A Global Greenhouse Gas Monitor

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Abstract. We present an advanced new sensor, the Greenhouse Gas Monitor (GGM^{TM}), which will revolutionize the global measurement of greenhouse gas levels. The GGM^{TM} is an ideal compact, passive instrument for deployment on future-generation small LEO satellites. The Kyoto summit on greenhouse gas and carbon emissions has demonstrated the urgent need for accurate, global monitoring of a range of greenhouse gases. Levels are currently estimated by making precise ground-based measurements at a few points around the world; coverage of the Earth's surface can be vastly improved by making measurements from space along a closely spaced grid. We are developing an advanced tuneable etalon spectrometer, tuned to the near infrared bands (1.2 to 1.7 μm), which will scan the reflected sun-glint on the Earth's surface and measure CO_2 absorption spectra and atmospheric column amounts. In addition to the primary Greenhouse gas, carbon dioxide, the GGM^{TM} can also measure the column amounts of methane (CH_4), water vapour and oxygen. The instrument will scan a swath width of 400km with a grid spacing of 50km and provide about 1000 samples per month on a 8° x 10° grid. The target standard error in monthly averages is about 0.3% corresponding to about 1ppm CO_2.

Introduction

The Kyoto summit on greenhouse gas and carbon emissions (and the associated reduction targets for countries) has demonstrated the urgent need for accurate, global monitoring of a range of greenhouse gases. Levels are currently estimated by making very precise ground-based measurements at a few points around the world and extrapolating or modelling points in between. The coverage of the Earth's surface can be vastly improved by making measurements from space along a closely spaced grid. An instrument with sufficient accuracy has not been forthcoming.

In this paper we intend to establish that great science can be achieved through the measurement from space of greenhouse gases to a required accuracy. We show that the best method for measuring greenhouse gases from space is through the use of etalon absorption spectroscopy. In addition, we have designed an instrument capable of measuring the main greenhouse gases to more than sufficient accuracy.

The Science

The identification and attribution of actual sources and sinks of greenhouse gases is currently a global political and economic issue of immense importance for the future of our planet. This knowledge forms the basis for verification of compliance with carbon emissions treaties or protocols, and will become the basis for any international carbon trading.

A previous paper[1] explains how the measurement of greenhouse gases from space may be used to dramatically increase our understanding of the sources and sinks of these gases on a global scale.

Briefly, our present understanding of sources and sinks for greenhouse gases derives primarily from a sparse network of surface stations (see Figure 1). The individual measurements are of high precision, but each station samples only a small and uncertain part of the atmosphere. In addition, the distribution of surface stations is strongly biased towards clean ocean environments of the northern hemisphere.

The uncertainties (giga-tonnes of carbon emissions, GtC, per year) in the distribution of carbon emissions, based on the surface network, are shown in Figure 2. It is clear that there are large uncertainties particularly over land, and there is little prospect for any regional attribution of sources and sinks.

Satellites measure the total column amount of CO_2, and offer excellent spatial and temporal coverage at the cost of reduced precision compared with the land-based measurements. The question is, what level of accuracy is required from space for it to be useful?

Rayner[2] showed that the standard error in the global carbon budget based on column CO_2 from space is equal to the standard error from the current ground network if the error of individual observations is 2.7ppm. If observations are only made over the oceans, then the standard error required from column CO_2 reduces to 1.5ppm.

Further work carried out by Rayner and O'Brien[3] broadened the assumptions by assuming a more realistic signal return, depending on the surface reflectance. This showed that the attribution of sources and sinks of greenhouse gases from a space platform reduces the errors to a uniform low level (<0.1 GtC per year), compared with the huge errors illustrated in Figure 2 from the ground network (up to 1 GtC per year).

