MOPITT

Measurement of Pollution in the Troposphere

ALGORITHM THEORETICAL BASIS DOCUMENT

Conversion of MOPITT Digital Counts into Calibrated Radiances
in Carbon Monoxide and Methane Absorption Bands

(Level 0 to Level 1)

University of Toronto and
NCAR MOPITT Team

Version 2

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Algorithm Theoretical Basis Document (ATBD)

Production of Located, Calibrated MOPITT Radiances from Instrument Output Counts

(Level 0 to Level 1)

1.0 Introduction

This document briefly outlines the Measurement of Pollution in the Troposphere (MOPITT) investigation. It then describes the physics and mathematics of the algorithms that convert the instrument outputs from raw digital counts (Level 0 data) to calibrated radiances that are located over the globe (Level 1 data). The Level 0 inputs to these algorithms are:

- The telemetered instrument outputs, including those from the detectors, all temperature, pressure, time and angle sensors, and other monitors of instrument state and performance.
- Data on the spacecraft position and attitude as a function of time.

The Level 1 outputs from these algorithms will subsequently be used as inputs to the algorithms that retrieve vertical profiles of carbon monoxide, and total column amounts of carbon monoxide and methane (Level 2 data). The algorithms that create the Level 2 data from the Level 1 data are discussed in a separate ATBD.

The algorithms described here are the Version 1 prototype algorithms. These are being developed by the Instrument Team at the University of Toronto on their facilities, where they will be used to explore different approaches to the most efficient recovery of the information from the MOPITT output data, including taking account of the instrument effects expected to be present in the flight data.

Subsequently, these algorithms will be incorporated into formally documented codes which will be written and tested on the NCAR Science Computing Facility (SCF). These codes will then be ported to the Langley DAAC, where their operation and outputs will be verified. They will be run on data acquired in orbit during the flight phase of the program.

This first version of the Level 0 to Level 1 ATBD will reflect the present status of the prototype algorithms. With time the algorithms will evolve to include the capability to handle more complex situations, and the ATBD will be updated to reflect these increased capabilities.

APPLICABLE DOCUMENTS AND PUBLICATIONS

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Reichle Jr., H. G. , V. S. Connors, J. A. Holland, W. D. Hypes, H. A. Wallio, J. C. Casas, B. B. Gormsen, M. S. Saylor, and W. D. Hesketh, Middle and upper tropospheric carbon monoxide mixing ratios as measured by a satellite-borne remote sensor during November 1981, *J. Geophys. Res., 91*, 10865-10887, 1986.
Reichle, Jr., H. G., V. S. Connors, J. A. Holland, R. T. Sherrill, H. A. Wallio, J. C. Casas, E. P. Condon, B B.Gormsen, and W. Seiler, The distribution of middle tropospheric carbon monoxide during early October 1984, *J. Geophys,. Res., 95*, 9845-9856, 1990.
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2.0 Overview and Background Information

2.1 Experimental Objective

The MOPITT experiment has been described by Drummond (1992). The primary objective of the MOPITT investigation is to enhance our knowledge of the chemistry of the troposphere, and particularly how it interacts with the surface/ocean/biomass systems, atmospheric transports, and the carbon cycle. The particular focus is the time evolution of the distributions of CO and CH_4 in the troposphere. From these a better knowledge of their chemical interactions, transports, sources and sinks will be obtained. 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.

For CO the objective is to obtain profiles with a resolution of 22 km horizontally, 4 km vertically and with an accuracy of 10% throughout the troposphere. For CH_4 the objective is to measure the column in the troposphere to a precision of better than 1%, with a spatial resolution similar to that of the CO measurement. The column measurements will only be available on the sunlit side of the orbit.

The global distribution of these profiles and column amounts will be used in descriptive studies of these gases on a global basis, providing the first detailed information on their horizontal, vertical and temporal variations, and their relationships to other activities such as biomass burning, industrial activity, thunderstorm venting of the boundary layer, etc. They will also be used in parallel modelling 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.

2.2 Historical Perspective

There has been no previous use of these algorithms. However, they are typical of those used frequently to calibrate the outputs of radiometers, and to locate the observations made by space-based instruments on the earth's surface.

2.3 Instrument Characteristics

The measurement concept and ideas of correlation radiometry are outlined here. Drummond (1992) has outlined the MOPITT instrument. The approach and viewing geometry are shown in Figure 2.3.1. MOPITT, on the AM1 platform, measures upwelling thermal emission from the atmosphere and surface, and solar radiation that has passed through the atmosphere, been reflected at the surface, and transmitted back up through the atmosphere.

