Fabry-Perot Interferometer for Column CO_2

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Abstract. **Global atmospheric CO_2 measurements are essential to resolving significant discrepancies in our understanding of the global carbon budget and, hence, humankind's role in global climate change. The science measurement requirements for CO_2 are extremely demanding (precision ~0.3%). No atmospheric chemical species has ever been measured from space with this precision. We are developing a novel application of a Fabry-Perot interferometer to detect spectral absorption of reflected sunlight by CO_2 and O_2 in the atmosphere. Preliminary design studies indicate that the method will be able to achieve the sensitivity and signal-to-noise detection required to measure column CO_2 at the target specification. The objective of this program is to construct a prototype instrument for deployment on an aircraft to test the instrument performance and our ability to retrieve the data in the real atmosphere. To date we have assembled a laboratory bench system to begin testing the optical and electronic components. We are also measuring signal and noise levels in actual sunlight to evaluate component performance.**

I. Introduction

The Earth's climate is changing as a result of human activity including emission of greenhouse gas chemicals. Carbon dioxide (CO_2) constitutes the largest current and projected anthropogenic climate forcing [1]. Yet, in spite of its primary importance in climate forcing and response, large uncertainties exist in the global carbon budget that must be resolved before reliable impact predictions and remedial strategies can be derived. High precision global measurements of atmospheric CO_2 are essential to resolving these issues [2]. Such measurements are not currently available. At present, regular measurements are limited to surface sites, and large areas of the globe are not sampled. We are developing a remote sensing technique for measuring atmospheric CO_2 that should be precise enough to match the very stringent science requirements, but will be reliable, low cost, and easily deployable enough to enable global satellite measurement of CO_2 on a continuous and extended basis. The instrument is based on a novel application of a Fabry-Perot interferometer, which allows multiple CO_2 lines to be sampled simultaneously with a narrow bandpass centered on each line. This method has significant performance benefits compared to other potential methods for measuring CO_2. These measurements have the potential to substantially enhance our understanding of the consequences of Earth system change and our ability to predict future changes.

A. Science Measurement Requirements

Carbon budget studies have determined that a substantial fraction of the emitted CO_2 cannot be accounted for by the observed atmospheric increase and calculated uptake by oceans (e.g., [3]). This discrepancy has led to speculation about the nature of the "missing sink" for carbon. A widely-held hypothesis is that the unaccounted CO_2 is being taken up by the northern hemisphere biosphere [4, 5]; however, there are large uncertainties in the magnitude, spatial/temporal distribution, and mechanism for this implied vegetation uptake [6, 7, 8, 9]. This leads to our guiding science question: What is the global distribution of CO_2 sources and sinks on a regional and seasonal basis? Approaches to solving this problem are currently data-limited to a large extent [10, 11].

Globally distributed remote sensing CO_2 concentration measurements with sufficiently high precision have the potential to better constrain CO_2 surface sources and sinks than is possible with existing networks [11]. Although most CO_2 concentration variability related to surface source/sink forcing occurs in the lower atmosphere (~1000 to 800 mbar), available sensing technology indicates that total column measurements are currently much more feasible from space than altitude profiling approaches. For a column average, mixing ratio gradients of 1 to 3 ppmv over spatial scales of about 1000 km are induced by the surface forcing (Fig. 1). Transport inversion model experiments indicate that global column measurements with a precision better than 1% (3 ppmv on the 370 ppmv background) on a time scale of 1 month are required to improve surface flux estimates beyond the capability of the existing network [11]. Thus our measurement goal is 1 ppmv precision for total column CO_2 mixing ratio.

Obviously the extremely high precision requirement, better than 1%, is the main driver in developing a measurement strategy and instrument approach. We have designed a candidate system with a clear pathway to space that should meet the requirements. The analysis is shown below. We have assembled a laboratory bench model of key components, which we are currently testing, and we will construct a space-scalable prototype of such an instrument system for testing and deployment on an aircraft. The objective of this instrument is to demonstrate that the detection technique will perform as predicted in the real atmosphere and that it will be able to achieve the required performance in a system that is robust, inexpensive, and easily deployable for regular CO_2 space measurement.

