Retrieval Algorithm

Generally, the following description of the MOPITT retrieval algorithm applies to both the Version 3 (V3) and Version 4 (V4) products. Differences between the V3 and V4 retrieval algorithms are described in detail in the V4 User's Guide available here. A paper describing the V3 CO retrieval algorithm was published previously (Deeter et al., JGR, 2003). The mathematical basis of the MOPITT retrieval algorithm is also contained in (Pan et al., JGR, 1998).

An optimal estimation-based retrieval algorithm and a fast radiative transfer model are used to invert the measured A and D signals to determine the tropospheric CO profile. In principle, retrievals of CO may involve up to twelve measured signals (calibrated radiances) in two distinct bands: a near-infrared (NIR) band near 2.3 microns, and a thermal-infrared (TIR) band near 4.7 microns. The TIR radiances are sensitive to thermal emission from the earth's surface as well as atmospheric absorption and emission. The NIR radiances are sensitive to atmospheric CO solely through absorption of solar radiation. (However, the NIR radiances are not actually in either V3 or V4 products.) Currently, only clear-sky radiances (i.e., radiances uncontaminated by clouds) are fed to the retrieval algorithm. A detailed description of the MOPITT cloud-detection algorithm can be found in (Warner et al., Appl. Opt., 2001).

In atmospheric remote sensing, the common problem of inverting a set of measured radiances to determine aspects of the atmospheric state (temperature profile, trace gas mixing ratio profiles, etc.) is often ill-conditioned, meaning that no unique solution exists without added constraints. Thus, additional information of some type is usually required to constrain the retrieval to fall within physically reasonable limits. The CO retrieval algorithm used for MOPITT exploits an optimal estimation technique. More precisely, MOPITT exploits the technique referred to by Rodgers as "Maximum A Posteriori", or "MAP" [C. D. Rodgers, *Inverse Methods for Atmospheric Sounding: Theory and Practice*, World Scientific, 2000]. The general strategy of such techniques is to seek the solution most statistically consistent with both the measured radiances and the typical observed patterns of CO profile variability (as described quantitatively by both the a priori mean profile and the a priori covariance matrix).

The TIR and NIR radiances depend not only on the vertical distribution of tropospheric CO but also on various other atmospheric quantities (such as the atmospheric temperature and water vapor mixing ratio profiles) and surface parameters (surface temperature and emissivity). Reasonably accurate values for all of these geophysical parameters must be obtained to produce accurate retrievals. Atmospheric temperature and water vapor profiles are obtained by spatially and temporally interpolating reanalysis profiles from NCEP to the location and time of each MOPITT pixel. However, sources of geophysical data such as NCEP are unable to provide accurate values of surface temperature and emissivity (both of which are highly variable) at the temporal and spatial resolution demanded by the MOPITT retrievals. Fortunately, information contained in the TIR radiances allows retrieval of the surface temperature and emissivity along with the CO profile, and makes external data sources for these quantities necessary only for providing a priori values. Thus, rather than assuming fixed values for the surface temperature and emissivity, these two parameters are included in the retrieval state vector (along with the elements of the CO profile). (A closer inspection of the roles of surface temperature and emissivity reveals that their effects on the TIR radiances are similar but not identical. Thus, to first order, surface temperature and emissivity together represent a single degree of freedom with respect to variability in the TIR radiances.)

The MAP technique combines two independent estimates of the same vector quantity (i.e., the state vector determined solely from the measurement vector and the "virtual" measurement represented by the a priori state vector) with generally unequal covariances. Retrievals of the CO profile consist of a "floating" surface-level retrieval (tied to the pixel-dependent surface pressure value) and retrievals on a set of fixed pressure levels. V3 retrievals exploited a seven-level grid with levels at the surface, 850, 700, 500, 350, 250, and 150 hPa. V4 retrievals exploit a ten-level grid with levels at the surface, 900, 800, 700, 600, 500, 400, 300, 200, and 100 hPa. The retrieved CO total column value is obtained as a byproduct of the retrieved profile and is obtained simply by integrating the retrieved profile from the surface to the top of the atmosphere. The MOPITT CO Level 2 Product therefore consists of retrieved values and estimated uncertainties of the CO profile, CO total column, surface temperature, and surface emissivity. The V4 Level 2 Product also includes the retrieval averaging kernel matrix (an important diagnostic) for each retrieval. In the earlier V3 product, the retrieved error covariance matrix was provided to facilitate calculations of retrieval averaging kernels (as described here).

"Phase-I" CO Retrievals (March, 2000 - May, 2001)

For both the V3 and V4 Products, the radiances used for the Phase I period include the A signal for Channel 7, and the D signals for Channels 1, 3, and 7.

"Phase-II" CO Retrievals (August, 2001 - present)

In May, 2001, one of MOPITT's two coolers failed, effectively disabling channels 1 - 4. After extensive diagnostics and some minor reconfiguration of the Channel 7 PMC, MOPITT resumed operations in August, 2001 with channels 5 - 8 fully functional. No MOPITT products are available for the period between May 7 and August 24, 2001. For both the V3 and V4 Products, the radiances used for the Phase II period include the A signal for Channel 5, and the D signals for Channels 5 and 7. As documented in (Deeter et al., GRL, 2004), Phase I and Phase II CO retrievals are similar (but not identical) in terms of vertical resolution and information content.

MOPITT Forward Modeling

Forward modeling of the MOPITT channel radiances must combine accuracy and precision while providing for variations in target and contaminating gases, temperature, viewing geometry and surface properties. To achieve this, a set of radiation models has been developed. The following is a very brief overview of this work. An expanded, though simplified, discussion can be found in "Channel radiance calculations for MOPITT forward modeling and operational retrievals" (Francis et al., SPIE, 1999). A detailed discussion of the MOPITT forward model is presented in (Edwards et al., JGR, 1999).

