Measurement of Pollution in the Troposphere (MOPITT) Data Validation Plan

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Abstract

This is the version 4.0 of the MOPITT data validation plan. The format recommended by EOS Validation Scientist was followed in the generation of this document. It should be regarded as an evolving document: it is intended that it will continue to be refined over time as the MOPITT program progresses.

The Measurement of Pollution in the Troposphere (MOPITT) is an eight-channel gas correlation radiometer to be launched on EOS/AM1 spacecraft in 1998. The goal of the experiment is to support studies of the oxidizing capacity of the lower atmosphere on large scales by measuring the global distributions of carbon monoxide (CO) and methane (CH_4) and thus, will represent a significant advancement in the application of space based remote sensing to global tropospheric chemistry research. Validation of data processing algorithms and products is an essential component of the MOPITT project. Standard MOPITT data products and their characteristics will be described. Strategies and techniques to verify MOPITT measurement precision, accuracy, and resolutions will be discussed. The MOPITT data processing algorithms are being tested and validated using existing airborne and satellite before launch. Post-launch correlative measurements for MOPITT algorithm and data validation include measurements by airborne remote sensing and in-situ techniques and ground-based spectroscopic techniques. Methods for the intercomparison of various correlative measurements and MOPITT measurements will be discussed.

Document History

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Related and Reference Document

RD1. MOPITT Mission Description Document (MDD).
Available at http://www.atmosp.physics.utoronto.ca/MOPITT/home.html.

RD2. MOPITT Level 0-1 Algorithm Theroretical Basis Document (L0-1 ATBD).
Available at http://eos.acd.ucar.edu/mopitt/home.html.

RD3. MOPITT Level 1-2 Algorithm Theroretical Basis Document (L1-2 ATBD).
Available at http://eos.acd.ucar.edu/mopitt/home.html.

RD4. To Validate the MOPITT Program Data.
Available from G. R. Davis at University of Saskatchewan.

RD5. MTPE EOS Data Products Handbook. Volume 1, TRMM & AM-1, 1997.
Available from Code 902, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

RD6. EOS Validation Program WWW site at
http://eospso.gsfc.nasa.gov/validation/valpage.html.

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1.0 Introduction

1.1 EOS AM-1 Mission

The EOS AM-1, planned for launch in 1998, is described in the <<EOS Reference Handbook>>. It will be placed into a polar, sun-synchronous, orbit with nominal orbit altitude of 705 km and inclination of 98.2^o. EOS AM-1 will have an equatorial crossing time of 10:30 AM. The payload consists of ASTER, CERES, MISR, MODIS, and MOPITT.

1.2 MOPITT Instrument Characteristics

In order to understand MOPITT data products, particularly the radiance product, which is referred to as the MOPITT level 1 data product, it is important to know the MOPITT measurement technique and instrument characteristics.

Drummond (1992) has outlined the MOPITT instrument concept. The approach and viewing geometry are shown in figure 1. MOPITT measures upwelling thermal emission from the atmosphere and surface in the thermal channels, and reflected solar radiation in the solar channels that has passed through the atmosphere, been reflected at the surface, and transmitted back up through the atmosphere. The characteristics of each instrument thermal and solar channels is summarized in Table 1. Total atmospheric transmittance derived from reflected solar radiation measurement is a convenient way to determine the total column amount of an atmospheric trace gas. This technique requires that the target gas has a spectral band in a region with adequate solar radiance, and the total optical depth along such a path is not too large. CO has its first overtone band at 2.3 μm that meet the requirements. For vertical profiling, the requirements are that significant and measurable portions of the signal must originate in different atmospheric layers, which means there must also be a source of radiation in the atmosphere. Thermal emission is a radiation source, and the CO fundamental band at 4.7 μm has enough opacity to determine atmospheric amounts, as demonstrated by Reichle *et al.* (1986, 1990, 1997).

Since all gases in the atmosphere are emitting/absorbing simultaneously, it is essential that the effect of the gas of interest can be separated out from the overall signal. Furthermore, since the information about the vertical distribution of the gas is contained within the shape of an individual absorption/emission line, it is necessary to be able to resolve the line shape, which generally requires high spectral resolution. High spectral resolution leads to low signal to noise, which means low instrument sensitivity. Therefore, high sensitivity and high spectral resolution requirements for tropospheric trace species remote sensing are difficult to implement with conventional dispersing instruments. Correlation spectroscopy, a non-dispersing spectroscopy technique, offers the opportunity for high spectral resolution as well as high signal to noise. The

Table 1. Characteristics of MOPITT CO and CH_4 channels. There are four CO thermal channels, two CO solar channels and two CH_4 solar channels. The nominal PMC and LMC cell pressure, temperature and length are also listed.

Ch #	Primary Purpose	Modulator Type	Cell Pressure (mb)	Cell Temperature (K)	Cell Length (mm)	Center Wavenumber[1] (cm-1)
1	CO	LMC1	200	300	2 - 10	2166 (52)
2	CO	LMC1	200	300	2 - 10	4285 (40)
3	CO	PMC1	50 -100	300	10	2166 (52)
4	CH_4	LMC2	800	300	2 - 10	4430 (140)
5	CO	LMC3	800	300	2 - 10	2166 (52)
6	CO	LMC3	800	300	2 - 10	4285 (40)
7	CO	PMC2	25 - 50	300	10	2166 (52)
8	CH_4	LMC4	800	300	2 - 10	4430 (140)

(1) Numbers in parenthesis are band filters full width at half maximum (FWHM).

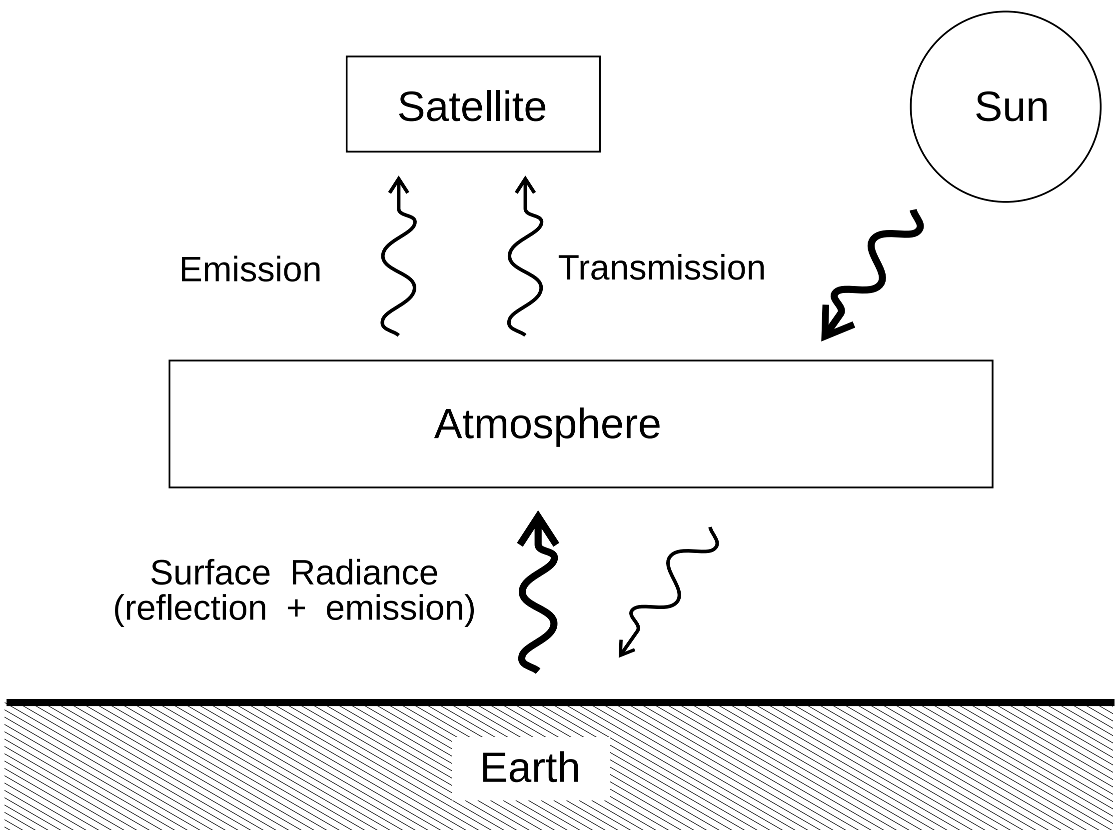

Fig. 1. Schematic diagram of MOPITT measurement system.

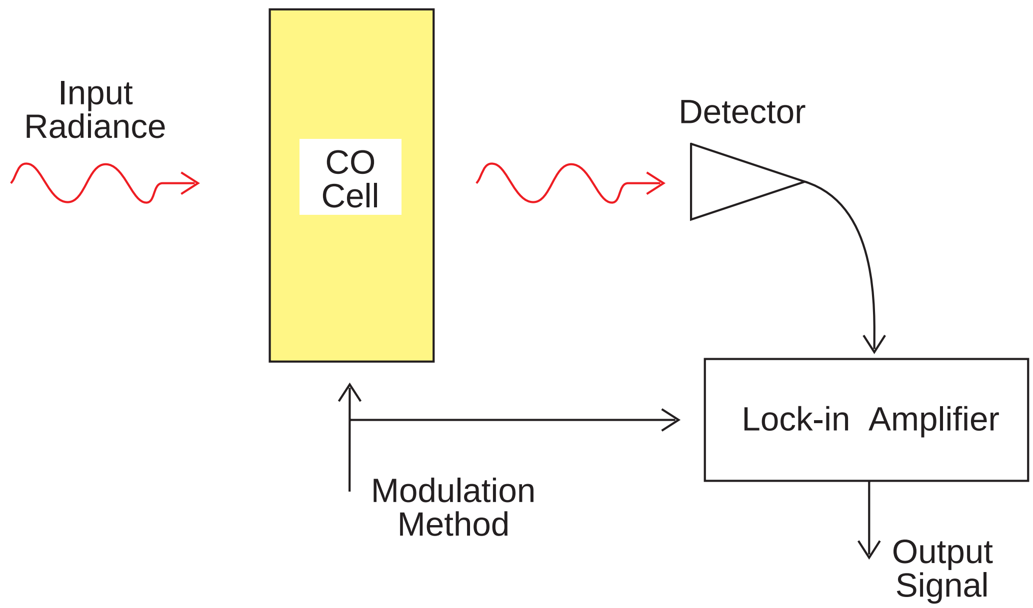

Fig. 2. A basic correlation radiometry system.

fundamental techniques of correlation spectroscopy for CO remote sensing are illustrated in figure 2. MOPITT makes use of two methods to modulate the transmittance in the gas cell. The first is by varying the cell pressure through the use of pressure modulated cells which have been described in detail by Taylor (1983). The second is by varying the amount of gas in the cell through length modulated cells (Drummond, 1989). Two pressure modulated radiometers (PMR's) with different mean pressures and four length modulated radiometers (LMR's) are used in MOPITT. Separating the 2.3 µm and 4.7 µm channels with dichroic beam splitters results in 8 separate spectral channels. The LMR channels contain cells with higher pressure to optimize instrument sensitivity to the lower and middle troposphere, and the PMR channels contain cells with lower pressure to optimize instrument sensitivity to the upper troposphere. Each channel produces an average signal(A), which is the average of the instrument signals corresponding to the two states of the modulating cell, and a difference signal(D), which is the difference of the instrument signals corresponding to the two states of the modulating cell. For the LMC channels, the two states are defined by the two alternative cell path length of 2mm and 10mm. For the PMC channels, the two states are defined by the alternative high and low cell pressures. Theoretical and experimental studies indicate that a PMC cell can be fairly accurately represented by a two-pressure system (May *et al*, 1988; Roscoe and Wells, 1989; Berman *et al*., 1993). Radiative transfer calculations indicate that the difference signals are more sensitive to atmospheric CO and CH_4 changes, and the average signals are more sensitive to Earth surface and cloud characteristics.

The channel average signals are converted into geolocated channel average radiances in the MOPITT level 0-1 processor, and the channel difference signals are converted into geolocated channel difference radiances in the MOPITT level 0-1 processor. Details of the MOPITT level 0-1 algorithm are described in MOPITT level 1 algorithm theoretical basis document (ATBD), which is available at the WWW site (http://eos.acd.ucar.edu/mopitt/atbds.html). The geolocated channel average and difference radiances are referred to as the MOPITT level 1 data product. The level 1 data will be used in the MOPITT level 1-2 processor to generate tropospheric CO profiles, total CO and CH_4 columns, which are referred to as the MOPITT level 2 data. Details of the MOPITT level 1-2 algorithm can be found in the MOPITT level 2 algorithm theoretical basis document (ATBD) (available at WWW site http://eos.acd.ucar.edu/mopitt/atbds.html). Subsequently the level 2 data will be used to generate the MOPITT level 3 product, which is defined as the mapped CO and CH_4 distributions generated by mapping and possibly data assimilation techniques. The algorithm for MOPITT level 3 data product generation has not been defined yet.

1.3 MOPITT Measurement and Science Objectives

The Measurements of Pollution In The Troposphere (MOPITT) experiment has been described in detail by Drummond (*Drummond*, 1992; 1993). MOPITT is an eight-channel gas correlation radiometer, and each channel generates an average signal and a difference signal. The main scientific objective of the MOPITT experiment is long-term measurement of global distribution of tropospheric carbon monoxide (CO) and methane (CH_4). Those measurements will enhance our knowledge of troposphere chemistry, particularly how it interacts with the surface/ocean/biomass systems, atmospheric transports, and the carbon cycle. Global CO and CH_4 measurements from MOPITT will also be used in parallel modeling efforts to advance our understanding of global tropospheric chemistry and its relationship to sources, sinks, and atmospheric transports, which can be determined from other data. Understanding their biogeochemical cycles and their intimate interrelation with each other and with climate will lead to better prediction of possible effects of anthropogenic activities.

The primary measurement objectives of MOPITT are: (1) to obtain CO profiles with a resolution of 22 km by 22 km horizontally, 3-4 km vertically and with an accuracy of 10% throughout the troposphere; (2) to obtain total CO column amount measurement with a horizontal resolution of 22 km by 22 km and an accuracy of 10%; (3) to measure total CH_4 column to an precision of 1%, with a spatial resolution similar to that of the CO measurement.

