

SENSITIVITY OF MICROMAPS CARBON MONOXIDE RETRIEVAL ALGORITHM TO SURFACE TEMPERATURE

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Abstract

The scientific goal of the Micro Measurement of Air Pollution from Satellites (μ MAPS) project is to measure carbon monoxide (CO) mixing ratios in the middle troposphere from an airborne platform. Recent work has focused on the development of a data processing algorithm to determine precise scientific total column amounts of carbon monoxide from μ MAPS flights. The data processing algorithm uses flight signals to infer surface temperature then uses the inferred surface temperature in calculating CO mixing ratios. In this paper, the sensitivity of this data processing algorithm to surface temperature is studied. MicroMAPS data is used from Proteus flights over the mid-Atlantic and South Pacific. Synthetic and measured surface temperature profiles are used to calculate CO mixing ratios with the μ MAPS data retrieval algorithm. These results are compared to determine the sensitivity of the CO retrieval algorithm in different climates.

I. Introduction

Carbon monoxide (CO) is a colorless, odorless gas found in the troposphere that is produced by both natural and anthropogenic activities. Understanding the sources, sinks, transport, and distribution of CO is critical to understanding the overall chemistry of the troposphere. The major natural source of CO is the oxidation of hydrocarbons, such as methane (CH_4), in both the northern and southern hemispheres. The major anthropogenic sources are technological activities, such as the combustion of fossil fuels in the northern hemisphere and the burning of biomass primarily in the tropics.¹ These sources of atmospheric CO now appear to be of comparable magnitude.² A detailed discussion of the sources of CO is found in the references.³

The principle sink for CO is its oxidation by the hydroxyl radical (OH) in the troposphere. The hydroxyl radical is produced naturally in a two step process involving the photolysis of ozone (O_3) and a reaction of $\text{O}(^1\text{D})$ with water vapor (H_2O). This radical is the major oxidizer of all reduced species in the atmosphere. The increase in world wide agricultural and human technological activity has caused a significant increase in CO concentration in the atmosphere. Because CO accounts for the destruction of about 80% of OH in the troposphere, and because OH is the principal oxidizer of all reduced species, the emissions of CO can have a significant effect on the chemistry of the troposphere.⁴ For example, OH is a principal oxidizer of CH_4 , which is radiatively active, and other higher hydrocarbons, which are chemically active. An increase in CO concentration leads to the destruction of OH in the atmosphere, which in turn leads to increased levels of radiatively and chemically

active gasses that contribute to changes in the planetary radiation balance.

Carbon monoxide was first detected in the atmosphere using solar spectroscopic observations.⁵ The presence of the gas was confirmed by direct measurement techniques with average mixing ratios on the order of 100 ppbv in rural areas and up to 3 times higher in urban areas.¹ The current understanding of the concentration of CO in the atmosphere is very well studied and documented.⁶ In the 1960's, the National Aeronautics and Space Administration (NASA) sponsored studies to determine the feasibility of measuring the distribution of pollutant gasses from an orbiting satellite. These studies showed that CO would be measurable through the use of the gas filter cell radiometer (GFCR) technique.⁷

A successful GFCR project was NASA's Measurement of Air Pollution from Satellites (MAPS) experiment. The measurement of near-global distribution of CO was the primary science goal of MAPS. This experiment was flown on the Space Shuttle four times during November 1981, October 1984, and April and October 1994. The four Space Shuttle based MAPS missions lasted up to 10 days and covered a latitude range of up to 57° inclination orbit. The results from these test flights are presented in several works.^{1,8-11}

In the summer of 1994, CTA Inc., was awarded a contract from NASA to build the Clark spacecraft as part of the NASA Small Satellite Technology Initiative (SSTI) program. In the spring of 1995, Resonance Ltd. received a contract from North Carolina State University to design and build MicroMAPS (μ MAPS), a digital computer based gas filter correlation radiometer, to be flown on the Clark

spacecraft. Because of budgetary overruns and schedule delays, the Clark mission was cancelled and the payload stored at NASA Goddard until August 2000. In 2002, the μ MAPS instrument was retrieved from storage and functional analyses determined that the instrument was still fully operational. Calculations and models were produced to determine the feasibility of integration of μ MAPS onto the Proteus,^{12,13} the highest flying private aircraft in the world. Integration onto the Proteus, (Scaled Composites, Inc., Mojave, CA), was sought because it would operate at an altitude of about 16 km, allowing for detection of CO in the troposphere.

