MOPITT Mechanisms: 16 Years In-Orbit Operation on Terra

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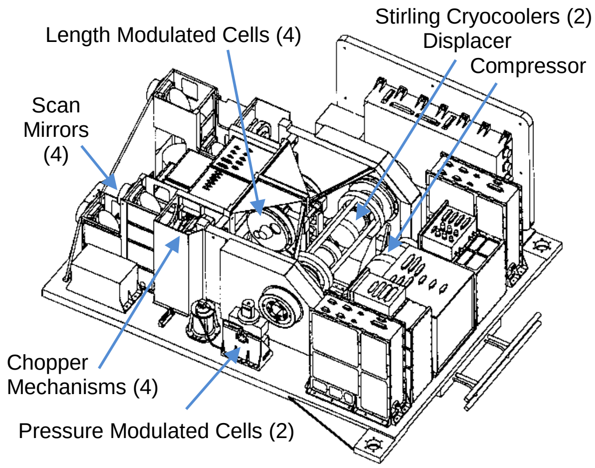
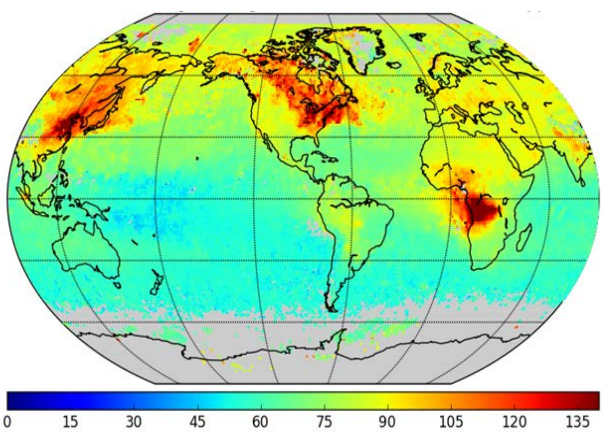
Abstract

The 16th anniversary of the launch of NASA's Terra Spacecraft was marked on December 18, 2015, with the Measurements of Pollution in the Troposphere (MOPITT) instrument being a successful contributor to the NASA EOS flagship. MOPITT has been enabled by a large suite of mechanisms, allowing the instrument to perform long-duration monitoring of atmospheric carbon monoxide, providing global measurements of this important greenhouse gas for 16 years. Mechanisms have been successfully employed for scanning, cooling of detectors, and to optically modulate the gas path length within the instrument by means of pressure and gas cell length variation. The instrument utilizes these devices to perform correlation spectroscopy, enabling measurements with vertical resolution from the nadir view, and has thereby furthered understanding of source and global transport effects of carbon monoxide. Given the design requirement for a 5.25-year lifetime, the stability and performance of the majority of mechanisms have far surpassed design goals.

With 16 continuously operating mechanisms in service on MOPITT, including 12 rotating mechanisms and 4 with linear drive elements, the instrument was an ambitious undertaking. The long life requirements combined with demands for cleanliness and optical stability made for difficult design choices including that of the selection of new lubrication processes. Observations and lessons learned with regards to many aspects of the mechanisms and associated monitoring devices are discussed here. Mechanism behaviors are described, including anomalies, long-term drive current/power, fill pressure, vibration and cold-tip temperature trends. The effectiveness of particular lubrication formulations and the screening method implemented is discussed in relation to continuous rotating mechanisms and stepper motors, which have exceeded 15 billon rotations and 2.5 billion steps respectively. Aspects of gas cell hermeticity, optical cleanliness, heater problems and SEU effects on accelerometers are also discussed.



MOPITT Instrument Layout
(showing mechanism locations)



Carbon Monoxide Average Mixing Ratio (in ppbv)
(measured June-July 2015)

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Introduction

The MOPITT instrument is a multi-channel thermal infrared (TIR) and near infrared (NIR) instrument that continuously measures the concentration of carbon monoxide (CO) on a global scale. The instrument was funded by the Canadian Space Agency and built by the prime contractor COM DEV International. Prior to the launch of MOPITT on the NASA Terra platform, the only global data available was for four short periods of measurements by the MAPS instrument on the Space Shuttle. Instrument retrievals have helped to understand the relationship of CO to ozone, which is linked to climate change. With MOPITT's high sensitivity to surface CO from simultaneous NIR and TIR signals, this has also been useful to support estimation of CO_2 sources. Data have also been used in combination with that of other instruments to produce improved data products as described by Gille [1]. The current baseline, given existing fuel, is to continue operation of Terra until the early 2020s.

The Terra platform is in a sun-synchronous polar orbit at an altitude of 705 km. From Terra, MOPITT has a horizontal spatial resolution of around 22 km x 22 km and a swath width of ~640 km, which allows global coverage every 3 days. MOPITT uses gas-cell correlation radiometry to detect atmospheric CO absorption at 4.6 µm (TIR channels) and 2.3 µm (NIR channels), [2]. The instrument contains a set of long life mechanisms shown in Figure 1, which provide critical functionality in the collection of CO data.

