

Trace gas flux measurements by the eddy correlation technique

A time domain stability criterion for stationary tests

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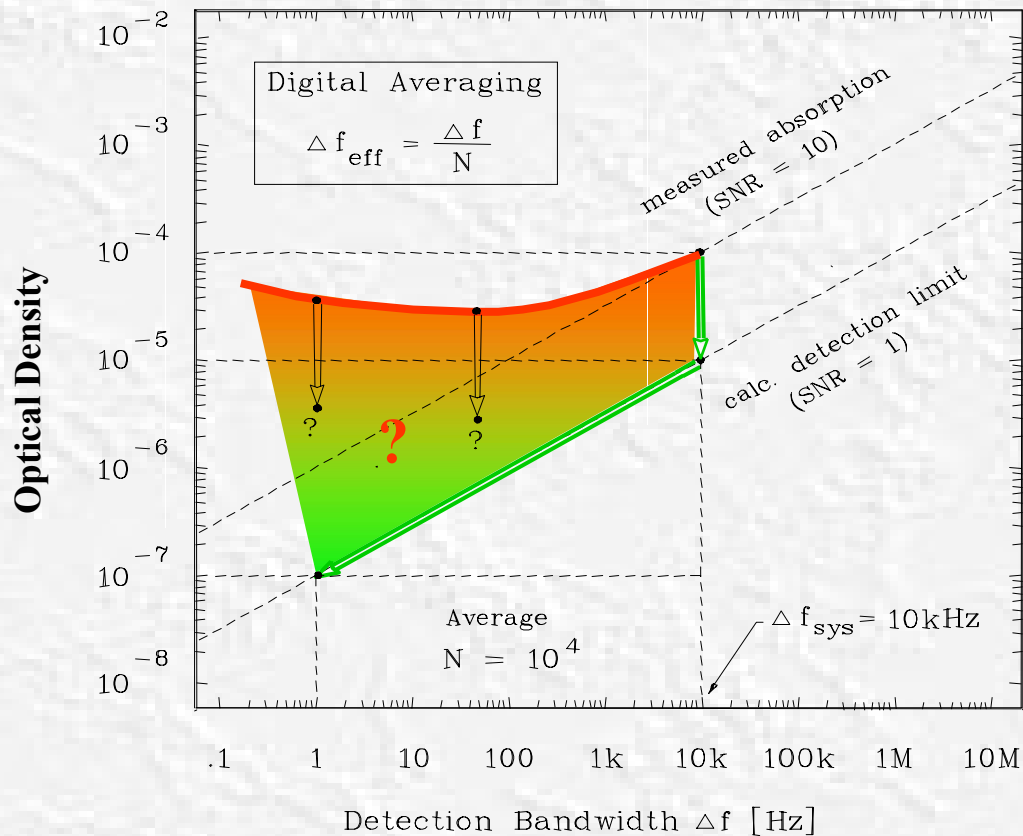
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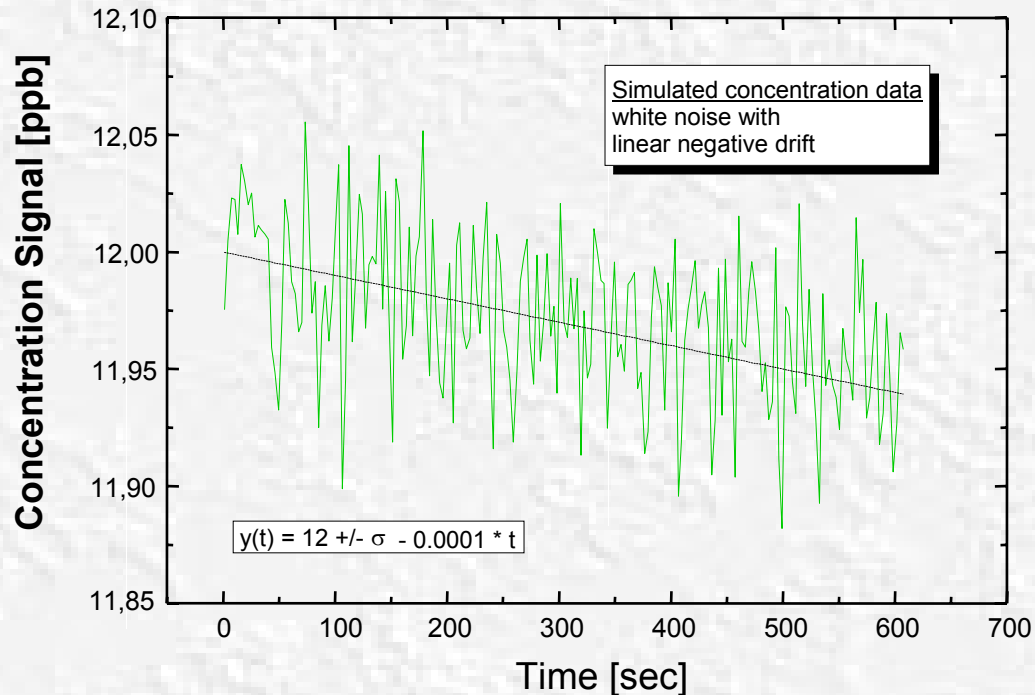
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What are the Limits of Signal Averaging ?

What is the result of digital averaging of 10^4 spectra ?
or Where do you go to my ... Signal ?