Since its initial integration onto the Proteus in June, 2004,¹³ μ MAPS has participated in four scientific missions conducted in: North America (Intercontinental Chemical Transport Experiment-North America Science Team – INTEX-NA), Europe (Aerosol Direct Radiative Impact Experiment – ADRIEX and European AQUA Thermodynamic Experiment – EAQUATE), and Australia (Tropical Warm Pool Intercontinental Cloud Experiment – TWP-ICE). This work will focus on the July 22, 2004 flight during the INTEX-NA campaign and the February 4, 2006 flight during the TWP-ICE campaign. The July 22nd flight, which collected data off the Eastern coast of North America, has been fully analyzed by Hopkins, *et al.*¹⁴ The February 4th flight data took place over the Northern coast of Australia. During this flight, the Proteus held a circular pattern centered around -12.4 deg. Latitude, 130.9° Longitude. The flight tracks for the July 22nd and February 4th flights are shown in Fig. 1(a) and (b), respectively.

Due to the tropical atmosphere in this region of the southern hemisphere during the February 4th flight, the models used in CO retrieval for data from this flight (along with all the data from the TWP-ICE campaign) must be different than the models used in CO retrieval for the INTEX-NA and EAQUATE campaigns.¹⁴ This paper examines the sensitivity of these models and the CO retrieval algorithm to surface temperature. In the next section, the specifics of the atmospheric models used in CO retrievals are presented. In section III, the CO retrieval algorithm is discussed. Section IV examines the sensitivity of CO retrieval to surface temperature.

II. Atmospheric and Instrument Models

In order to predict the CO VMR detected by μ MAPS, the instrument's response to varying levels of CO in the atmosphere was calculated with various atmospheric and instrument models. The atmospheric models used in this work consider only thermal radiation emitted by the earth as modified by the

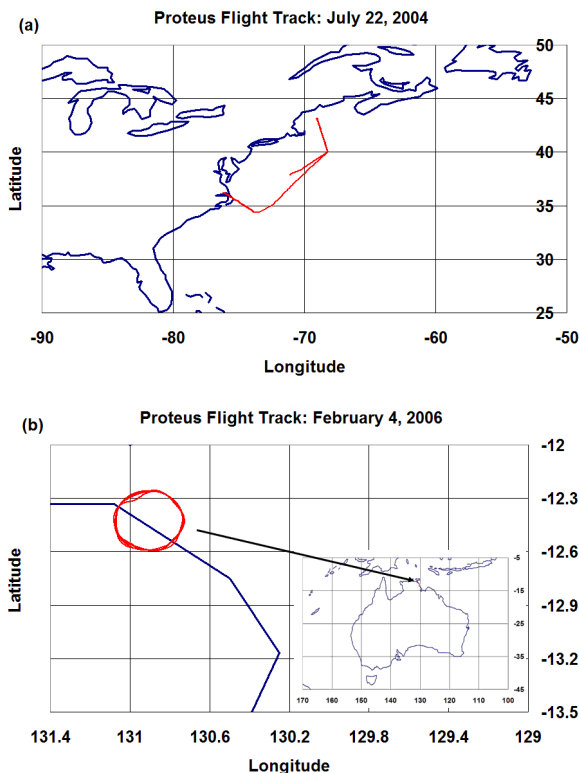


Fig. 1. Proteus flight path on (a) July 22, 2004 and (b) February 4, 2004. The flight on February 4th did not fly over a large area of the earth's surface. The inset in Fig. 1(b) shows the area on the Northern part of Australia where the Proteus held its circular flight pattern.

absorption and emission of the atmosphere. At these wavelengths reflected sunlight accounts for less than ten percent of the upwelling radiation.¹⁵ The most significant source of radiation is the earth's surface. As this radiation travels upward, it is absorbed by the various constituents in the atmosphere. These gasses, in addition to absorbing the upwelling radiance, also emit radiation thereby contributing to the radiation detected by the instrument.