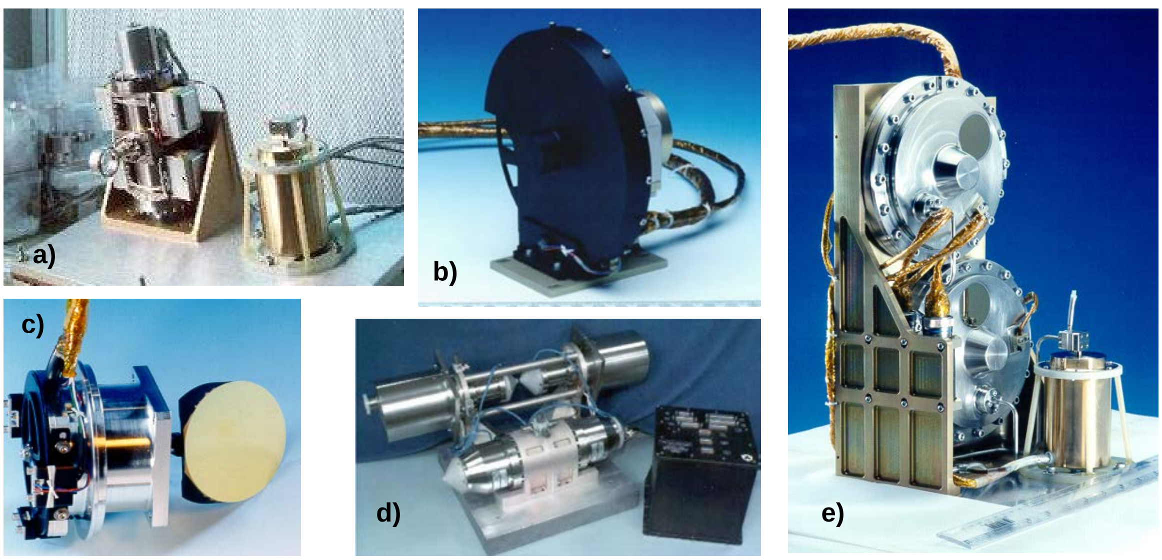

Figure 1. MOPITT's Continuously Operating Mechanisms: a) Pressure Modulator Cell & Molecular Sieve, b) Rotating Vane Chopper, c) Scan Mirror Mechanism, d) Airbus Stirling Cooler & Lockheed Cooler Drive Electronics, e) Length Modulation Cells & Sieve

MOPITT contains four optical chains which are each split into two independent channels (total of 8 channels). A summary of the optical channels and the mechanisms involved in each channel is given in Table 1. The optical signals are acquired via four stepper motor driven scan mirrors, each initiating an optical chain at the front end. The hybrid stepper motors for the scan mirrors were manufactured by Tecstar (now MOOG) and have achieved long lifetimes on the order of $2.5 \cdot 10^9$ steps (1.8°) or travel equivalent to 12 million rotations, with bearings lubricated with MAC grease (Rheolube 2000).

The optical input signal is routed from the scan mirrors to four optical choppers, which turn continuously at fixed speeds of 1500 and 1800 RPM, with 16 vanes per rotation. Designed and built by COM DEV, three of the four chopper mechanisms have each achieved over 15 billion revolutions. Long life achievements have been facilitated by the use of MAC (multiply-alkylated cyclopentane) oil lubricated bearings (Nye 2001T with 1.0% tricresyl phosphate and 0.3% phenolic anti-oxidant). The formulation is only slightly different from the more common additive formulation for Nye 2001, but was based on Draper Lab's long life heritage with PAO oils.

Table 1. MOPITT Optical Channels and Mechanism Configuration/Timings

Optical Channel Number	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7	Channel 8
Chopping & Scanning Mechanism Numbers	Chopper & Scan Motor 1		Chopper & Scan Motor 2		Chopper & Scan Motor 3		Chopper & Scan Motor 4	
Modulating Mechanism	LMC 1		PMC 1	LMC 2	LMC 3		PMC 2	LMC 4
Gas Species in Modulating Mechanism	CO		CO	CH_4	CO		CO	CH_4
Pressure of Modulating Mechanism [kPa nominal]	20		7.5	80	80		3.8	80
Wavenumber Range [cm^{-1}]	52	40	52	139	52	40	52	139
Mid-Wavelength [µm]	4.617	2.334	4.617	2.258	4.617	2.334	4.617	2.258
Wavelength Range [µm]	0.111	0.022	0.111	0.071	0.111	0.022	0.111	0.071
Modulator Frequency (LMC or PMC Rate) [Hz nominal]	11.2		48.6	13.5	11.2		43.3	12
Nominal Chopper Frequency [Hz]	401		486		401		433	
LMC Angular Encoder Pulses [pulses per rotation]	72		N/A	72	72		N/A	72
Pressure Control Device Number	Sieve 1		Sieve 2	N/A	Sieve 3		Sieve 4	N/A
Stirling Cryocooler System	Compressor & Displacer 1 (Side B)				Compressor & Displacer 2 (Side A)			

= indicates Side-B (partially redundant channels)

The input signals are optically chopped/filtered in various ways using gas samples via two types of specialized mechanisms: the Length Modulated Gas Cells (LMC) (1 per optical chain), and the Pressure Modulated Cells (PMC) – in 2 of 4 chains.

As described previously [4], each of the four LMC mechanisms contain a pair of optical rotors spinning inside separate cells at fixed speeds between 672 and 810 RPM. A brushless DC motor directly drives the rotor in the evacuated cell ('compensator cell'), which in turn drives a co-linear rotor located in the second sealed gas cell ('modulator cell') charged with CO or CH_4 via a magnetic coupling. The LMC motor and bearing configuration (including lubrication) is identical to that of the choppers, except for the housing material and bearing preload. All of the LMCs have achieved ~6 billion revolutions to date.

