Uncertainty in EC flux measurements of CH_4 and N_2O

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Energy research Centre of the Netherlands

Delft University of Technology

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P.S. Kroon[1,2], A. Hensen[1], H.J.J. Jonker[2] & H.G. Ouwersloot[1,2]

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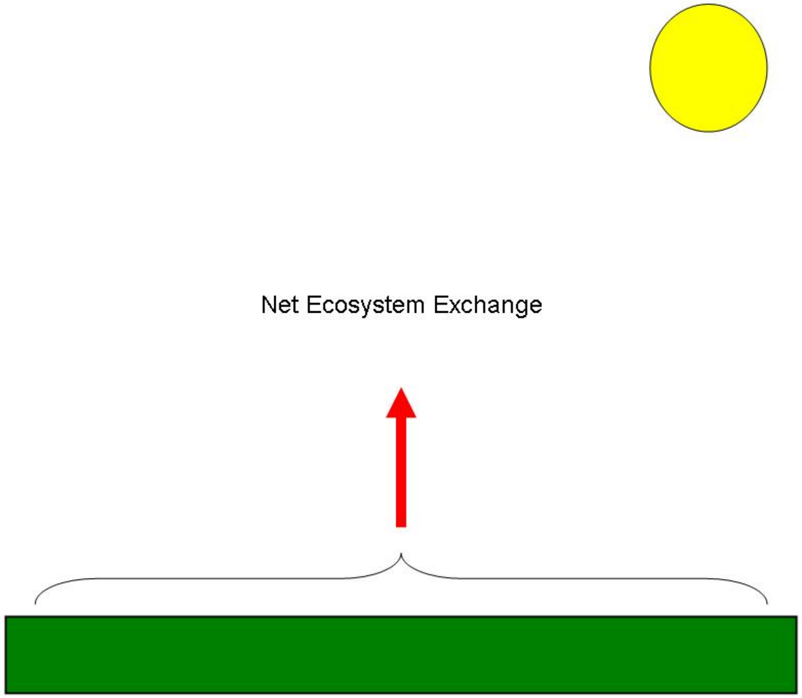
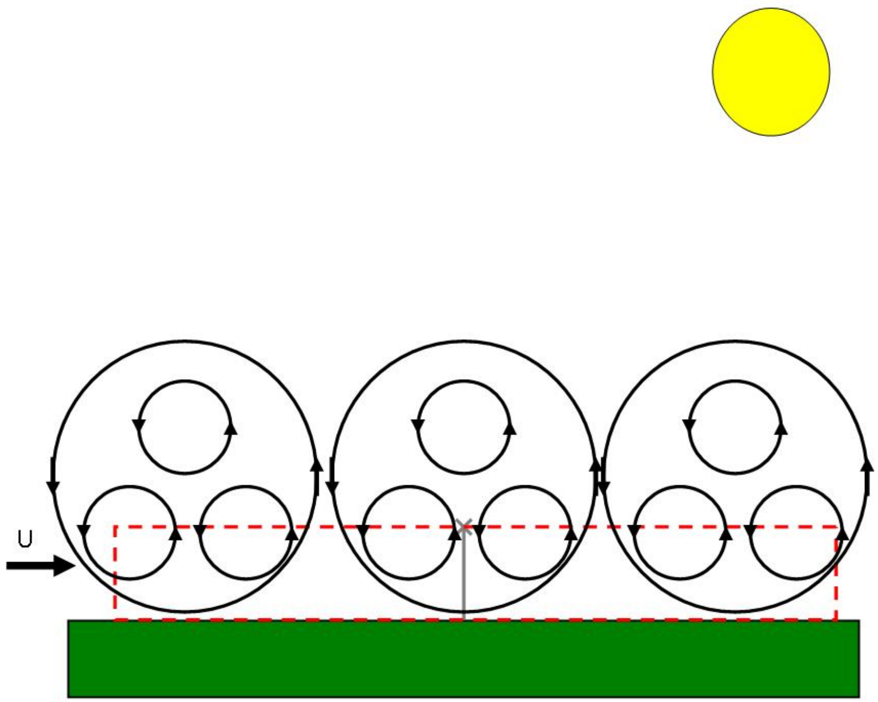
Outline

- Eddy flux and uncertainty theory
- Measurement site and instrumentation
- Some uncertainties highlighted
- Conclusions and discussion points

Eddy flux theory



Eddy flux theory



Tracer conservation equation

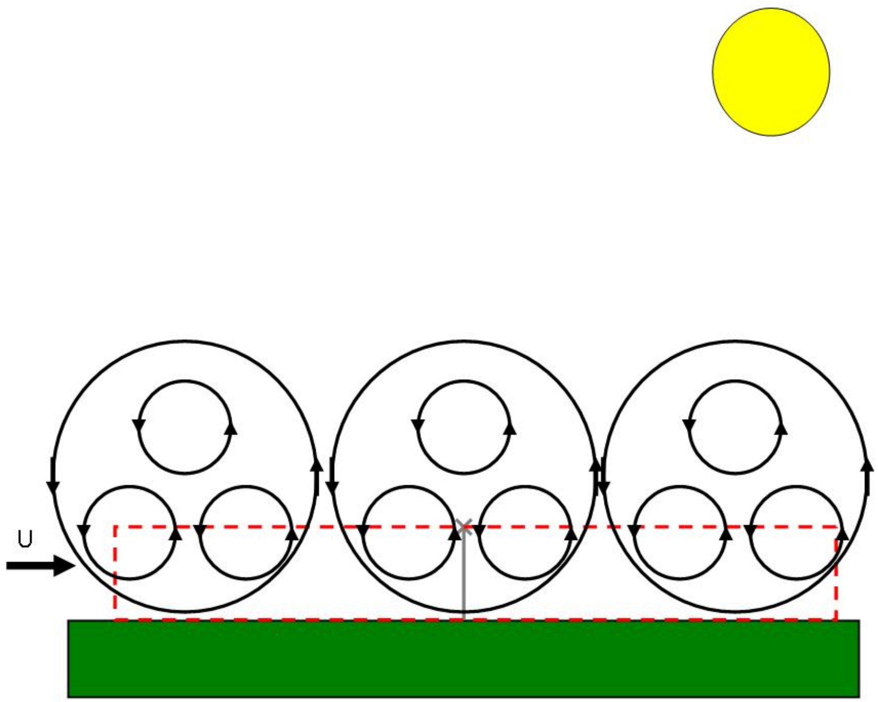
$$\frac{\partial c}{\partial t} = -\left(\bar{v}\nabla\right)c + \left(\nabla D \nabla c\right) + r$$

$$\underbrace{\int_0^h S_c dz}_{\text{NEE}} = \underbrace{\int_0^h \frac{\partial \bar{c}}{\partial t} dz}_{\text{Storage}} + \underbrace{\overline{w'c'}\,|_h}_{\text{Eddy flux}}$$

After Reynolds decomposition
Assuming:

- Horizontal homogeneity
- Steady state
- Flat terrain
- Viscous diffusion negligible

Eddy flux theory



Tracer conservation equation

$$\frac{\partial c}{\partial t} = -(\bar{v}\nabla)c + (\nabla D \nabla c) + r$$

$$\underbrace{\int_0^h S_c \, dz}_{\text{NEE}} = \underbrace{\int_0^h \frac{\partial \bar{c}}{\partial t} dz}_{\text{Storage}} + \boxed{\underbrace{\overline{w'c'}\,|_h}_{\text{Eddy flux}}}$$

After Reynolds decomposition
Assuming:

- Horizontal homogeneity
- Steady state
- Flat terrain
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Uncertainty theory

General uncertainty:

$$u^2(F_c) = \boxed{u^2(Statistical)} + \boxed{u^2(Fundamental)}$$

Uncertainty theory

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$$u^2(F_c) = \boxed{u^2(Statistical)} + \boxed{u^2(Fundamental)}$$

