

MICROMAPS MODELING AND DATA REDUCTION

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MicroMAPS (Microprocessor-based Measurement of Air Pollution from Satellite) is a second-generation gas filter correlation radiometer that measures carbon monoxide levels in the troposphere. Previous work centered on the construction of a theoretical model to predict instrument behavior at a given instrument state with prescribed atmospheric conditions. This paper details the refinement of that model with a focus on instrument test flights on board the Proteus high altitude research aircraft during Summer 2004. Several modifications including temperature shifts were made that improved accuracy and increased relevancy to the test flights. Also outlined is the theory behind the averaging kernel sensitivity tool. The averaging kernel is calculated and validated against previous *in situ* readings taken during flights of the precursor MAPS instrument. Compared to the weighted vertical profiles produced by MAPS, the MicroMAPS averaging kernel differed by approximately 2% thus proving its effectiveness as a data reduction tool.

Introduction

Carbon monoxide (CO) is a pollutant that originates primarily from the use of fossil fuels in the northern hemisphere and biomass burnings in the tropics. By reacting with the hydroxyl radical (OH) which is the principal oxidizer of methane and other gases, increased levels of CO could lead to dangerous levels of greenhouse gases.¹ Measurement and tracking of CO has primarily been done by *in situ* measurements, meaning that the instrument or sensor must actually reside in the area of study. However, since CO is a trace gas that varies significantly with time and location, a method with broader scope is required.

In 1981 NASA deployed a space-borne remote sensor of CO; MAPS or Measurement of Air Pollution from Satellite. This instrument was flown aboard the space shuttle in November 1981, October 1984, April 1994, and October 1994. MAPS viewed the troposphere from the nadir and focused on the 4.67 μm band of CO. It used gas filter correlation radiometry (GFCR) to compute the amount of upwelling energy. The flights proved to be extremely successful and produced excellent global observation of carbon monoxide^{2, 3}. Still, these flights averaged merely between 7 and 10 days in duration, and a year-round platform on a satellite was needed to effectively monitor global CO levels. To meet this need, NASA created a second-generation instrument, MicroMAPS (Microprocessor-based MAPS). Fully

digital, MicroMAPS still employs GFCR methodology yet is able to attain better resolution.

Thus far, investigations involving MicroMAPS have focused on creating a theoretical model that would simulate the radiometric readings for given atmospheric and instrument conditions. This paper begins by discussing the historical model for familiarity followed by a detailing of the refinements made. Next the paper outlines the theory of the averaging kernel and where it fits in the data reduction procedure. Throughout, emphasis is placed on the testing flights of MicroMAPS from Summer 2004.

Theoretical Model

Model Basics

When talking about atmospheric modeling, it is necessary to first identify the two main sources of energy that must be considered for nadir remote sensing of tropospheric gases. The first and most pronounced is thermal radiation emitted by the surface of the Earth. This energy behaves according to Planck's Function, which describes how much energy is emitted at each wavenumber (or wavelength) at a given temperature. Surface radiation is the dominant source of energy in the vertical pathway that is viewed by the instrument. As this radiation continues upward it comes in contact with various components of the atmosphere which absorb or scatter this incoming radiation as well as emit their own spectrum. Molecular scattering,

absorption and emission comprise the second level of radiation that needs to be accounted for in any modeling of the atmosphere.

The program used to model this is Line-By-Line Radiative Transfer Modeling (LBLRTM), an industry standard atmospheric modeling program. It takes into account the source emission as well as molecular absorption, scattering and emission for specified surface temperature, height above ground, and selected molecules. So powerful is this program that it serves to model every major parameter before the instrument itself.

