An Early Look At "Near Real" MOPITT Data

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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 Satellite, EOS-AM1, scheduled for launch September 1999. This paper describes the analysis of a twenty four hour data set that was recorded during the latter stages of testing at the University of Toronto Instrument Characterisation Facility (ICF). This data set represents the best "near real time" contiguous data available and it is being used to help understand the instrument behaviour and characteristics, as well as with algorithm development with the goal of the University of Toronto team being to determine the gain, offset and noise parameters for all channels from the in-flight calibration system.

Keywords: Terra, EOS-AM1, MOPITT, Methane, Carbon Monoxide, Correlation Spectroscopy, Infra Red, Calibration

1. INTRODUCTION

1.1 Instrument Science, Methodology and Description

The **M**easurements **O**f **P**ollution **I**n **T**he **T**roposphere (MOPITT) experiment will 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 EOS-AM1 platform, scheduled for launch from Vandenberg Airforce Base in August 1999, and is designed for a five year mission life. The results will not only be used to map the global CO and CH_4 concentrations but will also be assimilated into 3-D models in order to study the chemistry and dynamics of the lower atmosphere.

CO and CH_4 concentrations will be measured using correlation spectroscopy [1,2,3]. The CO profile measurements are made using upwelling thermal radiance in the 4.6μm fundamental band. The troposphere is resolved into about four layers with approximately 3km vertical resolution, 22km horizontal resolution and 10% accuracy. CO and CH_4 column measurements are made using reflected solar radiance in the 2.3μm CO and the 2.2μm CH_4 bands. The horizontal resolution is 22km 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.

MOPITT is a scanning, nadir viewing eight channel IR radiometer. 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 (SCC's). 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 provides a stable thermal environment and is used as the thermal sink for all modules except the main power supply module which is thermally isolated from the baseplate and radiatively cooled to space.

A more complete description of the science goals, the measurement methodology and the instrument description can be obtained from other papers presented at this conference and the references contained therein [4].

2. INSTRUMENT CONFIGURATION AND TEST SCENARIO

2.1 MOPITT Test Configuration

The instrument has four dual band calibration sources that allow in-flight calibration of all eight channels. However, due to spacecraft power constraints only one of these can be switched on at full power or two switched on at half power. Since the 4.7 µm channels, channels 1,3,5 and 7 are thermally sensitive, this test was set up to concentrate on these channels. Hence, the blackbody sources for channels 1 and 3 were set to 338K (near full scale). The blackbody sources for channels 5 and 7 were left off (295K), however reasonable signals would still be obtained. The 2.3-2.4µm solar channels, channels 2,4,6 and 8 would yield very small signals, however it would be interesting to see if gain and offset parameters could none the less be determined, this would result in getting solar channel calibration in between the monthly long calibration events.

Other then switching on the two calibration sources, the instrument was placed in science mode, coolers on. This is the nominal instrument operating mode and it was left in condition and operated for approximately thirty seven hours. The twenty four hours data set refers to the last portion of the test once the instrument has stabilised, for example coolers and detectors are at operating temperature and the instrument baseplate has stabilised.

2.2 MOPITT Scan Sequence

During MOPITT nominal operations the four input scan mirrors “cross track” scan in order to improve global coverage. The four by one along track pixel array for each channel, which has an instantaneous field of view of 22 x 88 km on the ground is increased to 632 x 88 km due to the swath coverage. The input scan mirrors “cross track” scan +/- 14 fields about the nadir position, with a 1.8 degree steps, in fact the scan pattern is such that the scan is interleaved. Each step within the scan takes approximately 450ms and each scan takes approximately 13 seconds. For this test the scan mirrors view the vacuum chamber walls and test instrumentation during nadir view “cross track” scanning

After the completion of ten such scans, the scan mirrors rotate through 90° to obtain a space view “zero radiance” calibration. This zero radiance calibration is used to trend and monitor the instrument offset term due to thermal variation of the front optics. The mirrors are held for a space view calibration for 5 stares (2.25 secs) and this occurs every 133 secs. For this test the scan mirrors view the MOPITT space view black body held at 78K.

Once the instrument has completed fifty of the “cross track” scans, the scan mirrors rotate through 90° to obtain a space view calibration as described above. The scan mirrors then rotate through a further 90° in order to view the internal calibration blackbody targets and hence carry out a two point calibration (gain and offset). The mirrors are held at the internal calibrator position for approximately 20 stares (9 secs) and a two point calibration occurs approximately every 11 minutes.

This scan and calibration pattern is shown in Figure 1 and it is autonomously executed. The scan pattern, calibration frequency, hold times can all be re-programmed, if necessary via a table load. Using the two point calibration events and the more frequent space view calibration events, the Average and Difference signals can be determined and by using the blackbody radiance information the gain and offset can be calculated.

