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

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Abstract

This is the third draft of the MOPITT data validation plan. The format of UARS data validation plan and the outline recommended by EOS Project Science Office were followed in the generation of this document. It should be regarded as an evolving draft: it is intended that it will continue to be refined over time as the MOPITT program progresses. The document will be updated based on input from the MOPITT team and the scientific community.

Document History

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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 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 troposphere chemistry, and 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 predictions of possible effects of anthropogenic activities.

The primary measurement objectives of MOPITT are: (1) to obtain CO profiles with a resolution of 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 22km and an accuracy of 10%; (3) to measure total CH_4 column to an accuracy 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.

1.3 Science Data Products

Standard MOPITT science data products are discussed in this section.

1.3.1 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).

1.3.2 Level 2 Data Products

Product MOP2.1: Tropospheric CO profiles. Average mixing ratio or layer amount of 3 tropospheric layers (lower, middle, and upper troposphere) for each nominal 22kmx22km pixel. 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 level 2 MOPITT 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 level 2 MOPITT product.

1.3.3 Level 3 Data Products(Experimental at Launch)

Product MOP3.1: gridded global CO distribution at 3 levels of the troposphere (global maps) produced by mapping procedures and data assimilation models.

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

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

2.0 Data Validation Objectives and Criteria

2.1 Validation Objectives

The objectives of MOPITT data validation are to produce validated global CO and CH_4 measurements of demonstrated quality with quantifiable uncertainties. The measurements which need to be validated include the channel average and difference radiances, column amount of CH_4, column amount of CO, and CO profiles at 3 layers in the troposphere (lower, middle, and upper troposphere).

2.2 Overview of Validation Strategy

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 situations, 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 simplicity 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.

Therefore, the sequence of situations is planned to be as follows:

2.2.1 Clear Conditions

2.2.1.1 Ocean surfaces

Because of the low albedo, it is expected that there will not be a difference between day and night in this situation. For these evaluations, 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 DAO (or 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 are needed 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 Land Surfaces

Land Surfaces at night: 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.

Land Surfaces during daytime: 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 for 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 L1 validation. Subsequently the radiances will be compared to verify that the results are consistent with climatological values.

2.2.1.3 More Complex Land Surfaces

Small scale variability: Regions in which the reflectivity and temperature may change significantly from one pixel to the next will be identified, and used to measure the variability of the shortwave (SW) and longwave (LW) fluxes from pixel to pixel, and from sector to sector of the LMC, both in daytime and at night.

High and variable topography: 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 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, SW 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

Night: Criteria established from the LW 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 instruments cloud indications for validation.

Day: Both LW and SW 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’s 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. Correlative measurements from ground-based, airborne, and satellite-borne instruments, together with instrument/retrieval error analysis will be used to establish the accuracy 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 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.

(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 A/C 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.

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) 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).

(1). *Spatial and temporal consistency of retrieved profiles*: Present A/C 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) A/C data 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. We also strongly support the initiative by the Carbon Cycle Group of NOAA/CMDL to measure the atmosphere profiles of CO, CH_4, and other trace gases at about 10 NOAA/CMDL sites by using the automated flask system and small airplanes. Those measurements, currently panned at twice per week, will be very useful for the validation of MOPITT CO and CH_4 measurements; 2) Measurements with the A/C MOPITT. 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 beginning with the CANOPUS network (Canada), the Network for Detection of Stratospheric Change (NDSC) (William Mankin, *private communication*, 1996; web site, http://climon.wwb.noaa.gov/), FTIR measurements at 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 CO by other correlation radiometers such as the MicroMAPS (µMAPS) if there is overlap in the operations of MOPITT and µMAPS. 7) Measurements of column CO and CH_4 by other sensors, including IMG on the Japan ADEOS, AIRS on EOS PM-1, and TES on EOS CHEM-1.

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 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 MOPITT program will strongly encourage such intercomparison programs, such as the intercalibration and intercomparison project carried out in MAPS data validation (Novelli, 1995). 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.

3.0 Pre-Launch Algorithm Development & Test Activities

3.1 Instrument Concept and Characteristics

The MOPITT instrument has been described in publications and documents by Drummond (*Drummond*, 1992, 1993) and the MOPITT ATBD. Therefore, only a brief summary is included here. The approach and viewing geometry are shown in Fig. 3.1.1. MOPITT measures upwelling thermal emission from the atmosphere and surface in the long-wave channels (4.7 µm), and reflected solar radiation that has passed through the atmosphere, been reflected at the surface in the short-wave channels (2.2 & 2.3 µm), and transmitted back up through the atmosphere. Total atmospheric transmittance derived from reflected sunlight measurements will be used to determine the total column amount of CO and CH_4. Thermal channels in the CO fundamental band at 4.7 µm can be used to determine the tropospheric CO profile, as demonstrated by *Reichle et al.* (1986, 1989).

Correlation Radiometry(CR), a non-dispersing spectroscopy technique, offers the opportunity for making measurements with high spectral resolution as well as high signal-to-noise ratio. The fundamental techniques of correlation spectroscopy are illustrated in Fig. 3.1.2. The cell contains a sample of the target gas. Assume monochromatic radiation enters from the left and is detected by the system on the right, the output as a function of spectral frequency is shown in Fig. 3.1.3(a) for two different amounts of gas in the absorption cell. By cycling the amount of gas in the absorption cell between the two states, the detector will be alternatively looking through two different filters. The difference of the two signals will be identical to the output of a system in which the gas cell and its modulator are replaced by an optical filter of profile shown by the Effective Difference Transmission (EDT) curve in Fig. 3.1.3(b). The apparatus has the following unique characteristics:

(1). The 'equivalent filter profile' is zero between the spectral lines of the gas in the cell, eliminating signals from spectral regions subject to interference by other species as illustrated in Fig. 3.1.3(c).