The column amounts of CO and CH_4 will only be available on the sunlit side of the orbit as standard level 2 MOPITT products.

1.4 MOPITT Science Data Products

Standard MOPITT science data products, which need to be validated, are discussed in this section.

1.4.1 Level 1 Data Products

Product MOP1.1: 8 calibrated and geo-located instrument difference radiances for each stare (~ 400 ms).

Product MOP1.2: 8 calibrated and geo-located instrument average radiances for each stare (~ 400 ms).

1.4.2 Level 2 Data Products

Product MOP2.1: Tropospheric CO profiles. The average mixing ratio of five tropospheric layers (1000-700mb, 700-500mb, 500-400mb, 400-300mb, 300-200mb) for each nominal 22kmx22km pixel will be generated by the MOPITT level 1-2 processor. In certain regions of the atmosphere, the spatial resolution may be lower than 22kmx22km due to cloud clearing and/or signal averaging over many pixels to increase signal to noise ratio.

Product MOP2.2: Total CO for each atmospheric column over a nominal area of 22kmx22km. In certain regions of the atmosphere, the spatial resolution may be lower than 22kmx22km due to cloud clearing and/or signal averaging over many pixels to increase signal to noise ratio. The column amount of CO will only be available on the sunlit side of the orbit as standard MOPITT level 2 data product.

Product MOP2.3: Total CH_4 for each atmospheric column over a nominal area of 22kmx22km. In certain regions of the atmosphere, the spatial resolution may be lower than 22kmx22km due to cloud clearing and/or signal averaging over many pixels to increase signal to noise ratio. The column amount of CH_4 will only be available on the sunlit side of the orbit as standard MOPITT level 2 data product.

1.4.3 Level 3 Data Products(Experimental at Launch)

Product MOP3.1: Gridded global CO distribution (global map) of 5 nominal tropospheric layers (1000-700mb, 700-500mb, 500-400mb, 400-300mb, 300-200mb) produced by mapping procedures and data assimilation models.

Product MOP3.2: Gridded global CO column (global map) produced by mapping procedures and data assimilation models.

Product MOP3.3: Gridded global CH_4 column (global map) produced by mapping procedures and data assimilation models.

2.0 MOPITT Data Validation Objectives and Strategies

2.1 Validation Objectives

Following the definition by EOS Validation Program: "Validation is the process of assessing by independent means the uncertainties of the data products derived from the system outputs," the primary objectives of MOPITT data validation are to define the uncertainties of MOPITT level 1 and level 2 data products under different observation conditions by comparing MOPITT measurements and products with independent measurements of the same physical quantities under the same or very similar observing conditions. Measurement precision, accuracy and resolutions will be verified as a result of various validation activities.

2.2 Overview of Validation Strategy

The MOPITT validation program consists of the following two major components. the first component is the test and validation of MOPITT data processing algorithms, i.e. the level 0-1 algorithm and the level 1-2 algorithm. The level 0-1 algorithm produces geolocated MOPITT average and difference radiances from spacecraft and instrument telemetry streams and necessary ancillary data. The level 1-2 algorithm produces geophysical quantities (troposphere CO profiles, CO column and CH_4 column) using the level 1 product and ancillary data from other sources. The second component is the validation of geophysical products generated by the MOPITT data processing algorithms by comparison with independent measurements. The first component is the main focus of pre-launch validation activities, and the second component will be the main focus of the post-launch validation activities. However, the data processing algorithms will be continuously validated and improved throughout the MOPITT mission and possibly even after the mission. Any major changes to the data processing algorithm will require data re-processing.

In the implementation of MOPITT validation activities, a step-by-step approach will be used, in which emphasis will be placed on understanding the data from simpler situations (or observation conditions) first, learning from and assessing their results before fully addressing more complicated cases. However, data for all cases will be acquired as early and often as possible. Three areas in which distinctions can be made between less and more complex observation conditions are:

1) Cloudiness. Clear conditions are simpler than those with cloud;

2) Underlying surface. Sea surface, with its uniform elevation, albedo, and more uniform temperature, is less complex than the land surface;

3) Day/Night. Night conditions, in which there is no signal on the short-wave channels, are less complex than the daytime conditions.

Further explanation of those observing conditions is given in the following sections. It is expected that different MOPITT products uncertainties, particularly the level 2 data products uncertainties, will be associated with different observing conditions. In other words, error bars may be smaller for observations under simpler conditions, and bigger for observations under more complex conditions. More classifications of observing conditions may be made after launch when we learn more about the characteristics of the MOPITT measurements and observing conditions. The approach of classifying observing conditions into different regimes and processing the observations over the easiest regime first fits the step-by-step data processing philosophy favored by the EOS program, starting with processing 25% of the data and gradually increasing the processing percentage.

2.2.1 Clear Conditions

2.2.1.1 Clear Sky over Ocean

Observation over ocean under clear sky conditions is expected to be the easiest to understand and process. For these conditions, regions of the ocean with low climatological cloudiness will be identified before launch, and data from them will be screened and collected. The supporting meteorological data from the Data Assimilation Office (DAO) or National Meteorological Center (NMC) will also be collected-this includes surface temperatures, temperature and water vapor profiles. In addition, available operational data on aerosols will be collected. These will form the validation data sets.

Initial use will be to calculate the outgoing radiances, using climatological CO distributions for the appropriate latitudes and seasons. These will be used to verify that the radiances are within bounds that are understood, based on the instrument radiometric model and the atmospheric model. This will comprise an important part of the Level 1 validation. Subsequently, the radiances will be compared to verify that the results are consistent with climatological values. Vertical profiles of CO, CH_4 and possibly other ancillary data (e.g. temperature, H_2O, O_3) will be collected at a minimum of one oceanic location, preferably at a location at which there are significant variations, so that comparisons can be made over a range of values.

2.2.1.2 Clear Sky over Land at Night

MOPITT observations over land surfaces at night are expected to be the second easiest to understand and process. We note here that observations over certain land surfaces, such as uniform desert, may be as easy as observations over ocean to understand. However, generally speaking, observations over land are more difficult to interpret than observations over ocean because of large uncertainties and variations of land surface emissivity and temperatures. Again, regions (e.g. deserts) and seasons with low climatological cloudiness will be identified before launch, and data from them will be screened and collected. The supporting meteorological data will again be assembled to form validation data sets, which will be used as before. One goal will be to see whether cases in which surface temperatures differ from predicted values can be identified and clearly differentiated from cases with partial cloud. Subsequently, the radiances will be compared to verify that the results are consistent with climatological values.

2.2.1.3 Clear Sky over Land during Daytime

After having a better understanding of observations over the relatively easy ocean surfaces and land surfaces at night, we can move on to try to understand observations over land during daytime. The reason that observations over land during daytime are more difficult to interpret is because reflections of solar radiation by land surfaces introduce a new signal component which is dependent on the highly variable surface reflectivity. Again, regions (e.g. deserts) and seasons with low climatological cloudiness will be identified before launch, and data from them will be screened and collected. The supporting meteorological data will again be collected to form validation data sets. Initial use will be to evaluate the outgoing radiances and instrument difference signal to average signal ratios, using expected values of surface albedo for short-wave channels and climatological CO distributions for the appropriate latitudes and seasons. These will be used to verify that the radiances and ratios are within bounds that are understood, based on the instrument radiometric model and the atmospheric model. This will also comprise part of the level 1 data validation. Subsequently the radiances will be compared to verify that the results are consistent with climatological values.

2.2.1.4 Clear Sky over More Complex Land Surfaces

After the examination of observations over relatively homogeneous land surfaces, we will start looking at more complex land surfaces, such as regions in which the reflectivity and temperature change significantly from one pixel to the next. The effects of relatively large emissivity and temperature variations from pixel to pixel and topographies will be investigated. Regions of high plains will be used to verify proper forward radiance calculations and retrievals for high terrain. This will be done first at night, and then in the daytime. Subsequently, terrain in which there is large variability will be evaluated, for determining whether predicted surface temperatures are reliable and useful, and to determine whether there are additional problems with pixels having uneven lower topography.

2.2.2 Cloudy Conditions

2.2.2.1 Ocean Surfaces

This case will allow testing of the spatial coherence method (Coakley and Bretherton, 1982) for determining cloud-top temperatures for the MOPITT pixels. This can be compared with those from other instruments and techniques, as well as predictions. It will also allow testing of cloud filtering techniques and of carrying out retrievals, which will be able to be compared to climatology, and results from nearby clear regions. In this case, MOPITT short-wave channel radiances will be usable as a strong indicator of clouds, and may enable situations with low cloud to be handled with better success.

2.2.2.2 Land Surfaces at Night

Criteria established from the MOPITT long-wave channel retrievals made in clear conditions over land at night will be used as a basis for retrievals over partly cloudy land areas. Cloud filtering techniques will depend on the assumption that the pixels are spatially independent but geographically close. Thus differences in the observed channels will be the result of attenuation of the radiances due to the presence of clouds. If these assumptions hold true, clear air radiances can be calculated from adjacent pixels. The clear air radiances will be retrieved and verified that the results are consistent with climatological values. Consistency checks will also be made, over time, for all locations comparing day and night retrievals. Pixel radiances rejected by the cloud algorithm , as too cloudy to clear, will be analyzed and compared with other instrument cloud indications for validation.

2.2.2.3 Land Surfaces during Daytime

For daytime observations, both MOPITT long-wave and short-wave channel radiances can be used to indicate the presence of clouds in the field of view. Criteria for the retrievals will be based on values derived during the day in clear conditions. Cloud filtering techniques will be applied to all channels. Retrieved methane values will be compared to climatological values for validation. Rejected radiances will be analyzed and compared to other instrument cloud indications for validation. Retrieved methane values obtained when all tests indicate clear conditions (i.e. excluding cloud cleared radiances) will be kept in a gridded historical file. As the MOPITT mission progresses, this statistical data set will also be used as a criteria to accept and or reject retrievals in partly cloudy conditions over both land and ocean.

2.3 Overview of Validation Approaches

All levels of MOPITT data, Level 0, Level 1, Level 2, and Level 3, will be checked and validated in the data quality assurance and validation processes. Appropriate mathematical models and software will be developed; detailed pre-launch and post-launch instrument calibration will be carried out to determine instrument parameters used in data processing and validation; detailed pre-launch and post-launch error analysis will be performed to determine the expected errors in MOPITT data products under various observing conditions. Correlative measurements from ground-based, airborne, and satellite-borne instruments, together with instrument/retrieval error analysis will be used to establish the precision, accuracy, and resolution of MOPITT CO and CH_4 measurements.

2.3.1 Level 0 Data (Raw Instrument Output)

Raw data from the MOPITT instrument will be checked for long and short-term consistency in flight operation and monitoring at University of Toronto by the MOPITT Instrument Support Team. Instrument signals will be examined to identify spikes, data gaps, and other anomalous changes on a day to day basis. Quality assurance will also be done as part of the data ingest phase of the level 0-1 Distributed Active Archive Center (DAAC) processing.

2.3.2 Level 1 Data (Calibrated and Geolocated Radiances)

The calibrated radiances from the instrument will be assessed by the following checks:

(1). *Calibration history file*: A history file of all MOPITT calibration events will be accumulated as part of the DAAC processing. This file will be analyzed as part of the calibration verification effort.

(2). *Spatial and temporal consistency of observed radiances*: The calibrated radiances will be examined for consistency along the orbit, and for consistency from orbit to orbit, day-to-day, day-to-night, and with latitudinal and seasonal changes.

(3). *Comparison of observed radiances with climatological calculations:* The observed radiances will be compared to computed radiances using temperature, CO, H_2O, CH_4, O_3, N_2O, and aerosol profiles from climatology, NMC, ECMWF, and DAO at specific sites. For example, the tropical central Pacific Ocean and Department of Energy Atmospheric Radiation Measurement (DOE/ARM) (Stokes, *et. al*., 1994) sites at Southern Great Plain (SGP) in Oklahoma, North Slope of Alaska (NSP), and Tropical Western Pacific (TWP).

(4). *Comparison of observed radiances with values calculated from correlative measurements:* In situ measurements of the vertical distributions of temperature, CO, and interfering species will be made, and used to calculate the outgoing radiances. Collocated MOPITT radiances will be compared with the calculated radiances.

(5). *Comparison with aircraft measured radiances*: Two aircraft (A/C) instruments are envisioned at this time. The MOPITT Algorithm Test Radiometer (MATR) is a relatively simple instrument being developed at NCAR. MATR will be operational before MOPITT launch in 1998. First engineering test flight of MATR took place in June, 1996. The MOPITT Aircraft Instrument (MOPITT-A), currently funded by the Canadian Space Agency (CSA), will resemble the MOPITT instrument more closely. MOPITT-A may not be operational until after launch. One of the principal uses will be for vicarious calibration and level 1 data validation, where the radiances of MOPITT-A on an high altitude aircraft (e.g. the ER-2) underflying the EOS AM-1 platform over validation sites will be compared directly with MOPITT radiances. Some corrections may need to be made for the atmospheric levels above the A/C. However, simulations indicate that the contribution of the atmosphere above 20 km to MOPITT channel radiances is negligible, therefore very little correction is needed if MOPITT-A is fitted to the NASA ER-2 flying at about 20 km. Because of the differences in field-of-view (FOV), the aircraft observations will need to be averaged to achieve a match with the EOS MOPITT FOV. This will be most important in regions with variable clouds. Details of MOPITT-A can be found in the document entitled “To Validate the MOPITT Program Data” by Davis (Reference Document RD4, G. R. Davis, 1996).

