4.8 NEW TYPE OF CO_2 SENSOR FOR ECOLOGICAL MEASUREMENTS

Christer P. Helenelund *
Vaisala Oyj, Helsinki, Finland

1. INTRODUCTION

Growing environmental awareness and political willingness to fund more ecological research has increased the need for CO_2 measurements in many countries. So far the measurements in the field have, to a large extent, been made with high performance, expensive, and often also bulky analyzer type of instruments. With a few exceptions these analyzers have not been especially suitable for use in harsh outdoor environments. In order to be able to use these instruments in the field, sampling systems, shelters, power systems etc., need to be considered in the measurement setup.

This paper describes a new type of CO_2 sensor that enables a simplified measurement setup for ecological CO_2 measurements.

Because the CO_2 sensor is diffusion aspirated and has the shape of a probe, the new instrument is referred to as the ***new CO_2 probe***.

2. ECOLOGICAL CO_2 MEASUREMENTS

2.1 Various applications

Ecological CO_2 measurements can be grouped or classified in different ways. A classification can be done based on the different measurement sites within the carbon cycle:

- below ground or in the ground water
- at the soil surface
- in towers
- from aircraft and balloons
- from satellites
- from buoys and ships
- in the deep sea

Each type of measurement site has different requirements. For instance, a CO_2 sensor for large concentrations that is buried in the soil is not normally suitable for measuring small CO_2 changes in free air. Nor is a CO_2 analyzer for ambient air monitoring useful for ground water or deep sea measurements without modification. However, much time in the ecological research community is spent to modify, re-build or extend laboratory analyzers for use in various applications.

* *Corresponding author address:* Christer P. Helenelund, Vaisala Oyj, P.O.Box 26, FIN-00421 Helsinki, Finland, e-mail: christer.helenelund@vaisala.com

2.2 Spatial resolution of ecological CO_2 measurements

The spatial resolution of today's stationary ecological CO_2 measurements is for several reasons varying and in many geographical areas even poor. This represents a major uncertainty factor in many research areas. Several attempts to improve the spatial resolution has been proposed by the scientific community, national, and international organizations *Trenberth et al*. (2002), *Ciais et al*. (2004). Many of these proposals seem economically unrealistic and are lacking essential funding. A major problem in improving the spatial resolution is the lack of CO_2 sensors with low power consumption and capabilities to withstand the harsh outdoor environment, and which also are cost-efficient to be used in large quantities.

3. A NEW CO_2 MEASUREMENT CONCEPT

3.1 The measurement technology

The measurement technology used in the new CO_2 sensor is based on the measurement of Infra-Red (IR) absorption utilizing a small silicon based, electrically tunable Fabry-Perot Interferometer (FPI), acting as a tunable bandpass filter. The development of this technology started in 1992 and has been in commercial use since 1997.

The silicon based measurement technology can be seen as a modern version of the traditional filter wheel NDIR (Non-Dispersive Infra-Red) sensor, commonly also known as the NDIR Single-Beam Dual-Wavelength method. This classic sensor structure is used in some high performance gas analyzers and is known for its excellent long term and temperature stability. However, the filter wheel assembly is bulky, power hungry and requires periodical maintenance. This is not the case with the new silicon based sensor, which is practically solid state. Refer to Figure 1 for further details.

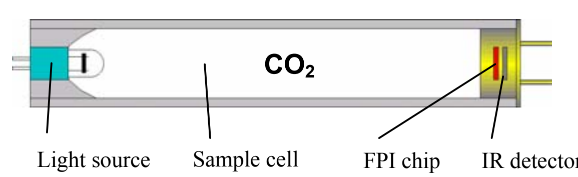

Figure 1 A simple CO2 sensor based on the new NDIR Single-Beam Dual-Wavelength structure

The operating principle of the new sensor is the following: The light source at the left-hand end of the measurement chamber (Figure 1) is electrically modulated, i.e. turned on and off periodically. Light enters the gas chamber, where the gas absorbs a part of the light energy at certain wavelengths. The electrically tunable FPI is tuned so that its passband coincides with the absorption wavelengths of the gas. The IR detector measures the strength of the signal passed through.