(2). The filter profile has a maximum at each spectral line and therefore the energy from each spectral line in a broadband emission is collected simultaneously. Therefore, the system is very sensitive to radiation with a spectrum identical or similar to that of the gas in the cell. Obviously the spectrum of the gas itself is best correlated with the filter profile.

(3). The apparatus does not require any high precision optical adjustments. In fact the only thing that affects the alignment is Doppler shift caused by relative motion between gas in the cell and the emitting atmospheric gas, and this is negligible in the case of MOPITT.

(4). The shape of the equivalent filter is sensitive to the amount of gas in the cell. If small amounts of gas are placed in the cell, the spectral lines will be narrow with incomplete absorption at the centers of the lines. The EDT will have peaks in line centers, where absorption

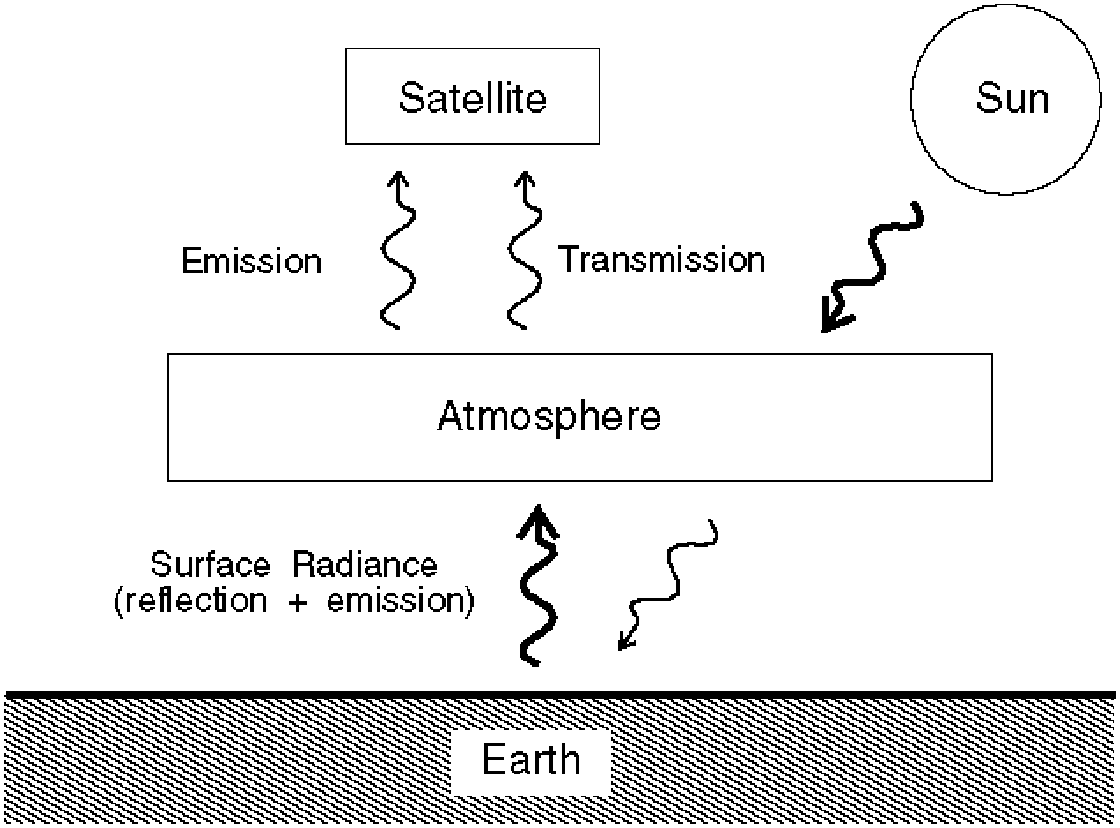

Fig. 3.1.1 Schematic diagram of MOPITT measurement system.

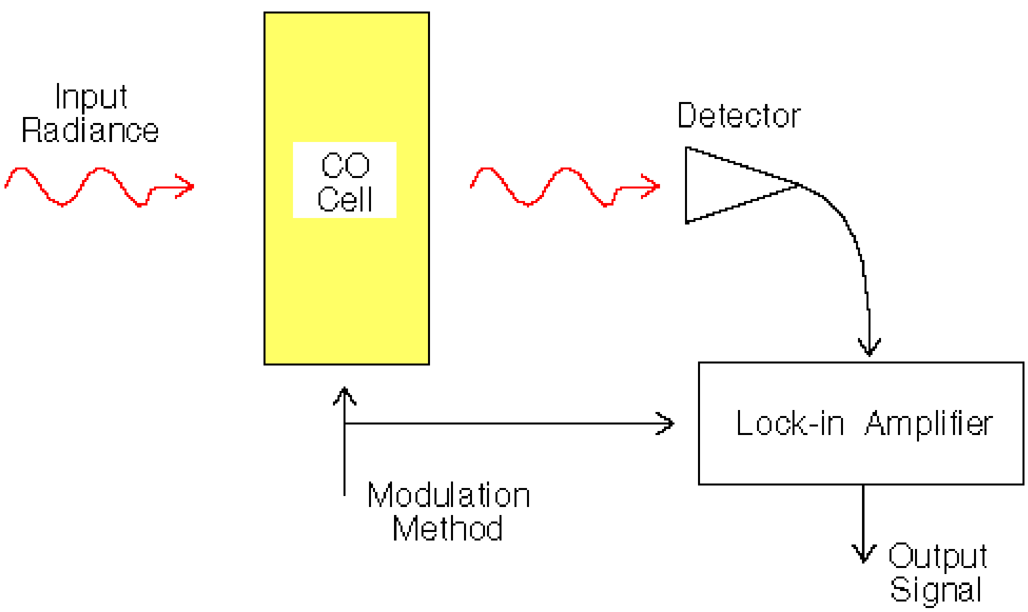

Fig. 3.1.2 A basic correlation radiometry system.