2.3.3 *Level 2 Data (Retrieved Profiles and Column Amounts)*

The next step in the validation of MOPITT data will be to compare retrieved profiles of CO and column amounts of CO and CH_4 with climatological results and correlative measurements from ground-based, airborne and other satellite instruments. We plan to examine how ground-based in-situ measurements, column CO and CH_4 (Pougatchev & Rinsland, 1995; Zhao *et al.*, 1997) derived from ground-based remote sensing instruments (such as FTIR), and CO and CH_4 derived from airborne instruments should be compared as part of the pre-launch algorithm development and validation planning activities. Joint CO measurement validation activities with the AIRS team are planned. Free troposphere CO column is one of the data product from AIRS. Preliminary studies using the High-resolution Interferometer Sounder (HIS) data indicate that 10% accuracy is achievable (McMillan *et al.*, 1996). A MOPITT correlative team has been formed with support from the MOPITT project and NASA EOS Validation Program through the EOS Validation Announcement of Opportunities (AO) in 1997. A brief summary of MOPITT level 2 data validation activities are given here. They include:

(1). *Spatial and temporal consistency of retrieved profiles*: Present aircraft and satellite measurements of CO and CH_4 mixing ratios suggest that they do not show large spatial and temporal gradients in the midlatitude Southern Hemisphere during the wet season, and do not show large vertical gradients in the tropics (Reichle, *et. al*., 1986, 1990; Connors, *et. al*., 1994). Examination of the profiles for along orbit and orbit to orbit consistency, through plots and statistical evaluation, will be useful in locating problems in the retrievals, or in instrument performance. However, one must be cautious not to rely too heavily on this information as unusual profiles may occur as a result of strong convective activity combined with strong surface sources during the dry season (e.g. biomass burning).

(2). *Comparison of retrieval amounts with climatological data:* Data on the vertical and horizontal variations of CO now exist in the literature, and in the databases of recent experiments (e.g., MAPS CO data archive at NASA Langley). These data can be used immediately after launch to verify that the retrieved profiles are consistent with prior CO measurements and the observed differences between the two hemispheres, including the observed latitudinal and vertical variations. Such comparisons will allow a rapid check for unforeseen systematic errors. Similar comparisons can be done for the CH_4 column.

(3). *Comparison of retrieved CO & CH_4 amounts with simultaneous correlative measurements*: Sources of such data include: 1) Aircraft measurements of CO and CH_4 profiles with in-situ measuring devices, such as the tunable diode laser system and automated flasks system developed at the NOAA Climate and Diagnostics Laboratory (NOAA/CMDL). Such campaigns are planned over DOE/ARM sites in Oklahoma (ARM/SGP), Alaska (ARM/NSP), and Tropical Western Pacific (ARM/TWP), North America, Australia, and possibly over China and other countries; 2) Measurements with the MOPITT airborne instruments. These will be some of the same flights as those mentioned in 1) above, but not necessarily all; 3) Balloon measurements of CO and CH_4 profiles for selected times and places. If a lightweight, inexpensive instrument can be developed, the possibility of many measurements from small balloons, launched from a variety of locations, would be extremely useful. The balloons would need to reach an altitude of only about 20 km; 4) Ground based spectroscopic measurements of CO and CH_4 total column and CO profiles over a wide latitude range. Possible ground stations include the CANOPUS network (Canada), the Network for Detection of Stratospheric Change (NDSC) (more information can be found at the WWW site http://climon.wwb.noaa.gov/), DOE/ARM sites, and other existing stations such as those operated by the Institute of Atmospheric Physics in Russia. Measurements of this type will be especially valuable in evaluating the long term behavior of the MOPITT instrument. Currently, the CANOPUS network doe not have CO measurement capability, CO measurement systems will need to be added to the network for MOPITT validation. Where appropriate we will encourage the establishment of new stations; 5) Free troposphere CO retrieval from HIS measurements during joint MOPITT and AIRS (or MODIS) validation campaigns; 6) Measurements of column CO and CH_4 by other satellite instruments.

2.3.4 Level 3 Data (Gridded CO and CH_4 Data)

The global and regional structures of CO and CH_4 from level 3 data will be compared to atmosphere features such as temperature structure, tropopause height, winds, and convection. Level 3 data will also be compared with 4-D chemical model results. Data assimilation will be used to facilitate comparisons of MOPITT data with surface CO measurements.

2.4 Intercomparison Approaches Between MOPITT Level 2 Data and Correlative Data

What is a valid intercomparison between MOPITT level 2 CO and CH_4 data with aircraft in-situ CO and CH_4 measurements ? An inherent difficulty is to establish that the in-situ instrument and MOPITT on the EOS/AM-1 satellite measure the same air mass, or find satellite overpasses that are close enough in space and time to the site of the in-situ sampling to yield a valid intercomparison. What is a valid intercomparison between MOPITT level 2 CO and CH_4 data and CO and CH_4 retrievals from ground-based spectroscopic measurements ? Generally the ground-based spectroscopic measurements looking-up will have lower vertical resolution and different sensitivity to different altitude region than MOPITT measurements looking down. Appropriate weights using the weighting functions of ground-based measurement system and MOPITT need to be used to get meaningful intercomparison.

2.4.1 Criteria for Coincidence

As discussed in the last paragraph, it is important to establish the appropriate criteria for space and time coincidence between MOPITT observations and correlative measurements to yield valid intercomparisons. If the criteria is too loose, MOPITT observations and in-situ measurements are done on very different air masses, then the intercomparison will have large uncertainties, and will not be useful for MOPITT data validation. If the criteria is too tight, then the number of valid correlative measurements will be greatly reduced, leading to inadequate number of intercomparisons to yield any meaningful statistical results.

Because of the possibility of large and rapid constituent fields variability in the troposphere, it is almost imperative to require that the correlative measurements be nearly simultaneous with the MOPITT observations. In terms of space coincidence, the correlative measurements should be within the field-of-view (FOV) of the MOPITT (22km by 22km) measurement to be intercompared. It is desirable to have several correlative measurements, which have smaller FOV, in the MOPITT FOV over regions with large spatial inhomogeneity. In terms of time coincidence, the difference in time between the MOPITT observation and the correlative observation should be less than 1 hour. An alternative approach is to use trajectory analysis and try to intercompare the MOPITT measurement and correlative measurement over the same air mass. Since both CO and CH_4 are relatively long-lived species, with CO having a life time of months and CH_4 having a life time in the order of 10 years, the trajectory analysis approach may be better than the space and time windows approach to ensure valid intercomparison. Trajectory analysis has been successfully used in the validation of many aircraft and satellite measurements (Thompson *et al.*, 1994; Pickering *et al.*, 1996; Schwab *et al.*, 1996).

2.4.2 Measures of Success

It should be understood that both correlative measurements used for intercomparison and MOPITT observations will have error bars. Therefore, the correlative measurements data are not "truth" and do not provide an absolute standard against which the validity of the MOPITT measurements can be judged. However, they will be very useful for intercomparisons and will provide an important input to the data validation studies if they are accompanied by a continuing program of interlaboratory intercalibration that allows the adjustment of all measurements to a common, agreed upon standard. The correlative measurements for MOPITT data validation should have smaller error bars compared with MOPITT measurements. The objective of MOPITT intercomparisons with other measurements will be considered satisfied when either the estimated error bars of MOPITT and any correlative measurements data overlap or when reasons for the differences are understood.

2.5 Development of MOPITT Data Validation Software

Data validation is critical for the success of the MOPITT program. Flexible, efficient software for data manipulation, data comparison, data transfer and display are needed. The primary Level 0 data requirement is for trend plot software to identify changes, if any, in important instrument parameters and characteristics. Software to be developed for Level 1 validation includes computer programs to plot and compare the observed radiances with calculated radiances with climatology and collocated atmospheric profiles measurements. Interactive graphic programs and graphical user interface (GUI) will be developed to display data on different scales, in different forms, etc. A statistical intercomparison package will be developed that can select one or many profiles for comparison. Similar software and tools will be developed for the Level 2 data validation.

3.0 Correlative Measurements for MOPITT Data Validation

A correlative team, consisting of MOPITT instrument team members and new investigators selected by the NASA EOS Validation Announcement of Opportunities (AO) (NRA-97-03) in 1997, has been formed. A brief discussion of measurement needs and planned correlative measurements is presented in this section.

3.1 Correlative Measurement Needs for MOPITT Validation

Because previous measurements from satellites have shown that regular validation must be made over the lifetime of the instrument, MOPITT validation will occur on a regular basis. Our validation of the MOPITT measurements is based on two approaches. The first is to use several intensive studies for algorithm and initial phase data validation where as many of the atmospheric parameters needed in the retrieval are measured. These include vertical profiles of temperature, H_2O, O_2, and CO. Surface reflectivity in the 4.6 and 2.2/2.3 μm region, and cloud heights and fractions are also needed for MOPITT data validation. The vertical distributions and total column measurements of CH_4 and CO will be used for comparison to retrieved CO and CH_4 from MOPITT measurements.

The accuracy of the products needed for intensive studies and algorithm validation are as follows. Temperature profiles should be better than 2 K from the surface to about 20 km, and the accuracy of the ozone profile should be better than 20% to an altitude of 30 km. Both of these are achievable using currently available methods. The water vapor profile should be better than 10% from surface to 15 km. Radiosondes can provide this accuracy only from the surface to the tropopause, above which H_2O concentrations are relatively low. Aircraft and satellite measurement of H_2O can be used above tropopause. Radiosondes, Raman lidar and/or microwave radiometer can be used for temperature and water vapor profiling. Ozone sondes at or near validation sites are necessary for ozone profile measurements. The accuracy of surface reflectivity measurements should be better than 5-10%. Cloud heights and fractions should be better than 20%.

For the long term validation of MOPITT geophysical products (level 2 products), mixing ratios determined from the MOPITT data will be compared to correlative measurements from ground and aircraft based instruments on a regular basis. The accuracy of CO profile measurements should be better than 10% from the surface to about 15 km. This accuracy is well within the capabilities of current analytical techniques. Profiles to about 9 km are easily made from small aircraft, measurements to 12-13 km are possible from jets. However, measurements above 13 km are logistically difficult. Fortunately, many studies have shown that CO levels are greatest in the troposphere and decline rapidly in the lower stratosphere. Total column amounts of CO and CH_4 determined from spectroscopic methods provide a useful comparison to space-based measurements. We require an accuracy in column CO better than 10%, and that for methane of 1%. These can probably be achieved with current techniques.

The data needed for MOPITT validation will be acquired, in part, through collaboration with several ongoing projects. Some of these make the necessary measurements on a regular basis, others will need to be expanded to meet the data requirements of the validation. Cloud detection lidars and cloud imaging radiometers may be used for cloud measurements to validate the MOPITT detection algorithm. Airborne and surface measurements are needed for the surface reflectivity measurements. DOE/ARM sites can provide most of the required measurements, except CO and CH_4 profiles, for which aircraft overflights are needed. DOE/ARM sites will be used for MOPITT algorithm and products validation. Co-located aircraft measurements will provide the necessary data for MOPITT level 2 products validation.

Many of the correlative aircraft flights will be conducted in collaboration with established research programs at NASA, NOAA, and various universities. Airborne in-situ CO sensors, such as non-dispersive infrared (NDIR) device and tunable diode laser system (TDLS) can provide detailed information on the vertical distribution of CO and CH_4, respectively, but they can be costly to acquire and operate, especially the TDLS. An alternative method for determining the main features of the vertical profiles of CO and CH_4 (plus CO_2, N_2O and other species) is the automated flask sampling system used by NOAA/CMDL. This method uses automated sampling instrumentation to collect samples of air at predetermined altitudes, along with the required time, sampling and position information. All samples are measured at a central laboratory, thus ensuring internal consistency. This system is relatively inexpensive and can be easily operated at many sites. For total column CO and CH_4 measurements, ground-based high resolution FTIR measurements can be used. These spectroscopic measurements are made at several locations around the world (such as the NDSC sites listed in Appendix C). However, the CO and CH_4 column amounts are not routinely determined from the spectra, and for comparison to the MOPITT results, the CO and CH_4 column need to be derived from FTIR spectra with specially developed retrieval algorithm and adjusted with the MOPITT averaging kernel.

In summary, for long term MOPITT level 2 data products validation, the NOAA/CMDL CO program and her collaborator sites, with enhanced CO and CH_4 profiling capability using automated flask system and small airplanes, will be used to determine vertical CO and CH_4 profiles at several carefully selected locations to fulfill tropospheric CO profile validation requirements. Spectra obtained at NDSC and DOE/ARM sites will be used for the validation of MOPITT CO and CH_4 column amounts.

3.2 Aircraft in-situ Measurements of CO and CH_4

Vertical profiles of CO, CH_4 and other trace gases (CO_2, N_2O, H_2 and HF6) at five carefully selected sites in the existing National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL) cooperative air sampling network will be measured using airborne in-situ technique. Locations of the five sites and reasons for choosing each of the site are listed in table 2. The profile measurement will be conducted every two weeks. The exact time of the measurement at each of those five sites will be determined based on MOPITT overpass prediction. Automated flask system mounted on small aircraft will be used to collect and store air samples, and those samples will be brought back to NOAA/CMDL for analysis using gas chromatographs (GCs) and a non-dispersive infrared instrument (NDIR). All measurements are referenced to the internationally recognized calibration scales as shown in table 3. The data resulting from the analysis are internally consistent and thus directly comparable. CO and CH_4 profiles will be available for intercomparison with MOPITT measurement within 2-4 weeks after the sampling. Turbocharged propeller aircraft will be chartered to attain sampling altitudes of approximately 30,000 ft (9.1 km), with sample resolution of at least 500 m. The flask system has been tested extensively with regard to sample stability at NOAA/CMDL. Similar flasks have been used in the NOAA/CMDL cooperative air sampling network for many years. The aircraft sampling system has been successfully flown over Carr, Colorado since 1992.

The CO and CH_4 profiles measurement at the five sites will be used as long-term anchor validation sites for MOPITT data validation, particularly the MOPITT level 2 data products. Dr. Paul Novelli from NOAA/CMDL is the principal investigator, with Drs. E. J. Dlugokencky, P. P. Tans and D. Guenther as Co-investigators, of this effort. The in-situ CO and CH_4 profiles will be averaged by the MOPITT weighting functions (averaging kernels) to produce the equivalent

Table 2. Long-term CO and CH_4 aircraft in-situ profiling sites for

MOPITT validation.

Sites	Location (Lat./Long.)	Environment & Reasons	Measurement Frequency
Harvard Forest, Massachusetts	42.54 N/72.18 W	Continental polluted Forest region	Once per two weeks
Barrow, Alaska	71.32 N/156.6 W	High northern latitude Pollution from Europe	Once per two weeks
Carr, Colorado	40.15 N/104.13 W	Continental, northern plains	Once per two weeks
Mauna Loa, Hawaii	19.53 N/155.58 W	Oceanic, northern central Pacific	Once per two weeks
American Samoa	14.57 S/170.57 W	Oceanic, southern eastern Pacific	Once per two weeks

Table 3. Trace gas analysis methods and precision.