After this the passband of the tunable FPI is electrostaticly shifted to either side of the absorption band; a band without interfering absorption lines. As there is no absorption there, only the light transmission in the system is measured. This constitutes the reference signal. The ratio of these two signals indicates the degree of light absorption and further on the gas concentration. In the measurement system, the mechanically rotating filter wheel of the traditional Single-Beam Dual-Wavelength method has been replaced by a small electrically tunable FPI made of silicon. Silicon is an ideal material not only for electronic components, but also for opto-mechanical structures. It is transparent at the IR wavelengths, mechanically stable and ideal for mass fabrication. Further information on this sensing technology and the structure of the FPI chip can be found from *Blomberg et al.* (1997) and *Helenelund and Jalonen* (2000).

3.2 Properties of the FPI based measurement technology

As the new measurement technology provides a true reference measurement, a stable measurement can be obtained. Only one single IR detector is used for both the absorption and the reference measurement, which eliminates the error caused by the difference in temperature dependency of two IR detectors. The stability is therefore not only good in terms of time, but also in terms temperature - Good to the extent that no additional temperature compensation is needed in CO_2 sensors for simple applications such as ventilation control (more demanding research applications obviously require additional temperature compensation). It is also worth emphasizing that the temperature stability results also in a reasonably good stability with flow, which is an important feature, especially in diffusion based measurements.

The good stability is however obtained at the expense of noise and response time, because compared with two-detector structures, the integration time is shorter since the CO_2 absorption band is only measured a part of the time. The rest of the time is used to switch the FPI to the reference band, to measure the reference band and to return back to the absorption band.

3.3 The structure of the new CO_2 probe

The structure of the new CO_2 probe is presented in Figure 2. It differs from the simple CO_2 sensor structure (Figure 1) in the following ways:

- The sample cell is open in order for the gas to move freely through the sensor by means of diffusion
- The light source and the TO-5 encapsulated FPI/detector are both located at the same side of the sample cell and located together with the electronics behind a heated sapphire window, inside an IP67/Nema 6 housing.
- On the opposite side of the sample cell there is a gold plated, specially coated focusing mirror. The mirror is also heated.
- A sensor measuring the gas temperature is located in the sample cell.

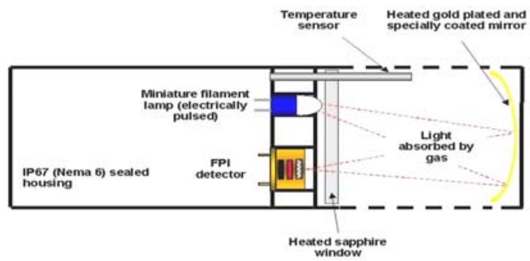

Figure 2 The structure of the new CO_2 probe for ecological measurements

3.4 Properties of the new CO_2 probe

As can be seen from Figure 2, the structure of the new CO_2 probe differs from the structure of CO_2 measurement instruments for ecological measurements available on the market today. In addition to a competitive price, the new structure has the following advantages:

- diffusion based sampling,
- low power consumption,
- can be used in harsh environments,
- good long term stability,
- small size and weight,
- excellent possibilities for performance optimization, as well as
- no additional power supply is needed when used with an optional portable indicator/datalogger

The diffusion based sampling is a welcomed alternative in many ecological applications, especially in cases where the pump sampling can create problems or even errors in the measurement. For instance, in soil chambers the pump sampling can sometimes generate underpressures that accidentally increase the CO_2 flux from the soil. The flushing of the sampling system can sometimes create a flat part in the beginning of the curve (refer to Figure 3), which has to be taken into consideration when the data is analyzed. The main advantage of a diffusion-based sensor is however that it is less complex, less power consuming and requires less maintenance. The possibility to use the product without any protective and thermostated shelter is also an advantage. These shelters, that often need to be customized, add cost and require additional work by the end user. If these shelters are heated or air-conditioned, they increase the overall power consumption.

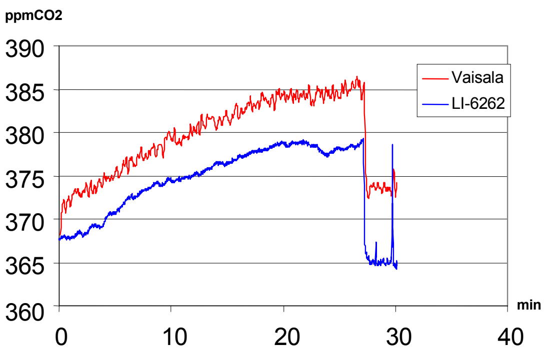

Figure 3 An initial soil chamber measurement with the new CO_2 probe. The measurement was made with the Finnish Meteorological Institute's (FMI) 60x60x80 cm respiration chamber using their standard LI-6262 analyzer as a reference. The two curves have been subject to an offset adjustment in order to better notice the different shapes of the curves in the beginning of the measurement. Note also that the new CO_2 probe has larger output noise.