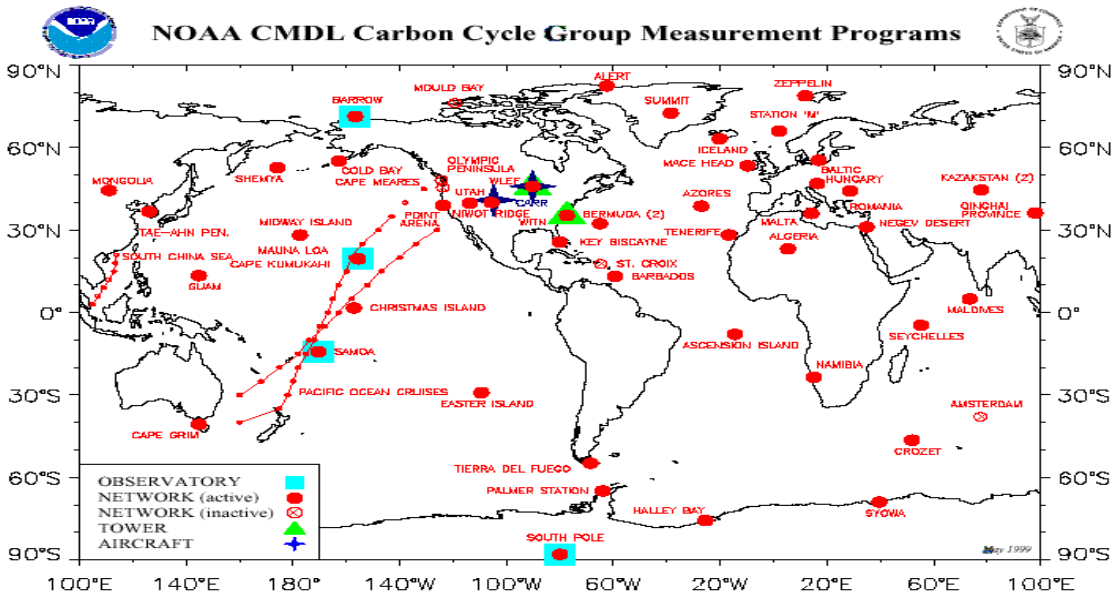

Figure 1. The Locations of the Surface Stations Currently Measuring Greenhouse Gases (source: NOAA)

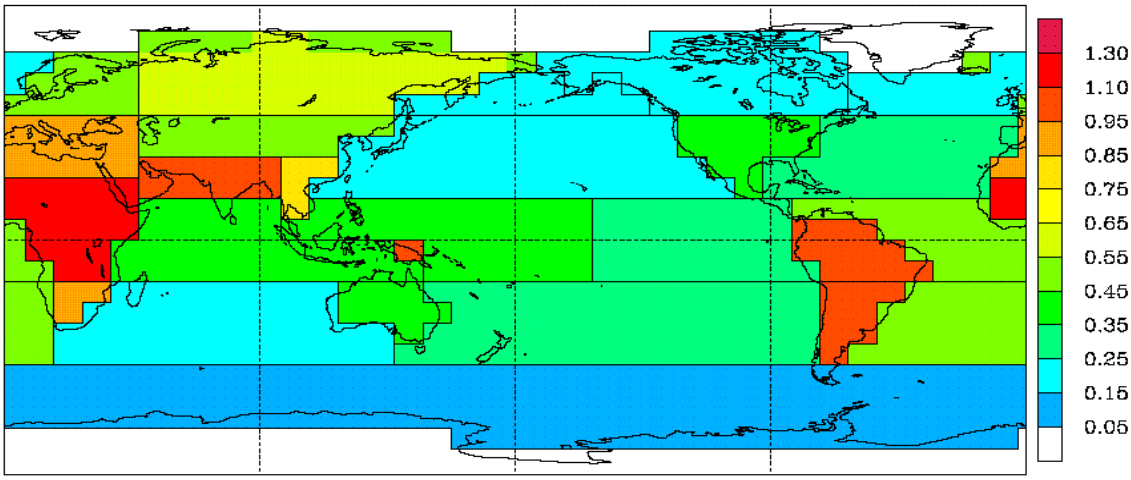

Figure 2. Map of the Likely Uncertainties in CO_2 Sources and Sinks ($GtCy^{-1}$) from the Surface Network (Source: Rayner 2000 [2]).

The Technology

The previous paper[1] showed that attempting to measure CO_2 through emission spectroscopy is unlikely to succeed due to its high sensitivity to the atmospheric temperature profile, low sensitivity to the CO_2 column amount and the need for absolute calibration.

Absorption spectroscopy, however, offers far greater potential. This method offers high sensitivity to trace gas concentrations and high signal-to-noise ratios, without the need for absolute calibration.

