Pre-flight Testing of the MOPITT Instrument

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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 late in 1999. This paper primarily describes the pre-flight testing conducted at the University of Toronto, Instrument Characterisation Facility (ICF) and will also very briefly describe testing, post integration to the spacecraft at the Lockheed Martin, Valley Forge integration and test facility and at the Vandenburg launch site.

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 late 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].

2.0 PRE-FLIGHT TESTING

2.1 Introduction

MOPITT pre-flight calibration and characterisation was conducted at the University of Toronto Instrument Characterisation Facility (ICF). The MOPITT flight model (FM) was delivered to the ICF in April 1997 and underwent four months of troubleshooting and testing before being delivered for spacecraft integration in August 1997. Prior to delivery to the ICF the instrument had undergone vibration testing and EMI/EMC testing at the David Florida Laboratories (DFL), Ottawa.

Some further testing and trending was done when the spacecraft underwent thermal vacuum testing in February and March 1998 at the Lockheed Martin integration and test facility. Since then periodic trending of engineering parameters (gas pressures, motor currents etc) has been conducted, in ambient conditions, when the instrument is operational to support spacecraft testing or participates in launch and operational readiness exercises.

2.2 The Instrument Characterisation Facility

The ICF is located in the Department of Physics at the University of Toronto. As shown in Figure 1 it consists of a class 10000 clean room with an adjoining preparation room. The facility also has a general purpose area and the control room.
A four section cryo-pumped vacuum chamber 2.2m in diameter and 6m long, shown in Figure 2, was used for all tests. The tank had electrical, gas, liquid and liquid nitrogen feedthroughs to support the instrument and the wide variety to test equipment used. A detailed description of the ICF is available elsewhere [5,6].