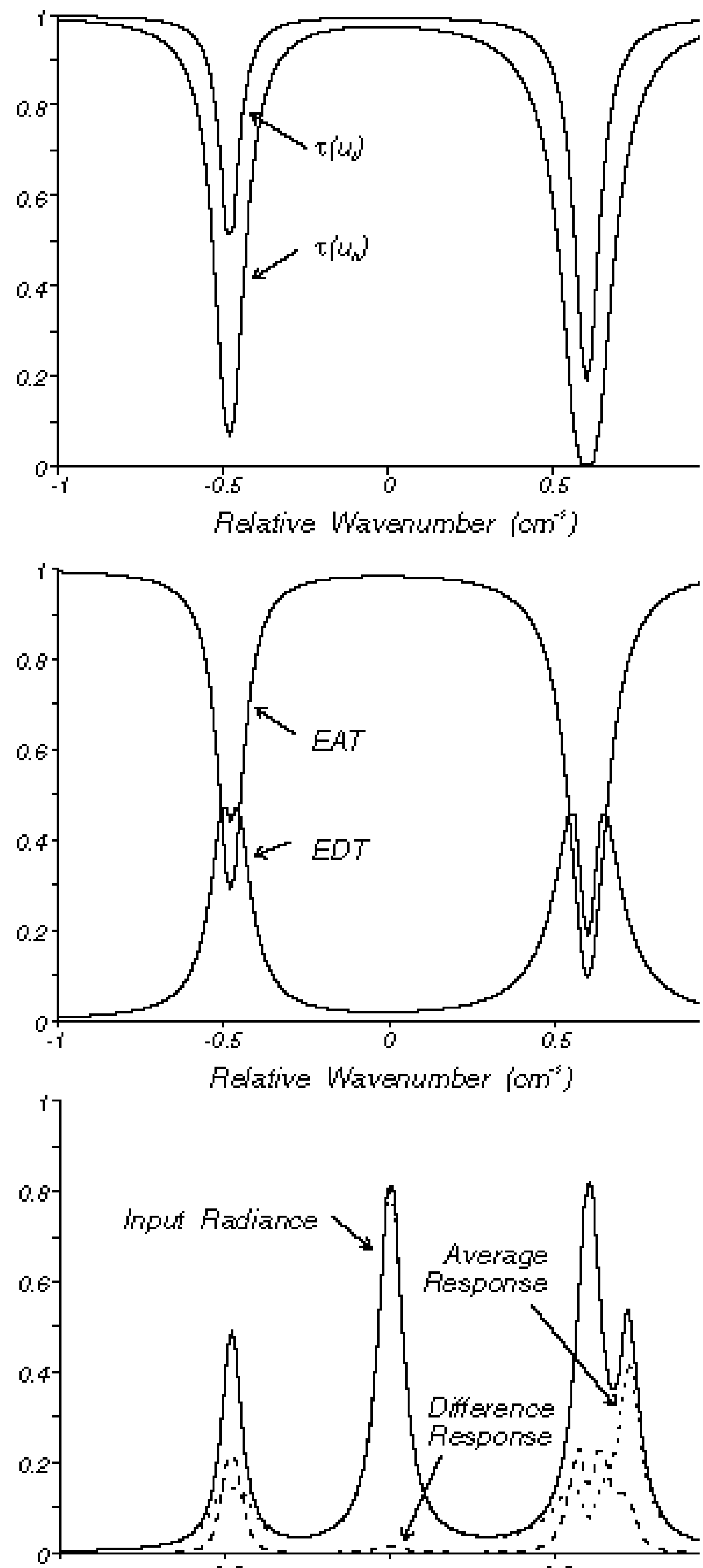

Fig. 3.1.3 Operation of a correlation spectrometer in spectral space. EAT stands for Equivalent Average transmission, EDT stands for Equivalent Difference Transmission.

