The Measurements of Pollution in the Troposphere (MOPITT) Instrument: Overall Performance and Calibration Requirements

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ABSTRACT

The Measurements of Pollution in the Troposphere (MOPITT) instrument will monitor the global concentrations of carbon monoxide and methane. It will be flown on the Earth Observing System Satellite *AM-1*.

This paper briefly describes the scientific objectives, performance requirements, and specifications. It primarily focuses on the pre- and postlaunch calibration requirements. The hardware requirements and methodology for calibration are also discussed as well as cross-calibration and validation of MOPITT with an underflying aircraft MOPITT.

1. Introduction

a. Science goals

The objective of the Measurements of Pollution in the Troposphere (MOPITT) experiment is to measure some of the pollutants in the lower atmosphere, in particular the global concentrations of carbon monoxide (CO) and methane (CH_4). The instrument will be flown on the Earth Observing Satellite (EOS) *AM-1* platform in June 1998 and is designed for a 5-yr mission life. The results will not only be used to map the global CO and CH_4 concentrations but will also be assimilated into 3D models to study the chemistry and dynamics of the lower atmosphere.

Carbon monoxide is a relatively short-lived gas (3 months) in the troposphere and is thus susceptible to atmospheric transport phenomena without completely mixing; it exhibits a 3-to-1 interhemispheric surface difference [50–150 ppbv, Logan et al. (1981)]. Carbon monoxide profiles and column measurements will be used to identify surface sources, natural and anthropogenic. The profile measurements will reflect the CO concentration in the lower, mid- and upper troposphere and improve understanding of the transport properties from surface source to the upper layers.

Global CO measurements will also help in understanding the chemistry of the OH (hydroxyl) radical, which due to its short life (2 min) and low concentration cannot be directly measured. (Carbon monoxide along with nitrogen oxide and ozone are the major agents in the recycling of OH and HO_2.) The OH radical induces much of the chemical activity in the troposphere.

In spite of its importance, the only global CO tropospheric dataset is that measured by Reichle et al. (1986) using the MAPS instrument (measurement of atmospheric pollution from satellites) on board the space shuttle. MOPITT will be the first instrument to comprehensively measure global concentrations and temporal variations.

Methane is the most abundant hydrocarbon in the atmosphere [≈1650 ppbv, Steele et al. (1987)] and as an infrared (IR) active gas contributes to the greenhouse effect (at 7.7 μm at the edge of the 8–13-μm atmospheric window). It has a long lifetime (7 years) and as a result is almost completely mixed in the troposphere. It shows an 8% interhemispheric difference as well as a seasonal variation. Since CH_4 is well mixed, column measurements are sufficient to identify surface sources (with 3D tracer models). However, since it is evenly mixed, higher precision is required to measure any spatial and temporal variations.

b. Instrument methodology

The CO and CH_4 concentrations will be measured using correlation spectroscopy. The spectral selection of CO and CH_4 radiation is done with a sample of the same gas as a filter. The correlation effect refers to the fact that the gas cell spectral lines will align perfectly with the CO and CH_4 incoming radiance spectral lines. By modulating the gas between two states, in this case by either changing the pathlength or the gas pressure, the transmission at the frequencies of the spectral lines varies, and an average and difference transmission is obtained. The difference signal carries information on

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Table 1. Summary of science requirements.

Parameter	CO profiles	CO column	CH_4 column
Wavelength (μm)	4.617	2.334	2.258
Midwavenumber (cm^{-1})	2166	4285	4430
Wavenumber range (cm^{-1})	52	40	139
Modulator type	LMC/PMC	LMC	LMC
Vertical resolution (km)	3	—	—
Horizontal resolution (km)	22 × 22	22 × 22	22 × 22
Temporal resolution (s)	0.4	0.4	0.4
Precision (%)	10	10	1