Uncertainty	Description
U(1)	Precision of concentration measurement
U(2)	Drift in concentration measurement
U(3)	Precision of wind velocity measurement
U(4)	Alignment sonic anemometer
U(5)	Delay time determination

Uncertainty theory

General uncertainty:

$$u^2(F_c) = \boxed{u^2(Statistical)} + \boxed{u^2(Fundamental)}$$

$$\boxed{u^2(Fundamental) = u^2(4) + u^2(5)}$$

Uncertainty	Description
U(1)	Precision of concentration measurement
U(2)	Drift in concentration measurement
U(3)	Precision of wind velocity measurement
U(4)	Alignment sonic anemometer
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Uncertainty theory

General statistical uncertainty:

$$Y = f(x_i, \ldots, x_n)$$

$$u^2(Y) = \sum_{i=1}^{n} \left(u_i^2(Y)\right) = \sum_{i=1}^{n} \left(u(x_i) \frac{\partial f}{\partial x_i} \right)^2$$

Eddy flux statistical uncertainty:

$$F_c = \overline{w'c'}\,|_h = \frac{1}{n_s} \sum_{k=1}^{n_s} w_k' c_k'$$

$$\boxed{u^2(Statistical) = \frac{1}{n_s} \overline{w'^2} u(c')^2 + \frac{1}{n_s} \overline{c'^2} u(w')^2 + \frac{2}{n_s} \overline{c' w' u(w'c')}}$$

Uncertainty theory

Eddy flux uncertainty:

$$\boxed{u^2(Statistical) = \frac{1}{n_s}\overline{w'^2}u(c')^2 + \frac{1}{n_s}\overline{c'^2}u(w')^2 + \cancel{\frac{2}{n_s}\overline{c'w'u(w'c')}}}$$

$$\boxed{u(c')^2 = u(1)^2 + u(2)^2}$$

$$\boxed{u(w')^2 = u(3)^2}$$

Uncertainty	Description
U(1)	Precision of concentration measurement uncertainty
U(2)	Drift uncertainty
U(3)	Precision of wind velocity measurement uncertainty
U(4)	Alignment sonic anemometer uncertainty
U(5)	Delay time determination uncertainty

Uncertainty theory

Eddy flux corrected uncertainty:

$$F_{new} = \alpha\beta\gamma\delta\varepsilon F_c$$

$$u^2(F_{new}) = \boxed{\left(\beta\gamma\delta\varepsilon F_c u(\alpha)\right)^2 + \left(\alpha\gamma\delta\varepsilon F_c u(\beta)\right)^2 + \left(\alpha\beta\delta\varepsilon F_c u(\gamma)\right)^2 + \left(\alpha\beta\gamma\varepsilon F_c u(\delta)\right)^2 + \left(\alpha\beta\gamma\delta F_c u(\varepsilon)\right)^2} + \boxed{\boxed{\left(\alpha\beta\gamma\delta\varepsilon u(F_c)\right)^2}}$$

Uncertainty	Description
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Uncertainty theory

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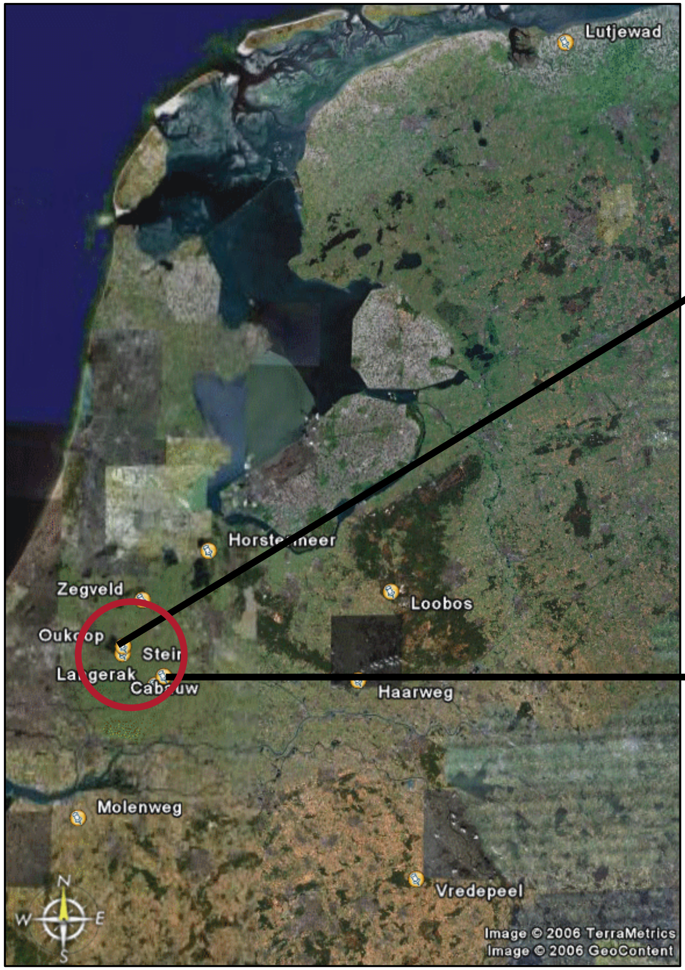
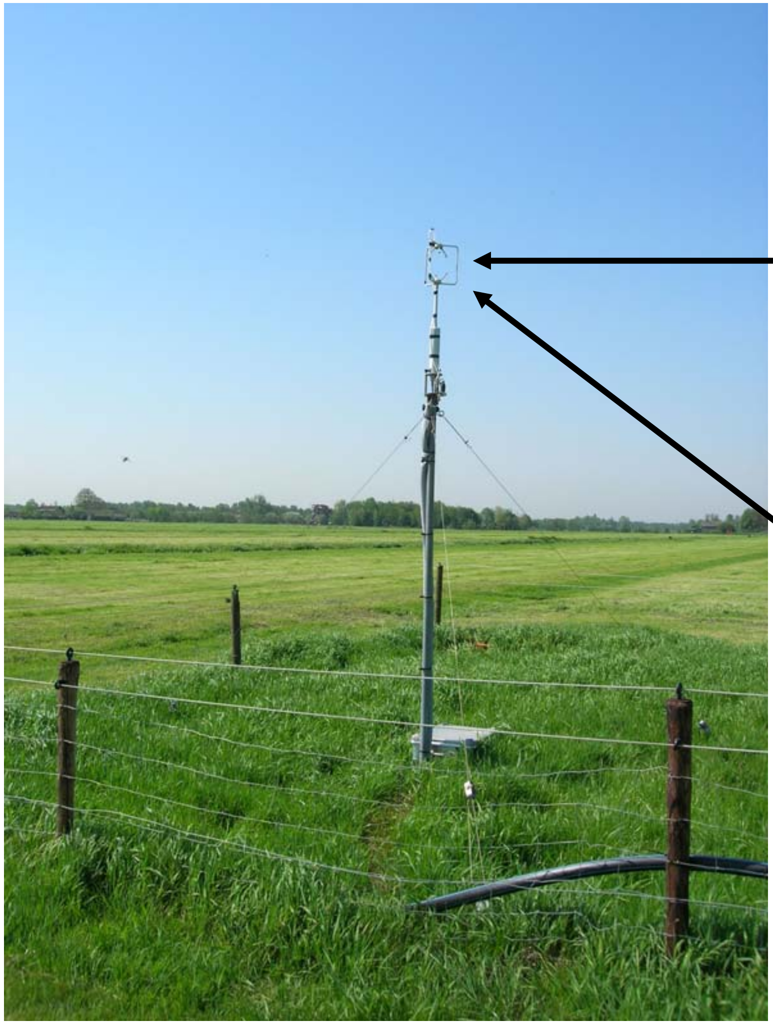
Measurement sites and instrumentation