The two PMC mechanisms provided by Oxford University have continued to operate reliably, representing the longest running in-orbit heritage for PMCs to date, exceeding $2{\cdot}10^{10}$ cycles of linear motion. The MOPITT version was specially characterized to run at higher fill pressures (≤10 kPa). These devices are lubricant-free, utilizing diaphragm springs and clearance seals, with direct heritage from the Pressure Modulated Radiometer flown on the ISAMS instrument on UARS [5]. As they are the predecessors that enabled the current generation of long-life space cryocooler technology, lifetime results are not surprising.

To maximize signal-to-noise ratio and achieve optimal performance, indium antimonide infrared detectors were designed to be cooled to <90K using a pair of 50–80K Airbus Stirling Cycle Coolers (formerly BAe/Matra Marconi/Astrium) [3,9]. The coolers are driven by Cooler Drive Electronics manufactured by Lockheed Martin. The cryogenic cooling system for the detectors represents a duality of results in terms of life, having demonstrated one of the shortest and longest life-times in-orbit for Stirling devices to date. The failure of one displacer drive system after just over a year in orbit led to adjustments which allowed the 2nd cooler to continue running, with nominal vibration compensation provided by the opposing compressor. Partial redundancy of the optical channels reduced the impact of the failure on science return. Alongside the TIR ASTER cooler also on Terra, the prevailing MOPITT cooler system represents the longest in-orbit Stirling cooler heritage point to date, surpassing those on the ERS satellites and leading slightly ahead of another Airbus cooler (from the same batch) flying on ODIN. Specific device behaviors, including updates on cooler vibration compensation, decontamination cycles, and accelerometer response to radiation environment are discussed later in the paper.

A summary of the mechanism life record is shown in Table 2, with some key tribological parameters and notes included for reference. The instrument is taken offline once per year for decontamination (approximately one week duration, usually in March), hot calibrations, and a PMC characterization sweep.

Two additional mechanisms on board MOPITT, the Earth and Space Port Covers, deployed successfully on 28 Feb 2000, retaining the ability to be re-closed if necessary. The port covers, as well as the other mechanisms, have been described previously [3,4]. Refer to these references for details of the mechanism designs and operation in the MOPITT instrument, and for a previous review of in-orbit mechanism performance after 5 years in orbit. The following section provides an update to that review, with further discussion of observations and status for the continuously operating mechanisms.

In-Orbit Performance of Continuously Operating Mechanisms

<u>Scan Mirror Mechanism Performance</u>
The scan mirror sequence was described by Caldwell [3], covering a ±25.2° swath with periodic swings to a space view and to an internal blackbody calibration. Figure 2 shows that the drive currents have been extremely stable over the mission duration. The current itself proves that the device was commanded reliably, while the response of the unit has been confirmed through consistency of data and encoder readings. The customized IR encoder readings, which provide 3 bits of information to indicate the center and edges of the swath, as well as calibration positions, have not generated any significant errors over the mission lifetime. An anomaly occurred with Scan mirror 1 on 06 Apr 2002, with current rising rapidly and oscillating for about 90 seconds before the voltage dropped to zero (see Figure 4a). The voltage drop is consistent with either a blown fuse or power supply failure. The current increase which preceded the failure was brief, with no obvious warning signs noted previously, so it is thought that the failure is more likely to be an electrical fault than a mechanism failure. Because this side of the instrument was already non-operational due to the cooler failure, no further in-depth investigation was pursued.

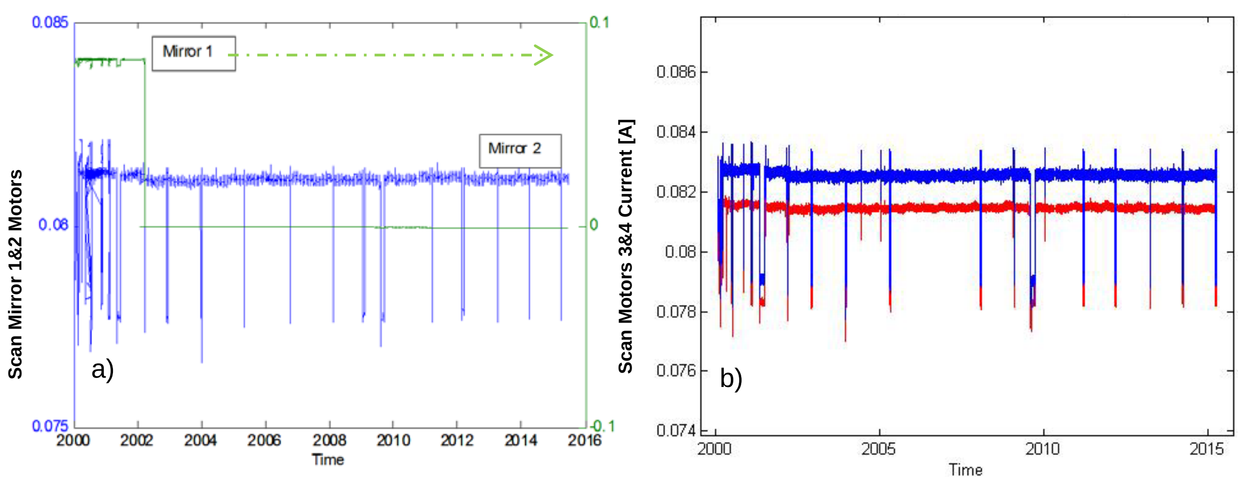

Figure 2. Stepper Motor Current vs Time for a) Scan Motors 1 and 2, b) Scan Motors 3 and 4