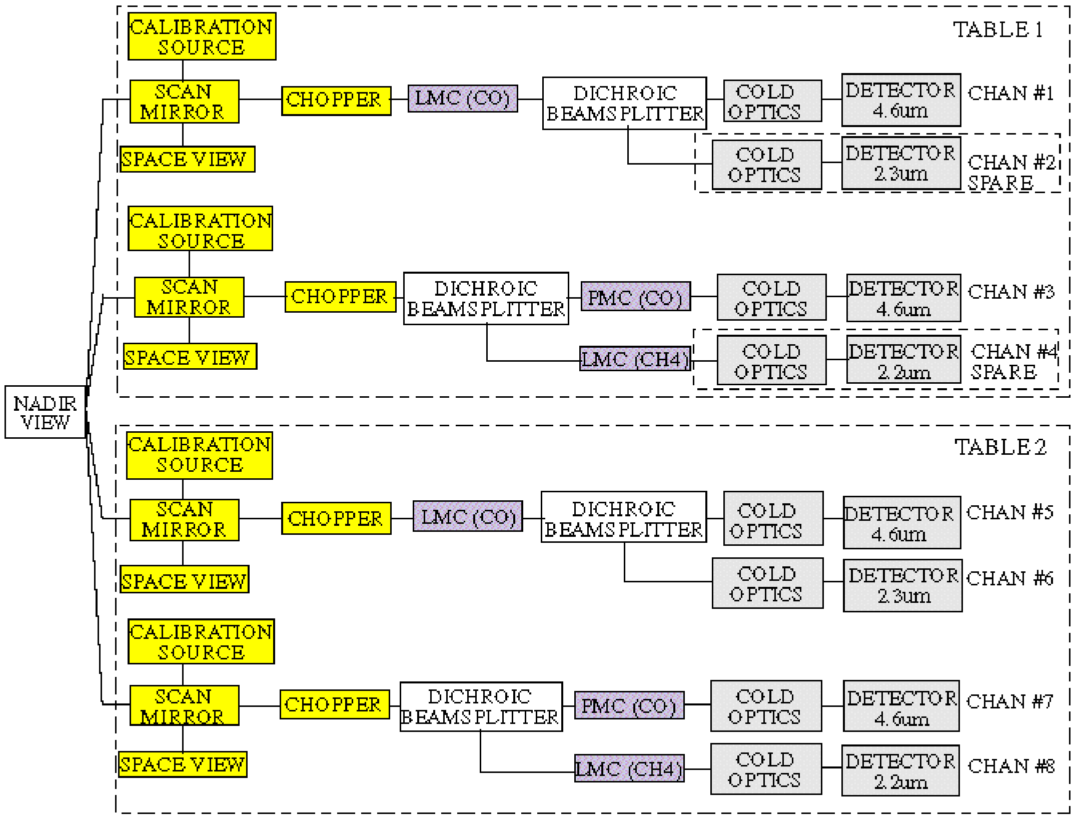

Fig. 3.1.4 MOPITT optical channel diagram.

coefficients are largest. If larger amounts of gas are placed in the cell, the lines will be broader and completely absorbed in the centers. In this case, the EDT will have peaks in the line wings, where absorption coefficients are smaller. By placing different amount of gas in the cell, different parts of the spectral line will be sampled, leading to altitude discrimination or vertical resolution. The largest part of the upwelling signal emitted by the atmosphere comes from the altitude region in which the optical depth is near unity. Thus, a cell that is sensitive to the line center will respond to signals originating higher in the atmosphere, while a cell with larger amounts of gas will respond to signals originating in the wings of the pressure broadened lines, at higher pressures (lower altitudes).

MOPITT makes use of two methods to modulate the gas transmittance. The first is by pressure modulation through the use of pressure modulated cells which have been described in detail by *Taylor* (1983). The second is by modulating the length of the gas cell in the optical path, through length modulated cells (*Drummond*, 1989). A block diagram of the MOPITT optical arrangement is shown in Fig. 3.1.4. Two pressure modulated radiometers (PMR's) with different mean pressures and four length modulated radiometers (LMR's) are used. Separating the 2 µm and 4.7 µm channels with dichroic filters results in 8 separate spectral channels. Each channel produces an average (A) and a difference (D) signal.

3.2 Forward Model Development and Test

MOPITT forward model and instrument sensitivity studies have been discussed in detail in the 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. A thermal channel at 4.7 µm will be used to obtain profile information about the tropospheric CO distribution. Short-wave solar reflectance channels at 2.2 and 2.3 µm will be used for CO and CH_4 total column retrieval, respectively. Each channel will generate a difference signal and an average signal, resulting in 16 signals from eight-channels of MOPITT.

3.2.1 Radiative Transfer Model

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

$$S_a = G_a \int_{-\infty}^{+\infty} \left\{ I_s(\nu) + \int_0^{\infty} \left[B(\nu, T(z)) - I_s(\nu) \right] \frac{d\tau(\nu, z, \infty)}{dz} \right\} \tau_f(\nu) \left[\frac{\tau(p_l) + \tau(p_h)}{2} \right] d\nu \qquad (3.2.1)$$

$$S_d = G_d \int_{-\infty}^{+\infty} \left\{ I_s(\nu) + \int_0^{\infty} \left[B(\nu, T(z)) - I_s(\nu) \right] \frac{d\tau(\nu, z, \infty)}{dz} \right\} \tau_f(\nu) \left[\tau(p_l) - \tau(p_h) \right] d\nu \qquad (3.2.2)$$

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; 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; 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,

$$S_a = G_a^{\Theta} \int_{-\infty}^{+\infty} r(\nu) I_{\Theta}(\nu) \exp\left[-\int_0^{\infty} k(z) \rho_{co}(z) (\sec\theta_{sat} + \sec\theta_{sun}) dz \right] \tau_f(\nu) \left[\frac{\tau(p_l) + \tau(p_h)}{2} \right] d\nu \qquad (3.2.3)$$

$$S_d = G_d^{\Theta} \int_{-\infty}^{+\infty} r(\nu) I_{\Theta}(\nu) \exp\left[-\int_0^{\infty} k(z) \rho_{co}(z) (\sec\theta_{sat} + \sec\theta_{sun}) dz \right] \tau_f(\nu) \left[\tau(p_l) - \tau(p_h) \right] d\nu \qquad (3.2.4)$$

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; $r(\nu)$ 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; $\tau_f(\nu)$ 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. 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. 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).

3.2.2 Spectroscopic Database

Spectral line parameters currently used in MOPITT radiative transfer calculations are from the 1992 edition of the HITRAN database (*Rothman, et al*., 1992). For CO, the accuracies 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 current 1992 HITRAN database, and insufficient studies have been done about the effects of CH_4 line mixing. Therefore, there is a need for coordinated EOS AM-1 effort to verify/improve existing line parameters.

3.2.3 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.

3.2.4 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).

3.2.5 Fast Forward Model (MOPfas) Validation Activities

Validation activities of the forward model will be composed of the following activities:

(1). Compare the calculations by MOPfas and line-by-line (LBL) radiative transfer models, such as GENLN2, 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 , and the Amazon, Arctic, Atmospheric Boundary Layer Experiment in North Canada (ABLE-3 B); b) 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; c) measurements of atmospheric temperature and many trace species profiles at the DOE/ARM sites. Special arrangements will be needed to include CO profile measurements at those sites for data validation campaigns.

(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 is planned for 1997. The measured radiances will be compared with forward calculated radiances to verify our understanding of the operations of the MOPITT instrument and the instrument model. In this comparison, LBL calculations will be used because the amount of data from aircraft flights is not large enough as to warrant the development of a fast model for MATR.

(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.