Oukoop

Cabauw

Measurement sites and instrumentation



Sonic anemometer

Wind measurements

Temperature measurements

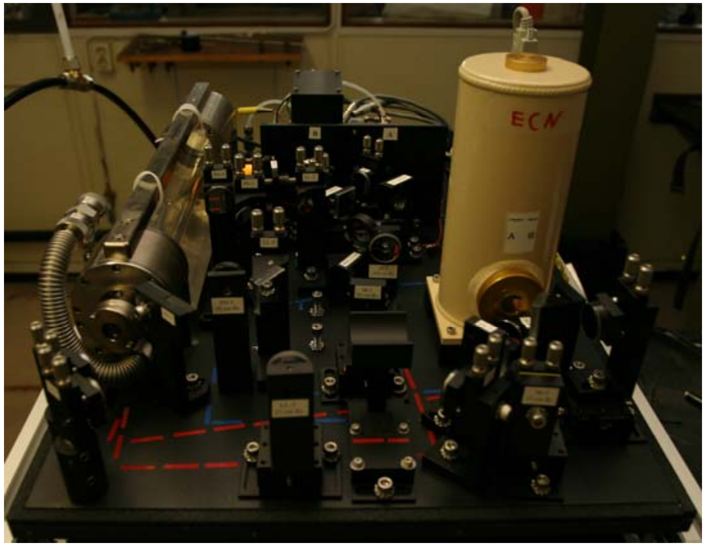
Tube connected to QCL

CH_4 measurements

N_2O measurements

Measurement sites and instrumentation

Quantum cascade laser



Requirements eddy covariance measurements:

- Sampling frequency at least 10 Hz
- Stationair at least over 30 min
- Continuously running
- Sensitivity of 0.3 ppb and 1 ppb for N_2O (average 310 ppb) and CH_4 (average 1800 ppb)

Kroon et al., BG, 2007

Highlighted some uncertainties: U(1) & U(2)

Uncertainty	Description
U(3)	Precision of wind velocity measurement uncertainty
U(4)	Alignment sonic anemometer uncertainty
U(5)	Delay time determination uncertainty
U(α)	Webb-correction uncertainty
U(β)	Damping correction uncertainty
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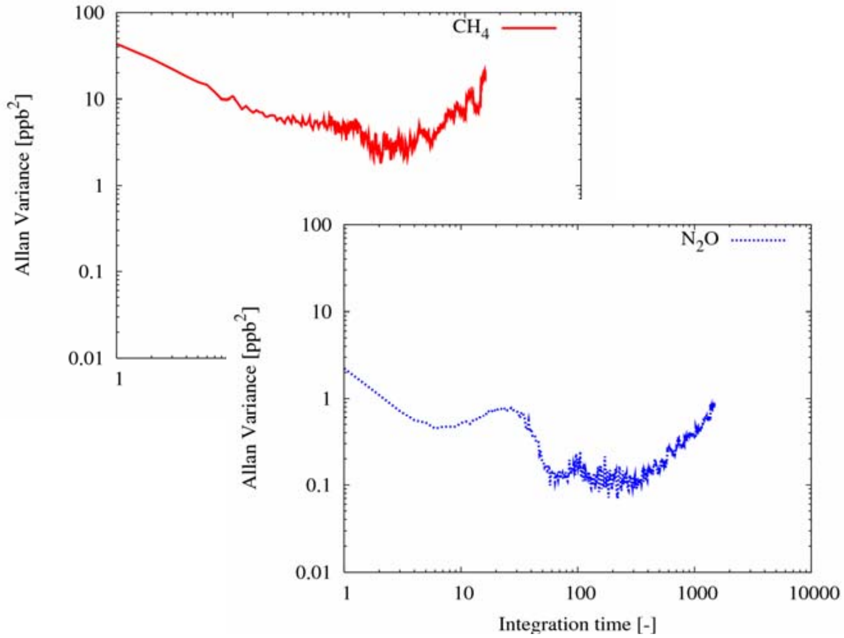


$$u(1) = 2\sqrt{\sigma_A^2\Big|_{x=1}}$$

$$u(2) = 2\sqrt{\sigma_A^2\Big|_{x=18000}}$$

Highlighted some uncertainties: U(3)

Uncertainty	Description
U(1)	Precision of concentration measurement uncertainty
U(2)	Drift uncertainty
U(4)	Alignment sonic anemometer uncertainty
U(5)	Delay time determination uncertainty
U(α)	Webb correction uncertainty
U(β)	Damping correction uncertainty
U(γ)	Non-detected eddies correction uncertainty
U(δ)	Low frequency correction uncertainty
U(ε)	Calibration correction uncertainty

GILL INSTRUMENTS

Omnidirectional (R3-50) Ultrasonic Anemometer

User Manual

Doc No. 1210-PS-0011
Issue 04

13. TECHNICAL SPECIFICATION

13.1 Wind Measurement

Measurement Rate:	$50s^{-1}$ (Full 3 axis measurement)
Data Output Rates:	From 0.4 to $50s^{-1}$
Wind Speed Range:	0 to $45ms^{-1}$
Wind Speed Accuracy:	<1%rms
Wind Speed Resolution:	$0.01ms^{-1}$
Wind Speed Offset:	<±$0.01ms^{-1}$
Directional Accuracy:	<±1°RMS
Directional Resolution:	1°

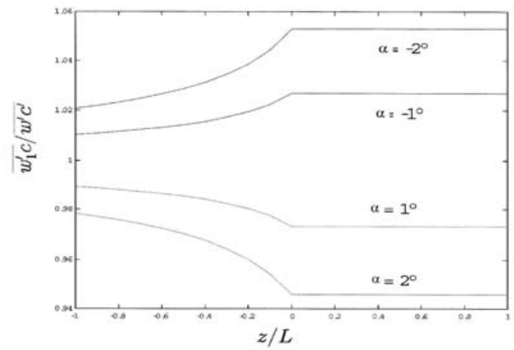
$$u(3) = 2 \cdot 1\% \sigma_w$$

Highlighted some uncertainties: U(4)

Uncertainty	Description
U(1)	Precision of concentration measurement uncertainty
U(2)	Drift uncertainty
U(3)	Precision of wind velocity measurement uncertainty
U(5)	Delay time determination uncertainty
U(α)	Webb-correction uncertainty
U(β)	Damping correction uncertainty
U(γ)	Non-detected eddies correction uncertainty
U(δ)	Low frequency correction uncertainty
U(ε)	Calibration correction uncertainty

Flux bias due to tilt error :

- momentum flux : > 10 % per degree !
- scalar eddy flux : < 5 % for tilts below 2°



(From Lee, Handbook, 2004)

Assumption that this uncertainty is negligible after coordinate rotation.