B. Measurement Approach

The mission concept is to measure the spectral absorption of reflected sunlight by CO_2 in the atmosphere. This method is well established, similar to the Total Ozone Mapping Spectrometer (TOMS), which achieves about the most precise

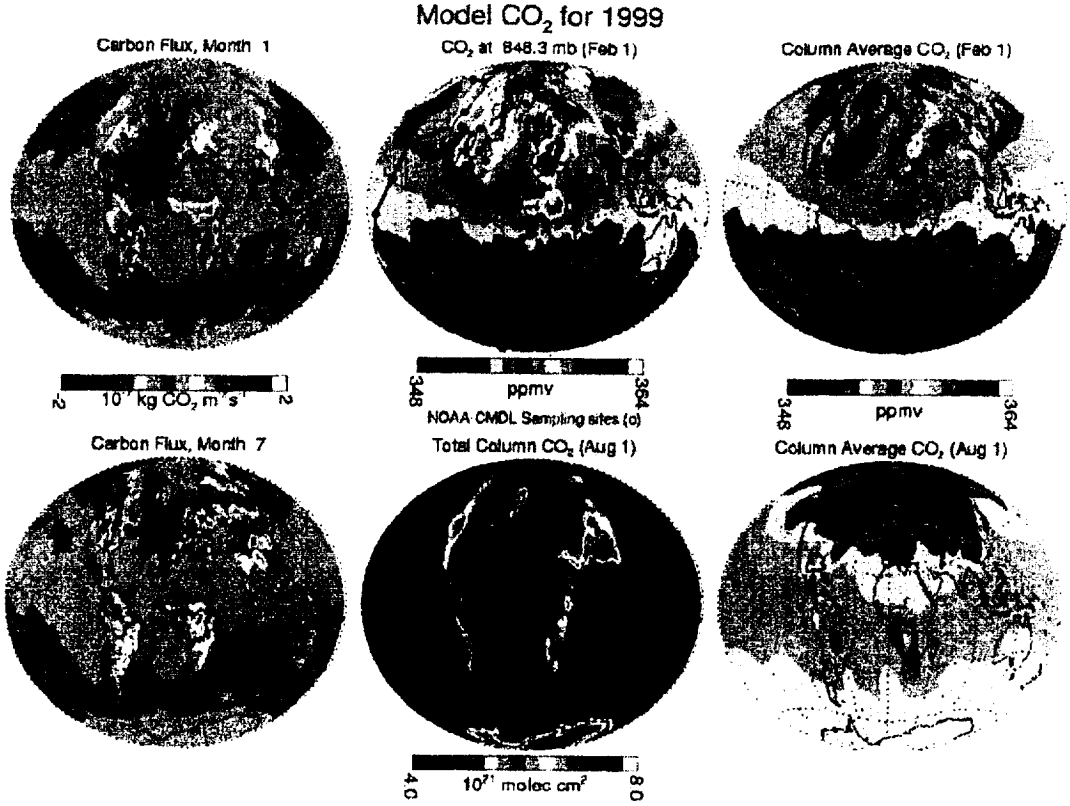


Fig. 1. Global model simulation showing CO_2 variations induced by variations in the surface sources and sinks and transport using assimilated winds for 1999. Left two panels show the net CO_2 surface flux for January and July adapted from the TRANSCOM scenarios [12]. Center upper panel shows CO_2 mixing ratio in the lower atmosphere varies substantially in response to surface flux regional variations. Model horizontal resolution is 2x2.5° with 70 levels in the vertical through the stratosphere. Existing surface CO_2 monitoring sites are also shown. Most of these sites take samples approximately weekly. Center lower panel shows that variations in total CO_2 column concentration are dominated by variation in terrain height and surface pressure. Right panels show column average CO_2 mixing ratios for two example days of the simulation.

and accurate current global measurement of atmospheric constituent abundances. The near-nadir viewing approach stands the best chance of detecting CO_2 variability near the surface in the presence of clouds, and using the sun as a light source enables high signal-to-noise detection of spectral absorption.