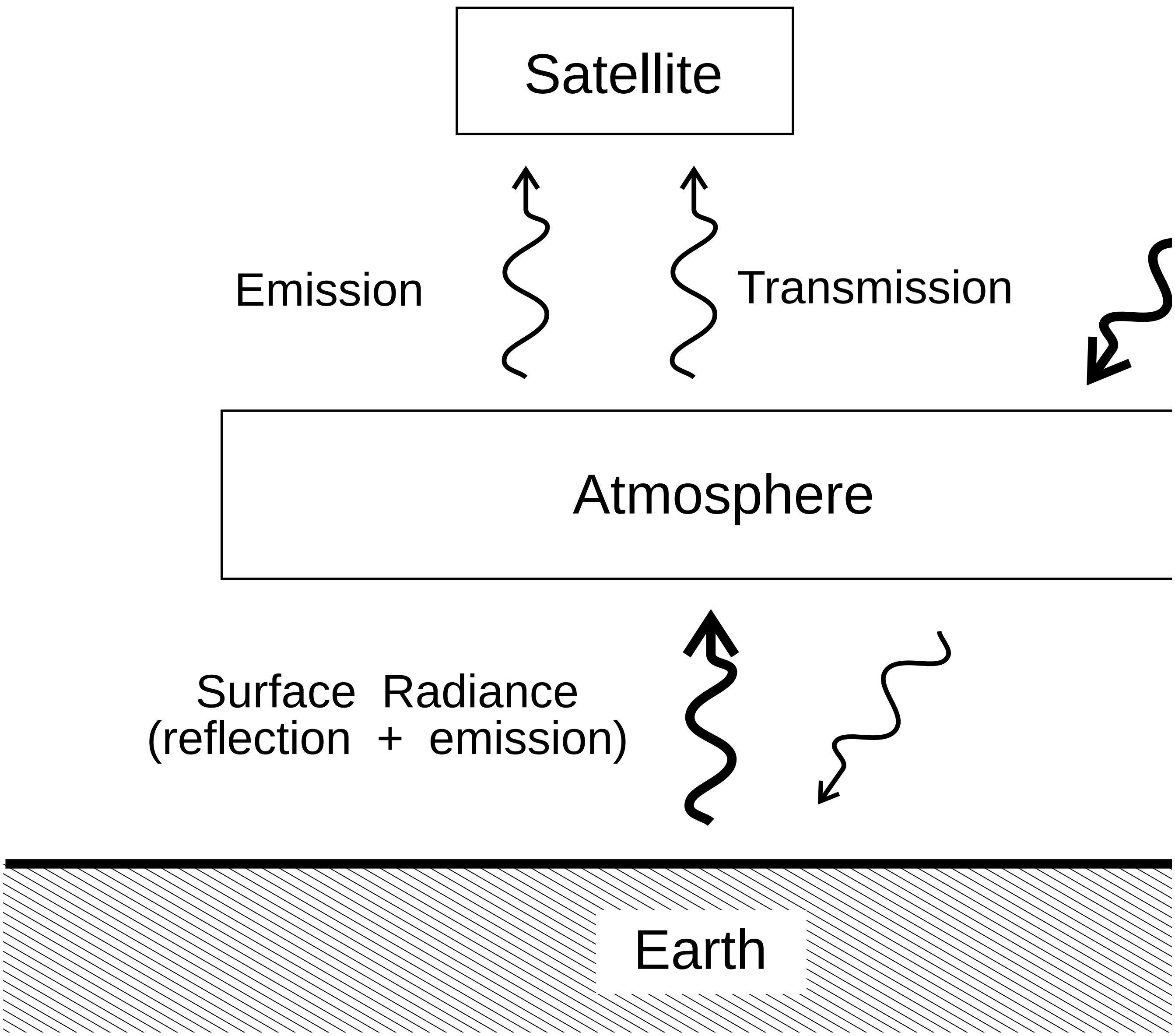


Fig. 2.3.1 Schematic of MOPITT measurement system.

Measurement of the transmittance of reflected sunlight is a convenient way to determine the total column amount of a trace gas. In order for this to work, the gas must have a spectral band in a region with large solar radiance, and for which the total optical depth along such a path is not too large. Methane has a set of overtone and combination bands near 2.2 µm which provide a measurable but not too large total absorption for such a path. For carbon monoxide, the first overtone band, at 2.3 µm, is suitable for a total column measurement.

For vertical profiling, the requirement is that significant and measureable portions of the signal must originate in different atmospheric layers, which means that there must be a few values of different but appreciable opacity in the atmosphere, and that there must also be a source of radiation in the atmosphere. Thermal emission is a radiation source, and the CO fundamental band at 4.7 μm has enough opacity to determine atmospheric amounts, as demonstrated by Reichle et al. (1986, 1990).

All three of these bands are in regions of the spectrum with other gas bands, and the lines of interest are mixed with those of interfering species. In principle it is possible to measure total emission or transmission in a spectral band, and then correct for the contributions of the interfering species to arrive at a measurement of the species of interest. However, the contributions of the other species are considerably larger than those of the gases of interest, and their amounts are often not known with sufficient accuracy. The uncertainties of the corrections may significantly degrade, or even mask, the detection of changes in the gas of interest.

The MOPITT approach to meeting this challenge is to enhance the sensitivity of the instrument to the gas of interest. Since all gases in the atmosphere are emitting/absorbing simultaneously it is essential that we be able to separate out the effect of the gas of interest from the general radiation field. Further, since we shall see that the information about the height distribution of the gases is contained within the shape of an individual absorption/emission line, it is necessary to be able to resolve the line shape in some manner.

There is, however, a fundamental problem, since the above implies high dispersion to separate the fine details of the spectrum. With high dispersion comes low sensitivity and high precision requirements that are difficult to implement in a space-based instrument.Correlation Radiometry (CR) offers the opportunity for high selectivity without the attendant low sensitivity and high precision requirements.

The fundamental techniques of correlation radiometry are illustrated using the apparatus illustrated in Figure 2.3.2. The cell contains a sample of the gas under consideration. If monochromatic radiation enters from the left and is detected by the system on the right then the output as a function of spectral frequency is shown in Figure 2.3.3(top) 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 alternately looking through two different filters. If the difference of the two signals is taken, this signal will be identical to the output of a system in which the gas cell and it's modulator are replaced by an optical filter of profile shown by the Effective Difference Transmission (EDT) curve in Figure 2.3.3(middle)

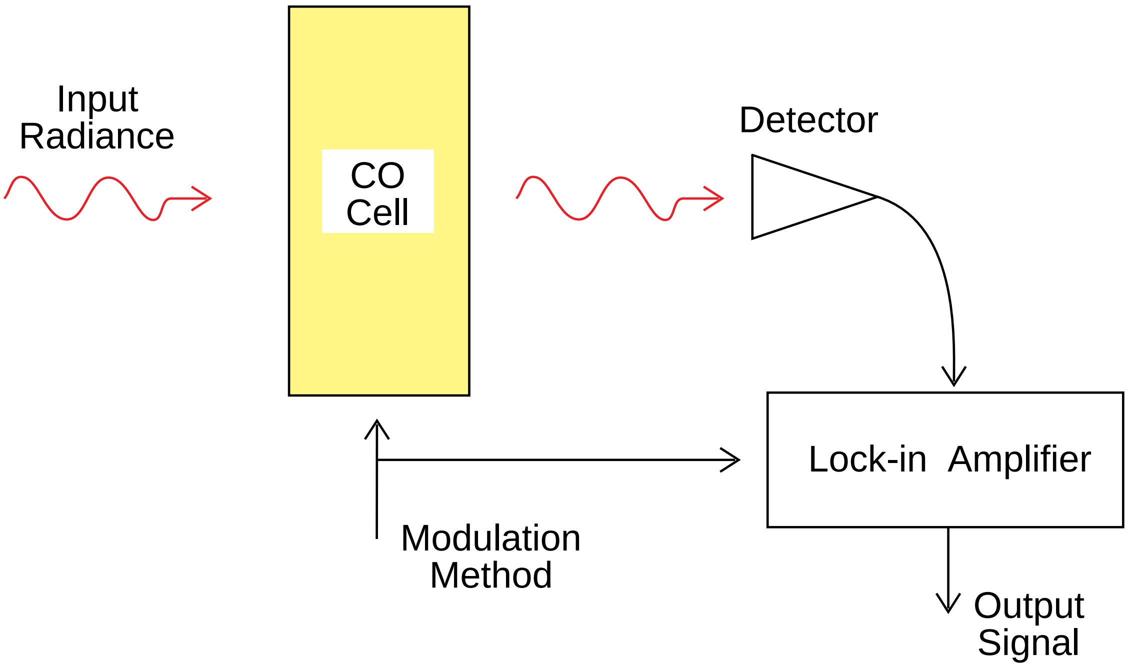
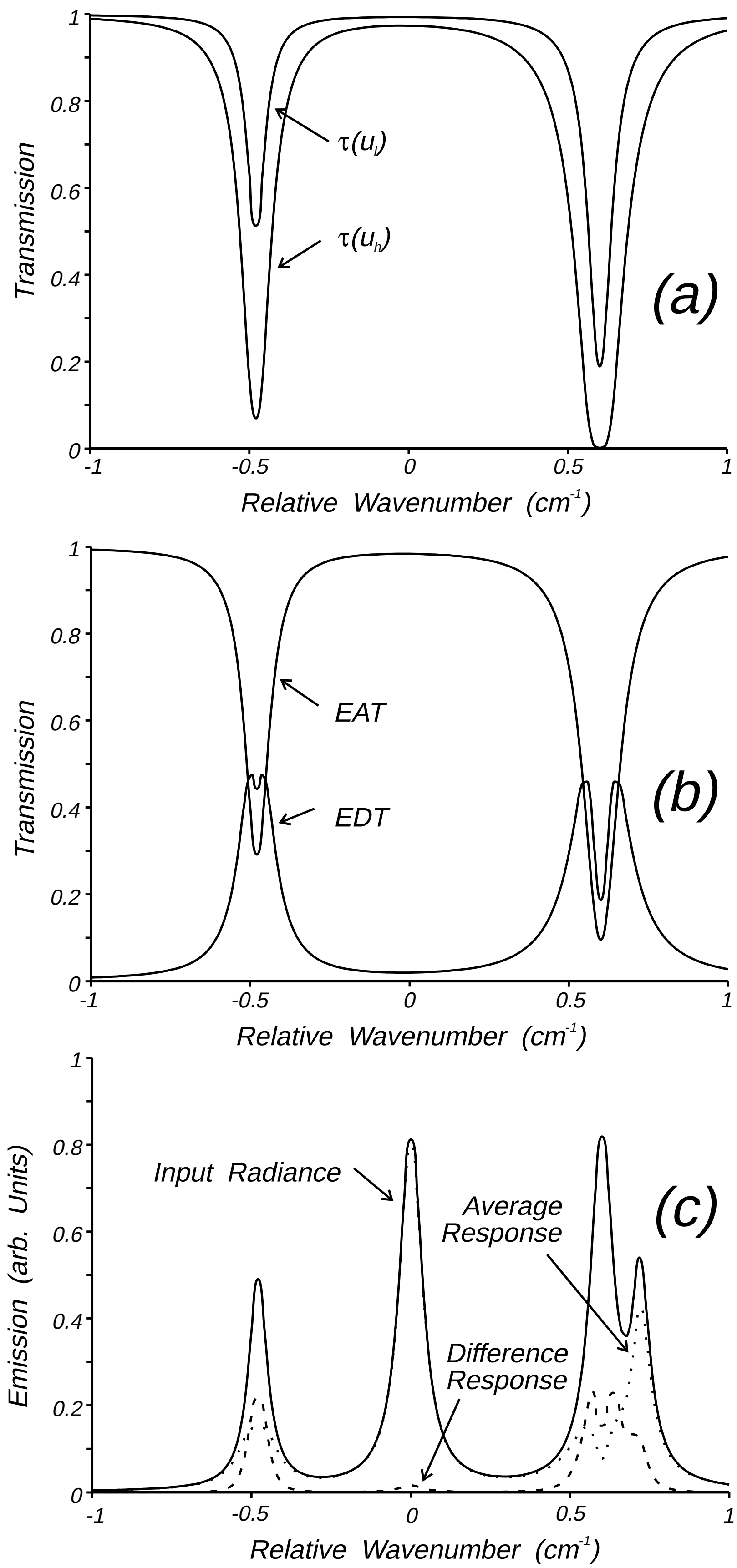