Highlighted some uncertainties: U(5)

Uncertainty	Description
U(1)	Precision of concentration measurement uncertainty
U(2)	Drift uncertainty
U(3)	Precision of wind velocity measurement uncertainty
U(4)	Alignment sonic anemometer uncertainty
U(α)	Webb-correction uncertainty
U(β)	Damping correction uncertainty
U(γ)	Non-detected eddies correction uncertainty
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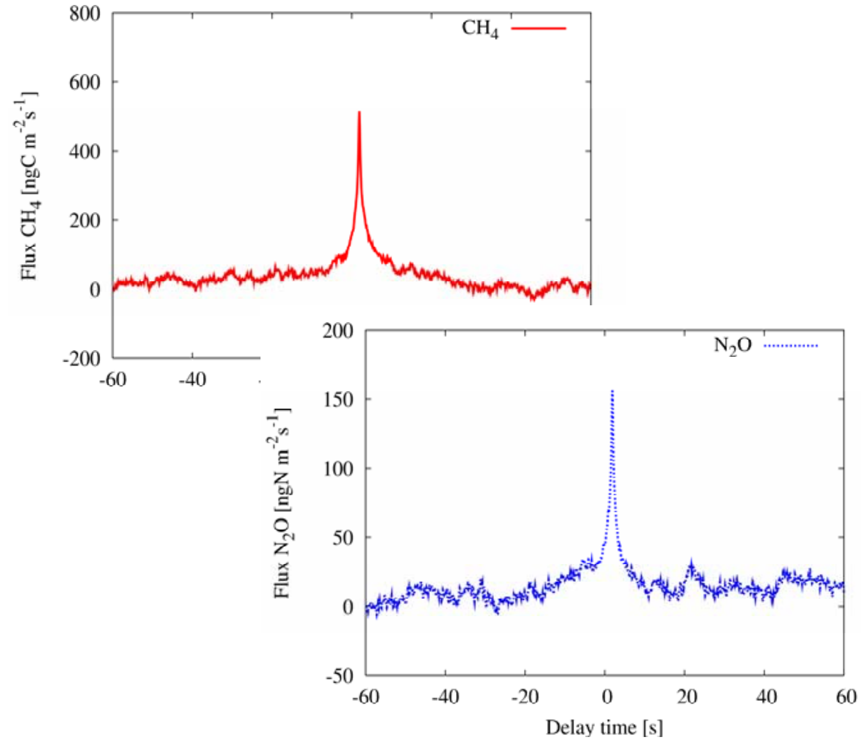


$$F_c(n\Delta t) = \frac{1}{n_s}\sum_{k=1}^{n_s} w_k^{'} c_{k+n\Delta t}^{'}$$

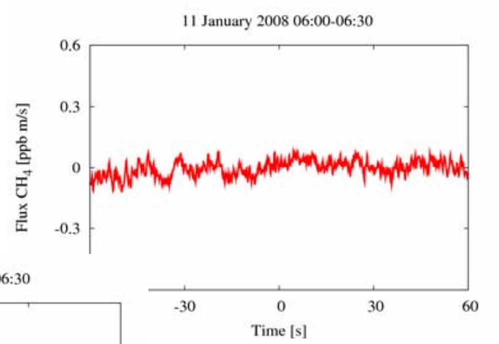
Delay time determination

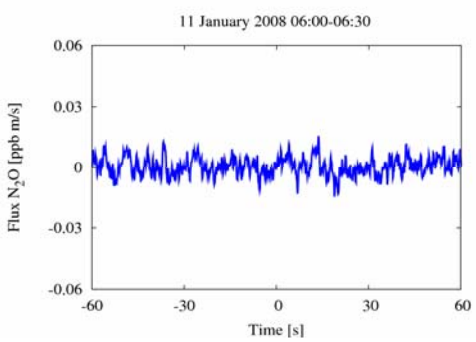
Outcome questionnaire:

- Every one determined the exact delay time using the maximum cross correlation for each 30-min interval

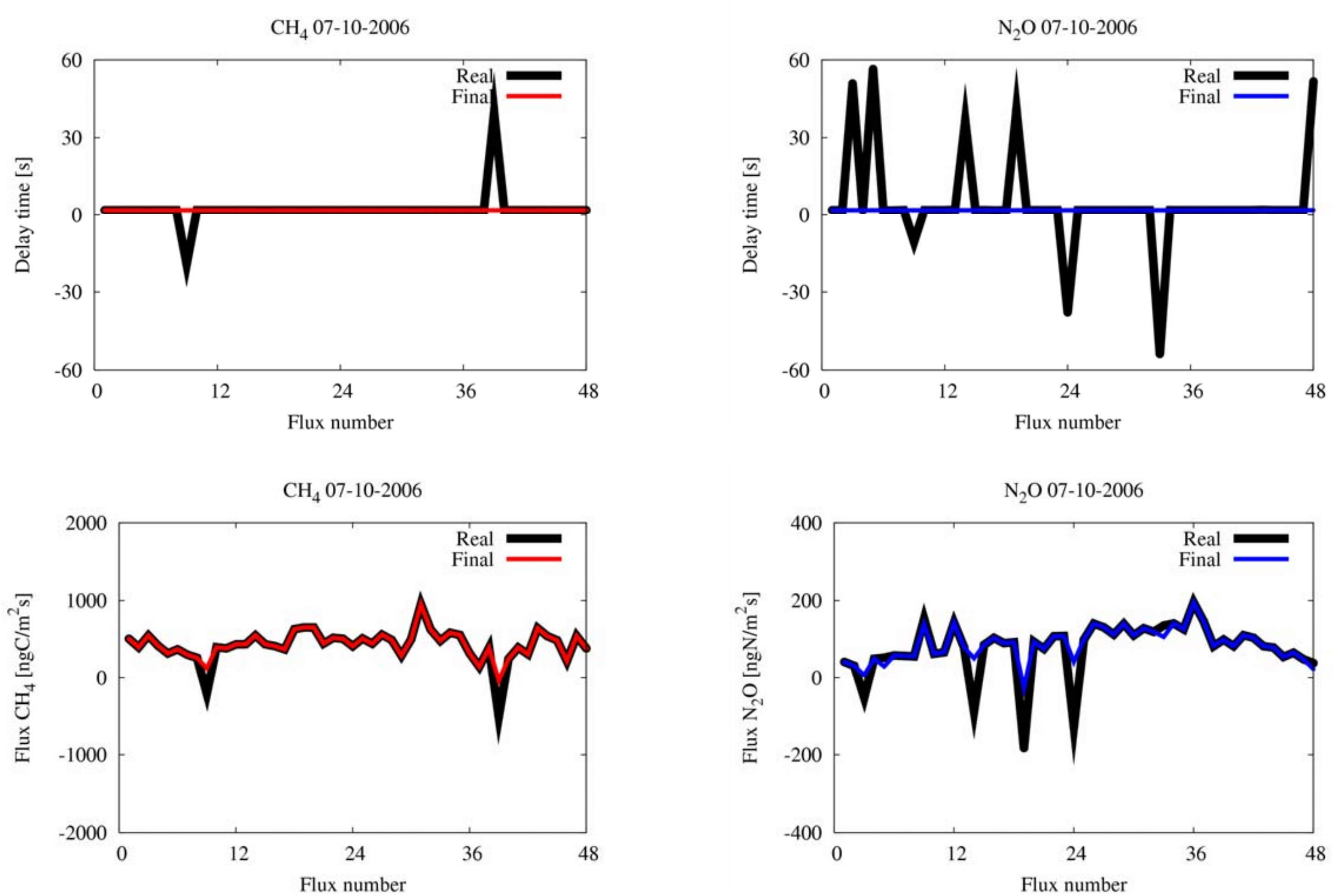
Discussion points:

- How do we manage not well defined cross correlations?