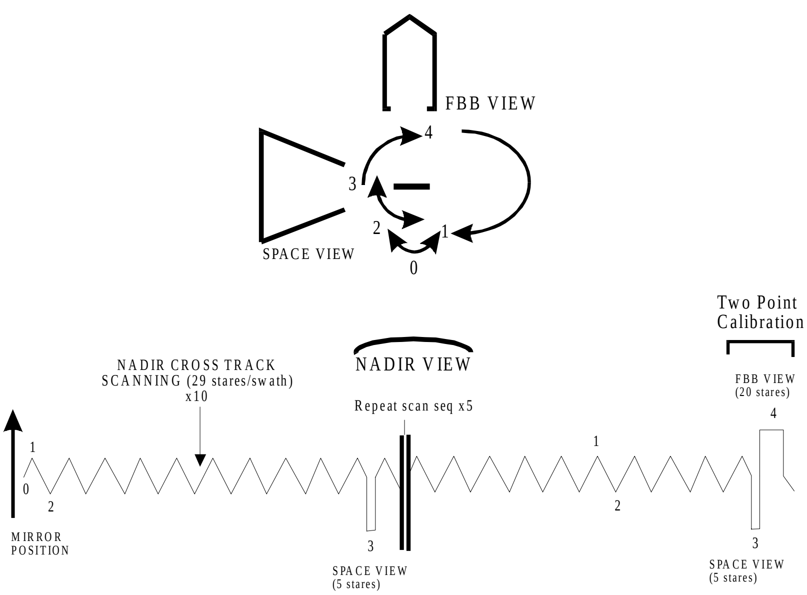


Figure 1 MOPITT Scan and Calibration Sequence

3.0 TEST RESULTS

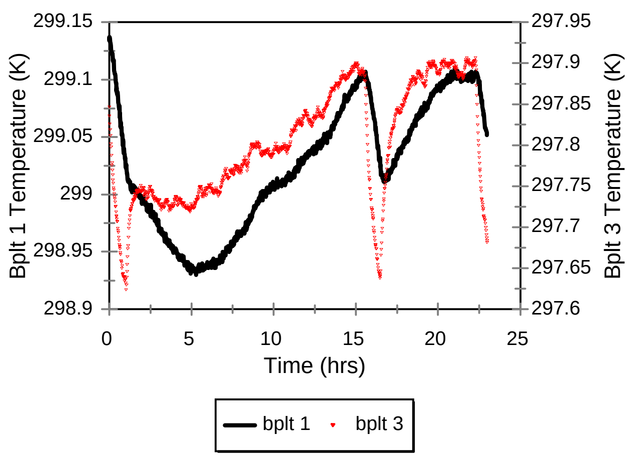
3.1 Engineering Results

The instrument has a large number of transducers that monitor various temperatures, voltages, currents, pressures and positions. These enable the instrument health to be determined, the most critical and sensitive sub-set of telemetry points to trend and monitor are the baseplate, chopper, blackbody and detector temperatures and the modulator cell pressures. These, in general will give a top level indication of the instrument status, other telemetry can then be looked at based on the results of the above.

MOPITT engineering data is generated every 8 seconds, for the trend plots shown below it has been averaged on a per minute basis.

3.1.1 Baseplate Temperatures

Figure 2 MOPITT Baseplate Temperatures



The results of the two baseplate transducers are shown in Figure 2. The 2K spread in temperatures between them is explained by the fact that thermistor 3 lies over the coldplate and thermistor 1 is at the front end of the instrument, near the scan mirrors and choppers and furthest away from the coldplate system. The three "kinks" most evident from the thermistor 3 plot are from the coldplate system. In the test configuration the coldplate, which is attached to the underside of the baseplate, is operated via a fluid loop controlled by a chiller. The "kinks" correspond to when the temperature delta between the actual chiller reservoir temperature and it set point temperature is exceeded and the active loop "kicks in" in order to reduce the temperature delta. This results in a sudden lowering of the fluid temperature which is reflected in the baseplate temperature. It is most apparent in thermistor 3 since it lies over the coldplate and the effect is modulated as seen in the thermistor 1 plot. These "kinks" are not expected on-orbit since the coldplate system operates on a saturated ammonia fluid loop using capilliary pump mode.

In general for the duration of the test the baseplate has remained stable to within 1K, on-orbit, orbital fluctuations of <5K are expected.

3.1.2 Chopper Temperatures

The chopper has a high emissivity blade that when closed acts as a fast single point reference, it is therefore important to monitor its temperature carefully and since it has a high emissivity surface, small temperature changes could have a significant effect. The temperature trend plots for the four choppers along with the chopper currents are given in Figures 3a-d. In general the four temperature plots show similar gross trends but quite different fine characteristics. For instance all four show a general reduction in temperature during the first part of the test that correlates to the baseplate temperature changes. They also show the more dramatic temperature reduction late in the test, corresponding to the chiller "kicking in" as described above (compare with bplt1, figure 2).