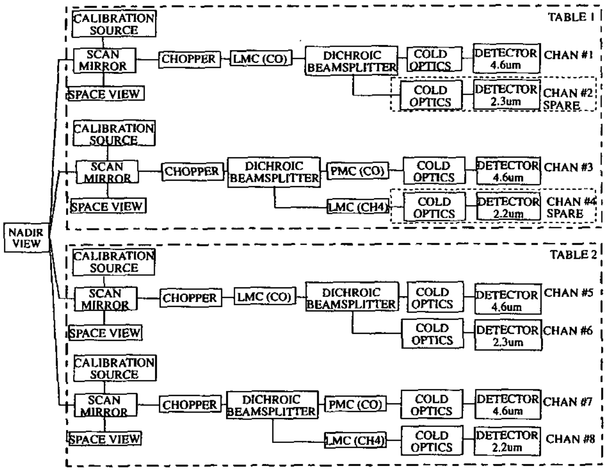


Fig. 1. Optical channels diagram. This shows the two table redundant configuration with radiance entering the instrument at the left-hand end.

the gas of interest, while the average signal carries information on total incoming radiance (minus the gas of interest). A discussion of correlation techniques can be found in Taylor (1983), Drummond (1989), and Berman et al. (1993).

The CO profile measurements are made using upwelling thermal radiance in the 4.6-μm fundamental band. The troposphere is resolved into about four layers with approximately 3-km vertical resolution, 22-km horizontal resolution, and 10% accuracy. Pressure-modulated cells (PMCs) are used to view the upper layers, while length-modulated cells (LMCs) are used for the lower troposphere measurements. By varying the cell pressures, the modulators can be biased to view the different layers.

The CO and CH_4 column measurements are made using reflected solar radiance in the 2.3-μm CO and the 2.2-μm CH_4 bands. The horizontal resolution is 22 km with a 10% and 1% precision requirement for the CO and CH_4 columns, respectively. Column measurements will be made using LMCs and will only be possible over the sunlit side of the orbit. The MOPITT instrument requirements are summarized in Table 1.

c. MOPITT instrument description

MOPITT is a scanning, nadir-viewing eight-channel IR radiometer. Figure 1 shows the optical system, the heart of the instrument, in diagrammatic form, and Fig. 2 shows the isometric layout. The instrument has two identical "mirror imaged" optical tables with calibration sources, scan mirrors, choppers, modulators, and cold dewar assemblies containing the cold optics and detector packages. The dewar is cooled by a pair of low-vibration, back-to-back stirling cycle coolers (SCCs). The largest heat dissipating units, namely the coolers and cooler drive electronics modules, are located on the coldplate, and other critical electronic modules are placed close to the coldplate.

The coldplate is located underneath the MOPITT baseplate (Fig. 2). It is dedicated to the instrument and provides a stable thermal environment (20°–25°C if the heat flux does not exceed 1 W in.$^{-2}$). It operates using capillary action with ammonia as the working fluid. The loop extracts heat at the coldplate and radiatively rejects it to space. The coldplate is used as a thermal sink for all modules except the main power supply module that is thermally isolated from the baseplate and radiatively cooled to space (Fig. 2).

The optical channel diagram (Fig. 1) shows the four MOPITT inputs. The front end of each input consists of a calibration source, a deep space view, an input scan mirror, and a chopper. Each beam is split resulting in eight output channels. Two inputs have modulator cells before the dichroic beamsplitter, and two have them after the beamsplitter. This configuration minimizes the number of modulator cells needed to make the required measurements. Fore, mid, and rear optics are used to relay the beam from the input scan mirrors, through the