Line-by-line Calculations

Gas correlation spectroscopy introduces a high resolution spectral filter into the measurement process, having line widths of order 0.1 cm^{-1}. In addition, calculations with spectral resolutions as fine as 0.0025 cm^{-1} are required to construct the databases which are key components of the higher-level MOPITT radiation codes MOPABS and MOPFAS discussed below. Line-by-line (LBL) calculations must therefore be performed to provide these filters and databases. These are provided by the general purpose radiance and transmittance model GENLN2. Although too cumbersome for operational use, top-of-atmosphere radiances provided by GENLN2 also give benchmarks against which faster MOPITT codes can be assessed.

MOPABS: An optical-depth lookup table model

An intermediate step in the MOPITT radiation code hierarchy, MOPABS computes channel radiances through a monochromatic absorption coefficient fitting scheme. This technique explicitly mirrors much of the underlying physics of the radiative transfer. It yields transmittance and radiance spectra across each channel passband, which are integrated to give the MOPITT channel signals. The method has essentially LBL accuracy and is considerably faster. Channel radiance calculations for a given test atmosphere can typically be completed in a few minutes. While this is still too slow for operational retrievals, MOPABS is an important tool for the development of a truly fast forward model. In addition, MOPABS has broad applications to other MOPITT work.

MOPFAS: The MOPITT operational fast forward model

MOPFAS achieves faster performance than MOPABS by reformulating the calculation so that time-consuming spectral integrations are avoided. A regression scheme based on the OPTRAN technique is applied to establish a correspondence between channel-integrated transmittances and atmospheric state profiles, such that the former can be inferred accurately and quickly given the latter. The regression maps a set of predictors, obtained from the state profiles, onto corresponding values of channel transmittance obtained from MOPABS. The predictors are functions of absorber amount, pressure, temperature and viewing geometry. The regression coefficients are pre-computed through a least-squares fit over a representative atmospheric ensemble. MOPFAS channel radiances are in good agreement with MOPABS. Typically, MOPFAS and MOPABS have mean differences of 0.05 - 0.1% , with maximum differences of 0.4 - 0.7% depending on channel and band. In addition, a MOPFAS calculation is about 10^5 times faster than GENLN2 LBL calculations. This is fast enough for MOPFAS to be used in operational retrievals.

MOPITT Cloud Detection

The cloud detection algorithm described below applies to both V3 and V4 products.

The MOPITT cloud detection algorithm detects and removes measurements contaminated by clouds before they reach the retrieval algorithm. MOPITT cloud detection exploits both MOPITT radiances and the MODIS (MODerate-resolution Imaging Spectroradiometer) cloud mask product to achieve maximum coverage and accuracy. The cloud detection technique using only MOPITT radiances (MOPCLD) is described in (Warner et al., Appl. Opt., 2001).

The MOPCLD threshold method compares the observed radiances with calculated clear sky radiances, and currently uses only one MOPITT thermal channel at 4.7 μm. The threshold, based on observed channel radiance and forward model calculated clear column radiance, is: $R_{observed}/R_{calculated} < 0.955$. Only latitudes within 65° North and South are included in this threshold test to avoid complications due to temperature inversions. MOPITT solar channels are not currently used in the L2 cloud detection processing.

The MOPITT and Terra/MODIS instruments produce nearly simultaneous measurements overlapping a large geographical area close to nadir. MOPITT sensors scan across the track to a maximum satellite zenith angle of 27° on both sides of nadir, pausing for approximately 0.45 seconds to take measurements of an array of four 22 km by 22 km pixels. The MODIS swaths are more than twice as wide as those of MOPITT and provide complete overlap for MOPITT measurements. The spatial resolution of the MODIS cloud mask is 1x1 km. Therefore, each MOPITT pixel is collocated to approximately 484 MODIS 1x1 km pixels.

To maximize accuracy and global coverage, MODIS cloud mask and MOPCLD are combined in the MOPITT cloud detection algorithm. A MOPITT pixel is considered clear when both methods agree it is clear and when there is only low cloud in the field of view (FOV). Note that there is a 5% cloud allowance (as determined by MODIS) in each MOPITT pixel for it to be considered as clear. Cloud description flags are included in MOPITT Level 2 files to indicate the cloud decisions made for each pixel (see table below). Additional MODIS flags are used to locate low level clouds when the MODIS cloud mask classifies a pixel as cloudy and MOPCLD classifies it as clear (flag=4). In all other cases, when MODIS cloud mask classifies a pixel as cloudy and MOPCLD classifies it as clear, this pixel is considered cloudy (no retrieval performed). The final decision is clear when MODIS says clear and MOPCLD says cloudy (flag=3). In areas where MODIS cloud mask is not available only MOPCLD is used (flag=1). Only MODIS cloud mask is used in the polar-regions (above 65°N and below 65°S) (flag=5).

Currently, only our best estimates of cloud-free pixels are included in the Level 2; retrievals are not performed on cloudy pixels. Therefore, users should not need to filter the data according to the cloud flags included in the Level 2 files. For reference, the cloud flags used in both V3 and V4 products are listed below.

Cloud Description Flags used in V3 and V4

Flag	Description
1	MOPCLD only clear, thermal only
2	MOPCLD and MODIS cloud mask agree on clear
3	MODIS cloud mask only clear (when MOPCLD cloudy)
4	MOPCLD overriding MODIS cloud mask over low clouds (MODIS test flags used)
5	MODIS cloud mask only, clear over polar regions

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