3.3 Retrieval of CO Profile and Column Amounts of CO and CH_4

3.3.1 Retrieval Algorithm

The theoretical basis and algorithms for the retrieval of profiles of CO and column amounts of CO and CH_4 have been described in detail in the 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,

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

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

$$X_{n+1} = X_0 + S_x K_n^T (K_n S_X K_n^T + S_\varepsilon)^{-1} [Y - Y_n - K_n (X_0 - X_n)], \quad (2)$$

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, which has been calculated analytically in the algorithm. 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 if the convergence criterion is 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 ATBD.

3.3.2 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, are being collected 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 tests and validations using MATR, MOPITT-A and correlative measurements. The retrieved CO and CH_4 profiles and columns will be compared with correlative measurements during MATR flights.

3.3.3 MOPITT Cloud Clearing Algorithm Development and Validation

The MOPITT cloud clearing approaches and algorithms are described in the ATBD. The cloud identification and clearing algorithms 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 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:

Current Data Sets:

(1). EOS Pathfinder data sets will be used as input for model studies on surface and atmospheric conditions. The HIRS FOV of 20x20km is close to the MOPITT FOV of 22x22km 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: FIRE(10/91), ASTEX(6/92), 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.

Future Data Sets:

(1). MATR flights in the fall of 1996, will fly in clear conditions with data being recorded by the 2.2 and 2.3μm LMR. Future flights plan to include the 4.7μm channels and fly in coastal areas in clear and cloudy conditions. Data from these 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. Data from MOPITT-A will also be used in the validation of MOPITT cloud clearing algorithm.

3.4 Error Analysis

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. These 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 estimate of instrument noise (*Wang, et al.*, 1996) After launch, the error analysis will be updated with the in-orbit instrument performance data.

3.4.1 Systematic Errors

Primary sources of systematic errors 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,

$$S_b = DC_b D^t \tag{3.4.1}$$

where D is the instrument contribution function matrix, C_b is the forward model error sensitivity matrix, and t is matrix transpose.

(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 longwave channel is +/- 0.2 K, and the total calibration uncertainty for shortwave channel 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,

$$S_{M,cal} = DC_{\varepsilon,cal} D^t \tag{3.4.2}$$

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, ...). 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,

$$S_{M,inst} = DC_{\varepsilon,inst} D^t \tag{3.4.3}$$

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,

$$D_T = \frac{\partial \hat{x}}{\partial T} \tag{3.4.4}$$

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

$$S_T = D_T \, C_T \, D_T{}^t \tag{3.4.5}$$

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,

$$D_{H2O} = \frac{\partial \hat{x}}{\partial x_{H2O}} \tag{3.4.6}$$

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,

$$S_{H2O} = D_{H2O} \, C_{H2O} \, D_{H2O}^t \tag{3.4.7}$$

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,

$$S_{sm} = (A - I)C_a(A - I)^t \tag{3.4.8}$$

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

3.4.2. 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.

$$S_N = DC_{\varepsilon,noise} D^T \tag{3.4.9}$$

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.

3.4.3. Total Error

The total error covariance is given by

$$S_t = S_b + S_{M,cal} + S_{M,inst} + S_T + S_{H2O} + S_{sm} + S_N \tag{3.4.10}$$

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

3.4.4. 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).

$$\begin{aligned} \hat{X} - X = (A - I)(X - X_a) \quad & \textit{Smoothingerror} \\ + D_y K_b (B - \hat{B}) \quad & \textit{Model parametererror} \\ + D_y \Delta f (X, B, B') \quad & \textit{Forward modelerror} \\ + D_y \varepsilon \quad & \textit{Errorduetoinstrumentnoise} \end{aligned} \tag{3.4.11}$$

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

$$\begin{aligned} \hat{X} - X - (A - I)(X - X_a) &= (\hat{X} - AX) - (X_a - AX_a) \\ &= \hat{X} - AX \end{aligned} \tag{3.4.12}$$

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 might 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.

3.5 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.

3.6 End-to-End Data Processing Simulations

Complete end-to-end data processing simulation from Level 0 data to Level 2 MOPITT data will be conducted before launch as part of the rehearsal for after launch data processing and data validations. It is hoped that problems will be uncovered and solutions will be found in this process. Simulated Level 0 data will be generated from Level 2 profiles, Level 0 to Level 1 processor will be used to generate simulated Level 1 data, and the operational retrieval algorithm (Level 1 to Level 2 processor) will be used to generate Level 2 data which will be compared with the original data sets used to generate simulated Level 0 data.

4.0 Post-Launch Data Validation Activities

After the EOS-AM1 reaches the planned orbit, a sequence of tests will be carried out in the 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. Major post-launch data validation activities are discussed below.

4.1 Planned Field Activities and Studies

The MOPITT team continues to define field experiments that are essential to the validation of MOPITT data processing algorithm and scientific products. The following is a preliminary summary of planned field activities, details and more activities will be added later.

The MOPITT Algorithm Test Radiometer (MATR) engineering flight took place in June 1996. More flights are planned over the DOE/ARM sites with MATR and MOPITT-A being developed in Canada. Joint MOPITT, MODIS, and AIRS validation activities with ER-2 carrying MAS, MOPITT-A, HIS, etc. are planned. Frequent aircraft flights with small airplanes carrying NOAA automated flask trace gas measurement (CMDL suitcases) system are planned over NOAA/CMDL sites. We also plan to have aircraft measurement campaigns in South America during biomass burning seasons.

We plan to use some existing measurement networks, including the DOE/ARM sites at SGP, NSP, and TWP, the NOAA/CMDL trace gas measurement network, and the NDSC sites. It will be desirable for MOPITT personnel to participate in the DOE/ARM program as adjunct science team members to facilitate the use of ARM data and the planning of overflights over ARM sites for MOPITT algorithm and data validation. It is anticipated that samples collected at NOAA/CMDL & collaborators sites will be analyzed at NOAA/CMDL through some joint projects between AM-1/MOPITT and NOAA/CMDL. FTIR spectra from NDSC sites will be analyzed at NCAR to retrieve CO and CH_4 total column. Table 4.1 & 4.2 give more details on our plan for aircraft campaigns for MATR and MOPITT-A, and table 4.3 lists ground-based networks for MOPITT data validation.

