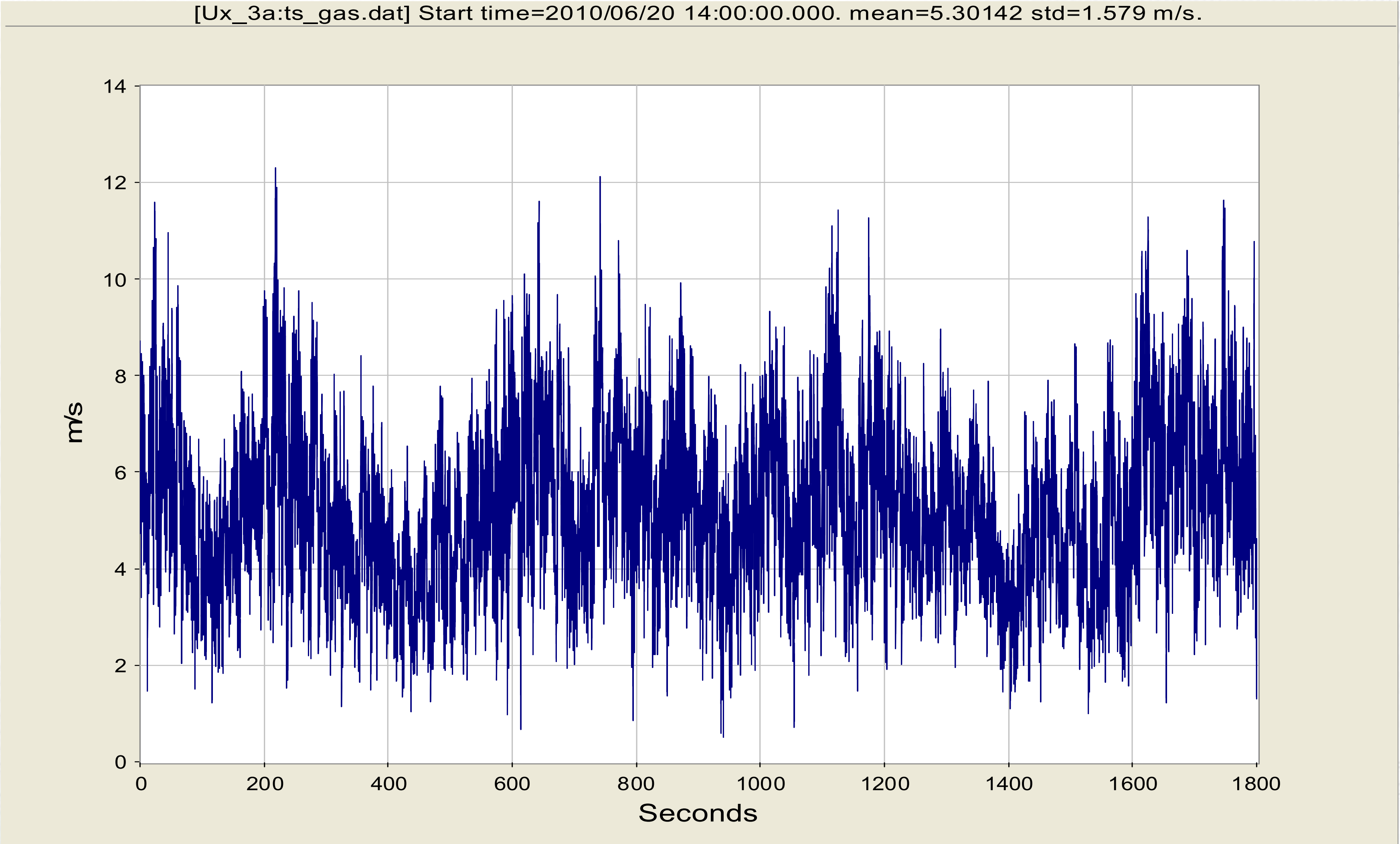
Spectra with Custom Filter



Custom Filter Normalized by -5/3 Power Law



Measured Wind Data

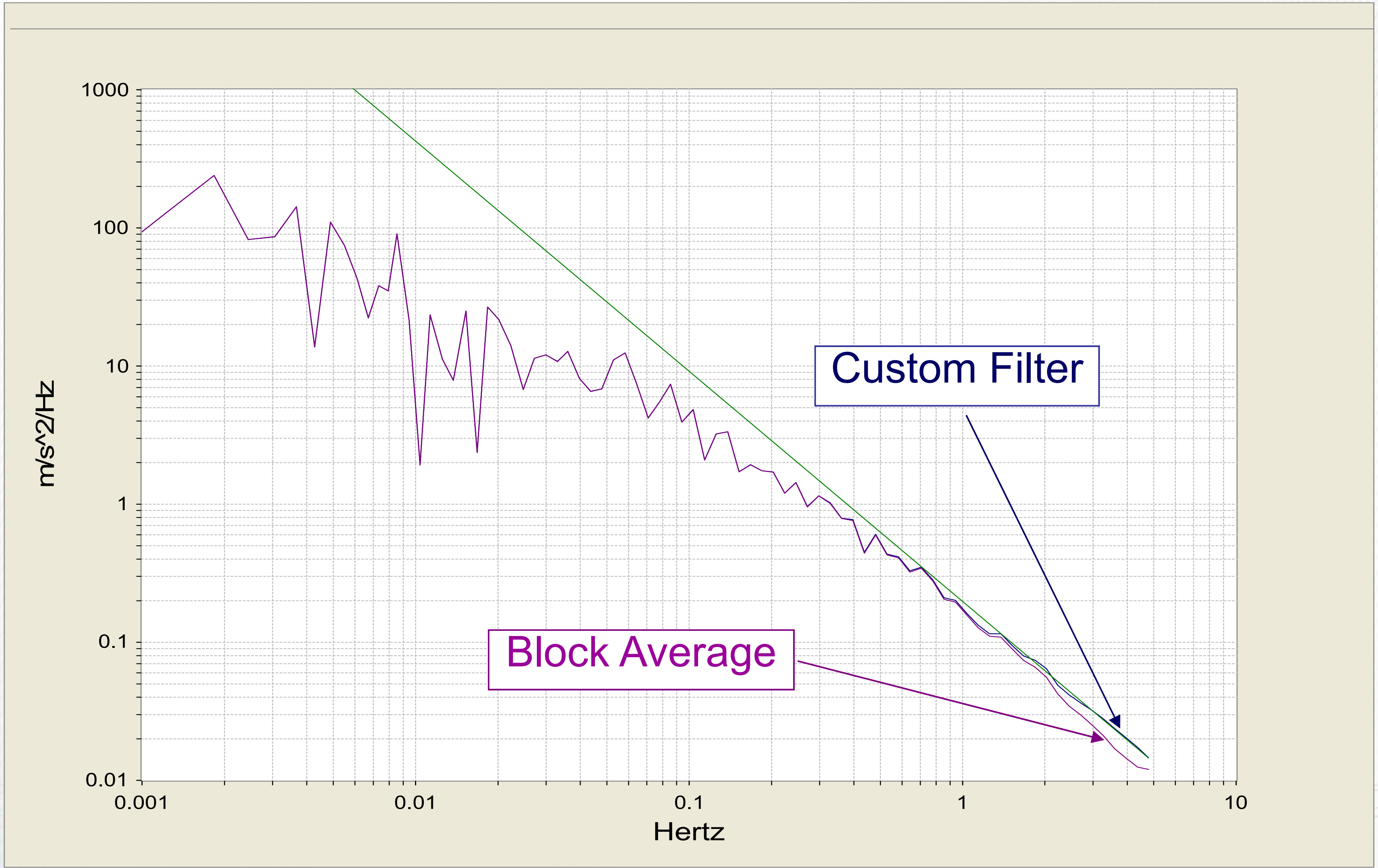


Spectra of Measured Data

Filters Applied

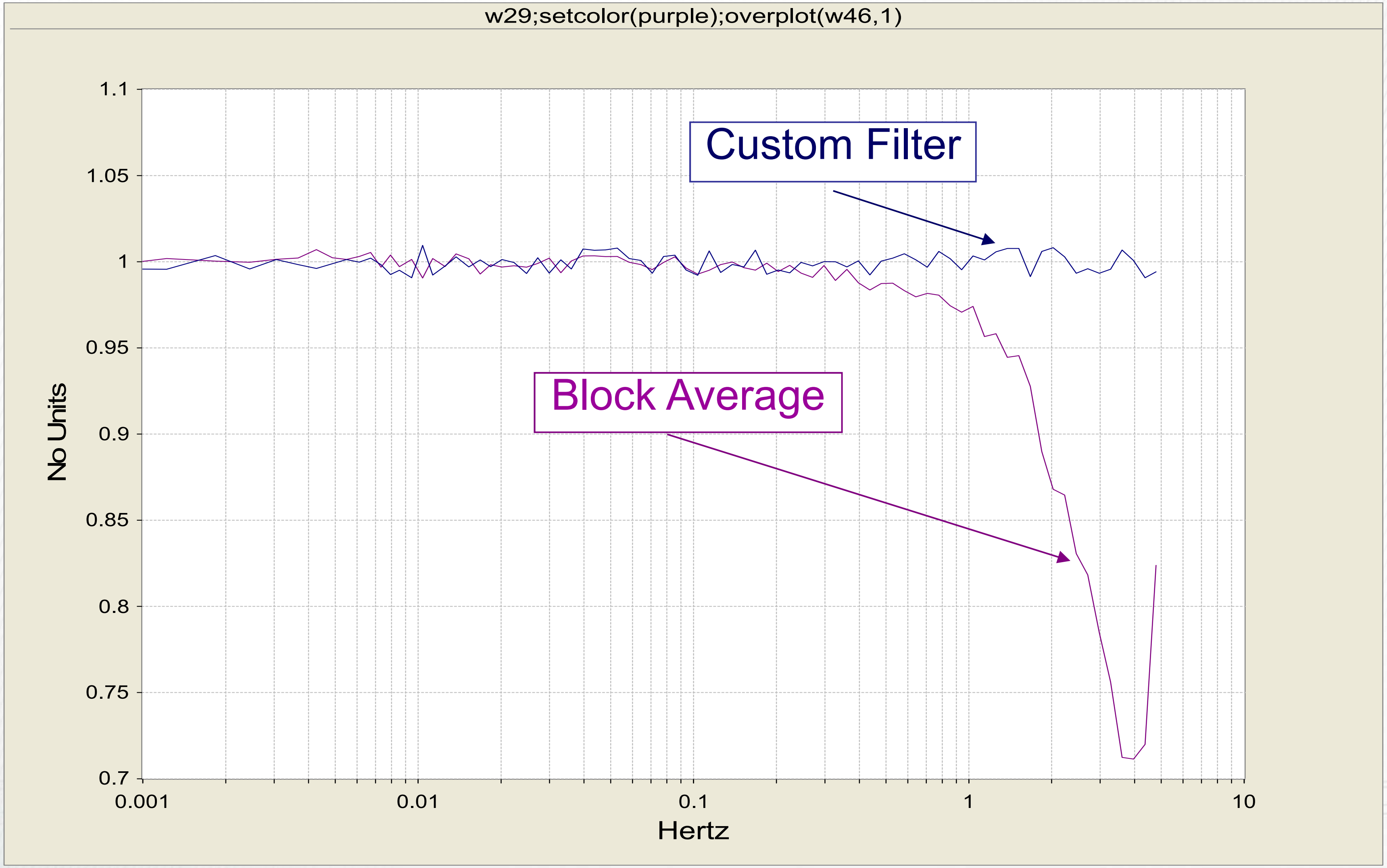
Spectra of Measured Data

Filters Applied and Downsampled



Measured Spectra

Spectra Normalized by -5/3 Power Function

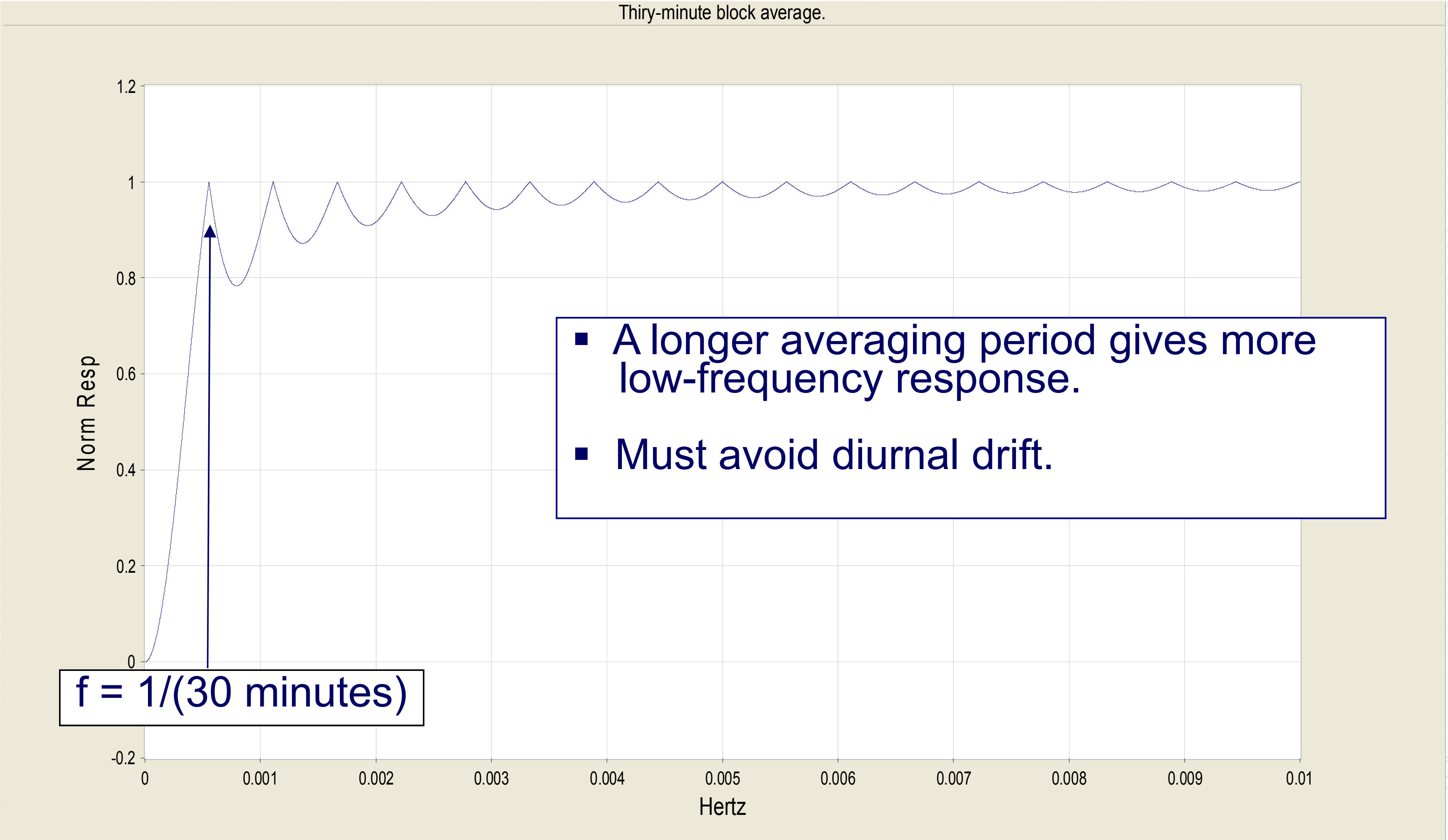


Low Frequency Response

- **Frequency response is also an issue at the low end of the spectrum.**

Low Frequency Response

High-Pass Filter from Thirty-Minute Averaging Period



- A longer averaging period gives more low-frequency response.
- Must avoid diurnal drift.

A: Frequency-Response Limitations:

- Path (and volume) averaging
- Non-instantaneous measurements
- Signal-processing filters
- Other (e.g. thermometer time constants)
- Closed-path gas analyzer unique issues

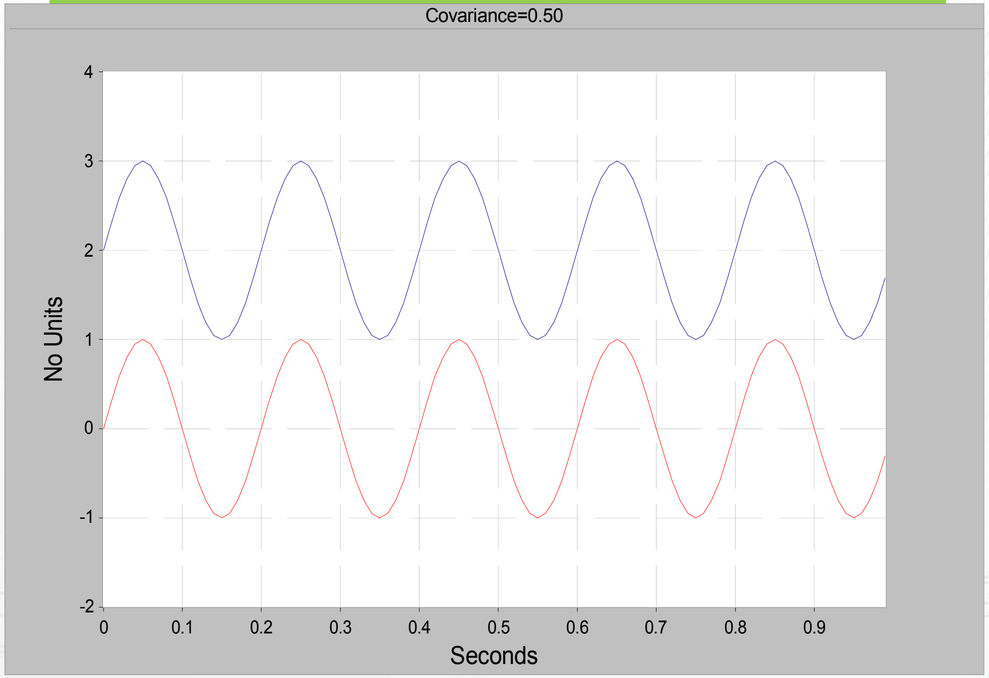
A: Frequency-Response Limitations:

- Path (and volume) averaging
- Non-instantaneous measurements
- Signal-processing filters
- Other (e.g. thermometer time constants)
- Closed-path gas analyzer unique issues

Other General Requirements

- Minimize disturbance (flow distortion, heat loading)
- Rugged
- Low Power
- Fairly Accurate

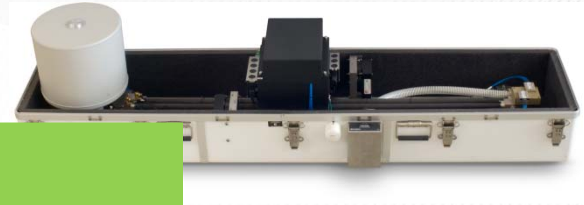
Q: Why is absolute accuracy less important than precision in EC measurements? Or a better question is why are offset errors okay but not gain errors?



$$NEE = \int_0^{h_m} \overline{\rho_d} \frac{\partial \overline{\chi_s}}{\partial t} dz + \left. \overline{\rho_d}\, \overline{w' \chi_s'} \right|_{h_m}$$ = Eddy Covariance: A familiar measurement…

1975 – CR5

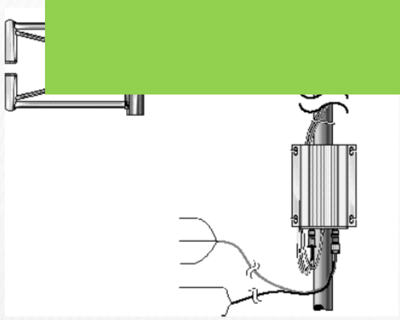
1993 – TGA100



1979 – CA27

Q: Why do you think CSI pursued making a 3-D sonic anemometer for EC measurements rather than sticking with a 1-D sonic anemometer?