Model simulations (Fig. 1) show that variations in terrain height and surface pressure create gradients in CO_2 column concentration comparable to or larger than those induced by surface flux variations. Optically thick clouds introduce variability by changing the effective height of the reflective surface. The effect of aerosol scattering will also be significant in some conditions. Hence a measure of the total atmospheric path, over which the CO_2 absorption takes place, is required. High-resolution spectral measurement of O_2 absorption has been shown to permit derivation of surface pressure and cloud height with high precision (better than 1%) [13, 14, 15, 16]. Thus the CO_2 instrument system is designed to include co-aligned spectrometric measurements of both CO_2 and O_2 absorption. Our high-level data product will be dry air column average CO_2 mixing ratio.

Variations in surface and cloud reflectance at CO_2 wavelengths are relatively large, so a small sample footprint is desired to reduce this source of variance as well as to maximize cloud-free samples. On the other hand, a sufficient amount of light at the instrument is needed for high signal-to-noise detection. We have chosen a 10-km sample for a space instrument so as to resolve surface features on the scale of urban, forest, or agricultural areas, as well as attain global coverage over several days. The aircraft version is scaled accordingly.

Note that the ocean surface is relatively dark (albedo ~0.03 versus ~0.3 over land surfaces) at CO_2 wavelengths so the reflected signal would be more difficult to detect. However the instrument sensitivity, as outlined below, should be sufficient to detect CO_2 with high signal-to-noise even over ocean.

II. Instrument Technology

The proposed instrument operates by measuring solar flux reflected off the surface of the Earth in 2 channels. The first channel covers a relatively broad spectral range which

includes a number (~10) of CO_2 spectral features but for which the CO_2 absorption represents only a small fraction of the total reflected light. The second channel employs a Fabry-Perot interferometer to restrict the detected light to include only those regions where CO_2 absorption is significant. A small change in the CO_2 column then produces an insignificant change in the signal obtained from channel 1 but a relatively large change in the signal from channel 2. Factors influencing the signal strength other than changing CO_2 column, such as changing Earth albedo or the shadow of a cloud, affect both channels proportionately so that the ratio of channel 2 signal to channel 1 signal is quite sensitive to a change in the CO_2 column but relatively insensitive to changes in other parameters.

A. CO_2 and O_2 Spectroscopy

We have chosen to design our instrument to operate on the CO_2 absorption band near 1.58 μm because the solar flux is relatively high here and because detectors are more efficient in this band. Fig. 2 shows a spectrum of CO_2 in this region at a temperature of 250 K.

As noted in section I, it is necessary to normalize the CO_2 column density by the total column density of the atmosphere. Measurements of the O_2 column with a precision of better than 0.1% have been made using a grating spectrometer operating from an aircraft platform [17]. We have chosen to operate the O_2 channel of the instrument in the O_2 A-band located near 0.76 μm to avoid problems with airglow interference that could arise for space-based observations. Our system will ultimately require a minimum of three Fabry-Perot channels because O_2 must be measured at two different wavelengths in the A-band to account for temperature and pressure variations.

B. Operation of a Fabry-Perot Interferometer

A Fabry-Perot interferometer is constructed of two very flat, partially reflecting mirrors held parallel to one another at a fixed distance. Interference occurs among the multiple reflections leading to the condition that wavelengths that exactly divide the spacing between the mirrors by an integer are transmitted very efficiently and all other wavelengths are reflected. Thus if the plates are held fixed at a separation of 10 μm, then radiation at 10, 5, 3.333, ... μm will be transmitted. Note that these wavelengths are equally spaced in energy according to the relationship $E=hc/l$, where l is the wavelength of the light and h and c are Planck's constant and the speed of light, respectively. Our proposed technique makes use of these multiple passbands to increase the measurement signal and the resulting signal to noise ratio.