Chopper 1 (Figure 3a) shows a small (0.2K) but distinct increase in temperature followed by a smaller decrease in temperature. The initial temperature increase has been correlated to a sudden 8mA increase in current, whilst the decrease can be correlated to the sudden change in the baseplate temperature due to the chiller "kicking in". Further investigation of the sudden current increase indicates that the increase is due to a change in mechanism resistance and not a change in the supply voltage. Chopper 2 (Figure 3b) has a similar trend to chopper 1, a small increase in the temperature followed by a larger decrease in temperature. In this case however, the initial increase cannot be correlated to the chopper current . In fact the plot can be correlated to the changes in the baseplate temperature. Chopper 3 (Figure 3c) has a "saw tooth" type temperature trend that can be directly correlated to the motor current. The period of this oscillation is approximately 2 hours. This oscillation is

Figure 3a Chopper 1 Characteristics

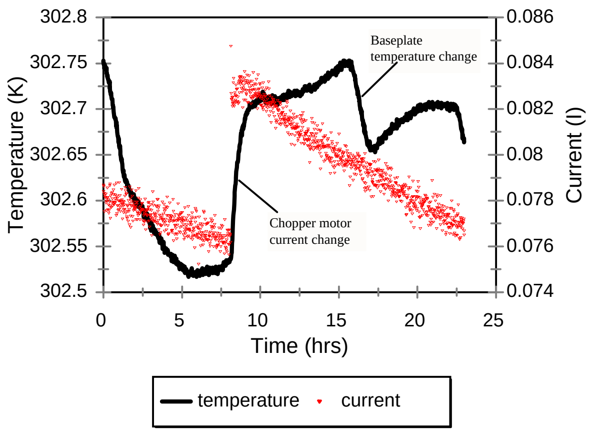


Figure 3b Chopper 2 Characteristics

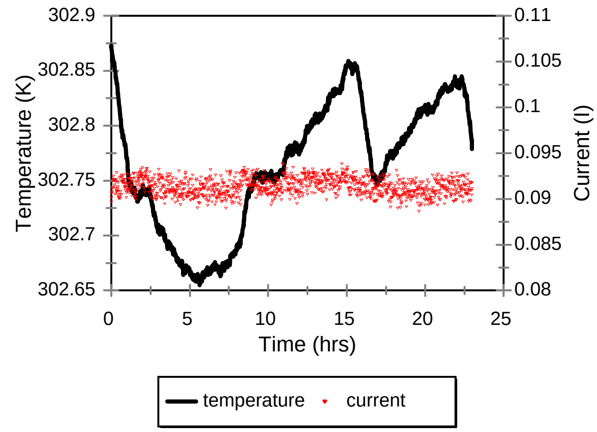


Figure 3c Chopper 3 Characteristics

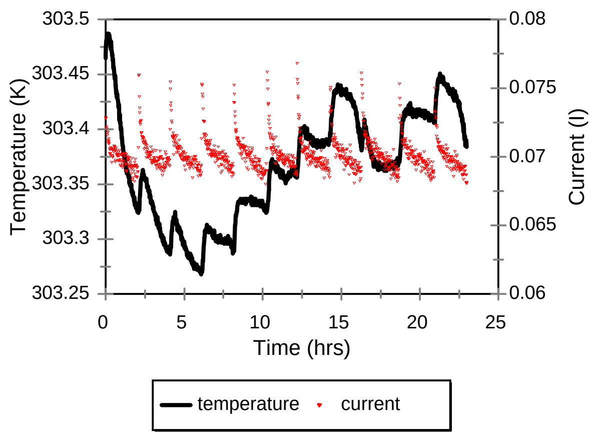
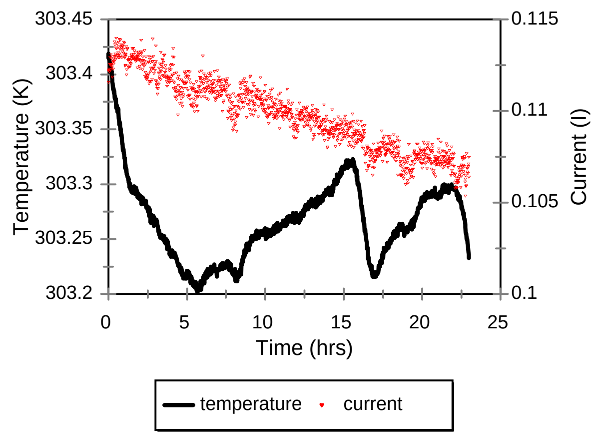


Figure 3d Chopper 4 Characteristics



superimposed onto the baseplate temperature changes. The chopper 4 (Figure 3d) trend is similar to the chopper 2 trend and can be correlated to the baseplate temperature changes.