1985 – KH20



1999 – LI7500

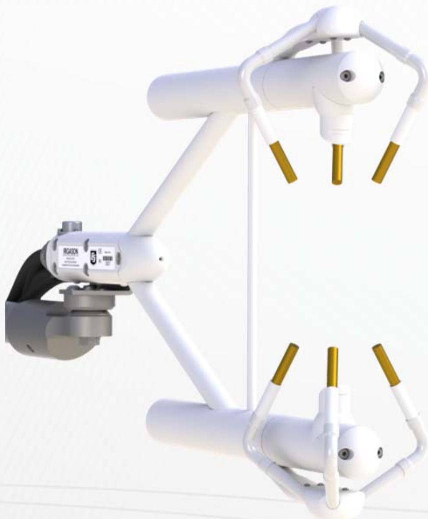
$$NEE = \int_0^{h_m} \overline{\rho_d} \frac{\partial \overline{\chi_s}}{\partial t} dz + \overline{\rho_d}\, \overline{w' \chi_s'} \Big|_{h_m}$$

= Eddy Covariance! A familiar measurement…

2010 – EC150

2010 – CPEC200

2012 – IRGASON



$$NEE = \int_0^{h_m} \overline{\rho_d} \frac{\partial \overline{\chi_s}}{\partial t} dz \quad + \quad \overline{\rho_d}\,\overline{w'\chi_s'}\Big|_{h_m}$$

Storage Term

1990's – TGA Sampling Systems

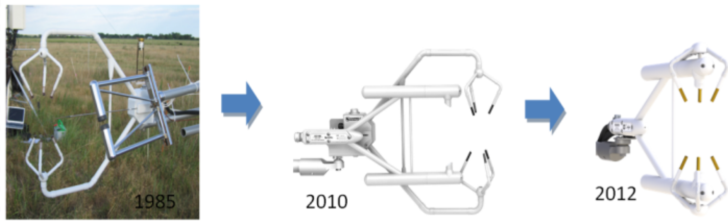
1999 – Special Profile Systems

2012 - AP200

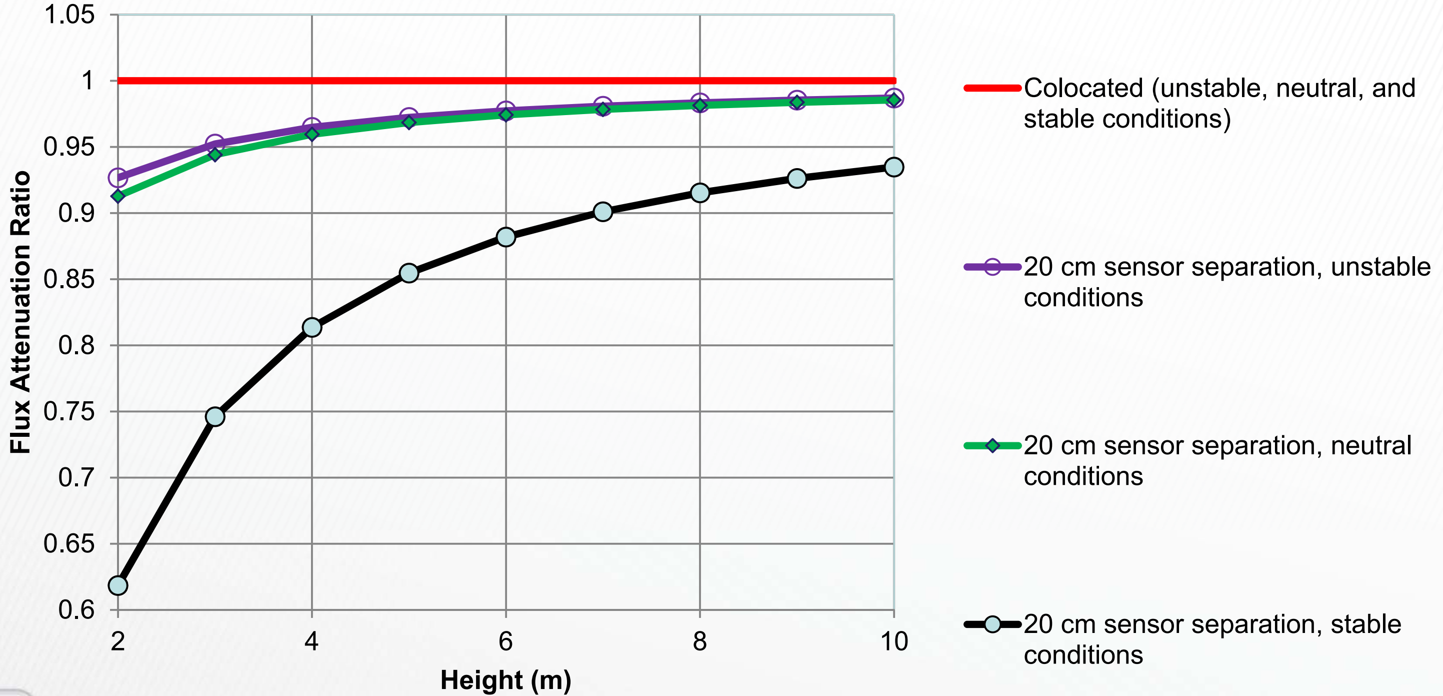
Performance Advantages

Colocation

Evolution of Campbell Colocated Design.



Flux Attenuation Ratio for Colocated and 20cm-separated Sensors for Various Stabilities Conditions



Single Electronics for both gas and wind measurements

Example EC System:

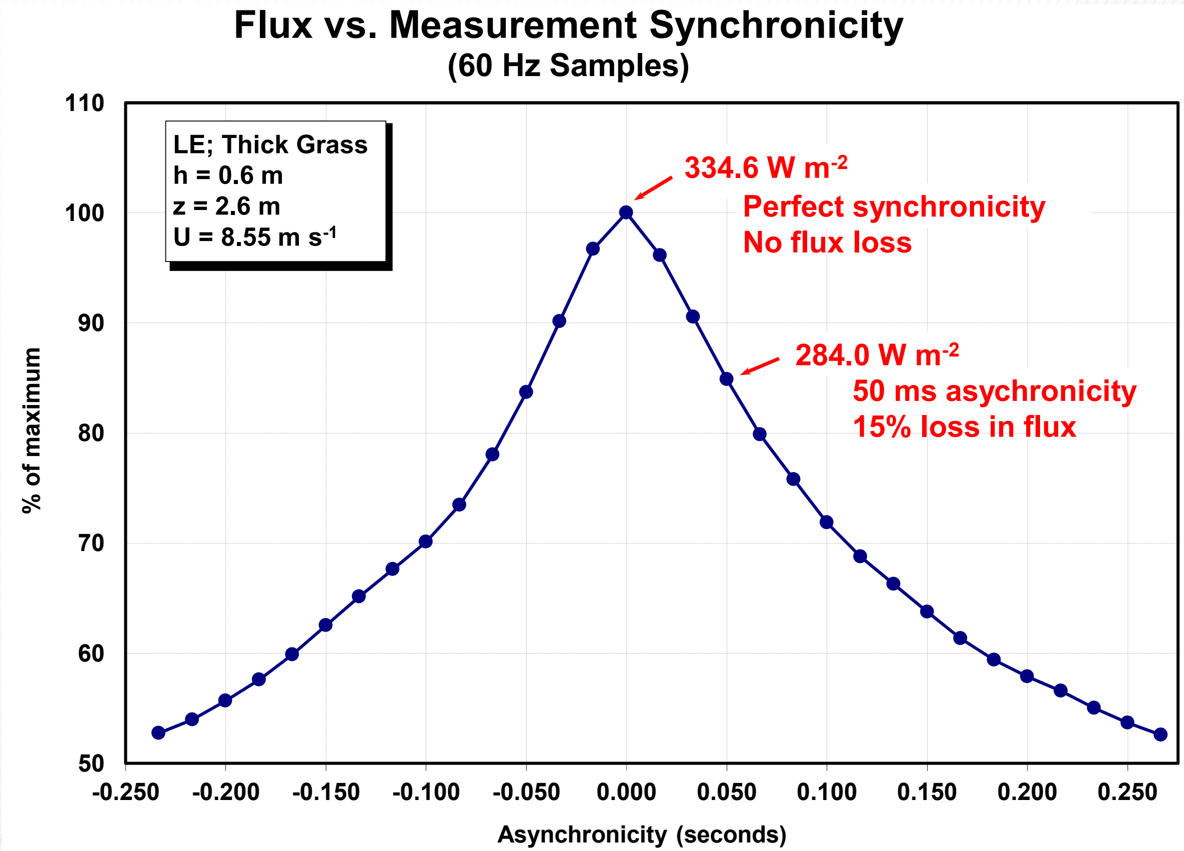
- Sample rate: 10 Hz
- Sample interval: Δt_s = 100 ms
- CSAT3 measurement delay: $2\Delta t_s$ = 200 ms
- LI7500 measurement delay: programmable

  186 + n(6.5) = 296.5 ms, n = 17

EC System with EC100 Electronics:

- **Fully integrated electronics for sonic anemometer and gas analyzer.**
- **Synchronized to better than 1 msec, essentially *simultaneous*.**
- **Fixed number of scans to synchronize other analog measurements.**
- **The same custom filtering on both gas and wind**

Single electronics allows *simultaneous*, synchronized measurements

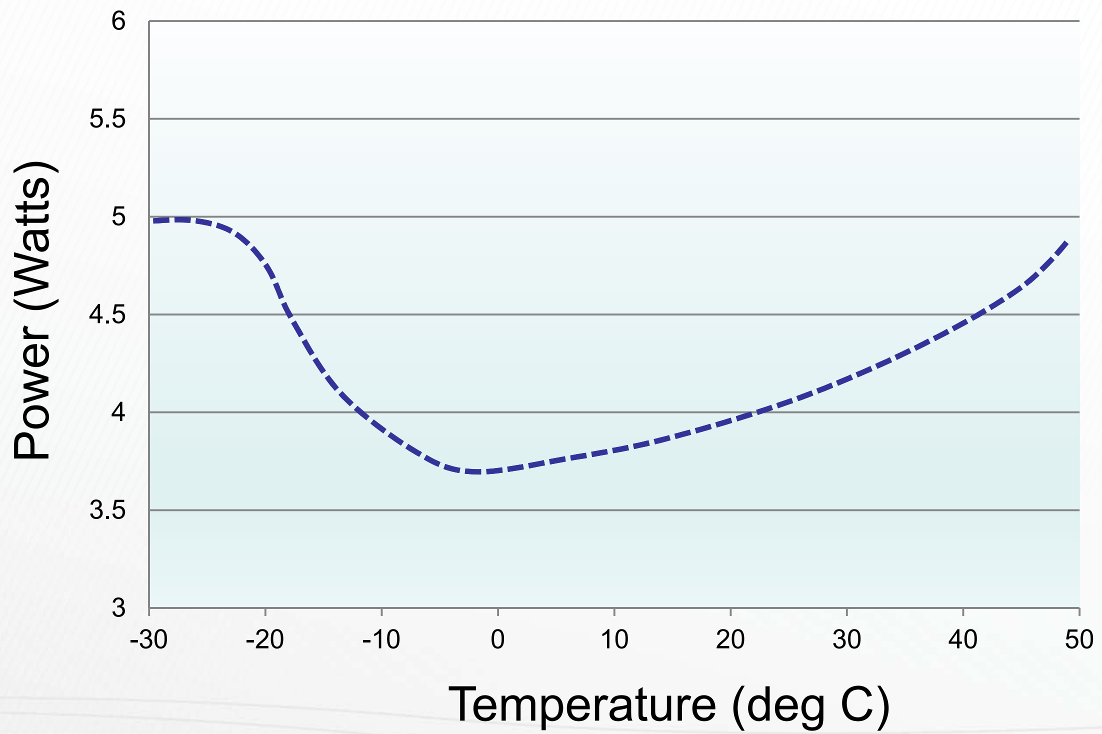


Low Power

<6W for EC150/CSAT3A or IRGASON (less than half of older open path systems)

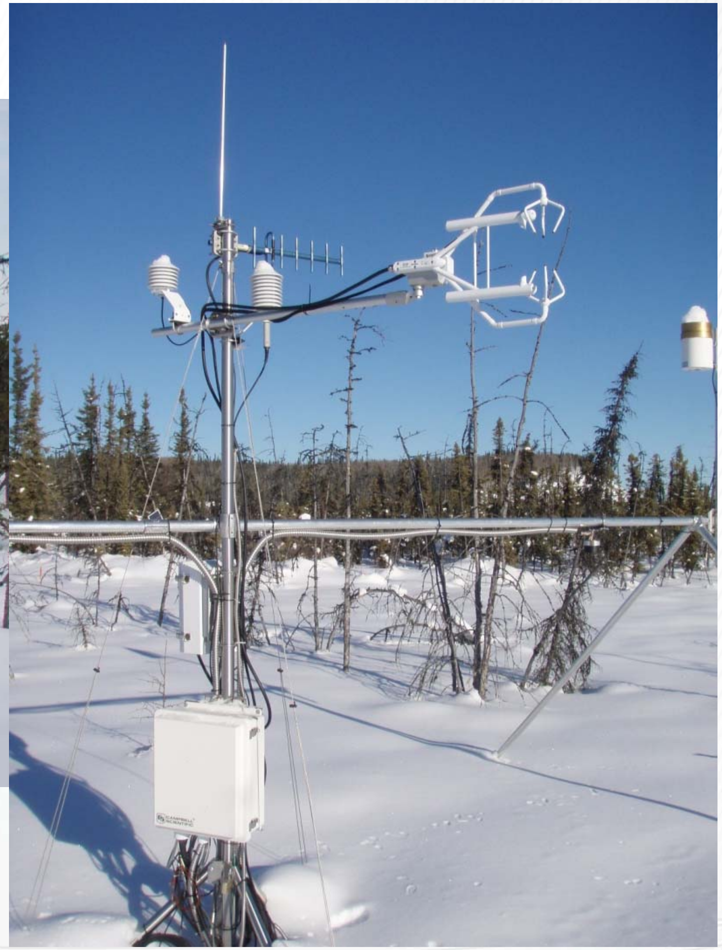
12W for CPEC200

13W for AP200



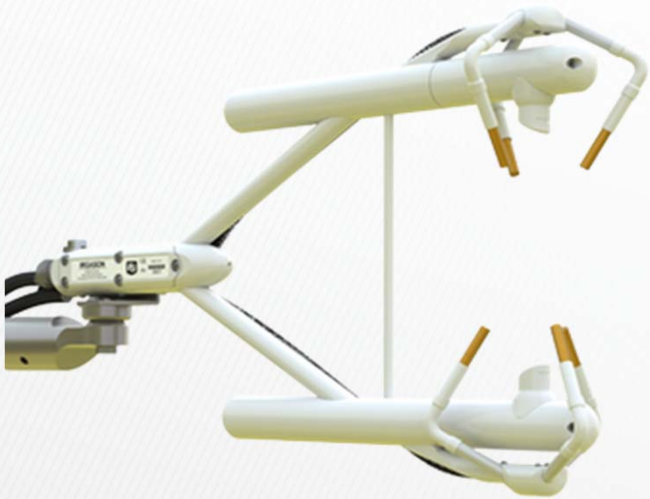
Low Power

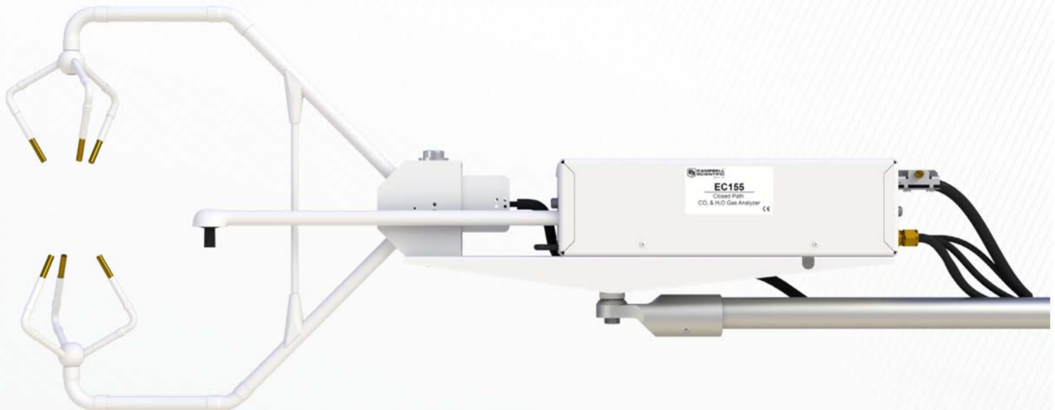

C. Edgar, University of Alaska Fairbanks



Aerodynamic

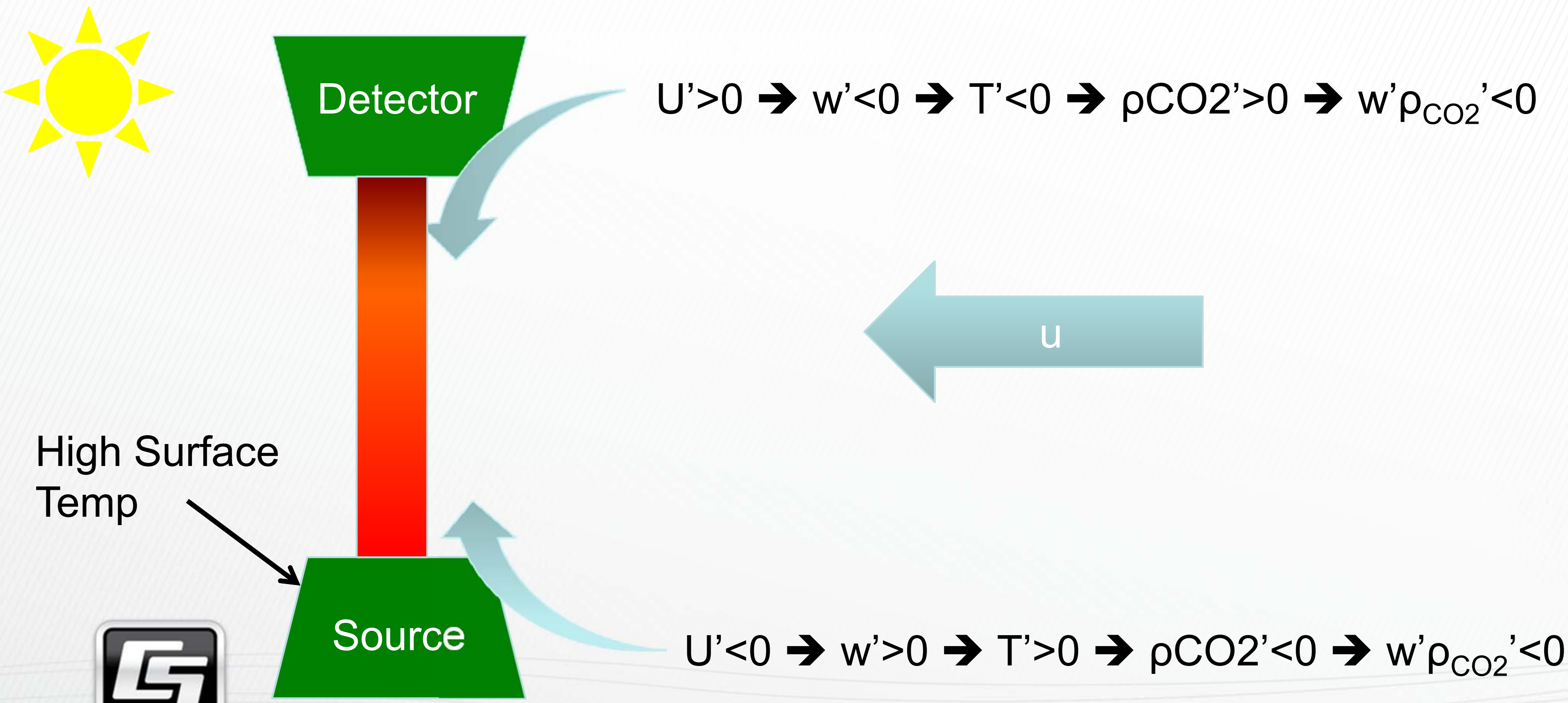
- No support struts in measurement volume
- Path length to housing diameter ratio high
- Vertical symmetry
- Snouts extend optical path beyond BL of housing





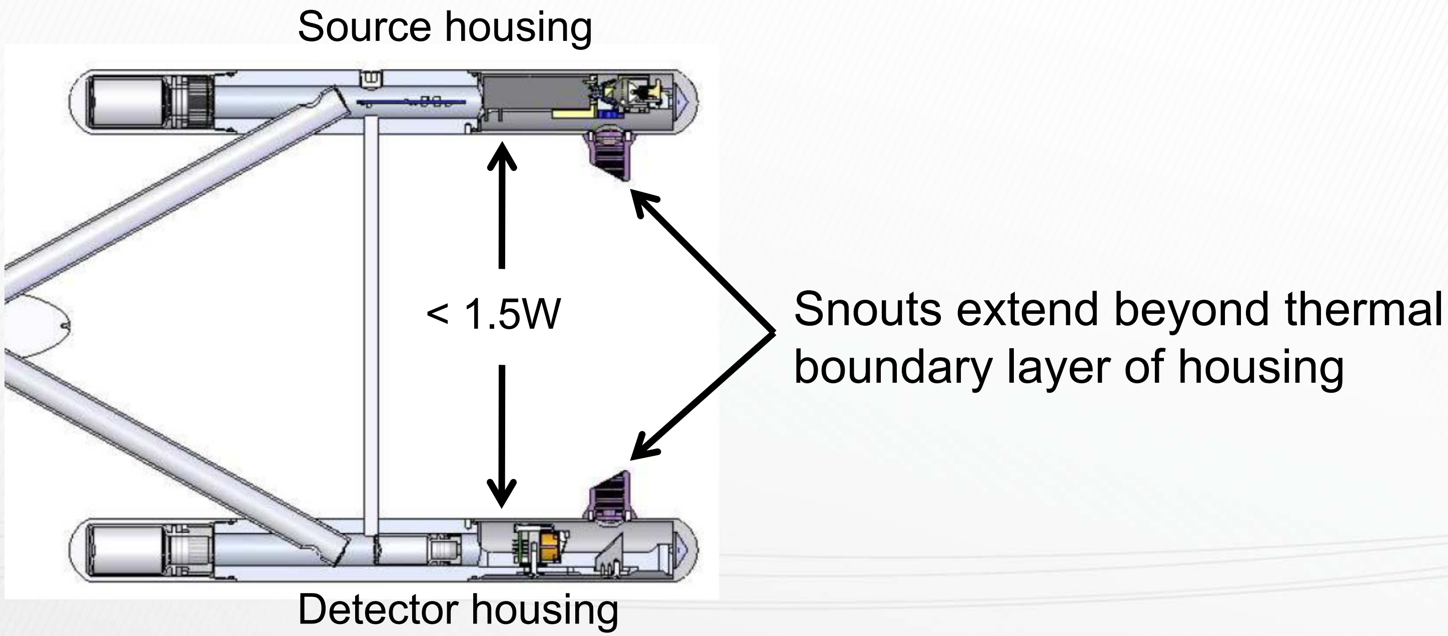
Body-Heating Effects

- CO2 uptake was observed to be several hundred percent too high by open-path EC systems during winter (0.1 mg/m2/s)
- At mild temperatures, Hs was 14% higher than ambient, and was worse in cold temperatures.
- WPL corrections using Hs from a spatially separated anemometer led to 33% overestimation of CO2 uptake. Source: Burba et al., 2008.