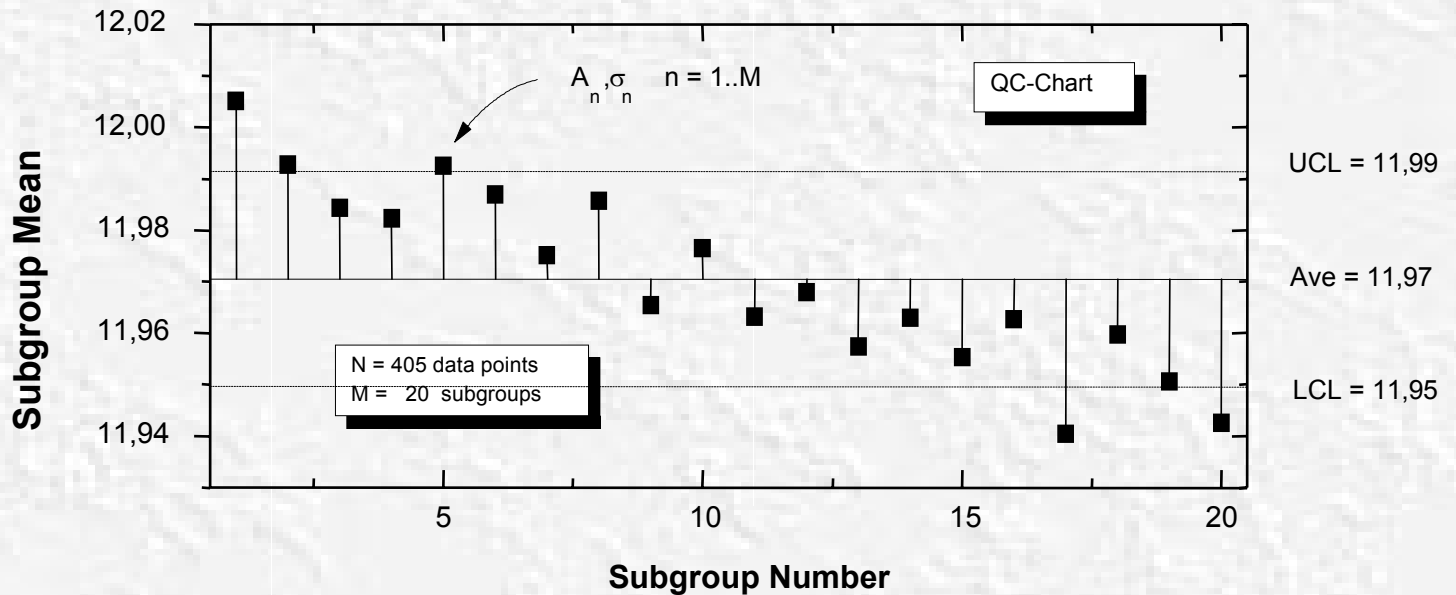


Let's assume white noise and linear drift



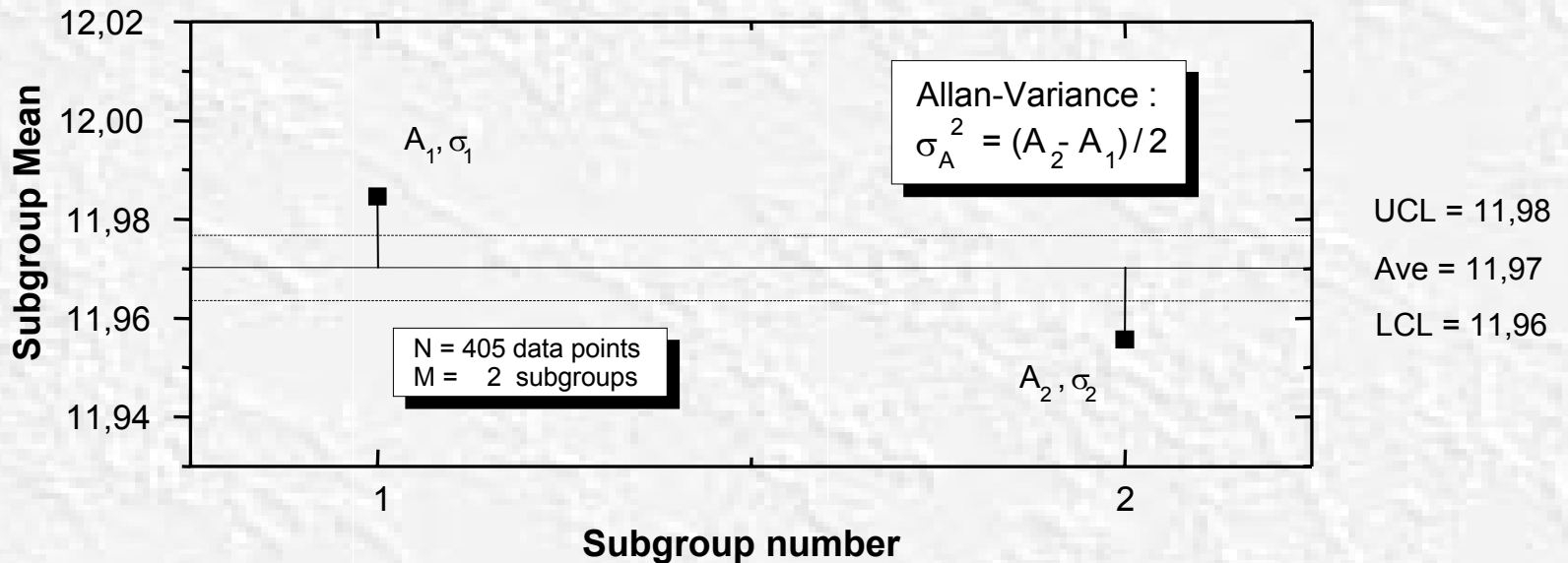
Simulated concentration time series data containing white noise and a linear negative drift

A first approach to „see the drift“



QC-Chart of data from time series data.

Looking at differences seems to be the right way ...



QC-Chart where a special choice of $M=2$ was made.

Sample Variance

Typically, the sample variance is calculated from a data sample using the relation:

$$\sigma_{STD DEV y}(\tau) = \sqrt{\frac{1}{M-1} \sum_{i=1}^M (y_i - \bar{y})^2}$$

Where it is implicitly assumed that the y_i 's are **random and uncorrelated** (i.e., white) and where \bar{y} is the sample mean calculated from the same data set.

When using **pink noise** as a model, as the number of data points increases, **the standard deviation monotonically increases without limit**. Some statistical measures have been developed which do not depend upon the data length and which are readily usable for characterizing random fluctuations in precision oscillators.

IEEE subcommittee on frequency stability ...

... has recommended what has come to be known as the "Allan variance" taken from the set of useful variances developed, and an experimental estimation of the square root of the Allan variance is

$$\sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2}$$

This equation is very easy to implement experimentally as one simply need **add up the squares of the differences between adjacent values of y_i** , divide by the number of them and by two, and take the square root.