Fig. 2.3.2 A basic correlation radiometry system.



Transmission
Relative Wavenumber (cm^{-1})
$\tau(u_l)$
$\tau(u_h)$
(a)
EAT
EDT
(b)
Emission (arb. Units)
Input Radiance
Average Response
Difference Response
(c)

Fig. 2.3.3 Operation of a correlation spectrometer in spectral space. EAT is the Equivalent Average Transmission. EDT is the Equivalent Difference Transmission.

Note that this apparatus has the following properties:

- The "equivalent filter profile" approaches zero between the spectral lines of the gas in the cell, eliminating signals from most of the spectrum.
- The filter profile has a maximum at each spectral line and therefore the energy from each spectral line in a broadband emission is seen simultaneously. The system is therefore very sensitive to radiation with a spectrum identical or similar to that of the gas in the cell. Evidently the spectrum of the gas itself is the best correlated with the filter profile.
- The apparatus contains no high precision optical adjustments. Quantum mechanics keeps the spectra aligned. In fact the only phenomena which affects the alignment is Doppler shifting of the cell and the emission spectrum. The effect of the filter is shown in Figure 2.3.3(bottom) where it can be seen that the spectral emission from lines coincident with spectral lines of the gas in the cell (even if they originate from another gas) is detected and other emission lines are suppressed.
- Although not shown explicitly here, 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 be largest at the line centers, where absorption coefficients are largest. If larger amounts of gas are in the cell, the lines will be broader and completely absorbed in the centers. In this case, the differences will be larger in the line wings, where absorption coefficients are smaller.

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, corresponding to lower altitudes.

The average of the signals obtained at the two states of the CR cell can also be obtained. The resulting Effective Average Transmittance (EAT) is also shown in Figure 2.3.3(middle). It has the property that it’s transmittance is near unity away from the lines in the cell, but it reduces the signals at the centers of the lines. Thus, it is sensitive to other gases, and especially to the surface contribution to the upwelling radiation in the spectral regions considered here.

MOPITT makes use of two methods to modulate the gas transmittance. The first is by pressure modulation, through use of pressure modulated cells (PMC's), which have been described by Taylor (1983). The second is by modulating the length of the gas cell in the optical path, through length modulated cells (LMC's), which have been described by Drummond (1989). The MOPITT optical arrangement, shown in Figure 2.3.4, employs 2 pressure modulated radiometers (PMR’s) with different mean pressures, and 4 length modulated radiometers (LMR’s). Dichroic filters are used to separate the 2.2 μm and 2.3 μm channels from the 4.7 μm channels, thus producing a total of 8 separate channels. The characteristics of the channels are given in Table 2.3.1. Each produces an Average (A) and Difference (D) signal. It is the outputs of these radiometers that must be calibrated and located.