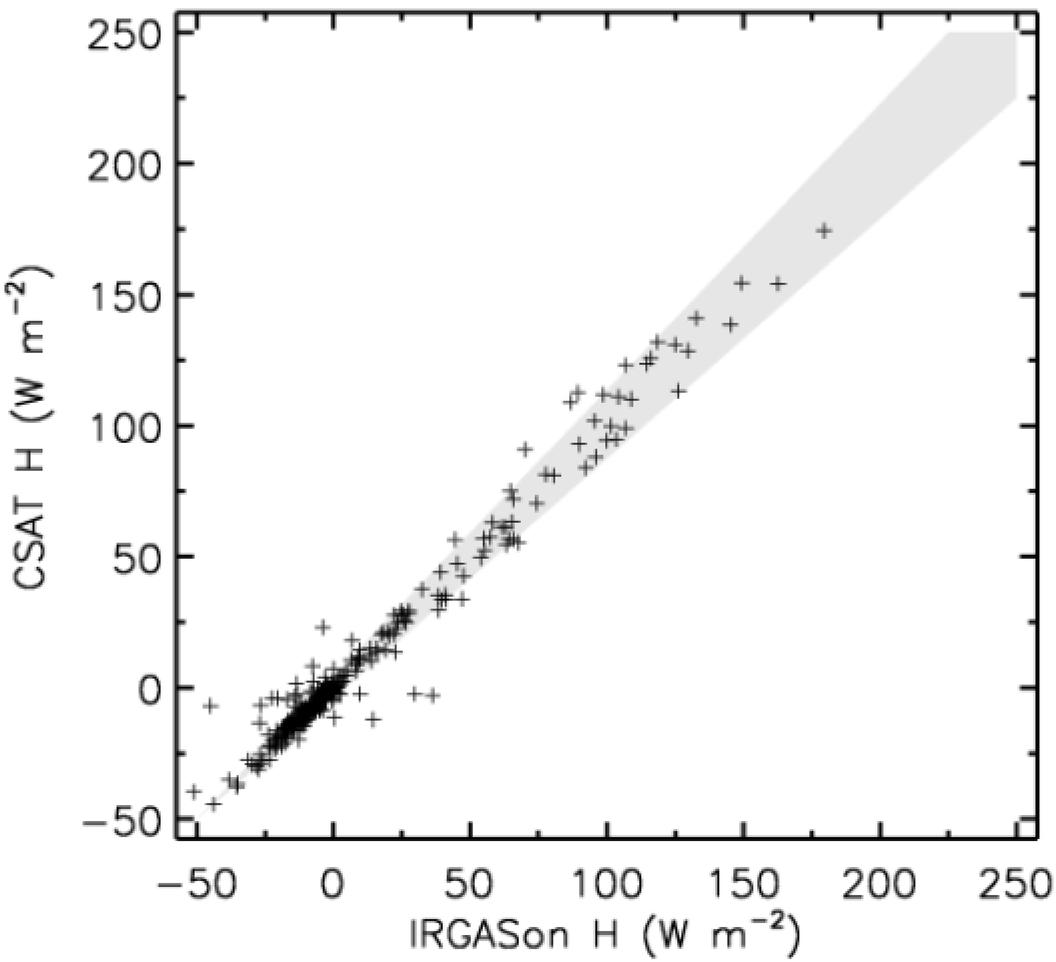


Body Heating Effects

- Design Solutions:
  - Reduce heat from electronics
  - Place motor and detector behind sample volume
  - Place motor on top arm
  - Snouts extend beyond thermal boundary layer of housing
  - Aerodynamic design with no spars/struts (ratio of optical path to housing diameter increased)
  - Hs from a colocated instrument correctly applies WPL.

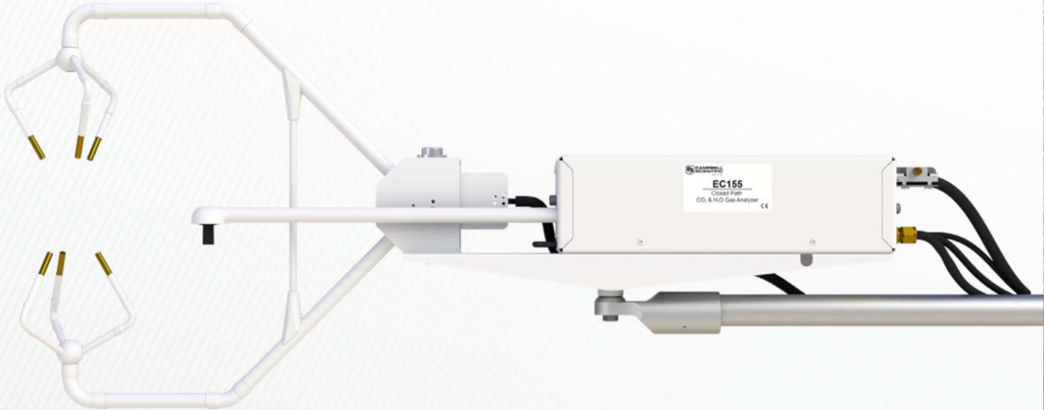


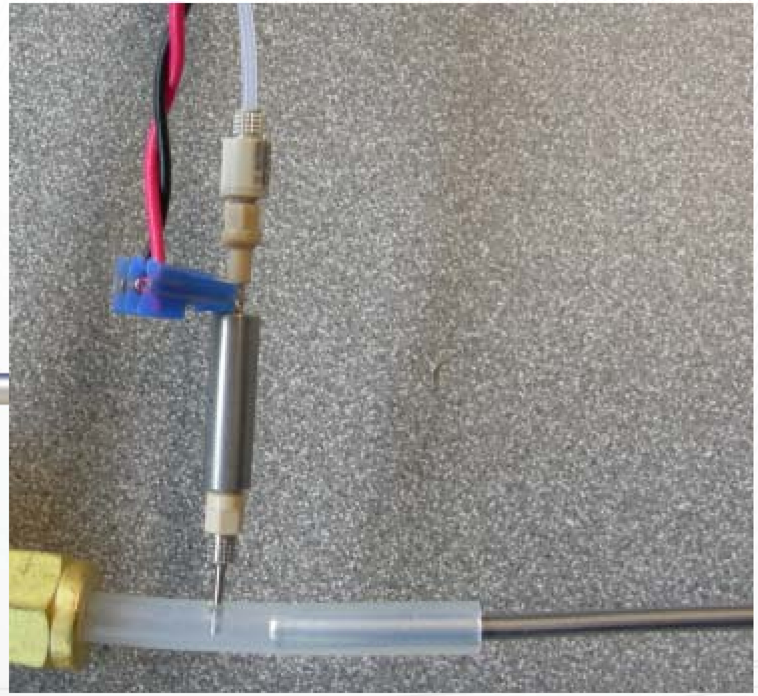
Sensible Heat Flux Comparison



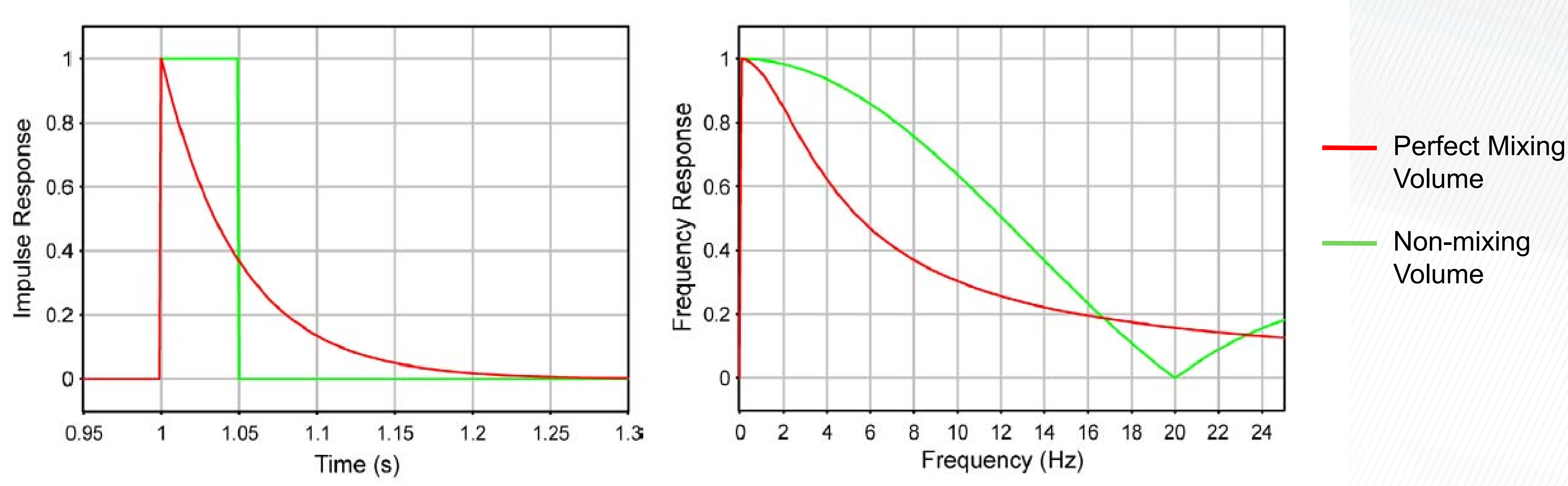
Closed-Path Frequency Response

- Closed-Path requires some separation, but frequency response can be improved by design of tubing, sample cell, and flow rate

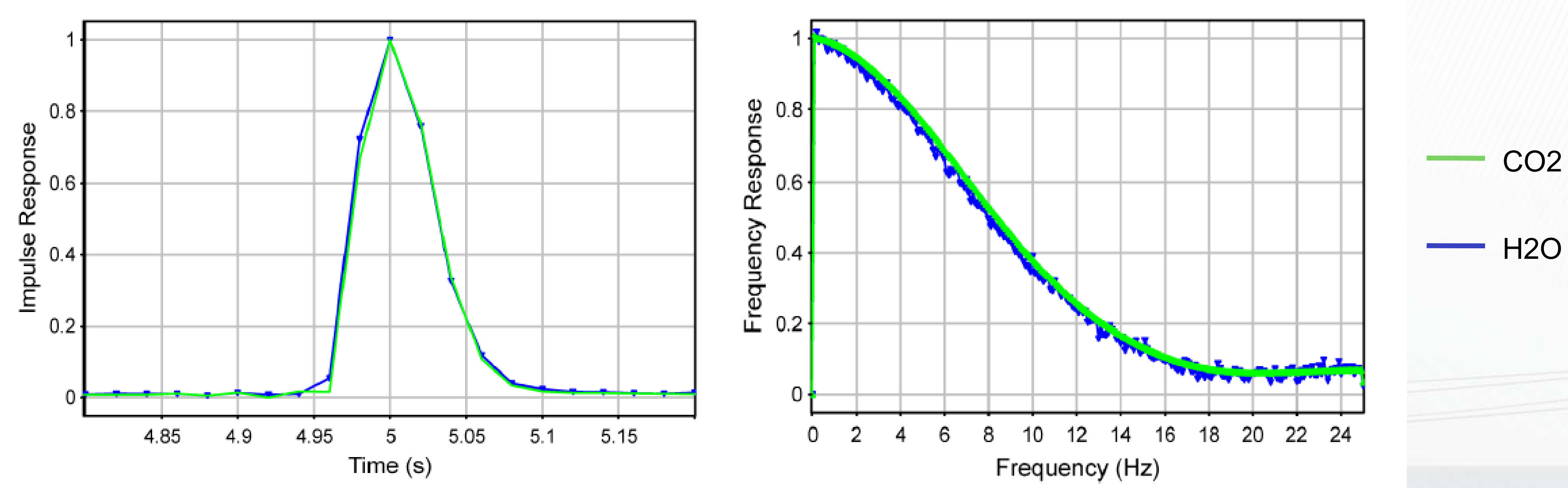




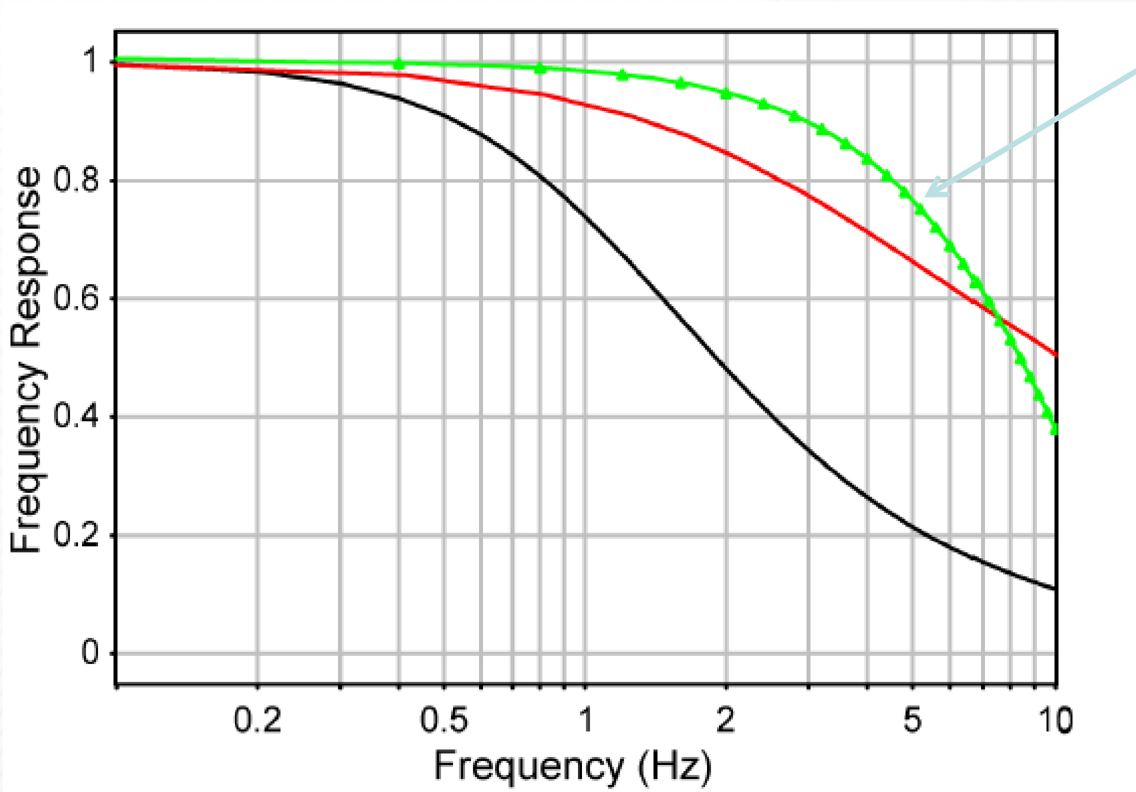
Pulse responses for mixing and non-mixing volumes. V=5.9 mL, F=7 LPM



Pulse response for the CPEC200



Closed-path Frequency Response



5.8 Hz half-power bandwidth

EC155

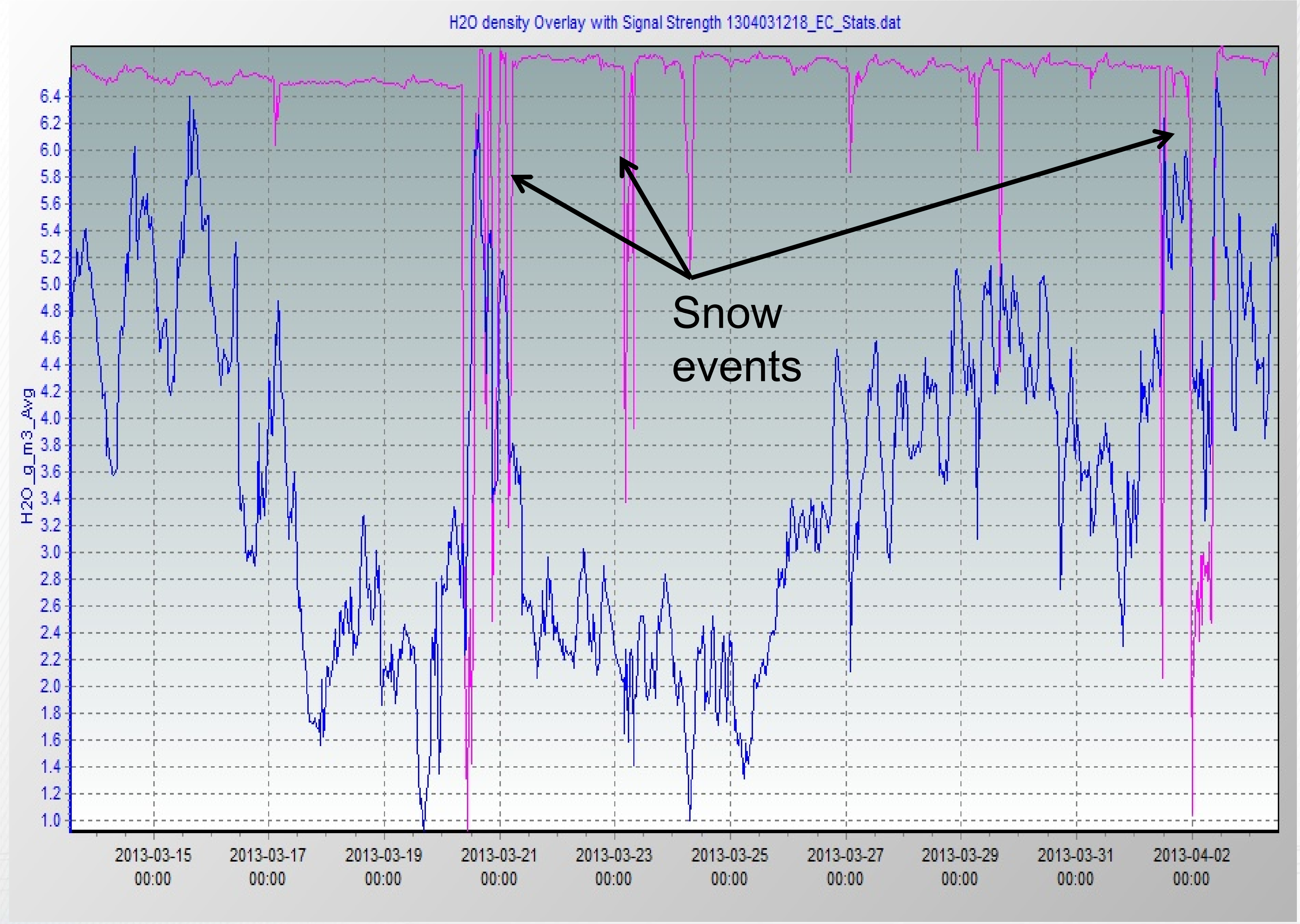
Open-Path at u=1 m/s

Traditional closed-path at 15 LPM (Fratini et al., 2012)

- Note under higher wind conditions, the open-path frequency response will be better than a closed-path.
- Closed-path frequency response does not change with wind speed.
- The open-path frequency response in this model is limited by path averaging.