There are advantages to using conventional grating spectroscopy to measure gas column amounts, particularly the multiplicity of lines that may be observed at one time. However, the technique suffers from severe aliasing problems. With only a few sampling points across a narrow line profile, there is always going to be a high degree of error involved in measuring the central line position, and the depth of the line, in the presence of noise.

In contrast, an etalon based system scans across a single line profile with numerous sampling points. So, even in the case of a noisy signal, there will be accurate registration of the line centre, allowing self spectral calibration and thereby avoiding problems with aliasing.

Hence, the best technology for the measurement of greenhouse gases from space is currently absorption spectroscopy using an etalon-based filter system.

The Instrument

The basic concept design for a new space-based instrument to measure greenhouse gases is shown schematically in Figure 3.

The main operational mode for such a satellite-borne device, the Greenhouse Gas Monitor (GGM™), is to view and scan the sun-glint region on the Earth's surface, and detect the absorption of sunlight in its path through the atmosphere.

The four gases to be monitored by the GGM™ are shown in Table 1. They include the two primary greenhouse gases – carbon-dioxide (CO_2) and methane (CH_4); water vapour (to determine the level of H_2O contamination in the spectra); and oxygen (to determine the level of undetected faint cirrus cloud).

In a submission to Japan's NASDA to include our instrument on their GCOM-A1 (Global Climate Observation Mission) satellite, we targeted physical parameters appropriate for a micro-satellite mission, with a mass of 40kg, average power requirement of 30W and a data acquisition rate of up to 100kbps.

The instrument design is based on the TERSE design put forward by Aoki, Fukabori & Aoki 1993.[4]

A prototype system was designed and built by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and Vipac Engineers & Scientists, called the Atmospheric Pressure Sensor, or APS.[5-9] Two prototypes, using different technology, were developed and tested.

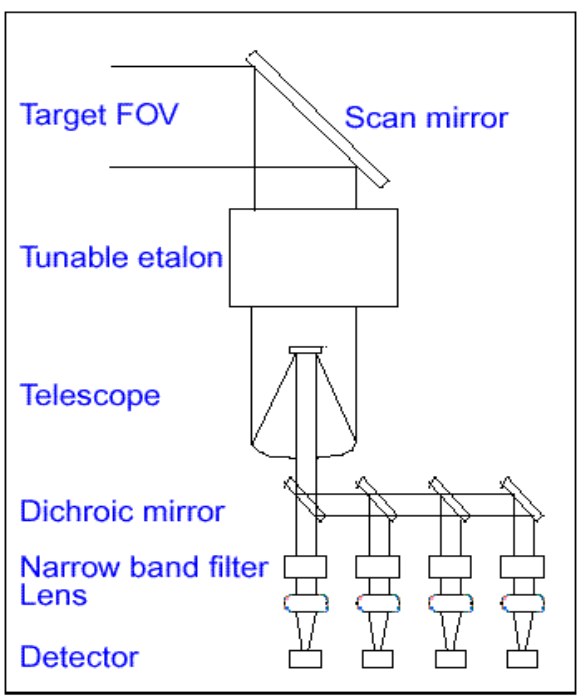

Figure 3. Schematic concept of an instrument to measure greenhouse gases from space.

Table 1. The Four Gases Monitored by GGM™

Gas	Frequency	Wavelength
CO_2	6237 cm^{-1}	1.603 µm
H_2O	7659 cm^{-1}	1.306 µm
O_2	7899 cm^{-1}	1.266 µm
CH_4	6057 cm^{-1}	1.651 µm

Prototype I

The first APS prototype used a grating spectrograph design in Littrow configuration, with a focal length of 500mm at f/2.3, and a cooled silicon diode array for the detector. This was a single gas device designed to measure absorption in the oxygen A-band.

The instrument was tested on a range of high altitude aircraft flights, by taking the aircraft pressure height as a proxy for air pressure.

The flights experienced widely varying conditions, including thin cirrus above the plane, descent through hazy/smoke layers, and both calm and rough seas. The retrieved data gave a good correlation between predicted and measured pressure heights, accurate to ±0.1 kPa (see Figure 4).

