Using theory to make good measurements

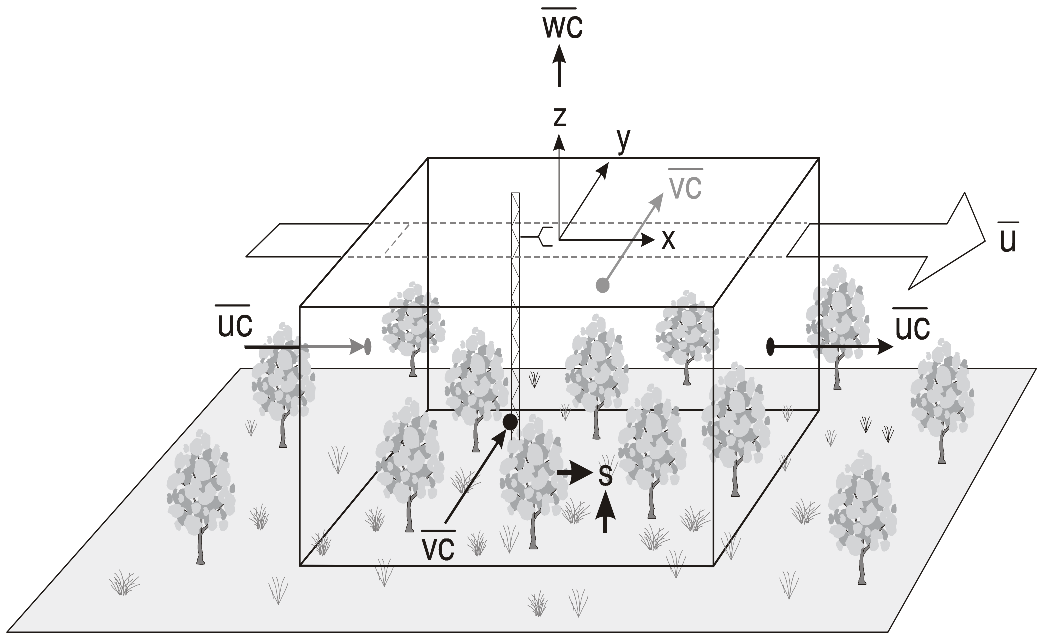
Ray Leuning

CSIRO Marine and Atmospheric Research, Canberra, Australia

www.csiro.au

Design considerations for eddy flux measurements

- Measurement height
- Fetch/footprint - rule of thumb z_m = x/100
- Horizontal homogeneity of surface and topography
- High frequency filtering - instrumentation
- Low frequency filtering -averaging
- Application of WPL theory
- Open-path instruments
- Closed-path instruments
- Change in storage terms



Minimum measurements needed

Top of mast

- 3-D wind vector (20Hz)
- CO_2 and H_2O concentrations (20Hz)
- Net radiation
- Incoming solar radiation
- Reflected solar radiation
- RH and air temperature
- Rainfall
- Wind speed and direction

Minimum measurements needed (cont[d])

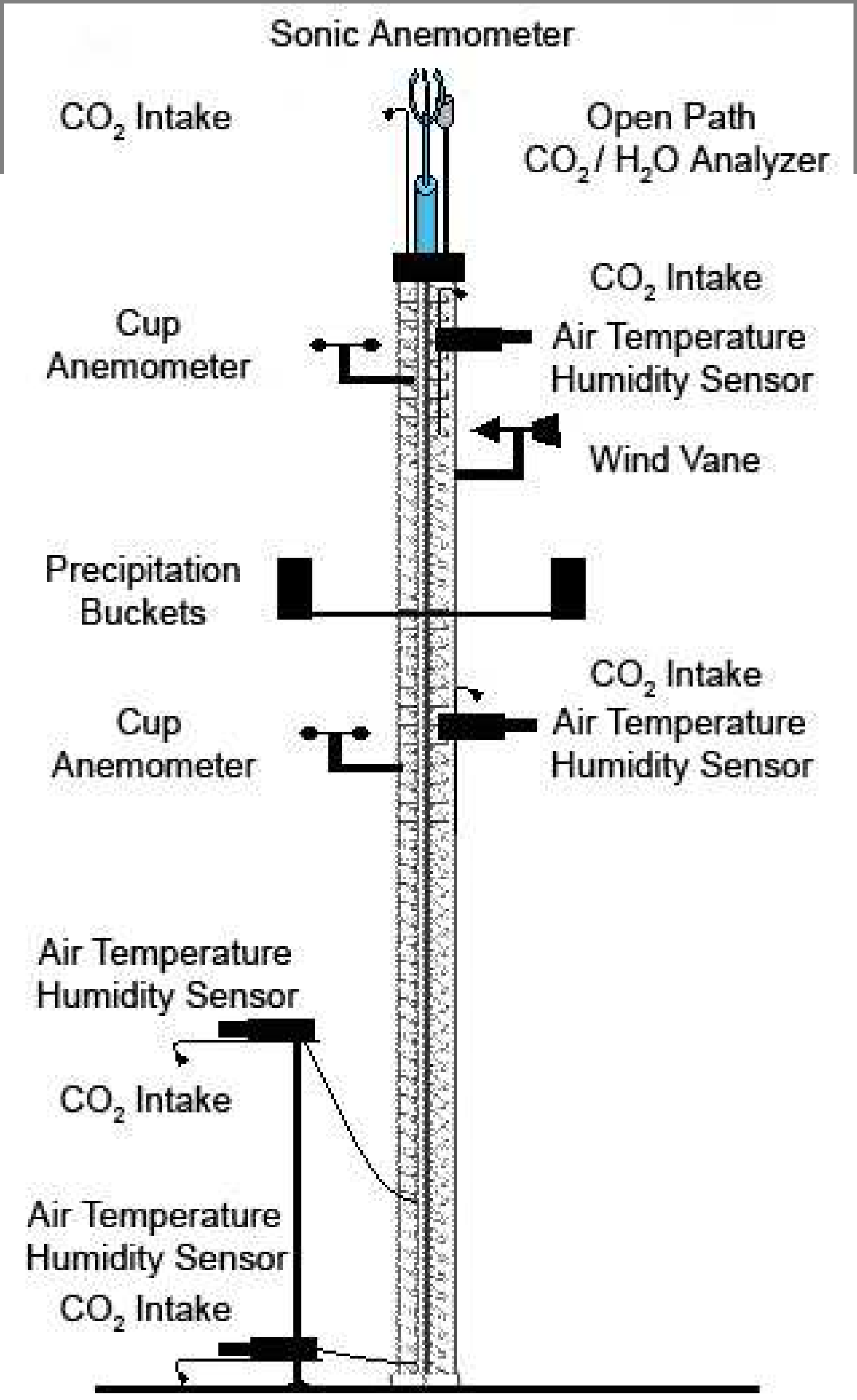
Ground

- Soil temperature
- Soil heat flux
- Soil moisture
- Rainfall
- Tree trunk temperature

Profiles (multiple levels, 1 Hz)