Statistics of Atomic Frequency Standards

DAVID W. ALLAN

Abstract—A theoretical development is presented which results in a relationship between the expectation value of the standard deviation of the frequency fluctuations for any finite number of data samples and the infinite time average value of the standard deviation, which provides an invariant measure of an important quality factor of a frequency standard. A practical and straightforward method of determining the power spectral density of the frequency fluctuations from the variance of the frequency fluctuations, the sampling time, the number of samples taken, and the dependence on system bandwidth is also developed. Additional insight is also given into some of the problems that arise from the presence of "flicker noise" (spectrum proportional to $|\omega|^{-1}$) modulation of the frequency of an oscillator.

The theory is applied in classifying the types of noise on the signals of frequency standards made available at NBS, Boulder Laboratories, such as: masers (both H and N^2H_2), the cesium beam frequency standard employed as the U. S. Frequency Standard, and rubidium gas cells.

"Flicker noise" frequency modulation was not observed on the signals of masers for sampling times ranging from 0.1 second to 4 hours. In a comparison between the NBS hydrogen maser and the NBS III cesium beam, uncorrelated random noise was observed on the frequency fluctuations for sampling times extending to 4 hours; the fractional standard deviations of the frequency fluctuations were as low as 5 parts in 10^{14} .

I. INTRODUCTION

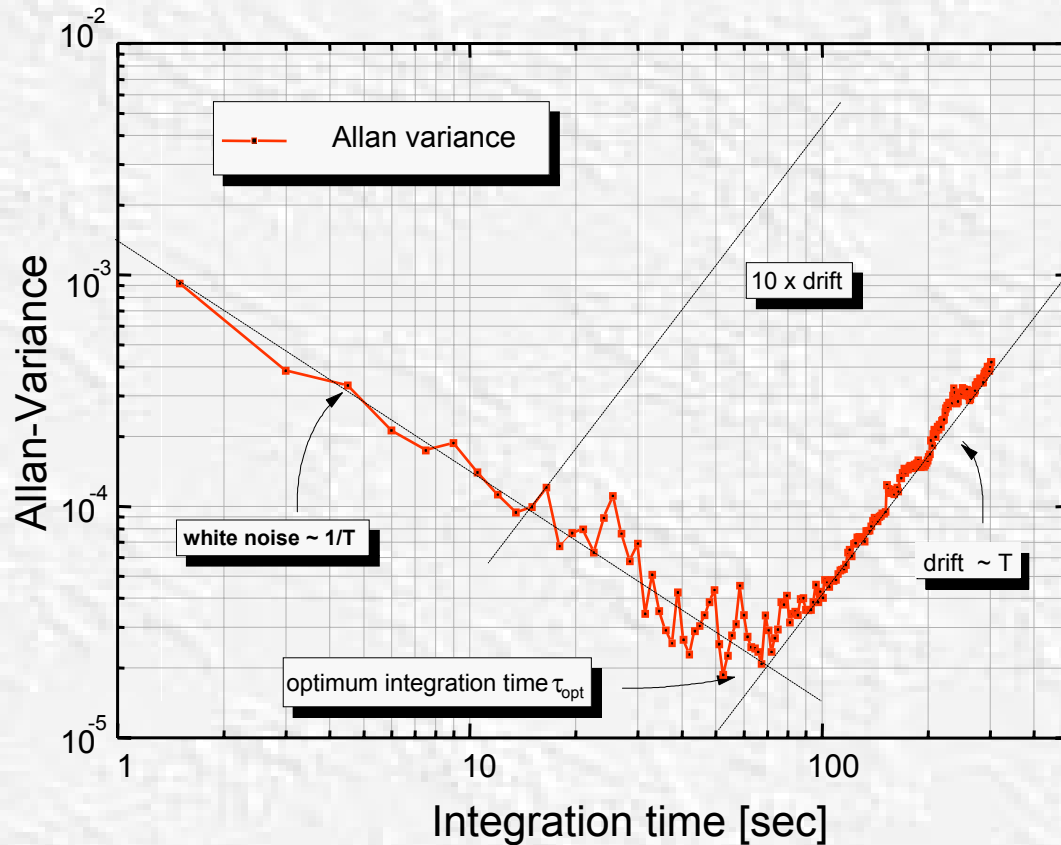
AS ATOMIC TIMEKEEPING has come of age, it has become increasingly important to identify quality in an atomic frequency standard. Some of the most important quality factors are directly related to the inherent noise of a quantum device and its associated electronics. For example, a common method of measuring

a frequency standard is to compare two such standards by measuring the period of the beat frequency between the two standards. It is again the intent of the author to show a practical and easy way of classifying the statistics, i.e., of determining the power spectral density of the frequency fluctuations using this type of measuring system.

An analysis has already been made of the noise present in passive atomic frequency standards [1], such as cesium beams, but a classification of the types of noise exhibited by the maser type of quantum-mechanical oscillator has not been made in the long term area, i.e., for low frequency fluctuations. Though this paper is far from exhaustive, the intent is to give additional information on the noise characteristics of masers. Because a maser's output frequency is more critically parameter dependent than a passive atomic device, it has been suggested [2] that the output frequency might appear to be "flicker noise" modulated, where "flicker noise" is defined as a type of power spectral density which is inversely proportional to the spectral frequency $\omega/2\pi$. It has been shown that if "flicker noise" frequency modulation is present on a signal from a standard, some significant problems arise, such as the logarithmic divergence of the standard deviation of the frequency fluctuations as the number of samples taken increases, and also the inability to define precisely the time average frequency. It thus becomes of special interest to determine the "flicker noise" spectrum present on

D. W. Allan, "Statistics of atomic frequency standards,"
Proc. IEEE, vol. 54, pp. 221-230, Feb. 1966.

Allan Plot



"Allan-Plot" for two different drift components. The rightmost trace corresponds to the "white noise and drift" data shown before.