Long term stability seems to be crucial in most CO_2 measurement applications, including ecological measurements. Long term stability is perhaps not the most important requirement in soil chamber measurements, but in long term ambient measurements it certainly is. Also, the more remote the location of the measurement site is, the more important is long term stability.

As with any new instruments, the new CO_2 probe has some points that should be carefully considered by the user before adaptation into use, the main ones being:

- new measurement technology,
- large peak-to-peak noise,
- slow response time, and perhaps also
- no built-in pressure or humidity sensor

Although the sensing technology has been in commercial use since 1997, it has so far only been used in reasonably simple measurement applications such as ventilation control, greenhouse automation and safety alarming. In these applications long term stability is essential, although ultimate accuracy is not. It is therefore clear that more demanding measurement applications will require some additional attention at least in the beginning of the products life span.

The peak-to-peak noise of the new sensor is large, mainly because of the low power light source and the simple thermopile detector used in the system. The time multiplexed operating scheme of the FPI (refer to section 3.2) is another reason for the slow response. However, this is the price to be paid for obtaining low power consumption as well as a true reference measurement, and consequently a good stability. One could of course argue about the stability when the measurement is so noisy, but if the output is numerically filtered the long-term stability behavior will be good.

Although the new CO_2 sensor has advanced built-in pressure and humidity compensation algorithms, there are several reasons for the probe not to contain a pressure or humidity sensor. Firstly, not all measurement applications need active pressure and humidity compensations since the pressure and humidity remain reasonably constant throughout the measurement. Secondly, considering the wide environmental specification as well as the diffusion based measurement, properly encapsulated pressure and humidity sensors would not have been easy to obtain without a considerable cost penalty. Thirdly, at many sites pressure or humidity data is already available, and if so, this data can easily be linked to the compensation algorithms available in the new CO_2 probe.

4. USING THE NEW SENSOR IN A FEW ECOLOGICAL CO_2 MEASUREMENT APPLICATIONS

4.1 Soil chamber measurements

As the new CO_2 probe was launched a few months ago, there is naturally not much practical experience in using the instrument. Some trial measurements have however been made in cooperation with some universities and research institutes. Together with the University of Helsinki, Department of Forest Ecology, we have designed and manufactured a cylinder shaped soil respiration chamber of transparent plastic (refer to Picture 1). The new CO_2 probe and a humidity and temperature probe were fitted to the top of the cylindrical chamber. CO_2+RH+T data was logged with the optional measurement indicator. A small battery driven computer fan was used to mix the air in the chamber. A pump aspirated PP Systems' Environmental Gas Monitor EGM-3 was used as a reference instrument.

A few trial measurements were made mainly to try out the CO_2 probe with accessories in practice.

Picture 1 The soil respiration chamber and the measurement setup for the trial measurements conducted at the Hyytiala Forestry Field Station in Hyytiala, Finland

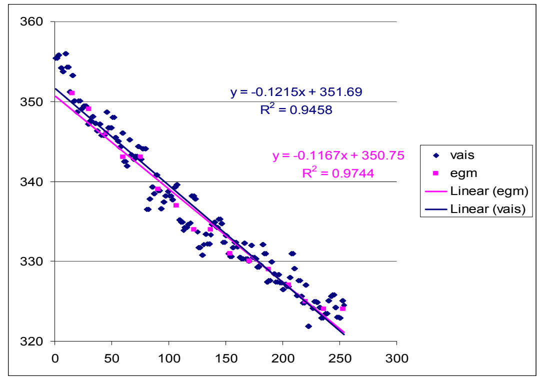

Figure 4 Daytime respiration of soil with main vegetation of blueberry (Vaccinium myrtillus) using the cylindrical soil chamber at the Hyytiala Forestry Field Station in June 2004. The raw output signal of the new CO_2 probe is logged once per second. Despite the large output noise, the slope of the measurement is roughly the same as the slope from the reference measurement

Figures 4 and 5 illustrate the results of a few trial soil respiration chamber measurements made at the University's forestry field station in Hyytiala, Finland. In regard to soil properties and vegetation please refer to http://honeybee.helsinki.fi/HYYTIALA/english.htm.