- Temperature
- CO_2
- H_2O vapour
- 2- or 3-D wind vectors

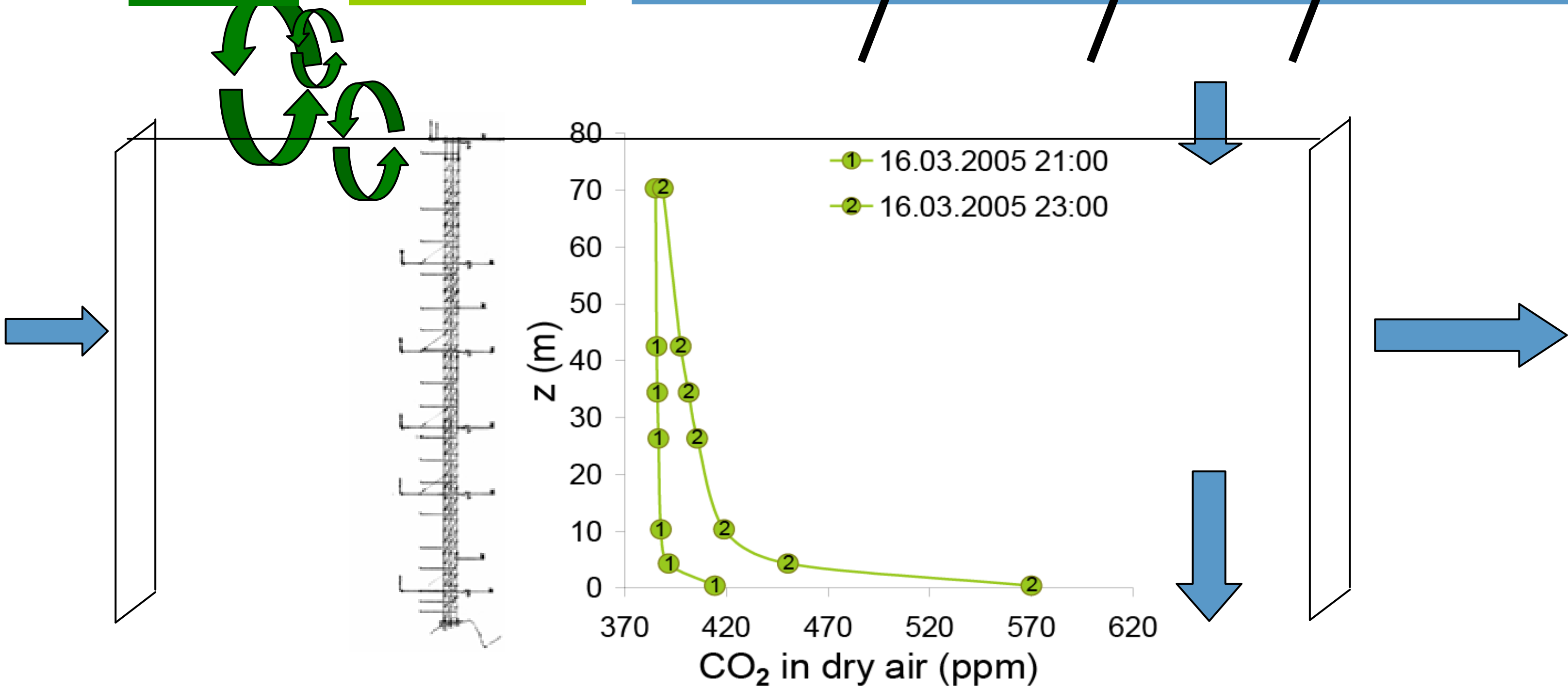
Tower schematic



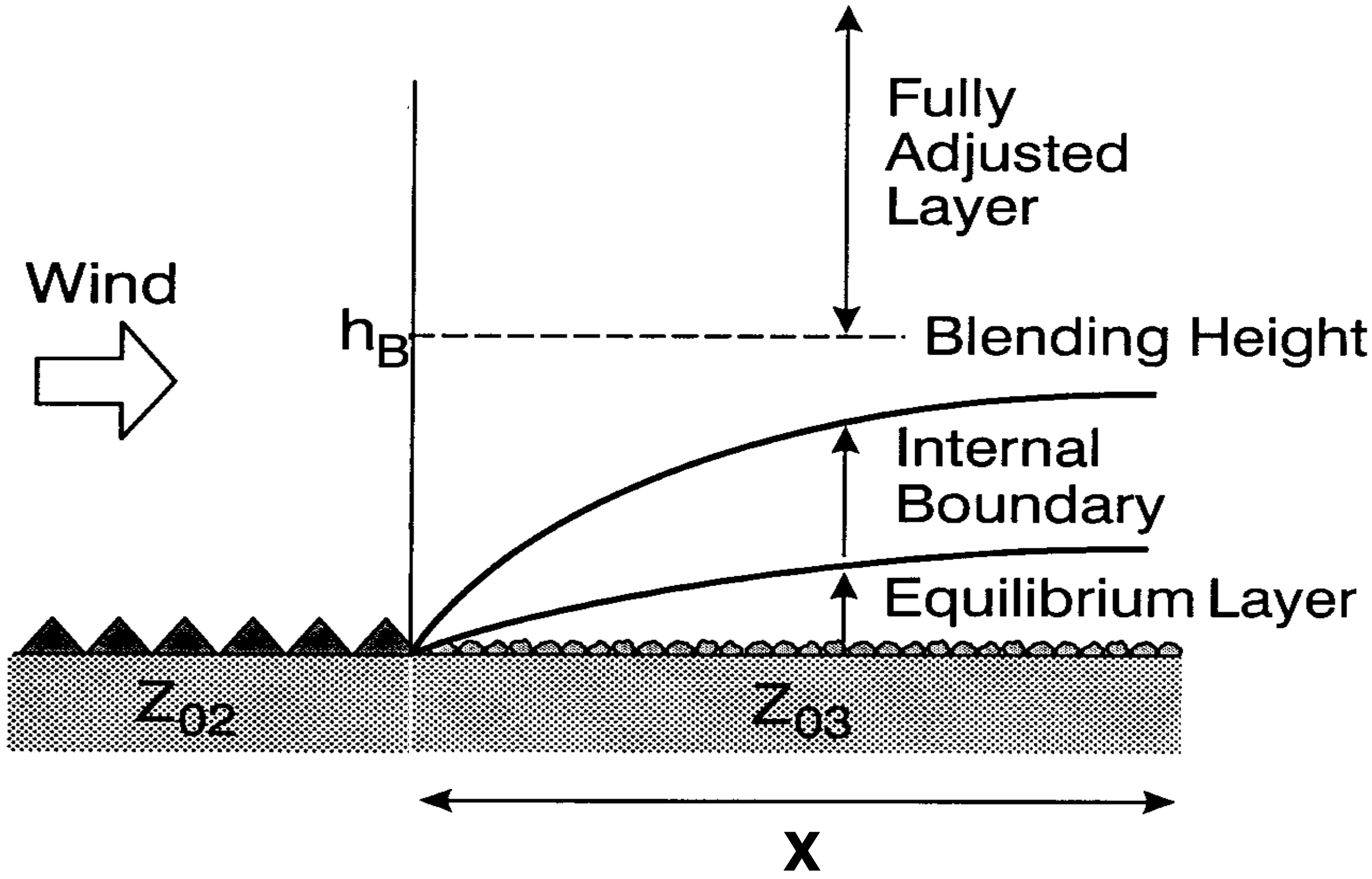
Reminder of assumptions

Horizontally homogeneous flow – no advection

$$F_c = \overline{c_d}\,\overline{w'\chi_c'} + \int_0^h \overline{c_d}\,\frac{\partial \overline{\chi_c}}{\partial t}\,dz + \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\overline{u c_d}\,\frac{\partial \overline{\chi_c}}{\partial x} + \overline{v c_d}\,\frac{\partial \overline{\chi_c}}{\partial y} + \overline{w c_d}\,\frac{\partial \overline{\chi_c}}{\partial z} \right] dx\,dy\,dz$$



Internal boundary & equilibrium layers



Height-to-fetch ratio

100:1 fetch rule of thumb

- Neutral conditions
- > for stable conditions
- < for unstable conditions

$$z_m \leq X/100$$

Instrument placement

- Often a compromise between a representative footprint and avoiding advective effects

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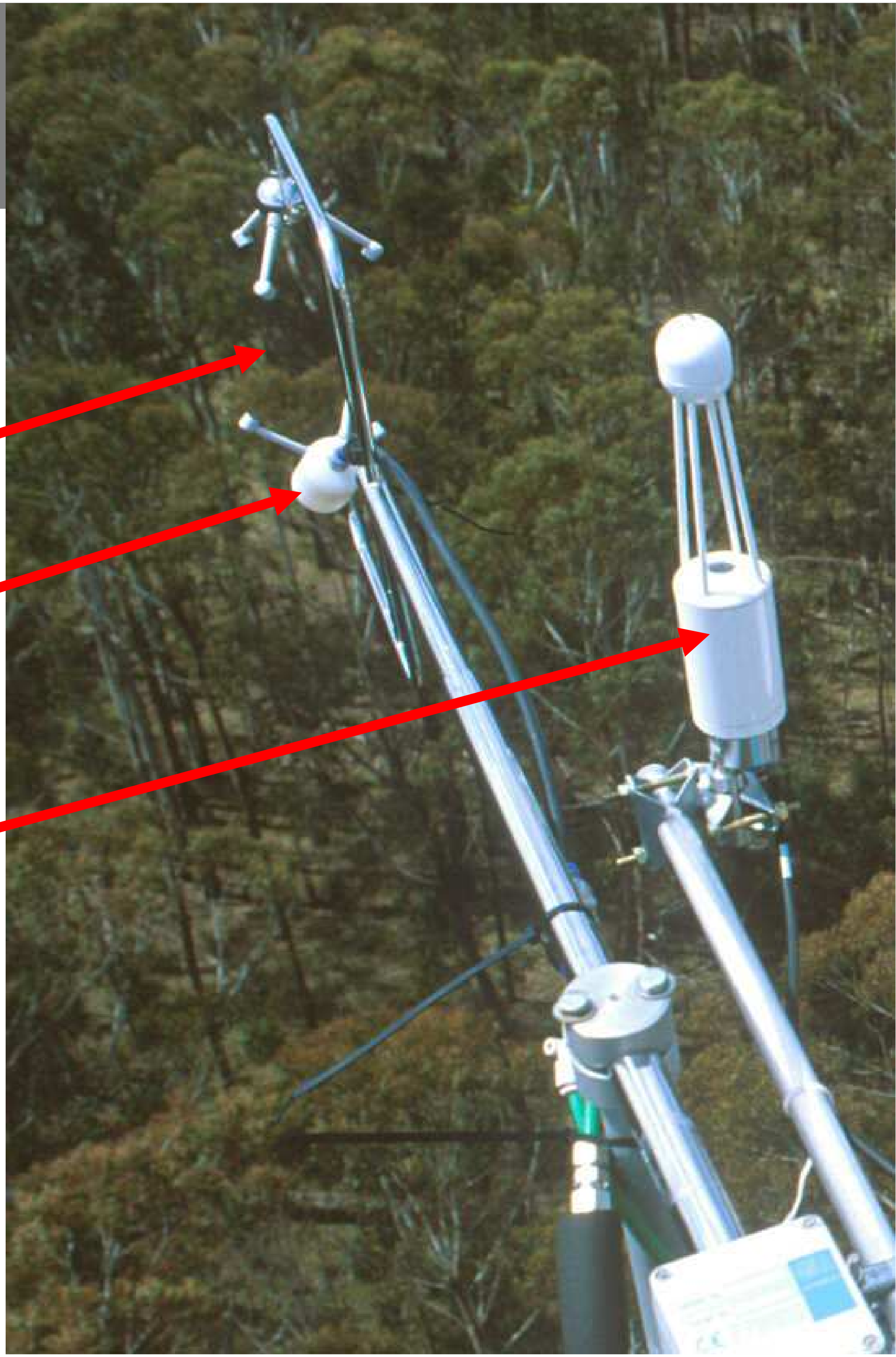
Typical eddy flux instrumentation