The monochromatic upwelling radiation at the instrument, $L(\nu)$, includes not only the radiation from the Earth's surface, but also the absorption and emission from gasses in the atmosphere. $L(\nu)$ is calculated using the Line By Line Radiative Transfer Model (LBLRTM). LBLRTM is a product of Atmospheric and Environmental Research, Incorporated (AER), and is considered the industry standard for accurate atmospheric modeling. LBLRTM is a FORTRAN-based program that extracts data from the HITRAN 1992 database and it is used to predict and simulate the transmission and emission of radiation in the atmosphere.¹⁶ LBLTRM is used with input parameters appropriate to the μ MAPS flights and

conditions to generate a range of atmospheric radiation models. Inputs for LBLRTM include: specific molecules to consider (i.e. which absorption characteristics to incorporate from the HITRAN 1992 database), wavenumber range of interest, surface temperature, surface emissivity, and altitude of nadir viewing. In addition, LBLRTM allows for a custom defined atmosphere by defining pressure, temperature, and molecular number density in user defined atmospheric layers at different altitudes.

Incident radiation was modeled in the wavenumber range of 2080cm^{-1} - 2280cm^{-1} in 0.01 cm^{-1} increments. The flight altitude for μMAPS on Proteus flights is 15 km, or about 50,000 ft above the earth. The earth was modeled at seven different surface temperatures (280 K – 310 K) and a surface emissivity of 0.98 is assumed. For CO retrieval, LBLRTM was run with two different atmospheres: the 1976 standard atmosphere and the standard atmosphere supplement at -15° Latitude which simulates a tropical atmosphere.¹⁷ In these calculations, a custom atmosphere is defined in LBLRTM input using altitude specific pressures and temperatures from the different atmospheres in each layer, and specifying CO as the only molecule present. The amount of CO in each layer was varied to change the total column density. A uniformly mixed column was implemented, and calculations with CO spanning 30 – 210 ppbv were performed.

The instrument models describe the effects of the instrument on the upwelling radiation. The effects of the gas cells and the bandpass filter must be taken into account. HITRANPC was used to model the transmission of the gas cells. For this application, HITRANPC, using the HITRAN 1992 database, allows the user to input the gas through which the energy will be transmitted, the partial pressure of the gas in the cell, the temperature in which the gas cell is maintained, and the size of the gas cell. The pressures of the sealed cells are temperature sensitive and vary in accordance with Boyle's Law. One assumption used in the model of the instrument is the temperature of the gas cell is equivalent to the temperature of the μMAPS bandpass filter. The temperature of the gas cell wheel, or chopper, is output in the μMAPS data stream. This, along with varying temperatures of the earth in LBLRTM, allowed for the theoretical model to be calculated at varying source temperatures and varying gas cell and bandpass filter temperatures. The transmissions through the vacuum cells are assumed as unity.

The upwelling radiance from the atmospheric model is transmitted through the gas and vacuum cells and the bandpass filter and the result is integrated over the wavenumber spectrum. The difference signal between the vacuum cell and high pressure CO cell in the μMAPS output during operation is of interest when

modeling a CO only atmosphere. A trapezoidal integration scheme was used to numerically integrate of the spectrum. These calculations were performed several times using earth source and instrument temperatures that were representative of the temperatures encountered during the Proteus flights. The theoretical radiance described above can be mathematically expressed as:

$$\begin{aligned} \Delta L_{f_STD/TROP}(T_e, T_i, \text{VMR}) = & \\ \int_{\nu} L_{CO}(\nu, T_e, \text{VMR}) \tau_{bpf}(\nu, T_i) & \quad (1) \\ \times [\tau_{vac}(\nu, T_i) - \tau_{CO266}(\nu, T_i)] d\nu & \end{aligned}$$

where ΔL represents the differenced radiometric signals as calculated from the theoretical upwelling radiance seen through the vacuum cell differenced with the high pressure CO cell, ν is the wavenumber, T is the temperature of the earth's surface or the instrument, τ is the transmission of a μMAPS component, and VMR is the CO volumetric mixing ratio used when defining the CO atmosphere. The subscripts of the transmission terms refer to the bandpass filter, vacuum cell, and high pressure CO cell. The subscript f on ΔL refers to modeling flight conditions and STD/TROP references the type of atmospheric model used in the calculations (STD = 1976 standard atmosphere and TROP = -15° Latitude supplemental atmosphere).