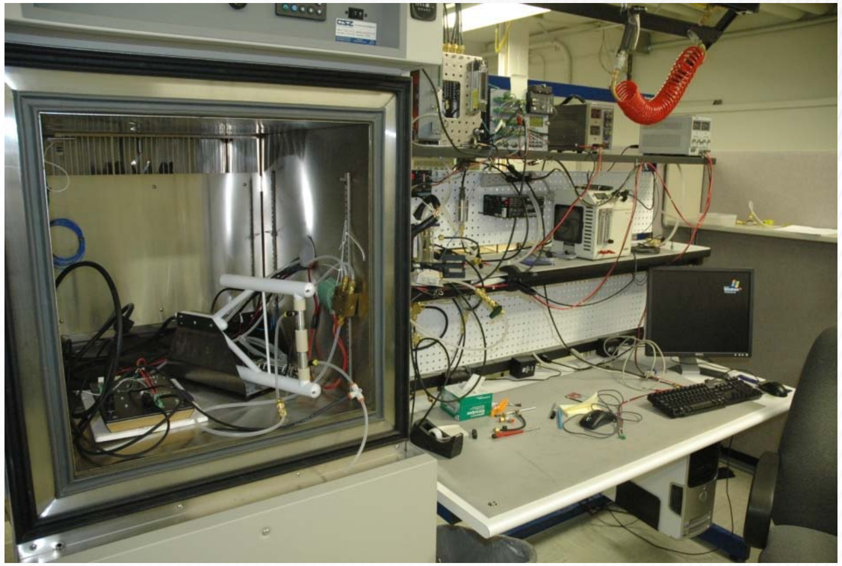
Precipitation

- Open-path analyzers do not perform as well in precipitation. Design solutions:
  - Slanted windows
  - Hydrophobic coating
  - Wicks
  - Auto window heating
  - Calibration for partially blocked signal (e.g., snow)



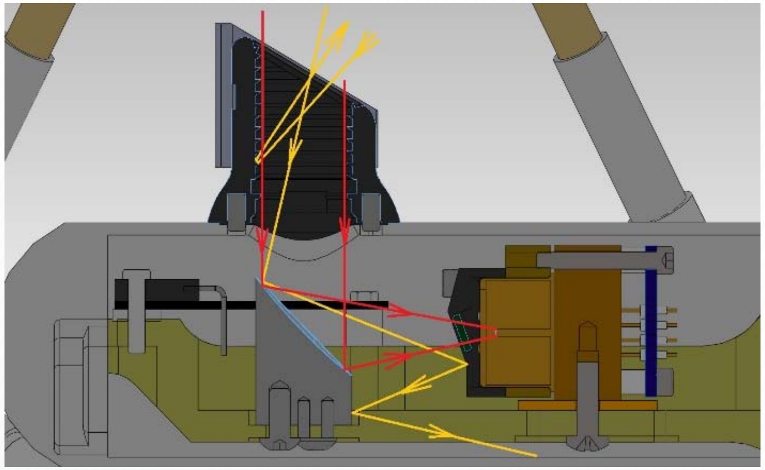
H2O density Overlay with Signal Strength 1304031218_EC_Stats.dat
H2O_g_m3_Avg
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
2013-03-15 00:00
2013-03-17 00:00
2013-03-19 00:00
2013-03-21 00:00
2013-03-23 00:00
2013-03-25 00:00
2013-03-27 00:00
2013-03-29 00:00
2013-03-31 00:00
2013-04-02 00:00
Snow events

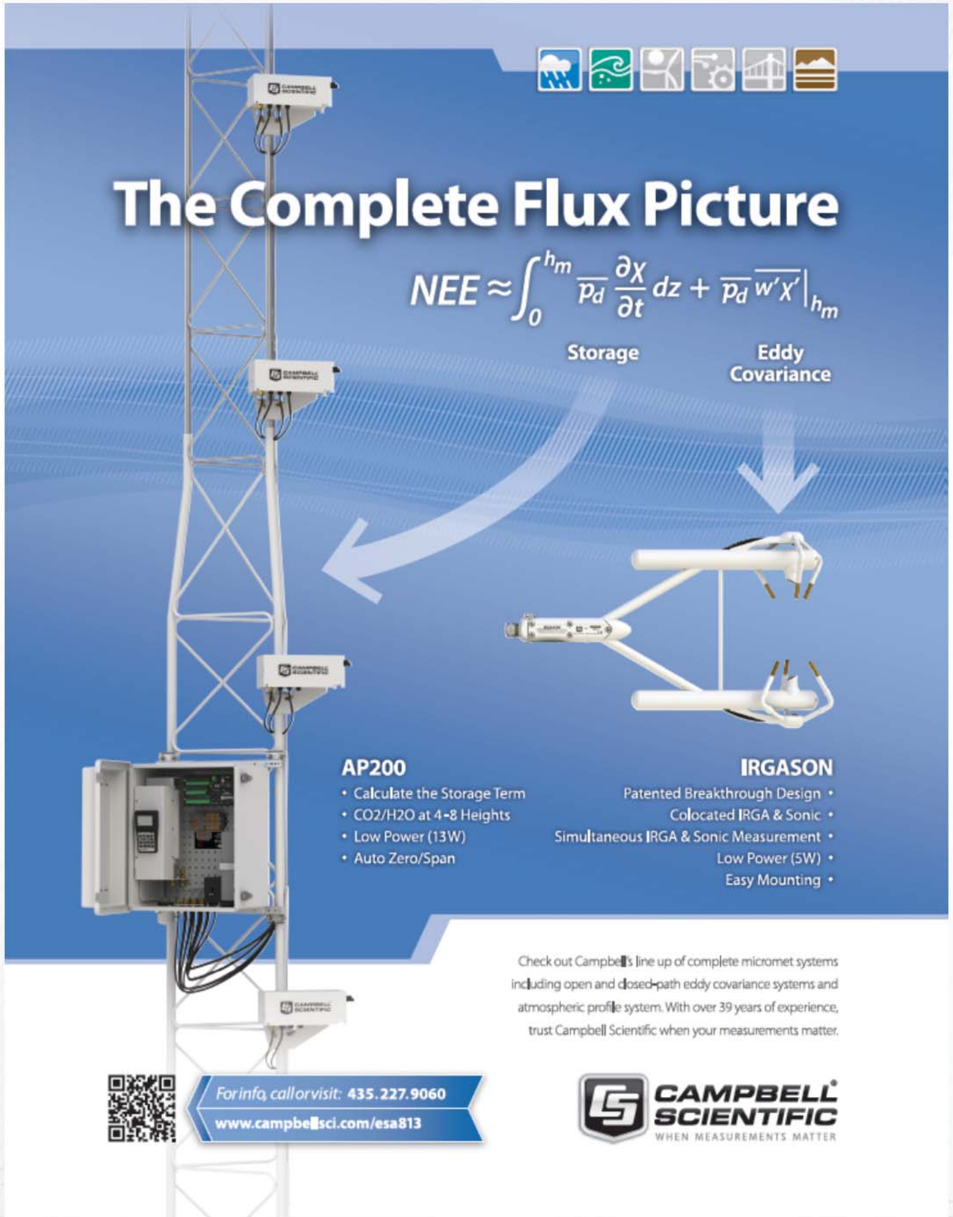
More Robust Factory Calibration



- factory calibration (7 CO_2 concentrations, 3 pressures, 11 temperatures and 15 dew points in combinations encountered in practice, plus dirty window cal)
- field calibration (2 point calibration with zero air and span air)

Resistance to Solar Contamination




The Complete Flux Picture
$NEE \approx \int_0^{h_m} \overline{\rho_d} \frac{\partial \chi}{\partial t} dz + \overline{\rho_d}\, \overline{w'\chi'}\big|_{h_m}$
Storage
Eddy Covariance
AP200
• Calculate the Storage Term
• CO2/H2O at 4-8 Heights
• Low Power (13W)
• Auto Zero/Span
IRGASON
Patented Breakthrough Design •
Colocated IRGA & Sonic •
Simultaneous IRGA & Sonic Measurement •
Low Power (5W) •
Easy Mounting •
Check out Campbell's line up of complete micromet systems including open and closed-path eddy covariance systems and atmospheric profile system. With over 39 years of experience, trust Campbell Scientific when your measurements matter.
For info, call or visit: 435.227.9060
www.campbellsci.com/esa813
CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

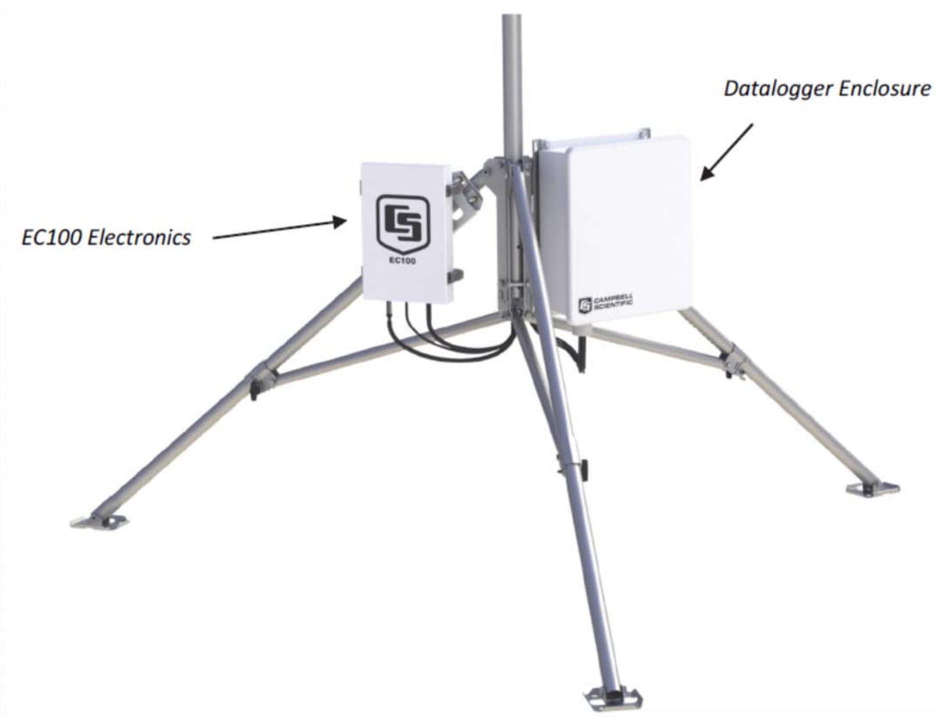
Other advantages:

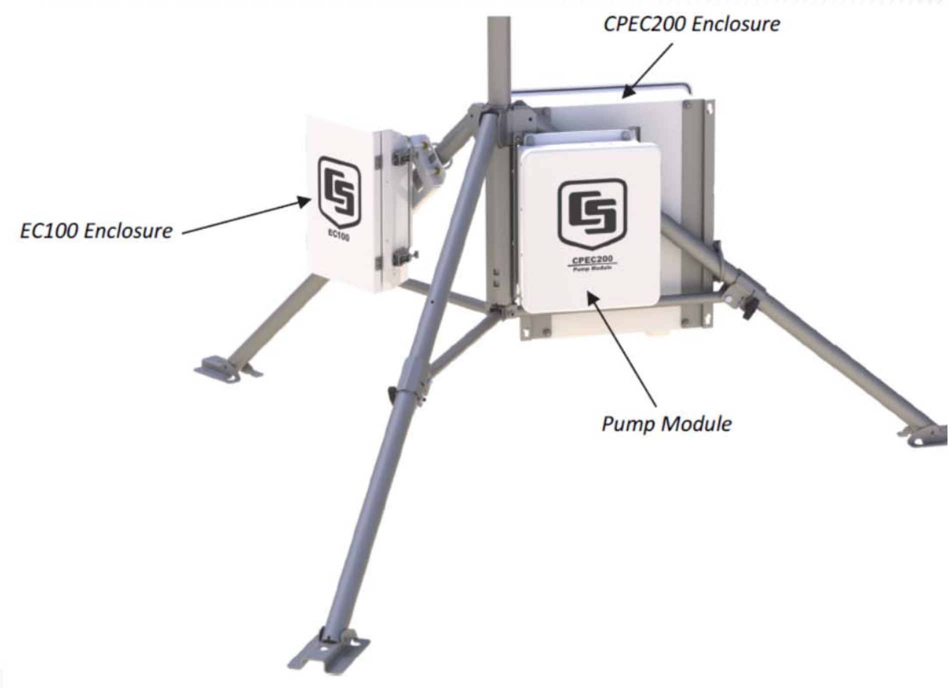
- Flexibility of CS dataloggers (add sensors)
- Only sonic anemometer manufacturer to also produce gas analyzers → better system integration
- Temp fluctuations dampened on CPEC200, so a fine wire TC not required (they can be a pain)
- Turn-key closed-path system w/ auto zero/span
- Turn-key profile system w/ auto zero/span
- Expertise and experience (CSI’s first EC system was a CA27 and TC in late 1970’s!)

Design Rationale: Easy Installation

All Systems:

– Setup tower/tripod and mount enclosures



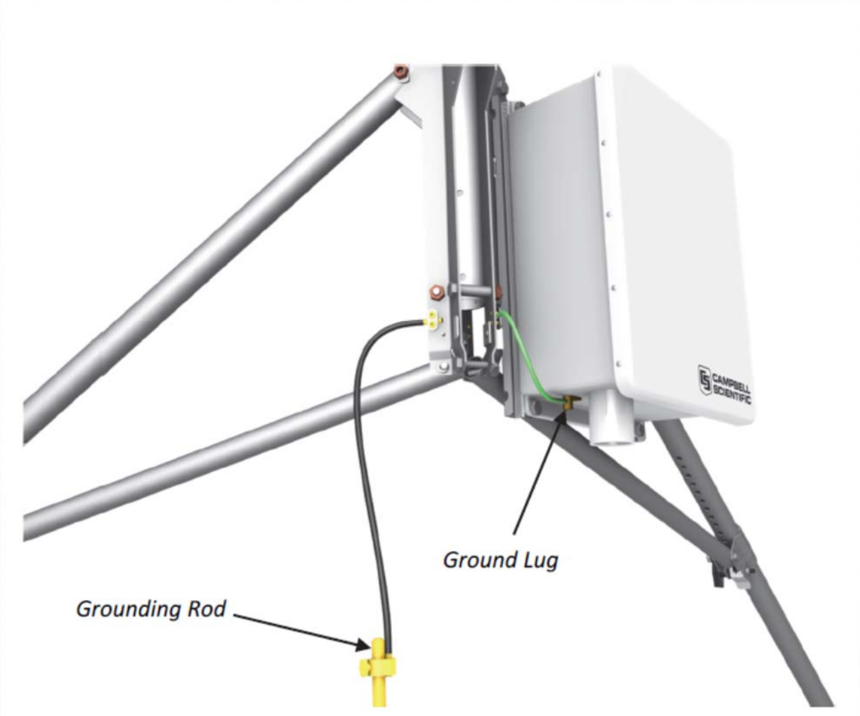


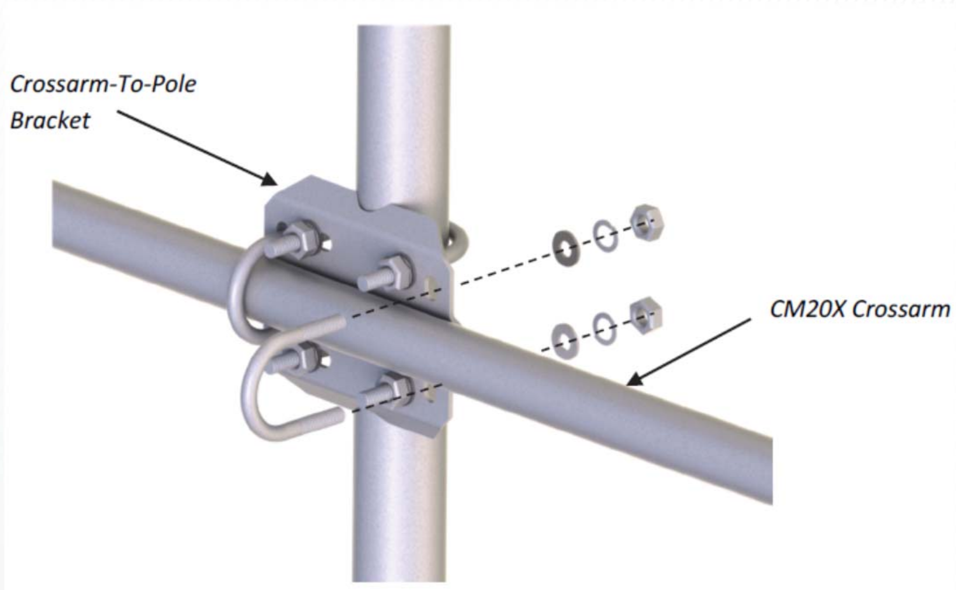
All Systems

– Ground enclosures to earth

EC Systems

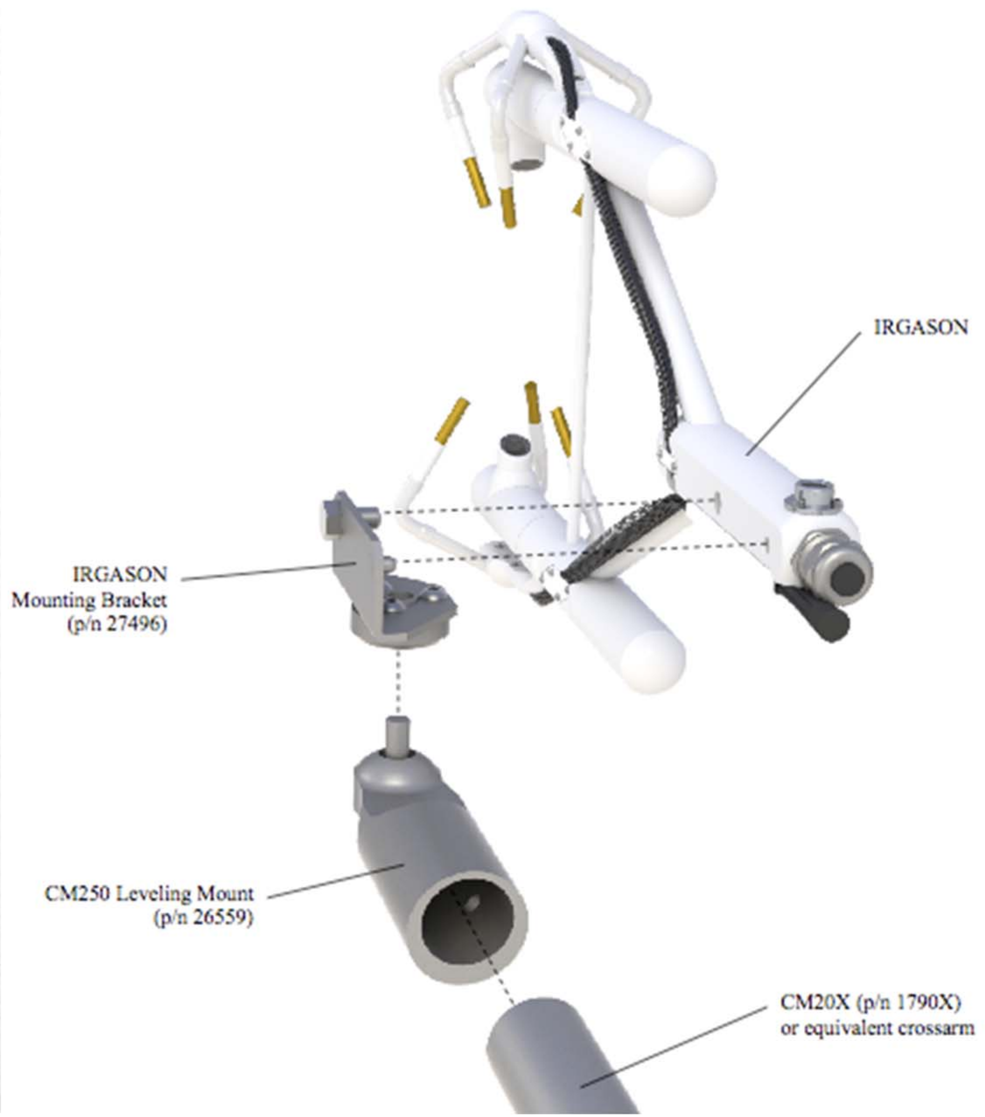
– Mount crossarm

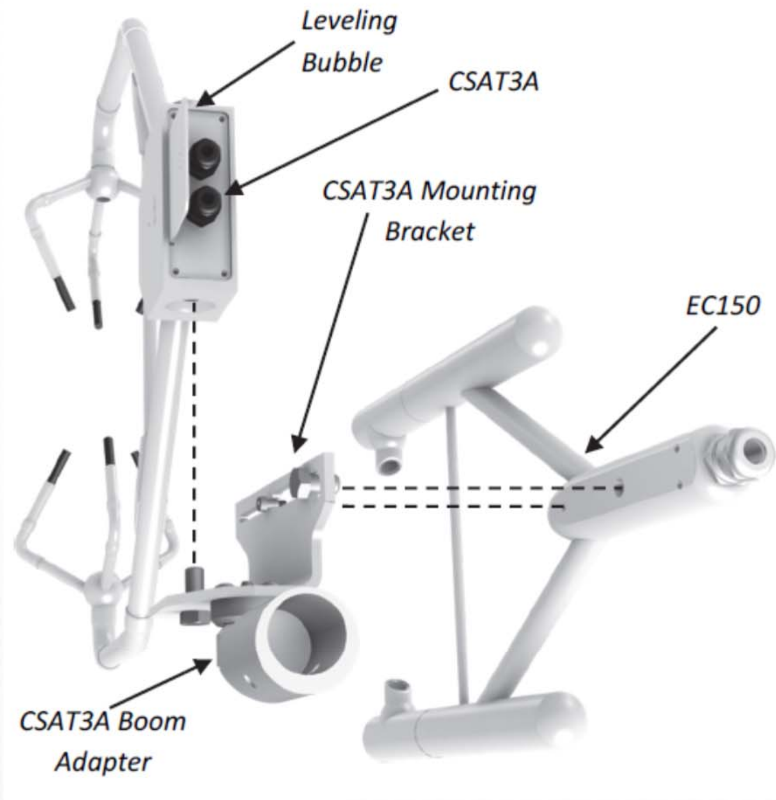




Open-Path EC Systems

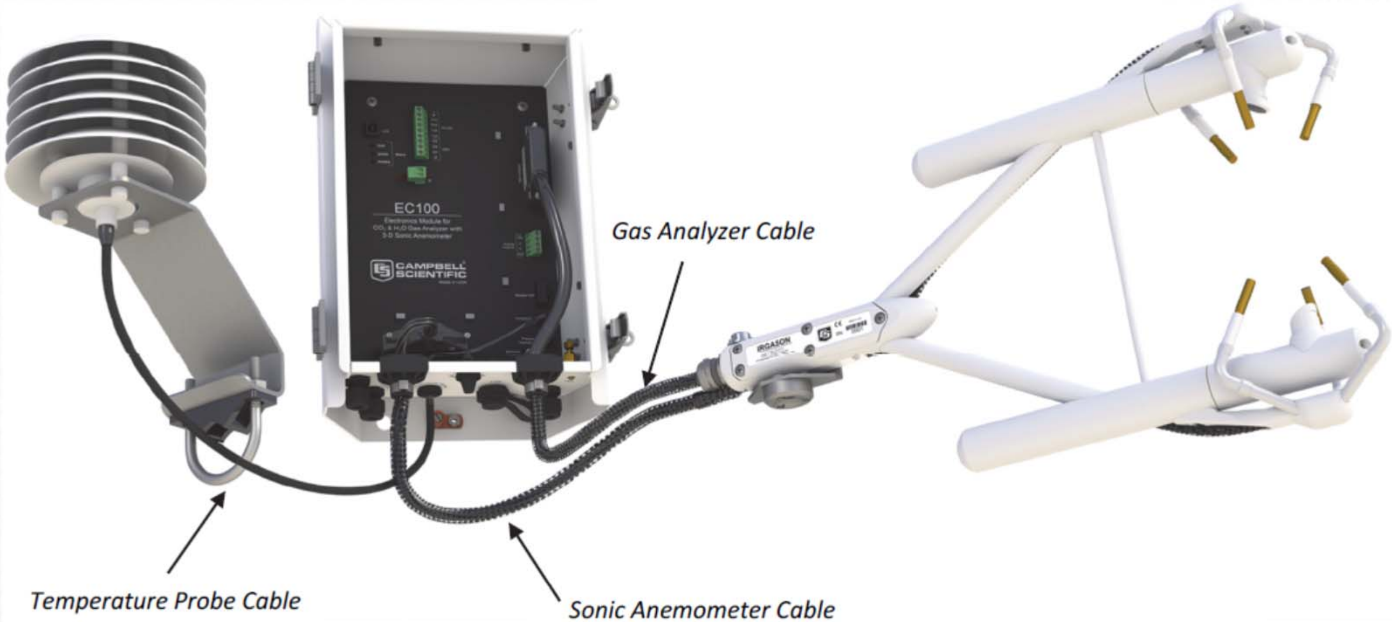
– Mount IRGASON or EC150/CSAT3A





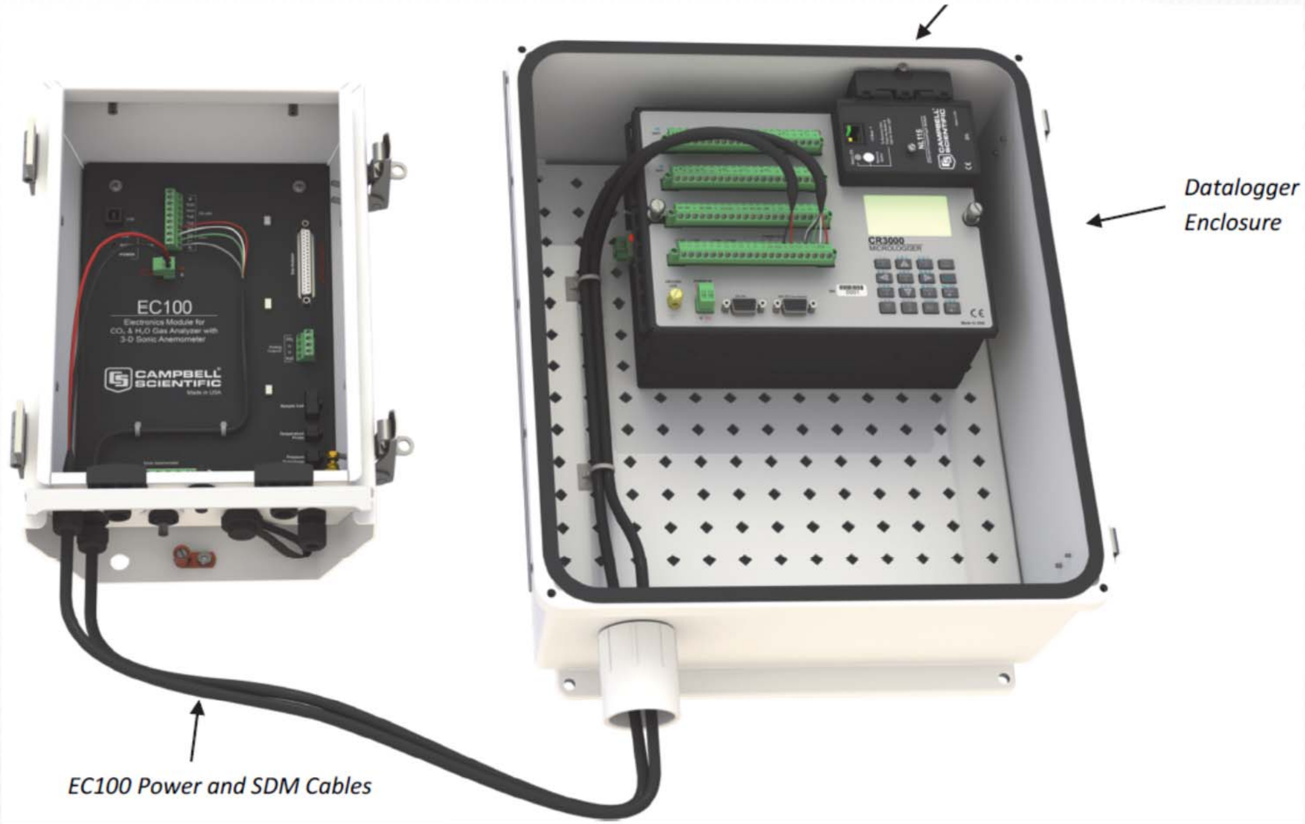
Open-Path EC Systems

– Connect gas analyzer, sonic anemometer, and temperature probe to EC100 electronics.



Open-Path EC Systems

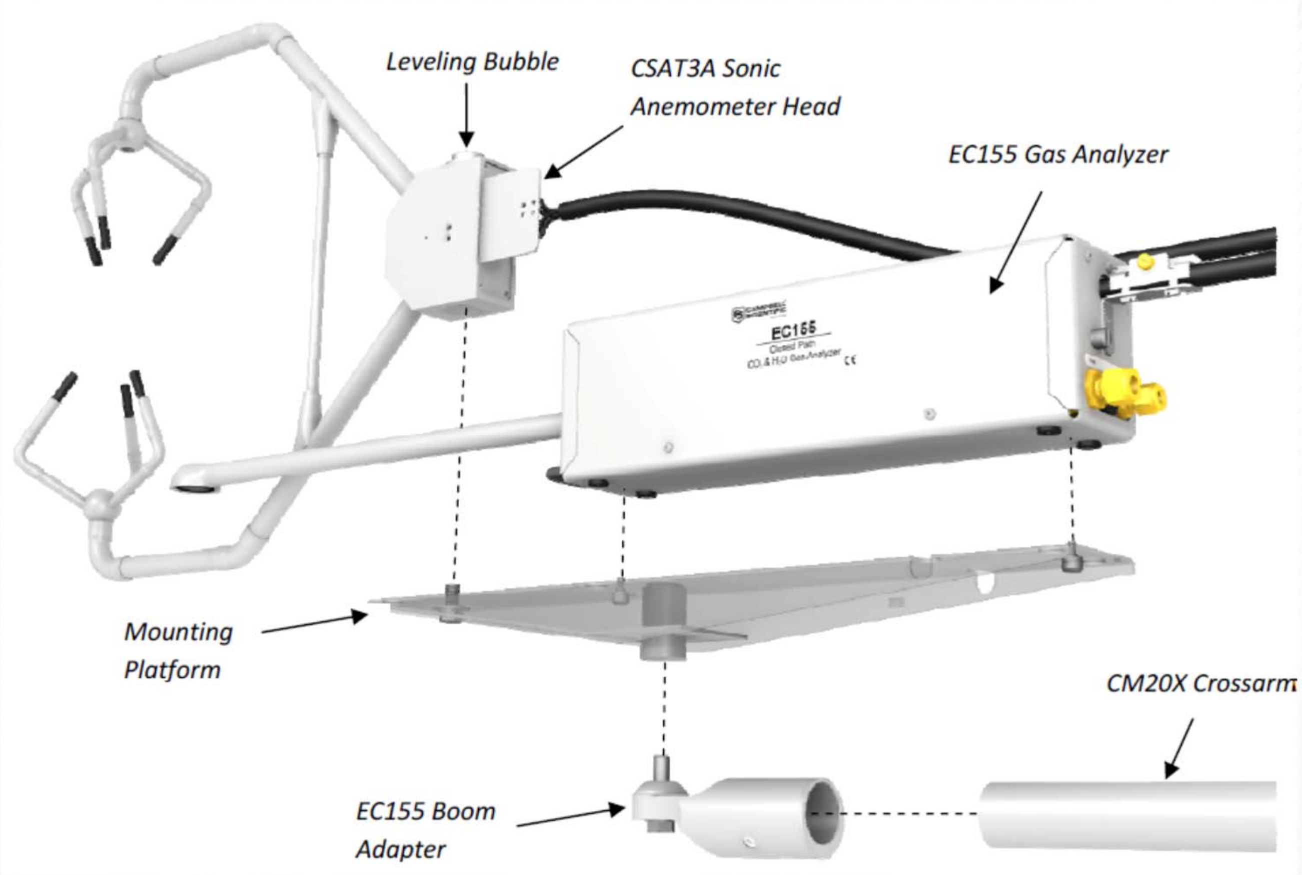
– Connect power and SDM between logger and EC100.



Installed EC150/CSAT3A EC system

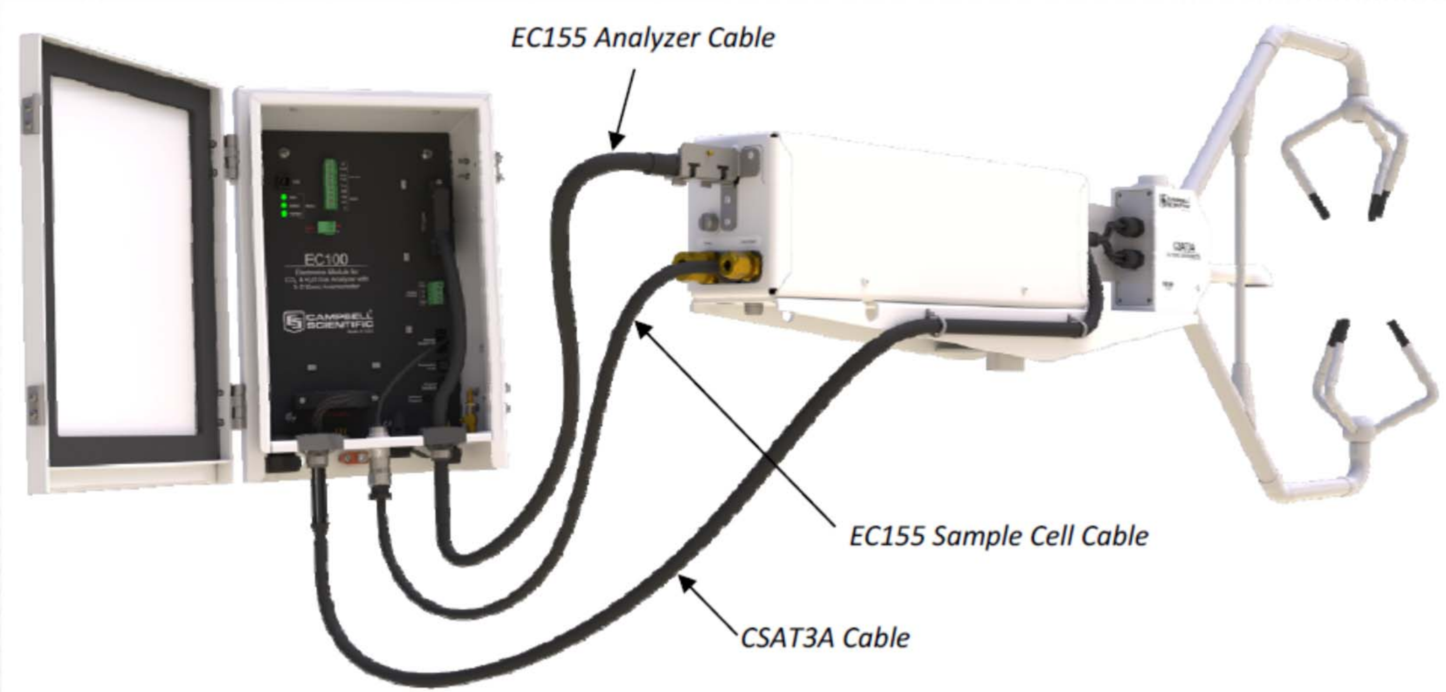
CPEC200 System

– Mount EC155/CSAT3A



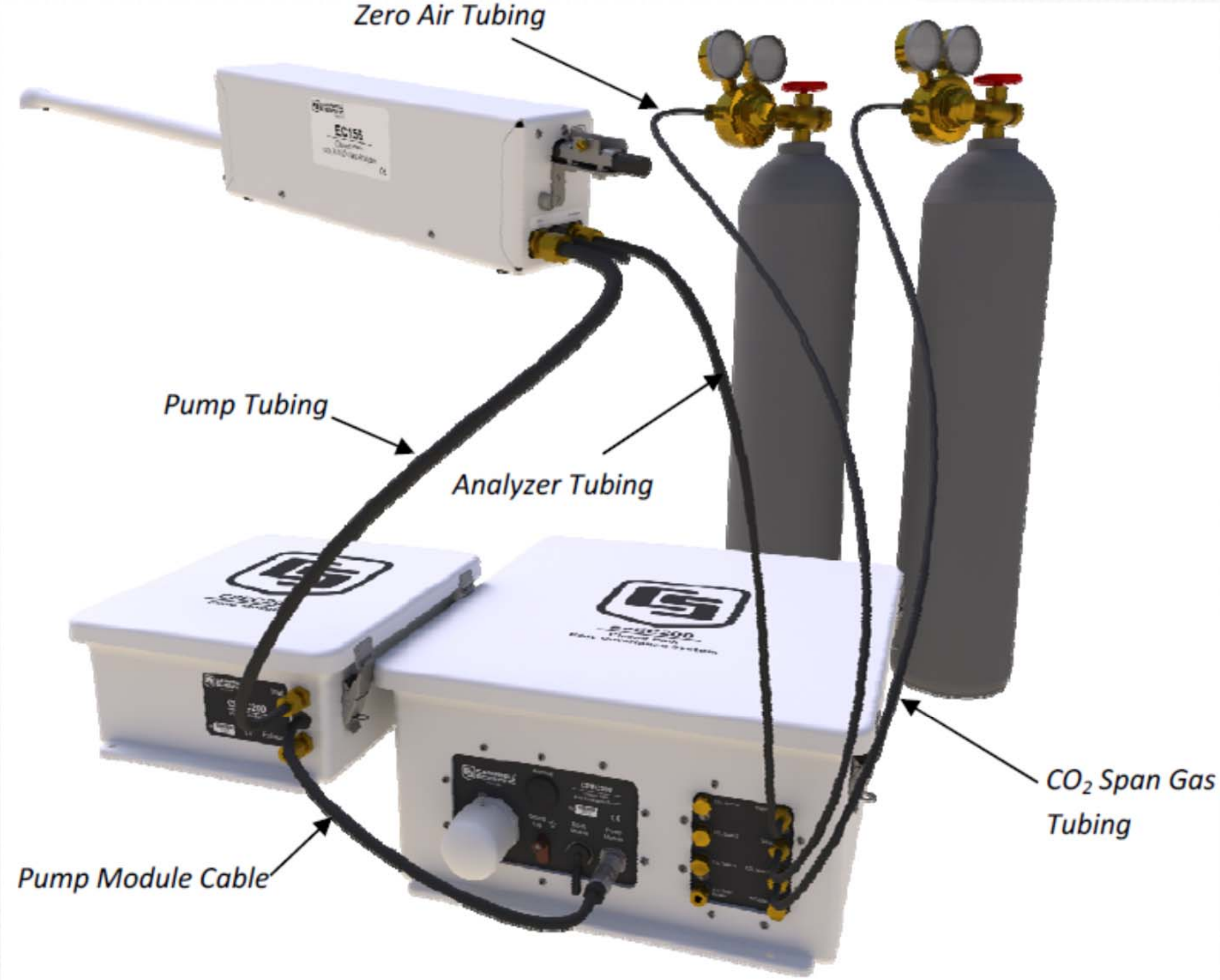
CPEC200 System

- Connect gas analyzer, sonic anemometer, and sample cell cables to EC100.