Uncertainty in delay time determination



Uncertainty in delay time determination

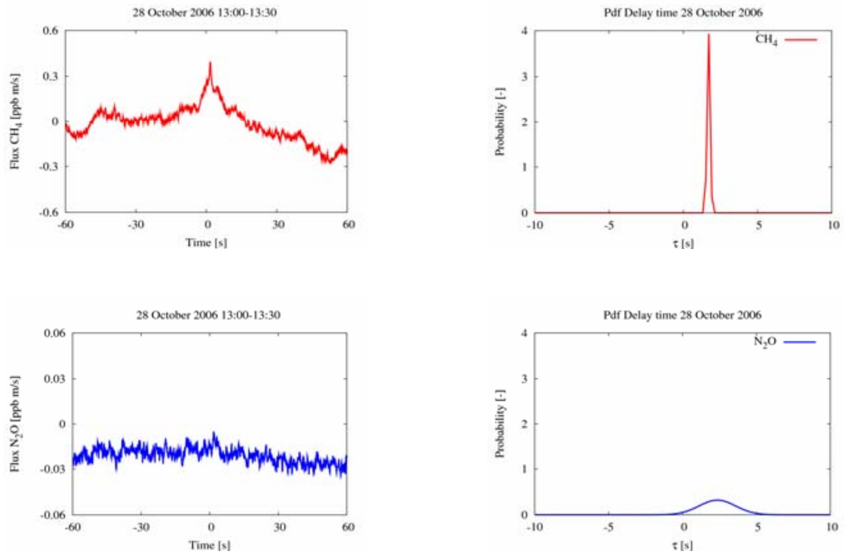
Possible strategy in delay time determination:

- Determine the exact delay time using the maximum cross correlation for each 30-min interval
- Take the most occurred delay time of CH_4 for the delay time of all 30-min intervals

Uncertainty in delay time determination with this strategy:

$$u^2(5) = \left(\frac{\partial F_c}{\partial \tau} u(\tau) \right)^2$$

$$u(\tau) = 2\sigma_\tau$$



Highlighted some uncertainties: U(α)

Uncertainty	Description
U(1)	Precision of concentration measurement uncertainty
U(2)	Drift uncertainty
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U(4)	Alignment sonic anemometer uncertainty
U(5)	Delay time determination uncertainty
U(β)	Damping correction uncertainty
U(γ)	Non-detected eddies correction uncertainty
U(δ)	Low frequency correction uncertainty
U(ε)	Calibration correction uncertainty

Outcome questionnaire:

- Almost everyone applies the Webb-correction

Assumption that this uncertainty is negligible after applying the correction.

Highlighted some uncertainties: U(β)

Uncertainty	Description
U(1)	Precision of concentration measurement uncertainty
U(2)	Drift uncertainty
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U(4)	Alignment sonic anemometer uncertainty
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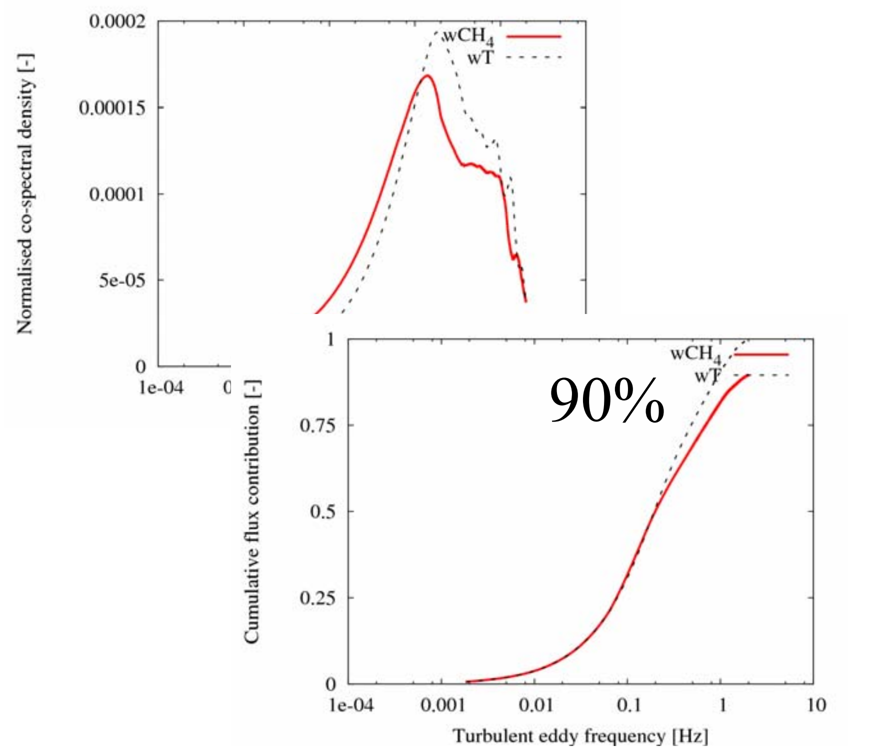


$$Og^{D}_{wc}(f_m) = \sum_{i=1}^{m} \left| Cov_{wc}(f_i) \right|$$

$$f_i = \frac{i}{(n_s - 1)\Delta t}; m = 1,2,\ldots,\left[\frac{(n_s - 1)\Delta t}{2\Delta t}\right]$$

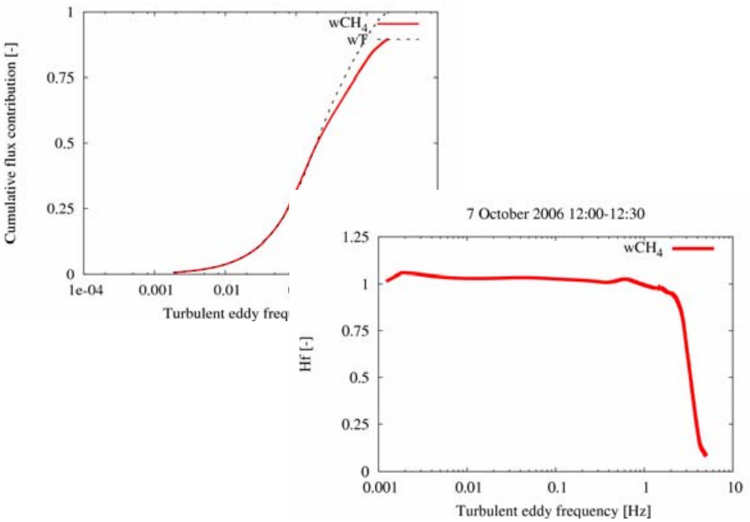
Damping correction

Outcome questionnaire:

- A damping correction is applied 62% of the time.

They use different damping corrections strategies:

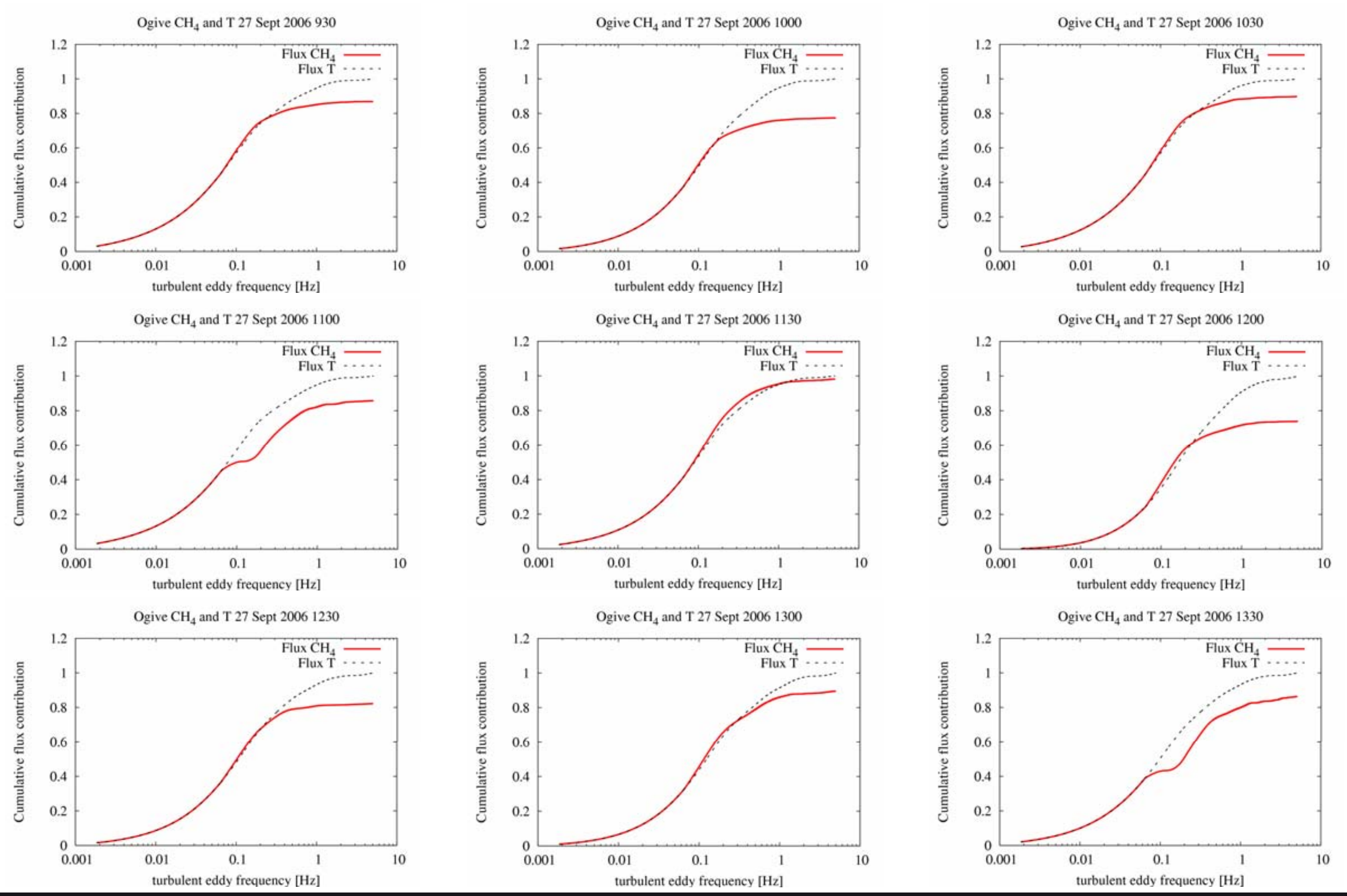
- CarboEurope protocol
- High frequency Butterworth filter
- According to Moore (1986)
- Ogives



