Influence of Surface Reflectivity Variability on MOPITT 2.2-2.3 μm Channel Radiances and the Retrieval of CO and CH₄

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Abstract—The MOPITT (Measurement of Pollution in the Troposphere) instrument uses gas-correlation spectroscopy to retrieve the tropospheric profile of CO and the total column of CO and CH₄. The instrument's 2.2-2.3 μm channel signals can be used to determine the CH₄ and CO columns. At these wavelengths, surface effects are important since the channel radiances are determined by reflected solar radiation. Small changes in scene during data acquisition for a given pixel can introduce important variations in surface reflectivity, even when averaged over the instrument field-of-view. These variations must be carefully accounted for to ensure a quality column retrieval. MOPITT simulations based on reflectivity measurements from the MODIS Airborne Simulator are used to construct examples illustrating these effects, along with a method for their mitigation.

Keywords—forward modeling, correlation spectroscopy, MOPITT, carbon monoxide, methane

I. INTRODUCTION

The MOPITT (Measurement of Pollution in the Troposphere) instrument aboard the Terra spacecraft is designed to provide the first global, continuous, long-term measurements of the tropospheric profile of CO and the total column of CO and CH₄. The nature of the measurement process for the CO and CH₄ column requires a careful understanding of the interplay between the characteristics of the MOPITT sensors and geophysical effects at the surface introduced by the nadir viewing geometry. In Section II we summarize features of the MOPITT radiometry that make the column measurements possible. Section III discusses further issues surrounding the MOPITT sensors and the measurement process. The role of surface reflectivity in shaping the retrieved column is presented in Section IV, and conclusions are given in Section V.

II. THE MOPITT INSTRUMENT

MOPITT is a nadir-viewing, cross-track scanning instrument which uses gas-correlation spectroscopy to infer the vertical profile of tropospheric CO and the total column of CO and CH₄ [2]. The measurement requirement calls for retrieval of the CH₄ total column to a precision of 1 percent, and the CO profile and CO column to a precision of 10 percent. The gas correlation radiometers are used to extract a target gas signal and separate its contribution to the top-of-atmosphere (TOA) radiance from that due to contaminating species and the underlying surface. Both pressure modulated radiometers (PMR) and length-modulated radiometers (LMR) are employed.

In a gas correlation radiometer, TOA radiance passes through a cell containing the same gas as the target gas (CH₄ or CO). By regularly varying the cell length (LMR) or pressure (PMR) between two states, the optical depth of the correlation cell is modulated at the positions of the spectral lines of the target gas. As a result, two different signals are obtained in each channel, corresponding to each of the two cell states. The average (A) of these two signals yields information about the surface and contaminating gases, while the difference (D) of the two signals gives information about the target gas.

The i-th channel radiance measured by MOPITT has the form [4]

\[ S_i^{A,D} = \int I(\nu) \rho_i^{A,D}(\nu) \psi_i(\nu) d\nu \]  

where \( S_i^{A,D} \) is the average or difference channel radiance, \( \rho_i^{A,D}(\nu) \) is the correlation cell A or D response, \( \psi_i(\nu) \) is the normalized channel blocker filter, \( I(\nu) \) is the monochromatic radiance at TOA, and \( \nu \) is wavenumber. In both the CO shortwave band (4220 - 4340 cm⁻¹) and the CH₄ shortwave band (4280 - 4600 cm⁻¹), which are used to retrieve the CO and CH₄ columns, the TOA radiance during the day is dominated by reflected solar radiation. In this case, the primary contribution to \( I(\nu) \) can be written as follows:

\[ I(\nu) \sim r(\nu) \frac{F_0(\nu)}{\pi \sec \theta} \tau(\nu, p, \theta) \tau(\nu, p, \theta_{sat}), \]  

where \( r(\nu) = 1 - \varepsilon(\nu) \) is the reflectivity of the surface (assumed Lambertian), \( \varepsilon(\nu) \) is the surface emissivity, \( F_0(\nu) \) is the solar flux at TOA, \( p \) is surface pressure, and \( \tau(\nu, p, \theta) \) is the monochromatic transmittance from pressure level \( p \) to TOA at zenith angle \( \theta \). Solar and satellite zenith angles are denoted by \( \theta_0 \) and \( \theta_{sat} \), respectively.