III. CO Retrieval

Retrieval of CO VMR was pursued by establishing relationships between the theoretical and measured signals during instrument calibration, ΔL_c and ΔS_c , respectively, and applying this relationship to the theoretical and measured signals during flights, ΔL_f and ΔS_f . The specific details about instrument calibration data and the flight signals are thoroughly discussed in the references.^{13,14}

The signal detected by μMAPS during the flight, from which CO VMR was extracted, is related to the radiance emitted from the earth surface, which is dependent on the surface temperature. Therefore, a temperature dependent proportionality constant relating the μMAPS output signals to the theoretical radiance was calculated from the calibration data. This constant was then multiplied by the theoretical radiance during flights to calculate the predicted instrument output signal during flight at a given instrument temperature, source temperature, and CO VMR. This is mathematically expressed as:

$$\Delta S_{predicted}(T_e, T_i, VMR) = \frac{\Delta S_c}{\Delta L_c(T_e, T_i)} \times \Delta L_{f_STD/TROP}(T_e, T_i, VMR) \quad (2)$$

where the aforementioned proportionality constant is $\Delta S_c/\Delta L_c(T_e, T_i)$. ΔL_f was calculated for a wide range of CO mixing ratios with Eq. (1); ΔL_c was calculated in a similar fashion with parameters representing calibration conditions. ΔS_f was then matched to $\Delta S_{predicted}$ at the corresponding CO mixing ratio by linear interpolation, which is a valid assumption in the range of CO mixing ratios appropriate for CO.¹⁵ The results of the CO retrieval from the July 22nd flight are shown in Fig. 2.

For the majority of the July 22nd flight, μ MAPS measured 110 – 150 ppbv CO. AIRS and μ MAPS reported about 130 ppbv CO when in the same vicinity. DACOM measurements were lower than μ MAPS for the majority of the flight. This could be a result of DACOM flying at a lower altitude than μ MAPS, and below that peak concentration of CO in the standard atmosphere, about 9 km.^{13,17} In general, the close agreement of μ MAPS to other instruments validates the retrieval process and confirms that μ MAPS is an accurate radiometer for CO measurements. The calculations in Fig. 2 used a priori surface temperature profile. Since μ MAPS is a radiometer, it theoretically should be able to retrieve a surface temperature and use this to determine CO VMR.¹⁴ The first step in achieving capability is to determine the sensitivity of the CO retrieval algorithm to surface temperature.

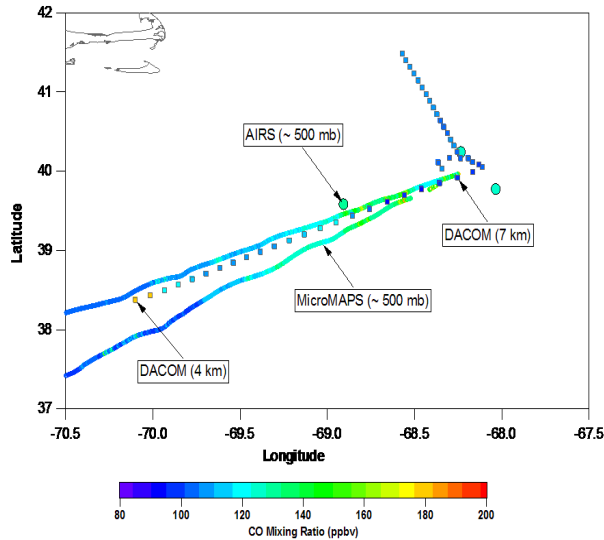


Fig. 2. CO mixing ratio measurements on July 22nd. Measurements during the μ MAPS are shown for the entire flight. Selected AIRS and DACOM measurements are presented for comparison.