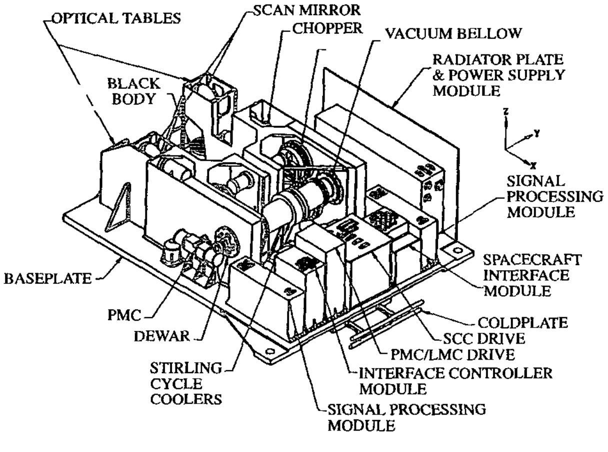


Fig. 2. MOPITT isometric layout. The baseplate dimensions are 1062.41 mm × 846.58 mm. The calibration sources are located beneath each scan mirror and protrude below the baseplate.

modulator cells and onto the cooled detectors. Each detector is a 4 × 1 array, giving four pixels in-line along the velocity vector. This results in a 88 km × 22 km imprint on the earth (MOPITT has a 7.2° × 1.8° nadir field of view). However, to improve global coverage MOPITT uses cross-track scanning. The input mirror scans across track by ±14 fields resulting in an overall earth swath of 88 km × 612 km. The scan mirror also rotates through 90° to view "space" as a radiation zero through ports on the side of the instrument and through a further 90° to view the calibrated blackbody sources (see below). The scan mirrors are driven by stepper motors and monitored by optical encoders. Thus, the mirror positions are known precisely with respect to one another. The nadir position is aligned to the spacecraft axes before launch. A summary of the MOPITT channel characteristics is given in Table 2.

TABLE 2. MOPITT channel characteristics.

Channel characteristics	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8
Optical table	1				2			
Scan mirror/chopper number	1		2		3		4	
Modulator type	LMC1		PMC1	LMC2	LMC3		PMC2	LMC4
Modulator gas	CO		CO	CH_4	CO		CO	CH_4
Modulator pressure (kPa)	20		7.5	80	80		3.8	80
Modulator frequency (Hz)	11		52	11	11		42	11
Chopper frequency (Hz)	518		518		600		600	
Cold filter midwavenumber (cm^{-1})	2166	4285	2166	4430	2166	4285	2166	4430
Cold filter FWHM (cm^{-1})	2192–2140	4305–4265	2192–2140	4500–4360	2192–2140	4305–4265	2192–2140	4500–4360
5% cutoff wavenumber (cm^{-1})	2199–2136	4316–4254	2199–2136	4519–4344	2199–2136	4316–4254	2199–4344	4519–4344
Minimum peak trans (%)	70	50	70	55	70	50	70	55
Out-of-band blocking (%)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Filter temperature (K)	95–110				95–110			
NER ($\mu W\ m^{-2}\ sr^{-1}$)	84	2.69	55	10.60	68	3.48	23.4	10.6

Figure 1 shows that the CO and CH_4 column channels have full redundancy (channel 2 redundant with 6, and 4 redundant with 8). The profile channels (1, 3, 5, and 7) can be reconfigured by changing fill pressure to cover for a failed channel.

A detailed description of the instrument is available in the MOPITT Mission Description Document (Drummond 1993).

d. Predicted radiometric performance

The radiometric performance is determined from the precision requirements given in Table 1. The CO profile and column must be measured to a 10% precision, and the CH_4 column to 1% precision. These requirements are transferred into an equivalent radiance sensitivity at the instrument input by calculating the radiance seen by the instrument for typical CO and CH_4 conditions and then perturbing the profile or column by 10% or 1%. The instrument radiometric noise-equivalent radiance (NER) should not exceed the equivalent radiance sensitivity value for 10% and 1% level measurements. The NER will be made up of a combination of factors such as detector noise, noise due to component temperature changes, polarization noise, etc. The overall channel NER requirements are given in Table 2. A comprehensive performance prediction shows that for the CO profile channels 1, 3, 5, and 7, thermal stability of the chopper and fore optics is of greatest concern and for channels containing LMCs (1, 2, 4, 5, 6, and 8) the optical balance condition should be carefully analyzed.