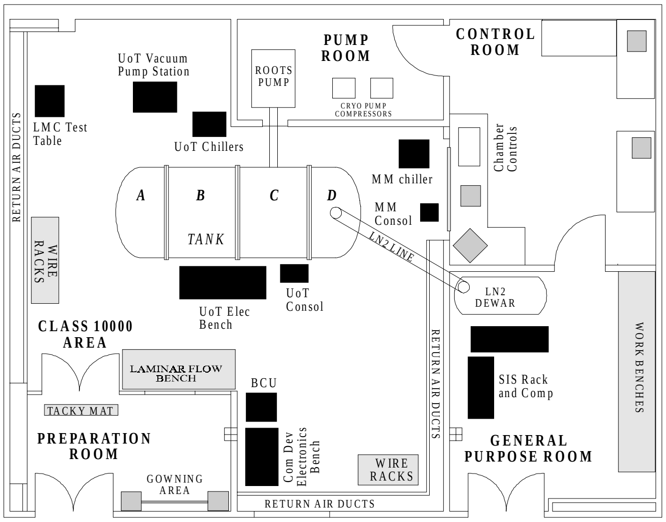


Figure 1 Instrument Characterisation Facility Layout

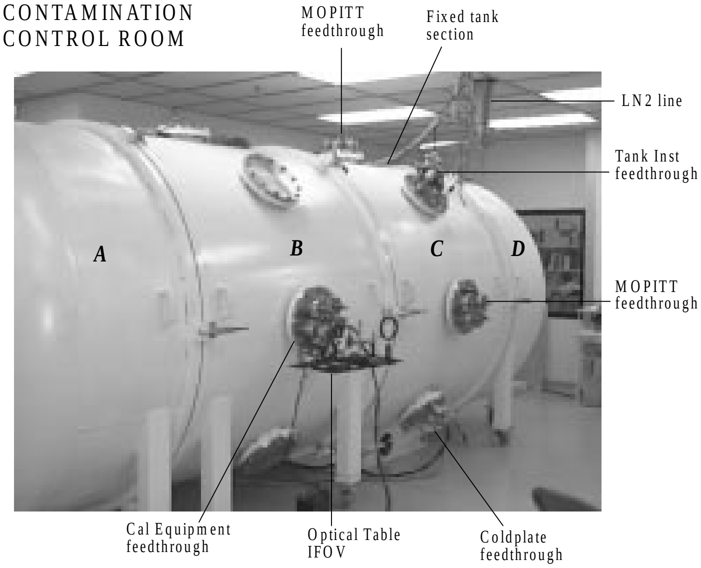


Figure 2 The Vacuum Chamber

2.3 ICF Pre-Flight Tests

Rigorous pre-flight charterisation and calibration is vital in understanding the on-orbit instrument behaviour over various time scales, to end of life. Pre-flight data sets can be incorporated into the retrieval algorithm producing more accurate final data sets. MOPITT characterisation fell into three categories, radiometric , spatial and spectral characterisation. In addition MOPITT thermal testing was also conducted at the ICF, thus ensuring that the complete suite of engineering type tests (thermal, vibration and EMI/EMC) were done. Table 1 shows all the tests that were conducted at the ICF.

Table 1 MOPITT Pre-flight tests

		Channels#							
		1	2	3	4	5	6	7	8
Radiometric	Channel Response (linearity, gain, offset, noise & dynamic range)	x	x	x	x	x	x	x	x
	Temperature Sensitivity Effects	x		x		x		x	
	Cross Calibration	x	x	x	x	x	x	x	x
	Simulated Atmospheric Signal	x	x	x	x	x	x	x	x
Field Of View	Instantaneous Field of View	x	x	x	x	x	x	x	x
	Pixel Co-Alignment	x	x	x	x	x	x	x	x
	Detector Co-Registration	x	x	x	x	x	x	x	x
	Response to Polarised Light	x	x	x	x	x	x	x	x
Spectral Tests	In Band Response	x	x		x	x	x		x
Thermal Tests	Thermal Soaks (-20C to +60C)	x	x	x	x	x	x	x	x

2.3.1 Radiometric tests

Radiometric calibration was performed in order to determine the instrument radiance response function, that is determine the instrument output for a known radiance input. It was also used to calibrate to the instrument to an absolute standard. The latter is necessary since MOPITT will use other data sets (temperature profiles and humidity data) during the retrieval process. Furthermore, MOPITT data sets may be used by others within the community. Therefore, an absolute radiometric calibration to International Standards is essential.

The MOPITT radiometric tests consisted of the following: the channel response test, the simulated signal response test, temperature sensitivity effects test and the cross calibration of the internal calibration sources.

2.3.1.1 Channel Response Test (linearity, gain, offset , noise and dynamic range)

This test is conducted to determine the prime radiometric parameters, that being the gain, offset and noise equivalent radiance (NER) for all channels and all pixels. It was also used to determine the dynamic range by driving each channel into saturation.

The test was conducted using the MOPITT Calibration Blackbody (MCBB) in conjunction with the MOPITT Space Blackbody (MSBB) [9]. The MCBB is a variable temperature calibration source which when used for the MOPITT thermal channels (1, 3, 5 and 7) was operated in the 260K-350K temperature range. For the solar channels (2, 4, 6 and 8) it was used in the 440K-500K temperature range. In both cases the source was ramped in 10K increments and allowed to stabilise. The MCBB was positioned at the instrument nadir view and translated to each of the four MOPITT inputs in order to calibrate all the channels. The MSBB, is a 77K target that was positioned at the instrument space view and used to provide a “zero” radiance and hence determine the offset.

The results of the gain and offset measurements, tabulated in Table 2, show that the gain factors for the CO prime and redundant channels (6 and 2) are similar as are those of the CH_4 channels (4 and 8). The small differences may be due to the differences in the optical transmission and the filter characteristics. The CO thermal channels 1 and 5 employ LMC’s whilst channels 3 and 7 employ PMC’s. The differences in the gain values is primarily due to the fact that a different number of samples are being sampled for these channels due to the different frequencies of the various mechanisms. A general point to note on all channels is that the outer pixels, pixels 0 and 1, have slightly lower gain values then the inner pixels, pixels 2 and 3. This pairing is simply due to the pixels alignment with respect to the centerline optical axis. Furthermore, it should also be noted that channel 5 pixel 1 and channel 6 pixel 0 have lower gain values (approximately 5-7%) then their corresponding outer pixels. These channels have a common front optics and LMC and since the pixel ordering is such that the two pixels complement each other, it is likely that there is a common reason for the lower gain values.