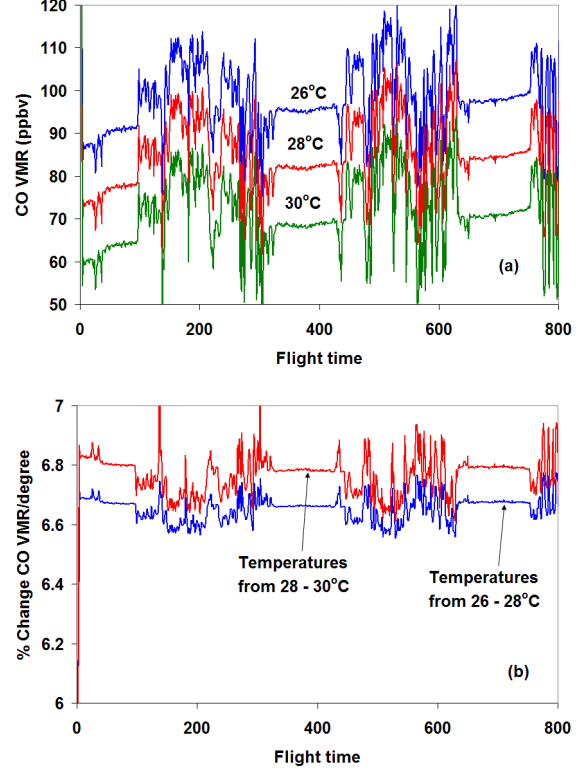


Fig. 3. Analysis of surface temperature sensitivity of CO retrieval with a tropical atmospheric model for the February 4th μ MAPS mission. (a) Retrieved CO VMR for surface temperatures of 26°C, 28°C, and 30°C. The surface temperatures were assumed constant during the entire flight. The difference among the CO mixing ratios are equal, which is apparent from the % change in CO mixing ratio per degree, shown in (b). These values are calculated by differencing the CO mixing ratios at two temperatures and dividing by the temperature difference. The results differ by less than 0.4%

IV. Surface temperature dependency on CO retrieval

To estimate surface temperature ranges in which to test the sensitivity of the μ MAPS retrieval algorithm, previously measured surface temperature data were collected from the Physical Oceanography Distributed Active Archive Center (PO.DAAC). PO.DAAC, part of the JPL, is responsible for archiving and distributing data relevant to the physical state of the ocean. Daily global sea surface temperatures are available publicly through the PO.DAAC Ocean ESIP Tool (POET).¹⁸ The temperature corresponding to the Proteus flight paths from the February 4th and July 22nd flights ranged from 26 – 30°C and 12 – 28°C, respectively. Since the Proteus covered a much smaller area in the February 4th flight than the July 22nd flight, the narrower range of sea surface temperature is

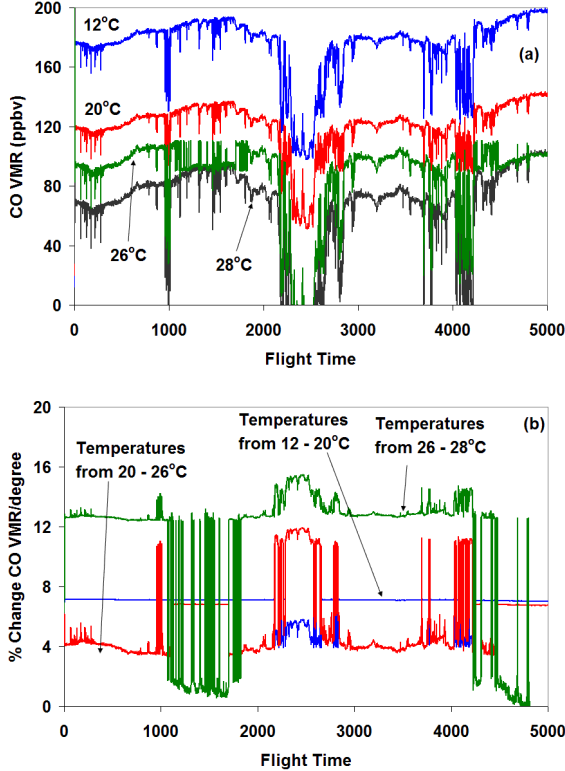


Fig. 3. Analysis of surface temperature sensitivity of CO retrieval with 1976 standard atmospheric model for the July 22nd μ MAPS mission. (a) Retrieved CO VMR for surface temperatures 12°C, 20°C, 26°C, and 28°C. (b) % change in CO mixing ratio per degree.