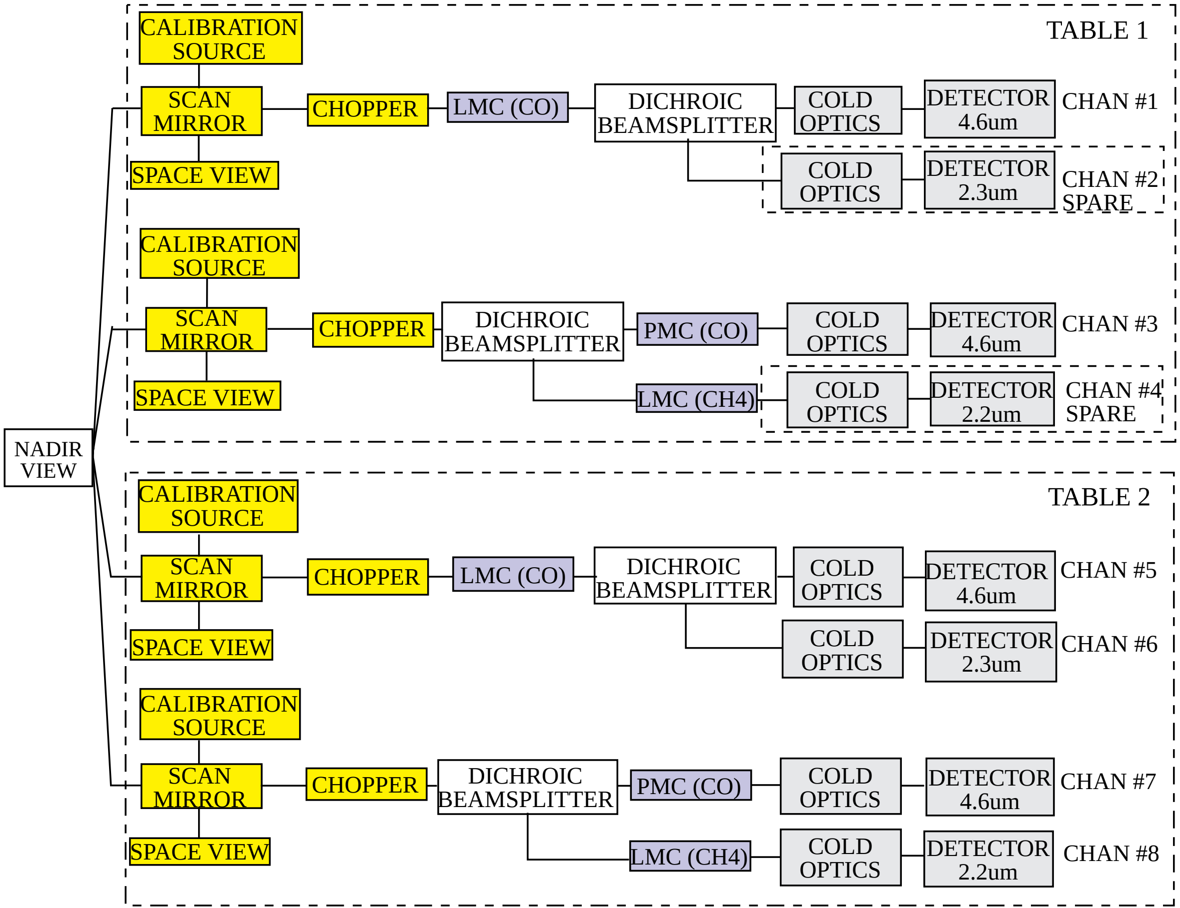


Fig. 2.3.4 MOPITT optical channel diagram.

Channel Characteristics	1	2	3	4	5	6	7	8
Gas Species	CO	CO	CO	CH_4	CO	CO	CO	CH_4
Nominal Gas Pressure (kPa)	20	20	7.5	80	80	80	3.8	80
Mid-Wavenumber (cm^{-1})	2166	4285	2166	4430	2166	4285	2166	4430
Wavenumber Range (cm^{-1})	52	40	52	139	52	40	52	139
Mid-Wavelength (mm)	4.617	2.334	4.617	2.258	4.617	2.334	4.617	2.258
Wavelength Range (mm)	0.111	0.022	0.111	0.071	0.111	0.022	0.111	0.071
Modulator Type & Number	LMC1	LMC1	PMC1	LMC2	LMC3	LMC3	PMC2	LMC4
Nominal Modulator Freq (HZ)	11.78	11.78	51.85	11.78	11.54	11.54	42.85	11.54
Nominal Chopper Freq (Hz)	518.5	518.5	518.5	518.5	600	600	600	600
Scan Mirror/Chopper Number	#1	#1	#2	#2	#3	#3	#4	#4

Calibration Source Number	#1	#1	#2	#2	#3	#3	#4	#4
Optical Table	#1	#1	#1	#1	#2	#2	#2	#2

Table 2.3.1 MOPITT channel characteristics. Channels 1,3,5, and 7 are CO thermal channels. Channels 2 and 6 are CO solar channels. Channels 4 and 8 are CH_4 solar channels.

3.0 Algorithm Description

The description of the Level 0 to Level 1 processing will begin with a discussion of required inputs to the algorithm and brief descriptions of MOPITT instrument operations and its optical system. This will be followed by a detailed discussion of theoretical and practical aspects of the algorithm.

3.1 Theoretical Description

The first step in the data processing of the MOPITT instrument is the conversion of the science data stream values, which reflect the output of the analog-to-digital converters, into calibrated radiances. The fundamental assumptions of the calibration procdure are:

- All emissions within the instrument obey Planck's Radiation Law.
- The optical system obeys Scharzchild's equation.
- The optics, detector and electronic systems are linear.
- Temperatures drift slowly and are monitored.

The two required radiances are:

- The average signal over the two states of the correlation cell.
- The difference signal between the two states of the correlation cell.

The optical system has twelve states (see below). The driver behind such a complex set of states are the need to counteract two significant causes of systematic error in the instrument:

- Temperature drifts in all optical components. This is particularly a problem for the 4.7 μm channels. These are short-term variations and tend to be cyclic or random in nature.
- Long-term drifts in the system transfer function (gain) and in the electronic offsets. These are due to changes in the optical system, the detector system and the electronic system. These tend to be systematic over long (month-years) periods of time.

An overall “road map” of the Level 0 → 1 processing is shown in Figure 3.1.1 which should be consulted along with the following description.