Table 2 MOPITT Gain and Offset Values

		Channel #							
Parameter	Pixel #	1	2	3	4	5	6	7	8
Gain [counts/(W/m2/sr)]	1	45258	2177386	67793	514810	37134	2262299	71993	486635
	2	45857	2308232	69035	540019	39316	2338381	73469	504450
	3	45718	2315704	68267	545591	39559	2317987	73624	506853
	0	45602	2189609	63859	523424	39096	2104936	72786	480310
Offset [normalised counts]	1	-8548	109	-32	-73	-7295	383	-39	-473
	2	-8614	112	-33	-42	-7757	447	-110	-420
	3	-8545	107	-11	-44	-7815	440	-122	-406
	0	-8521	-19	-3	-101	-7752	375	-95	-375

The instrument noise performance results are summarised in Figure 3. It shows that all channels, all pixels meet the Mission Description Document requirements. The solar channel (2, 4 , 6 and 8) noise is close to the predicted level whilst for the thermal channels it is greater then the prediction. The thermal channel data, in particular channels 3 and 7 data, is being re-analysed and the predictions are being re-evaluated in order to explain the discrepancy.

Figure 3 Noise Performance Summary

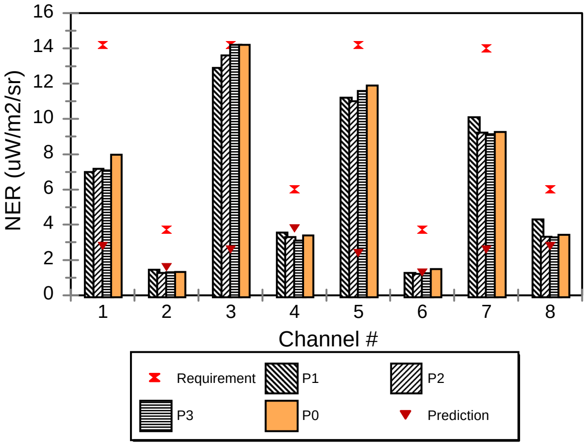
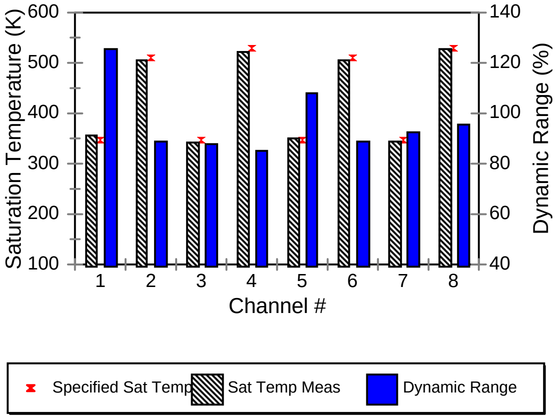


Figure 4 Dynamic Range Summary



The dynamic range of each channel is summarised in Figure 4, it shows that solar channels radiance dynamic range is about 5-15% below the desired value, as is the case for thermal channels 3 and 7. Channels 1 and 5 are 25% and 10% above the desired values.

2.3.1.2 Temperature Sensitivity Effects

The MOPITT 4.7µm thermal channels (1, 3, 5 & 7) are sensitive to changes in the instrument temperature, in particular to changes in the fore-optics and chopper temperature. Although the instrument is well thermostatted by the cold plate system against large thermal orbital fluctuations, small changes (<3K) are nevertheless expected. Sensitivity to such changes will lead to a more frequent two point calibration. A change in the fore-optics and chopper temperature leads to a change in the offset whilst a general change in instrument temperature leads to a change in the gas modulator pressure and hence a corresponding change in the channel gain.

The test was conducted for the thermally sensitive 4.7µm channels only, the coldplate was initially held at 290K and the MCBB was varied in 10K steps from 300K-340K, the coldplate temperature was then increased by 5K and held at 295K and the test repeated. The results of this test are summarised in Table 3