expected. The warmer temperature range from the February 4th flight is also expected due to the warmer climate and atmosphere around Australia in February than in the northern hemisphere flights. As previously mentioned, the effects of these differing temperatures and atmospheres are taken into account in the theoretical radiance calculated with Eq. (1) by using appropriate atmospheres in the LBLRTM calculations to determine $L_{CO}(T_e, T_b, VMR)$.

To analyze the sensitivity of CO retrieval on the February 4th flight data, the tropical atmospheric model was used with the CO retrieval algorithm assuming constant surface temperatures of 26°C, 28°C, and 30°C. To compare the CO retrievals, the results are plotted vs. time of flight in Fig. 3(a). During this flight, the Proteus circled several times over the coast line of northern Australia, which is apparent in the data. When μ MAPS was taking data over the sea, the signal was much cleaner than the data over land due to the constant emissivity of the ocean. As the surface temperature gets warmer, the apparent CO VMR in the atmospheric column observed by μ MAPS decreases. Comparing the data over a portion of the ocean around a flight time of

400, the retrieved CO VMR decreases from 95 to 65 ppbv at a constant rate. In Fig 3(b), the change in CO VMR per degree Celsius is calculated from the data in Fig. 3(a) assuming that the decrease in CO VMR between each temperature point is linear. Figure 3(b) quantitatively supports the qualitative observation in Fig. 3(a) that the decrease in retrieved CO from a 26°C surface to a 30°C surface is uniform over the temperature range. Therefore, over the temperature range of interest in a tropical climate, the CO retrieval with a tropical model demonstrates a constant linear sensitivity with surface temperature.

The July 22nd data were analyzed with the 1976 standard atmosphere and assuming constant surface temperatures of 12°C, 20°C, and 28°C. These retrievals are noisier than the February 4th retrievals which could be due to the relatively large temperature changes in sea surface temperature observed over the flight path. The large dips in signal around a flight time of 1000, 2500, and 4000 are due to a cloudy field of view for μ MAPS instrument, and can be ignored in this study. Still, the general trend of decreasing CO VMR with increasing surface temperature is apparent in Fig. 4(a). Figure 4(b) reveals that the changes in CO per degree Celsius among the three temperature intervals are not equal. From 12° – 20°C, the change in retrieval CO is relatively constant at about 7%/degree and insensitive to noisy data. Over 20 – 26°C, the change is about 4%/degree and is much more sensitive to the large dip around 2500. Over 26 – 28°C, the retrieval loses sensitivity to much of the noise, yet the change in retrieved CO VMR is around 13%/degree, much larger than the changes at other temperatures and much larger than the change shown in Fig. 3(b) for the tropical data over the same temperature range. This shows that the surface temperature sensitivity of the CO retrieval is dependent on the ambient atmosphere and climate.

V. Conclusions

This paper examines the sensitivity of the μ MAPS CO retrieval algorithm to changes in surface temperature. The signal from the μ MAPS instrument output that represents the amount of CO in the atmosphere is related to the underlying surface temperature. Therefore, in order to accurately deduce CO levels from the μ MAPS output, accurate knowledge of the surface temperature is critical.

To determine the sensitivity of the retrieval algorithm to surface temperature, two μ MAPS flights were studied: the July 22, 2004 flight in the INTEX-NA campaign and the February 4, 2006 flight in the TWP-ICE campaign. These two flights compared μ MAPS' sensitivity to two different atmospheres and climates. In the warmer, tropical climate during the February 4th

flight, CO retrieval was relatively insensitive to the range of surface temperatures experienced. The July 22nd flight retrieval was much more sensitive to temperature changes, which indicates that the surface temperature sensitivity of the CO retrieval is dependent on the ambient atmosphere and climate.

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