A Fabry-Perot can be tuned to transmit different wavelengths by changing the (optical) spacing between the mirrors. This is commonly done by employing piezo-electric transducers to translate the mirrors by very small distances, while maintaining the very precise parallelism between them. Fixed gap Fabry-Perots can be tuned by tilting, which changes the effective path length between the plates; by using the thermal expansion and contraction of the spacers between the mirrors; and by changing the composition or pressure of the gas that fills the space between the plates, which alters the index of refraction thereby changing the optical separation. Finally, Fabry-Perots can be constructed using a solid substrate of fused silica or optical quality glass onto which reflective coatings are deposited. These devices can be angle tuned or temperature tuned. As part of this investigation we will examine various tuning methods and select the optimum for our application. A schematic of a measurement module is given in Fig. 3.

The quantum mechanical rules that govern the permitted energies for absorption and emission of light via rotational transitions within a molecule frequently give rise to spectral lines separated by nearly constant energy. Near 1.58 μm the spacing between CO_2 lines is quite regular for a span of several lines (Fig. 2). We will exploit this feature by aligning the passbands of a Fabry-Perot with multiple CO_2 spectral lines. Fig. 4 illustrates our method. Ten passbands of a Fabry-Perot with an optical spacing of 0.26023 cm^{-1} and a reflective finesse of 30 are shown as well as ten absorption lines of CO_2 in the P branch of the 1.58 μm spectral region. Because the passbands are nearly the same width and location as the molecular lines, CO_2 absorbs more than 10% of the total light transmitted through the etalon in this example.

Use of multiple lines provides much higher signal than

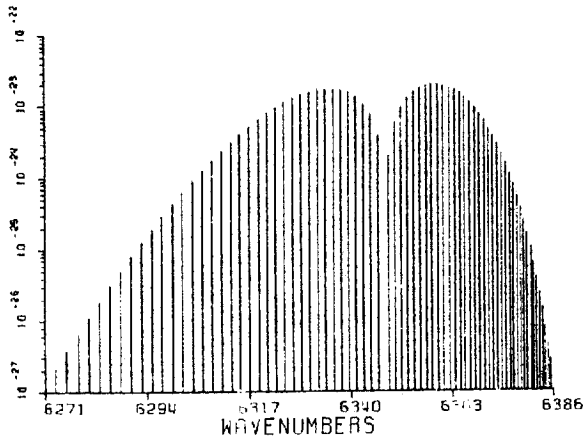


Fig. 2. The30012-001 band of CO_2. This region is nearly free of interference from other species and has suitable absorption cross sections for measuring CO_2 column.

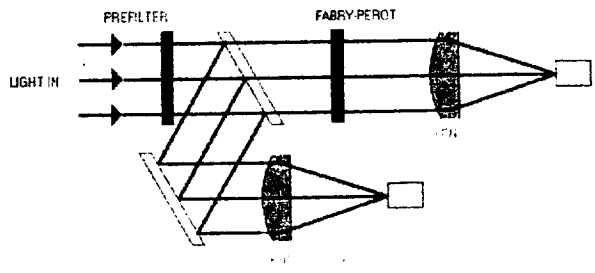


Fig. 3. Schematic illustration of light path through the CO2 instrument system. The O_2 systems are conceptually identical.

techniques using a single line. Our proposed instrument will not need a telescope because of the large signal return. A prefilter with a bandpass on the order of 2 nm will isolate the Fabry-Perot from photons outside the spectral region of interest (Fig. 4). Such multilayer dielectric filters are readily available.

III. Performance Simulations

The ability to detect changes at the level of 1 ppmv in the total column with an average mixing ratio of 370 ppmv requires measurement precision of better than 370:1. In this section we present some simulations of Fabry-Perot performance to indicate how an actual measurement will be accomplished.