2. Prelaunch calibration and characterization

Preflight calibration and characterisation of MOPITT will be conducted at the University of Toronto's Instrument Characterisation Facility (ICF). As shown in Fig. 3, this facility consists of a class 10 000 clean room with adjoining preparation and control rooms. A cryo-pumped vacuum chamber 2.2 m in diameter and

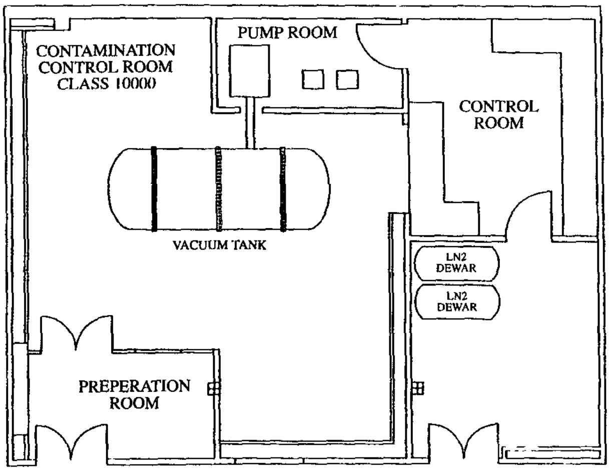


FIG. 3. Instrument characterization facility. The vacuum tank is 6.5 m long and 2.2 m in diameter.

6 m long will be used for all tests. An example of the field of view test configuration (see below) is shown in Fig. 4.

The tests conducted will fall into three distinct categories: radiometric, field of view (FOV), and spectral tests. Figure 5 shows the tests to be conducted, while Table 3 lists the major equipment requirements for the above tests. The tests are discussed in further detail below.

a. Radiometric tests

A radiometric calibration will be performed on all channels to determine instrument performance and to calibrate to absolute standards. The latter is necessary since MOPITT will use other datasets (such as a temperature field) during the retrieval process. The MOPITT requirements are an absolute accuracy of ±0.5 K for the CO profile channels and ±1 K for the CO and CH_4 column channels, based on an error budget from the 10% and 1% measurement requirements described in section 1d. Table 4 shows a top-level traceable noise equivalent temperature error budget (NEΔT) for each MOPITT channel, through the flight blackbodies to the ICF internal standard and to an international standard. Detailed analysis is provided in the MOPITT calibration peer review document (Mand 1994) and in the MOPITT radiometric analysis report (Hackett 1995).

The channel linearity, gain, and offset will be determined by using temperature variable blackbody (BB) targets based on the Along Track Scanning Radiometer laboratory targets (Mason 1991) and the Improved Stratospheric and Mesospheric Sounder laboratory targets (Nightingale 1992). The earth- and solar-reflected blackbodies (EBB and SRBB) will be used to calibrate the thermal and solar channels, respectively, over the expected input radiance range. A cold space blackbody (SBB) positioned at the space view ports will be used as a "zero" reference to determine the offset.

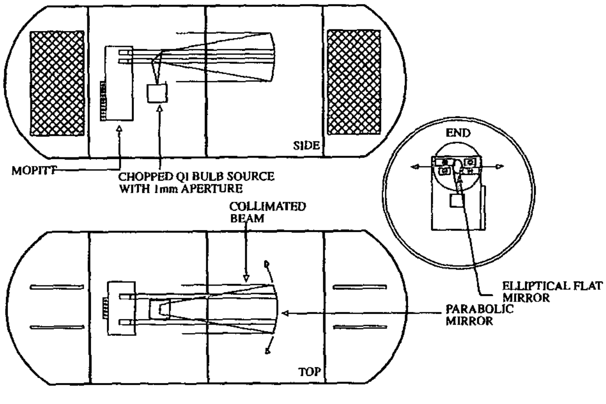


FIG. 4. Test tank configuration for the field-of-view tests.