Sonic anemometer

Air intake for closed-path CO_2 & H_2O analyser

Open-path CO_2 & H_2O analyser



High frequency attenuation

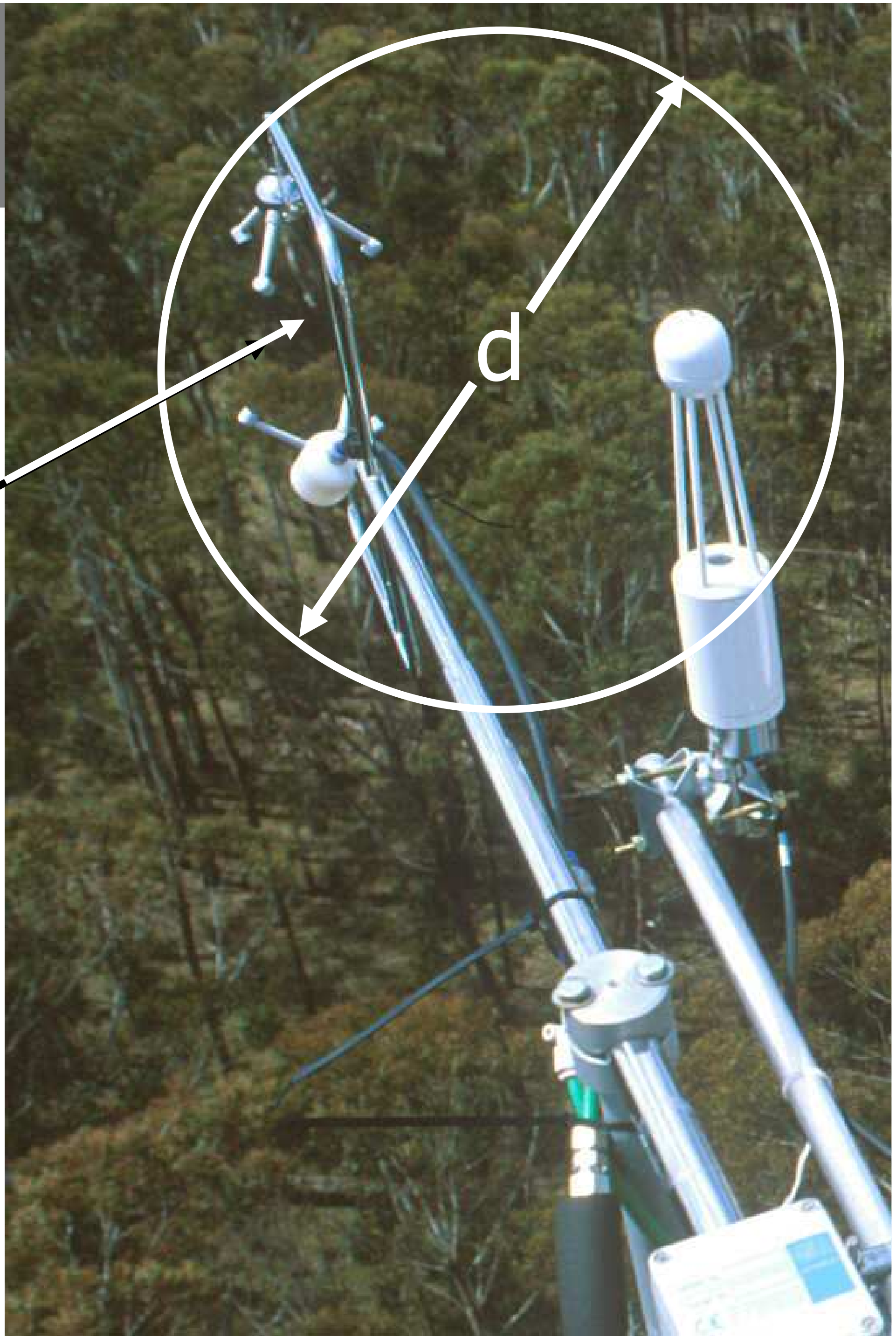
Line-averaging along instrument path

– loss of variance

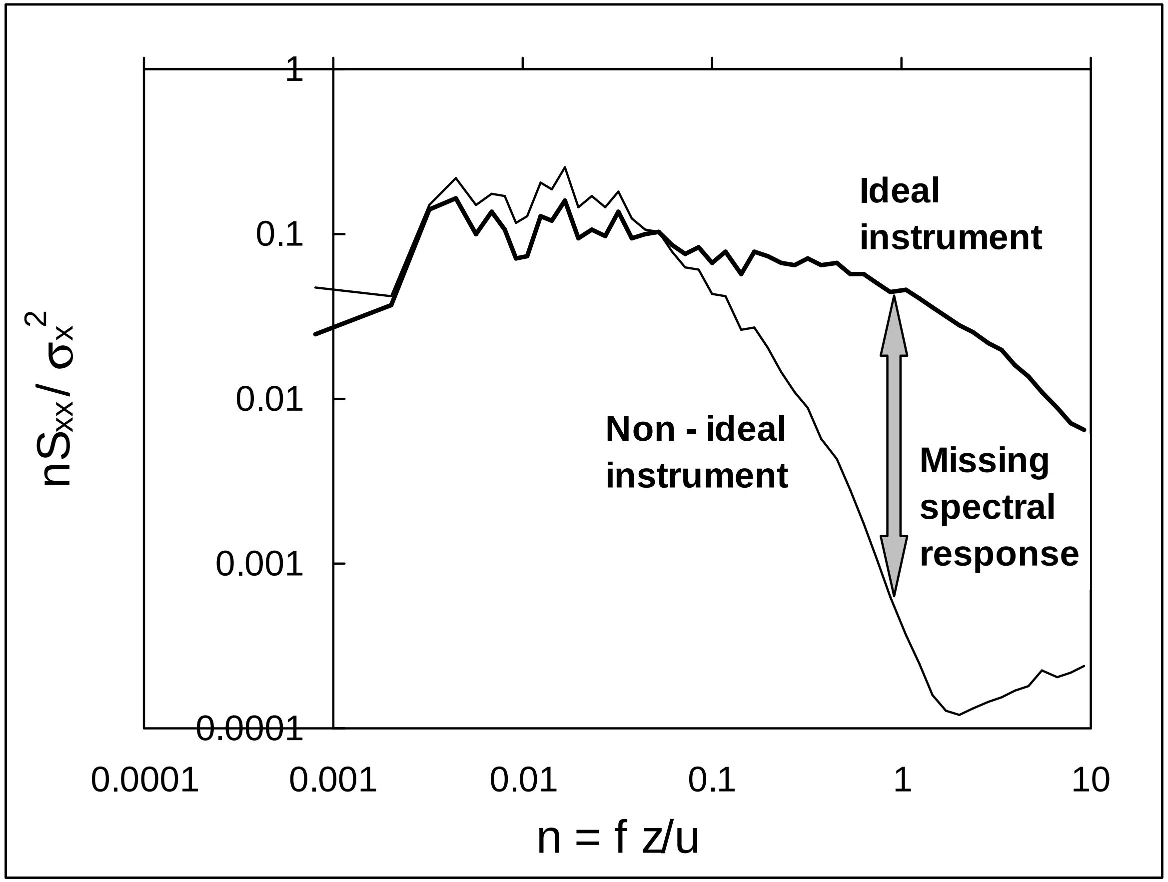
Spatial separation between instruments

– loss of covariance

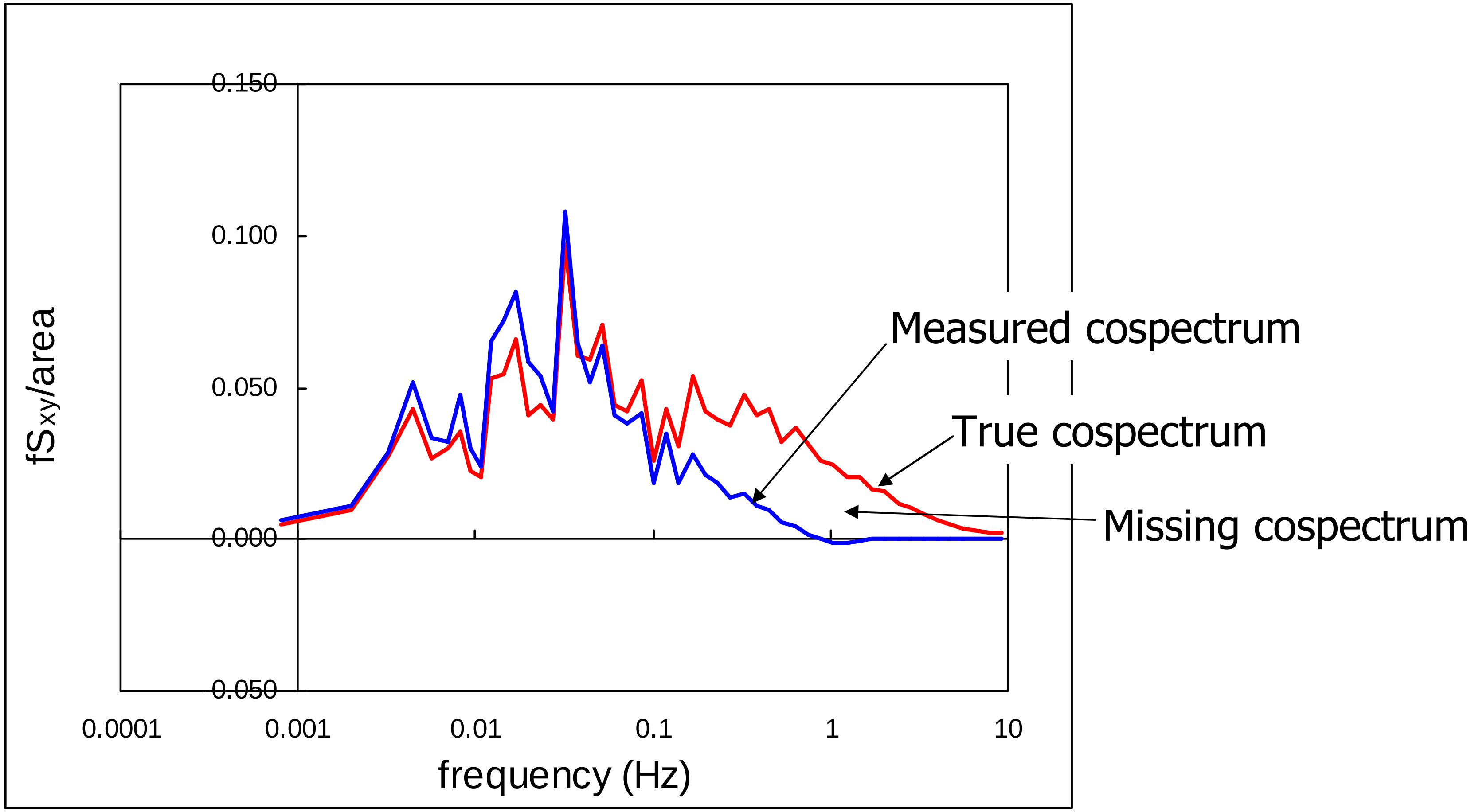
- Samples eddies > ~2d



Variance spectrum - high-cut filter

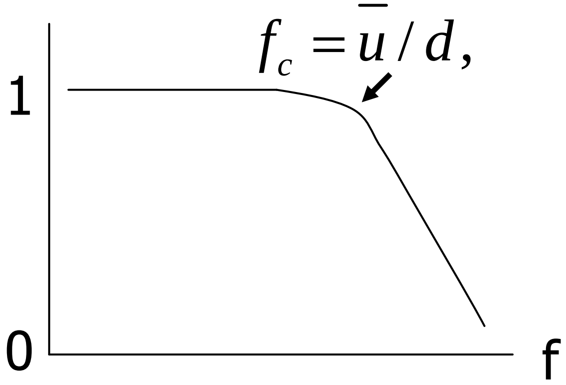


Covariance spectrum – high cut filter



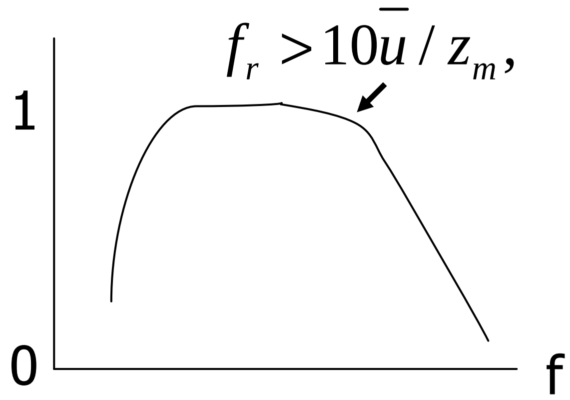
Measurement height – a compromise

System filter



$$\geq$$

Atmospheric turbulence



$$f_c \geq f_r \quad \rightarrow \quad z_m \geq 10d$$

Remember equilibrium layer

$$z_m \leq X/100$$

Low frequency covariance

Average for long enough to

- $\bar{u}$ and *x* axis are parallel to the ground
- *z* is normal to the ground
- include all significant low-frequency contributions to the covariance