Gas Species	Method	Reference Scale	Precision (%)	Reference
CO	GC + HgO	CMDL/WMO	0.5 -1.5	Novelli *et al*, 1992
CH_4	GC + FID	CMDL	0.1	Dlugokencky *et al*., 1994
CO_2	NDIR	WMO	0.01	Conway *et al*., 1994
N_2O	GC + ECD	CMDL	0.2	Geller *et al*., 1996
SF_6	GC + ECD	CMDL	1	Geller et al., 1996

average CO mixing ratios of five tropospheric layers (1000-700mb, 700-500mb, 500-400mb, 400-300mb, 300-200mb), CO total column and CH_4 total column reported by the MOPITT level 1-2 algorithm for intercomparison.

In addition to the long-term CO and CH_4 profiles measurement at the five anchor validation sites, CO and CH_4 profiles will also be measured during validation campaigns. Specific validation campaigns over biomass burning regions in Africa, South America and Southeast Asia are of particular interest. As an example of such campaigns, a 2-week intensive period of flights during the biomass burning period (July - September) and the CO minimum time (February - April) of 1999 in Africa will be conducted. Four to six flights up to 12-15 km with a Learjet will be conducted during each of the intensive periods. At this time one of the two core sites, Kruger National Park and Mongu, Zambia, appears to be a likely location for the Learjet CO and CH_4 profiling. Mongu may be a preferred location because biomass burning signal during the burning season is expected to be more consistent. The principle investigators of the aircraft CO and CH_4 profiling in Africa are Drs. Anne Thompson and Jeffery Privette from NASA Goddard Space Flight Center (GSFC) with funding provided by the NASA EOS Validation Program. A summary of CO and CH_4 profiling in 1999 Africa campaigns is shown in table 4. Those measurements will be very useful for both the validation of MOPITT measurements over biomass burning regions and scientific investigations on the roles of biomass burning in CO budget and tropospheric O_3 chemistry.

Table 4. CO and CH_4 Aircraft In-Situ Profiling in Africa.

Campaign Period	Campaign Location	Measurement	Precision
July - Sept., 1999 (2 weeks)	Kruger National Park, or Mongu, Zambia	CO CH_4	~ 1% ~ 0.1%
Feb. - April, 1999 (2 weeks)	Kruger National Park, or Mongu, Zambia	CO CH_4	~ 1% ~ 0.1%

3.3 Aircraft Remote Sensing Measurement of CO and CH_4

Aircraft remote sensing measurements will be mainly consisted of measurements by MATR (Smith and Shertz, 1997), MOPITT-A and airborne high resolution interferometers, such as the High resolution Interferometer Sounder (HIS) and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Aircraft Sounder Testbed -Interferometer (NAST-I). MATR will participate in approximately two MOPITT validation campaigns per year during the first 2-3 years of MOPITT operation. Details of the projected MATR flight schedules can be found at the EOS Validation WWW site (http://eospso.gsfc.nasa.gov/validation/valpage.html). MOPITT-A is still being developed at the University of Toronto with funding from the Canadian Space Agency (CSA). Details of the planned MOPITT-A flight schedules can also be found at the EOS Validation WWW site. McMillan *et al*. showed that free troposphere CO column can be derived from HIS measurement with a accuracy of about 10%. It is expected that both HIS and NAST-I will be flown on ER-2 many times as part of validation campaigns or science investigations supported primarily by other programs during MOPITT operation, and those data will be used for MOPITT level 2 data validation. An investigation by Drs. W. Wallace McMillan, L. Strow, G. Morris, W. L. Smith, A. M. Thompson, and J. Wang was selected by the NASA EOS Validation AO to use CO derived from observations by ground-based, airborne, and satellite-borne interferometers for MOPITT validation.

Table 5. Ground-based Spectroscopic Measurement sites for MOPITT Data Validation

Organization and Station	Location (lat./long.)	Elevation (m)	Instrument	Expected Precision
Atmospheric Environment Service, Eureka, CA	80.05N/86.4W	610	FTIR Bomem DA8	~ 10%
Alfred Wegner Institute for Polar and Marine Research(Germany) Spitsbergen, Norway	78.90N/11.90E	10	FTIR Bruker 120M	~ 10%
Swedish Environmental Research Institute Harestua, Sweden	60.00N/11.00E	560	FTIR Bruker 120M	~ 10%
Institute of Atmospheric Physics, Zvenigorod Russia	55.40N/36.50E	200	Grating spectrometer	~ 10%
Fraunhofer-Institut Fuer Atmosphaersche Umweltforschung, Zugspitze, Germany	47.40N/11.00E	2964	FTIR Bruker 120HR	~ 10%
International Scientific Station, Jungfraujoch, Switzerland	47.00N/8.00E	3580	FTIR	~ 10%
University of Nagoya, Moshiri, Japan	44.36N/142.3W	20	FTIR Bruker 120HR	~ 10%
Atmospheric Environment Service, Egbert, Canada	44.20N/79.80W	251	FTIR Bomem DA8	~ 10%
University of Nagoya Rikubetsu, Japan	43.50N/143.8E	215	FTIR Bruker 120M	~ 10%
Institute of Atmospheric Physics, Kislovodsk, Russia	43.50N/42.40E	2100	Grating Spectrometer	~10 %
National Solar Observatory Kitt Peak, USA	32.00N/111.5W	2090	FTIR	~ 10%
National Institute of Water				

and Atmosphere (NIWA), Lauder, New Zealand	45.00 S/169.8E	370	FTIR	~ 10%
University of Denver & NIWA, Arrival Heights, Antarctica	78.00S/167.0E	180	FTIR Bruker 120M	~ 10%
University of Wollongong Wollongong, Australia	34.00S/151.0E	35	FTIR Bomem DA8	~ 10%
University of Denver Mauna Loa, Hawaii	37.00N/98.00W	3100	FTIR Bruker 120HR	~ 10%
DOE/ARM SGP Site Lamont, Oklahoma	36.80N/97.50W	318	FTIR Bruker 120M	~ 10%
DOE ARM TWP Site	2.06S/147.4W	6	FTIR Bruker 120M	~ 10%
University of Alaska Fairbanks, Alaska	64.83N/147.7W	150	FTIR Bruker 120M	~ 10%

3.4 Ground-based Spectroscopic Measurement

In addition to airborne in-situ and remote sensing measurements, CO and CH_4 columns, and possibly tropospheric CO profiles, derived from ground-based solar absorption and atmosphere thermal emission measurements using interferometers and spectrometers will be the second component of the MOPITT validation correlative measurement. It has been shown that total atmosphere CO column can be derived from ground based solar absorption measurements using Fourier transform interferometers and grating spectrometers with a precision of 10% or better (Pougatchev and Rinsland, 1995; Yurganov *et al.*, 1997). Recently, it has been shown that it is also possible to derive tropospheric CO profile information from solar absorption measurement using high resolution Fourier transform interferometers (Zhao *et al.*, 1997). As demonstrated in the MAPS experiment, measurements by ground-based spectroscopic techniques are useful for tropospheric CO remote sensing from space (Reichle *et al.*, 1997).

Three investigations proposed by Pougatchev *et al*., Murcray *et al*. and Yurganov *et al.* have been selected by the NASA EOS Validation AO to provide ground-based spectroscopic measurements for MOPITT CO and CH_4 validation. The locations of the measurement sites are listed in table 5. Most of those sites are part of the Network for Detection of Stratospheric Change (NDSC). In the selection of sites, we tried to use as much as possible existing ground stations and facilities to reduce cost. Frequency of measurements for MOPITT validation at those sites will vary from station to station. There will be two types of measurement activities:

(1) routine NDSC measurements (daily or weekly); (2) intensive validation campaigns (2-3 times per year) with daily measurements. The exact time of measurement at a particular station will depend on the MOPITT overpass time prediction.

4.0 Pre-Launch Algorithm Development and Validation

4.1 Forward Model Development and Test

MOPITT forward model and instrument sensitivity studies have been discussed in detail in MOPITT level 1-2 ATBD. Therefore, only a brief summary of some aspects of the radiative transfer model and instrument model that are important to data validation is included here.

The MOPITT instrument will make measurements in three spectral regions. Thermal channels at 4.7 μm will be used to obtain profile information about the tropospheric CO distribution. Short-wave solar channels at 2.2 and 2.3 μm will be used for CO and CH_4 total column retrieval, respectively. As discussed in section 1.0, each channel will generate a difference signal and an average signal, resulting in 16 signals from eight-channels of MOPITT.

4.1.1 Radiative Transfer Model

For the MOPITT spectral regions of interest, the average and difference signals for the thermal channels are given by,

$$S_a = G_a \int_{-\infty}^{+\infty} \left\{ I_s(\nu) + \int_0^{\infty} \left[B(\nu, T(z)) - I_s(\nu) \right] \frac{d\tau(\nu, z, \infty)}{dz} dz \right\} \tau_f(\nu) \left[\frac{\tau(p_l) + \tau(p_h)}{2} \right] d\nu \qquad (4.1)$$

$$S_d = G_d \int_{-\infty}^{+\infty} \left\{ I_s(\nu) + \int_0^{\infty} \left[B(\nu, T(z)) - I_s(\nu) \right] \frac{d\tau(\nu, z, \infty)}{dz} dz \right\} \tau_f(\nu) \left[\tau(p_l) - \tau(p_h) \right] d\nu \qquad (4.2)$$

where $I_s(\nu)$ is the monochromatic radiance at the surface [W/(m^2.sr.cm^{-1})]; $\tau(\nu, z, \infty)$ is the monochromatic atmospheric transmittance from z to satellite (top of the atmosphere); $B(\nu, T(z))$ is the Planck function [W/(m^2.sr.cm^{-1})]; G_a is the gain for the average signal; G_d is the gain for the difference signal; $\tau_f(\nu)$ is the transmission of the instrument; $\tau(p_l)$ is the CO cell transmittance at low pressure; $\tau(p_h)$ is the CO cell transmittance at high pressure; S_a is the channel average signal; and S_d is the channel difference signal. Similarly, the average and difference signals for the CO solar channels are given by,

$$S_a = G_a^{\Theta} \int_{-\infty}^{+\infty} r(\nu) I_{\Theta}(\nu) \exp\left[-\int_0^{\infty} k(z)\rho_{co}(z)(\sec\theta_{sat} + \sec\theta_{sun})dz \right] \tau_f(\nu) \left[\frac{\tau(p_l) + \tau(p_h)}{2} \right] d\nu \tag{4.3}$$

$$S_d = G_d^{\Theta} \int_{-\infty}^{+\infty} r(\nu) I_{\Theta}(\nu) \exp\left[-\int_0^{\infty} k(z)\rho_{co}(z)(\sec\theta_{sat} + \sec\theta_{sun})dz \right] \tau_f(\nu) \left[\tau(p_l) - \tau(p_h) \right] d\nu \tag{4.4}$$

Where G_a^{Θ} is the gain for the solar channel average signal; G_d^{Θ} is the gain for the solar channel difference signal; r(ν) is surface reflectivity; $I_{\Theta}(\nu)$ is the solar spectrum at the top of the atmosphere; $\rho_{CO}(z)$ is the total CO column from altitude z to the top of the atmosphere; k(z) is the absorption coefficient; θ_{sat} is the satellite zenith angle; θ_{sun} is the solar zenith angle; τ_f (ν) is the transmission of the instrument; $\tau(p_l)$ is the CO cell transmittance at low pressure; $\tau(p_h)$ is the CO cell transmittance at high pressure. The CH_4 solar channel average and difference signals are calculated in the same way.

Full line-by-line calculations of atmospheric transmittance and radiance are most accurate, but they are too slow to be of practical use in forming the forward model of an operational retrieval scheme or a prototype algorithm that is to be run for a large number of cases. It is, therefore, necessary to have a fast transmittance algorithm. This must be capable of reproducing channel transmittances and their dependence on the important variables of temperature and contaminating gas amount, particularly H_2O in the case of MOPITT, and the observing geometry. Given an analytical form of the fast model, full line-by-line calculations can be performed once using GENLN2 to create a data base of transmittance coefficients with dependencies on the variable parameters. The MOPITT fast transmittance model (MOPfas) was developed using the method of McMillin and Fleming (1976; Fleming and McMillin, 1977; McMillin *et al*., 1979; Susskind *et al*., 1983, McMillin *et al.*, 1995). Preliminary test indicates that MOPfas can reproduce simulated MOPITT signals with an accuracy of about 0.5% compared to full line-by-line calculations with a speed 10^5 faster than GENLN2.

4.1.2 Spectroscopic Database

Spectral line parameters currently used in MOPITT radiative transfer calculations are from the 1996 edition of the HITRAN database (Rothman, *et al*., 1996). For CO, the accuracy for the transition wavenumbers and the line strengths are considered to be better than 10^{-4} cm^{-1} and 2-5% respectively. For CH_4, new laboratory results are included for the lines of interest in the 2.3 μm spectral region. The line positions are known to better than 10^{-3} cm^{-1}, and the strengths to within 5-10%. However, only average values are available for the line width parameters. As discussed in a recent paper by Brown *et al*. (1995), many weak lines in the 2.3 μm band of CH_4 are missing from the 1996 HITRAN database, and insufficient studies have been done about the effects of CH_4 line mixing. Currently there are several efforts devoted to the improvement of the CH_4 spectroscopic database for atmospheric remote sensing applications.

4.1.3 Atmospheric Model

The plane-parallel approximation is used in the MOPITT atmospheric model. The Curtis-Godson approximation is used in generating layer quantities for input to the radiative transfer model. The atmosphere is divided into 100 layers from the surface to 100 km.

4.1.4 Solar Irradiance Data

Solar spectra at the top of the atmosphere in the 2.2 and 2.3 μm region are needed for the short-wave channels of MOPITT, and solar CO lines need to be included. Our current plan is to use the solar irradiance data derived from ATMOS measurements (Abrams *et. al*., 1996) for the calculations of MOPITT solar channel signals as done by Tolton (*private communication*, 1996).