Table 3 MOPITT Temperature Sensitivity Effects

	Channel #								
Parameter	Pixel #	1	3	5	7	Parameter	1	3	5	7
dGain AV	1	-0.64	-0.02	-1.91	-1.91	dOffset AV	20.55	21.25	16.05	20.68
hot/cold	2	-0.61	-0.01	-1.83	-1.83	hot/cold	20.75	21.37	16.10	20.64
[%]	3	-0.63	-0.02	-1.84	-1.84	[%]	20.73	21.39	16.06	20.80
	0	-0.69	0.24	-1.89	-1.89		20.52	21.99	15.98	18.69
dGain DIFF	1	5.14	1.34	4.01	3.47	dOffset DIFF	27.55	21.52	22.90	31.24
hot/cold	2	5.11	1.30	4.03	3.53	hot/cold	27.71	21.24	22.86	31.24
[%]	3	5.08	1.32	4.01	3.59	[%]	27.66	21.48	22.80	31.39
	0	5.08	1.56	4.03	1.41		27.48	22.83	22.84	29.24

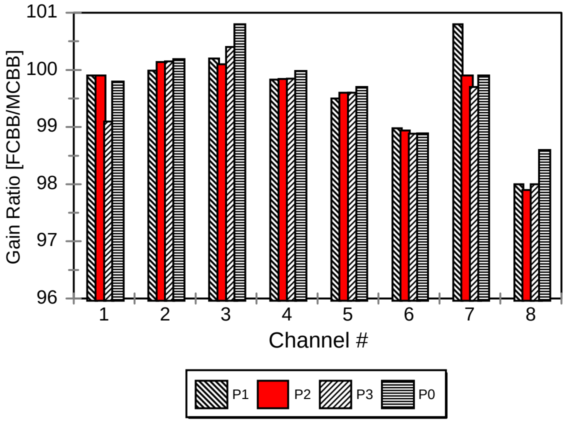
The results show that as expected the Average (AV) and Difference (DIFF) signal offset have changed by 20-30% due to the equivalent percentage change in the fore-optics and chopper temperatures. Furthermore, the DIFF signal gain has changed by up to 5% , this is due to a increase in the sieve temperature leading to a increase in the modulator cell pressure, hence an increase in the amount of gas modulation and therefore a increase in the gain. It is also worth noting that the NER increases by 5-10% because there is an increase in the chopper closed noise due to its higher temperature.

These results show the extreme case, where the baseplate temperature itself has been directly changed through the coldplate system. Instrument temperature variations due to orbital temperature fluctuations are expected to be significantly smaller since the instrument is thermally controlled by the coldplate, a system immune to orbital fluctuations and the instrument is thermally well isolated from the environment. Once the real on-orbit fluctuations are known these results can be used to determine how frequently the two-point calibration needs to be done in order to compensate for these fluctuations (at present the two point gain calibration, is done every 11mins and a single point offset calibration is done every 2 mins).

2.3.1.3 Internal Sources Cross Calibration

MOPITT has four dual band calibration sources that enable on-orbit gain and offset calibration of all the channels. These sources need to be cross-calibrated to the ground standard calibration source, the MCBB and through the MCBB to National Standards.

Figure 5 Summary of Cross Calibration



The cross calibration was done by initially setting the two blackbodies to the same nominal temperature and chopping between the two using the input scan mirror. The MOPITT detectors were used to transfer the standard. The MCBB temperature is then incremented while the flight source temperature is slowly ramped up. For the thermal channels (1,3,5&7) the flight sources are calibrated in the 300-340K range in 10K increments and for the solar channels (2,4,6&8) in the 440-500K range in 10K increments. The channel gain, offset and noise are determined for the two calibration sources and the gain values compared to determine the delta between the two sources.

The results, given in Figure 5, show that for the thermal channels (1, 3, 5 and 7) the gain values from the two sources agree to within +/- 1%. The gain values for channels 2 and 4 also agree to the same level but their corresponding redundant channels, channels 6 and 8 respectively have flight source gain values that are approximately 2.5% lower then the equivalent MCBB measurements. The differences in the gain values from the two sources can probably be explained by the uncertainty in the blackbody emissivity calculations, however the results for channels 6 and 8 in particular need to be re-analysed.

This test also re-confirms some of the results seen in the channel response test, for instance channel 5 pixel 1 and channel 6 pixel 0 low gain values, inner and outer pixels gain "pairing".

2.3.1.4 Simulated Signal Response Test

Rather then just using a smooth blackbody type radiance response to characterise the instrument a more realistic test where the atmospheric gas column is simulated was also conducted. This test is used to check and verify that the various MOPITT channels are indeed most sensitive in the regions they are expected.