Averaging period increases with

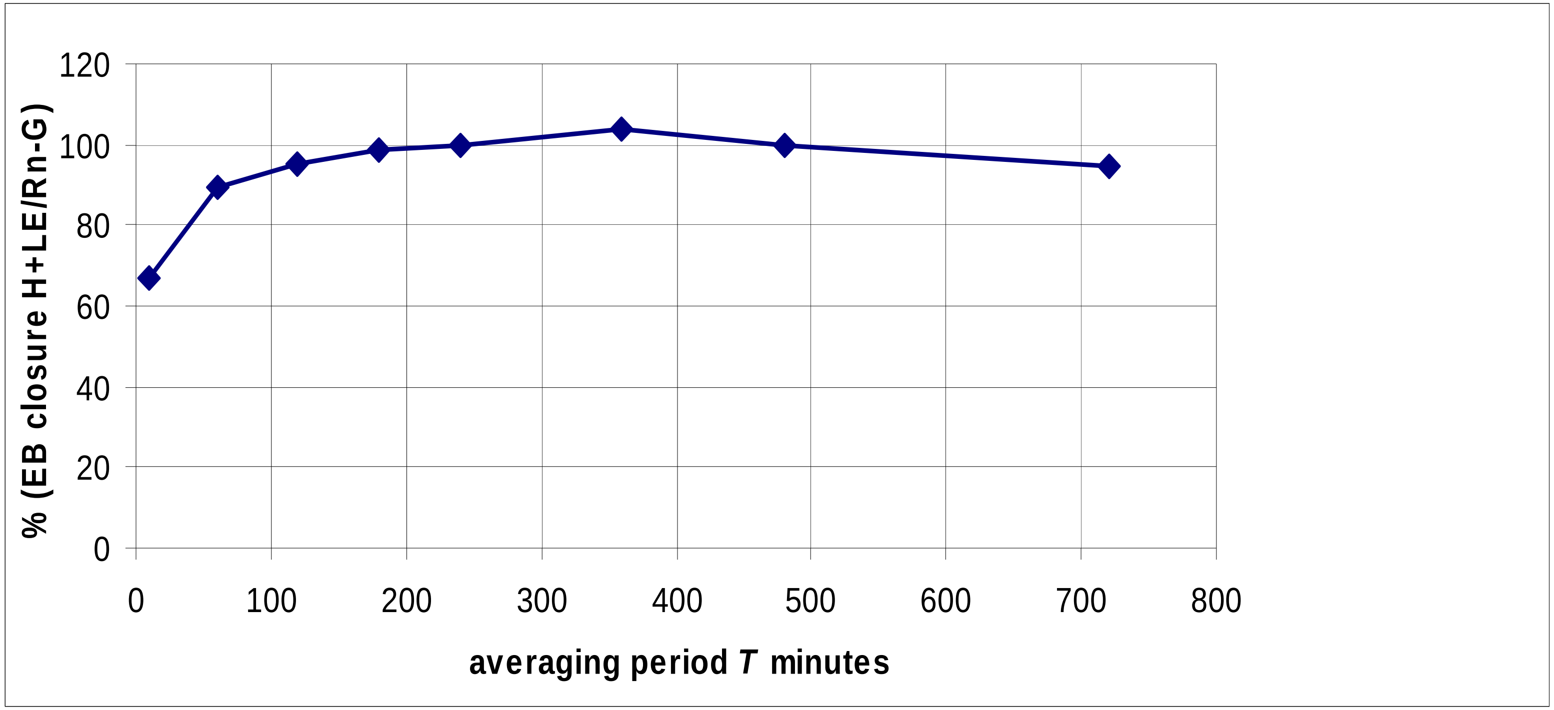
- measurement height
- free convection (unstable boundary layers)
- complex topography

Check averaging period

Usual 30-min period may be too short to capture all the significant low frequency covariance

Convective conditions at Manaus tropical forest site ensure significant low frequency content in the covariance.

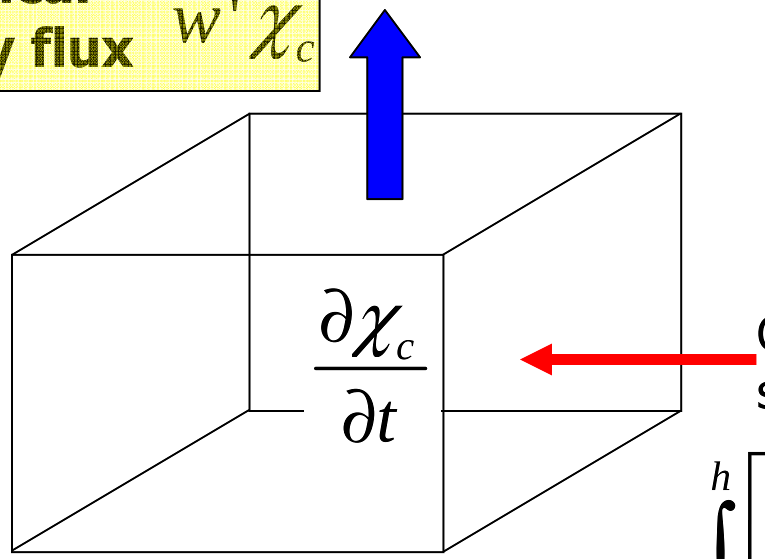
This is lost if the averaging period is < ~4 hours



Measurements on a single tower

$$\overline{F_0} = \overline{c_d}\int_0^h \overline{\frac{\partial \chi_c}{\partial t}}\,dz + \overline{c_d}\;\overline{w'\chi_c'}$$

Vertical eddy flux $\overline{w'\chi_c'}$



$$\frac{\partial \chi_c}{\partial t}$$

Change in storage

$$\int_0^h \left[\overline{c_d}\,\overline{\frac{\partial \chi_c}{\partial t}}\,dt \right] dz$$

Sonic anemometer gives:

$$\overline{u}, \overline{v}, \overline{w} \quad u', v', w'$$

$$H = \rho \overline{c}_{pd} \overline{w' T_v'}$$

Where sonic virtual temperature is

$$T_v = T(1 + 0.514q)$$

Still require

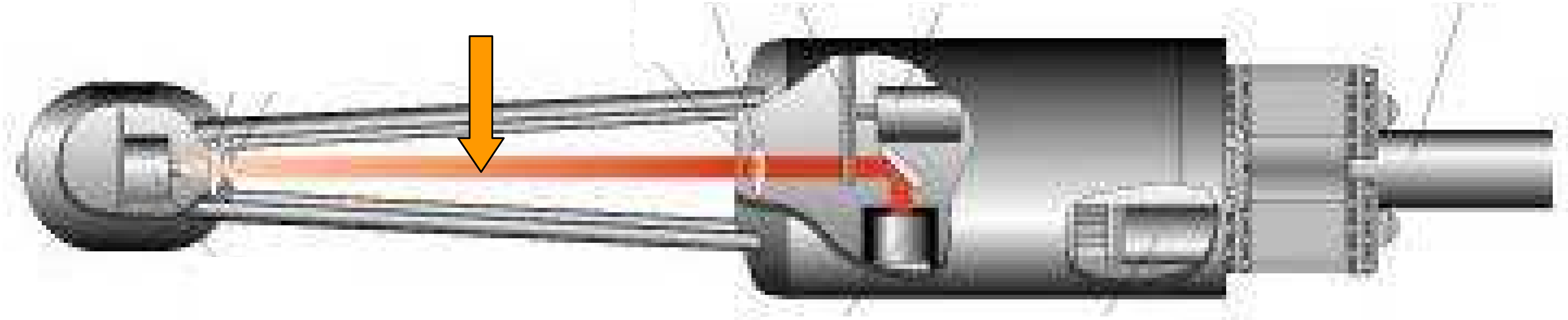
$$\lambda E = \lambda \overline{c}_d \overline{w' \chi_v'}$$

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

CO_2 and H_2O flux measurements

Licor 7500 Measures mol m^{-3} in optical path,

not required mixing ratios χ_v χ_c



But! Eddy fluxes have been expressed in terms of mixing ratio. What to do?

$$\overline{F_c} = \overline{c_d}\,\overline{w'\chi_c'}$$

Eddy flux for trace gas – WPL

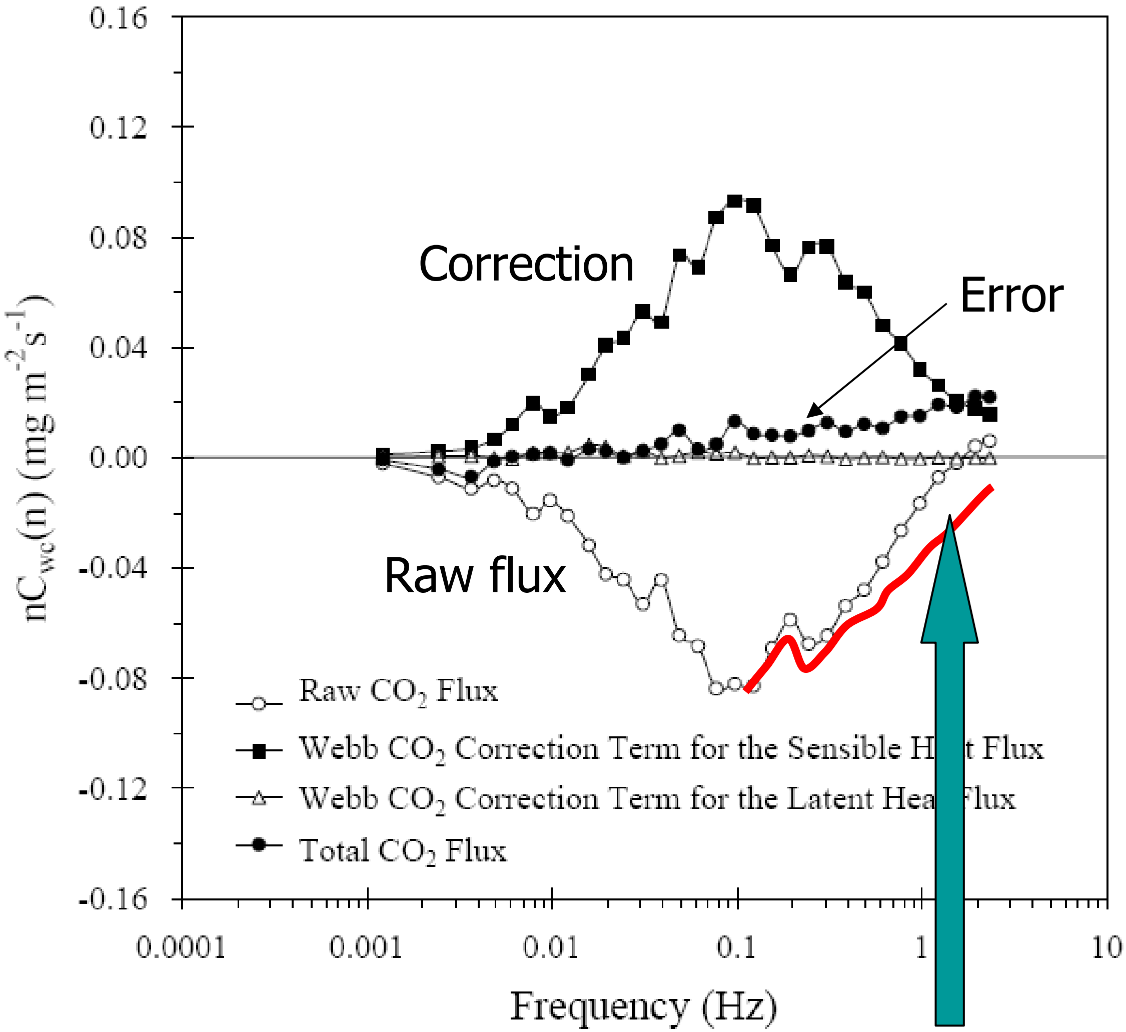
$$\overline{F_c} = \bar{c}_d\,\overline{w'\chi_c'} = \overline{w'c_c'} + \overline{\chi_c}\left[\overline{w'c_v'} + \bar{c}\,\frac{\overline{w'T'}}{\overline{T}}\right]$$