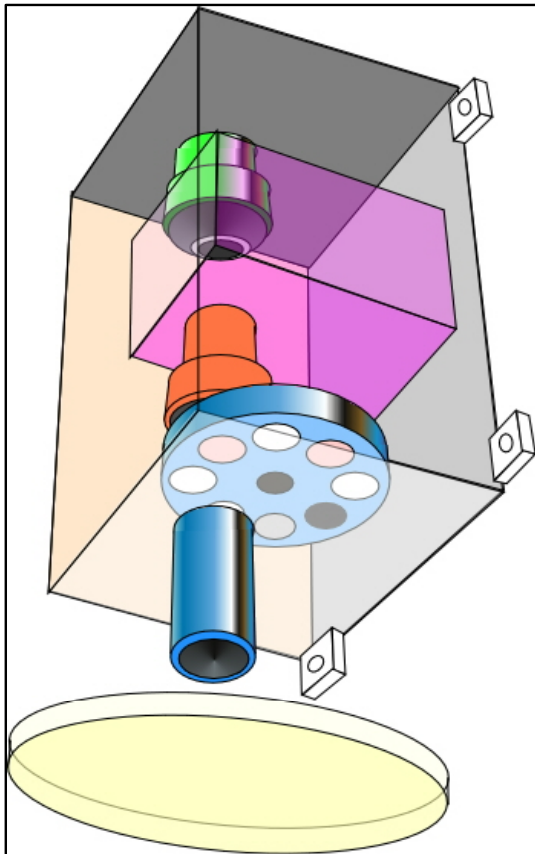


Figure 1: Schematic of the MicroMAPS instrument. Bottom-most component is the enclosure window; the gas cell wheel can clearly be seen with its individual cells; the box above that is the bandpass filter; and finally at the top of the instrument is the detector.

The instrument, as seen in Figure 1, contains several components that must be modeled. First, at the bottom of the image which corresponds to the nadir and would be the first component to experience the radiation is the enclosure window. The window serves the function of protecting the instrument from the environment. Next, the radiation travels through

the instrument and reaches the gas cell wheel. It houses cells that contain specified pressures of gas that exhibit behavior which mimics that of corresponding gases in the atmosphere itself. In order to model the gas cells, a high-resolution transmission program (HITRANPC) was used. It outputs the monochromatic transmission of a particular gas at pressure at a specified temperature. MicroMAPS contains three gas cells: carbon monoxide at 76 torr (0.1 atmospheres), carbon monoxide at 266 torr (0.35 atmospheres), and nitrous oxide at 115 torr (0.15 atmospheres). All cells are 1 cm in length. Interspersed with these sealed absorption cells are vacuum cells.

The reason for the vacuum cells is the following. When the radiant energy is passing through the atmosphere it comes in contact with various elements that have their own absorption and emission spectrum. This spectrum, and therefore the amount of energy upwelling, retains its integrity if it passes only through a vacuum cell on its way to the detector. However, if a gas cell is placed in front of the detector, the gas inside will cancel out the energy due to that same gas in the atmosphere because it contains the same spectrum characteristics. In effect this allows the energy due to all the constituents with the exception of the gas of interest to pass through the gas cell. Therefore, since there now is a signal derived from viewing all the gases in the atmosphere, and a signal due to all the gases less the contribution of the gas in question, a simple difference can be taken in order to obtain the amount of energy upwelling due to the target gas. This is the fundamental concept behind MicroMAPS and indeed all GFCR devices.

Directly aft of the gas cell wheel is the bandpass filter. This serves to isolate only the wavenumber range of interest by zeroing out all the energy that occurs outside the range. Data for this component were obtained experimentally rather than through computer simulation. Finally, behind the bandpass filter is the detector. Here is where the energy finally is collected, integrated, and recorded.

Governing Method

As was done with MAPS, the fundamental equation used as the governing condition for setting up the theoretical model is

$$\Delta L = \int_{\nu} L_T(\nu) * [\tau(\nu)_{gas} - \tau_{vac}] * F \quad (1)$$

where

- ΔL is the total integrated difference signal;
- $L_T(\nu)$ is the total monochromatic upwelling radiance;
- $\tau(\nu)_{gas}$ is the monochromatic transmission of the gas cell;
- τ_{vac} is the effective transmission of the vacuum cell;
- F is the instrument response function.⁴

Furthermore

$$F = \tau(\nu)_{win} * \tau(\nu)_{bpf} \quad (2)$$

where

- $\tau(\nu)_{win}$ is the monochromatic transmission of the window;
- $\tau(\nu)_{bpf}$ is the monochromatic transmission of the bandpass filter.⁵

As stated above, each term was computed monochromatically, that is for each individual wavenumber. The wavenumber range selected stretched from 2080 cm^{-1} to 2280 cm^{-1} at an increment of 0.01 cm^{-1} . This covers a wide enough spectrum at a sufficient refinement that fluctuations in energy levels should derive mostly from changes in CO. The reason it works out that way is that the fundamental band of CO, 4.67 μm (2141 cm^{-1}), lies in the middle of the selected range while the other major tropospheric gases are most active outside of this range. Finally, after computing the product and difference of these terms, the whole data set is integrated across the wavenumber range.

In order to get a comprehensive understanding of how the radiometric signal changes with conditions, models were made for varying surface temperatures at an increment of 5 Kelvin starting at 280 K and going to 310 K. Furthermore, for each of these surface temperatures, a range of instrument temperatures was run again covering from 280 K to 310 K. Thusly, the theoretical model is more than just one solitary algorithm, but a database of smaller models created using the two above equations in the specified manner. The reasoning behind creating such a vast database is explained in detail during the data reduction discussion.