The MOPITT response of all channels to a gas mixture simulating the atmosphere was conducted by inserting the MOPITT gas cell (MGC), filled with the appropriate gas mixture, between the instrument nadir view and the MCBB. In addition to the MCBB the MOPITT Solar Reflected Simulator (MSRS) was used to characterise the performance of the solar channels.

For the thermal CO channels (1,3,5&7) the MCBB was maintained at 335K and the channel response measured by changing the gas pressure of a 5% CO/N_2 gas mixture from 0-100kPa.

For the solar channels the MCBB was replaced by the MSRS. For the CO solar channels (2&6) the 5%CO/N_2 gas mixture pressure was changed from 0-100kPa. For the solar CH_4 channels pure CH_4 gas was used and cell pressure changed from 0-100kPa.

A further test in which the gas cell was filled, from 0-100kPa, with N_2 and air was also conducted on all channels to study the effect of an interfering gas.

Figure 6 Simulated Signal Response

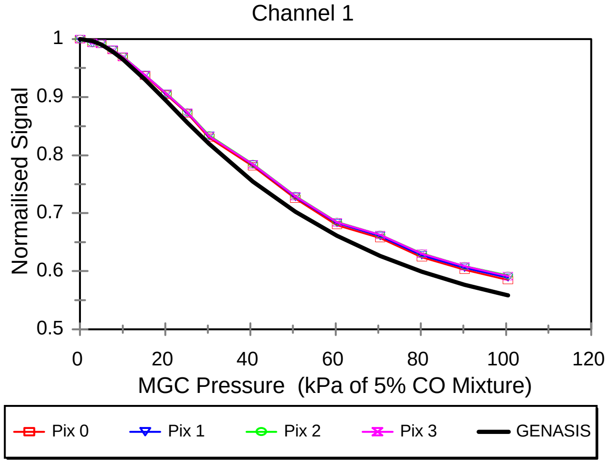


Figure 6 shows typical results in this case for channel 1. The response of the four pixels is very similar and it has been compared to the theoretical GENASIS line by line calculation. The number of molecules in a typical atmospheric column corresponds to a gas cell pressure of approximately 30kPa. The discrepancy between the measurement and calculation at this point is 5%. For the other channels this discrepancy varies between 0.3-6.5%.

An analysis is on going to determine which factors could lead to such a delta. The leading candidates, at present, seem to be the correlation cell length and the LMC and MGC cell pressures.

In all cases the interfering gas had a <0.06% effect at maximum gas cell fill pressures.

2.3.2 Field Of View Tests

The field of view (FOV) tests will determine the instrument spatial response. The detector uniformity and response have to be mapped on a pixel by pixel basis (MOPITT has eight channels each of which has a 4x1 pixel array) in order to complement the radiometric calibration. Furthermore, the instrument pointing can also be verified.

The MOPITT FOV tests consisted of the following: instantaneous field of view test, pixel co-alignment and detector co-registration test and a response to polarised light test.

2.3.2.1 Instantaneous Field of View Test (IFOV)

This test was conducted to map out the response of each of the 32 pixels (8 channels each with a 4x1pixel array). The objective was to determine the pixel uniformity.

This test is conducted using the MOPITT Collimator System [6] (MCS). The MCS was initially aligned to the MOPITT optical cube, which in turn had been aligned to the MOPITT optics. The MCS was then translated to the desired input and the detector array mapped out point by point, line by line (a 28µm spot was translated in 45µm steps, resulting in approximately 2800 points/detector). At the end of the scan the MCS alignment was re-verified by aligning to the MOPITT optical cube and the test repeated until all eight channels were mapped (since the channels have common inputs, two detector arrays can be mapped simultaneously, hence the above process was repeated more three times). This test was extremely time intensive, requiring approximately 14 hours to map an array. The results of a typical test are shown in Figures 7a and 7b.