Raw CO_2 flux | Water vapor flux | Heat flux

Applies for horizontally homogeneous flow for both steady and non-steady conditions

Cospectra

Error due to differing frequency responses for cospectra of wT and wc_c



Need to correct for loss of covariance before WPL correction

Open path measurements – calculation sequence

1) $\overline{H} = \overline{\rho} c_p \overline{w'T'}$

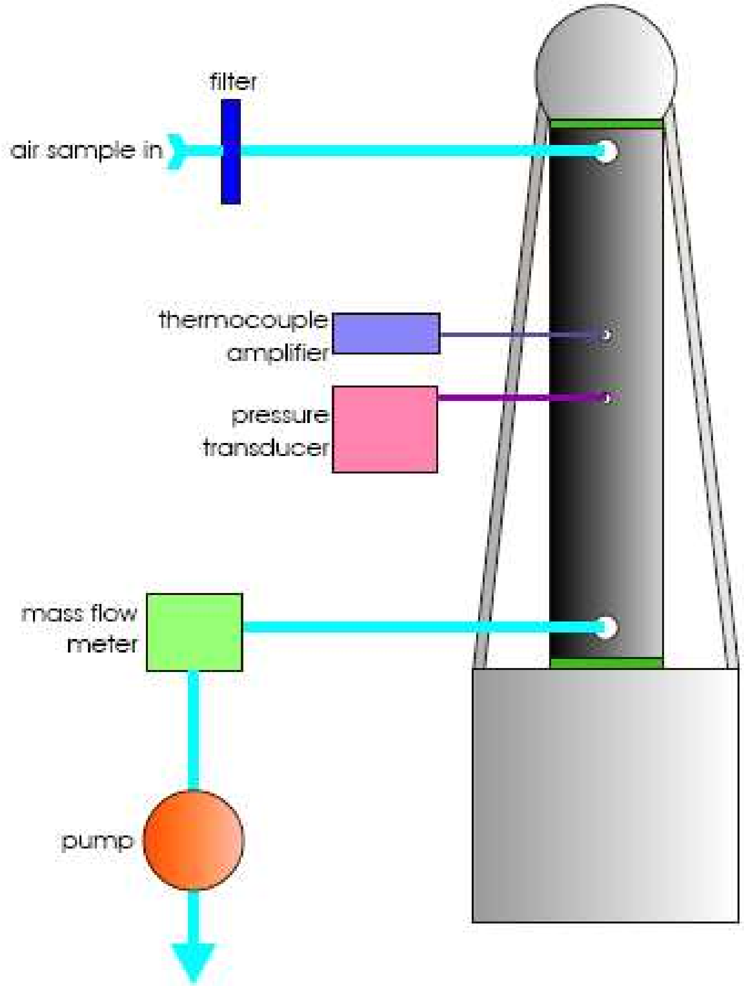
2) $\overline{E} = (1 + \overline{\chi}_v)\left[\overline{w'c_v'} + \frac{\overline{c}_v}{\overline{T}} \frac{\overline{H}}{\overline{\rho} c_p} \right]$

3) $\overline{F}_c = \overline{w'c_c'} + \overline{c}_c \left[\frac{\overline{E}}{\overline{c}} + \frac{\overline{H}}{\overline{\rho} c_p \overline{T}} \right]$

Assumes *H*, *E* & F_c have already been corrected for high & low frequency filtering

Closed-path analyser

Conversion of Li7500



Closed-path analyser

Measure c_c, c_v, T & P simultaneously in gas analyser and calculate mixing ratio at sampling rate used for eddy covariance

$$\chi_v = \frac{c_v}{P_i/(RT_i) - c_v}, \quad \chi_c = \frac{c_c}{P_i/(RT_i) - c_v}$$

Must also consider

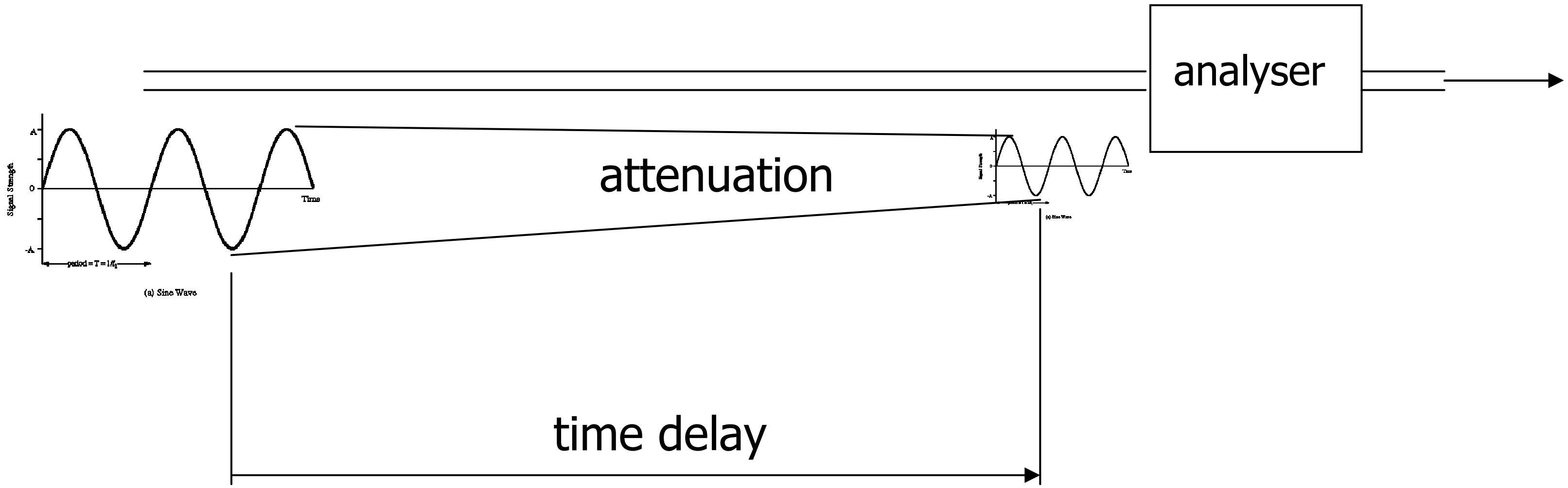
- Time-lag
- Hi-frequency attenuation by air flow in tubing

High Frequency Attenuation
- Closed path

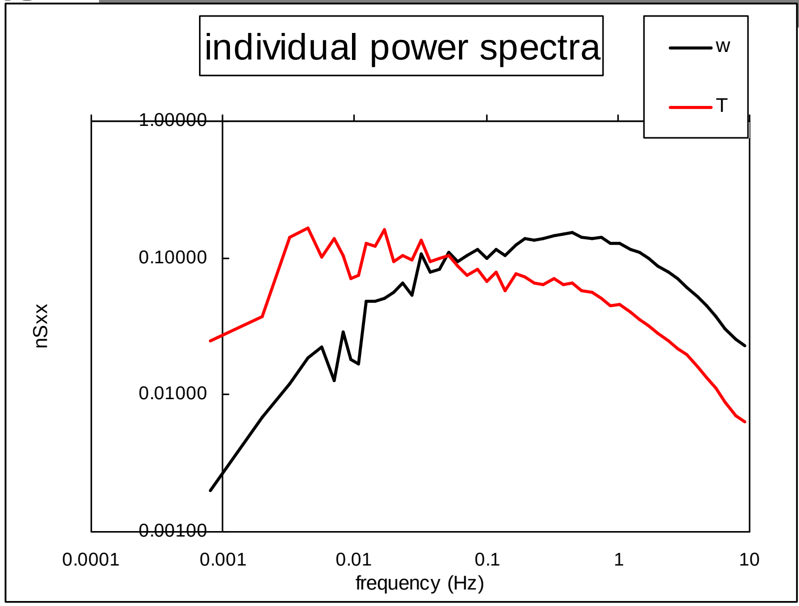
Tubing acts like a low-pass filter by mixing the air

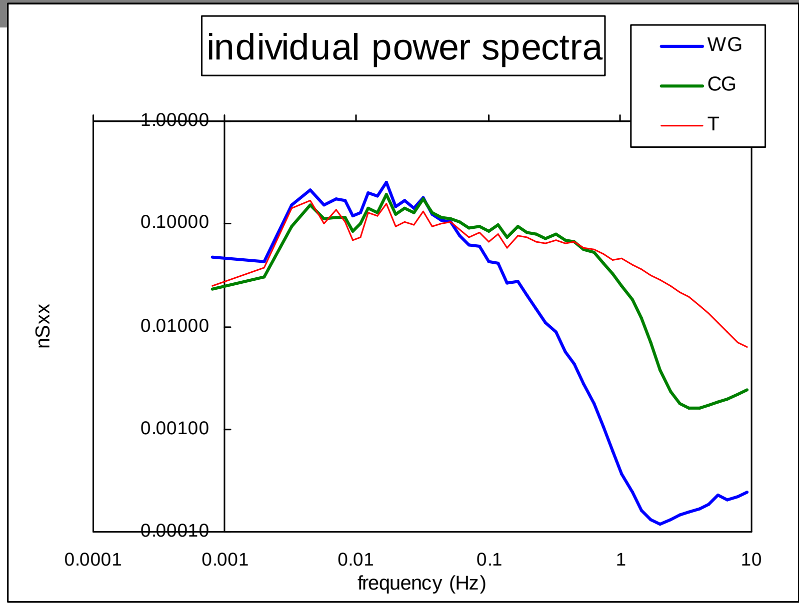
Higher frequencies strongly attenuated – depends on:

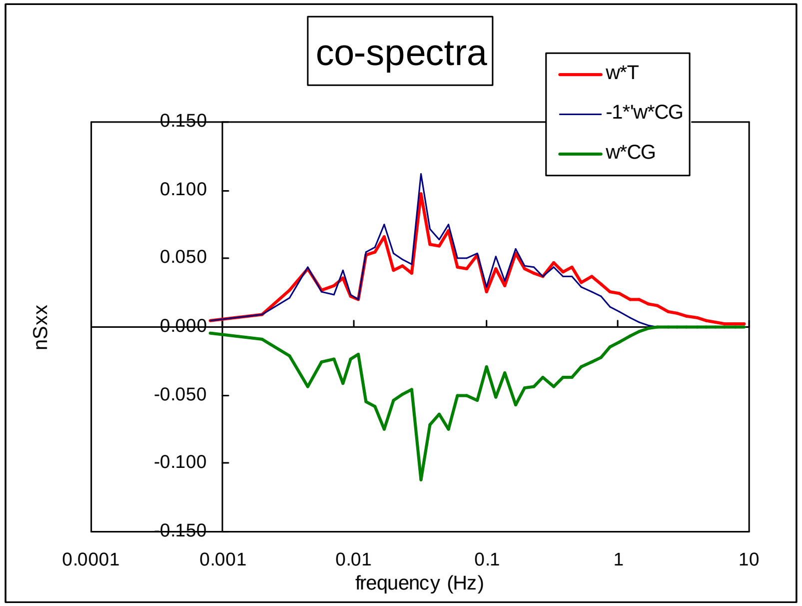
- Flow rate through tube
- Tube diameter, length and material