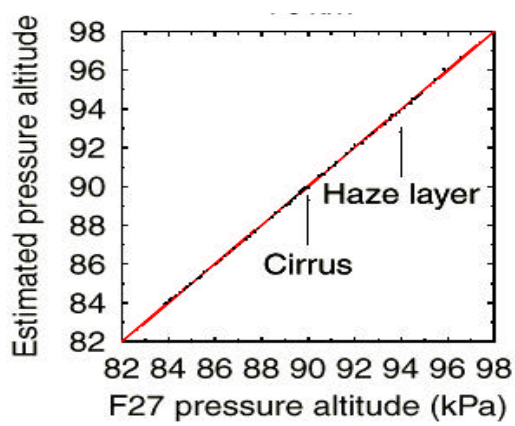

Figure 4. Plot of correlation between predicted and measured pressure height from prototype flight trial.[6]

Prototype II

The second prototype (Figure 5) was based on an electro-optically tuneable etalon spectrometer, using a lithium-niobate spectral element.[10] It is effectively a narrow-band Fabry-Perot interference filter with a voltage-tuneable refractive index.

This advanced design was much more compact than Prototype I, with a 100mm aperture at f/1. Indeed, it is also more robust and has a fixed alignment with no moving parts (apart from the external scan mirror).

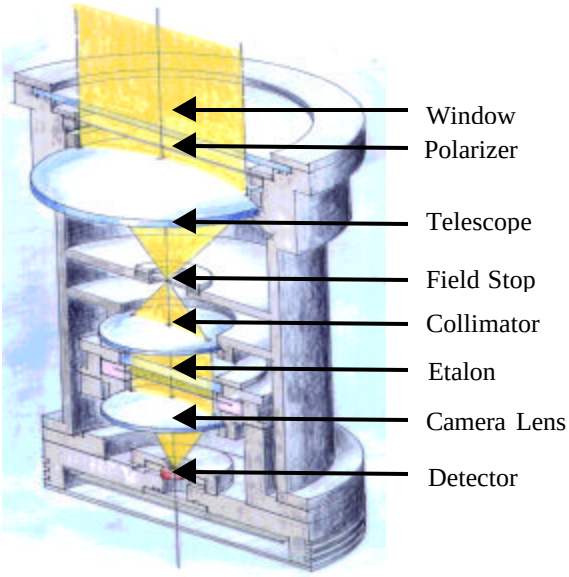

Figure 5. Cut-away view of the Prototype II.

Laboratory tests showed that this device had similar data retrieval capabilities as the first prototype. In other words, it was capable of measuring air pressure to ±0.1 kPa, a comparable accuracy to ground based measurements.

Planned Mission & Observations

Although space measurements made towards the sun-glint surface returns the highest signal-to-noise, experiments with the APS and TERSE instruments showed that this was unnecessarily restrictive.

The GGM^{TM} device requires a LEO orbiting satellite and can operate at a range of altitudes and orbit inclinations. With a two-axis scan mirror, the instrument can scan a swath width of 400km with a grid spacing of 50km (with a footprint size of about 5km, depending on the orbit altitude).

Simulations for the GCOM-A1 orbit show that there would be in excess of 1000 observation samples within any 8 x 10 degree box (over the period of about a month), depending on the orbit inclination.

However, the noise sources will not be uncorrelated. As a conservative estimate, it is assumed that at least 10% of the observations would be statistically independent. With individual measurement accuracy better than 3%, the standard error in monthly averages of CO_2 would be about 0.3%, or 1 ppm.

A low measurement error reduces the ultimate cost of carbon emissions control for government/industry by limiting any under- or over-estimate of emissions.

Conclusion

The greenhouse gas monitor is a versatile instrument capable of addressing carbon emission/greenhouse gas issues. Australia currently leads the world in the technology. The results would have major scientific significance and would save governments money.

The GGM^{TM} instrument on a small satellite platform would provide greenhouse gas measurements with good spatial coverage and accuracy, enabling vital identification of global CO_2 sources and sinks.

The potential inclusion of the GGM^{TM} on NASDA's GCOM-A1 satellite has great potential. Such a mission would also provide a focus for future development of the Australian satellite and space industry, with a global vision towards building a constellation of satellites with GGM^{TM} capabilities.

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