4.1.5 Forward Model Test and Validation

An accurate and efficient forward model is essential for the level 1-2 processing of MOPITT data. Test and validation of the forward model will be consisted of the following activities:

(1). We will compare the calculations by MOPfas and line-by-line (LBL) radiative transfer models, such as GENLN2 and FASCOD3, for a variety of atmospheric conditions, including extremes of possible atmospheric CO, H_2O, and temperature profiles. Real atmospheric profiles from radiosonde and aircraft measurements will be used in this comparison. Potential data sources include: a) CO profile measurements during the Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE-A) experiment, the Amazon, Arctic, Atmospheric Boundary Layer Experiment in North Canada (ABLE-3B), atmospheric CO profiles taken by NOAA/CMDL at Carr, Colorado from 1992 to 1996, and atmospheric CO profiles taken at Cape Grim by CSRIO of Australia; b) the TOVS Initial Guess Retrieval (TIGR) atmospheric temperature, H_2O and O_3 data set (Monie *et al*., 1987); c) data sets provided by Revercomb and Knuteson at the University of Wisconsin for the ITRA (Chedin, *et al*., 1988) and SPECTRE (Ellingson, *et al., 1992*) experiments.

(2). MATR and MOPITT-A (if operational before MOPITT launch in June 1998) will be flown as many times as possible before MOPITT launch to obtain data for both forward model and retrieval algorithm verification. The first flight of MATR, the engineering flight, took place in June 1996, and the first science flight took place in 1997. The measured radiances will be compared with forward calculated radiances to verify our understanding MOPITT instrument operation and the instrument model. MATR will also participate in the Pre-launch MOPITT Validation Exercise (Pre-MOVE) at the Department of Energy Atmospheric Radiation Measurement (DOE/ARM) site at Oklahoma from March 2 to March 7, 1998. Details of Pre-MOVE will be discussed later. MATR data from Pre-MOVE will be used to test MOPITT forward model and our understanding of MOPITT instrument operations.

(3). Between flights, MATR and a ground-based correlation radiometer from University of Toronto (Tolton, *private communication, 1995*) will be used for ground-based measurements, such as solar absorption in the 2.2 μm band of CO and 2.3 μm band of CH_4. Those measurements will also be compared with forward model calculations using line-by-line techniques.

4.2 MOPITT Retrieval Algorithm Development and Validation

4.2.1 Retrieval Algorithm

The theoretical basis and algorithm for the retrieval of CO profiles and column amounts of CO and CH_4 have been described in detail in the MOPITT level 1-2 ATBD. Therefore, only a brief summary of certain aspects of the retrieval algorithm is included here.

The MOPITT retrieval algorithm is based on the maximum likelihood inversion method (Rodgers, 1976). The retrieval algorithm uses a "damped" form of the classical Newton iteration procedure for the non-linear inversion of the simulated radiance “observed” by MOPITT. At each iteration, the retrieval algorithm minimizes a cost function between the actual and calculated radiances, Y^m and Y(x), with a measure of the distance between the solution profile and a supplied "background" or first guess profile X_0,

$$J(x) = (Y^m - Y(x))^t S_\varepsilon^{-1}(Y^m - Y(x)) + (X - X_0)^t S_x^{-1}(X - X_0). \qquad (4.5)$$

The solution is updated from X_n to X_{n+1} by the following equation,

$$X_{n+1} = X_0 + S_x K_n^T (K_n S_X K_n^T + S_\varepsilon)^{-1}[Y - Y_n - K_n(X_0 - X_n)], \qquad (4.6)$$

where X_0 is the first guess vector of the CO profiles, Y is the vector of "measured" or ""true" signals (e.g. radiance), Y_n is the calculated signal in the iteration process ($Y_n=F(X_n)$), $K_n=\partial F/\partial X$ is the Frechet derivative. S_x is the covariance matrix of the *a priori* information, and S_ε is the covariance matrix of the measurement. The iteration process is stopped when the convergence criteria are met, such as $X_{n+1}-X_n$ is acceptably small. At this point, the profile X will be substituted back into the MOPITT forward model, and the differences $Y^m-Y(x)$ should be of the order of measurement error in all channels. If this is not the case, it suggests a problem with either the measurements or the forward model, such as gross errors in the radiances or the presence of more complex atmospheric conditions than the forward model allows for. This offers a natural and powerful mechanism for quality control. In principle, large errors in the background profile could also have the same effect, leading to the rejection of good measurements by the retrieval/analysis system (Eyer, 1989). More detailed description of the MOPITT retrieval algorithm and retrieval simulations can be found in the MOPITT Level 1-2 ATBD.

4.2.2 Retrieval Algorithm Validation Activities

MOPITT retrieval algorithm and computer codes test and verification activities include:

(1). Prior CO measurements by other missions, such as MAPS (Reichle *et al.*, 1986, 1990; Connors, 1994), TRACE-A, ABLE-3, atmospheric CO profiles taken by NOAA/CMDL at Carr, Colorado from 1992 to 1996, and atmospheric CO and CH_4 profiles taken at Cape Grim by CSRIO of Australia are being used to put together a representative CO profile covariance. The covariance will be continuously updated as new measurements become available.

(2). Conduct retrieval experiments using simulated MOPITT measurements to test robustness of the retrieval code.

(3). Conduct algorithm test and validation using MATR, MOPITT-A and correlative measurements. The retrieved CO and CH_4 profiles and columns will be compared with correlative measurements collected during MATR flights.

4.2.3 MOPITT Cloud Clearing Algorithm Development and Validation

The MOPITT cloud clearing approaches and algorithm are described in the MOPITT level 1-2 ATBD. The cloud identification and clearing algorithm are based on understanding the MOPITT instrument response to changes in atmospheric attenuation due to the presence of clouds. By combining satellite, aircraft and ground based measurements along with model simulations, we plan to carry out the following: (1) Identify those scenes in the MOPITT field-of-view (FOV) which are completely clear; (2) Determine the limits and accuracy to which “cloud cleared” radiance can be obtained. Our approaches for the MOPITT cloud clearing algorithm validation and data sources are summarized below:

(1) EOS Pathfinder data set will be used as input for model studies on surface and atmospheric conditions. The HIRS FOV of 20kmx20km is close to the MOPITT FOV of 22kmx22km and can provide information on a scale MOPITT will encounter. The HIRS PATH-B data set provides retrieved quantities of surface temperature, atmospheric profiles of temperature and water vapor and cloud fraction which can be used as input to MOPITT simulations. AVHRR and TM (Thematic Mapper) data sets will be scaled to the MOPITT FOV and used to study the impact of surface emissivity and cloud scales on cloud detection and clearing algorithms..

(2) MAS data from the NASA Langley DAAC and Goddard Space Flight Center can be used to further develop the MOPITT cloud algorithm. Radiance from MAS channel 6 (2.139μm) and channel 8 (4.695μm) along with supporting ground and satellite measurements from the field experiments during FIRE(10/91), ASTEX(6/92) and TOGA/COARE(1/93) will provide information on the effects of different cloud types (ice/water) on the MAS channels close to MOPITT wavelengths. Also the impact of surface conditions, humidity, and semi-transparent clouds can be modeled from this data set and used to refine the cloud detection and clearing algorithms.

(3) Data from MATR flights will be used to quantify how well cloud signals can be distinguished from variations in surface topography, retrieved accuracy of cloud filtering and establish limits for cloud cleared retrievals.

4.3 MOPITT Retrieval Algorithm End-to-End Test Using Exiting Satellite Data

After extensive self-consistency test of the MOPITT forward model and retrieval algorithm, it is important to apply the algorithm to real satellite data. Since there is no satellite data that can be used directly for MOPITT algorithm validation, we have developed a new digital gas correlation (DGC) technique which generates MOPITT-like signals from high resolution spaceborne Fourier transform interferometer observations. The MOPITT-like signals are then used as inputs to the MOPITT level 2 algorithm to retrieve tropospheric CO profiles. The DGC method is based on the application of the gas correlation radiometry principle to the analysis of interferometer observations. High resolution interferometer observations will be pre-processed to generate MOPITT equivalent average and difference signals, then the MOPITT retrieval algorithm is applied to retrieve tropospheric CO. Despite the loss of the Advanced Earth Observing Satellite (ADEOS) in July 1997, the Interferometric Monitor for Greenhouse Gases (IMG), launched on the Japanese Advanced Earth Observing Satellite (ADEOS) in August of 1996, has provided about 9 months of valuable data in the 4.7 μm band of CO with high spectral resolution (Ogawa *et al*., 1994). One of the major pre-launch MOPITT validation activities is to validate the MOPITT algorithm using IMG data and the DGC method. A brief description of IMG data characteristics and the DGC method is given here. More details can be found in Wang *et al.* (1997).

Table 6. IMG Instrument characteristics (Ogawa et al., 1994).

Spectral range	714 - 3030 cm^{-1} (3.3 - 14 μm)
Spectral bands	3
Band 1	2325-3030 cm^{-1} (3.3 - 4.3 μm)
Band 2	2000-2500 cm^{-1} (4.0 - 5.0 μm)
Band 3	714 - 2000 cm^{-1} (5.0 -14.0 μm)
Spectral points	
Number	
Band1	$1.6x10^5$
Band 2 & 3	$1.0x10^5$
Spacing	
Band 1	0.0301326 cm^{-1}
Band 2 & 3	0.0401771 cm^{-1}
Spectral resolution	
Maximum OPD(1)	10 cm
Resolution	0.05 cm^{-1}
Field-of-View (FOV)	8 km x 8 km

(1) OPD = optical path difference

4.3.1 IMG Instrument and Data Characteristics

IMG uses Fourier transform spectrometry to measure the top of the atmosphere spectral radiance between 3.3 μm and 14 μm in 3 separate bands (Ogawa *et al*. 1994). It is on board the Japanese ADEOS satellite launched in August, 1996. Atmospheric temperature and various atmospheric trace gases including H_2O, CH_4, N_2O, CO and O_3 can be retrieved. Up to now, about 6 months of data has been collected by IMG. By applying the DGC method and MOPITT retrieval system to IMG observations, the MOPITT retrieval algorithm can be tested with real

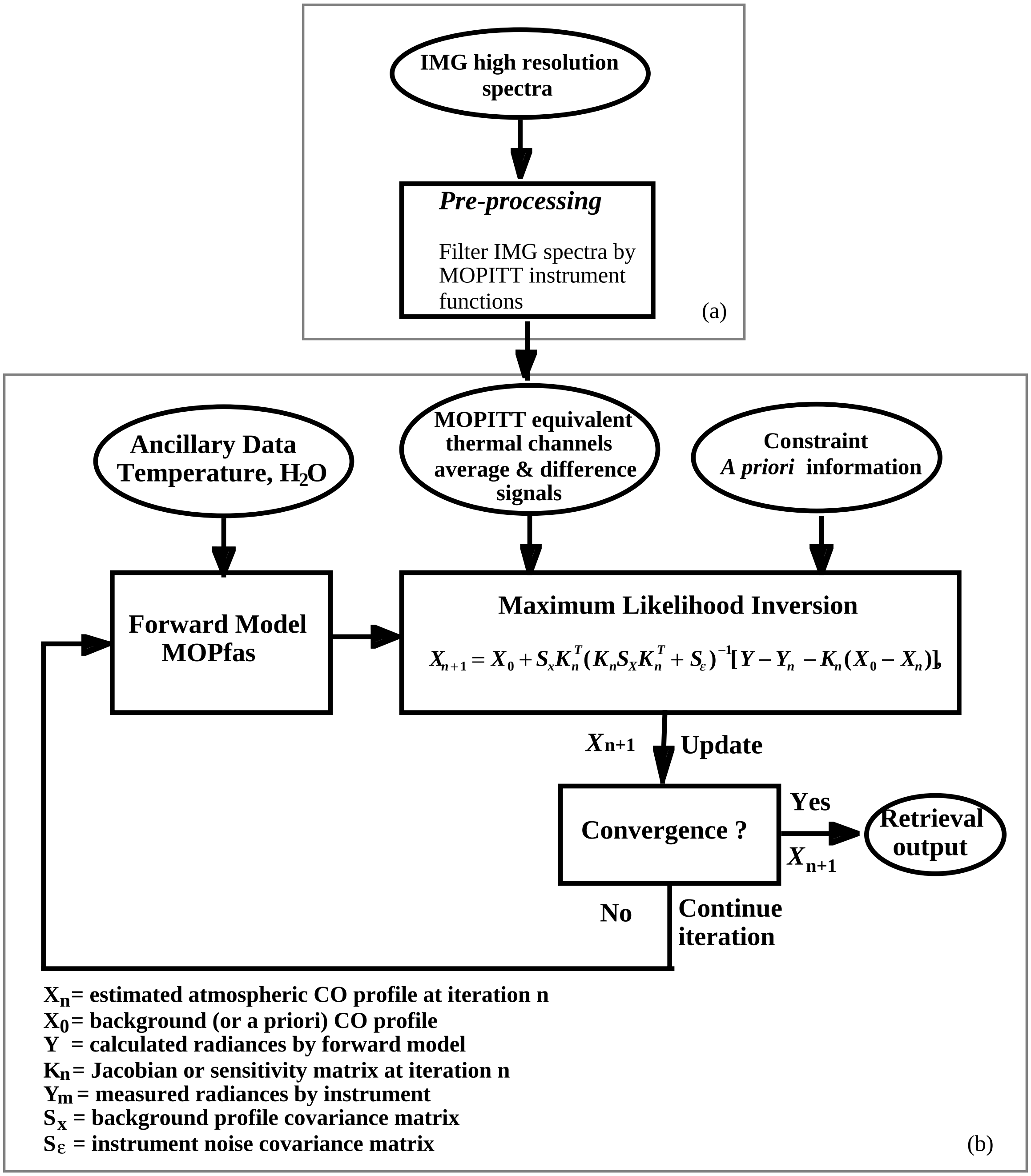

Figure 3. Flow diagram of CO retrieval from IMG observations using the DGC method: (a) pre-processing of IMG spectra to generate MOPITT equivalent thermal channel average and difference signals; (b) the standard MOPITT CO retrieval system.

data before MOPITT launch, and global CO distributions can be retrieved with a new independent algorithm. A summary of IMG instrument characteristics is listed in table 6. For tropospheric CO retrieval using the 4.7 μm band, IMG band 2 will be used. In band 2, an unapodized spectral resolution of 0.05 cm^{-1} and sampling interval of 0.0401771 cm^{-1} are achieved (Hidemichi Saji, *private communication*, 1997).