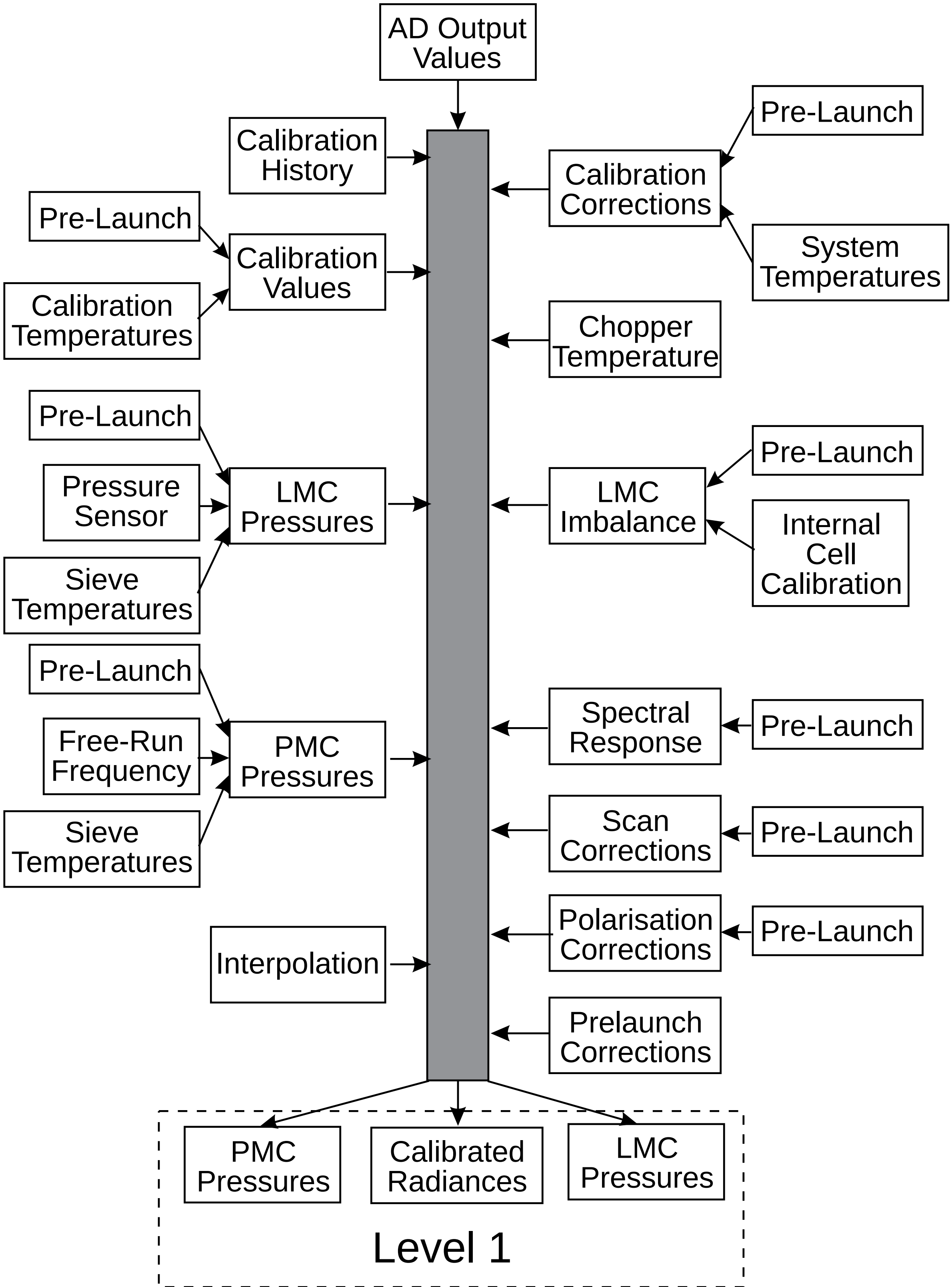


Fig. 3.1.1 Level 0 to Level 1 flow processing diagram.

3.1.1 Physics of the Problem

INPUTS TO THE LEVEL 0 → 1 ALGORITHM

- Count outputs from the signal channel analog-to-digital converters (one per channel).
- PRT and calibration voltage outputs for calibration sources at previous and future calibration times.
- PRT and calibration voltage outputs for:
  - chopper
  - molecular sieve units
- Thermistor analog-to-digital and calibration voltage outputs of:
  - correlation cells
- Encoder outputs for the scan mirrors
- Sampling totals for the analog-to-digital converter accumulators
- Spacecraft position
- Spacecraft attitude
- Time of measurement

INSTRUMENT OPERATIONS

The operation of the instrument can be described as follows. A series of earth views is taken with a set period of view. The scanning system combined with the spacecraft forward motion moves this view across the planet such that the center of a given view in all channels is collocated. These views are denoted as EARTH views. Periodically the scanning is interrupted and a SPACE view and an INTERNAL view are taken as calibration points. During most calibration sequences the calibration blackbodies are maintained close to or at the instrument base plate temperature (short calibration) but periodically the blackbodies are elevated to above 400 K for a short-wave calibration (long calibration). This scanning sequence is illustrated in Figure 3.1.2.

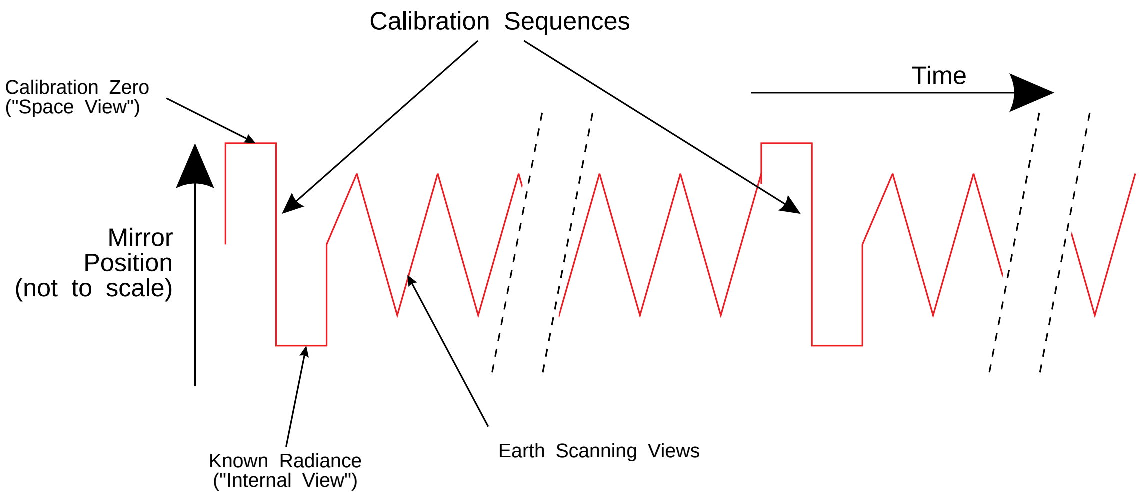


Fig. 3.1.2 Typical MOPITT scanning sequence.

Each dwell time in the scan is called a "stare" and all data processing is done in units of a stare. A stare view time is 0.4 s in length with 0.054 s between stares. The inter-stare time exists to permit the data-processing system time to read out the signals and the mirror time to step and settle. However all data is considered on a stare basis even if the mirror does not move. Thus a view of a calibration target may be described as "32 stares" implying that there will be 32 data units 0.4 s in length to be averaged for that radiance input.

OPTICAL SYSTEM DESCRIPTION

A simplified diagram of a single channel optical system is shown in Figure 3.1.3. Monochromatic radiation striking the input mirror of the optical system within the field of view (FOV) of the instrument is transferred to the detector through an optical system with a finite transmission. At the same time the optical system emits radiation within the FOV which is also relayed to the detector with an effectiveness which varies with the position of the emitting component in the optical train.

It should be recognized that the input radiance has a strong spectrally varying component and the presence of the correlation cells implies that this is also true for the optical system.