Table 2. Mechanism Usage Summary Over 16 Years in Orbit (to 17 Jan 2016)

Mechanism	Gas Fill	Freq/ Rate	Key Unit Parameters	Years Nominal Running	Cycles/ Rotations / Steps*	Mechanism Status	Specific Notes
Cooler 1 (B) – Compressor	He	44/43 Hz	13 bar fill pressure (abs)	15.5	2.1E+10 cycles	Continues to operate nominally. ~3 months for investigations. Displacer ceased nominal operation in 07 May 2001	Current compressor Stroke (A,B)=(6.24,5.00 mm_{p-p}). Displacer strokes (A,B)= (2.99,3.69 mm_{p-p}) Displacer B continues to move freely, driven by pressure wave as per Figure 9.
Cooler 1 (B) - Displacer	He	44/43 Hz	90 K cold-tip (transitioning to ~310 K, 326 K)	1.2	1.6E+09 cycles		
Cooler 2 (A) Compressor & Displacer	He	44/43 Hz	84 K±0.3 K over life	15.5	2.1E+10 cycles	Continues to operate nominally	14 decontamination cycles completed
PMC 1	CO 7.5kPa	48.6 Hz	Q factor of ~3, drive current of X	15.7	2.4E+10 cycles	Continues to operate nominally	Characterisations performed during decontamination cycles, used to monitor resonance/fill pressure. PMC 2 losing ~1% of pressure per year, current temp of 297-300 K. PMC amplitudes (1,2)=(4.84, 6.41mm)
PMC 2	CO 3.8kPa	43.3 Hz	Q factor of ~7 (at lower pressure), Drive current of 0.2A	15.7	2.1E+10 cycles	Continues to operate nominally	
Chopper 1		25.1 Hz 1505 rpm	Nye 2001T (130mg), TCP soaked 440C R6 duplex bearings preload of 12.6±4.4N, Meldin 9000 retainers. Lubricant Screening by Draper Labs (up to 5 cycles). Optical encoder 16 pulses/rotation.	15.7	1.2E+10 rotations	Continues to operate nominally	All choppers have 16 vane openings. Duplex bearings operate in vacuum.
Chopper 2		30.4 Hz 1822 rpm		15.7	1.5E+10 rotations	Continues to operate nominally	
Chopper 3		25.1 Hz 1505 rpm		1.3	1.0E+09 rotations	Stopped in open vane position 04-Aug-2001	Chopper 3 failure had no impact to science, due to stability of signal/background
Chopper 4		27.1 Hz 1624 rpm		15.7	1.3E+10 rotations	Continues to operate nominally	
LMC 1	CO 20kPa	11.2 Hz 672 rpm	Nye 2001T (130mg), TCP soaked 440C R6 duplex bearings preload of 22±4.4N, Meldin 9000 retainers. Lubricant screening by Draper Labs. Optical encoder with 72 pulses/rotation.	15.7	5.5E+09 rotations	Continues to operate nominally	Modulator duplex bearing run in gas. Compensator duplex bearings run in vacuum (vented). Bearing assembly bake-out post screening performed to reduce optical contaminants from lubricant additives.
LMC 2	CH_4 80kPa	13.5 Hz 810 rpm		15.7	6.7E+09 rotations	Continues to operate nominally. Lost 70kPa fill in 5 yr	
LMC 3	CO 80kPa	11.2 Hz 672 rpm		15.7	5.5E+09 rotations	Continues to operate nominally	
LMC 4	CH4 80kPa	12.0 Hz 720 rpm		15.7	5.9E+09 rotations	Continues to operate nominally	
Scan Mirror 1			Rheolube 2000, 440C bearings with TiC-coated balls, Nylasint lubricant reservoir	1.9	3.0E+08 steps	Unit Stopped 13-Dec-2002	Failure not believed to be mechanism related
Scan Mirror 2				15.7	2.5E+09 steps	Continues to operate nominally	Mirrors settle in <50 ms, stares for 400 ms per step over ±25.2° swath + deep space & blackbody calibration views ±90°
Scan Mirror 3				15.7	2.5E+09 steps	Continues to operate nominally	
Scan Mirror 4				15.7	2.5E+09 steps	Continues to operate nominally	

Rotating Vane Chopper Performance

The rotating vane choppers 1, 2 and 4 were shown to have stabilized after 5 years, as reported previously [3]. The stable performance has continued over the subsequent 11 years. This slow stabilizing behavior and periodic trends are believed to represent effects of the porous polyimide retainers, with small changes in wear and related coupling to the bearing races (refer to Figure 3). Differences in the average current levels are partly driven by the relatively large preload tolerances, speed of operation, and manufacturing and assembly tolerances (described in Table 2).