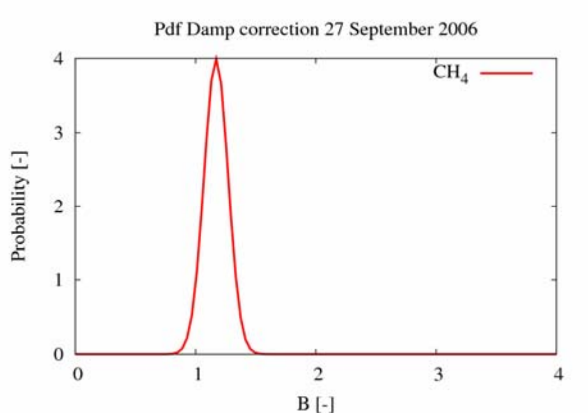
Discussion point:

- What will be the right strategy for determining the damping correction?

Uncertainty in damping correction



Uncertainty in damping correction



$$u(\beta) = \frac{2\sigma_{\beta}}{\sqrt{N}} F_c$$

Discussion points:

- Which technique should be used to determine the damping correction?
- In which frequency should the damping correction be determined?
  - For each 30-min interval
  - For each day
  - For some meteorological classifications
  - For some instrumental classifications

Highlighted some uncertainties: U(γ)

Uncertainty	Description
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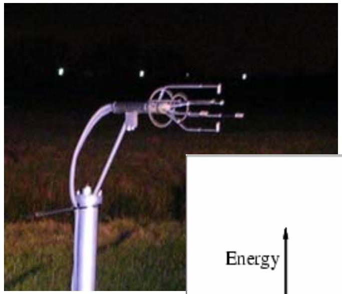

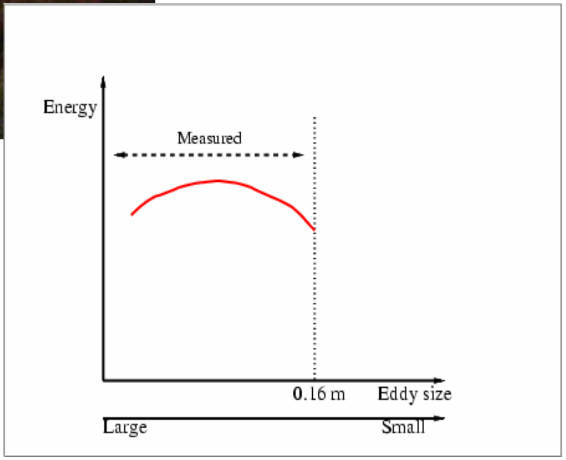

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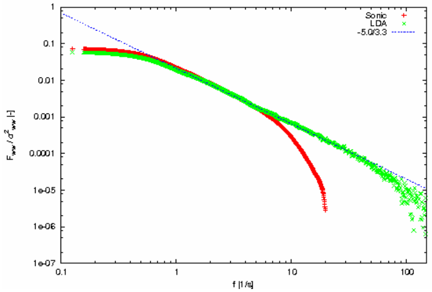

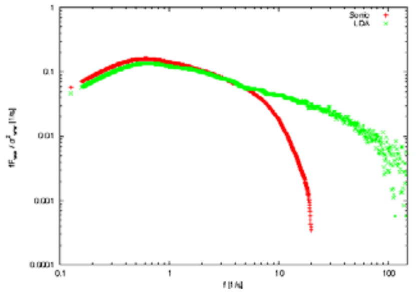

Courtesy: A. Schuitmaker

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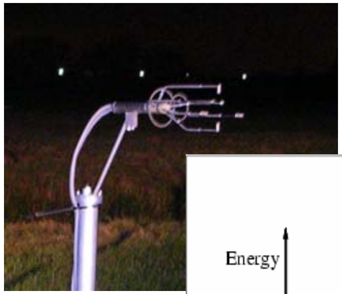

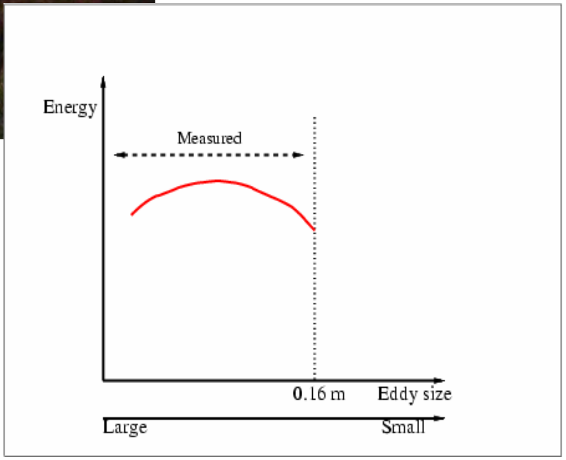

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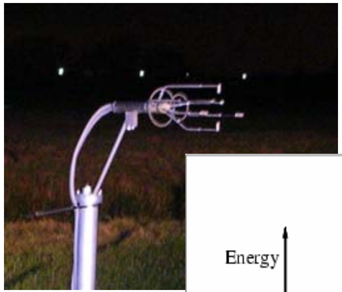