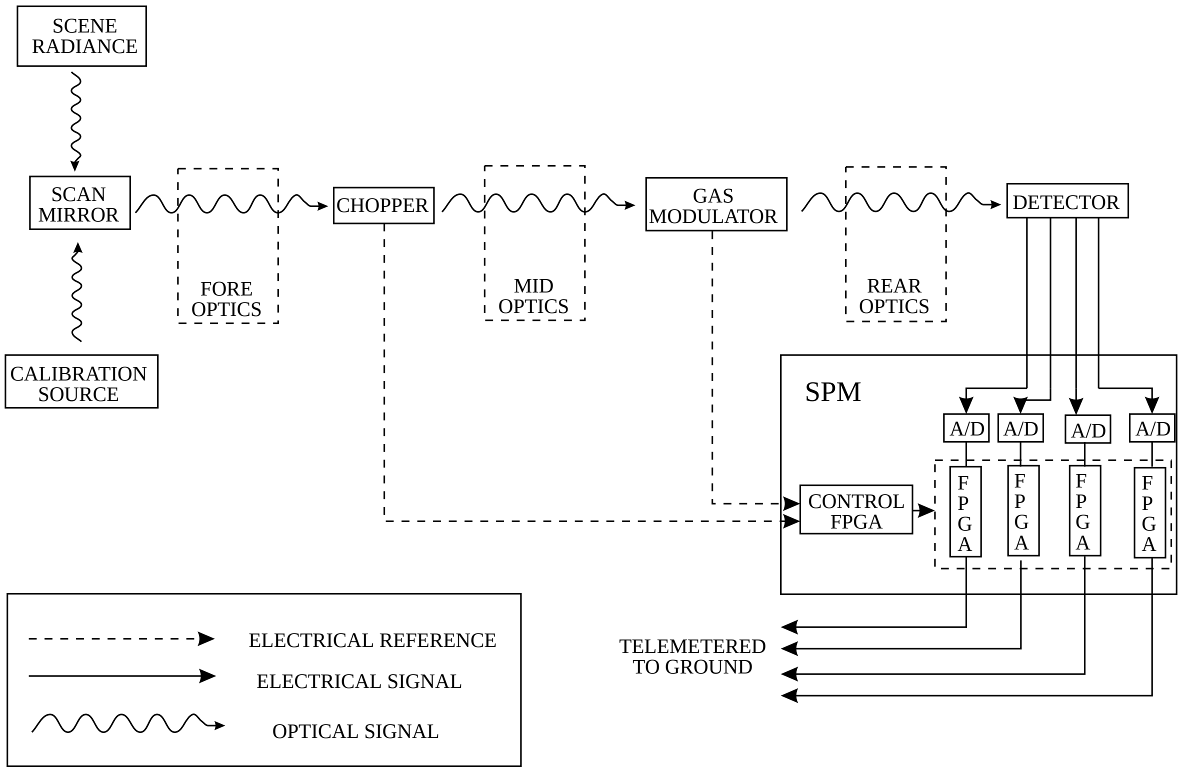


Fig. 3.1.3 Single channel optical functional diagram.

SYSTEM CHOPPING AND CORRELATION CELL MODULATION

Two mechanisms cause the optical system to change its configuration with time: the correlation cell and the "chopper".

The correlation cell is a cell of gas whose physical state (either pressure, for a pressure modulator cell (PMC) or length (LMC)) is modulated at a known rate in a known manner. The purpose of this cell is to produce a signal which is indicative of radiance around the absorption lines of the cell gas alone. In this analysis the correlation cell is considered as a device with two states, generically referred to as the UP and DOWN states. This description is adequate for the LMC, but in practice a more detailed model of the PMC will be required. Modulation rates are approximately 20 Hz for LMCs and 40 Hz for PMCs

The chopper is used to partially eliminate the instrument emission signals from the problem. It consists of a blade which blocks the input beam and substitutes a known radiance (the back of the chopper blade) for the input radiance. The measurement of a known radiance at frequent intervals enables the changes in the instrument emission signals to be monitored.

The chopper in MOPITT is a rotating chopper, and this fact is used advantageously to make the chopping asymmetric (the OPEN time is longer than the CLOSED time). This is done to minimize the noise contributions from the two states. For some channels the noise in the OPEN state is higher due to the increased photon flux and for nearly all channels the smoothing of the CLOSED states (see below) effectively decreases the noise.

The total (OPEN + CLOSED) chopping interval is about 1.6 ms per cycle. This fast interval is also linked to the data acquisition system and to the correlation cell rates, thus all rates are synchronized for optimum data collection.

DATA ACQUISITION

The data acquisition system in MOPITT is designed to be as stable as possible which implies a high digital content. The signals are amplified and minimally filtered before being digitized and averaged over the chopper OPEN and chopper CLOSED situations. The averages are taken during the period of OPEN and CLOSED only, specific gating being applied to eliminate transitional data. This restricts the data taken, but ensures that they are stable and valid at all times.

The analog-to-digital converter actually samples at an extremely high rate (about 320 kHz) but this rate is reduced to one sample per sector internally to the Signal Processing Module (SPM) in MOPITT by summing a large number of samples. This total, along with the knowledge of how many samples are being summed, becomes the signal for the chopper state. The signals transmitted to the ground system are:

- For a PMC the sum of the chopper OPEN and chopper CLOSED states for each of the PMC UP and DOWN states for one stare (4 signals/stare).
- For an LMC the sums of the chopper OPEN and chopper CLOSED states for each of the LMC sectors in the stare (16 signals/stare). The interpolation to 4 signals/stare is discussed below.

The two sums just listed are converted to average values as part of the processing after the signals are received on the ground. Because the detector output is sampled only when the chopper is fully open, or fully closed, there is no chopping factor that enters into the L0 to L1 processing.

INPUT RADIANCES

The discussion in the following sections is deliberately presented in terms of radiances, since the radiances are the relevant quantities. A highly simplified optical diagram is shown in Figure 2.3.4. The corresponding equation for the signal S at any time with the chopper OPEN is:

$$S = \frac{G}{T_o}\int_{v_1}^{v_2}\{([L_{input}\tau_1 + L_1]\tau_2 + L_2)\tau_g\tau_3 + L_3\}\tau_4\tau_f dv + F \tag{1}$$

where T_o is the time the chopper is open, L_{input} represents the input radiance, L_1, L_2, L_3 represent the system emissions from before and after the chopper and correlation cell, τ_1, τ_2, τ_3, τ_4 the broadband optical transmissions, τ_g the gas transmission of the correlation cell, τ_f the normalized filter transmission, G the system gain and F the system offset. With the chopper CLOSED the equation becomes:

$$S = \frac{G}{T_c}\int_{v_1}^{v_2}\{([L_{chopper}]\tau_2 + L_2)\tau_g\tau_3 + L_3)\}\tau_4\tau_f dv + F \tag{2}$$

where Tc is the time the chopper is closed.

Therefore the signal observed at any instant in time can be considered to be a combination of emission from the instrument and the input signal to the optics with appropriate weighting of the two terms. This weighting varies with the state of the optics, scanning and time. By measuring the variation of the signal with optical state and understanding the mechanisms which cause the variation, the input signal alone can be deduced.

As an example of the process of elimination of the instrument terms consider the case where the emission signals L_2 and L_3 are stable on the time scale of the chopper. The above equations can be differenced to get:

$$\Delta S = G\int_{v_1}^{v_2}[L_{input}\tau_1 + L_1 - L_{chopper}]\tau_2\tau_g\tau_3\tau_4\tau_f dv \tag{3}$$

The terms L_1 and $L_{chopper}$ will be eliminated in the next step of the calibration process using the calibration sources. The signal ΔS will be referred to as the "chopper difference signal" (CDS).

Overall, each channel of input has twelve states and twelve radiances from which two representations of the input signal are derived. The twelve states are:

State	Chopper Condition	Correlation Cell Condition	Scan Condition
1	OPEN	UP	EARTH
2	CLOSED	UP	EARTH
3	OPEN	DOWN	EARTH
4	CLOSED	DOWN	EARTH
5	OPEN	UP	SPACE
6	CLOSED	UP	SPACE
7	OPEN	DOWN	SPACE
8	CLOSED	DOWN	SPACE
9	OPEN	UP	INTERNAL
10	CLOSED	UP	INTERNAL
11	OPEN	DOWN	INTERNAL
12	CLOSED	DOWN	INTERNAL

The definitions for the various mechanism states are:

Chopper [OPEN]. Chopper is fully clear of the optical system
Chopper [CLOSED]. Chopper fully blocks incoming radiation
Correlation Cell [UP (DOWN)]. For a length modulator cell (LMC), this refers to the short (long) path condition. For a pressure modulator cell it refers to the condition with the piston above (below) the average time point. The average time point in turn is the point which the piston spends 50% of the time above and 50% of the time below.
Scan Condition [EARTH]. Scan system is disposed so that the input radiance comes from some part of the planet; these data are the ones required.
Scan Condition [SPACE]. The instrument scanning system uses the side ports to direct the view to space. The input radiance is effectively zero under these conditions.
Scan Condition [INTERNAL]. The instrument scanning system directs the view into the appropriate on-board calibration blackbody.