Chopper 3 stopped working in 2001 after 1.3 years of operation. Current at the drive amplifier was observed to increase over about 45 seconds before going to zero (refer to Figure 4), which could be consistent with a short in the harness or some other electrical component failure (not consistent with an open circuit). The chopper failure was attributed to a previous issue with a blown fuse, while a NASA report cites the most likely cause of the blown fuse was related to a Transistor Drive Circuit [10]. Fortunately, the chopper stopped at a completely open position, which allowed for the reconfiguration of data processing without the chopper. The failure actually had no impact on scientific data due to the thermal stability of the instrument.

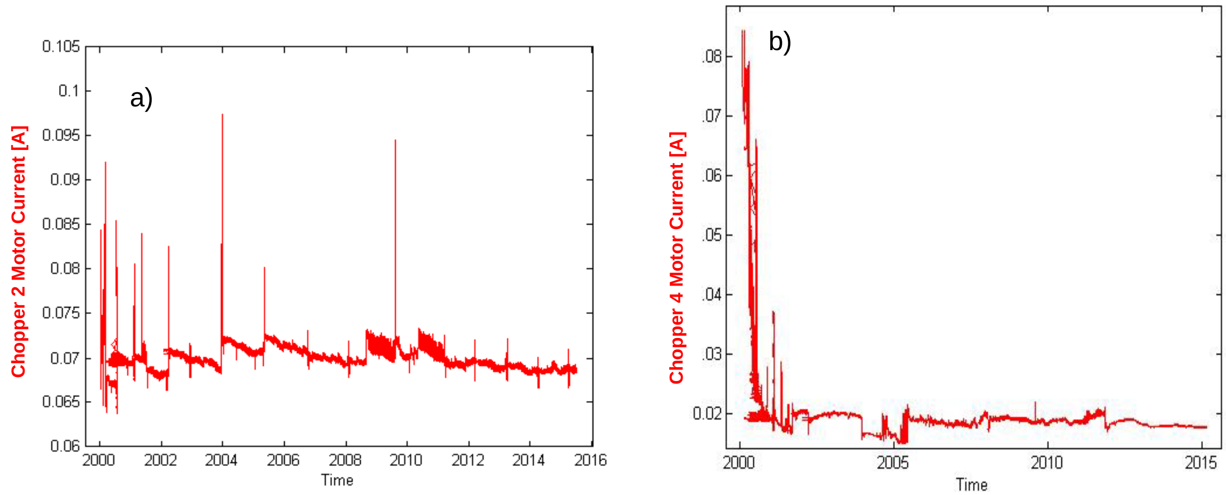

Figure 3. Chopper Brushless-DC Motor Currents of a) Chopper 2, b) Chopper 4

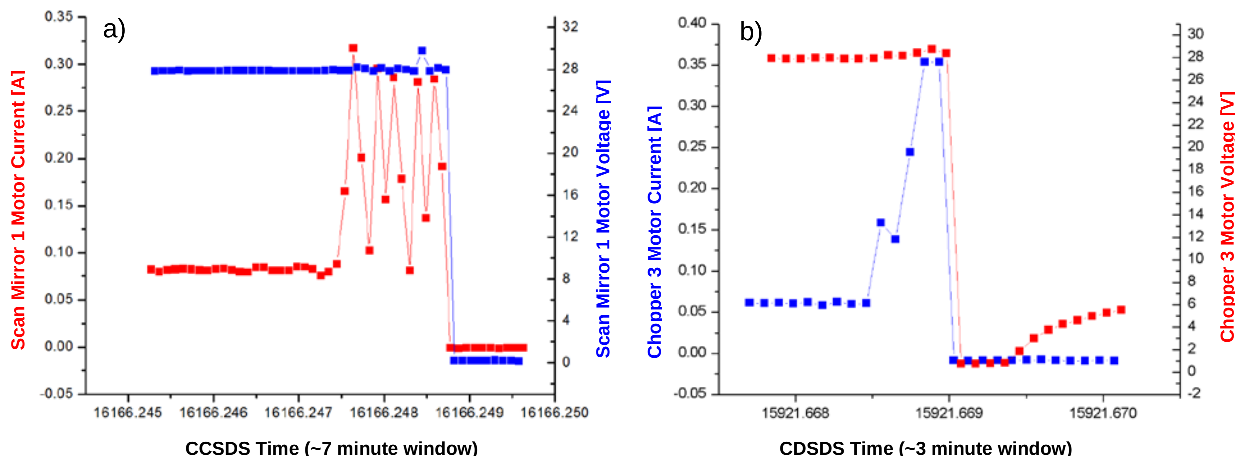

Figure 4. Motor Current and Voltage at Failure for a) Scan Mirror 1 and b) Chopper 3

Length Modulated Cell (LMC) Performance

The LMC devices all show similar current excursions to the choppers, with subsequent recoveries to nominal levels, as shown in Figure 5. The current generally dropped over a period of 1-2 years before rising sharply back to the original current levels for a brief period. This trend repeated in a slightly different manner each time without any overall rise in current, so it can be considered to be stable overall. Choppers 1, 2 and 4 show some similar features (Figure 3). With the commonality of the LMC and chopper designs, the settling behavior is likely resulting from a change in friction of the retainer coupling to the balls and races (the choppers and LMC have the same bearing size and retainer, manufactured by Draper Laboratories). As the retainer wears or accumulates lubricant film, thresholds are reached where the active site shifts to another ball location and proceeds to settle again.