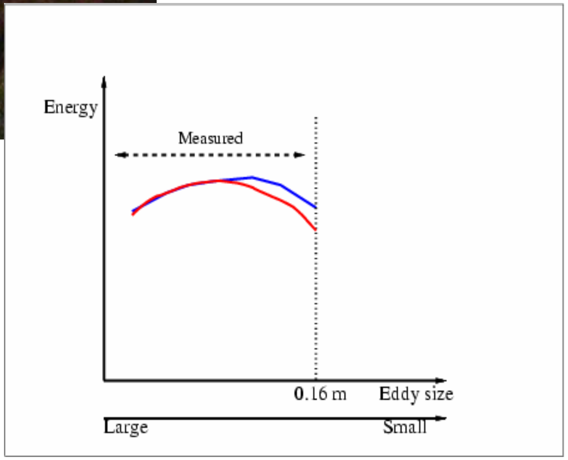

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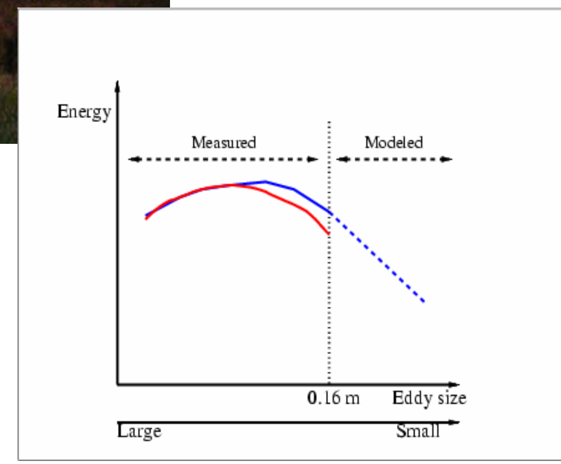

$$F_{ww}(k) = \alpha_w \varepsilon^{2/3} k^{-5/3}$$

ECN

Highlighted some uncertainties: U(γ)

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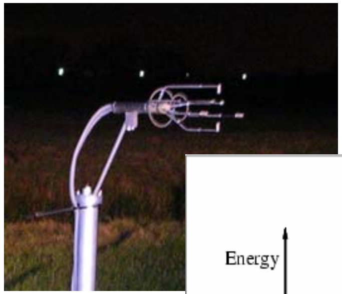

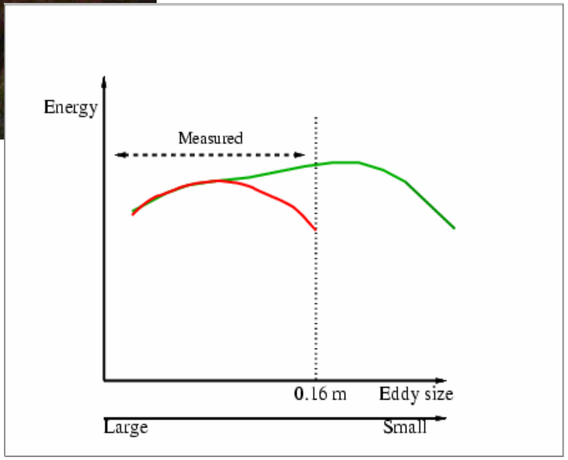

$$F_{ww}(k) = \alpha_w \varepsilon^{2/3} k^{-5/3}$$

Discussion point:

• Should we take into account the contributions of the non-detected eddies?

Highlighted some uncertainties: U(δ)

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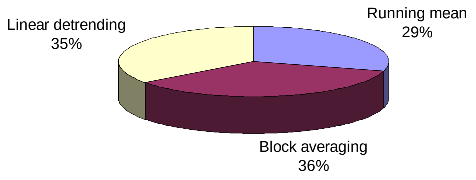
U(α)	Webb-correction uncertainty
U(β)	Damping correction uncertainty
U(γ)	Non-detected eddies correction uncertainty
U(ε)	Calibration correction uncertainty

Outcome questionnaire:

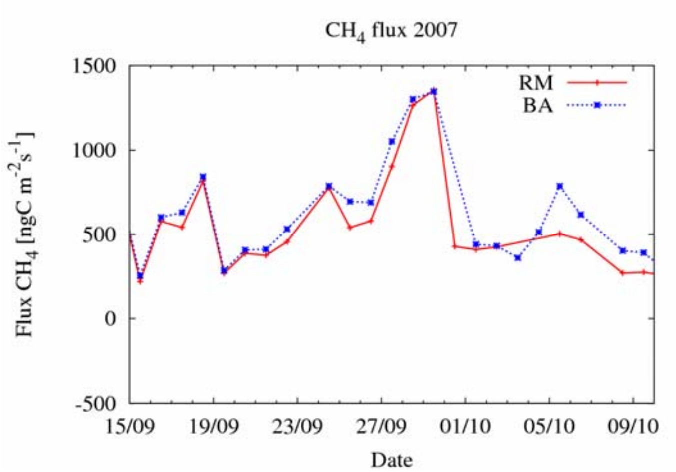
- Each filtering technique is used equally under the workshop participants

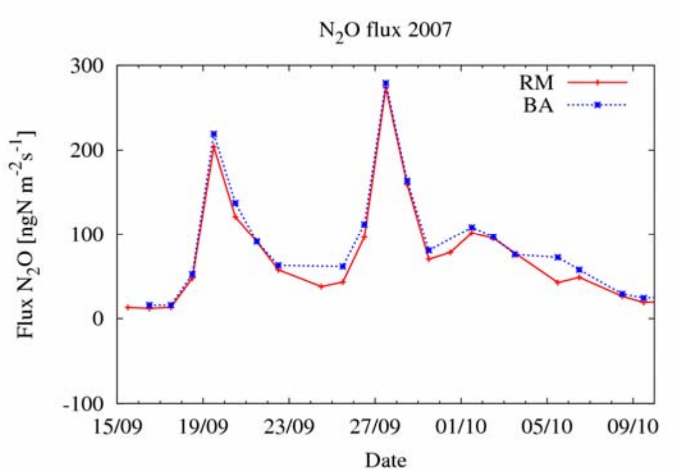


Discussion points:

- What's the best filtering technique for each instrument and component?
- How should we correct for low frequency losses?