CHOPPER DIFFERENCE SIGNALS (CDS)

The individual signals are first differenced to form six CDSs.

State	Signal	Correlation Cell Condition	Scan Condition
1,2	$S_{1,2}$	UP	EARTH
3,4	$S_{3,4}$	DOWN	EARTH
5,6	$S_{5,6}$	UP	SPACE
7,8	$S_{7,8}$	DOWN	SPACE
9,10	$S_{9,10}$	UP	INTERNAL
11,12	$S_{11,12}$	DOWN	INTERNAL

These differences are taken to eliminate instrument emission terms due to temperature drifts in the optical components. They only eliminate emission terms on the detector side of the chopper and only then if the rate of change of the emission signal is insignificant on the signal scale during a single chopper cycle. Since the chopper cycle is about 1.6 ms and the emission change with temperature is on a scale where 1 mK is small, temperature drifts of a fairly large magnitude can be suppressed.

The chopper closed signals have a number of properties which make a more sophisticated analysis appropriate:

- When the chopper is closed the instrument has no radiance input from outside and therefore can be expected to show the same signals for the same outputs from the internal temperature monitors within some fairly close limits.
- The chopper closed system input radiance is approximately the chopper blade temperature which is closely monitored. Thus although the $L_{chopper}$ term varies, the variations may be tracked through knowledge of the chopper temperature and the Planck function.

Thus the chopper closed signals can be smoothed through a period greater than one stare, potentially reducing the noise level on the signal and changes in the chopper closed signal can be explained by changes in the chopper temperature. These properties permit the thermal offsets of the instrument (the fast changing terms) to be better monitored since they are seen on the chopper time scale.

The variations in the stray radiance from the input optics L_1 may be tracked by monitoring of the temperature of the scan mirror and the surroundings. Changes in the emission over the short-term can be compensated for, but longer term changes will require a full calibration.

3.1.2 Mathematical Description of Algorithm

DERIVATION OF AVERAGE AND DIFFERENCE SIGNALS

The average signal may derived by taking the CDSs and then averaging over the states of the correlation cell during the stare period. e.g. $(S_{1,2}+S_{3,4})/2$.

The difference signal can be derived by taking the average of the difference of the CDSs for the two states of the correlation cell. e.g. $S_{1,2}-S_{3,4}$.

Attention must also be paid to the fact that the correlation cells also differ slightly in operation and in input signal characteristics.

The Pressure Modulator cells are treated on a "stare" basis as in the above description. All state signals are averaged over the stare time before being processed. The Length Modulator cells are treated differently for two reasons:

- The cell consists of four sectors, two "up" and two "down" which are used in sequence. Four complete rotations make up one stare time. The sectors are telemetered separately to permit individual interpretation.
- The signal may vary significantly over a "stare" time and care is required in the averaging. This is primarily because the sectors correspond to slightly different sampling times. Using the separately telemetered sectors a cubic polynomial is fitted through the four points of each sector permitting a better estimate of the time-weighted mean of the stare than a simple average would provide. The two center-time "up" states are then

averaged as are the two center-time "down" states to produce similar signals to the PMC channels.

A correction is applied at this point for the LMC channels to account for the fact that the cell rotors have slightly different transmissions in the two states and this causes an offset signal to appear in addition to the gas effect. This offset is calibrated before launch and also monitored during a long calibration sequence by the use of an internal gas cell which is placed in the beam. By altering the relationship between the average and difference signal, the offset is highlighted and can be monitored for changes. The six signals are now:

Signal	Scan Condition
Average	EARTH
	SPACE
	INTERNAL
Difference	EARTH
	SPACE
	INTERNAL

CALIBRATION OF THE DIFFERENCE AND AVERAGE CHANNELS

Although the calibration of the MOPITT instrument is a total operation, it is convenient to split the discussion into two parts: the derivation of the offset terms, L_1 and $L_{chopper}$ and the determination of the transmission terms.

We begin with the derivation of the offset terms. These are determined by looking through the SPACE port at which time L_{input} is zero and equation (3) becomes:

$$\Delta S_{space} = G\int_{v_1}^{v_2}[L_1 - L_{chopper}]\tau_2\tau_g\tau_3\tau_4\tau_f dv \qquad (4)$$

and the expression for the CDS becomes:

$$\Delta S = G\int_{v_1}^{v_2}[L_{input}\tau_1]\tau_2\tau_g\tau_3\tau_4\tau_f dv + \Delta S_{space} \qquad (5)$$

Since the radiance terms, which are temperature dependent, can change rapidly, under certain scenarios this part of the calibration may be performed more frequently than the part of the calibration which is used to determine the gain and transmission terms.

The term ΔS_{space} is evidently a function of the chopper and front optics radiances. Since these are carefully monitored it will be possible to interpolate space signals between the actual measurement times using these temperatures to determine the variations. In fact the calibration interval will be determined by the ability of the monitoring to track these changes reliably. Depending upon the actual values encountered the interval will be in the range of 3 minutes (shorter times prejudice the data integrity) and 30 minutes (nominal interval for GAIN measurement).

The next computation is essentially the determination the channel GAIN using the INTERNAL signal as a known radiance, followed by the application of these values to the EARTH signals. This leads to the general equation:

$$L_{earth} = L_{internal}\left(\frac{\Delta S_{earth} - \Delta S_{space}}{\Delta S_{internal} - \Delta S_{space}}\right) \tag{6}$$

This formula is applied to both the average and difference channels to produce the required radiances. The internal radiance $L_{internal}$ is derived from knowledge of the temperature and emissivity of the calibration source. This uses PRT sensors which are discussed below. A more sophisticated analysis can obviously be applied based on the fact that the long-term drifts are exactly that "long term" and the emission changes in the instrument are correlated with temperature changes. Thus we assume that all gain and offset factors change slowly compared with the calibration period and that the emission signals correlate with measured temperatures. Under these assumptions it is possible to build two additional inputs for the calibration system: an instrument characteristic emission model and a gain/offset history. Thus in determining the current radiometric calibration, the overall radiometric calibration uses: (1) current calibration values, (2) historic calibration values, and (3) instrument temperatures.