A. Precision

In the following calculation we assume a 5-cm diameter Fabry-Perot in a low Earth orbit at an altitude of 500 km. We assume the free spectral range of the Fabry-Perot filter is 1.6 cm^{-1}, which is roughly the separation of the CO_2 lines in this region. A finesse of 10 is chosen to give a bandpass of 0.16 cm^{-1}, which is similar to the width of the CO_2 lines.

The solar flux near 1.58 μm is approximately 250 W m^{-2} μm^{-1}, which is equivalent to 0.0625 W m^{-2}/cm^{-1}. The field of view is limited to ~0.02 radians by the requirement that the angular spread incident upon the Fabry-Perot be minimized so that angle tuning does not shift the absorption lines. From an altitude of 500 km, the area on the Earth's surface viewed by the instrument corresponds to a circle 10 km in diameter—an area of about 7.8×10^7 m^2. The total flux from the sun striking this circle that is within the passband of the prefilter (FWHM = 15 cm^{-1}) is 0.0625 x 7.8×10^7 x 15 = 7.3×10^7 W, which equals 5.85×10^{26} photons s^{-1} at 1.25×10^{-19} J $photon^{-1}$. This is the amount of light potentially available to the OFF line channel. The ON line channel has about 8 passbands each 0.16 cm^{-1} wide giving a total spectral width of about 1.3 cm^{-1}. Thus the ON line channel (in the absence of any absorption) has available about one twelfth as much light as the OFF line channel.

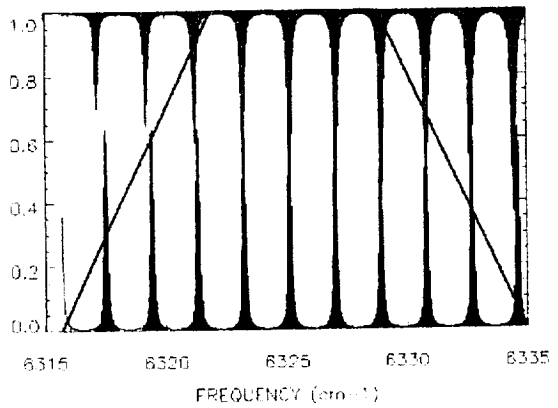


Fig. 4. Multiple passbands of a Fabry-Perot (blue) are shown with CO_2 absorption lines (gray) near 1.58 μm. A typical prefilter shape is shown in red.

The Earth albedo at this wavelength varies between 2-3% for the ocean to more than 30% for certain types of snow. For the purpose of this simulation we use a reflectance of 10% and assume that the scattering from the surface is Lambertian (i.e., the scattered photons are evenly distributed over a hemisphere). The surface area of this hemisphere by the time the scattered light reaches the spacecraft altitude of 500 km is 1.57×10^{12} m^2. The entrance aperture of the instrument has an area of 0.002 m^2 so the fraction of the scattered photons collected is $0.002/1.57 \times 10^{12} = 1.25 \times 10^{-15}$.

For a prefilter with a transmission of 60% and an InGaAs PMT detector with a quantum efficiency of 3%, the OFF line channel will have a signal on the order of 1.4×10^9 counts s^{-1}. With no absorption, the ON line channel would detect roughly 1.2×10^8 counts s^{-1}.