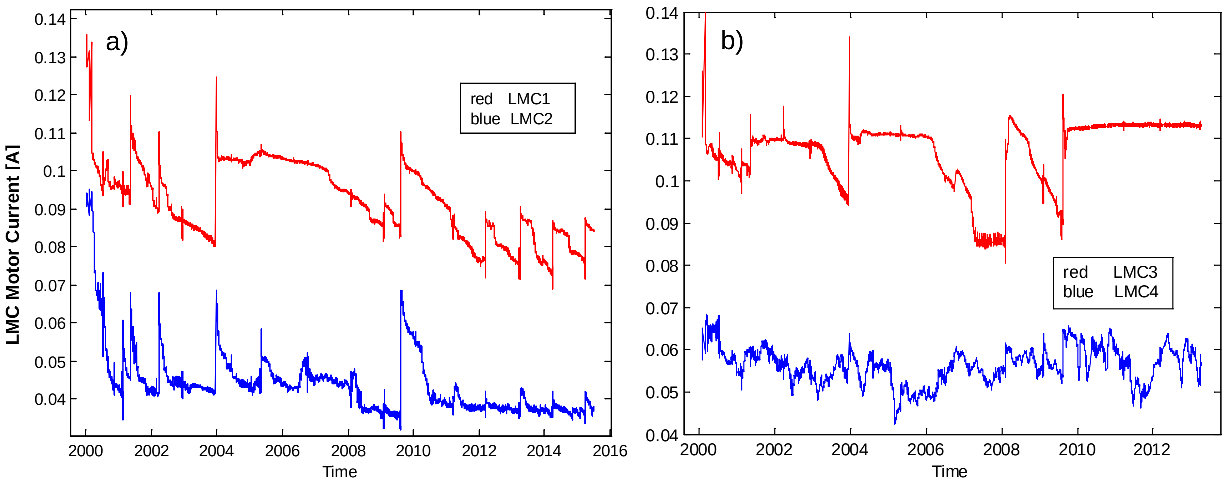

Figure 5. LMC Brushless-DC Motor Drive Currents for a) LMCs 1&2, b) LMCs 3&4

Optical cleanliness was one of the biggest design drivers for the LMC devices. In-orbit results demonstrate that contamination control was successfully managed as the long term radiometric gain measurements showed no significant build-up of contamination on optical surfaces over the mission, with the overall shift in gain being less than 1% in 16 years.

Each of the Length Modulated Cells were fitted with a pressure transducer, using high stability silicon-on-sapphire sensors (Sensotron). Pressure readings for these cells were expected to drop gradually due to gas leaks in the capillary bonded IR window seals (described previously in [4]), while the gold and indium plated Inconel seals around the largest perimeter of the gas cells could also contribute. The long-term trend for the pressure of LMC 3 and 4 showing the expected pressure drop is presented in Figure 6.

LMC 3 uses a molecular sieve to control the pressure and is showing a rate of pressure drop of about 1 kPa per year over the past few years. LMC 4 is a fixed pressure unit (no sieve), showing a slightly more rapid pressure decline since 2010 (~2.5 kPa per year), most likely due to leakage via the aging epoxy in the capillary bonds. LMC 1 lost about 10% of its pressure in the first 5 years. The LMC 2 pressure was stable at about 75 kPa for one year and then showed the most dramatic loss with pressure reduced to 5 kPa by 2005. The capillary bond for the optical windows was a newly developed process for this application, for which He leak testing, thermal cycling and ultrasonic inspection were performed to validate the engineering model hardware. The in-orbit results for two LMCs confirm that the bonding method is capable of lasting for a long-duration mission, but that screening methods and aging factors should be further considered (i.e., radiation testing and life-testing of the process is recommended prior to reuse). Alternatively, a diffusion bonding process could be evaluated as an option.

An anomaly was observed with Sieve 3 on 03 Oct 2009 (unrelated to the cooler anomaly) due to the heater for Sieve 3 turning off unexpectedly or failing. The heater can be activated to stabilize the pressure in LMC 3, but it had not been used for this purpose prior to this point in the mission. The effect was for the LMC 3 pressure to drop from ~68.5 kPa to ~65.3 kPa over 10 hours. The pressure then remained stable around 65.25 kPa. One attempt to reactivate the heater of Sieve 3 was unsuccessful. The resulting action was to modify the MOPITT forward model (for LMC new cell pressure) used for science data. This recalculation was performed by the NCAR team with a good result, and deemed to have zero impact on the quality of science data retrieved by MOPITT.