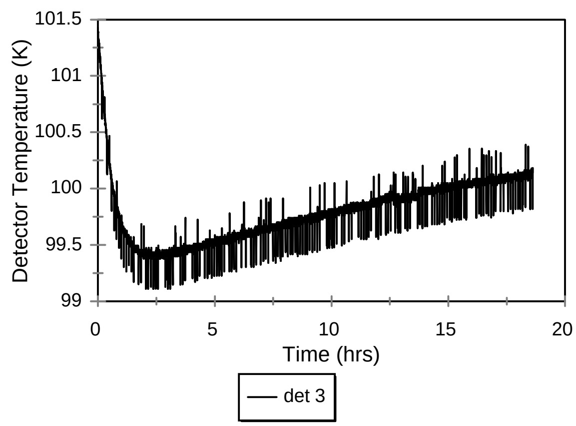
The results show that other then the expected baseplate temperature changes influencing the chopper temperature, the motor currents for choppers 1 and 3 also "tick" and influence chopper temperature. The significance of this is that when chopper closed data is being processed to determine the Average and Difference signals greater care will have to be taken to account for the signal changes due to the current effect. It must be noted that the effects are small and a second order correction will be necessary.

3.1.3 Blackbody Temperatures

During the two point calibration sequence the scan mirror views deep space and the internal calibration blackbodies. In order to determine the channel gain it is important to monitor the blackbody temperature precisely and convert that to a known radiance accurately. The two active sources, blackbodies 1 and 2 start off at 338.1K and 337.4K respectively and increase linearly in temperature by about 0.5K. The temperature of the two inactive sources, blackbodies 3 and 4, floats as expected with the baseplate temperature since they are weakly coupled.

3.1.4 Detector Temperatures

Figure 4 Detector Characteristics



In order for the Indium Antiminide (InSb) detectors to operate they must be cooled below 108K. This is achieved by the use of the Stirling Cycle Coolers. As the detectors start to contaminate, primarily icing due to water vapour, there is a three fold effect, firstly the increased load will lead to an increase in the detector temperature, this in turn will lead to an increase in the detector and hence overall noise. Thirdly as the cold optics ices up it becomes more opaque and decreases the optics transmission. This in turn will lead to a slow decrease in the channel gain as the ice gradually builds up. It is therefore very important to monitor the detector temperatures to determine when a cooler de-contamination cycle is necessary. A typical result for detector 3 is given in Figure 4, it shows the final cool down to stability and the gradual increase due to contamination buildup. This latter effect is more pronounced then expected because in the test environment the instrument has not been given an adequate chance to out gas .

A second effect that had not been noted during earlier testing were the spikes in the data. Negative spikes of the order of 0.4K are observed with an approximately six minute period. These were not seen previously because in most cases short data files were taken (<10mins). For the longer archived data files the data when processed was averaged using a five minute running average to decrease data volume and ease handling, which lead to a suppression of the spikes. The origin of the spikes is not known and for the present a de-spiking algorithm is being implemented within the data processing algorithms.

3.1.5 Modulator Cell Pressures

The instrument contains four Length Modulator Cells (LMC's) and two Pressure Modulator Cells (PMC's). In all cases the cell pressure and to a lesser extent the cell temperature are important parameters during the data retrieval process. The LMC pressures are measured directly but the PMC average cell pressures have to be determined through an involved and time consuming calibration process. This PMC calibration process was not conducted in the simulation. The results of the LMC cell pressures is shown in Figures 5a and 5b. As expected the methane sealed LMC's have a weaker coupling then the carbon monoxide LMC with sieves. The sieves are on stand-offs which are connected to the baseplate, a small change in the baseplate temperature results in a change in the sieve temperature which in turn results in a significant pressure change.

Figure 5a Methane Channel LMC Pressure

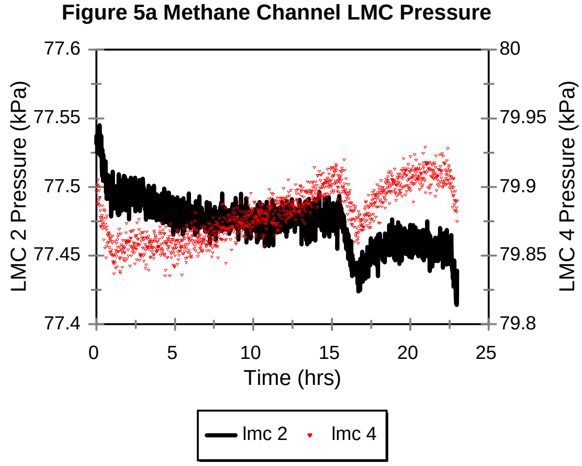
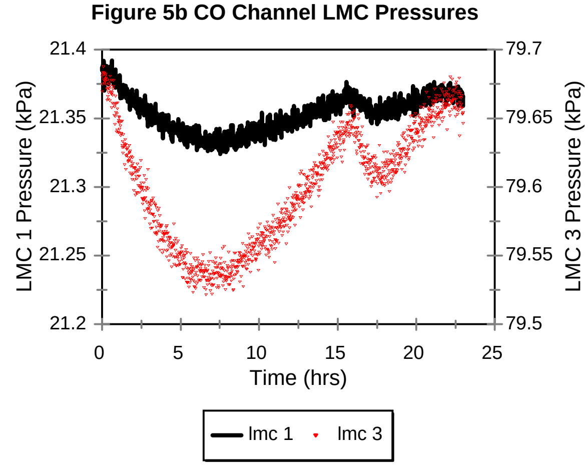