Using the EBB and SRBB targets, the noise performance can be verified for the average and difference channels by successive stares at a fixed temperature target. The difference channel noise performance should not exceed the NER requirements given in Table 2.

By inserting a gas cell, with either CO or CH_4 and an inert mixture, between MOPITT and the EBB or SRBB, a simulated atmospheric signal is obtained. The partial and total gas pressures of the cell are changed, and the signal response as a function of pressure is measured. To differentiate between the EBB and the cell, a temperature contrast is required between the two. In this case the cell is kept at ambient, and the EBB temperature elevated to give higher radiance.

The effect of temperature changes, in particular of the fore optics, chopper, and focal plane array (FPA) will be measured. Changes in the fore optics and chopper temperature will lead to more frequent two-point

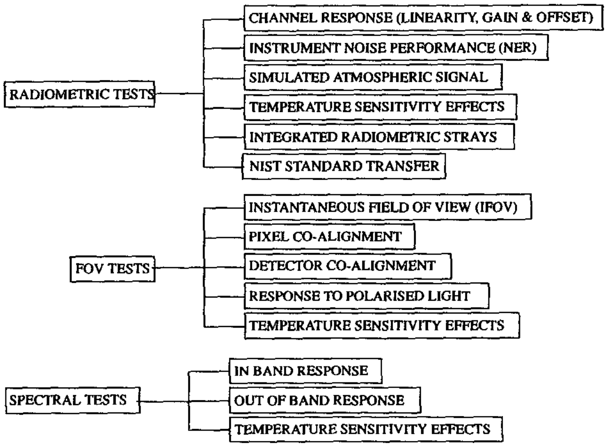


FIG. 5. MOPITT prelaunch test tree.

TABLE 3. Major ICF test support equipment.

	Radiometric tests equipment requirements		
BB requirements	EBB	SBB	SRBB
Aperture size (mm)	174 × 136 ellipse	360, circular	174 × 136 ellipse
Cavity	Baffled, grooved base	Baffled, grooved base	Baffled, grooved base
Cavity surface	3M diffuse black	3M diffuse black	MM enhanced black
Temp. range (K)	230–350	80	450–510
Estimated emissivity	⩾0.999	⩾0.99	⩾0.97
Total error (K)	±0.1	±0.1	±0.25
Other requirements	Gas cell	Stray plate	
Size (mm)	130 o.d. × 70 long	250 o.d. with a 165 × 110 elliptical aperture	
Temperature range (K)	298 ± 3	300–500	
Pressure range (kPa)	0–100	—	
	FOV and spectral test equipment requirements		
	Collimator	Pinhole source	Monochromator
Type and description	Newtonian, with 700-mm diameter parabolic mirror and 170 mm × 130 mm elliptical flat. Focal length of 2100 mm and a linear magnification of 70.	QI bulb operating @ 1000–2800 K, chopped @ ⩽5 Hz with a 1-mm output aperture diameter.	Czerny–Turner, with <0.01% stray light rejection and a 0.01% sorting filter rejection.

calibration (see below), while changes in FPA temperature will lead to increased detector noise and a higher instrument NER.

Radiometric stray effects could be due to diffraction effects, especially in the longwave channels, and scattering from mirrors and other surfaces. This effect will be measured by using an out of field of view stray plate that will be at a higher temperature than the EBB in the field of view.

The transfer of the National Institute of Standards and Technology (NIST) standard to the onboard calibration system is a two-step process. First the laboratory targets, namely the EBB and SRBB, will be calibrated using a NIST-supplied transfer radiometer. This standard will then be transferred to the flight blackbodies (FBB) by using the MOPITT detectors as a short-term standard. The input scan mirrors will be used to chop between the EBB/SRBB and the FBB with the detector system acting as a short-term transfer standard. An alternative link to the NIST standard is to calibrate the platinum resistance thermometers to the temperature scale and transfer to the radiance scale by using the calculated blackbody emissivities.

b. *Field-of-view tests*

These tests will be conducted for all channels in the nadir view and at the extreme cross-track scan angles. Each channel uses a 4 × 1 indium antimonide (InSb) detector array, and the FOV tests will be conducted on a pixel by pixel basis.