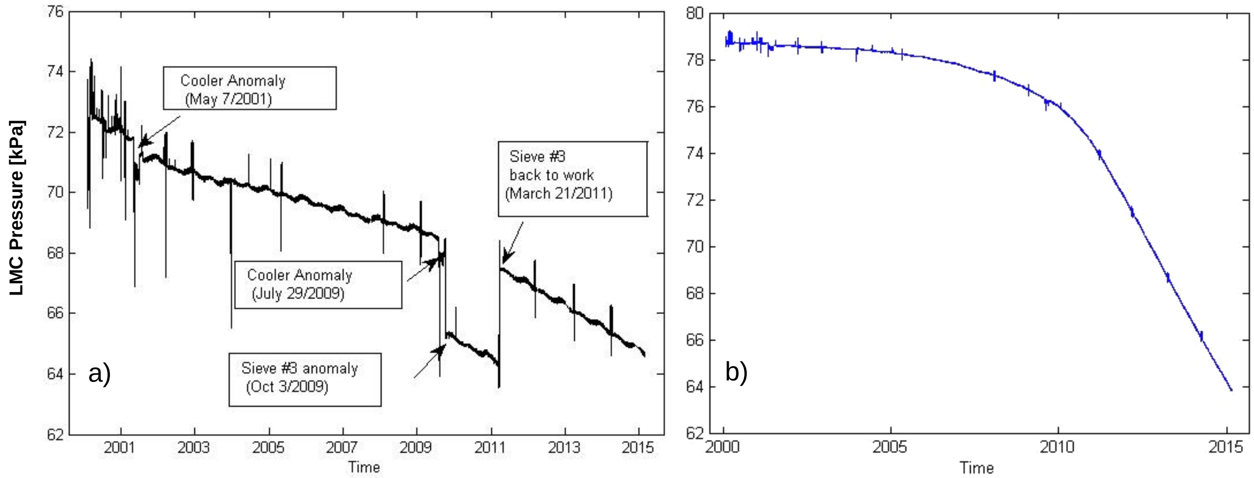

Figure 6. Length Modulated Cells - Pressure Sensor Signals Over Life for a) LMC 3, b) LMC 4

In 2011 the sieve was reactivated after an instrument reset during a calibration procedure, suggesting that the previous anomaly may have been due to an SEU effect. A later anomaly with Sieve 1 was thought to be similar to the Sieve 3 anomaly, occurring about a year later (02 Dec 2010) and resetting under similar circumstances.

Pressure Modulated Cell (PMC) Performance

The PMC devices have continued to operate as expected. Spikes in the data are believed to be due to effects related to decontamination cycles of the coolers. Referring to Figure 7b, the gradual drop in drive current for PMC 2 is consistent with a slow leak of gas approximately 1% per year, which affects the resonance of the mechanism. The step change in settings in 2001 is related to a change of setting after the cooler anomaly.

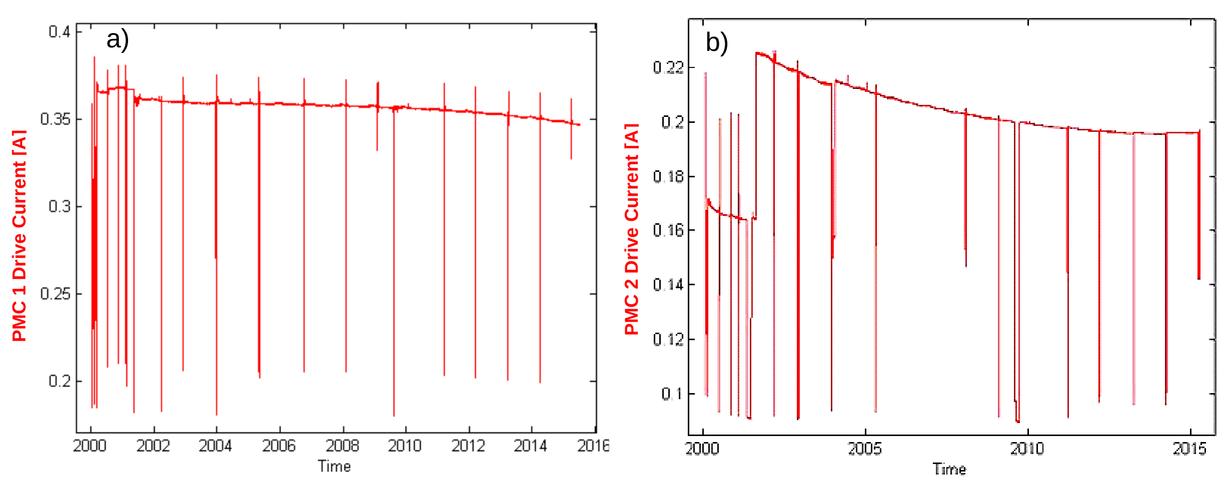

Figure 7. Pressure Modulator Cell Drive Currents for: a) PMC 1, b) PMC 2

In order to determine the mean operating pressure in the PMCs, it was necessary to make two sets of frequency scans with a change of sieve temperature between the two. The measurements of PMC motor current versus frequency were used to determine the resonant frequency of the PMC and using calibration runs obtained before and during spacecraft thermal-vacuum tests, a mean operating pressure could be determined. From the analysis done in March 2015, the PMC 2 pressure was 3.505 +/- 0.015 kPa. The rate of PMC2 pressure decrease is constant and is ~0.03 kPa/year. The resonance shift of PMC 2 is estimated to be ~1 Hz, having minimal effect on operation or efficiency. The ability to perform such in-orbit diagnostics is essential as the knowledge is needed for computations of optical filtering provided by the cell. This slow change in pressure has been accommodated through normal calibrations, allowing for updates to the optical filter models of this channel with little impact to data retrievals.