Table 4.1. MATR EOS Aircraft Utilization Plan for MOPITT Algorithm and Level-2 Data Validation

Mission	Dates	Place	Primary Purpose	Primary Sensors
Second joint vicarious calibration campaign, plus ocean flight	May - June 1997	Nevada and California Coast	Primary purpose is to check MATR atmospheric radiance calibration	MATR, CO in-situ sensor, Video camera.
Colorado	February 1998	Colorado (Carr, Boulder, Denver)	Collect data to test MOPITT retrieval algorithms. Compare MATR retrieved CO/CH_4 values with NOAA flask sample data over Carr, and with values derived from ground-based FTIR spectra at Boulder and/or Denver	MATR. NOAA/CMDL flask sample suitcase. Ground-based FTIR.
ARM-1	September 1998	Lamont, Okla. (DOE ARM site)	Collect validation data over land at a heavily instrumented ARM site after MOPITT launch. Overlap with MODIS validation campaign.	MATR NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS)
High Latitude	Winter 1999	North Slope, Alaska (DOE ARM site)	Collect validation data at high latitude site under low scene radiance conditions.	MATR. NOAA/CMDL flask sample suitcase. Ground-based FTIR. ARM instruments.
LBA	September 1999	Amazonia, Brasil	Collect validation data over land in tropical regions during biomass burning seasons. Overlap with MODIS validation campaign.	MATR NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS, AirMISR)
Ocean/Land	September 2000	TBD	Options of land/ocean and clear/cloudy. Focus will depend on MOPITT needs.	MATR. NOAA/CMDL flask sample suitcase, etc.
TBD	Twice in 2001	TBD	Two flights in 2001. Time and locations to be decided. Focus will depend on MOPITT needs.	MATR. NOAA/CMDL flask sample suitcase, etc.

Table 4.2. MOPITT-A EOS Aircraft Utilization Plan for MOPITT Algorithm and Level-2 Data Validation

Mission	Dates	Place	Primary Purpose	Primary Sensors
ARM-1	September 1998	Lamont, Okla. (DOE ARM site)	Collect vicarious calibration and validation data over land at a heavily instrumented site after MOPITT launch. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS)
ARM-2*	Apr-May 1999	Lamont, Okla. (DOE ARM site)	Collect vicarious calibration and validation data over land at a heavily instrumented site after MOPITT launch. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS)
California-1*	July 1999	Monterey to San Diego	Collect vicarious calibration and validation data over land with clouds and fog. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS, Air MISR)
Mid-Atlantic*	August 1999	Atlantic Ocean	Collect vicarious calibration and validation data over ocean. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS, Air MISR)
LBA*	September 1999	Amazonia, Brasil	Collect validation data over land in tropical regions during biomass burning seasons. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS)
California-2*	December 1999	Central Valley	Collect vicarious calibration and validation data over land with clouds and fog. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS, Air MISR)
Gulf of Mexico	January 2000	Gulf of Mexico region	Collect vicarious calibration and validation data over ocean. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS)
California and Pacific	September 20000	Pacific Northwest	Collect vicarious calibration and validation data over land and ocean. Overlap with MODIS validation campaign.	MOPITT-A NOAA/CMDL flask sample suitcase. MODIS validation instruments (MAS, HIS, CLS, Air MISR)
TBD	Twice in 2001	TBD	Collect vicarious calibration and validation data. Time and locations to be decided.	MOPITT-A NOAA/CMDL flask sample suitcase. MAS and HIS.

* Support will be requested for at least three of the five missions marked with an asterisk.

4.2 New EOS-targeted Coordinated Field Campaigns

To be added after more information become available from EOS Validation Office.

4.3 Needs for Other Satellite Data

Atmospheric temperature and water vapor profiles at the time and location of MOPITT observations are needed in the retrieval. Therefore, temperature and water vapor profiles from NOAA meteorological satellites, AIRS [after the launch of EOS PM-1], and NMC or Data Assimilation Office (DAO) analysis will be needed. Cloud and surface reflectivity products from MODIS on EOS AM-1 will be useful for the verification of cloud clearing of MOPITT observations or used directly in cloud clearing during data processing.

4.4 Measurement Needs at Calibration/Validation Sites

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 that 10% from surface to 20 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 are needed for the temperature and water vapor profiling; ozone sondes are necessary for the ozone profiles. The accuracy of surface reflectivity measurements should be better than 5-10%; and the cloud heights and fractions should be better than 20%.

Second, 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 20 km. This accuracy is well within current analytical techniques. Profiles to about 8 km are easily made from small aircraft, measurements to 12-13 km are possible from jets; however those 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%, from surface to about 20 km. 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 are needed for the cloud measurements. Airborne and surface measurements are needed for the surface reflectivity measurements. DOE/ARM sites can provide most of the required measurements, except the 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 with 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 sample are measured at a central laboratory, thus ensuring internal consistency. This system is relatively inexpensive and can be easily operated at many sites. It is anticipated that at least one location the flask system and an in situ sensor (such as the NDIR) will be flown simultaneously. For total column CO and CH_4 measurements, ground-based high resolution FTIR measurements are needed. These spectroscopic measurements are made at several locations around the world (such as the NDSC sites listed in Appendix D). 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, he 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 locations chosen to fulfill the requirements specified in section 2.2. Spectra obtained at NDSC and DOE/ARM sites will be used for the validation of MOPITT CO and CH_4 column amounts. Financial support from the EOS validation program is needed for those activities.