Equations (1) and (2) define a channel-integrated Beer's Law relation. Solar radiation is attenuated as it travels to the earth's surface, where a fraction is reflected upwards along a second ray path to the satellite, along which further attenuation occurs. The attenuated signal contains information about the optical depth of the target gas along the total ray path, hence it can be used to retrieve the column. In what follows, we phrase the discussion in terms of the CH₄ column retrieval. However, the principles discussed here are relevant to the CO column as well.

The CH₄ retrievals do not use the D and A radiances separately. Instead, the ratio D/A is used [6], since it is not very sensitive to spectrally flat components of (2). In this paper, D/A may be regarded as a predictor for the CH₄ column. The nature of the radiative transfer and the spectroscopy in the CH₄ channel passband imply that the column is a sensitive function of D/A. Specifically, achieving a 1% precision in CH₄ column requires that anomalous D/A variability be reduced to about 0.1 - 0.2%. This is a very exacting standard.

III. LMR MEASUREMENT PROCESS

Column retrievals use data collected by LMRs [3]. As the transmittance of the LMR is modulated, radiation streaming through it periodically undergoes high and low attenuation, and instrument counts are recorded for each high-transmittance ('short-path') and low-transmittance ('long-path') state. Each successive state is termed a 'sector measurement', in reference to the sectors of the rotating elements
within the LMR which modulate the optical depth. The duration of each sector measurement is about 28 ms.

During data acquisition for a given MOPITT pixel, the MOPITT scan mirror remains fixed. While this 'stare' occurs, eight short-path (S) counts and eight long-path (L) counts are recorded. The stare's duration is about 450 ms (∼16 x 28 ms). These data form an 'S,L timeseries' within each stare:

\[ S_1, L_1, S_2, L_2, S_3, L_3, ... , S_7, L_7, S_8, L_8. \]  

These counts are the raw information used to infer the CH₄ column for the corresponding pixel. They have a distinctive sawtooth pattern when plotted as a function of time (Fig. 1), which graphically shows the modulation of transmittance by the LMR, since high/low counts correspond to high/low transmittance. A calibration algorithm converts the counts to radiances.

While a stare is occurring, Terra continues in its orbit. As a result, during each sector measurement the 22 km² MOPITT field-of-view (FOV) moves as well. This causes about a one percent change in the FOV per sector measurement.

Thus, for a given stare, the L and S radiances that determine D/A contain information from a set of highly overlapping scenes, not a single scene. The central problem is how to best combine the scene information for each pixel (eight L and eight S radiances) to obtain an accurate estimate of D/A, and thus an accurate column.

IV. ROLE OF SURFACE REFLECTIVITY

The MOPITT forward model MOPFAS [4] was 'flown' over a synthetic reflectivity landscape in order to calculate the L and S radiances for each sector measurement. The forward model atmosphere was assumed to be unchanging along the 'flight path'. In particular, the CH₄ column was fixed. Thus, the modeled S and L radiances are shaped by surface reflectivity variability, and the effect of this on the variability of the CH₄ column (calculated once per stare) can be assessed.

Synthetic reflectivities, averaged over the MOPITT FOV, were constructed using high resolution reflectivity data from the MODIS Airborne Simulator (MAS) [1], [5] (Fig. 2). A series of MOPITT mirror positions were defined, corresponding to different parts of the MAS flight track. For each mirror position, sixteen overlapping MOPITT FOV’s were created, corresponding to the FOV change during each MOPITT sector measurement. The mean reflectivity was calculated for each sector measurement (Fig. 3). The step-function structure in Fig. 3 is a result of the individual mirror positions, which view disjoint regions of the surface. For a given mirror position, the sixteen overlapping FOV’s have different mean reflectivities, which cause the slopes and curvatures evident within each step. When these reflectivities are used in MOPFAS to calculate the L and S radiances, they affect the shape of the LMR sawtooth envelope (Fig. 1 shows examples using real data) and hence the resulting D and A signals. In MOPFAS, calculations are performed under clear-sky conditions, hence clouds in the MAS data are interpreted as high reflectivity regions at the surface.