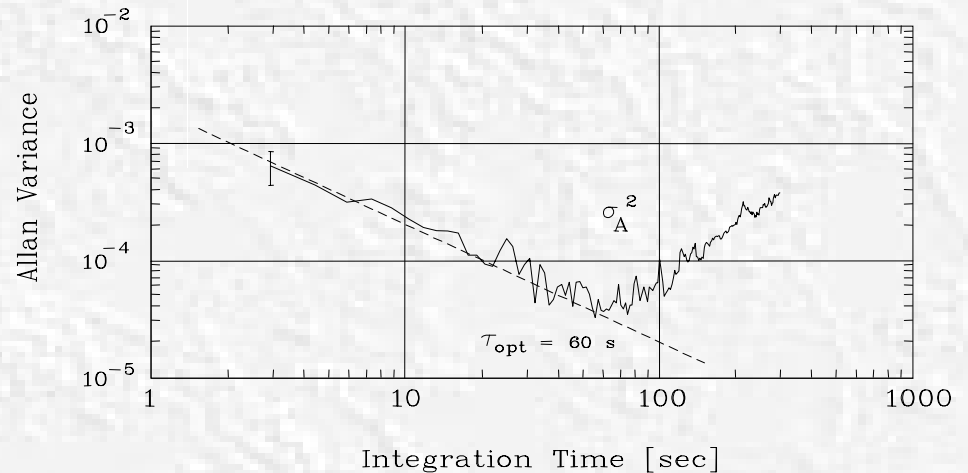
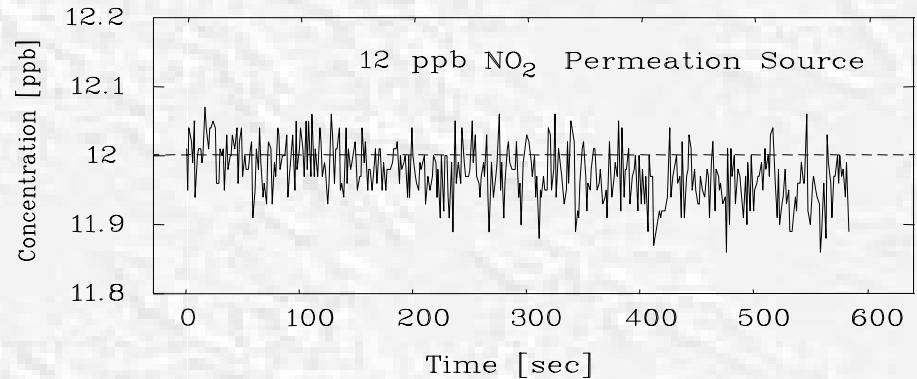
First application in trace gas analysis

The concept of the Allan Variance has been proposed and applied to characterize trace gas analyzers

P. Werle et al. „The limits of signal averaging in atmospheric trace gas monitoring“, *Appl. Phys. B* 57, 131-139 (1993).



and has become a well established tool for researchers and instrument developers to describe the performance of laseroptical trace gas sensors.

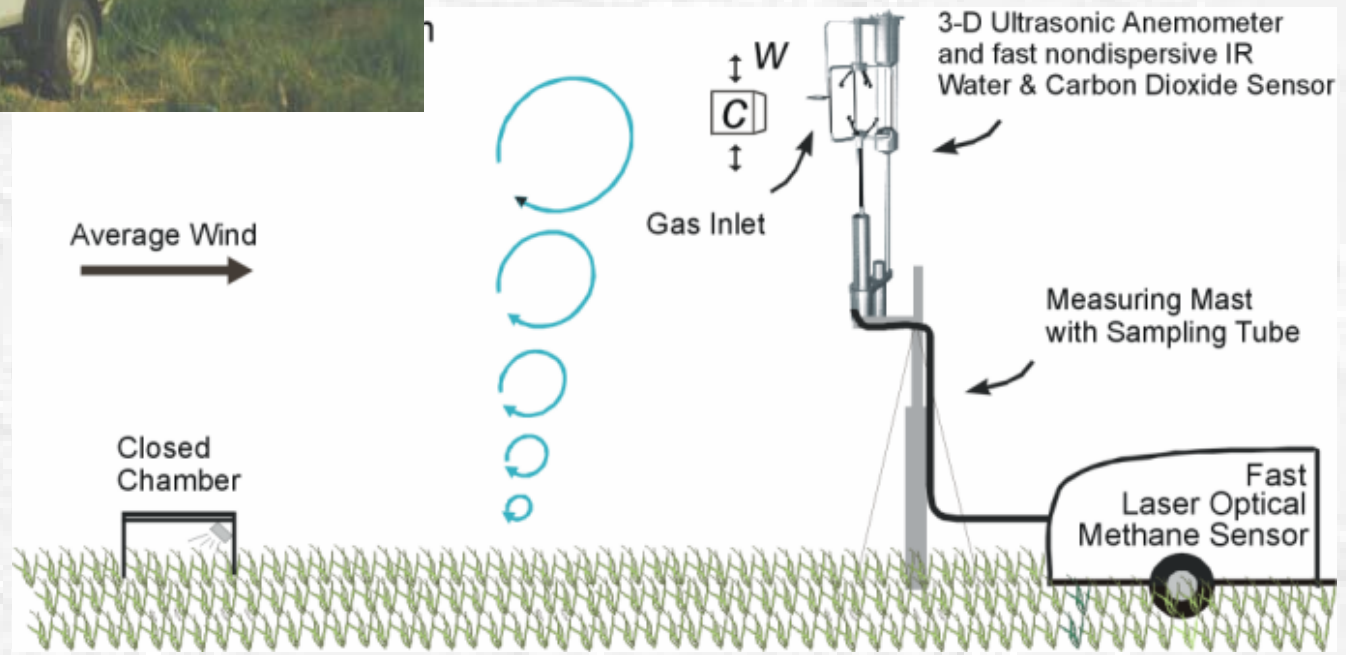


Back to application : flux measurements



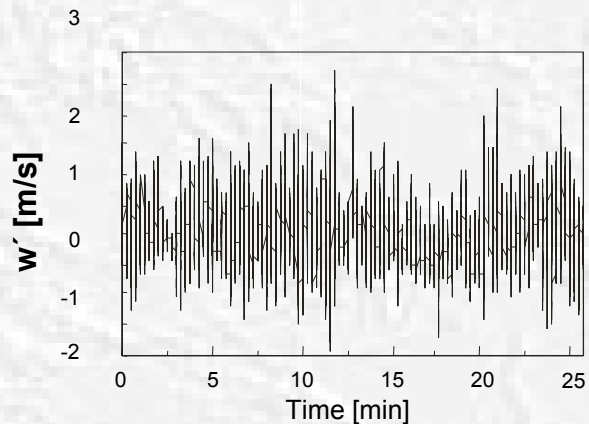
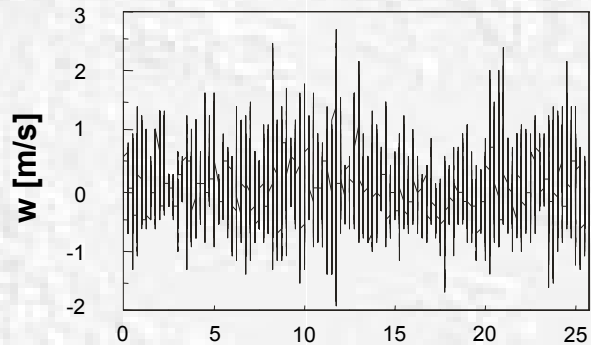
TO DO LIST :