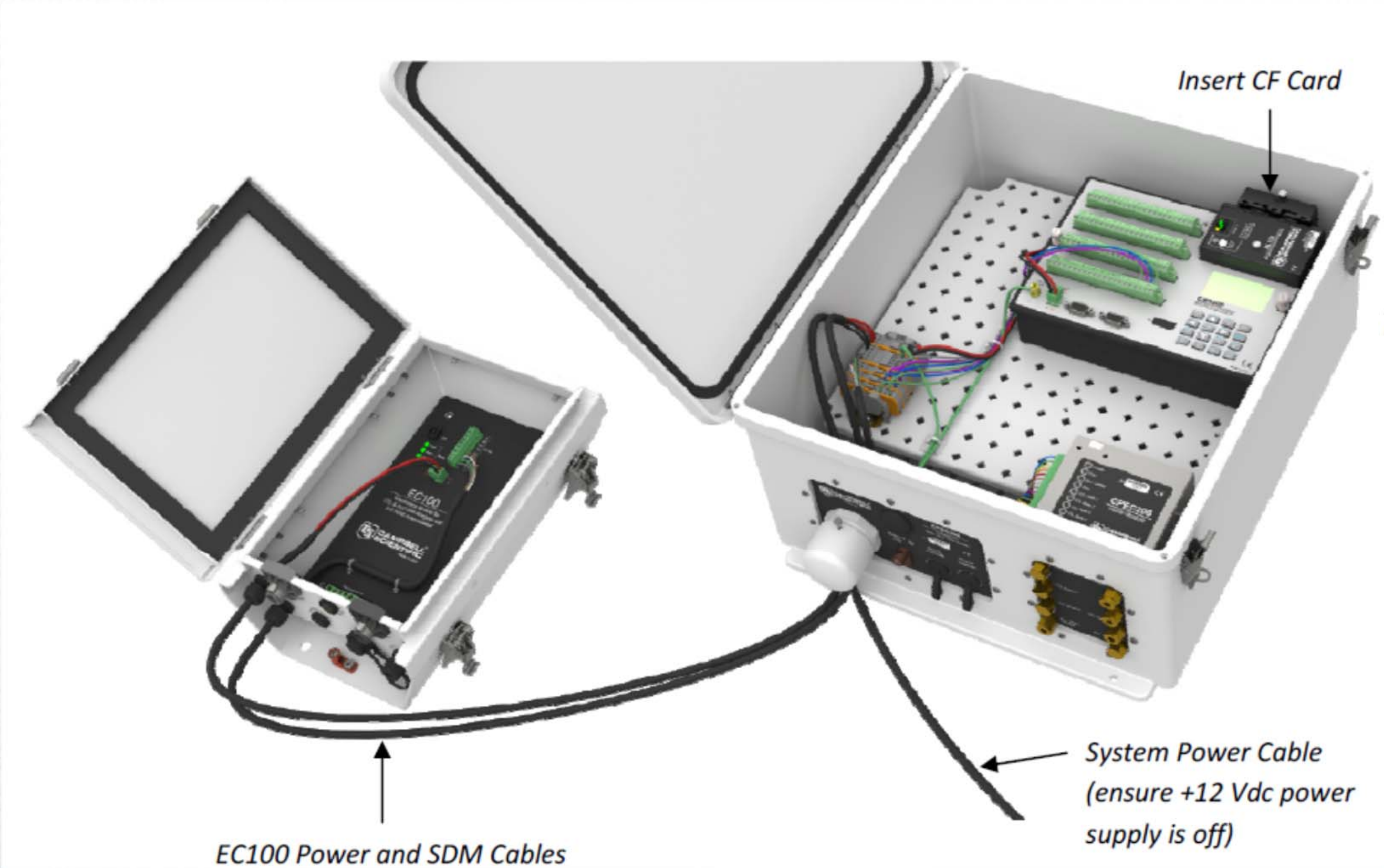
CPEC200 System

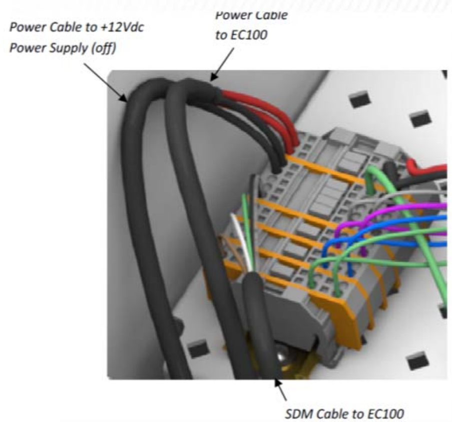
– Connect tubing connections.



CPEC200 System

– Connect SDM and power between EC100 and system enclosure.

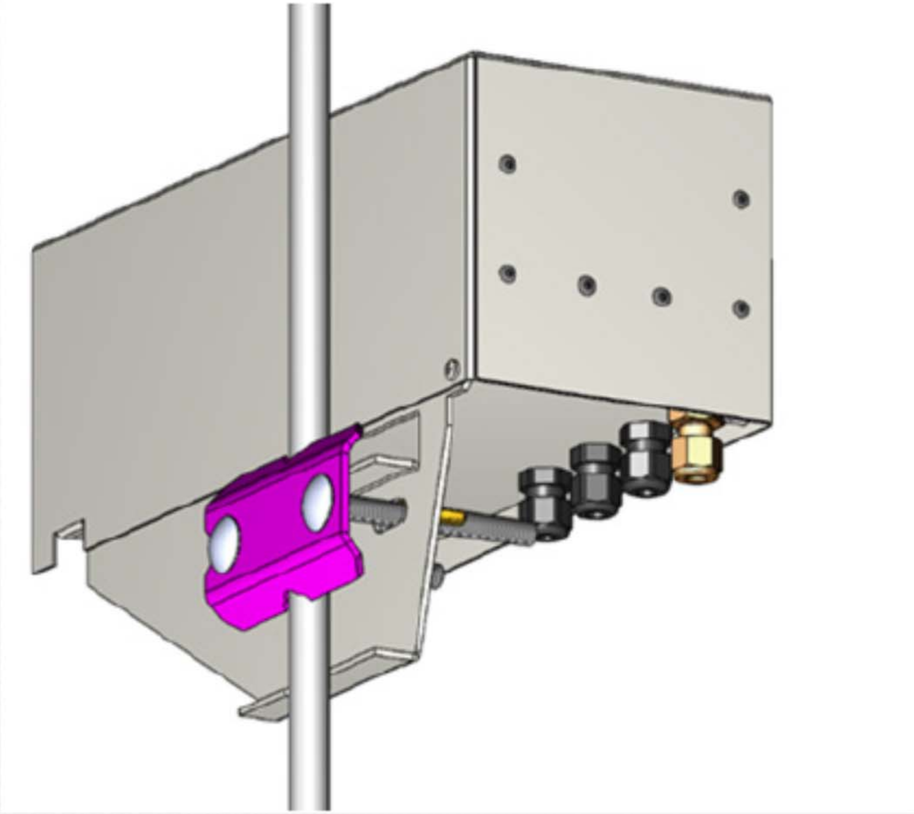


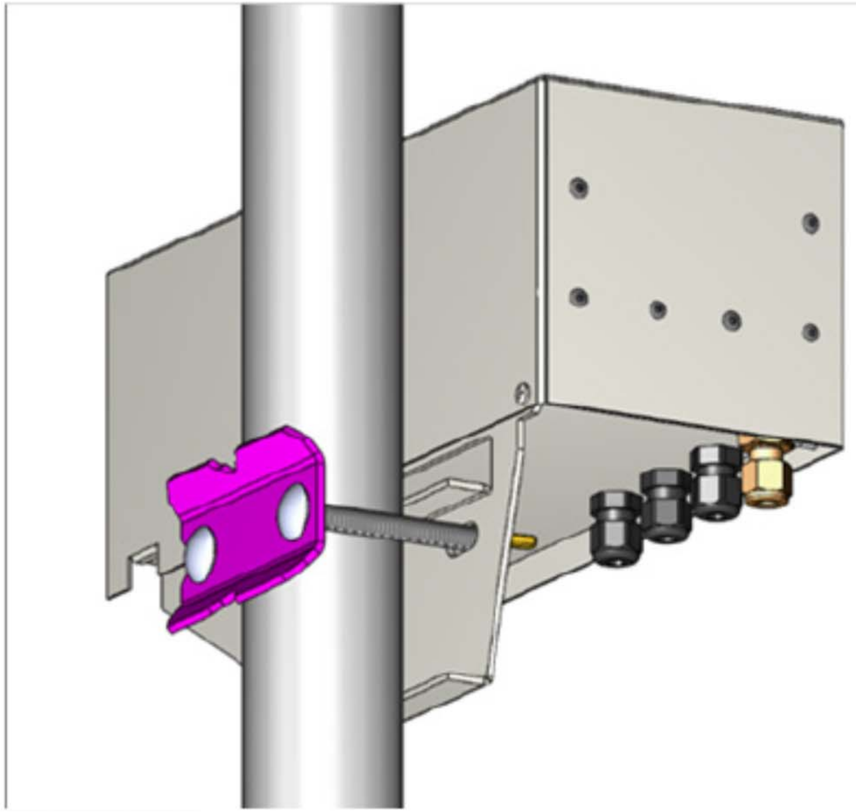


Installed CPEC200 System

AP200 System (enclosure already mounted)

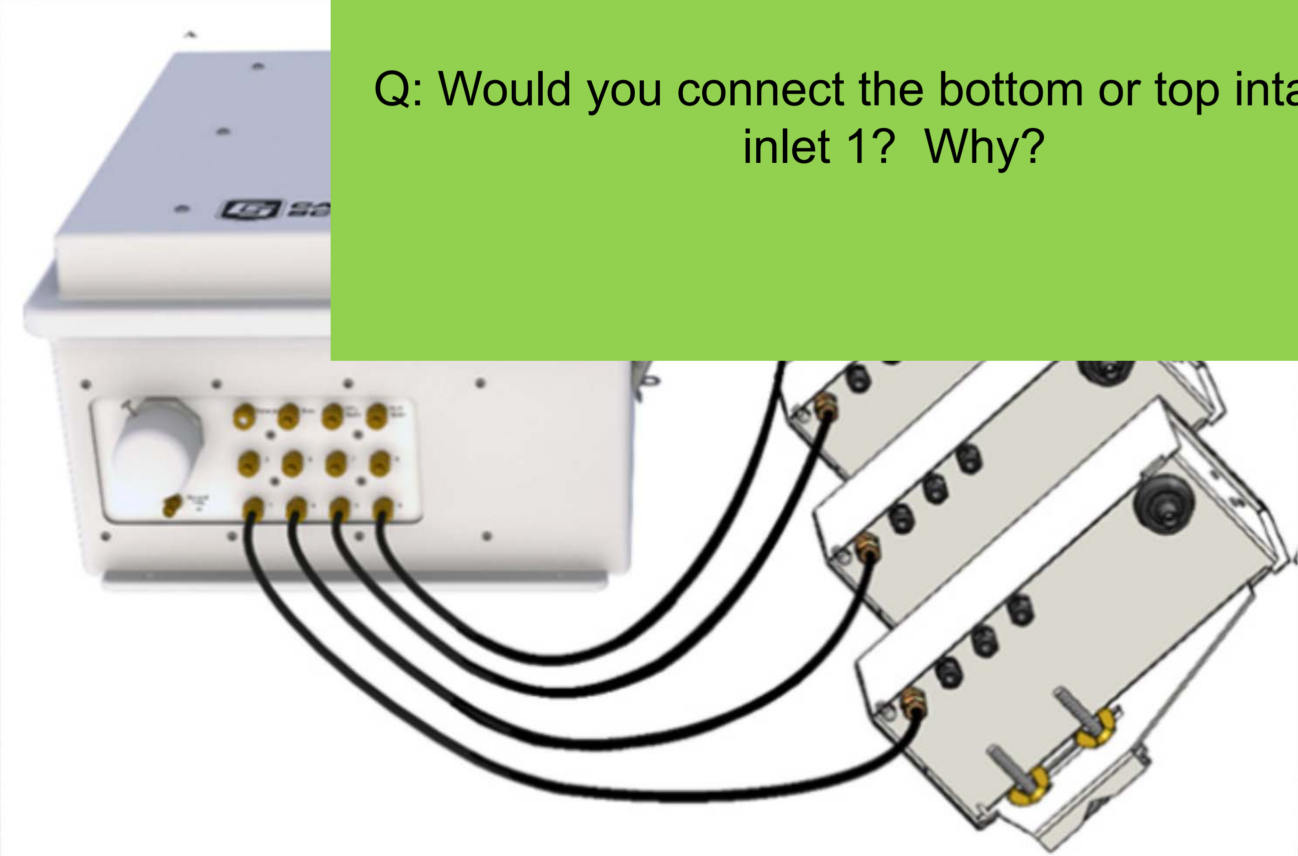
– Mount Intakes





AP200 System

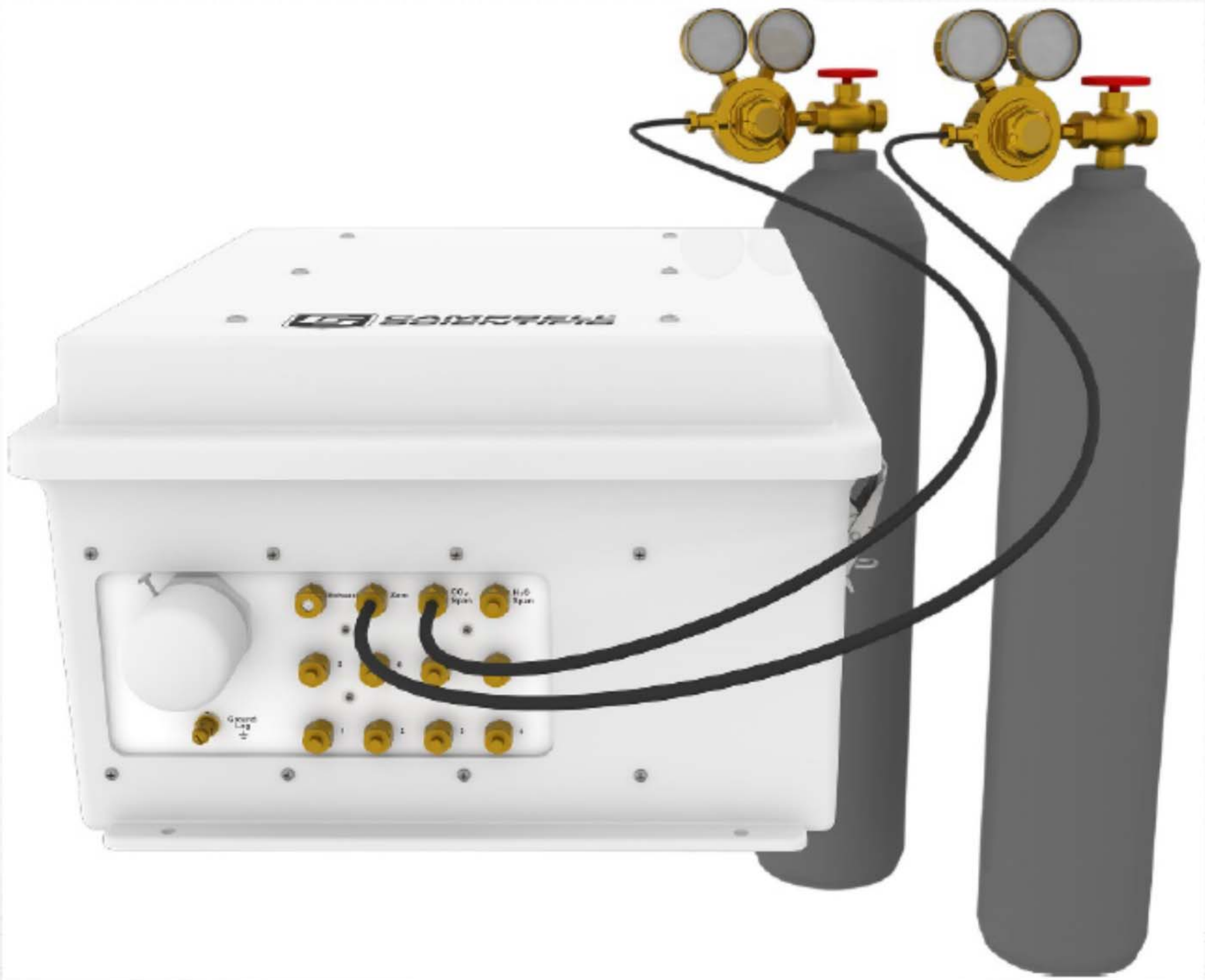
– Cut, swage, and connect tubing



Q: Would you connect the bottom or top intake to inlet 1? Why?