It is the slope and curvature of the sawtooth envelope, and not the overall step-function structure, which leads to variability in D/A. Specifically, if the reflectivity were constant during a stare, the same reflectivity would appear in all the L and S radiances. Hence, the same reflectivity would appear in both D and A, and it would cancel in D/A. Thus D/A would be independent of mirror position, and the resulting CH₄ column

Fig. 1. MOPITT LMR sawtooth counts for four consecutive mirror positions. The step function structure results from viewing disjoint regions of the surface. Within each mirror position, the sawtooth envelope exhibits slope (1,2,3,4) and curvature (3) due to reflectivity variability at the surface as the field-of-view changes slightly during a stare. Data from MOPITT CH₄ channel 4, southern Africa, August 2000.

Fig. 2. MODIS Airborne Simulator (MAS) 2.25 µm surface reflectivity data from a flight during the WInCE campaign on February 12, 1997. The MAS FOV is 50 m². Data is shown along a 50 m wide subset of a 37 km wide flight track over eastern Wisconsin and western Lake Superior. The reflectivity is highly variable, both over open farmland and over broken cloud underlain by lake ice and open water.

Fig. 3. MOPITT reflectivity derived from MAS 2.25 µm surface reflectivity data averaged over the MOPITT FOV. The MAS data is from the WInCE campaign, February 12, 1997.
would be constant.

These small effects can undermine otherwise plausible methods for calculating D/A. For example, a simple method is to first form the mean S and L radiances, and then obtain D and A from the means:

\[ S = \frac{\sum S_i}{N}, \quad L = \frac{\sum L_i}{N}, \quad D = S - L, \quad A = (S + L)/2. \tag{4} \]

This approach is inadequate. Fig. 4 (a) shows D/A resulting from this calculation, using the synthetic reflectivity data discussed above. Instead of being constant, D/A exhibits variability of about 1% over the initial flight path, and extremely large variations of 15% in the latter half of the dataset. Since the CH$_4$ uncertainty is ten times the D/A uncertainty, this leads to column uncertainties ranging from 10% to 150% and an accurate retrieval is not possible. Simply averaging the elements of the S, L timeseries ignores the slope and curvature of the sawtooth envelope, leading to inaccuracy in D/A.

A method for solving this problem has been developed. Consider the j-th ‘triplet’ of three consecutive elements $S_i, L_i, S_{i+1}$ in the S, L timeseries for a stare. $S_i$ and $S_{i+1}$ can be averaged to give an estimate $S_{i+1}$ of the (unmeasured) short radiance at the instant when $L_i$ was obtained. Then a j-th D, A, and D/A are computed from $S_{i+1}$ and $L_i$:

\[ S_{i+1} = (S_i + S_{i+1})/2 \]

\[ D_j = S_{i+1} - L_i, \quad A_j = (S_{i+1} + L_i)/2. \tag{5} \]

A parallel construction can be made for triplets of the form ‘L,S,L’. $D_j$ and $A_j$ are therefore based on measurements at a common time, which correspond physically to a common scene. A similar construction can be made for each triplet within the sixteen-element timeseries. Fourteen triplets, hence 14 $D_j/A_j$ values, can be constructed by overlapping the triplets. These fourteen are then averaged to give the D/A estimate for the stare.

Fig. 4 (b) shows results from the ‘triplet method’ calculation, which can be compared to the averaging method in Fig. 4 (a) for the same data. The dramatic reduction in D/A variability is striking, and is now about 0.1%. The corresponding CH$_4$ column variability has therefore been reduced to approximately one percent. By interpolating known information to common scenes, the triplet method can successfully deal with the presence of slope and curvature effects. It is a fast, efficient, and physically-based algorithm for eliminating anomalous column variability induced by rapidly changing surface scenes.

V. CONCLUSION

MOPITT column retrievals involve combining measurements from slightly different times as the FOV moves with the satellite. Small changes in scene can introduce important changes in surface reflectivity, even when averaged over the FOV. In the 2.2-2.3 $\mu$m channels, these variations can have an important effect on retrieval quality if they are not carefully accounted for. Forward model simulations based on reflectivity measurements from the MODIS Airborne Simulator are used to illustrate a method for mitigating these effects. The method can reduce anomalous column variability to a level that satisfies the MOPITT measurement requirement. It is now a part of the MOPITT operational retrieval algorithm. Other variability sources in the shortwave channels are currently under study, work that will further advance the development of accurate MOPITT column data products.

ACKNOWLEDGMENT

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

REFERENCES