- detrending
- frequency spectra
- covariance and cospectrum
- time lag
-

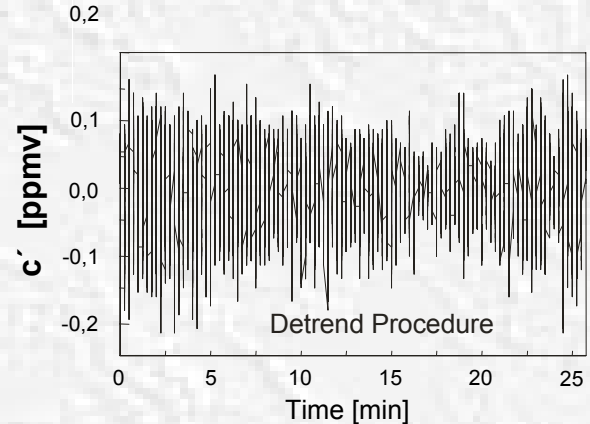
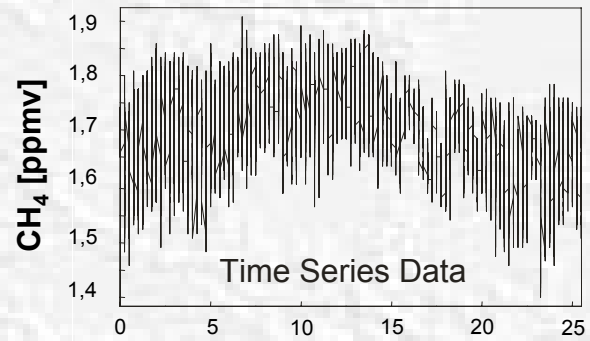


Time series data - Detrending

Ultrasonic anemometer
vertical wind measurement

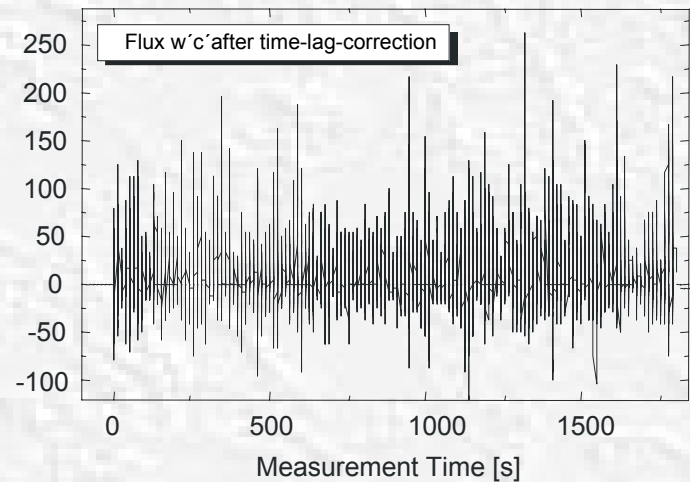
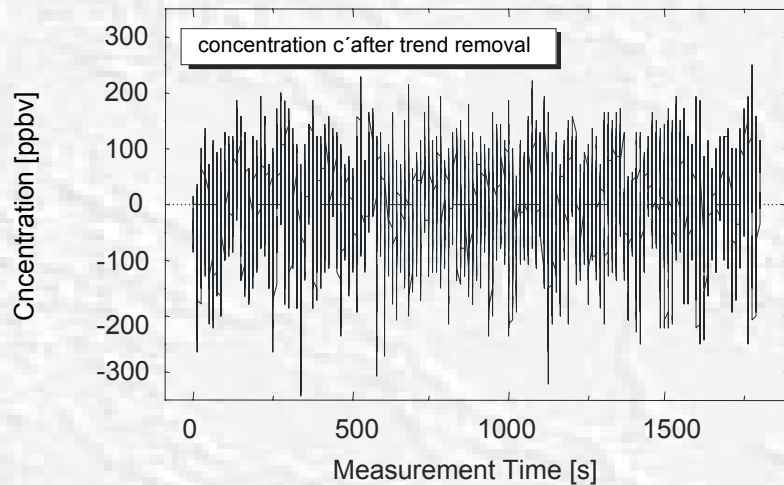
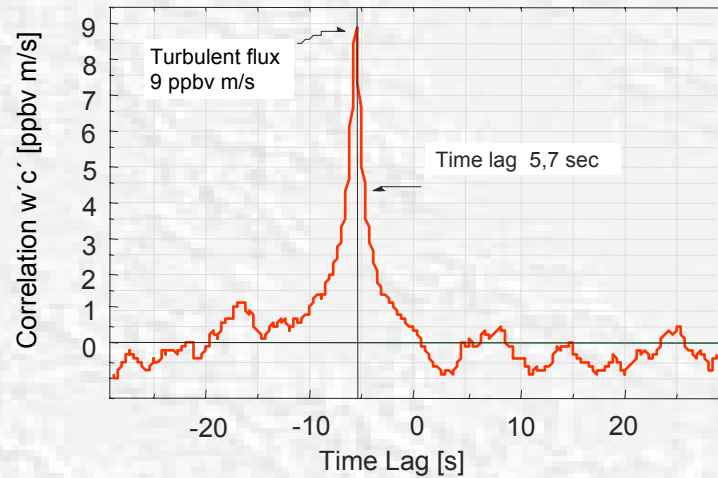
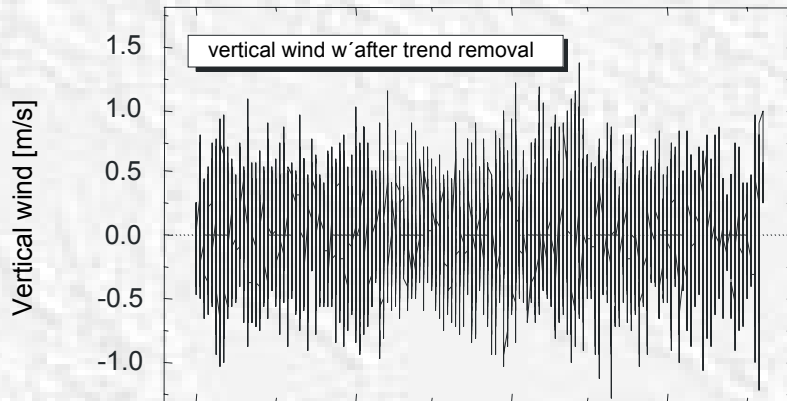