DERIVATION OF TEMPERATURES

Derivation of temperature from Platinum Resistance Thermometer (PRT) sensors is as follows:

1. Deduce the PRT resistances. The resistances are monitored by means of a potential divider circuit with a known resistor *R*, for which the input, output and zero voltages are measured in terms of analog-to-digital converter counts (N_i, N_o, N_z). The resistance R_{PRT} is therefore given by:

$$R_{PRT} = R\frac{N_o - N_z}{N_i - N_o}$$

2. Deduce the temperature from the PRT resistance. This is a known characteristic which although approximately linear can be better represented by a low order polynomial

$$T = \sum_{i=0}^{n} r_i (R_{PRT})^i$$

The coefficients for a PRT are already well known once the type of PRT has been defined. They are also verified before launch. Derivation of temperature from thermistor sensors follows the same general path except that the formula for the resistance versus temperature characteristic is more non-linear.

DERIVATION OF CORRELATION CELL PRESSURES

Additional inputs for the Level 2 data processing are the correlation cell pressures. These are required for two reasons:

- The pressure in the correlation cell affects the manner of interpretation of the Level 1 radiance(e.g., the difference signals are a strong function of cell pressure and go to zero if the cell pressure is zero).
- The cell pressure affects the shape of the weighting functions used in the Level 1 $\rightarrow$ 2 algorithm.

The Pressure Modulator Cell has a constant cell length, but continuously changing temperature and pressure. The strategy for determining the form of the time cycles of temperature and pressure involves both pre-flight and in-flight measurements. The pressure and temperature cycles of the PMCs aboard MOPITT will be determined pre-launch using spectrometric techniques developed at the University of Toronto (Berman et al., 1993). These cycles will be measured as a function of average cell pressure. In-flight, it is then necessary to determine average cell pressure in order to derive the temperature and pressure cycle. Average cell pressure can be derived in either of two ways.

- 1) By means of the free-run, or resonant, frequency. The frequency versus pressure relationship is constant with time for a given PMC (based on experience with several instruments such as SAMS, ISAMS, PMIRR, etc.) This relationship is characterized before launch. The resonant frequency is measured periodically in-flight (although for normal operation the PMC is driven slightly off resonance). A polynomial fit to the pre-launch data is then used to deduce the pressure, *p*, from the measured in-flight resonant frequency, *F*:

$$p = \sum_{i=0}^{n} f_i F^i$$

- 2) By means of the sieve temperature. This is not as precise as metheod 1, and is subject to a number of errors (eg gas contamination will not show up). However, this method can be used on a continuous basis. The sieve pressure versus temperature relationship is characterized before launch. The sieve temperatures will be monitored by means of PRT's in-flight. A polynomial fit to the pre-launch data is again used to deduce the pressure, *p*, from the measured in-fligth sieve temperature, *T*.

$$p = \sum_{i=0}^{n} t_i T^i$$

A length modulator cell is isothermal and only has two length states: "long" and "short". These lengths are measured before launch and cannot change without destruction of the LMC. The pressure can be monitored by an accurate pressure transducer on the cell and also (less precisely) by the temperature of the sieve system (CO cells only). The sieve temperature technique is as described above. The pressure sensor mounted on the LMC is strain gauge based.

It has its own electronic processing, and produces a voltage which is (almost) proportional to the pressure. Thus the calibration proceeds in two stages:

1. Deduce the voltage V from measurements of the voltage, a reference voltage V_r, and the zero voltage V_z measured in terms of converter counts (N, N_r, N_z):

$$V = (V_r - V_z)\frac{N - N_z}{N_r - N_z} + V_z 2.$$

2. Using pre-flight calibration data, relate the measured voltage to the pressure using a polynomial fit:

$$p = \sum_{i=0}^{n} v_i V^i$$

The balance error of the cell also needs to be measured. This can be done by a pre-launch measurement supplemented by in-flight calibrations using the MOPITT blackbodies. Corrections for the spectral distribution of the blackbodies and known pressure dependent effects (reflection losses at the interfaces) in the system are also required.

DERIVATION OF PIXEL LOCATION

The locations of observation points (pixels) on the surface of the earth are computed by combining knowledge of the MOPITT scan mirror position with spacecraft orbit and attitude information. Scan mirror positions are measured relative to a "reference" bore-sight axis by means of digital shaft encoders. Calibration of the encoders and mapping of the four pixel positions relative to the bore-sight are part of the pre-flight instrument characterization. The position of the MOPITT "reference" bore-sight axis relative to the spacecraft coordinate system is measured during integration of the instrument onto the spacecraft.

During flight, the mirror angles as measured by the shaft encoders are part of the Level-0 data stream at the time of each observation. The view directions of the pixels in the spacecraft coordinate frame are computed by combining the encoder outputs with the fixed "offset" of the reference bore-sight to the spacecraft axes. Geolocation is then accomplished by use of standard subroutines available in the Product Generation System (PGS) tool kit (NASA EOS Document 194-809-SD4-001). These routines include; coordinate transformation utilities which provide conversion from the spacecraft reference frame to the Earth Centered Inertial (ECI) frame and transformation from ECI to geodetic coordinates.

Other auxiliary information necessary for interpretation of the measurements at the pixel locations is likewise obtained from standard utilities in the PGS tool kit. This includes: (1) solar zenith angle, (2) height of terrain, and (3) surface codes indicating land, sea or coastline.

3.1.3 Variance and Uncertainty Estimates

The accuracy of the calibrated radiances is related to the measurement of the input radiance in terms of the calibration sources followed by their traceability to international standards. The calibration will initially be established in the Instrument Calibration Facility (ICF). The current specifications are:

long wave (4.7 µm) channels	±0.5 K
short-wave (2.3, 2.4 µm) channels	±1 K

Measured values for the variance and uncertainty will be available after calibration tests are performed on the engineering model of MOPITT. These will be far more valuable than any calculated values for the purpose of assessing instrument performance.

A note of caution is that the radiances are computed in the same manner as for a broad-band radiometer. However the nature of the spectral response of a correlation instrument is very different and caution should be exercised when comparing these radiances to radiances from a true broad-band radiometer. Further information is contained in the MOPITT Calibration Plan.

The resolution or repeatability of the MOPITT calibration is governed by a number of factors, some of which have a short characteristic time scale and some of which have a longer characteristic time. The objective of MOPITT is to measure gas concentrations in the atmosphere, not necessarily radiance. A detailed analysis of this objective shows that the repeatability of MOPITT measurements are, over the long term, more important than the accuracy of the initial calibration.

The short-term resolution of the MOPITT calibration is governed by a number of factors, the first of which is the noise level associated with the calibration itself. This can be adjusted by adjusting the length of time each target is viewed. Longer times permit better averaging of the radiance and temperature data.

Secondary factors which contribute to the calibration resolution are the applicability of the current calibration values to the radiance transformation. Temperature drifts are the primary cause of inaccuracy here and govern the time between calibration sequences. The primary elements in this operation are the chopper emissivity and temperature, which are both carefully controlled and, in the case of the temperature, carefully monitored. The governing time is that time in the middle of which the uncertainty in the corrections grows to a level which prejudices the consistency of the calibration. A target for calibration is 30 minutes for a room temperature source and monthly calibration with a hot source.

In practical terms the variance of the radiances can be found by using the fact that there are many calibration sequences that are measurements of known radiances and that the major features of the calibration (optical transmission, etc.) change slowly with time. Thus daily, weekly, monthly and annual estimates of the changes in calibration parameters from the calibration history give valuable information on the variance of the calibration parameters and their drift with time.