Corrections to Model

Foremost among the recognized deficiencies in the model was the temperature range over which we were operating. During the test flights instrument

temperatures dropped to as low as 240 K. These results make sense however when one considers that the Proteus aircraft is flying at approximately 15 kilometers and the temperature at altitude should cover a much lower spectrum than the surface temperatures. Fortunately, this problem was not only easy to identify, but also easy to correct. By reconfiguring HITRANPC it was possible to simulate the necessary instrument temperatures and then incorporate them into the model such that it now reflected more realistic environmental test conditions.

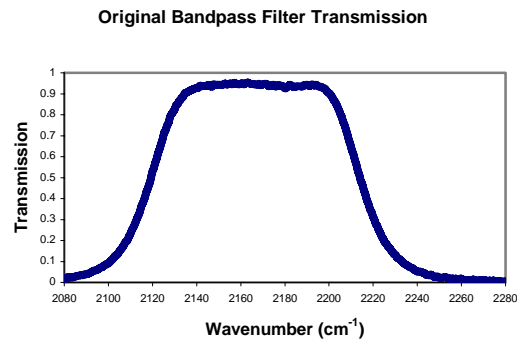


Figure 2: Original bandpass filter transmission spectrum. Plotted is transmission on scale from 0 to 1 versus wavenumber from 2080 cm^{-1} to 2280 cm^{-1} .

The second major correction to the model was much more subtle and required a more concerted effort to achieve. While thinking about the

temperature issues of the instrument, a question was raised about whether or not the bandpass filter is affected by the different temperatures encountered at altitude. Figure 2 shows the original transmission spectrum for the bandpass filter. However, the temperature during the experiment gathering this data was 295 K and as has already been mentioned above, the instrument might be that temperature on the ground, but it can change drastically when it gets to altitude. Therefore, it was necessary to go back to the model and spectrally shift the transmission of the bandpass filter according to the instrument temperature in that particular permutation of the model. The shift, which was determined from calibration testing, is characterized by the following equation:

$$\lambda_{T_2} = \lambda_{T_1} * [1 - (2.0 * 10^{-4}) * (T_2 - T_1)] \quad (3)$$

where

T_1 is the current temperature

T_2 is the target temperature

λ_{T_1} is the current wavenumber at a particular temperature

λ_{T_2} is the target wavenumber at the target temperature.

Put another way, the transmission value τ for a particular wavenumber λ at temperature T_1 , shifts to a different wavenumber when the bandpass filter is simulated for T_2 . Figure 3 shows the shifted bandpass filter transmission spectra. Note that it retains the same shape as the original, seen in Figure 2, but that the sensitivity to what is being allowed to pass through the instrument is no longer at the same wavenumbers.

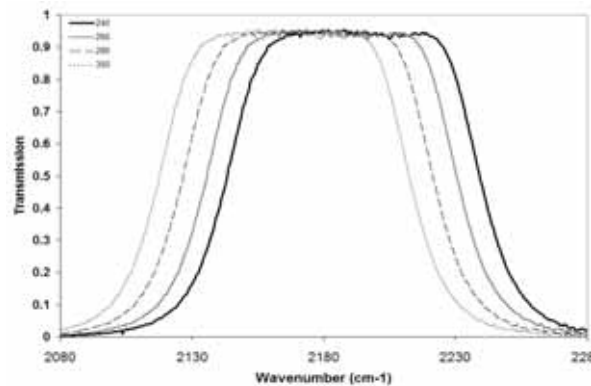


Figure 3: Shifted values for the bandpass filter transmission. Temperatures range from 240 K to 300 K. Transmission is plotted versus wavenumber range 2080 cm^{-1} to 2280 cm^{-1} .

Averaging Kernel

Theory

The averaging kernel is calculated to describe the varying sensitivity of μMAPS to CO at different altitudes. On some μMAPS flights, the Proteus will fly over another aircraft that is taking local CO measurements. The averaging kernel is used to compare the retrieved CO mixing ratio with a CO profile.⁶⁻⁸ μMAPS measurements are used to infer a column amount of CO, as represented by this basic equation.

$$Q_{ret} = C_{ret} \times Q_{air} \quad (4)$$

where Q_{ret} is the μMAPS measurement of the amount of CO in the vertical column, C_{ret} is the mixing ratio, and Q_{air} is the total amount of air in the field of view. Therefore, when the instrument sees and outputs its readings, the value which is assigned to the column is actually a weighted average of the CO mixing ratios throughout the vertical distribution of the column of interest.⁹ In equation form it can be represented as

$$Q_{ret} = Q_a + A(q - q_a) + e \quad (5)$$

such that q is the actual vertical profile of CO, q_a is the assumed a priori profile, Q_a is the value when $q = q_a$, and A is the averaging kernel, with A , q , and q_a being vectors. For this discussion, the error term e is assumed to be zero.¹⁰