4.3.2 Validation of MOPITT Retrieval Algorithm with IMG Observations

The flow diagram for the retrieval of tropospheric CO profiles from IMG band 2 observations using the MOPITT CO retrieval system is shown in figure 3. The only extra step compared with the standard MOPITT CO retrieval system is the pre-processing of IMG band 2 spectral radiances. In the pre-processing step, the IMG band 2 spectra are filtered with MOPITT thermal channel instrument function to generate MOPITT equivalent 4 average and 4 difference signals.

We have requested and received IMG observations over Carr, Colorado. The retrieved CO profiles from IMG observations with the DGC method and MOPITT algorithm will be compared aircraft CO profiles by NOAA/CMDL. As mentioned before, CO profile measurement has been conducted bi-weekly at Carr, Colorado by NOAA/CMDL since 1992.

4.4 Pre-launch MOPITT Validation Exercise (Pre-MOVE)

It is important to have confidence in the correlative data and associated data processing algorithms before they can be used to validate the MOPITT data products. It is also useful to test the intercomparison techniques which are to be used in post-launch MOPITT data validation. The Pre-launch MOPITT Validation Exercise (Pre-MOVE) is a validation campaign at the Southern Great Plain (SGP) Cloud and Radiation Testbed (CART) of the Department of Energy Atmospheric Radiation Measurement (DOE/ARM) program in Lamont, Oklahoma from March 2 to March 6 of 1998. The reasons for conducting Pre-MOVE at the CART site include: (1) it is a heavily instrumented site resulting in good characterization of surface and the atmosphere column; (2) We can make use of CART high resolution solar absorption interferometer (SORTI & ASTI), thermal emission interferometer (AERI), lidars, and radiosonde data. This saves us from deploying similar instruments ourselves for Pre-MOVE; (3) There is excellent logistic support.

4.4.1 Goals of Pre-MOVE

The primary goals of Pre-MOVE include:

(1) Test of the MOPITT Airborne Test Radiometer (MATR) and associated data processing algorithm by comparing the retrieved CO profiles from MATR observations with aircraft in-situ CO profile measurement by the NOAA/CMDL flask system.

(2) Validation of retrieval algorithm, which derives column CO from ground-based thermal emission interferometer (AERI) measurement, to be used by McMillan *et al*. for post-launch MOPITT data validation. The retrieved CO column will be compared with that derived from aircraft in-situ CO profile measurement by the NOAA/CMDL flask system and other techniques.
(3) Validation of the retrieval algorithm, which derives column CO and possibly tropospheric CO profile from ground-based solar absorption interferometer (SORTI and ASTI) measurement to be used by Pougatchev *et al*. for MOPITT validation. The retrieved CO column will be compared with that derived from aircraft in-situ CO profile measurement by the NOAA/CMDL flask system and other techniques.
(4) Validation of the retrieval algorithm, which derives column CO and possibly tropospheric CO profile from ground-based solar absorption interferometer (SORTI and ASTI) measurement, to be used by Murcray *et al*. for MOPITT validation. The retrieved CO column will be compared with that derived from aircraft in-situ CO profile measurement by the NOAA/CMDL flask system and other techniques. Two independent algorithms, one by Murcray *et al*. and one by Pougatchev *et al*., will be used and compared in the retrieval of columns of CO and CH_4 and possibly CO profiles from high resolution solar absorption measurements by Fourier transform interferometers. This will give us more confidence in the use of the large number of observations by Fourier transform interferometers around the world. The involvement of both groups give us the desired global coverage by ground-based Fourier transform interferometers and grating spectrometers.
(5) Validation of the retrieval algorithm, which derives total CO column from ground-based grating spectrometer measurement, to be used by Yurganov and Tolton for MOPITT data validation. Similar grating spectrometers have been used in Russia, China, and possibly other countries for many years to monitor total CO column. The validation of those kind of measurements as part of the Pre-MOVE will give us confidence to use similar measurements in Russia and China for MOPITT data validation.
(6) Intercomparison of all the instruments and techniques to be used in post-launch MOPITT data validation. It is expected that those intercomparisons will lead to the refinement of all the associated data processing algorithms and intercomparison protocols.

4.4.2 Instruments and Measurement Schedules

All instruments or instrument types to be used for post-launch MOPITT data validation will be part of the Pre-MOVE from March 2 to March 6, 1998 at the CART site. Each instrument and its measurement schedule are described below:
(1) MOPITT Airborne Test Radiometer (MATR) from NCAR. MATR will be fitted onto the Citation aircraft from Department of Energy Remote Sensing Laboratory in Las Vegas. The plan

is to fly Citation every day between March 2 and March 6, 1998 over the CART site for about 2 hours when the sky is clear. The Citation will be stationed at the Jefferson county airport. During clear days at CART site, the Citation will fly from the Jefferson county airport to the CART site, and then circles the CART site for about 2 hours at a constant altitude of 41,000 to 43,000 ft. After taking data for about 2 hours over the CART site, Citation will fly back to the Jefferson county airport the same day. The decision to fly or not will depend on the previous day's weather forecast.

(2) Automated flask sampling system from NOAA/CMDL. The NOAA/CMDL automated flask system will be carried by a chartered small aircraft (e.g. Cessna) in the vicinity of the CART site. The basic flight profile for the chartered small aircraft is to ascend from ground to about 30,000 ft, then descend from 30,000 ft to ground and take a set of air samples at a interval of approximately 0.5 km. The samples will be sent to the NOAA/CMDL laboratory for analysis. Therefore, one profile will be obtained for each up and down flight. Because of the availability of flasks, two profiles will be taken on March 2; one profile will be taken on March 4; and two profiles will be taken on March 6. Off course, there may be changes to this plan depending on the weather conditions at the CART site. Flights can be conducted under most weather conditions except snow, heavy fog and strong winds.

(3) University of Toronto ground-based grating spectrometer. The grating spectrometer will be shipped from University of Toronto to the CART site on February 26, 1998. Data acquisition will start on March 2 and last until March 6, 1998. Since the grating spectrometer measures the solar absorption, it will be operated only on days with clear or partially clear skies.

(4) ARM ground-based solar absorption Fourier transform interferometer (SORTI and ASTI). Details of SORTI and ASTI at the CART site can be found in papers by Revercomb *et al*. (1993). Based on current CART site operation plan, measurements by SORTI and ASTI are being conducted and archived by the ARM program every day. Those data will be available for analysis by Pre-MOVE participants and other interested researchers.

(5) ARM ground-based thermal emission Fourier transform interferometer (AERI). Details of AERI at the CART site can be found in papers by Revercomb *et al*. (1993; 1995). Based on current CART site operation plan, measurements by AERI are being conducted and archived by the ARM program every day. Those data will be available for analysis by Pre-MOVE participants and other interested researchers.

(6) Meteorological data by radiosondes. Based on the current CART operation plan, radiosondes launches are conducted three times a day at 7:00 AM, 12:00 noon and 6:00 PM local time. Because most of the Pre-MOVE measurements will be conducted around 10:00 AM local time. One extra radiosonde launch will be performed each day from March 2 to March 6, 1998 to support Pre-MOVE.

5.0 Post-Launch Data Validation Activities

After the EOS-AM1 reaches the planned orbit, a sequence of tests will be carried out in the instrument Safe Mode. All instrument operation parameters including major optical components temperatures, correlation cells temperatures and pressures, detector temperatures, voltages, currents, etc. will be monitored and compared to predictions to ensure the instrument is functioning properly from an 'engineering' point-of-view. Initial instrument performance will be evaluated based on the system noise in each channels, instrument drift characteristics, maximum/minimum signal levels, overall system gains, etc. After initial verifications, the instrument will be switched to the Science Mode for data collection. Routine instrument performance monitoring will be performed throughout the mission at University of Toronto.
For the definitions of different MOPITT operation modes, the MOPITT Mission Description Document (MDD) should be consulted (Drummond *et al.*, 1996). Major MOPITT post-launch data validation activities are discussed below.

The MOPITT team continues to define field experiments that are essential to the validation of MOPITT data processing algorithm and scientific products. Planned long-term correlative measurements for post-launch MOPITT data validation have been described in section 3.0. In this section, only planned intensive validation campaigns of relatively short time duration will be described.

5.1 Planned MATR Flights for MOPITT Data Validation

The MOPITT Algorithm Test Radiometer (MATR) engineering flight took place in June 1996. It will participate in Pre-MOVE as described in section 4.4. After MOPITT launch, we plan to conduct or participate in validation campaigns about twice per year. Table 5.1 gives more details on planned MATR flights.

5.2 Planned MOPITT-A Flights for MOPITT Data Validation

The MOPITT airborne simulator (MOPITT-A) is currently being developed at the University of Toronto with funding from the Canadian Space Agency (CSA). As discussed before, MOPITT-A is designed for the ER-2 platform, and its main goal is to provide measurement for MOPITT level 1 data validation. Therefore, its design is very similar to the of MOPITT. Many MOPITT engineering model parts are being used in the construction of MOPITT-A. The planned MOPITT-A flights for MOPITT data validation are listed in table 5.2.

Table 5.1 MATR EOS Aircraft Utilization Plan for MOPITT Algorithm

and Level-2 Data Validation

Mission	Dates	Location	Primary Purpose	Primary Sensors
Pre-launch MOPITT Validation Exercise (Pre-MOVE)	March 2-6, 1998	Lamont, Okla. (ARM site)	Validation of correlative instruments and algorithms	MATR; NOAA/CMDL flask suitcase; Interferometers; Spectrometers.
ARM-1 (in conjunction with MODIS validation campaign)	Oct., 1998	Lamont, Okla. (ARM site)	Re-visit ARM site after MOPITT launch in conjunction with MODIS ARM-1	MATR; NOAA/CMDL flask suitcase; Interferometers; Spectrometers.
ARM-2 (in conjunction with MODIS validation campaign)	March, 1999	North Slope of Alaska (ARM site)	Validation at high latitude in winter in conjunction with MODIS ARM-2	MATR; NOAA/CMDL flask suitcase; Interferometers; Spectrometers.
Kalahari Desert (in conjunction with MODIS validation campaign)	Aug.- Sept. 1999	Kalahari Desert	MOPITT validation in biomass burning regions in conjunction with MODIS campaign	MATR; MOPITT-A (?); NOAA/CMDL flask suitcase;
Gulf of Mexico (in conjunction with MODIS validation campaign)	January, 2000	Gulf of Mexico region	Collect vicarious calibration and validation data over ocean.	MATR; MOPITT-A; NOAA/CMDL flask suitcase; MODIS val. instruments.
Ocean/Land	Sept., 2000	TBD	Options of land and/or ocean. Focus will depend on MOPITT needs.	MATR; MOPITT-A (?); NOAA/CMDL flask suitcase.
TBD	Twice in 2001	TBD	Two flights in 2001. Time and locations to de decided.	MATR; MOPITT-A (?); NOAA/CMDL flask suitcase.

Table 5.2 MOPITT-A EOS Aircraft Utilization Plan for MOPITT Level-1 and Level-2 Data Validation

Mission	Dates	Location	Primary Purpose	Primary Sensors
ARM-1 (in conjunction with MODIS validation campaign)	Oct., 1998	Lamont, Okla. (ARM site)	Re-visit ARM site after MOPITT launch in conjunction with MODIS ARM-1	MOPITT-A; MATR; NOAA/CMDL flask suitcase; Interferometers; Spectrometers.
ARM-2 (in conjunction with MODIS validation campaign)	March, 1999	North Slope of Alaska (ARM site)	Validation at high latitude in winter in conjunction with MODIS ARM-2	MOPITT-A; MATR; NOAA/CMDL flask suitcase; Interferometers; Spectrometers.
California-1	June, 1999	Monterey to San Diego	Collect vicarious calibration and validation data over land with clouds and fog.	MOPITT-A; NOAA/CMDL flask suitcase; MODIS validation instruments.
Kalahari Desert (in conjunction with MODIS validation campaign)	Aug.- Sept. 1999	Kalahari Desert	MOPITT validation in biomass burning regions in conjunction with MODIS campaign	MOPITT-A; MATR; NOAA/CMDL flask suitcase; MODIS val. instruments.
Gulf of Mexico (in conjunction with MODIS validation campaign)	January, 2000	Gulf of Mexico region	Collect vicarious calibration and validation data over ocean.	MOPITT-A; MATR; NOAA/CMDL flask suitcase; MODIS val. instruments.
California and Pacific NW (in conjunction with MODIS validation campaign)	Sept., 2000	California & Pacific Northwest	Collect vicarious calibration and validation data over ocean, and burning area in Pacific NW.	MOPITT-A; MATR ; NOAA/CMDL flask suitcase; MODIS val. instruments.
TBD	Twice in 2001	TBD	Collect vicarious calibration and validation data. Time and location TBD.	MOPITT-A; MATR (?); NOAA/CMDL flask suitcase; etc.

5.3 MOPITT Data Validation and Science Studies in Conjunction with GTE PEM-Tropics B Mission

The Pacific Exploratory Mission in the north and south tropical Pacific Ocean basin (PEM-Tropics B) will be conducted as part of NASA's Global Tropospheric Experiment (GTE). It is the second of two planned Pacific Exploratory Missions in the tropical Pacific Ocean basin. In August-October, 1996 the GTE PEM-Tropics A mission utilized both the NASA DC-8 and P-3B aircraft in a coordinated project to study the chemistry of the troposphere over the central and eastern Pacific Ocean with a focus on the tropics. Unexpected high concentrations of CO and O_3 were found at elevated altitudes south of the South Pacific Convergence Zone. Trajectory analysis indicates that these pollutants appear to have originated from biomass burning in Africa and South America (Schultz, 1997). A major objective of PEM-Tropics B is to study the tropical Pacific atmosphere during a season when biomass burning impacts should be significantly less than during the PEM-Tropics A experiment. PEM-Tropics B is scheduled for deployment in the mid-January through April time frame of 1999 and will utilize the DC-8 and P-3B aircraft. More details about the PEM-Tropics B mission can be found in the PEM-Tropics B Research Announcement (NRA-97-MTPE-13).