Figure 7a Channel 6 IFOV Response

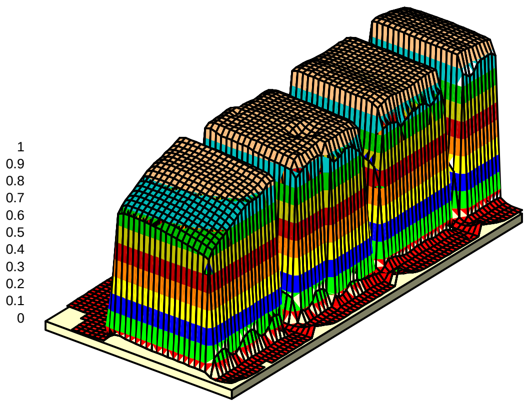
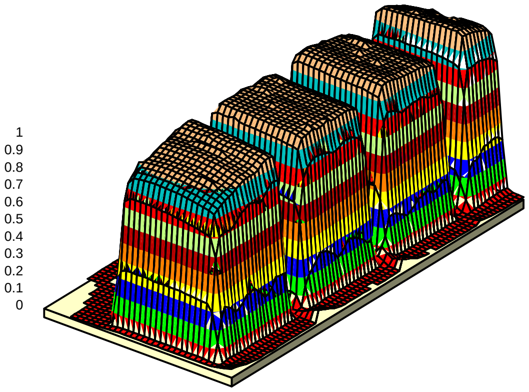


Figure 7b Channel 8 IFOV Response



Both the channel 6 and 8 data shows that the outer pixels, pixels 0 and 1 have a roll-off in the response that corresponds to the lower gain values seen in the radiometric tests and hence the pairing of inner and outer pixels (this roll off in the outer pixels has been observed for all channels that have been processed). Channel 6 pixel 3 also shows a small indentation that was also observed in the corresponding pixel in channel 5, pixel 2. This implies that the effect is not due to the detector response but something in the common optics of channel 5 and 6. Figures 7a and 7b also show that the outer pixels, in particular pixel 1 has not been fully mapped, in fact a closer comparison between the channel 6 and 8 maps shows that there may be some vertical, along track, misalignment.

2.3.2.2 Detector Co-Registration Test (Instrument Pointing)

This test was primarily designed to verify that the four input optics all co-locate within the specifications set out. This test also yields information on the spot size which can be verified to see whether it meets its specification.

This test is essentially a sub-set of the IFOV test, the alignment of the MCS to the optical cube and its re-verification is as described above. However, for a single 4x1 pixel array, four across track scans are run, one on each pixel and one along track scan is run along the whole array. This is then repeated by rotating the instrument through 90 degrees and viewing down the space view ports. By combining the nadir and space view data one can determine the pointing. Furthermore, as one goes across the pixel edge one can use that information to determine the spot size.

The detector co-registration, plotted in Figure 8a shows that there is indeed a misalignment between the four input scan mirrors. In fact, scan mirrors 2, 3 and 4 lie within the +/- 1km pointing specification (the box in Figure 8a) but are not aligned with this accuracy to the MOPITT optical cube. Mirror 1 is offset significantly from the other three scan mirrors and the optical cube. The cause of the mirror misalignment is believed to have occurred when the scan mirrors were finally aligned to the optical cube. This alignment process was done through the space view ports due to instrument and equipment configuration. However, when done in this manner, one degree of freedom is not controlled, resulting in an error when the mirrors are pointed to the nadir view. The results shown in Figure 8a are after scan mirrors 2,3 and 4 have been re-aligned in an attempt to get them closer to scan mirror 1 (scan mirror 1 could not be moved due to mechanical complexities and physical limitations, hence it was decided to move the other three mirrors to its position rather than the ideal where all four mirrors would have been aligned to the optical cube). It should be noted that this re-alignment was a best attempt conducted in the ICF under less then ideal conditions and late in the test program. It was decided by the MOPITT Science Team to leave the alignment as is, since the mirrors have a known offset with respect to the MOPITT optical cube and the offset could be software corrected. In fact this process is on-going and we are also investigating possible test scenarios in the activation phase where suitable coastlines may be used to verify these offsets.