As noted above the column abundance of CO_2 is ~6.5×10^{21} molecules cm^{-2} and the cross sections in the 1.58 μm region are on the order of 10^{-22}. For 2 passes through the atmosphere (noon sun condition) this give transmission of about 25%. However, when a realistic Fabry-Perot bandpass function is convolved with a theoretical CO_2 spectrum, transmission increases to ~80-90% depending on which lines are selected and the alignment of the spectral features with the passbands of the filter. The absorption signal produced by the CO_2 column therefore corresponds to a 10% change in the ON line channel, or roughly 1.2×10^7 counts s^{-1}. The uncertainty in the count of the ON line channel is the square root of the count, or $(0.9 \times 1.2 \times 10^8)^{1/2}$, which is less than 11000. The signal to noise ratio (SNR) for the absorption is then on the order of 1.2×10^7 /11000 i.e., a precision of 1100:1 in one second. In practice the actual determination of the CO_2 absorption will involve the ratio of the ON line count to the OFF line count, but the OFF line count is so large that it contributes only slightly to the overall noise. These calculations demonstrate that a measurement of the CO_2 column with a precision of 1 ppmv is well within the capability of the proposed instrument.

The above analysis is for nadir viewing at noon under clear sky conditions. At higher zenith angles the flux is reduced but the absorption signal increases with the longer path length. Radiative transfer simulations indicate that, in the absence of clouds, we will have good sensitivity for solar zenith angles as high as 80°.

B. Temperature Dependence

To minimize the instrument sensitivity to temperature change we will select a bandpass such that some CO_2 lines increase in strength and some decrease in strength with temperature. Although it should be possible to use analyzed temperature data to account for temperature variation, it is preferable to make the correction using data obtained from the instrument itself. The absorption coefficients for some of the lines in the O_2 A-band have large sensitivity to temperature and should permit a very precise determination of the average column temperature. Figs. 5 and 6 show sensitivity curves

for the column temperature and pressure for Fabry-Perot measurements of selected features in the O_2 A-band. The x-axis is the ON/OFF ratio for a channel measuring absorption from an O_2 line with strong temperature dependence. The y-axis is the ON/OFF ratio for a channel measuring the wings of a number of O_2 lines arising from lower lying energy levels. Some of these lines increase in strength with temperature and some decrease with temperature. This channel then exhibits a much stronger relative response to changes in the total number of O_2 molecules. The temperature and O_2 column (surface pressure) are derived by considering these channels together.

IV. Airborne Simulator Development

We will develop an instrument employing three Fabry-Perot interferometers—one for CO_2 measurement and two for O_2 measurements. The O_2 measurements will be used to infer surface pressure and column average temperature. The three subsystems are being prototyped on the laboratory bench to optimize Fabry-Perot characteristics, prefilter parameters, and detector types. The systems have been packaged for operation outside the lab and ground based tests are underway. The designs will be modified based on the ground test results and the instruments will be modified as appropriate for testing on an aircraft platform. Flight testing will include intercomparison with in situ CO_2 sensors and experiments to determine instrumental performance over varying surface types including ocean and under various meteorological conditions including severe aerosol loading.

The retrieval algorithm will utilize a "look-up-table" generated by running a radiative transfer model for a large number of pressure, temperature and CO_2 profiles that include a variety of aerosol and cloud scenarios. This strategy is similar to that used to infer O_3 column amounts from radiances measured by the TOMS instrument [18]. A

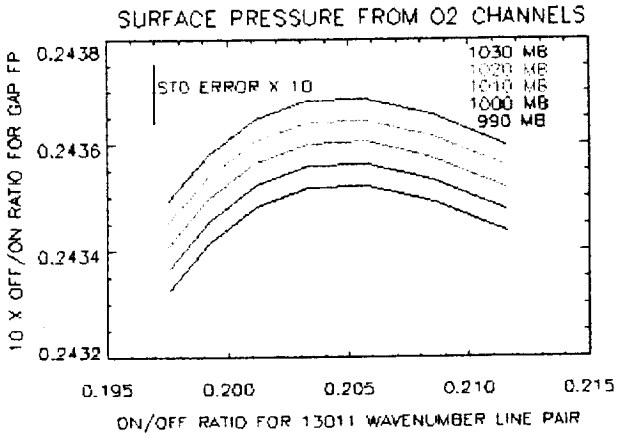


Fig. 5. Surface pressure as a function of the ON/OFF ratios for the two proposed O_2 instrument channels from radiative transfer calculations.