4.5 Needs for Instrument and Validation Program Development

There is a need for the development of a MOPITT airborne simulator. We are trying to meet this requirement by working with the Canadian Space Agency (CSA). An airborne MOPITT (MOPITT-A) is currently under consideration for development by CSA. Feasibility study and instrument definition supported by CSA are underway at the University of Saskatchewan in Canada. We need to purchase the automated flask CO and CH_4 measurement system from NOAA/CMDL and make arrangements with NOAA/CMDL to have frequent CO and CH_4 profile measurements with small airplane and jets preferably at NOAA/CMDL sites and

DOE/ARM sites. We would also like to have CO and CH_4 measurement devices installed at towers considered for deployment at EOS validation sites. CO measurement instruments need to be added to the CANOPUS network. Funding from EOS validation program is needed for the development of retrieval algorithm to retrieve CO and CH_4 from ground-based FTIR spectra taken at NDSC and DOE/ARM sites.

4.6 Geometric Registration Sites

The geometric registration requirement is not as high as other instruments on the EOS AM-1 platform. Therefore, no special requirements are needed for MOPITT, 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.

4.7 Intercomparisons with Other Satellite Instruments

Opportunities exist for the intercomparisons of MOPITT CO and CH_4 measurements with many instruments on the NASA EOS platform including, AIRS, TES, HIRDLS, IMG on the Japan ADEOS satellite, and IASI on Eumet satellite. Table 4.1 lists potential measurements by other EOS instruments that could be used for MOPITT data validation (*1995 EOS Reference Handbook*).

5.0 Implementation of Validation Results in Data Production

5.1 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 collaborating investigators. Personnel assignments and responsibilities will be discussed in future version of this document when they become more clear.

5.2 Role of EOSDIS

Results of validation 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. Details of the implementation of quality attributes to the data will be discussed in the future version of this document when more information become available from EOS Project Science Office.

5.3 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. It is suggested that issues related to the archival of validation data be discussed at future NASA validation related workshops and SWAMP meetings.

Table 4.3. EOS Instruments with CO and CH_4 Measurement Capabilities.

Platform	Instrument Measurement	Time Scale 98	99	00	01	02	03	04	05	06	07	08	09	10	11	Projected Accuracy	Altitude Range
AM-1	MOPITT																
	CO, profile	←	—	—	—	—	→									10%	0 - 15 km
	CO, column	←	—	—	—	—	→									10%	
	CH_4, profile																
	CH_4, column	←	—	—	—	—	→									1%	
PM-1	AIRS																
	CO, profile																
	CO, column				←	—	—	—	→							10%(1)	
	CH_4, profile																
	CH_4, column																
CHEM-1	HIRDLS																
	CO, profile																
	CO, column																
	CH_4, profile						←	—	—	—	→					1-10%	8 - 30 km(2)
	CH_4, column																
	TES																
	CO, profile																
	CO, column						←	—	—	—	→					?	
	CH_4, profile																
	CH_4, column						←	—	—	—	→					?	
PM-2	AIRS																
	CO, profile																
	CO, column										←	—	—	—	→	10%(1)	
	CH_4, profile																
	CH_4, column																

(1) CO column is potential research product of AIRS. The accuracy of 10% is based on current simulation studies (*Strow*, 1994).

(2) Depending on the cloud coverage and aerosol loading in the upper troposphere, the HIRDLS may extend to below 10 km under clear sky and low aerosol situation, it also may not be able to extend to 10 km under cloudy sky or high aerosol conditions.

6.0 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. In order to achieve this goal, adequate effort and resources need to be devoted to the development of MOPITT aircraft instruments, enhancing the CO & CH_4 profiling capability at many trace gas measurement sites (e.g., NOAA/CMDL sites), and aircraft campaigns over ARM sites, Asia (Japan, China, ..), and large scale biomass burning regions during the dry season over South America.

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 situations, 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.

The primary algorithm validation sites will be the DOE/ARM sites, the combination of aircraft overflights at ARM sites with MOPITT Airborne Simulator (MOPITT-A) carrying in-situ CO sensors (NDIR or TDLS) and CMDL automated flask system, ground-based instruments at the sites for the measurements of temperature, water vapor, ozone profiles, cloud fractions, cloud base height, surface temperature, and surface emissivity/reflectivity at 4.7 µm & 2.3 µm will enable us to verify the MOPITT cloud clearing and CO & CH_4 retrieval algorithm. Therefore, we plan to participate in all the AM-1 coordinated field campaigns at the ARM sites, and plan to carry out several MOPITT specific campaigns at the ARM sites.

For the validation of MOPITT CO profiles, CO and CH_4 total columns, we plan to use the NOAA/CMDL Cooperative Flask Sampling Network that can provide surface and troposphere profiles of CO and CH_4. We strongly encourage the early implementation of the trace gas measurement program with automated flasks and small airplanes proposed by the Carbon Cycle Group of the NOAA/CMDL. We plan to participate in the DOE/ARM program to obtain long-term column CO & CH_4 at ARM sites by using the AERI and SORTI data. We suggest that a mechanism be established in the joint NASA and DOE Science Plan for the participation of AM-1 instrument team members as adjunct ARM science team members to facilitate the use of ARM data for AM-1 data validations. We plan to use NDSC data to derive column CO and CH_4 at selected sites for MOPITT data validation. Many of the NDSC FTIR are located at mountain-top locations (more than 1.5 km above sea level), and can provide free troposphere CO and CH_4. Funding for the development of retrieval algorithm to retrieve CO and CH_4 from ground-based FTIR spectra taken at NDSC and ARM sites are needed. A limited number of high priority sites, which can provide continuous validation data reliably, will be selected from the ARM sites, NOAA/CMDL sites, and NDSC sites as anchor points for the continuous validation of MOPITT measurements throughout the whole AM-1 mission. Data from other sites will be used for validation less frequently than the high priority sites. Data from all sites and MOPITT measurements will be used together to achieve the scientific objectives of the MOPITT program. Therefore, correlative CO and CH_4 measurements are an integral part of the MOPITT program.