During the PEM-Tropics B mission, a large number of trace species will be measured by airborne instruments on the DC-8 and P-3B. CO will be measured with a precision of 5 ppbv, and tropospheric O_3 will be measured with a precision of 3 ppbv. Temperature, H_2O, and other important species will also be measured with good precision and resolution. With the scheduled launch of MOPITT in the summer of 1998, those measurements will be very timely and useful for MOPITT data validation. As discussed in section 2.0, MOPITT observations over ocean should be easiest to understand and interpret. We believe the MOPITT CO and CH_4 products over the PEM-Tropics B mission region will be ready for comprehensive intercomparisons with those obtained from airborne in-situ measurements. The collaboration between PEM-Tropics B and MOPITT science team members will provide an unique opportunity to study the tropical Pacific Ocean region with an integrated approach using satellite observations, aircraft observations and models. It is also a perfect opportunity to realize more closer collaboration between EOS validation and NASA's Research and Analysis (R&A) program as suggested by many researchers in both the EOS and the R&A communities. The global observations of tropospheric CO profiles and CH_4 columns will help to place the regional CO measurements by PEM-Tropics B in a global context, and allow improved interpretation of the aircraft measurements. While we expect the atmosphere to be less polluted by biomass burning during the PEM-Tropics B period than the PEM Tropics A period, it will still be important to determine the sources of CO, their locations, and the long distance transport of the products. There have been discussions with PEM-Tropics B program manager, Dr. Robert McNeal, and a number of scientists in the tropospheric chemistry community, who are expected to be part of the PEM-Tropics B mission, on closer collaboration between MOPITT and PEM-Tropics B. Based on preliminary discussion and negotiation, some arrangements may be worked out so that MOPITT science team members will be invited to attend the PEM-Tropics B science team meeting, and vice versa the PEM-Tropics B science team members will also be invited to attend the MOPITT science team meeting. We welcome anybody, who is interested in collaboration between MOPITT and PEM-Tropics B, to contact us and discuss how MOPITT observations can be useful to their investigations.

5.4 MOPITT Data Validation and Science Studies in Conjunction with the CAMEX-3 Mission

The Convection And Moisture EXperiment (CAMEX) is a series of field research investigations to study atmospheric water vapor and precipitation processes using a unique array of aircraft, balloon, and land-based remote sensors. The first two CAMEX field studies were conducted at Wallops Island, Virginia, during 1993 and 1995. The third in the series of CAMEX field studies (CAMEX-3) is planned for August - September, 1998. The main goal of CAMEX-3 is to study hurricane tracking and intensification using NASA-funded aircraft remote sensing instrumentation. In conjunction with CAMEX-3, a number of calibration and validation activities are planned for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Aircraft Sounder Testbed-Interferometer (NAST-I) and retrieval forward models of the Atmospheric InfraRed Sounder (AIRS) project (McMillan, *private communication*, 1998). In support of the calibration and validation activities, a ground-site on Andros Island will be established. The following instruments will be operating at the ground-site: (1) NASA/GSFC Scanning Raman Lidar (SRL); (2) a CIMEL sun photometer for daytime aerosol particle size distribution and total precipitable water measurements; (3) the University of Wisconsin Atmospheric Emitted radiance Interferometer (AERI); (4) radiosondes launches by Wallops Flight Facility and the University of Wisconsin.

We plan to take advantage of CAMEX-3 and the ground-site instruments and conduct an early MOPITT validation exercise by supporting trace gas (CO, CH_4, N_2O, CO_2, HF) measurements with small aircraft carrying the NOAA/CMDL flask system and a ground-based solar absorption Fourier transform interferometer if there is no delay in MOPITT launch. The NAST-I data will also allow us to test the accuracy of CO retrievals from airborne high resolution interferometer measurements. The combination of MOPITT data and CAMEX-3 may also allow us to study the sources and transports of pollutants from the east coast of continental United States.

Since AIRS team also intends to produce the free tropospheric CO column as a research product, there will be other opportunities for joint validation campaigns between MOPITT and AIRS both before and after its scheduled launch in the year 2000.

5.5 Participation in the MODIS-Atmosphere Kalahari Desert Campaign

A post-launch campaign is planned by the MODIS-Atmosphere group to study biomass burning, marine stratus and surface bi-directional reflection distribution function (BRDF) at Kalahari desert in August - September, 1999. Biomass burning is one of the major sources of tropospheric CO, and has significant impact on tropospheric O_3 formation and tropospheric chemistry. We plan to participate in the Kalahari campaign with an instrumented small aircraft carrying the NOAA/CMDL automated flask system to measure the profiles of CO, CH_4 and other trace species. The aircraft in-situ measurements and other ancillary data from the Kalahari campaign will be used to validate the MOPITT CO and CH_4 retrieval in biomass burning regions. We also plan to study the relationship between CO emission and biomass burning area/intensity using measurements from MOPITT, MODIS, aircraft instruments and ground-based instruments.

5.6 Validation of Geometric Registration

The geometric registration requirement is not as high as other instruments on the EOS AM-1 platform. Therefore, no special validation campaigns are planned for MOPITT geometric registration validation. We will try to use facilities and activities planned for other EOS AM-1 instruments as much as possible for MOPITT geometric registration verification. One possible approach to verify MOPITT geolocation is to compare MOPITT derived ocean/land boundaries with actual boundaries at EOS AM-1 geolocation validation sites.

5.7 Cross-Validation with Other Satellite Instruments

Opportunities exist for the intercomparisons of MOPITT CO and CH_4 measurements with many instruments, including AIRS, the Troposphere Emission Spectrometer (TES), and the High Resolution Dynamic Limb Sounder (HIRDLS), on the NASA EOS platforms. Cross-validation are planned between MOPITT and the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) to be launched on the European Space Agency (ESA) Environmental Satellite (ENVISAT) in 1999.

6.0 Error Analysis and Data Product Uncertainty Specifications

The objective of the error analysis is to determine the expected errors in the retrieved CO profiles and column amounts of CO and CH_4 from MOPITT data under diverse observing conditions. A detailed error analysis of a remote sensing system, including both the instrument and data processing algorithm, will lead to better understanding of the measurements and limitations. The errors can be both 'systematic' and 'random'. 'Systematic' errors are, at least to first order, independent of time; they usually represents constant bias in the 'zero' or 'scaling' of the results. 'Random' errors are time-varying; they must be described by some statistical parameter such as the expected standard deviation in the error; a ubiquitous source of random error is instrument noise. Rodgers (1990) has developed general techniques to characterize errors in atmospheric profiles retrieved from remote sounding measurements. We intend to apply Rodgers' techniques to MOPITT error analysis. The pre-launch error analysis is based on the estimated instrument noise (*Wang, et al.*, 1996) After launch, the error analysis will be updated with the in-orbit instrument performance data. As pointed out by the EOS Validation Scientist, Dr. David Starr, it is important to specify errors for different observing conditions. For example, the retrieved CO and CH_4 from MOPITT observations will have smaller error bars over remote clean oceanic region under clear sky conditions than over land with pollution and clouds.

6.1 Systematic Errors

Primary sources of systematic errors for MOPITT include:

(1). *Forward model errors.* Errors due to forward model include spectral line parameters, line shape, line mixing, continuum, and forward model approximations. The CO error covariance matrix due to forward model is given by,

$$S_b = D C_b D^t \qquad (6.1)$$

where D is the instrument contribution function matrix, C_b is the forward model error sensitivity matrix, and t is matrix transpose. A complete definition of different terms used in retrieval error analysis can be found in Rodgers (1990).

(2). *Errors due to calibration uncertainties.* Calibration errors (gain & offset errors) will contribute to the systematic error. During pre-flight instrument calibration, calibration uncertainties can be estimated by looking at stable blackbody sources. During flight, calibration uncertainties can be estimated to a certain degree by examining the time series of the calibrated space view radiances which is expected to be randomly distributed with a mean value of zero.

From the MOPITT calibration peer review document (*Calibration Peer Review*, March 2, 1994) the total calibration uncertainty for MOPITT longwave channels is specified to be +/- 0.2 K, and the total calibration uncertainty for shortwave channels is +/- 0.5 K. The calibration error covariance matrix is generated by setting the diagonal elements to the square of the channel radiance error due to calibration, and the off-diagonal elements to zero. The CO error covariance matrix due to instrument calibration uncertainties can be calculated as,

$$S_{M,cal} = D C_{\varepsilon,cal} D^t \tag{6.2}$$

where $C_{\varepsilon, cal}$ is the calibration error covariance matrix.

(3). *Errors due to instrument model.* Instrument model errors include spatial response error (FOV), detector misalignment, spectral response error caused by cell pressure & temperature error, spectral response error caused by band-blocking filter error (center wavelength uncertainties, filter spectral response error, filter degradation and shift, etc.). Those errors could become major part of the overall systematic error. For example, in the case of ISAMS, temperature retrieval systematic errors are dominated by the uncertainties in the spectral positions of ISAMS filters (Dudhia and Livesey, 1995). Similarly, the instrument model error covariance matrix can be formed by setting the diagonal elements to the square of the channel radiance error due to instrument model, and the off-diagonal elements to zero. The CO error covariance matrix due to instrument model errors can be calculated as,

$$S_{M,inst} = D C_{\varepsilon,inst} D^t \tag{6.3}$$

where $C_{\varepsilon, inst}$ is the instrument model error covariance matrix.

(4). *Errors due to atmospheric temperature profile errors.* This error source can be considered as part of the forward model error, but in order to examine the impact of atmospheric temperature error on the accuracy of CO and CH_4 retrieval, we will consider this error source separately. Define a temperature retrieval sensitivity matrix D_T as,

$$D_T = \frac{\partial \hat{x}}{\partial T} \tag{6.4}$$

where $\hat{x}$ is the retrieved CO profile. Therefore the error covariance matrix due to atmospheric temperature error is given by,

$$S_T = D_T\, C_T\, D_T{}^t \tag{6.5}$$

where C_T is the temperature error covariance matrix. It is important to include off-diagonal elements because temperature errors at different levels are correlated. Fortunately, atmospheric temperature measurements are widely available from radiosonde and meteorological satellite, and a realistic temperature error covariance matrix can be generated for the MOPITT retrieval error analysis.

(5). *Errors due to atmospheric water vapor profile errors.* Similarly, this error source can be considered as part of the forward model error, but in order to examine the impact of atmospheric water vapor profile error on the accuracy of CO retrieval, we will consider this error source separately. Define a water vapor retrieval sensitivity matrix D_{H2O} as,

$$D_{H2O} = \frac{\partial \hat{x}}{\partial x_{H2O}} \tag{6.6}$$

where $\hat{x}$ is the retrieved CO profile, and x_{H2O} is the water vapor mixing ratio profile. Therefore the error covariance matrix due to atmospheric water vapor profile error is given by,

$$S_{H2O} = D_{H2O}\, C_{H2O}\, D^t_{H2O} \tag{6.7}$$

where C_{H2O} is the water vapor profile error covariance matrix. It is important to include off-diagonal elements because water vapor profile errors at different levels are correlated. A realistic water vapor covariance matrix can be developed from data available from NMC or ECMWF. Errors in other atmospheric species, such as N_2O, O_3, CO_2, and surface parameters (emissivity and reflectivity) will also lead to errors in retrieved CO and CH_4. However, their variability are smaller compared with that of H_2O, and climatology values will be used in the forward model calculations. Those errors will be considered as part of the forward model error.

(6). *Smoothing error or a priori error.* The smoothing error or *a priori* error represents the difference between the retrieved smoothed atmospheric CO profile and the high vertical resolution CO profile represented by the *a priori*, mainly caused by the finite vertical resolution of the MOPITT measurement. In reality, it is relatively difficult to estimate the smoothing error because it is difficult to get an *a priori* that contains all the realistic small scale features of atmospheric CO. If a representative *a priori* covariance matrix can be constructed, the smoothing error can be calculated as,

$$S_{sm} = (A - I)C_a(A - I)^t \tag{6.8}$$

where A is the averaging kernel, I is the identity matrix, and C_a is the *a priori* covariance matrix.

6.2 Random Error

The main source of random error is the instrument noise. Potential random error sources include:

(1). *Errors due to instrument , detector, and electronics noise.* The noise-equivalent-radiance (NER) predicted by the MOPITT radiometric model is used to form the instrument noise covariance matrix $C_{\varepsilon,noise}$. Since instrument noise of different channels are not correlated, the off-diagonal elements can be set to zero.

$$S_N = DC_{\varepsilon,noise}\, D^T \tag{6.9}$$

where D is the contribution function matrix.

(2). *FOV smearing due to pointing jitter.* For a nadir sounder such as MOPITT with a nadir FOV of 22kmx22km, errors due to pointing jitter might be negligible. However, errors due to FOV smearing during instrument stare (~ 400 ms) may need to be considered.

6.3 Total Error

The total error covariance is given by

$$S_t = S_b + S_{M,cal} + S_{M,inst} + S_T + S_{H2O} + S_{sm} + S_N \tag{6.10}$$

As a preliminary estimate, the square root of the diagonal elements can be considered as the CO & CH_4 retrieval error.

6.4 Treatment of Smoothing Error

As pointed out by Rodgers (Rodgers, *et al.*, 1995), there are two ways to include the smoothing error in the total error. One way is to include smoothing error explicitly by treating the retrieved CO profile as an estimate of the real atmospheric CO profile with small scale vertical structure, the other way is to consider the retrieved CO profile as an estimate of the smoothed atmospheric CO profile with the MOPITT averaging kernel as the smoothing function.

Some researchers have used the second view in data validation by comparing the retrieved profiles with the correlative measurements smoothed by instrument averaging kernel as the smoothing function. The relationship between the two approaches can be seen clearly with the re-arrangement of the error equation.

Starting with the equation describing the difference between retrieved CO and the real atmospheric CO profiles of high vertical resolution (*Rodgers*, 1995).

$$\begin{aligned} \hat{X} - X &= (A - I)(X - X_a) && \textit{Smoothing error} \\ &+ D_y K_b (B - \hat{B}) && \textit{Model parameter error} \\ &+ D_y \Delta f(X, B, B') && \textit{Forward model error} \\ &+ D_y \varepsilon && \textit{Error due to instrument noise} \end{aligned} \tag{6.11}$$

If we move the smoothing error term to the left side of the equation and re-arrange, we get,

$$\begin{aligned} \hat{X} - X - (A - I)(X - X_a) &= (\hat{X} - AX) - (X_a - AX_a) \\ &= \hat{X} - AX \end{aligned} \tag{6.12}$$

Where $\hat{X}$ is the retrieved CO profile vector from MOPITT observations; X is the true atmospheric CO profile vector; X_0 is the first guess CO profile vector; A is the averaging kernel. We note that X_a-AX_a should equal to zero for a correctly formulated forward model and retrieval algorithm.