Figure 5b CO Channel LMC Pressures



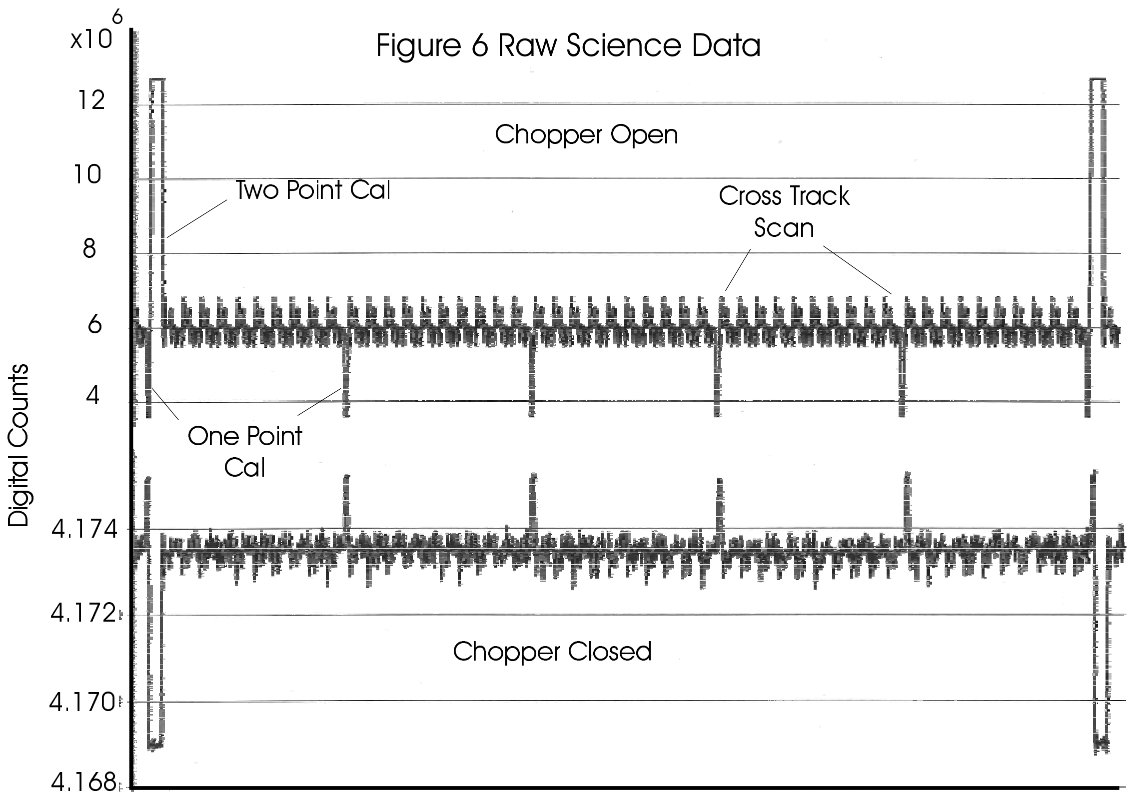
3.2 Science Results

The science data set consists of data for eight channels and all four pixels per channel. With the present test configuration, low signal levels were expected for the 2.3-2.4µm solar channels, channels 2,4,6 and 8 since the blackbody sources have not been set up for these channels. However, it may be possible to still determine the channel gain and offset from these signal levels. Thermal channels 1 and 3 should yield large signals since the calibration sources have been set up accordingly and channels 5 and 7 should yield normal signals. Furthermore, since these are thermally sensitive channels when cross track scanning the instrument is looking at the vacuum chamber walls and test equipment, hence some type of repetitive signals should be obtained in this case.

The ultimate purpose of the science data processing is to go from the raw data, pick out the single and two point calibration events and determine the gain and offset for all channels all pixels.