Figure 8a Nadir Pointing Measurements

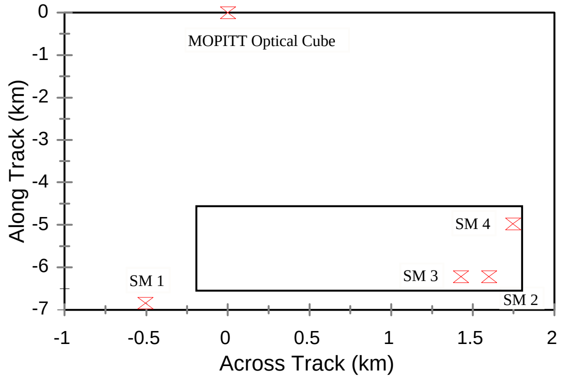
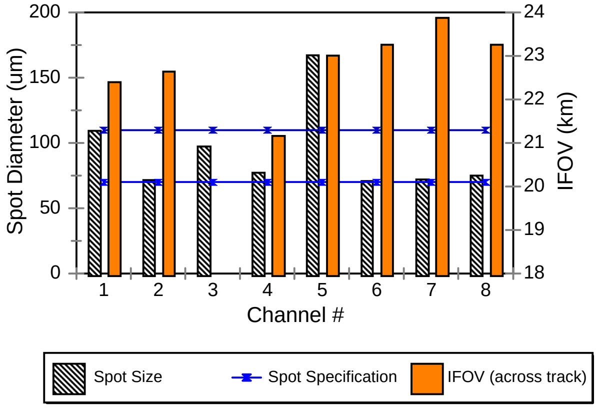


Figure 8b Spot Size and FOV



The spot size measurements show that in general all channels other than channel 5 fall within the desired range (80um<spot size <110um), the MOPITT optics have been deliberately de-focussed to minimise rapid changes in surface reflectivity per stare. The de-focussing was done by moving the final optical element back from the ideal position, this may explain the channel to channel differences in spot size. Figure 8b also shows the across track FOV, channel 3 had bad data but the data can be processed out from the IFOV response plots above. In general the IFOV is in line with the desired 22km footprint.

2.3.2.3 Polarisation Tests

Although the instrument has been designed to minimise the effects of polarisation, such effects will none the less occur, primarily due to the cross track scanning nature of the scan mirrors and also due to the optics (primarily the beam splitters) and optical coatings. It was therefore important to test the instrument response to polarised light.

The response of all channels was tested by using a wire grid polariser installed near the focal point of the MCS. The MCS was held at a known position on a pixel and the polariser rotated to make the measurement. Several measurements were taken on each pixel for all channels.

The results show that solar channels 2,4 and 8, have an approximately 4% effect whilst channel 6 has a 0.5% effect. The results from the thermal channels have proved to be inconclusive and another look has to be taken at that data. It should also be noted that the polariser itself was less then ideal, it was non-uniform across its surface, hence this data should be taken as an indicator of MOPITT's sensitivity to polarised light and the absolute measured values should be treated with care.

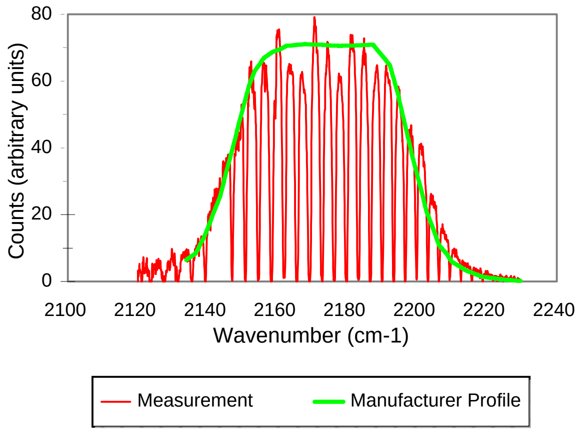
2.3.3 Spectral Tests

The instrument spectral response is limited by cold (≤110K) narrow band optical filters in each channel. Although the spectral response has been characterised at component level, spectral changes may occur during build and test. Spectral shifts may also occur because of filter location and due to changes in the FPA temperature (the filters were characterised at 105K at component level but are used at 90-110K,). Unknown filter shifts could, falsely, be interpreted as a non-linearity in the radiometric channel response. It is therefore, important to characterise the end to end spectral response of all channels.