Therefore, if we treat the retrieval as the estimate of the smoothed atmospheric CO profile, then the retrieval error will be composed of error due to model parameters, error due to forward model errors, and error due to instrument noise. This way of interpreting the retrieval results will also have implications for data validation. Instead of comparing the MOPITT retrieval directly with correlative measurements by other techniques and instruments, we should first smooth the correlative results with the MOPITT averaging kernel to get $AX_{corrrelative}$, and compare the MOPITT retrieved $\hat{X}$ with $AX_{correlative}$. This will be a more meaningful comparison than directly comparing $\hat{X}$ with $X_{correlative}$ since the stated vertical resolution of MOPITT measurement is about 3-4 km. This approach will be adopted in the comparison between MOPITT data products and correlative measurements for MOPITT data validation.

7.0 Implementation of Validation Results in Data Production

7.1 Implementation Approaches

The MOPITT data validation effort will be implemented by the MOPITT Science Team, with support from scientists and software engineers from NCAR, University of Toronto, and the MOPITT correlative measurement team.

7.2 Role of EOSDIS

Validation results of each MOPITT data products will be attached to the MOPITT metadata files archived in the DAAC. Quality flags will be assigned to each data product to inform the users if great caution need to be exercised in the use of certain data products.

7.3 Plan for Archival of Validation Data

It is desirable to archive all validation data at DAAC (for example, the DOE Oak Ridge DAAC) for future use and possible independent verification of data quality. However, this is not always possible. Sometimes the validation data providers are not willing to release their data for archive at DAAC for various reasons. We plan to archive MOPITT validation data as much as possible with the permission of the data providers. Certainly all correlative data obtained with funding from EOS validation program and the MOPITT project will be released and archived at the DAAC.

8.0 Summary

Our plan for the validation of MOPITT data processing algorithm and data products, Level 0 to Level 3, have been described in this document. The measurement of tropospheric CO and CH_4 by MOPITT is an important component of the Tropospheric Chemistry program, which is one of the four high-priority scientific areas for the USGCRP over the next decade as defined by the National Research Council Board on Sustainable Development (NRC/BSD) (the other being seasonal and interannual climate, ecosystems, and decade-scale climate change). By validating MOPITT CO and CH_4 measurements with other correlative measurements, we will be able to ensure the quality of MOPITT measurements and advance our understanding of tropospheric chemistry.

A step-by-step approach will be taken for the validation of the MOPITT data, in which emphasis will be placed on understanding the data from simpler observing conditions, learning from and assessing their results before fully addressing more complicated cases. However, data for all cases will be acquired as early and often as possible. Another advantage of the step-by-step approach and observing condition classification is that different error bars can be assigned to MOPITT data products, particularly the level 2 data product, based on observing conditions.

A MOPITT correlative measurement team has been established with the support by the EOS validation program and the MOPITT project. Long-term correlative measurements include bi-weekly airborne in-situ CO and CH_4 profile measurements at five carefully selected sites and ground-based spectroscopic measurements at eighteen sites worldwide. A number of intensive validation campaigns have been planned for both pre-launch and post-launch MOPITT data validation. Strong effort has been made to integrate MOPITT validation activities with planned NASA Research & Analysis program, such as the PEM-Tropics B and CAMEX-3 missions. A Pre-launch MOPITT Validation Exercise has been planned for March 2 to March 6, 1998 to test retrieval algorithms and intercompare of different correlative measurements. Procedures of a detailed error analysis has been described.

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Appendix A: DOE/ARM Sites

Sites Name	Lat/Long	Status	MOPITT validation activities
ARM Southern Great Plain (SGP)	36.80 N / 97.5 0W	Operational	Retrieval and cloud clearing algorithm validation. Aircraft over flights. Total CO and CH_4 column from AERI and SORTI measurements.
ARM Tropical Western Pacific at Manu Island (TWP)	2.06 S / 147.43 W	Operational in late 1996	Retrieval and cloud clearing algorithm validation. Aircraft over flights. Total CO and CH_4 column from AERI and SORTI measurements.
ARM North Slope of Alaska (NSA)	71.32 N/156.60 W	Operational in 1997	Retrieval and cloud clearing algorithm validation. Aircraft over flights. Total CO and CH_4 column from AERI and SORTI measurements.

Appendix B: NOAA/CMDL Cooperative Flask Sampling Network

Location (country)	Lat/Long	Cooperating organization	Operational date
Albert, N.W. T. (Canada)	82.45 N / 62.52 W	Environmental Canada/ Atmospheric Environment Service	JUN 1985
Ascension Island, Atlantic Ocean (U. K.)	7.92 S / 14.42 W	DOD/USAF and Pan American World Airways	AUG 1979
Assekrem, Algeria (Algeria)	23.18 N / 5.42 E	Tamanrasset GAW Observatory	SEP 1995
Terceira Island, Azores (Portugal)	38.77 N / 27.38 W	Instituto Nacional de Meteorologia e Geofisica	OCT 1994
Baltic Sea (Poland)	55.50 N / 16. 67 E	MIR, Sea Fisheries Institute	SEP 1992
St. David's Head, Bermuda (U. K.)	32.37 N / 64.65 W	Bermuda Biological Station	FEB 1989
Southhampton, Bermuda (U.K.)	32.27 N / 64.88 W	Bermuda Biological Station (AEROCE)	May 1989
Barrow, Alaska (U.S.A.)	71.32 N / 156.60 W	NOAA/Environmental Research Laboratory (CMDL Observatory)	APR 1971
Black Sea, Constanta (Romania)	44.17 N / 28.68 E	Romania Marine Research Institute	OCT 1994
Cold Bay, Alaska (U.S.A.)	55.20 N / 162.72 W	NOAA/ National Weather Service	AUG 1978
Cape Grim, Tasmania (Australia)	40.68 S / 144.68 E	CSIRO, Division of Atmospheric Research	APR 1984
Christmas Island, Pacific Ocean (Kiribati)	1.70 N / 157.17 W	Scripps Institution of Oceanography	MAR 1984
Cape Meares, Oregon (U.S.A.)	45.48 N / 123.97 W	Oregon Graduate Institute of Science and Technology	MAR 1982
Crozet, Indian Ocean (France)	46.45 S / 51.85 E	Centre des Faibles Radioactivities/TAAF	MAR 1991
Easter Island, PacificOcean (Chile)	29.15 S / 109.43 W	Direccion Meteorologica de Chile	JAN 1994

NOAA/CMDL Cooperative Flask Sampling Network (continued)

Location (country)	Lat/Long	Cooperating organization	Operational date
Guam, Mariana Islands (U. S. A.)	13.43 N / 144.78 W	University of Guam/ Marine Laboratory	SEP 1978
Dwejra Point, Gozo (Malta)	36.05 N / 14.18 E	Ministry of Environment, PCCU	OCT 1993
Halley Bay, Antarctica (U.K.)	75.67 S / 25.50 W	British Antarctic Survey	JAN 1983
Hegyhatsal (Hungary)	46.97 N / 16.38 E	Hungarian Meteorological Service	MAR 1993
Storhofdi, Heimaey, Vestmannaeyjar (Iceland)	63.25 N / 20.15 W	Iceland Meteorological Service	OCT 1992
Grifton, North Carolina (U. S. A.)	35.35 N / 77.38 W	WITN Television	JUL 1992
Tenerife, Canary Islands (Spain)	28.30 N / 16.48 W	Izana Observatory	NOV 1991
Key Biscayne, Florida (U. S. A.)	25.67 N / 80.20 W	NOAA/ Environmental Research Laboratory	DEC 1972
Cape Kumukahi, Hawaii (U. S. A.)	19.52 N / 154.82 W	NOAA/Environmetal Research Laboratory	JAN 1971
Park Falls, Wisconsin (U. S. A.)	45.93 N / 90.27 W	Wisconsin Educational Communications Board	NOV 1994
Mould Bay, N.W.T. (Canada)	76.25 N / 119.35 W	Environmental Canada/ Atmospheric Environment Service	APR 1980
Mace Head, County Galway (Ireland)	53.33 N / 9.9 W	University College Atmospheric Research Station (AEROCE)	JUN 1991
Sand Island, Midway (U. S. A.)	28.22 N / 177.37 W	DOD/ U. S. N.	MAY 1985
Mauna Loa, Hawaii (U. S. A.)	19.53 N / 155.58 W	NOAA /Environmental Research Laboratory (CMDL Observatory)	AUG 1969
NIWOT Ridge, Colorado (U. S. A.)	40.05 N / 105.58 W	University of Colorado/ INSTAAR	MAY 1967

NOAA/CMDL Cooperative Flask Sampling Network (continued)

Location (country)	Lat/Long	Cooperating organization	Operational date
Palmer Station, Antarctica (U. S. A.)	64.92 S / 64.00 W	National Science Foundation	JAN 1978
Qinghai Province (China)	36.27 N / 100.92 E	Chinese Academy of Meteorological Sciences	AUG 1990
Ragged Point, St. Phillips Parish (Barbados)	13.17 N / 59.43 W	University of Bristol (P. Simmonds)	NOV 1987
Mahe Island (Seychelles)	4.67 S / 55.17 E	DOD/USAF	JAN 1980
Bird Island, S. Georgia, Atlantic Ocean (U. K.)	54.00 S / 38.05 W	British Antarctic Survey	FEB 1989
Shemya Island, Alaska (U. S. A.)	52.72 N / 174.10 E	DOD/USAF	SEP 1985
Tutuila, American Samoa (U. S. A.)	14.25 S / 170.57 W	NOAA/Environmental Research Laboratory	JAN 1972
South Pole, Antarctica (U. S. A.)	89.98 S / 24.80 W	(CMDL Observatory)/ NSF	JAN 1975
Atlantic Ocean (Polarfront) (Norway)	66.00 N / 2.00 E	Norway Meteorological Institute (Ocean Station "M")	MAR 1981
Syowa Station, Antarctica (Japan)	69.00 S / 39.58 E	Upper Atmospheric and Space Laboratory, Tohoku University	JAN 1986
Tae-ahn Peninsula (Korea)	36.73 N / 126.13 E	Korea National University of Education	NOV 1990
Tierra Del Fuego, La Redonda Isla (Argentina)	54.87 S / 68.48 W	Servicio Meteorologico Nacional	SEP 1994
Wendover, Utah (U. S. A.)	39.90 N / 113.72 W	National Weather Service	MAY 1993
Ulaan Uul (Mongolia)	44.45 N / 111.10 E	Mongolian Hydrometeorological Research Institute	JAN 1992
Sede Boker (Negev Desert) (Israel)	31.13 N / 34.88 E	Weizmann Institute of Science	NOV 1995

NOAA/CMDL Cooperative Flask Sampling Network (continued)

Location (country)	Lat/Long	Cooperating organization	Operational date
Ny-Alesund, Svalbard (Norway/Sweden)	78.90 N / 11.88 E	Zeepelin Station/Univ.of Stockholm Meteorological Institute	FEB 1994
Pacific Ocean ships	40 S to 45 N	Blue Star Line, Ltd.	DEC 1986
SCS South China Sea ships	3 N to 21 N	Chevron	JUL 1991

Appendix C: NDSC Sites

Table C.1 Primary NDSC sites with FTIR instruments.

Sites Name	Lat/Long	Instrument & Status	MOPITT validation activities
Euraka, Canada	80.0 N / 86.4 W (Arctic station)	Bomem DA8 FTIR Deployed at Euraka in February 1993	CO and CH_4 total column from FTIR measurements
Ny Alesund, Spitsbergen	78.5 N / 11.9 E (Arctic station)	Bruker 120-M FTIR with 0.0035 cm^{-1} resolution. Solar and lunar (polar night) observations.	CO and CH_4 total column from FTIR measurements
Thule, Greenland	76.05N / 68.8 W (Arctic station)	Bomem 120M FTIR to be installed by late summer 1996.	CO and CH_4 total column from FTIR measurements
Jungfraujoch	47.0 N / 8.0 E (Alpine station)	Mobile Bruker FTIR instrument used primarily for intercomparisons and campaigns.	CO and CH_4 total column from FTIR measurements
Jungfraujoch	47.0 N / 8.0 E (Alpine station)	Two FTIR instruments since 1984 (0.0025 cm^{-1}) and 1990 (0.001 cm^{-1}). Limited database extends back to 1977.	CO and CH_4 total column from FTIR measurements
Mauna Loa / Mauna Kea	19.0 N / 115.6 W (Hawaii station)	Automated Bruker FTIR installed in August 1995.	CO and CH_4 total column from FTIR measurements
Lauder, New Zealand	45.05 S / 169.7W	Bruker 120M with 0.0035 cm^{-1} resolution. Operating since september 1990.	CO and CH_4 total column from FTIR measurements
Arrival Heights	78.0 S / 166.0 E (Antarctic station)	A permanent FTIR (Eocom with 0.03 cm^{-1} resolution)was installed in early 1991 and will be upgraded to a Bruker 2 in October 1996.	CO and CH_4 total column from FTIR measurements

Table C.2 Secondary NDSC sites with FTIR instruments.

Sites Name	Lat/Long	Instrument & Status	MOPITT validation activities
Harestua, Sweden	60.0 N / 10.0 E	Bruker 120M FTIR. Intercompared with NPL mobile unit in September /October 1994.	CO and CH_4 total column from FTIR measurements
Zugspitze	47.48 N / 11.06 E	Bruker FTIR (0.002 cm^{-1}). Began operations in 1993 as part of a new Environmental high Altitude Observatory.	CO and CH_4 total column from FTIR measurements
Table Mountain	37.6 N / 118.2 W	MkIV interferometer beginning in late 1996 or early 1997.	CO and CH_4 total column from FTIR measurements
Toyokawa, Japan	35.0 N / 137.0 E	Bruker 120M (0.0035 cm^{-1}) FTIR. Operating from December 1994 to April 1995. Moved to Rikubetsu in July 1995.	CO and CH_4 total column from FTIR measurements
Kitt Peak Observatory	32.0 N / 111.5 W	Continuous record of IR solar spectra using FTIR (0.005 cm^{-1} resolution) from 1976.	CO and CH_4 total column from FTIR measurements
University of Wollongong	34.4 S / 150.9 E	Bomem DA3 spectrometer at the University of Wollongong since December 1994.	CO and CH_4 total column from FTIR measurements