3.2.1 Raw Data

The instrument raw data is a digital count, for the LMC channels there are eight signals, corresponding to the four sectors and for each sector a chopper open and closed state. For the PMC channels there are four signals, one each for the PMC high and low state and for each state two signals for the chopper open and closed cases. An example of the raw science data for a particular PMC state is shown in Figure 6. The figures show the chopper open and closed data for channel 3 pixel 2 respectively. One can clearly see the frequent single point calibration followed by the two point calibration. In between the single point calibration ten cross track scans have been executed.



Several interesting things came to light by observation and analysis of the raw data.

3.2.1.2 Stare Position Offset

A one step shift was discovered between the recorded mirror position and the science data. This is very evident during the two point calibration event, when there are large signal changes. It was seen that when the scan mirror goes from the space view position (-50) to the blackbody position (-100) the science data indicates it is at the blackbody position one step before the mirror position indicator. Investigation on this and other data sets showed this was always the case, there is a systematic offset of one in the mirror position sequence for all scan mirrors.

Further investigation shows that this occurs due to the on-board software. After each stare the MOPITT Instrument Control Module (ICM) takes about 100ms to packetise the data. The mirror position stored in the packet is the position at the time of the packet generation and not the position at the time the stare was completed. This results in the nest mirror position being added to the stare packet data. The problem has been identified unambiguously in the software code and the present solution has been to correct the offset in the science data algorithm rather than do a code upload. A code upload will be conducted on-orbit once the instrument has been through its turn-on and verification phase and any other parameters that need change identified.

3.2.1.2 Chopper Closed "Additional" Signal (α correction)

A closer investigation of the chopper closed data, Figure 7, shows that when a calibration is done, a small signal of opposite sign is observed in the chopper closed data. When the scan mirror views space an additional positive signal is observed and conversely when the mirror views the calibration source an additional negative signal is observed.

Since the chopper lies after the scan mirror and is closed it should just have a near constant signal irrespective of what target the scan mirror is viewing. Furthermore, if it was a radiance leak around the chopper then a small signal of the same sign as the chopper open signal would be observed, that is a negative signal for the space view and a positive signal for the blackbody view. This additional signal and its sign can be explained by considering the detector and its associated electronics as a dynamical over damped system.

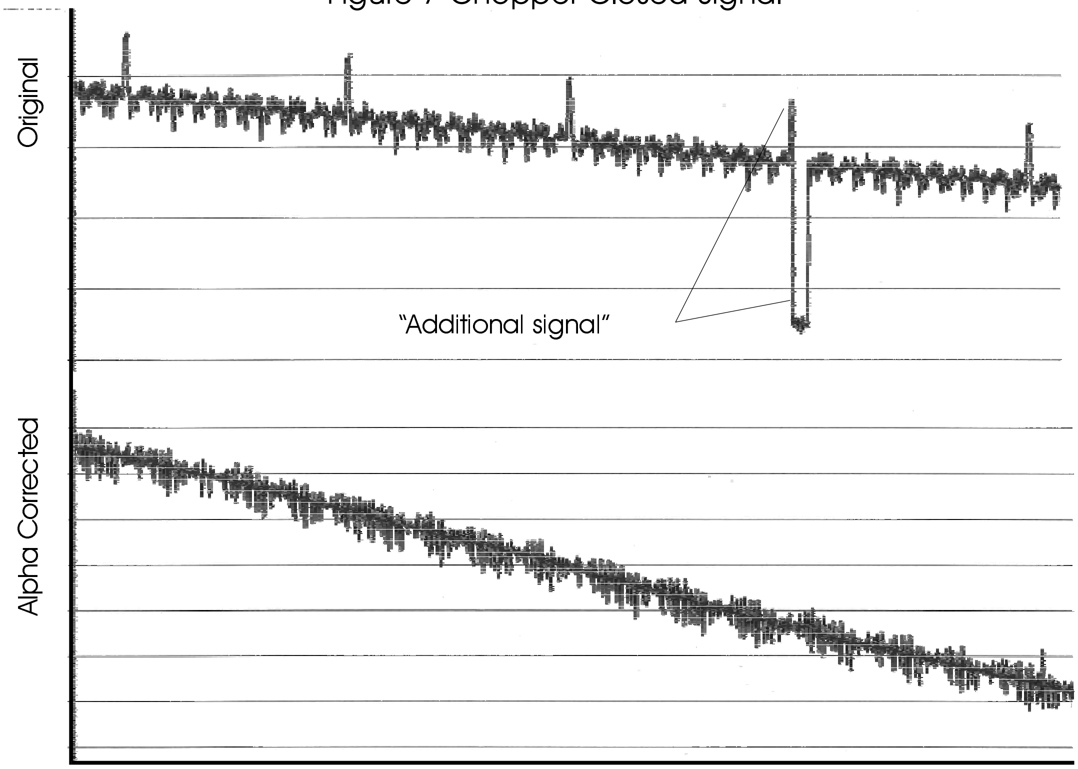
The detector and associated electronics system are highly linear and the detector/electrical system response is unlikely to change over short time scales the signal delta between the chopper open and closed positions is directly proportional to the input radiance. Since the additional signal is directly proportional to the signal delta and assuming that the chopper blade temperature is a smooth and slowly changing function of time the chopper closed signal may be described by the following equation