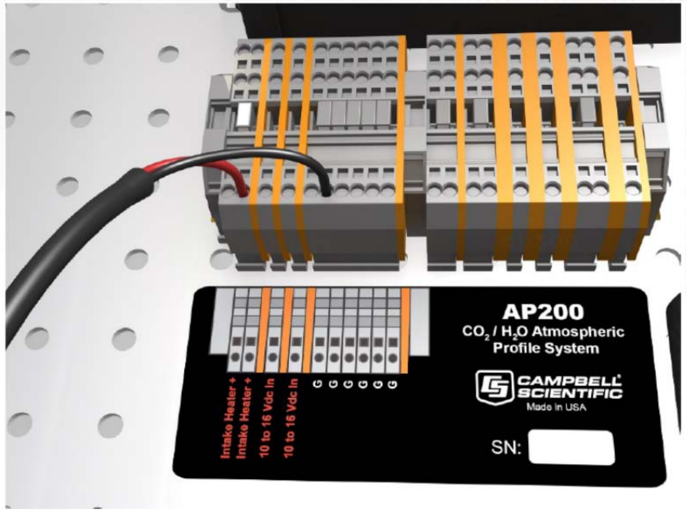
AP200 System

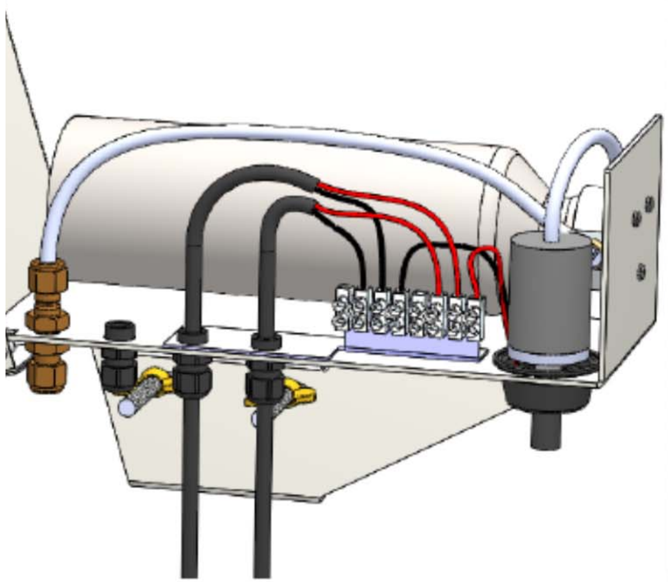
– Cut, swage, and connect tubing



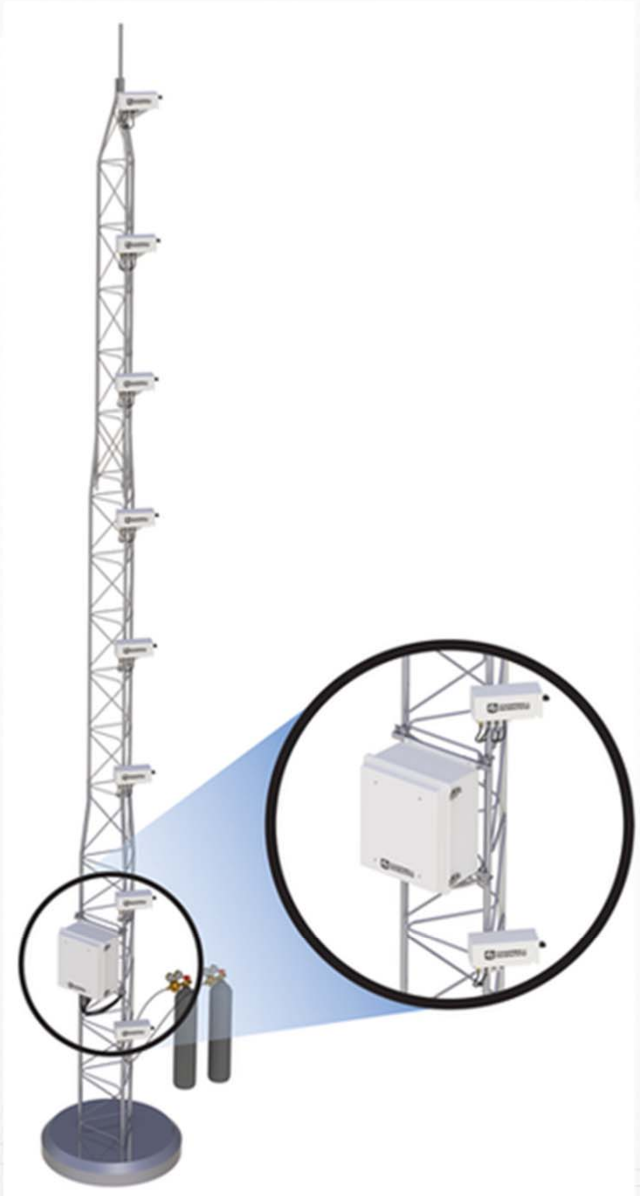
AP200 System

– Daisy chain heater cables





AP200 System



Design Rationale: Pre-programmed but user-editable for flexibility

OPEC Program

- If OPEC program ordered (PN18442/3), it comes with compiled switches, wiring diagram, and description of outputs.

```
'CR3000 Series Datalogger

'Copyright (c) 2002, 2006, 2010 Campbell Scientific, Inc. All rights reserved.

'3 Dec 12
'version 3.1.01


'Start of Constants Customization Section
'The following sensors are measured:
'
Const SENSOR_CSAT3       = FALSE  'CSAT3                      three dimensional sonic anemometer (overrides the sonic in an IRGASON or EC150)
Const SENSOR_EC150       = TRUE   'IRGASON or EC150 (CSAT3A) open path infrared gas analyzer (CO2 and H2O) and three dimensional sonic anemometer head
Const SENSOR_KH20        = FALSE  'KH20                       krypton hygrometer (H2O)
Const SENSOR_FW          = FALSE  'FW05                       finewire thermocouple probe
Const SENSOR_LI7500      = FALSE  'LI-7500(A)                 open path infrared gas analyzer (CO2 and H2O)
Const SENSOR_LI7700      = FALSE  'LI-7700                    open path methane gas analyzer (CH4), requires EC150 or LI-7500
Const SENSOR_TMPR_RH     = FALSE  'HC2S3/HMP155A/HMP45C       temperature and relative humidity probe

Const SENSOR_Q7_1        = FALSE  'Q7.1                       net radiometer
Const SENSOR_NR_LITE     = FALSE  'NR Lite                    net radiometer
Const SENSOR_CNR_2       = FALSE  'CNR 2                      net radiometer
Const SENSOR_NR_01_CNR_1 = FALSE  'NR 01/CNR 1                net radiometer
Const SENSOR_CNR_4       = FALSE  'CNR 4                      net radiometer
Const SENSOR_TCAV        = FALSE  'TCAV                       type E thermocouple averaging soil temperature probes
Const SENSOR_CS616       = FALSE  'CS616                      water content reflectometers (volumetric soil moisture)
Const SENSOR_CS65X       = FALSE  'CS650 or CS655             water content reflectometers (volumetric soil moisture)
Const SENSOR_HFT3        = FALSE  'HFT3                       soil heat flux plates
Const SENSOR_HFP01       = FALSE  'HFP01                      soil heat flux plates
Const SENSOR_HFP01SC     = FALSE  'HFP01SC                    soil heat flux plates
'End of Constants Customization Section
```

OPEC Program

Wiring

```
'*** Beginning of EC150 w/ CSAT3A sonic head wiring ***
'SDM-C1  SDM Data (green)
'SDM-C2  SDM Clock (white)
'SDM-C3  SDM Enable (brown)
'G       SDM reference (black)
'        SDM shield (clear)

'+12V    power (red)
'G       power reference (black)
'        power shield (clear)
'*** End of EC150 /w CSAT3A sonic head wiring wiring ***


'*** Beginning of HMP wiring ***
'2H      Temperature signal (yellow)
'2L      Signal reference (white)

'3H      Relative humidity signal (blue)
'3L      jumper wire to 2L
'gnd     Shield (clear)

'12V     Power (red)
'G       Power reference (black)
'*** End of HMP wiring ***


'*** Beginning of NR Lite wiring ***
'2H      Signal (white/red)
'2L      Signal reference (green/blue)
'gnd     short jumper wire to 2L
'        Shield (clear)
'*** End of NR Lite wiring ***
```

Output Desc.

CSAT3A	Hs	W/m^2	Sensible heat flux using sonic temperature
(EC100)	tau	kg/(m s^2)	Momentum flux
	u_star	m/s	Friction velocity
	Ts_stdev	C	Standard deviation of sonic temperature
	Ts_Ux_cov	C m/s	Covariance of sonic temperature and horizontal wind (x-axis)
	Ts_Uy_cov	C m/s	Covariance of sonic temperature and horizontal wind (y-axis)
	Ts_Uz_cov	C m/s	Covariance of sonic temperature and vertical wind
	Ux_stdev	m/s	Standard deviation of horizontal wind (x-axis)
	Ux_Uy_cov	(m/s)^2	Covariance of horizontal winds (x-axis and y-axis)
	Ux_Uz_cov	(m/s)^2	Covariance of horizontal wind (x-axis) and vertical wind
	Uy_stdev	m/s	Standard deviation of horizontal wind (y-axis)
	Uy_Uz_cov	(m/s)^2	Covariance of horizontal wind (y-axis) and vertical wind
	Uz_stdev	m/s	Standard deviation of vertical wind
	wnd_spd	m/s	Horizontal wind speed
	rslt_wnd_spd	m/s	Resultant horizontal wind speed
	wnd_dir_sonic	degrees	Resultant wind direction using compass coordinate system
	std_wnd_dir	degrees	Standard deviation of wind direction
	wnd_dir_compass	degrees	Resultant wind direction using the sonic's right handed coordinate system
	Ux_Avg	m/s	Average horizontal wind (x-axis)
	Uy_Avg	m/s	Average horizontal wind (y-axis)
	Uz_Avg	m/s	Average vertical wind
	Ts_Avg	C	Average sonic temperature
	sonic_azimuth	degrees	Azimuth of sonic negative x-axis
	sonic_samples_Tot	samples	Number of samples in the sonic statistics (fluxes, variances, means, etc.)
	no_sonic_head_Tot	samples	Number of samples of "no sonic head"
	no_new_sonic_data_Tot	samples	Number of samples of "no new sonic data"
	amp_l_f_Tot	samples	Number of "amplitude low" warnings from sonic head
	amp_h_f_Tot	samples	Number of "amplitude high" warnings from sonic head
	sig_lck_f_Tot	samples	Number of "poor signal lock" warnings from sonic head
	del_T_f_Tot	samples	Number of "delta temperature" warnings from sonic head
	aq_sig_f_Tot	samples	Number of samples of "sonic head acquiring ultra sonic signals"
	sonic_cal_err_f_Tot	samples	Number of "sonic calibration download failures"
EC150	Fc_wpl	mg/(m^2 s)	Carbon dioxide flux
	LE_wpl	W/m^2	Latent heat flux
	Hc	W/m^2	Sensible heat calculated from humidity corrected sonic temperature
	CO2_stdev	mg/m^3	Standard deviation of carbon dioxide density
	CO2_Ux_cov	mg/(m^2 s)	Covariance of carbon dioxide density and horizontal wind (x-axis)
	CO2_Uy_cov	mg/(m^2 s)	Covariance of carbon dioxide density and horizontal wind (y-axis)
	CO2_Uz_cov	mg/(m^2 s)	Covariance of carbon dioxide density and vertical wind
	H2O_stdev	g/m^3	Standard deviation of water vapor density
	H2O_Ux_cov	g/(m^2 s)	Covariance of water vapor density and horizontal wind (x-axis)
	H2O_Uy_cov	g/(m^2 s)	Covariance of water vapor density and horizontal wind (y-axis)
	H2O_Uz_cov	g/(m^2 s)	Covariance of water vapor density and vertical wind
	Tc_stdev	C	Standard deviation of humidity corrected sonic temperature
	Tc_Ux_cov	C m/s	Covariance of humidity corrected sonic temperature and horizontal wind (x-axis)
	Tc_Uy_cov	C m/s	Covariance of humidity corrected sonic temperature and horizontal wind (y-axis)
	Tc_Uz_cov	C m/s	Covariance of humidity corrected sonic temperature and vertical wind
	CO2_mean	mg/m^3	Average carbon dioxide density
	H2O_mean	g/m^3	Average water vapor density
	amb_tmpr_Avg	C	Average ambient temperature

OPEC Program

- Outputs raw 10Hz data
- Outputs 30 min (adjustable) statistical data
  - Includes E balance sensors
  - Includes flux estimates
    - Filtered for diagnostics (despike)
    - Sonic temp corrected for humidity
    - WPL correction applied
    - Other corrections not applied yet because preference has been for post-processing

CPEC200 Program

- Base program included w/ system
- Similar raw and 30 min outputs as OPEC
- Flux Estimates
  - Filtered for diagnostics (despike)
  - Accounts for average delay between gas and wind
  - No need for WPL

```
'******************* Begin Configuration Constants **************************

Const VALVE_MODULE = True
' True to enable the CPEC200 Valve Module
' False to reduce clutter in Public table and output tables
' Default: True

Const SCRUB_MODULE = False
' True to enable the CPEC200 Scrub Module
' False to reduce clutter in Public table and output tables
' Default: False

Const SaveAll_diagnostics = False
' True to save all diagnostic data in ts_data outptut table
' False to reduce clutter in output tables
' Default: False

Const Leaf_Wetness_Sensor = False
' True to use the leaf wetness sensor to control the EC155 intake heater power
' False to use full power all the time
' Default: False

'**************** End Configuration Constants ******************************
```

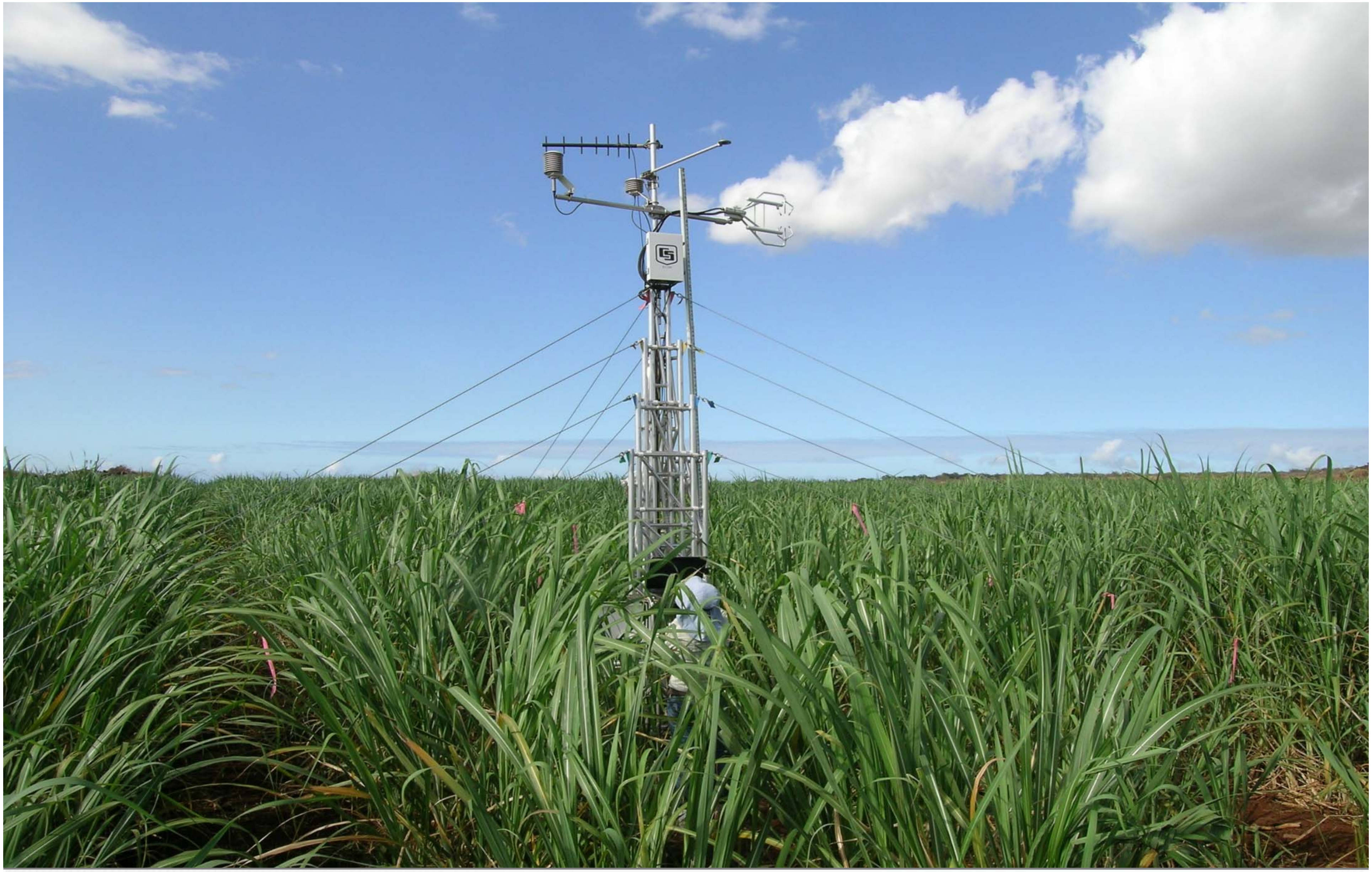
AP200 Program

- Program included w/ system
- Raw, Site average, and 30 min output tables

```
'Start of Constants Customization Section

'MaxLevels is the maximum number of profile levels. Normally this is 8, but it may be set to the actual
number of levels used (4-8) to avoid null data for unused Levels in the IntAvg table
Const MaxLevels = 8
'min=4
'max=8
'inc=1

'SaveAll_diagnostics: Normally this is False, but set it to TRUE to save all diagnostic data in RawData table
Const SaveAll_diagnostics = False '(default)
'value=False '(default)
'value=True

'N_AirTemps: Number of 107-L temperature sensors to measure (may be 1 to 8), or zero to disable air
temperature measurements
Const N_AirTemps = 0
'min=0
'max=8
'inc=1

'End of Constants Customization Section
```

INTERESTING APPLICATIONS

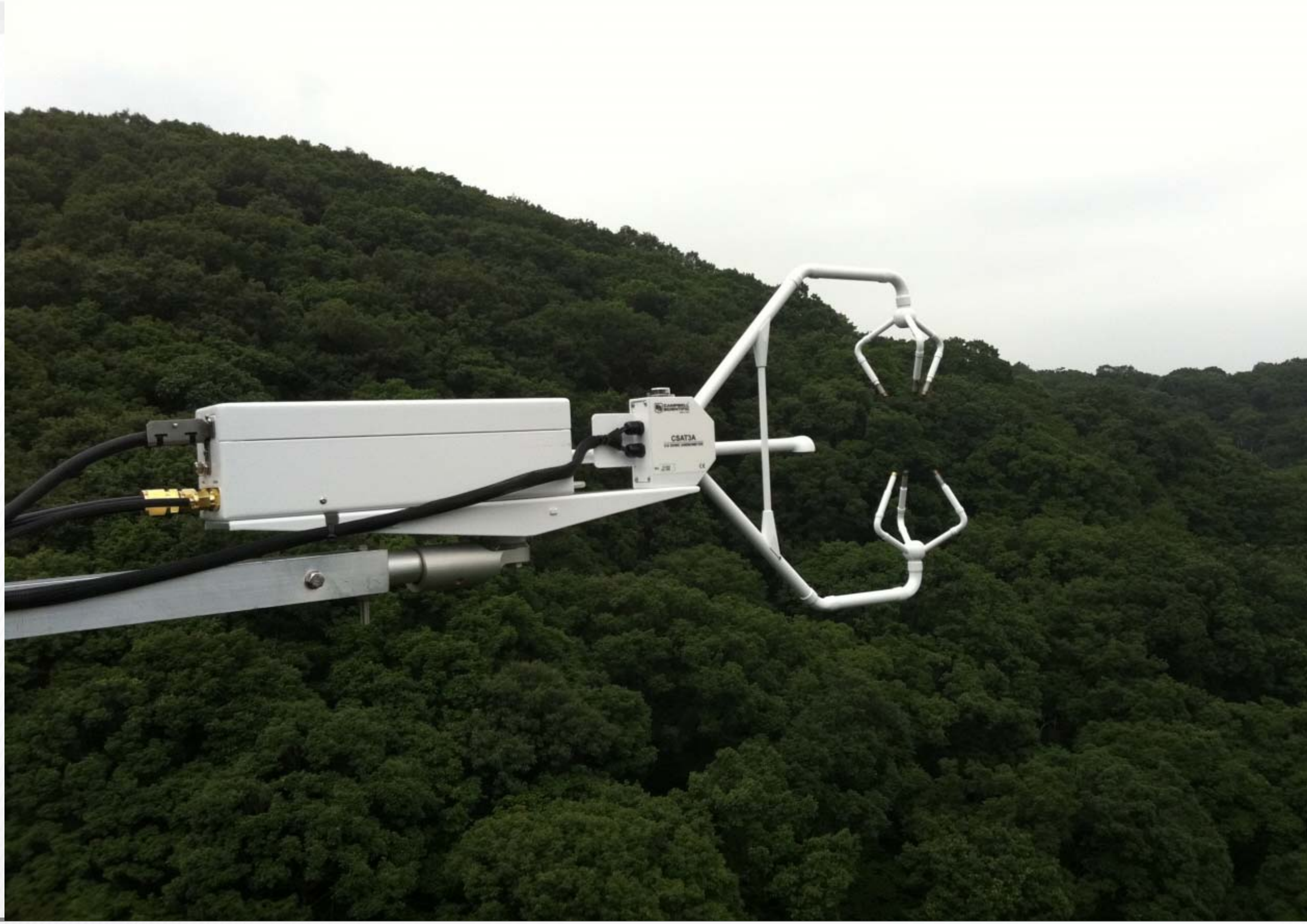
EC150 – Shetland Islands, Antarctica



Fluxes over Sugar Cane– Maui, USA

Complex Terrain Fluxes – China

Sea Fluxes with EC150 – China



Complex Terrain Fluxes – Korea

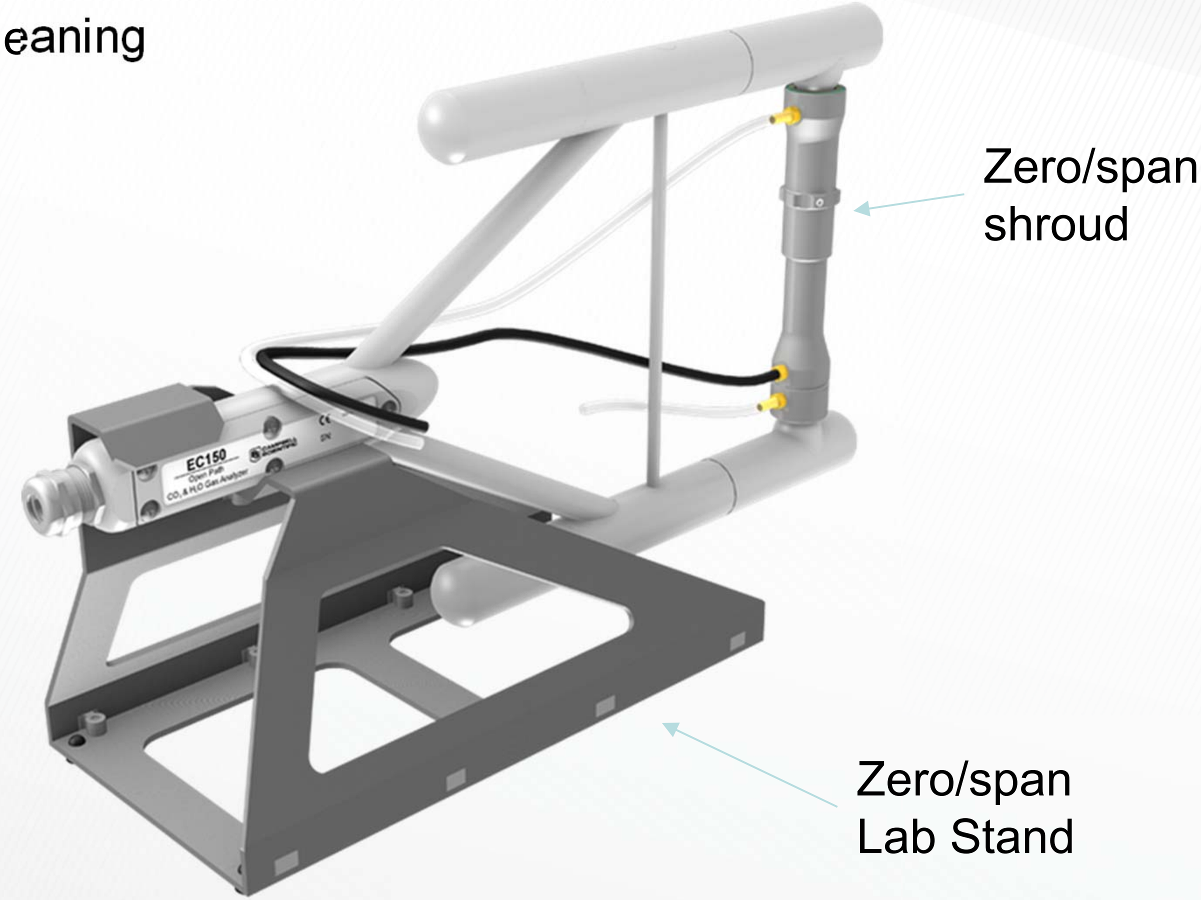
AP200 Profile System – Hawaii, USA


Thank you for your attention!