Concentration
measurement

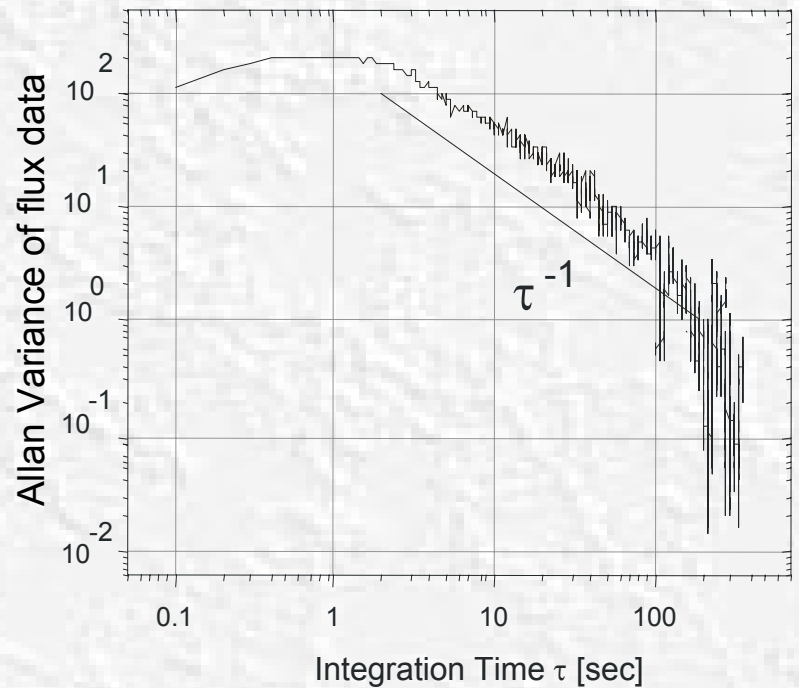
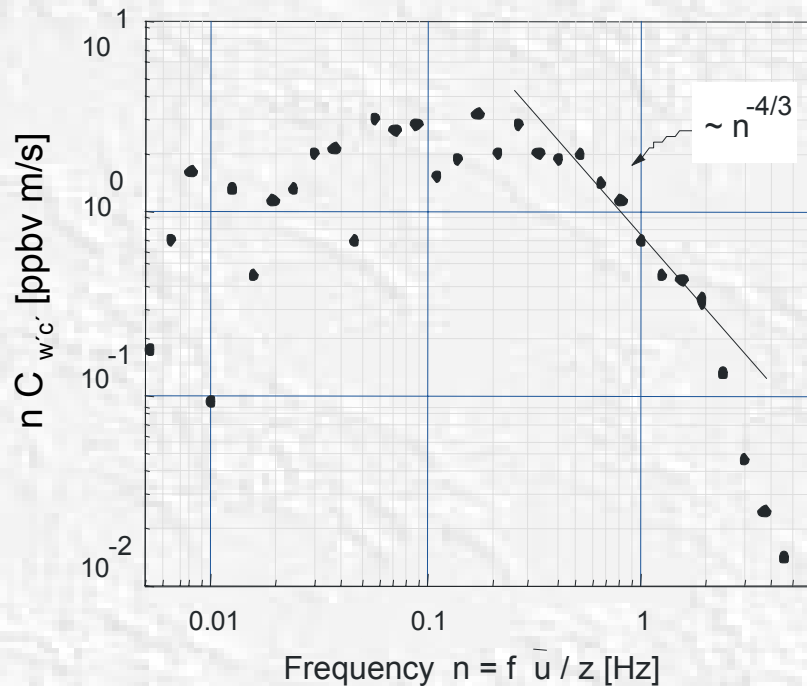


„running means“ or „high-pass filtering“ : Allan Variance and be used to determine the high pass constant

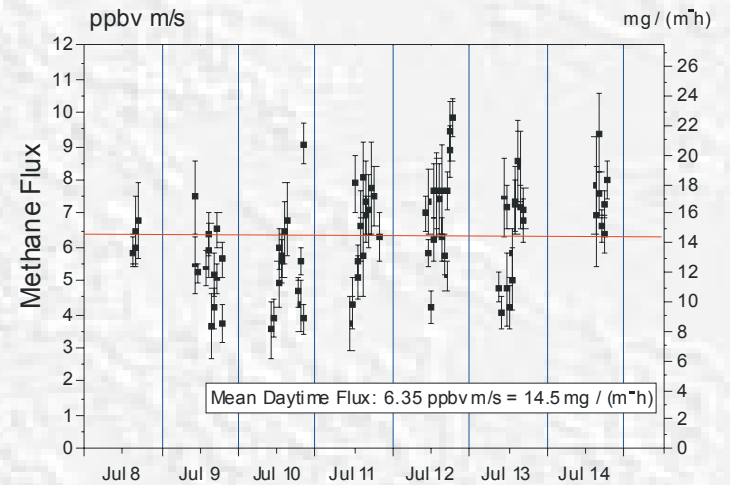
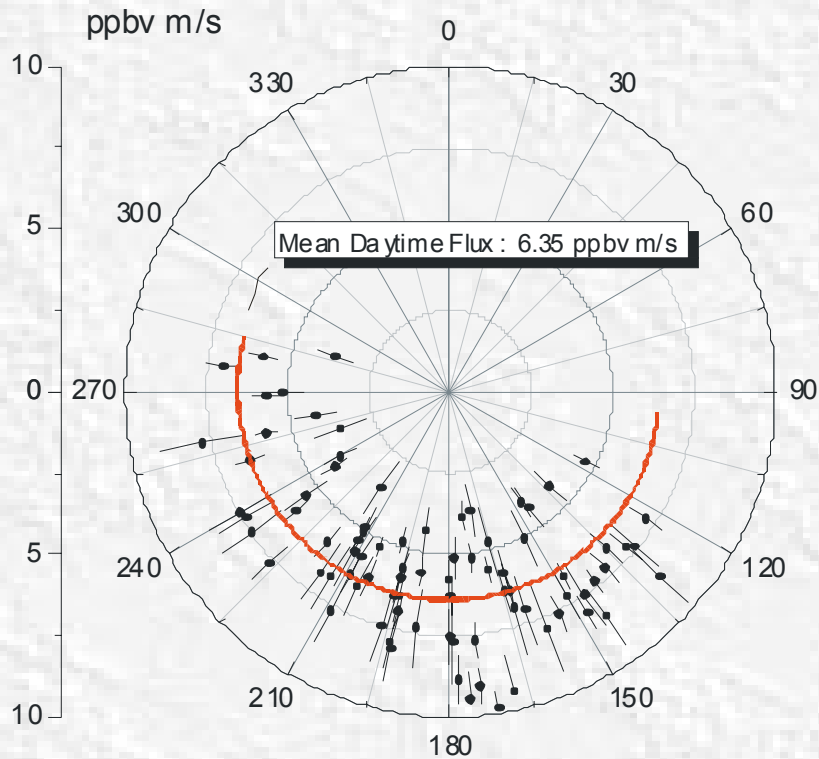
Turbulent flux after time lag correction