$$S_{closed}(t) = C(t) + \alpha[S_{open}(t) - S_{closed}(t)] \tag{1}$$

where S_{closed} (t) is the observed chopper closed digital count, S_{open} (t) is the observed chopper open digital count, α is the coupling coefficient, C(t) represents actual chopper blade radiance. By knowing the chopper closed signal for a variety of calibration cases the smooth function C(t) may be calculated. The α parameter has been calculated for each two point calibration event, it is assumed that it is constant between these events. Independent α parameters have been calculated for each sector to account for the differences in the optical transmission. For this twenty four hour data set the α parameter is stable to within 1%.

This α parameter correction has been incorporated into the data processing algorithm with the net result that the "additional" chopper closed signal can be compensated for resulting in the an as expected smooth slowly varying chopper closed signal. An example of the uncorrected and the α corrected chopper closed signal for channel 3 pixel 2 is given in figure 7..

Figure 7 Chopper Closed Signal



3.2.1.3 Excessive (systematic) Noise

The chopper open and closed signals for the PMC channels 3 and 7 showed an additional systematic noise component. Figure 7 shows this for the chopper closed case. Spectral analysis yielded a 2.23Hz fundamental frequency, which corresponds to the CCSDS packet generation frequency. When stare data is being packetised and transmitted down the 1553 bus, significant current oscillations occur, it is assumed that this is being picked up in the PMC channels and seen in its data.

The approach taken to reduce the overall noise has been to minimise the chopper closed systematic noise contribution by filtering. Equation 2 shows that the overall noise contribution is made up of the root sum square of the individual chopper open and closed noise components. Since the chopper temperature is known and varies slowly, its corresponding signal is also slowly varying on the per stare time scale. Hence it is reasonable to filter the chopper closed data to minimise the systematic noise contribution and hence the overall noise.

$$\sigma_{total} = \sqrt{\sigma_{open}^2 + \sigma_{closed}^2} \qquad (2)$$

A linear Kalman filter was utilised in order to reduce the chopper closed noise level, under the valid assumption that the chopper closed signal is slowly varying on the per stare (0.45secs) timescale. The chopper closed signal can be considered as a quasi_stationary process and may be expressed by the following equation

$$\dot{X} = U + W \qquad (3)$$

Where X is the observed process, U is the rate of process change, which in this case is zero (chopper closed signal slowly varying), and W is the statistical noise component. Under these conditions, the predicted standard deviation (noise) for the process is given by

$$\sigma_x^2(t_{k+1|k}) = \sigma_x^2(t_k) + \sigma_w^2 \cdot [t_{k+1} - t_k] \qquad (4)$$

Once the filtering parameters had been optimised, the systematic chopper closed noise has been reduced to a negligible value and this has resulted in a general noise reduction of about 50% for the average and difference signals. This filtering techniques was tested on channel 3 and 7 data but will be added to the data algorithm such that bit is applied to all chopper closed signals for all channels.

3.2.2 Processed Data

The chopper open and closed signals are divided into three segments, space view, calibration view and nadir view. Since these events are all occurring at different time scales, an interpolation scheme is required to get to a common time scale. The individual chopper open and closed signals are normalised using the appropriate weighting factors and manipulated to determine the Average and Difference signals for the three defined cases.

3.2.2.1 Gain and Offset

Using the Average and Difference signals for the space and calibration view (two point calibration) in conjunction with the space and calibration view radiance the channel gain and offset can be determined from the following equations