Low frequency filtering techniques





Only a small difference between RM and BA daily eddy fluxes

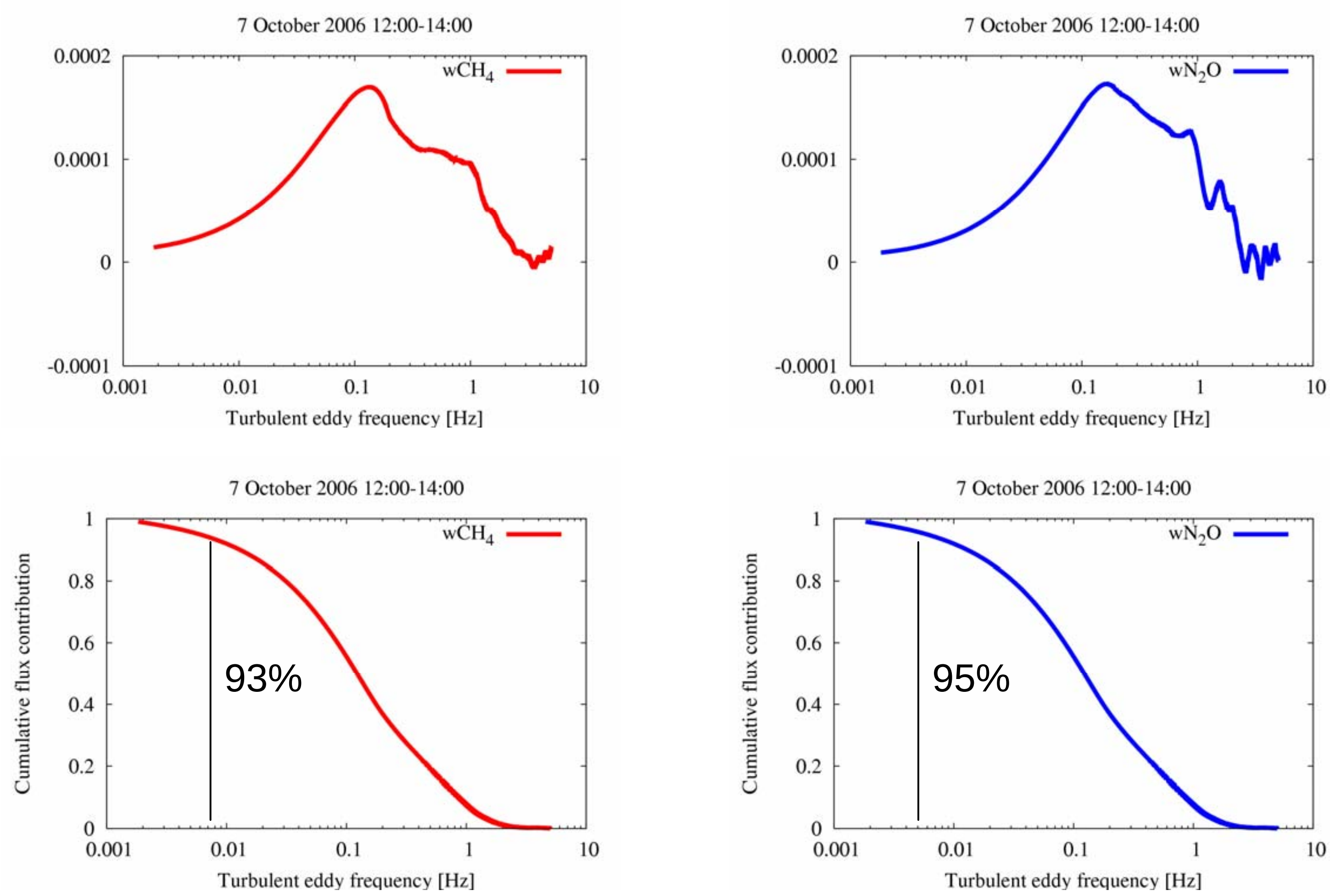
But

Much more fluxes are rejected by steady state tests for BA than RM

Discussion point:

- How should we apply the steady state tests in case of RM and BA?

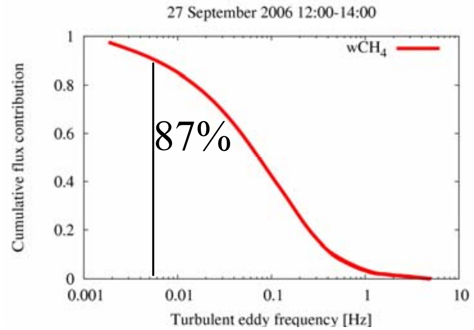
Low frequency filtering techniques: BA versus 120s RM



Low frequency filtering techniques: BA versus 120s RM

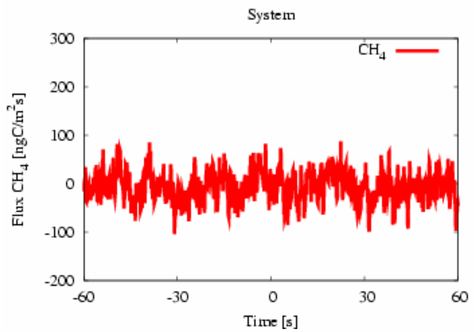
Possible flux underestimation by RM:

• Amount of underestimation dependent on meteorological circumstances.



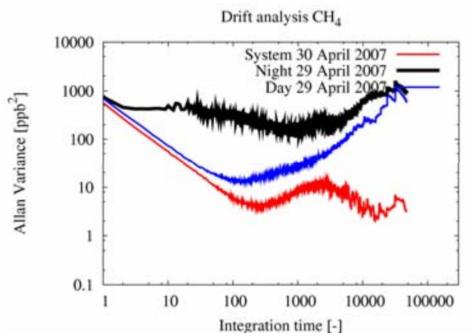
Possible flux overestimation by BA:

• Only, if laser drift is correlated with vertical wind velocity



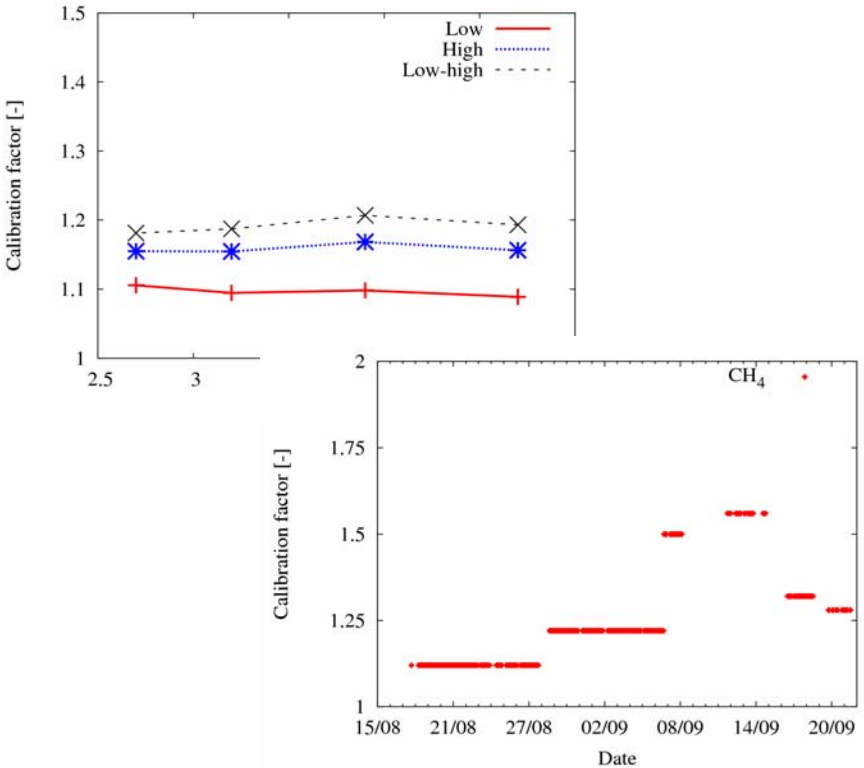
Discussion point:

• Which filtering technique should be applied for each instrument and component?



Highlighted some uncertainties: U(ε)

Uncertainty	Description
U(1)	Precision of concentration measurement uncertainty
U(2)	Drift uncertainty
U(3)	Precision of wind velocity measurement uncertainty
U(4)	Alignment sonic anemometer uncertainty
U(5)	Delay time determination uncertainty
U(α)	Webb correction uncertainty
U(β)	Damping correction uncertainty
U(γ)	Non-detected eddies correction uncertainty
U(δ)	Low frequency correction uncertainty



Conclusions and future plans

Conclusions:

- Many corrections should be applied for minimize the eddy flux error
- Each correction term has still an uncertainty

Future plans:

- Comparison total uncertainty in eddy flux for different correction strategies
- Determination of dependence total uncertainty in eddy flux on:
  - Eddy flux magnitude
  - Meteorological circumstances
  - Instrumental properties

Discussion points

Delay time determination:

- How do we manage not well defined cross correlations?

Damping corrections:

- What will be the right strategy for determining the damping correction?
  - Method (Transfer functions, Ogives, …)
  - Frequency (Each 30-min interval, each day, based on classifications, …)

Non-detected eddies:

- Should we take into account the contributions of the non-detected eddies?

Low frequency corrections:

- What's the best filtering technique for each instrument and component?
- How should we correct for low frequency losses?

- How should we apply the steady state tests in case of RM and BA?

ECN

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Program

- *P. Kroon* (ECN, Netherlands; TU Delft, Netherlands): Uncertainty in eddy covariance flux measurements of CH_4 and N_2O

- *P. Werle* (Research Center Karlsruhe, Germany): Trace gas flux measurements by the eddy correlation technique: A Time Domain stability criterion for stationary tests

- *W. Eugster* (ETH Zürich, Switzerland): Quality assessment and quality control in eddy covariance flux measurements: Needs for improvement and adaptation to CH_4 and N_2O flux measurements

- *A. Neftel* (Federal Research Station Agroscope Reckenholz-Tänikon, Switzerland): Quality control of EC flux measurements

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Uncertainty in EC flux measurements of CH_4 and N_2O

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