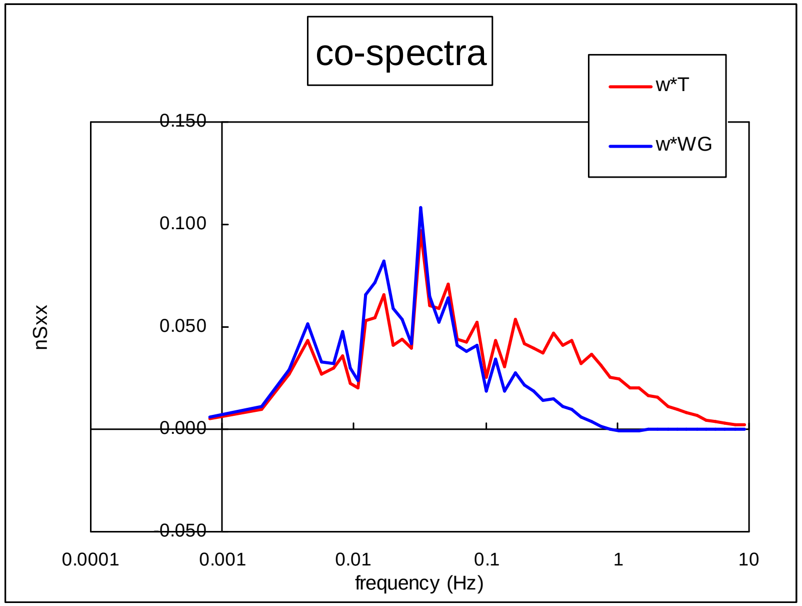


Closed path spectra and co-spectra

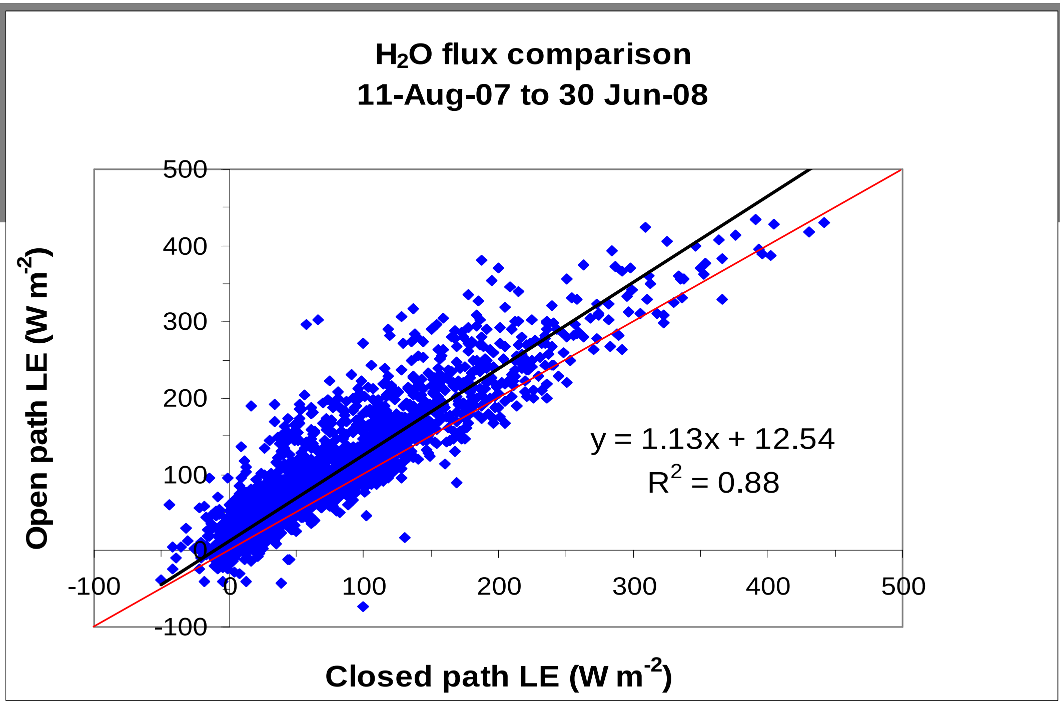






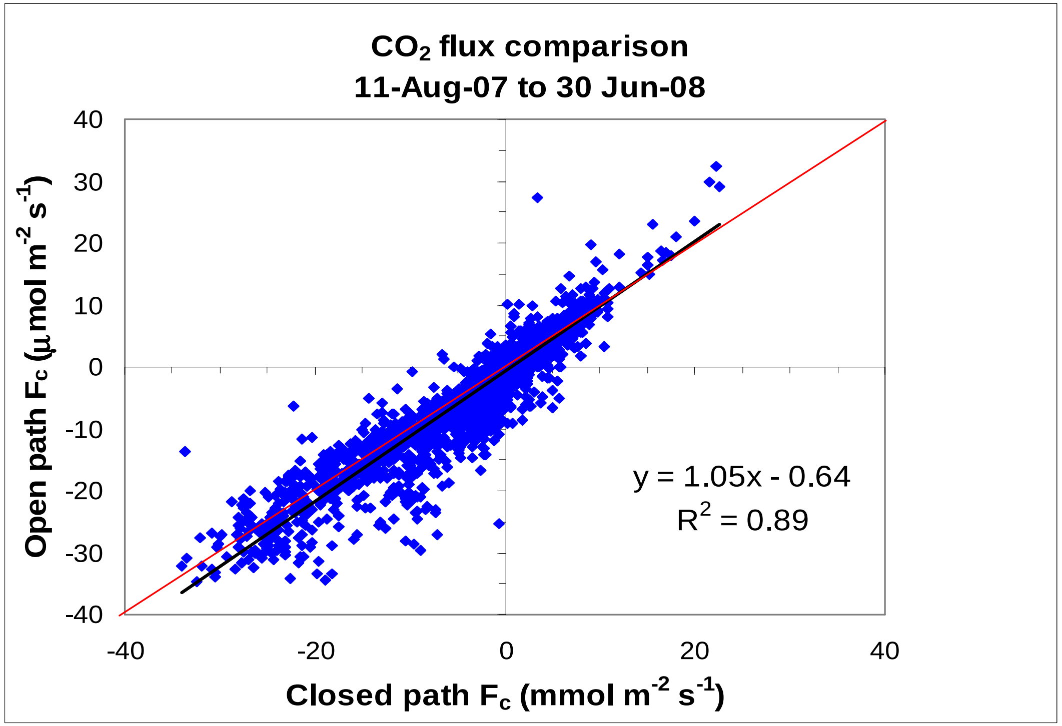


H_2O



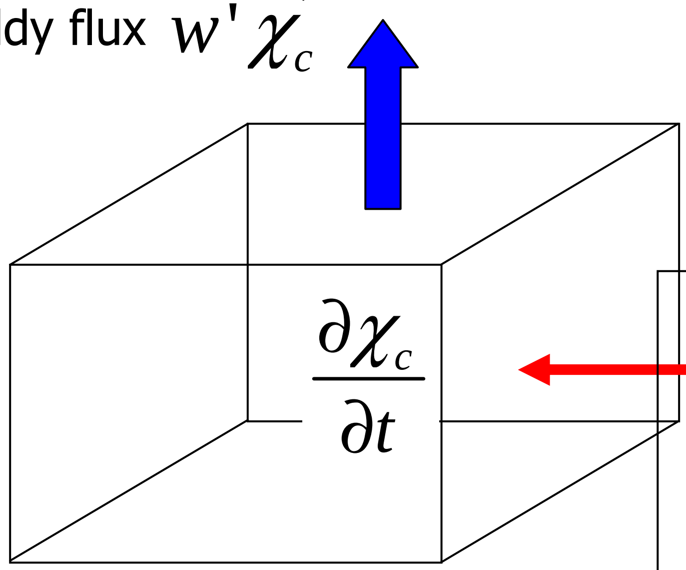
Open vs closed path instruments

CO_2



Measurements on a single tower – change in storage term

Vertical eddy flux $\overline{w'\chi_c'}$



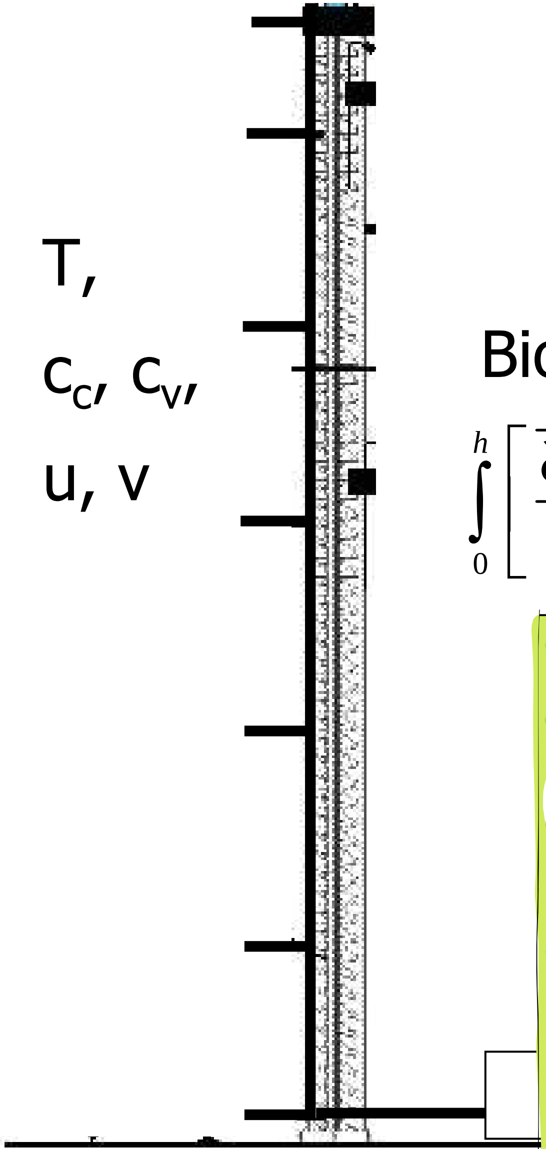
Change in storage

$$\int_0^h \left[\overline{c_d}\, \overline{\frac{\partial \chi_c}{\partial t}}\, dt \right] dz$$