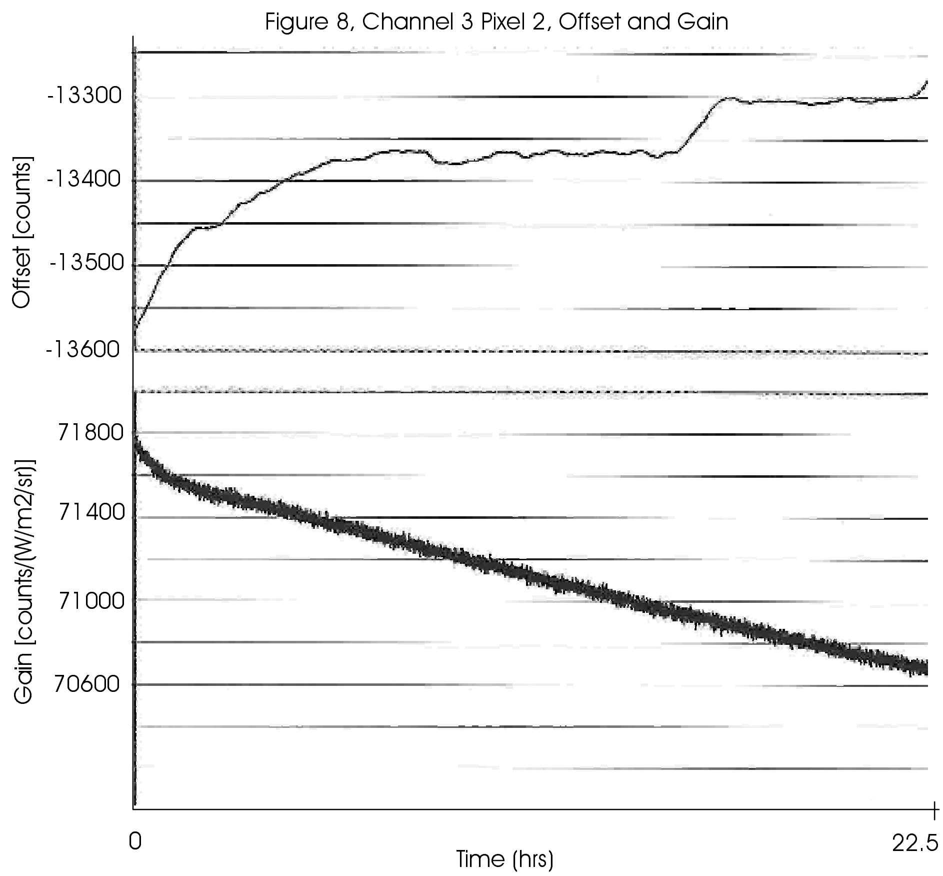
$$Gain, G = [S_{cal} - S_{space}] / R_{cal} \tag{5}$$

$$Offset, O = G * S_{space} \tag{6}$$

where S_{cal} and S_{space} are the calibration and space view signals respectively and R_{cal} is the calibration source radiance (note that the space view radiance is many orders of magnitude lower than the calibration view radiance is essentially zero, $R_{space} = 0$) .

An example of channel 3 offset and gain, as determined from the two point calibration sequence is given in Figure 8 respectively. The offset signal trends the changes in the instrument temperature, in particular the changes in the fore-optics. The gain signal shows a slow linear decrease that corresponds to detector contamination build up, icing of the cold optics that leads to a decrease in the optical transmission and hence a decrease in the gain. This effect is pronounced in the this data set because in the test environment there was not adequate time to allow the instrument to out gas and complete a decontamination cycle. Under other observed conditions when the instrument has been under vacuum for several weeks and been out gassed this contamination build up is less marked. On-orbit it is planned that several de-contamination cycles will be run with the period between such cycles slowly increasing to about once per month. It is none the less important to factor this effect into the retrieval, via the on-board calibration, since the gain factor will be slowly decreasing. It should also be noted that the gain plot is noiser then the offset plot because the offset calibration is being done more frequently.

As a further example a solar channel offset and gain plot is given in Figure 9. Since in this test environment the calibration source was not set for this channel to work actively the signals are small and hence the plots noisy. The offset plot shows as expected a much weaker coupling with the instrument temperature variations, while the gain plot shows a similar contamination trend. Despite the small signals the solar channel gain can be trended and some information can be obtained on this time scale (the solar channel long calibration, where the calibration sources are heated to be active is planned to be a once monthly activity).



3.2.2.2 Noise

At present work is ongoing to determine the noise equivalent radiance (NER) for each calibration event. This involves determining the digital noise associated with the signal and then using the appropriate gain and transmission factors to determine the NER. At present a preliminary determination of the thermal channel NER's has been made and the results are shown in Table 1.

4.0 Conclusion

This twenty four hour data set has provided a very useful insight of the instrument characteristics under nominal operations. It has helped uncover several engineering type characteristics that had not been previously noticed in the much smaller test data sets. It has also highlighted several interesting features in the science data and has helped immensely in the development of a data algorithm that can take the raw data and produce gain, offset and noise information from the in-flight calibration system, thereby giving near-real time feedback on the instrument performance.

On going work involves looking more closely at this data set, leading to more interesting questions and further work will involve implementing the above ideas and concepts to all channels all pixels.

ACKNOWLEDGEMENTS

The MOPITT project is funded by the Canadian Space Agency (CSA) with COM DEV Atlantic being the instrument prime contractor. The MOPITT Principal Investigator is J. R. Drummond (University of Toronto) and the Science Team includes groups led by the following co-investigators, G. P. Brasseur and J. C. Gille (NCAR, USA), H. G. Reichle, Jr. (North Carolina State University), G. D. Peskett (Oxford University, UK), J. C. McConnell (York University, Canada), N. Roulet (McGill University, Canada), G. R. Davis (University of Saskatchewan, Canada) and G. S. Mand (University of Toronto).