Frequency spectra and Allan Variance

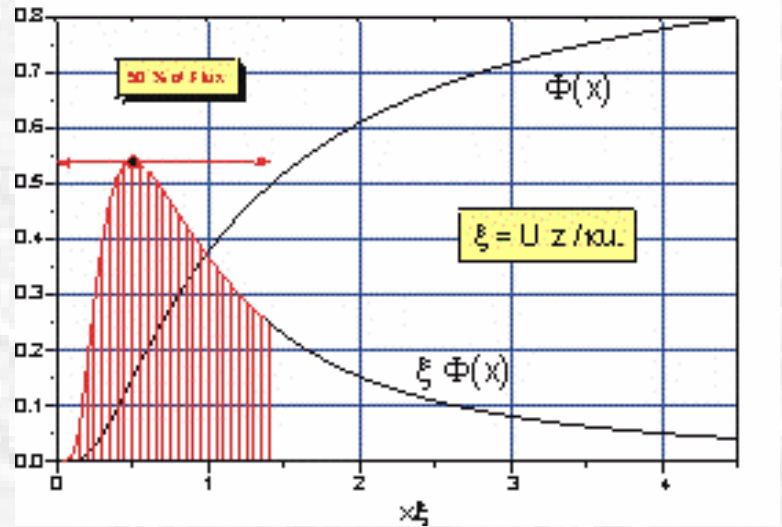
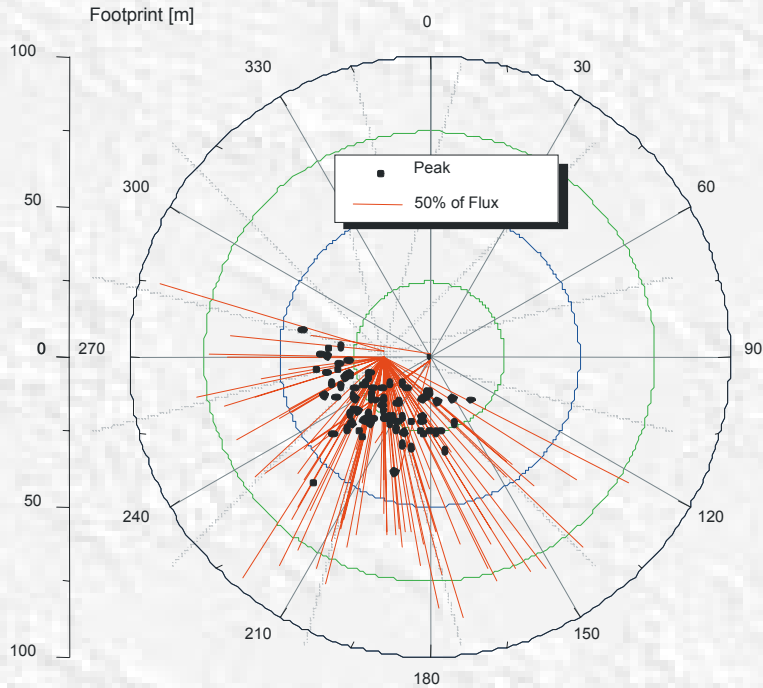


Mean daytime ...



Mean daytime flux : 6,35 ppbv m/s

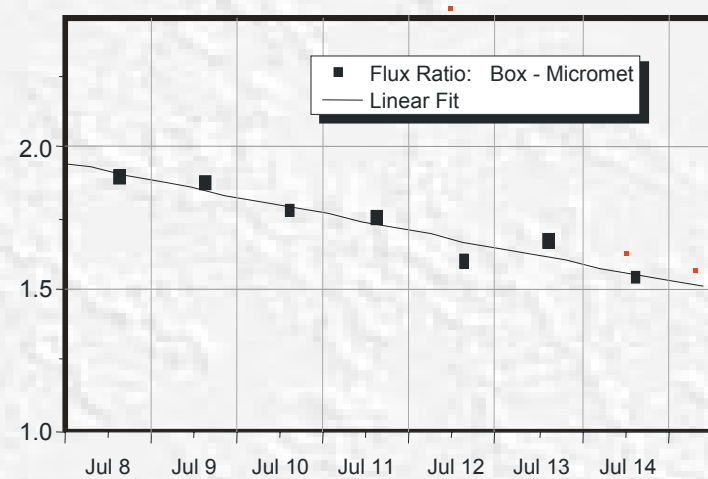
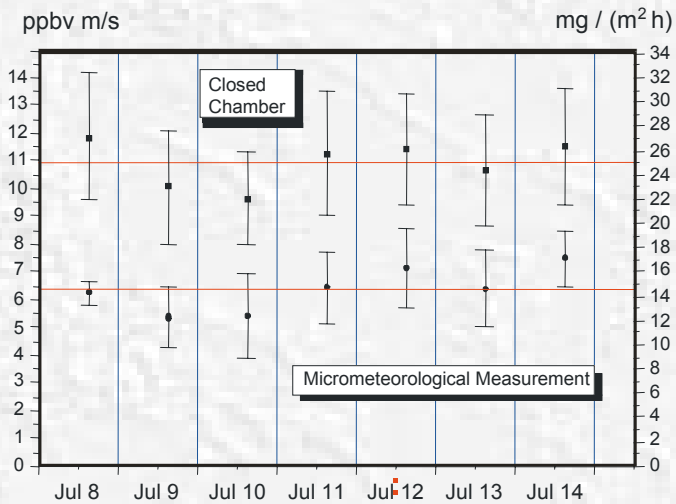
a footprint estimation