Validation

According to this theory and based on the calculation of the averaging kernel for MAPS, the MicroMAPS averaging kernel was calculated using the 1976 U.S. Standard Atmosphere. First an average tropospheric CO mixing ratio of 110 ppbv (parts per billion volume) was assumed to be evenly distributed in the vertical. Then, using the theoretical model at a height of 15 km, the mixing ratios were perturbed in LBLRTM and the resulting radiance was incorporated into the model. Using these resulting total integrated radiances and the baseline 110 ppbv radiance, it could be determined how sensitive the instrument is to CO at varying altitudes. A more thorough discussion of the calculation process can be found in Reichle et al. (1999) and the results for both the 76 torr and 266 torr CO channels are shown in Figure 4.

Once the averaging kernel was found, it needed to be checked for accuracy. It was decided to use data both from the original MAPS experiment

and from current MicroMAPS test flights. The reasoning is that the MAPS averaging kernel was already validated and if the new averaging kernel could mimic the old results and that it would align with the old averaging kernel on new data, then the MicroMAPS version was correctly determined and could be applied in the future. The data selected was taken near Cape Grim, Tasmania first by MAPS on April 12, 1994 and then near the same location on the 5th of October 2004 for which there were known *in situ* measurements from the MicroMAPS test flight. Working backward, the vertical distribution of CO mixing ratios was transformed by the averaging kernel into an average column amount of CO. Using the MAPS averaging kernel, the column amounts were 56.13 ppbv for the 1994 data and 76.78 ppbv for the 2004 data. Similarly, the MicroMAPS averaging kernel calculated column mixing ratios of 57.3 ppbv and 78.2 ppbv respectively resulting in only a 2% discrepancy from the MAPS results.

Future Data Reduction Procedure

Ultimately, this project aims to infer vertically distributed carbon monoxide mixing ratios from nadir viewing of the Earth and the atmosphere. Previously it was mentioned that the detector collects the impinging radiation after it has passed through the atmosphere and instrument and that it then integrates it into a signal. The output of the detector is an instrument signal displayed in counts. However the theoretical model output is a radiometric signal with units of $W/cm^2/sdr$. Therefore, the obvious first step is to relate the instrument data signal to a radiometric signal, or the amount of energy that is falling on the detector.

In order to accomplish this relation it is proposed to make use of the instruments internal functional calibration. Before each flight and in between data collection, the instrument runs a 30-minute self-test in order to ensure that everything is functioning properly. Reconfiguration occurs such that the instrument sees the calibration blackbody targets. These conditions are extremely well controlled including emissivity of the target and temperature of target and instrument. By modeling these conditions and comparing them to the instrumental output, it will be possible to determine how many counts correspond to what level of incident radiation.

Once this relationship is determined, attention can switch back to the data-gathering portion of the flights. The instrument output can be converted into radiometric output which now will be in terms that match with the theoretical model. However, recall that in the model there are several

factors that influence how much energy is seen. The first and simplest to deal with is the temperature of the instrument. For the entire duration of the flight MicroMAPS records its temperature and thus one variable is known.

Second among the parameters to address is the temperature of the surface. While MicroMAPS does not measure this directly, there is an extremely clever method for solving the problem. Recall that on the gas cell wheel there are 3 vacuum cells for purposes of differencing and isolating the amount of CO. However, these channels can also be used to work backward and determine the surface temperature. These cells will have a corresponding data stream of instrument outputs that can be converted into radiometric signals using the previously determined conversion factor. Furthermore, the instrument temperature is known at the time of each reading and the readings will not be sensitive to the CO in the atmosphere. Therefore, the only parameter left to find for the vacuum channel is the temperature of the surface. And since the vacuum cells are adjacent to the gas cells and the chopper rotates at such a high velocity, the inferred surface temperature can be applied to the gas measurement channels.

Now, the two big unknowns have been determined and all that is left to find is the CO mixing ratios themselves. Previously in the paper it was mentioned that several models have been created for differing surface and instrument temperatures creating a database of radiometric signals for different conditions. By running these models for different CO mixing ratios the database can be expanded to vary by instrument temperature, surface temperature and amount of carbon monoxide in the atmosphere. However, knowing the other two parameters, one can interpolate to find the appropriate mixing ratio for the temperatures and integrated radiance.

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