2.3.3.1 In and Out of Band Response Test

Monochromatic IR light was generated by using a Difference Frequency Laser System (DFLS). Two visible laser beams, one tunable, are brought into the ICF (from the High Resolution IR and Raman Spectroscopy Labs) using individual fiber optic cables. The mixing to produce the IR beam occurs on the optical breadboard mounted outside the vacuum chamber. The resultant beam went through a calcium fluoride window and was reflected off a 45° movable and gimbaled mirror and onto the MOPITT optics. For the thermal channels (1,3,5&7) the in-band response range is 2136-2199 cm^{-1}. This range is 4254-4316cm^{-1} for the CO solar channels (2&6) and the 5% cut-off points are 4344cm^{-1} and 4519cm^{-1} for the CH_4 channels (4&8).In order to test both the thermal and solar channels, the tunable laser dye has to be changed, the argon ion frequency has to be changed, the mixing crystal has to be changed and the optics re-aligned. All control of the DFLS, that is spectral sweep rate, spectral range and window etc, was done through the High Resolution IR and Raman Spectroscopy Labs. Further information on the apparatus and test set up can be obtained elsewhere.[6]

Figure 9 Channel 1 Spectral Response



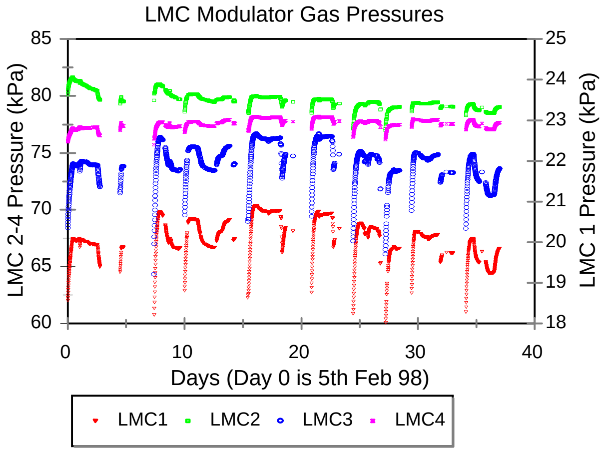
Due to time constraints not all channels could be tested, only one pixel each from channels 1,2,4,5,6 and 8 were tested. An example of the raw measured spectral profile is given along with the manufacturers data in Figure 9. The measured data shows the carbon monoxide gas lines, there is some evidence of an etalon effect and a baseline correction has to be made due to the measurement methodology leading to beam wander. Comparison with the manufacturers data shows that the profile has shifted to higher wave number, in general all channels show a similar shift varying from 0.6-2.6cm^{-1}. Part of this shift may be explained by the small filter temperature differences between the two data sets.

Work is still on going to determine the precise filter shapes and for the baseline correction. This has involved repeating some tests on the MOPITT Engineering Qualification Model (EQM).

2.4 Post Integration Tests

The MOPITT instrument was integrated onto the EOS AM-1 platform in November 1997. The spacecraft underwent thermal vacuum testing in February-March 1998 at the Lockheed Martin test facility in Valley Forge. During this time the MOPITT radiometric calibration was re-verified using the internal calibration sources. An example of the LMC modulator cell pressures is given in Figure 10. The fluctuations in pressure are due to thermal cycling of the spacecraft and the discontinuities occur when the instrument and spacecraft where switched off for re-configuration.

Figure 10 Post Integration TVac Data


LMC Modulator Gas Pressures

Since thermal vacuum the instrument has been periodically switched on, in an ambient environment, to either support spacecraft tests or to power up and ensure the mechanisms and modulators are behaving in a nominal fashion. The spacecraft was moved to Vandenberg Airforce Base (VAFB) in April 1999 in preparation for a late 1999 launch. Similar, ambient environment tests have been on-going at Vandenburg to ensure that from an engineering perspective the instrument is fine, it should however be noted that the last science data from the instrument was obtained in March-April 1998.

3.0 CONCLUSION

Pre-flight calibration and characterisation of the MOPITT instrument was conducted at the University of Toronto ICF from April to August 1997. MOPITT was under vacuum for 62 days and in science mode for 40 days of which 13 days were of uninterrupted operation. A further 37 days of science operation, under vacuum, were achieved post integration at the Lockheed Martin facility. All indications from the pre and post integration tests show that MOPITT is fully operational and launch ready. It should however be noted that the last science data was obtained in March-April 1998, approximately 18 months before launch.

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