As can be observed from Figures 4 and 5, the new CO_2 probe is suitable for soil respiration measurements, despite the fairly large raw data noise. The noise performance is one of the properties that will be subject for further studies during the ongoing field trials. The CO_2 probe has three built-in filtering algorithms that could be used to reduce the noise.

The optional RH+T measurement can be used for two purposes:

I) to provide a quality assurance test that the temperature during the chamber measurement will not increase to the level that it would have an impact on the photosynthesis

II) to link the RH data to the new CO_2 probe so that an active humidity compensation of the CO_2 measurement can be achieved

III) also the water flux can be measured (if desired)

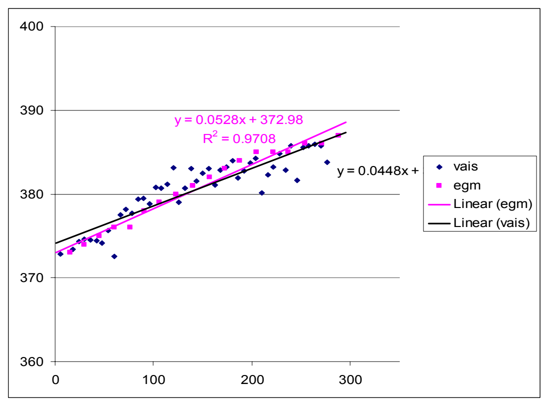

Figure 5 Daytime respiration of soil with main vegetation of lingonberry (Vaccinium vitis-idaea) using the cylindrical soil chamber at the Hyytiala Forestry Field Station in June 2004. Five minutes of logging of the output of the new CO_2 probe. Here the signal is an average of the three last measurements. The logging interval is 5 seconds.

4.2 Ground based CO_2 background measurements

Because of its capabilities to withstand harsh environments, one potential application for the new CO_2 probe could be outdoor CO_2 measurements in ground based measurement networks. I am not referring here to these really accurate background measurements made at a few well chosen locations around the world, rather to networks of various size where the price per measurement point has to be essentially smaller than what can be achieved with conventional CO_2 analyzers. In measurement applications where the response time is not of main importance, numerical filtration can be used to obtain a noise level at ambient around perhaps ±0.7 ppmCO_2.

In background measurements, good long-term stability and good temperature stability are essential. This requirement seems especially important at remotely located measurement sites, where frequent service is difficult or expensive to organize. Because of the true internal reference measurement, the stability of the new CO_2 probe is better than in many other CO_2 instruments on the market today. Note, however, that even if the stability of the new CO_2 probe is good, the requirements for long-term stability are in some ecological measurements so strict, that the stability can only be guaranteed by frequent manual or automatic re-calibrations against accurate WMO calibration gases.

Again, the new CO_2 probe has to be comprehensively tested before it can be used in any larger scale. Initially a few units have been tested at Vaisala's factory in Helsinki, Finland last winter. Although this test was only a rough field trial it showed that the new instrument technically works in the cold and occasionally also very humid winter climate in Southern Finland.

5. SUMMARY AND CONCLUSIONS

A new type of CO_2 sensor has been developed with the aim to obtain an instrument that can be used in harsh outdoor environments. It has several advantages compared to traditional CO_2 analyzers: diffusion-based sampling, good long-term stability, low power consumption, small size and light weight. It is therefore suited for measurements in remote locations lacking mains power supply. With the optional portable indicator/datalogger, the probe can be used for more that 6 hours in the field.

Since the raw peak-to-peak noise and the response time of the new CO_2 probe is larger than in traditional high-performance laboratory CO_2 analyzers, the new probe is not suitable for applications where low noise and a fast response are required at the same time. However, if the response time is not critical, output noise can be reduced with the built-in filtering algorithms. Also other possibilities for performance optimization exist.

The aim of the new CO_2 probe has been to provide a new type of instrument for ecological CO_2 measurement applications. It will not replace traditional high-performance analyzers; rather, it will serve as a new research tool in systems where environmental ruggedness, long-term stability, low power consumption and cost efficiency are required.

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