T,

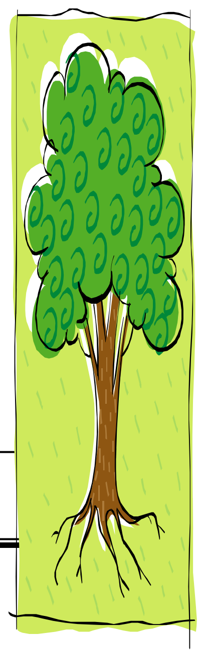
c_c, c_v,

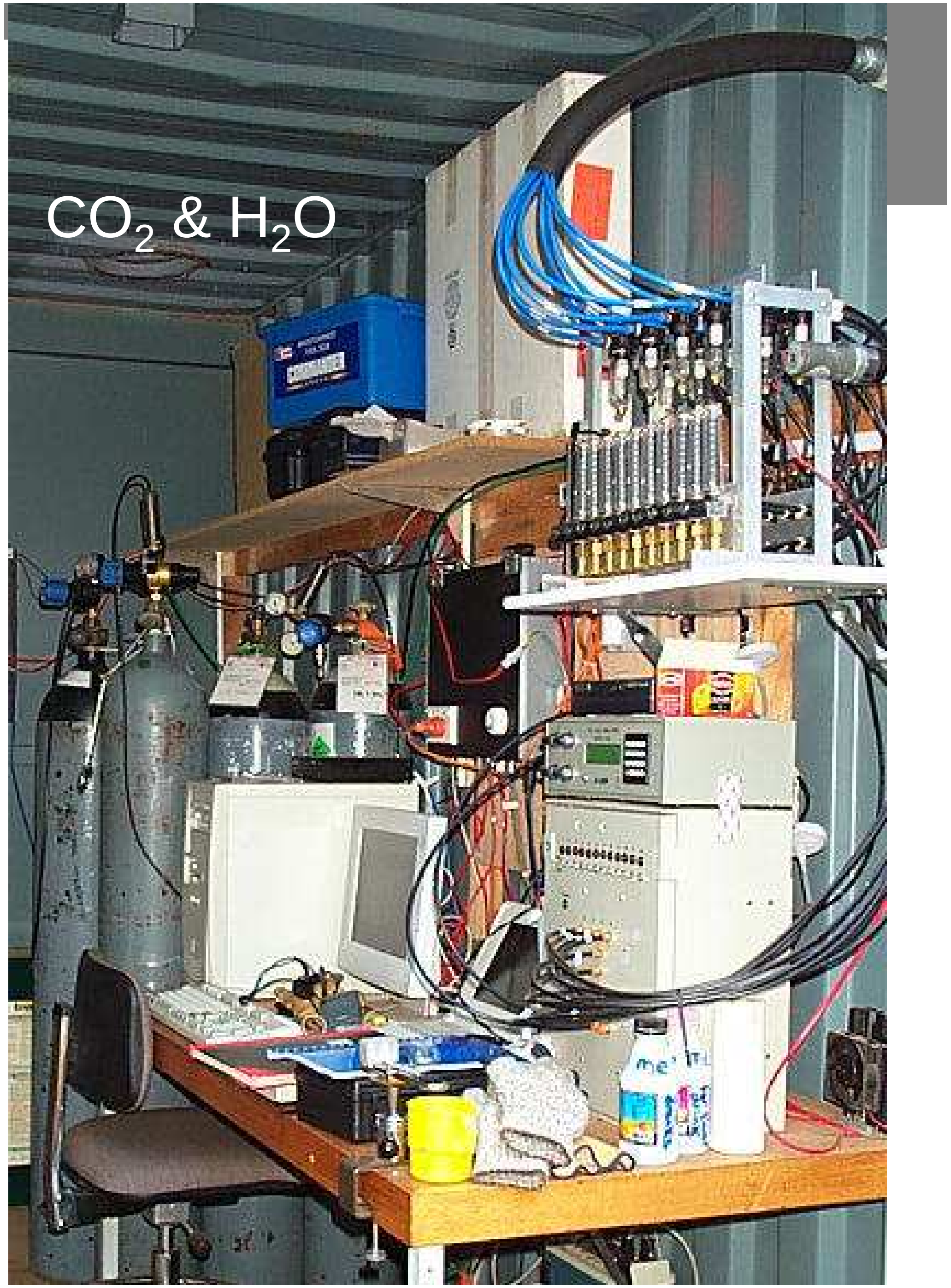
u, v



Biomass

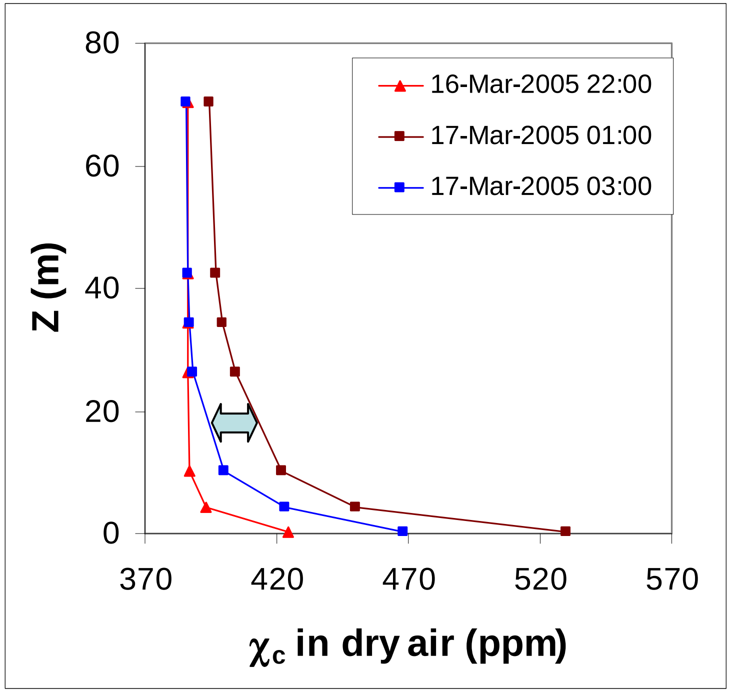
$$\int_0^h \left[\overline{\frac{\partial T}{\partial t}} dt \right] dz$$

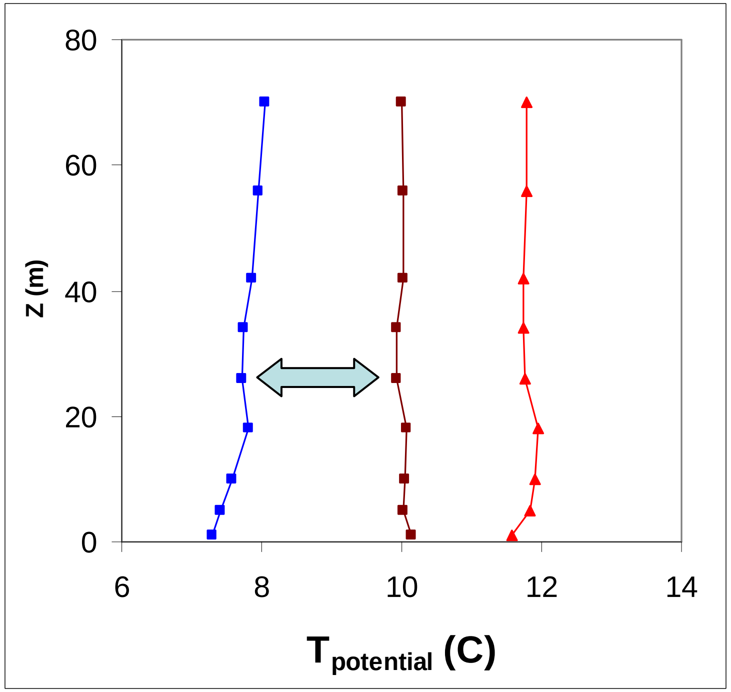




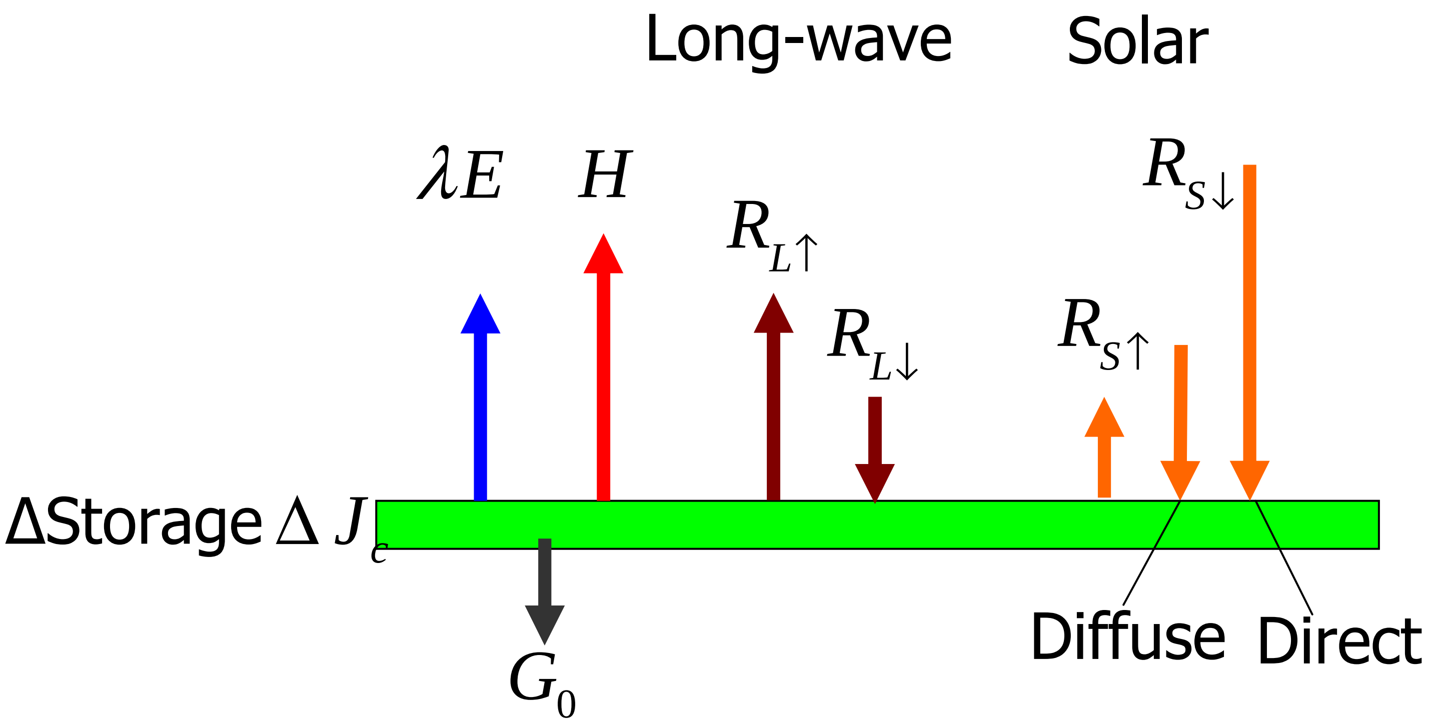
CO_2 & T profiles – change in storage term

$$F_{\Delta storage} = \frac{\overline{c}_d}{\Delta t}\left[\int_0^h \chi_c dz \Big|_{t=\Delta t} - \int_0^h \chi_c dz \Big|_{t=0} \right]$$