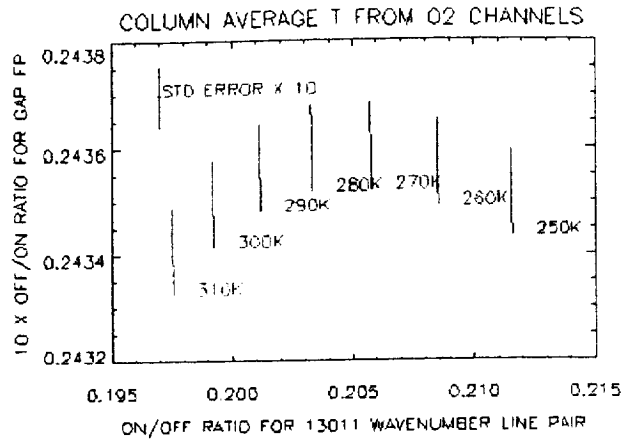


Fig. 6. Column average temperature as a function of the ON/OFF ratios for the two proposed O_2 instrument channels from radiative transfer calculations.

relatively sophisticated retrieval algorithm will be needed to account for the effects of clouds and aerosols.

After the initial test flights, we would propose to fly this instrument on field campaigns designed to study surface sources and sinks of CO_2 (e.g., a North American carbon budget experiment). An instrument capable of measuring the column CO_2 amount below the airplane would be a valuable addition to in situ measurements.

The instrument could also be deployed for ground-based sampling at a location where CO_2 profiles are obtained routinely from flask samples as part of the NOAA/CMDL cooperative air sampling network or at a site where up-looking spectrometers could provide additional data in the wavelength regions of interest. One of the major challenges for eventual space-based measurements of CO_2 will be to relate the column amounts to surface data. Augmentation of the current network with inexpensive, durable, up-looking column CO_2 sensors would provide a natural link, regardless of the type of sensor flown in space.

A. Pathway to Space

The instrument technology we plan to develop has a clear pathway to space and realistic potential to become a robust, low-cost systematic space measurement. The principal hardware challenge is achieving sufficient spectral control and stability of the Fabry-Perots to meet the required precision levels. While Fabry-Perots have already flown successfully in space, we are hoping to achieve an implementation with minimum complexity—no moving parts, no cryogens, a minimum of control interfaces—and unprecedented precision.

The aircraft system optics will have a volume of about 0.05 m^3 and weigh about 7 kg. The electronics will be standard laboratory rack mounted equipment and will take up about one fourth of a full height rack. The space borne system will be smaller and lighter. A total weight on the order of 4-5 kg should be possible including both optics and electronics. The estimated cost for a space system of this size is $8-10M. There are no moving parts in the baseline design.

Potentially the most significant challenge for measuring CO_2 from space is development of data analysis procedures to deal with cloud cover and aerosol conditions. In truly clear air the analysis is a relatively straightforward application of differential optical absorption techniques [18]. The footprint of the instrument is small in order to maximize the chance of simple cases, but most of the globe is covered by cloud and aerosol. The extent of the useful data will depend on our ability to treat cloud and aerosol scattering. Addressing this issue is one of the principal goals of the aircraft campaign.

V. SUMMARY

Global atmospheric CO_2 measurements are a very high priority; no other single measurement has similar potential to revolutionize our understanding of climate forcing and response. The science and technical requirements for CO_2 remote sensing are very stringent, requiring greater precision than any current satellite constituent measurement. We propose to develop a robust, inexpensive, compact and lightweight instrument system based on a unique application of a Fabry-Perot interferometer capable of measuring column CO_2 with a precision of 1 ppmv. We will design, build, test, and deploy an aircraft simulator to demonstrate that the instrument can perform to specifications in the real atmosphere. Once proven, this instrument technique will enable routine high-precision measurements of atmospheric CO_2 from space.

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