The instantaneous field of view (IFOV) will be determined by using a hot "pinhole" source and collimating optics. The source will be scanned across each pixel to determine its response and uniformity. The pixel IFOV will be mapped to 1/30 of a pixel. The align-

TABLE 4. Top-level traceable NEΔT budget.

Parameter	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8
MOPITT channel NEΔT (K)	0.33	0.14	0.42	0.028	0.069	0.044	0.39	0.028
Flight blackbody NEΔT (K)	0.3	0.8	0.3	0.8	0.3	0.8	0.3	0.8
MOPITT calibration blackbody NEΔT (K)	0.2	0.5	0.2	0.5	0.2	0.5	0.2	0.5
Transfer standard NEΔT allocation (K)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total RSS NEΔT (K)	0.53	0.97	0.59	0.96	0.42	0.97	0.57	0.96
MOPITT science requirement NEΔT (K)	1	2	1	2	1	2	1	2

ment of each pixel relative to the others within the detector array will be determined by running line scans across and along each pixel and relating the full-width half-maximum (FWHM) points to the source position.

Detector coalignment will be verified by all four input channels simultaneously looking at the same source. This will be achieved by relating detector centroids. The IFOVs of all four channels should coregister to within $1/20$ of a pixel.

The input scan mirror and beamsplitters will lead to a small polarization of the input radiance. The magnitude of this effect will be measured and recorded by inserting a polarizer between the source and MOPITT and controlling the polarization of the input.

Changes in the FPA temperature will be used to verify the optical stability, since such changes could lead to a focal shift resulting in a change in the IFOV.

c. Spectral tests

The instrument spectral response is limited by the cold narrowband optical filters in each channel. Although the spectral response will have been characterized at component level, spectral changes may occur due to the instrument build and test and any temperature changes of the FPA. Furthermore, the angle of incidence on the filter, which depends on filter location within the optical chain, may result in filter shifts if it sits in a noncollimated region. Unknown spectral shifts could (falsely) be interpreted as a nonlinearity in the radiometric channel response.

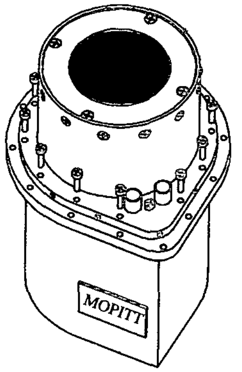
The spectral profile, shape, FWHM, and 5% cutoff points of each channel will be measured to a spectral resolution of 1 cm^{-1} by using a monochromater in conjunction with the collimating optics. Wider scans at a 5-cm^{-1} resolution will be conducted to check for any spectral leaks. The effects on the cold filter profile of changes to the FPA temperature will be measured and recorded.

3. In-orbit calibration and characterization

Of the above preflight radiometric, FOVs and spectral calibrations, MOPITT will only perform in-flight radiometric calibrations.

An onboard radiometric calibration is essential due to instrument variation over its lifetime. MOPITT has two forms of radiometric calibration: the main two-point calibration and a secondary, fast one-point calibration.

The two-point calibration uses the FBBs in conjunction with a deep space view, while the one-point calibration uses the back of the fast chopper as a target.



	4.7um CHANNEL	2.2-2.3um CHANNELS
TEMP (K)	285-350K	350-500K
POWER	0-1.5W	1.5-8W
APERTURE SIZE	2.21"	2.21"
COATING	ENHANCED MM BLACK	
EMISSIVITY	0.997	0.98
TOTAL ERROR	0.3K	0.8K

FIG. 6. MOPITT flight blackbody (built by BOMEM Inc.).