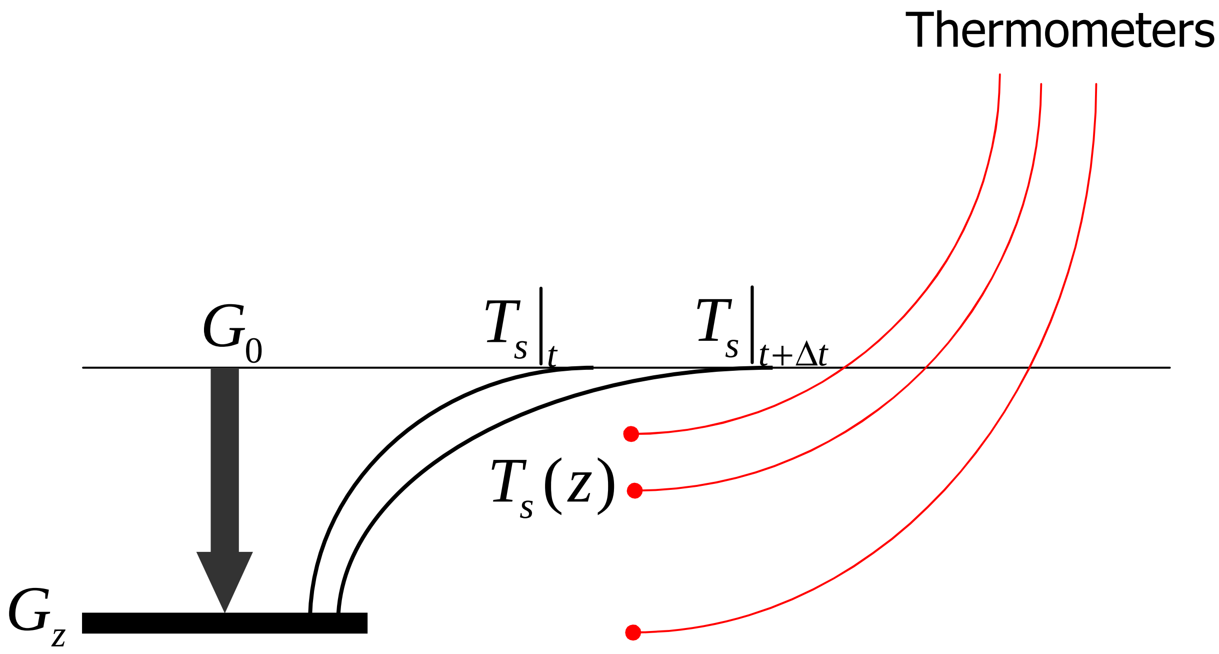
Energy balance



$$H + \lambda E = R_{S\downarrow} - R_{S\uparrow} + R_{L\downarrow} - R_{L\uparrow} - G_0 - \Delta J_c$$

$$H + \lambda E = R_n - G_0 - \Delta J_c$$

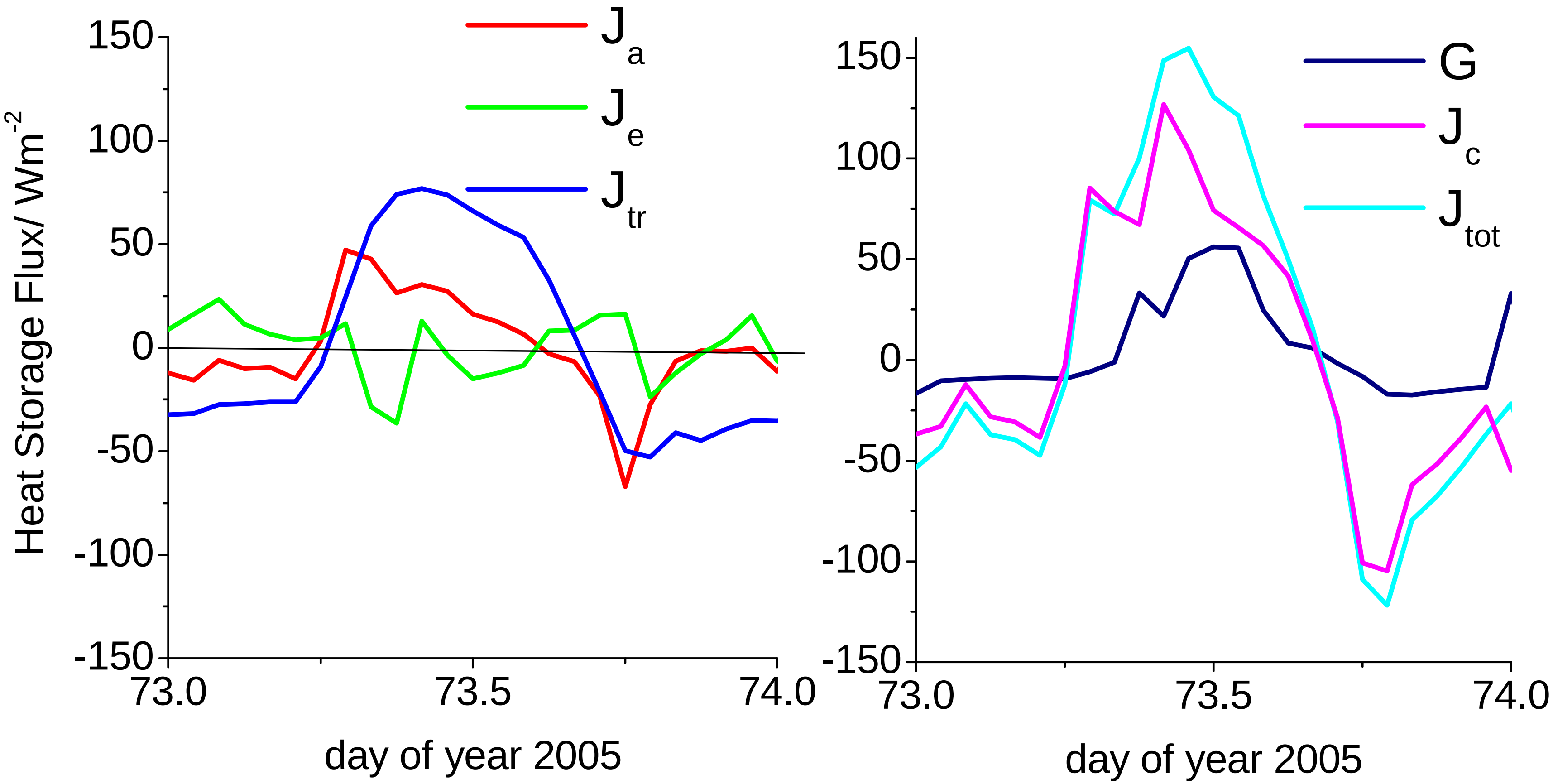
Soil heat flux



Soil heat flux plate

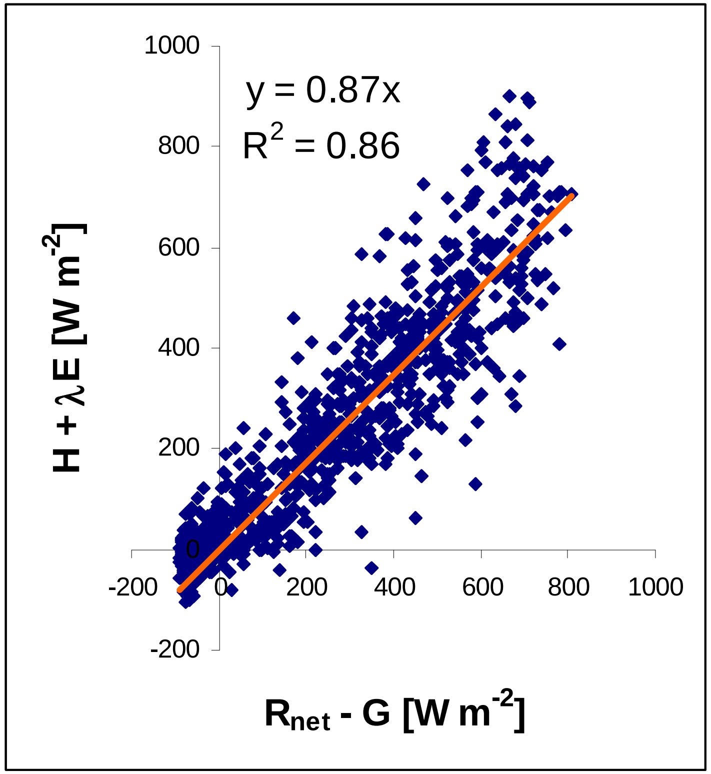
$$\Delta J_s = \frac{m_s c_s}{\Delta t}\left[T_s(z)dz\big|_{t+\Delta t} - T_s(z)dz\big|_t \right]$$

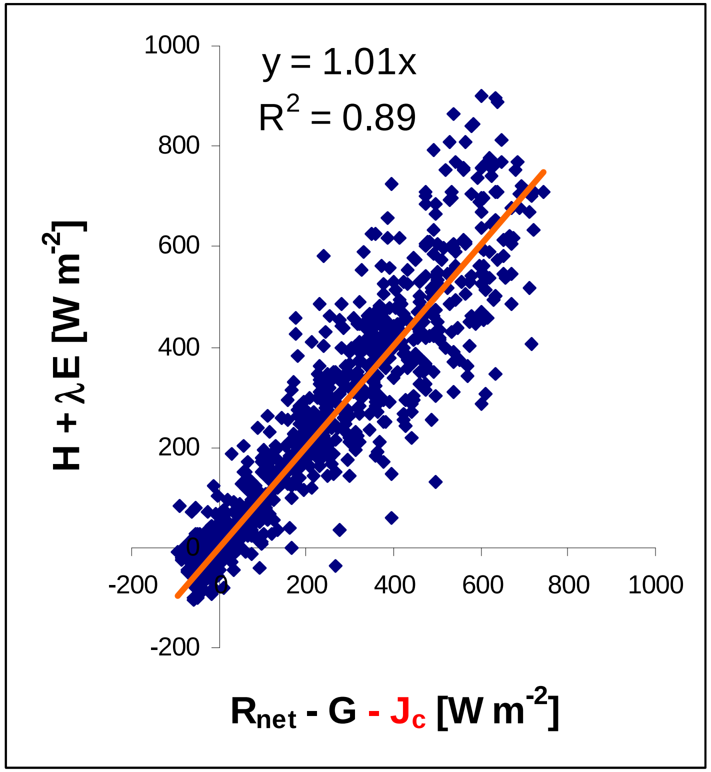
Magnitude of biomass heat storage term



Canopy Energy Balance - Tumbarumba

$$H + \lambda E = R_n - G_0 \left(-\Delta J_c \right)$$





Summary (1):

- Mass balance of a control volume
- Measurements in surface layer
  - Horizontally homogeneous flow
- Fetch requirements
  - Internal boundary layer
- Instrumentation as a band-pass filter
  - High frequency attenuation – instrument separation, line averaging
  - Low frequency attenuation – averaging period too short

Summary (2):

- WPL corrections for open-path analysers
  - Correct for high frequency loss before WPL
- Closed-path analysers
  - Use mixing ratio relative to dry air
  - Correct for lag & high frequency attenuation
  - Lag for CO_2 depends on flow rate
  - Lag for water vapour depends on flow rate & humidity
- Calibrate radiometers
- Change in storage term
  - Measure profiles of *u, T, q, c …*