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Appendix A: Brief Summary of MOPITT Data Validation Approaches

A.1 Vicarious Calibration and Validation of Radiance Products

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

Validation Approaches:

(1) *MOPITT 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.

(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.

(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. 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 A/C underflying the EOS AM-1 platform over validation sites will be compared directly with MOPITT radiances.

Validation Activities:

(1) Aircrafts carrying MOPITT-A, MATR, in-situ CO and CH_4 sensors (Tunable diode laser system, CMDL automated flask system) overflights the 3 ARM sites. Temperature, water vapor, ozone, clouds fraction, clouds height, surface temperature, and surface emissivity/reflectivity measurements will be provided by instruments at ARM sites.

(2) Aircrafts campaigns carrying MOPITT-A, MATR, in-situ CO and CH_4 sensors over CMDL sites in North America, biomass burning regions in South America, Asia (Japan & China),... Temperature, water vapor, ozone will be provided by radiosonde and ozone sonde.

Resources & Needs:

(1) Need resources to further develop and test MOPITT-A and MATR.

(2) Need resources to purchase automated flask systems from NOAA/CMDL and for the participation of CMDL in MOPITT validation activities.

(3) Need to establish mechanism for participation in the DOE/ARM program.

Potential collaborations within AM-1:

(1) Aircraft overflights over ARM sites can be conducted as part of AM-1 coordinated field activities. We intend to participate in overflights planned by other team (e.g., MODIS validation campaigns) with MOPITT-A and CMDL automated flask system.

(2) Flights over other sites around the world can also be planned in coordination with other AM-1 teams.

A.2 MOPITT Retrieval and Cloud Clearing Algorithm Validation

Products: retrieval algorithm for CO tropospheric CO profiles, CO column, CH_4 column.
cloud clearing algorithm.

Validation Approaches:

(1) Compare retrieved CO profiles, CO column, CH_4 column from MOPITT-A measurements over validation sites with measured CO and CH_4 using in-situ techniques (Tunable diode laser system, CMDL automated flask system).

(2) Compare the cloud clearing results (cloud fraction, ...) with directly measured cloud fraction and cloud heights or cloud products from MODIS, MAS, CLS, ... at validation sites.

Validation Activities:

(1) The primary algorithm validation sites will be the DOE/ARM sites. Algorithm validation campaigns with aircraft carrying MOPITT-A, MATR, in-situ CO and CH_4 sensors, video camera for cloud cover are planned.

Resources and Needs:

(1) Need resources to further develop and test MOPITT-A and MATR.

(2) Need to find aircraft and flight time for MATR over flights over ARM sites after our initial engineering flight in June 1996.

(3) Need resources to purchase automated flask systems from NOAA/CMDL and for the participation of CMDL in MOPITT validation activities.

Potential collaborations within AM-1:

MOPITT algorithm validation campaigns can be conducted as part of AM-1 coordinated algorithm validation activities at DOE/ARM sites. Collaborations with the MODIS team are planned.

A.3 MOPITT Higher-order Geophysical Data Products Validation

Products: Tropospheric CO profile
CO total column
CH_4 total column

Validation Approaches:

(1) Comparison of retrieved CO profile, CO column, CH_4 column with correlative CO and CH_4 measurements during intensive validation campaigns at ARM sites.

(2) Comparison of retrieved CO profile, CO column, CH_4 column with correlative CO and CH_4 measurements during MOPITT-specific validation campaigns over other sites, such as NOAA/CMDL sites.

(3) Comparison of MOPITT retrieved CO and CH_4 with CO and CH_4 profiles measured at NOAA/CMDL sites using automated flask system and airplanes.

(4) Comparison of free troposphere CO derived from MOPITT, MOPITT-A, MATR with those derived from AIRS and HIS. Joint CO validation campaigns with the AIRS team are planned.

(5) Compare CO and CH_4 column retrieved from FTIR spectra at NDSC sites and ARM sites with CO and CH_4 column retrieved from MOPITT observations.

(6) Continuous comparison of correlative measurements with MOPITT derived CO and CH_4 at several carefully selected anchor sites over the whole MOPITT mission.

Validation Activities:

(1) Intensive validation campaigns over DOE/ARM sites.

(2) Intensive validation campaigns at NOAA/CMDL & collaborator sites.

(3) Participate in MODIS and AIRS validation campaigns where MAS and HIS data are available.

(4) Conduct FTIR measurements during MOPITT overpass at NDSC sites. Archive and analyze FTIR spectra to retrieve CO and CH_4 column.

(5) Long-term validations at anchor sites selected from ARM sites, NOAA/CMDL & collaborators sites, and NDSC sites.

Resources and Needs:

(1) Need to add CO and CH_4 measurement capabilities at DOE/ARM sites. Need to obtain AERI and SORTI spectra at ARM sites for column CO and CH_4 retrieval.

(2) Expand NOAA/CMDL profile measurement sites. Need resources to measure CO and CH_4 profiles using CMDL automated flask system fitted on jets.

(3) Need funding from EOS validation program to analyze FTIR spectra taken at NDSC and DOE/ARM sites to retrieve column CO and CH_4. Currently, column

CO and CH_4 are not part of the NDSC or ARM scientific objectives. However, we will be able to request FTIR spectra from all sites for analysis.

Potential collaborations within AM-1:

(1) There are excellent opportunities for collaboration in AM-1 coordinated intensive validation campaigns at ARM sites and other validation sites (e.g., MODIS validation campaigns with MAS, HIS, and CLS).

(2) Including CO and CH_4 sensors on the validations towers will lead to the more efficient use of those towers.

(3) CO_2 flux can also be measured at NOAA/CMDL sites for use by other AM-1 instrument teams, such as MODIS.

(4) Atmospheric temperature, aerosol, trace species measurements at NDSC sites will also be useful for SAGE III, MODIS, MISR validations.

Appendix B: 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 C: 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 D: NDSC Sites

Table D.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 D.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