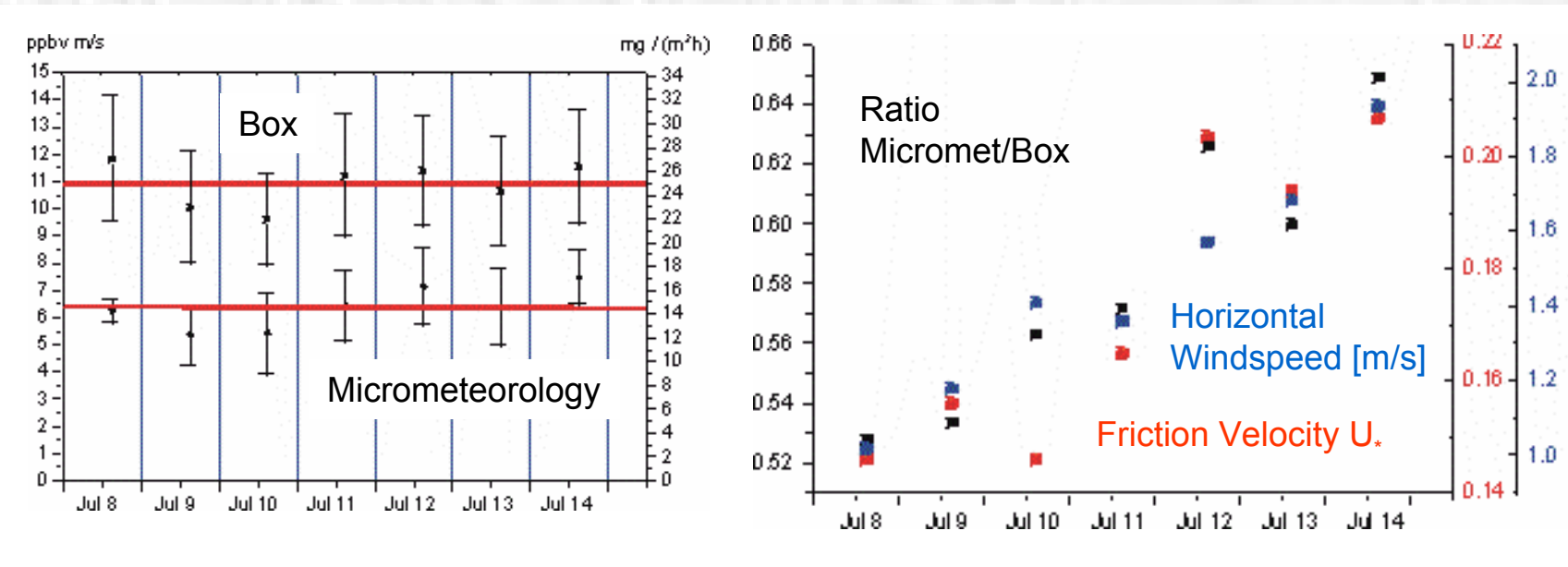
Schuepp et. al., Bound.-Lay. Met 50, 355 (1990)

to assure overlap between eddy flux measurements
and closed chambers measurements

Micromet vs. closed chamber (F. Conen)



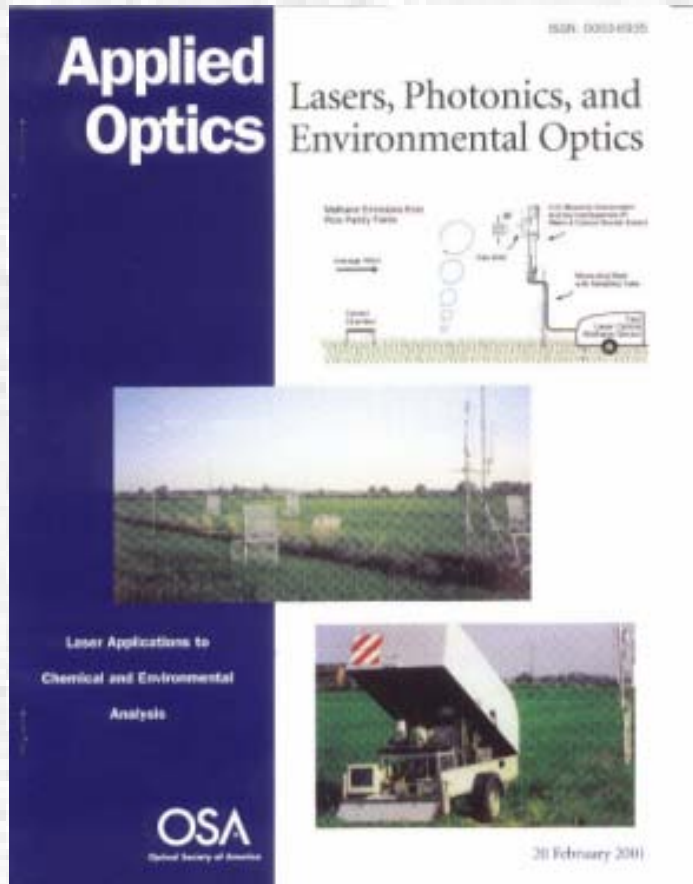
Results




The closed chamber measurements reported to about **70%** higher CH₄ fluxes than the eddy correlation instruments (3 independent systems).



all details are published



P. Werle and R. Kormann, 
"A fast chemical sensor for eddy correlation measurements
of Methane emissions from rice paddy fields",
Appl. Opt. 40, 846-858 (2001).