The FBBs are dual-temperature band sources capable of calibrating both the thermal and solar channels. Figure 6 shows one such FBB with its top-level requirements. Four such FBBs are used, each one located beneath the scan mirror. The general two-point calibration sequence is as follows. The FBBs are brought to the required temperature, the input scan mirror interrupts its nadir view scanning and rotates through 90° for a 40-s deep space view, it then rotates a further 90° for a 40-s FBB view before returning to its nadir view cross-track scanning mode. For the thermal channels the FBBs are held at 300 K, and the frequency of calibration is 30 min. Calibration is autonomous with the ability to change the frequency and dwell times if required. For the solar channels the FBBs are heated to 500 K before the calibration sequence is executed. This requires an 8-h ramp up (and ramp down). However, since these channels are far less susceptible to instrument temperature drifts, this calibration will be performed once a month. This will be initiated via a ground command.

The secondary one-point calibration is to use the back of the fast chopper. The chopper back face has a high-emissivity coating, while the front face is highly reflective to minimize radiative coupling. The chopper is enclosed in a temperature-controlled shroud. By using the chopper in this fashion, all components after the chopper can be calibrated on a 1.67–2-ms time period; thus, temperature drifts in these components do not pose a problem beyond this timescale. The chopper and all components before it are calibrated by the two-point calibration.

4. Retrieval algorithms

The data analysis and processing, from raw level 0 data to level 3 is the responsibility of the National Center for Atmospheric Research (NCAR) coinvestigative group. The retrieval flow from level 0 to 3 is shown in Fig. 7 along with the ancillary dataset requirements.

The raw level 0 data from the instrument will be in the form of average and difference channel signals on a per stare basis. They will be supplemented by the time, spacecraft position, and attitude information as well as information regarding cell and chopper frequencies and scan mirror position.

These data will be converted into level 1 calibrated average and difference channel radiances by using the

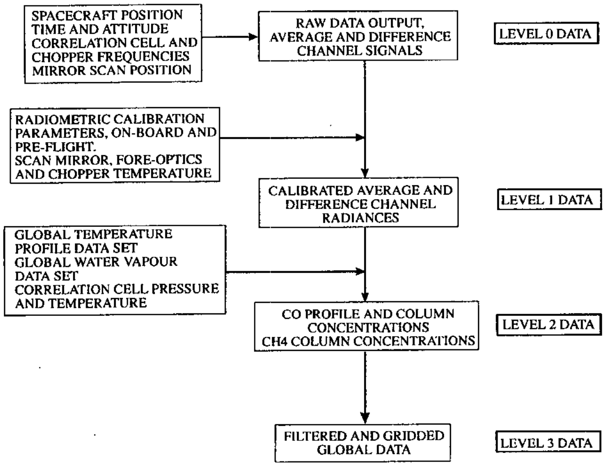


FIG. 7. Retrieval flow diagram.

onboard and preflight radiometric calibration information. This may be further supplemented with the fore optics and chopper temperature knowledge to improve the calibration accuracy.

To extract the level 2 profiles and column concentrations global temperature and atmospheric water vapor profiles will be required. Temperature profiles at each measurement location are needed to invert the radiative transfer equation, while the water vapor profiles will be used to correct the derived concentrations since it will be the main contaminant in the measurement.

Level 3 data will be the filtered and gridded level 2 data.

5. Data validation

MOPITT data validation at levels 1 and 2 will be done to ensure the retrieved concentrations are correct by using ''external'' checks on the data. An important feature of this activity is the use of an ''aircraft MOPITT.'' This will be principally used to underfly the satellite instrument and validate the level 1 data (some corrections will have to be made, for instance, different FOVs and corrections for the atmospheric levels above the aircraft). Level 2 data may also be compared between the two sensors.

Further level 2 validation will be through aircraft measurements of CO and CH_4 profiles with in situ measuring devices and balloon measurements at selected times and places. Total column CO and CH_4 validation will be through ground-based measurements. Level 2 total column measurements may also be compared with measurements by other EOS sensors, namely from the Atmospheric Infrared Sounder and the Tropospheric Emission Spectrometer instruments, when available.

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