MAINTENANCE

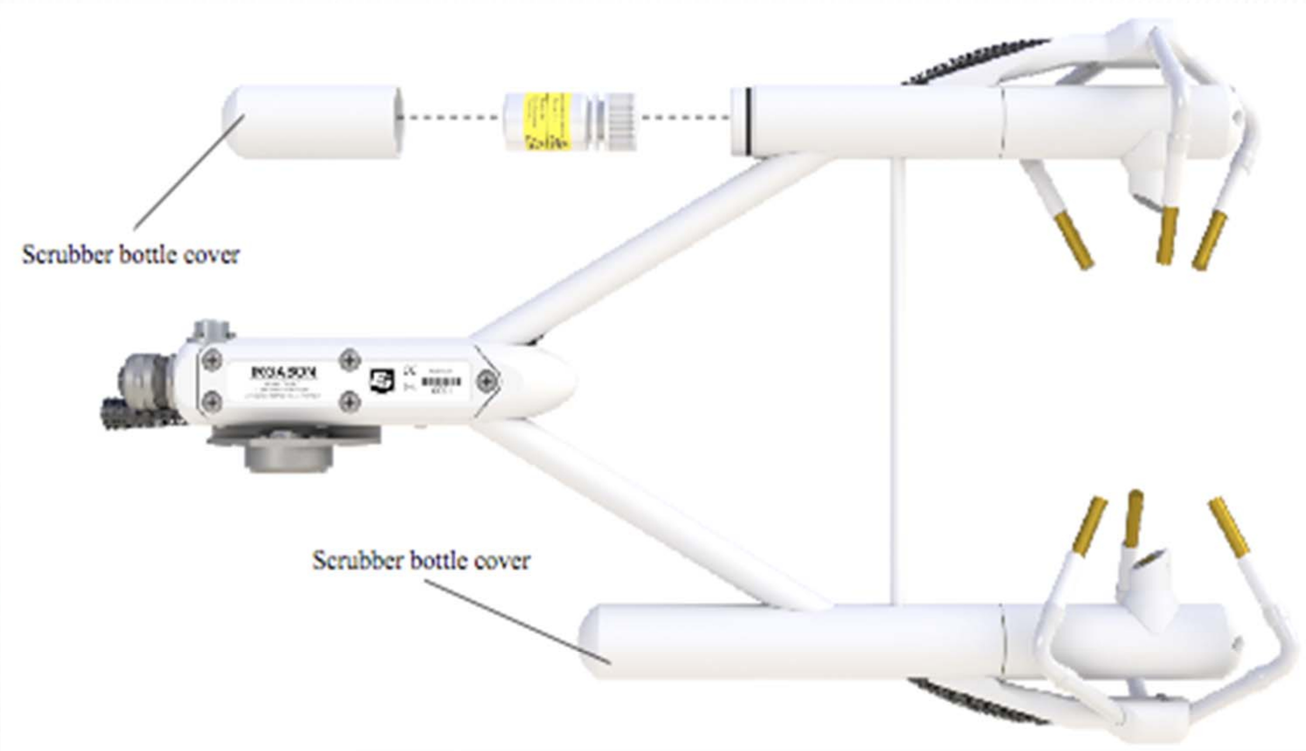
OPEC Maintenance

Monitor diagnostics (data, LED's)
Enclosure desiccant
Window cleaning
Zero/span



OPEC Maintenance

Replacing chemical bottles



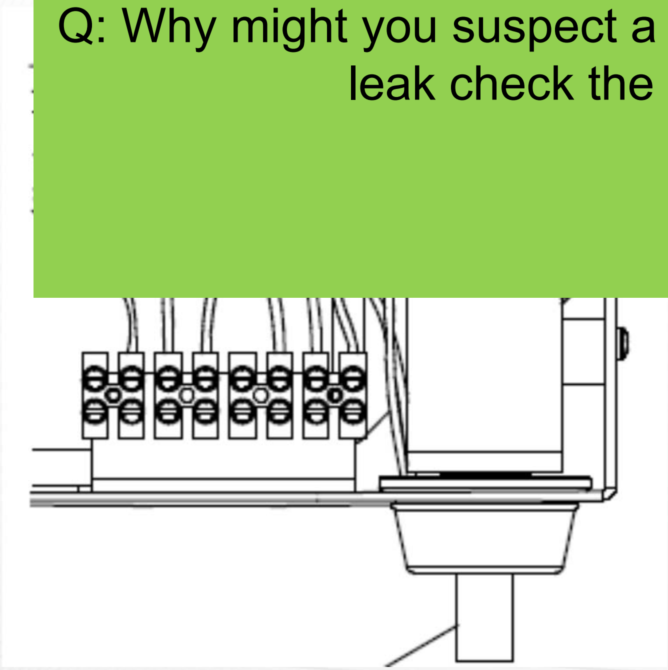
CPEC200 Maintenance

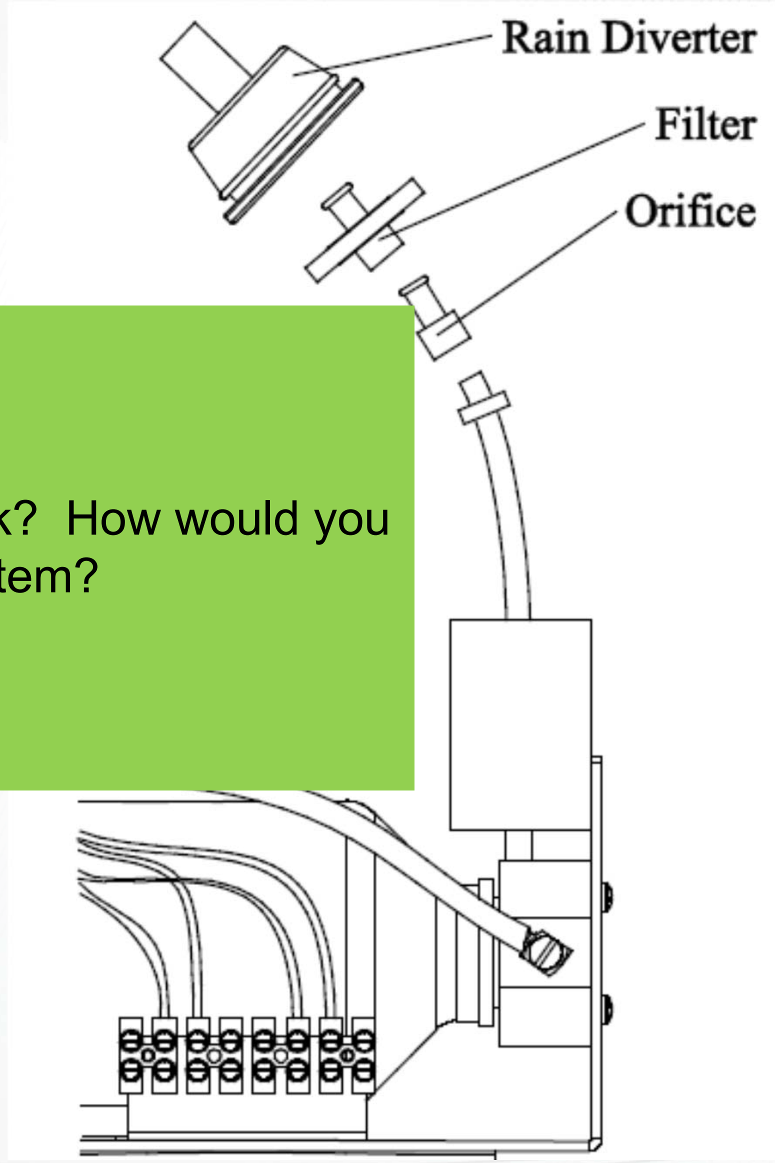
Monitor diagnostics (data, LED's)
Enclosure desiccant
Replace filter
Clean analyzer windows
Zero/Span (if not automatic)

AP200 Maintenance

Monitor diagnostics (data)
Enclosure desiccant
Replace filters (or orifices)
Ze

Q: Why might you suspect a leak? How would you leak check the system?





Troubleshooting ANY system

1. Visually inspect site, check connections/wiring, obstructions, etc.

2. Use manual to interpret diagnostic values. Look at raw data diagnostics for patterns or persistent states.

3. If no diagnostics, do a zero/span (analyzer) and zero wind test (sonic)

4. Contact an AE. Be prepared to send program, some raw data, serial numbers, OS version, status table information, applicable site history. (Photos are nice too!)

DATA

Data Collection

- 30 minute data may be transmitted practically by any normal method
- Collection or transfer of time series data(e.g. 10Hz data) may be limited to certain methods due to throughouput and/or cost.
- Even if online flux estimates are the only data of interest or the only data being collected via telemetry, time series data should be saved.

Time Series Data Transfer

Data is for a CR3000 running OS25 with a program that generates 15 IEEE4 values saved every 10Hz

Note duty cycle is dependent on cable lenths, network connections, transmission distance, etc. The below tests were done in good conditions.

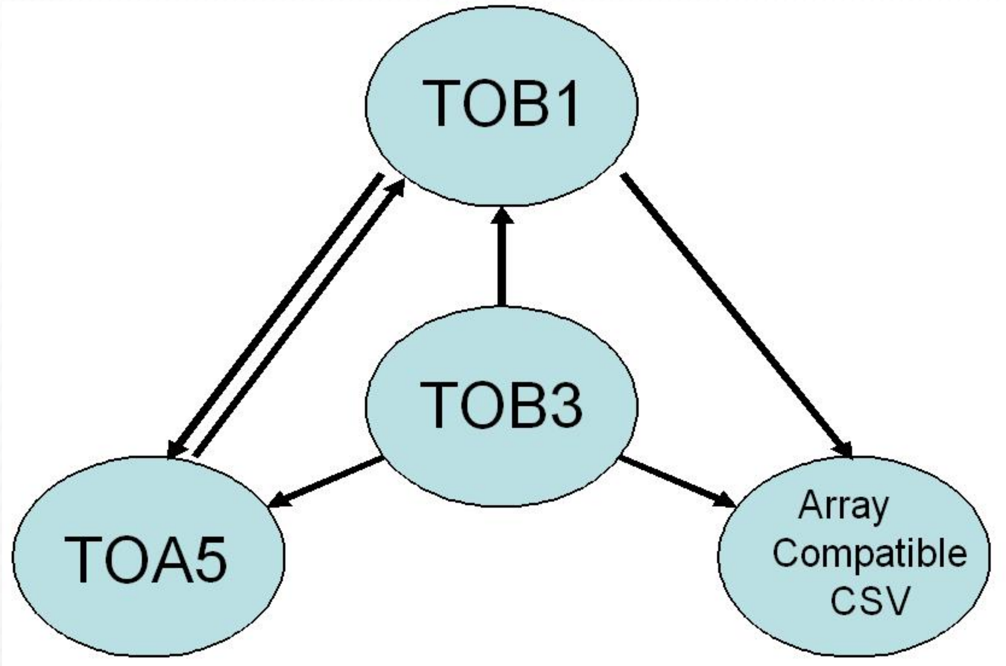
Method	Device	Duty Cycle	Comments
CF Card	NL115/CFM100	<3	Most reliable, not expensive, always recommended even if redundant
RS-232	CR3000 to PC	7	Least expensive
Short Haul/RS-485	-	7	Estimated to be similar to RS-232
Radio	RF-450	50	Highly variable
Ethernet (Internet)	NL115	34	Somewhat variable
Ethernet (LAN)	NL115	6	Somewhat variable
Wi-Fi	NL240	35	Serial server, ad-hoc
Wi-Fi	NL240	64	Bridge mode, LAN
Cellular	RavenXTG	28	LN server auto collects every half hour
Cellular FTP	RavenXTG	10	2.3 hrs to send a daily ts 58MB file, use FTPClient()
Cellular HTTP	RavenXTG	11	2.7 hrs to send a dialy ts 58MB file, initiated through web browser

Note that cellular coverage and rates depends on location. For this test, coverage was good and the rate was $60/mo for 5GB.

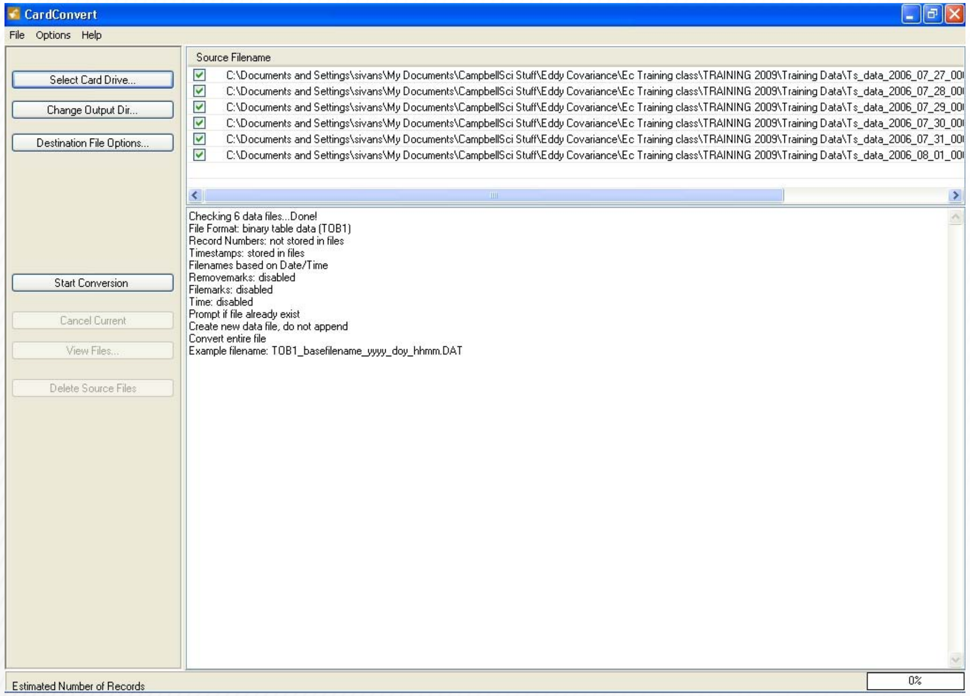
Remote Data Retrieval via a PC/CF Card

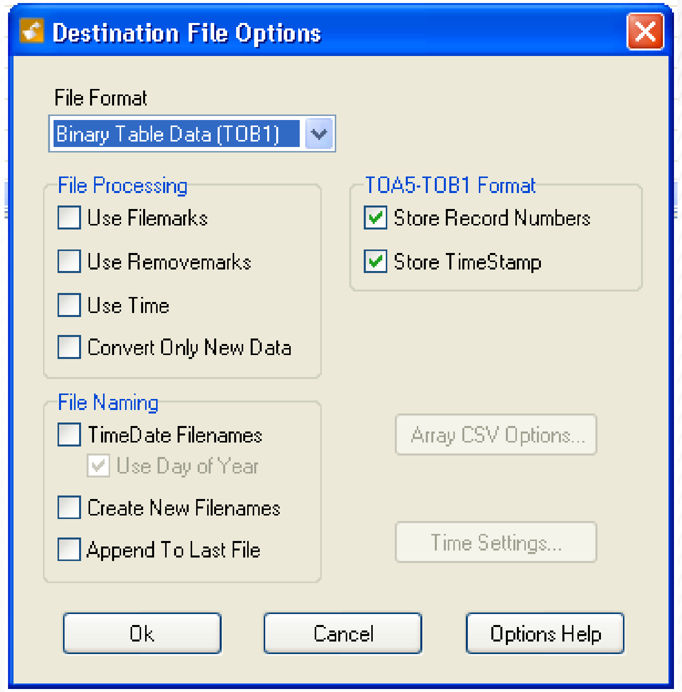
CSI Data Formats

Data on CF card is in TOB3
LoggerNet can collect as TOA5, TOB1, CSV
Most post-processing requires TOB1
After collection, Card Convert can be used to change formats



File management with CardConvert





Online Processing

Review of online processing the EC programs do:

Thirty minute statistics for the turbulence and meteorological variables, these include estimated fluxes, means, and standard deviations.

Estimated fluxes have removal of most spikes from diagnostic filtering and include corrections for sonic temperature (humidity), oxygen correction (KH20), time lag (CPEC200), and WPL (OPEC).

Common corrections that are not included as of now: coordinate rotation of wind, frequency correction (line averaging and spatial separation).

Off-line Processing

EdiRe

Free of charge software which can be downloaded from this website:

http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/Downloads.html

Author is Robert Clements

EdiRe

Basic Data Analyses

Advanced Data Analyses

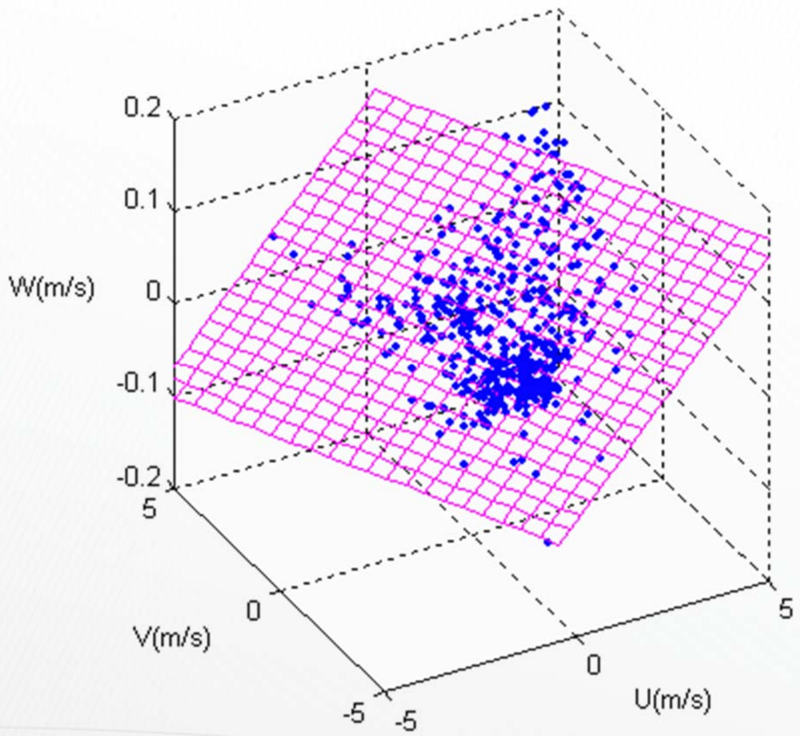
Off-line Processing - cont

Raw time series data are loaded into EdiRE or equivalent software, and then these corrections are most often applied:

1. Despike
2. Apply time delay (may include cross-correlation)
3. Coordinate Rotation (double coord. Rotation per Tanner & Thurtell 1969 or Planar-Fit method per Wilczak et al 2001)
4. Frequency corrections (path averaging, spatial separation, tube attenuation).
5. Sonic temperature correction for humidity
6. Density correction (Webb, Pearman, Leuning, 1980)

Off-line Processing - cont

Planar Fit (coordinate rotation)



Coordinate System Rotated About This Plane