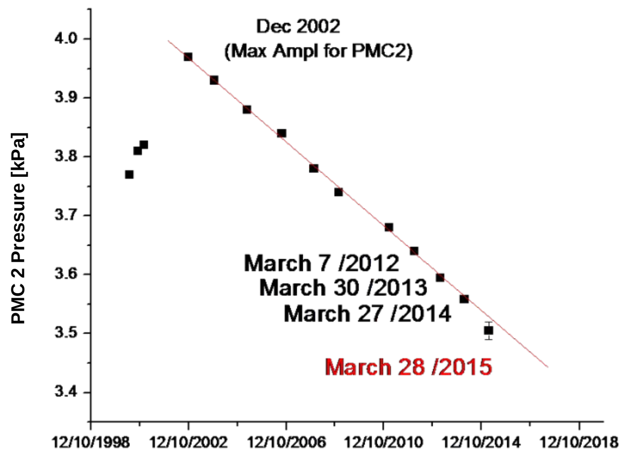

Figure 8. Pressure Modulator Cells Mean Pressure Drop Over Lifetime for PMC 2

<u>Stirling Cycle Cryocooler Performance</u>

On 07 May 2001 the cooler on side B of the instrument failed suddenly, without warning, as previously described [3]. One of the coolers had an out-of-limit condition for approximately 10 minutes before the instrument was put into Safe Mode, turning the coolers off. Observations [11] included a heating effect (2 K) at the displacer cold-tip B just before being turned off. Current telemetry indicated little change during the anomaly, which conflicted with possible explanations for the failure. It was learned from the vendor that the current telemetry for the displacer was not functional, which clarified the situation. The instrument was then power cycled, followed by a series of diagnostic tests which were run between 18 May and 26 Jun 2001, including the mapping of compressor to displacer stroke shown in Figure 9.

Phenomena consistent with pressure wave driving were observed in tests over varying amplitudes, explaining a different coupling between compressor B and its displacer. All tests showed that displacer B was not being driven electrically, but was coupled with the pressure wave from the compressor (phase control lost). Since that time, scientific data have been delivered by partially redundant channels 5-8 on side A, with the coolers working in an unbalanced mode to avoid end-stop collisions in the displacer. The cooler operating frequency was adjusted down slightly from 43.96 Hz to 43.0 Hz to reduce the cold-tip heating effect. This mode had cooler B operating at 82.5% of the amplitude of cooler A and produced some residual vibration, with the cooler working in the 'heating regime', warming the detector due to the lack of phase control (displacer B running free). The compressor B amplitude was fixed at 5.0 mm_{p-p}, while the amplitude of displacer B was held in the range of 3.65 ± 0.07 mm_{p-p}.

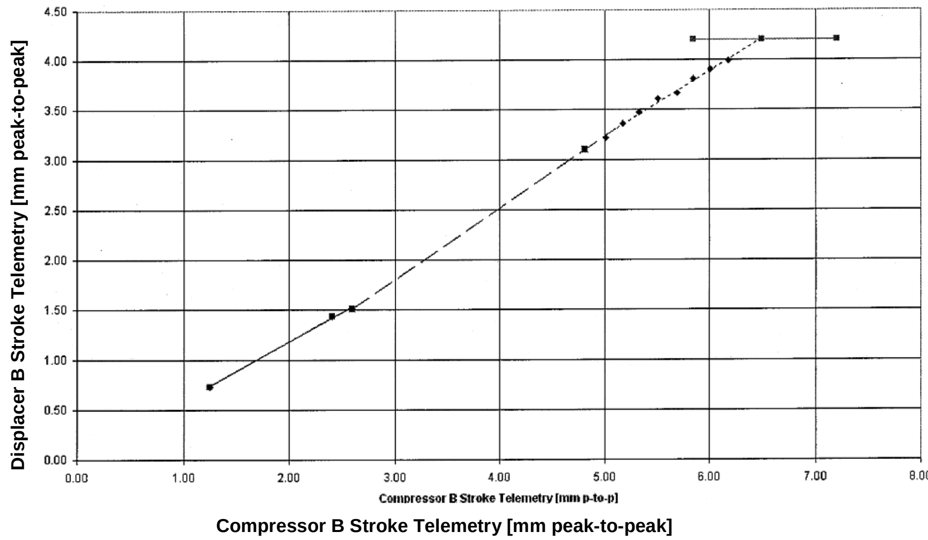

Figure 9. In-orbit Displacer Stroke vs Compressor Stroke for Cooler (B) After Anomaly

It has not been determined whether the displacer drive problem was related to the electronics, the harness or the displacer mechanism, just that an open circuit was experienced. From the behavior reported previously [6] and subsequent compressor operation, there was clearly no failure of gas seals, with no indication of pressure drop. The pistons were free to move so there was no obvious failure of a displacer coil bond to the coil former (a problem experienced due to silicone contamination affecting the bond of the motor coil, which was corrected in the subsequent batch of compressors built for the INTEGRAL mission [6]). It is notable that a lead-in spring failure was not completely ruled out and that the MOPITT cooler application is a rare case of a launch in the passive 'unshorted' condition (not actively controlled). Shorting had been reviewed as an option, but was not readily supported by the Lockheed Martin electronics. Displacers have inherently low damping compared to that of a compressor, so there was an acceptance of residual risk, with mitigation provided by testing to acceptance levels in this configuration. To preclude any residual risk of this nature in the future, it is recommended that coolers always be clamped by adequate shorting or active control during launch.

The long-term cooler displacer / compressor displacement data is shown in Figure 10. This shows the slow increase in 'stroke' needed to maintain the temperature control compensation for contamination build-up. The rate of increase reduces gradually with time and further decontamination cycles.

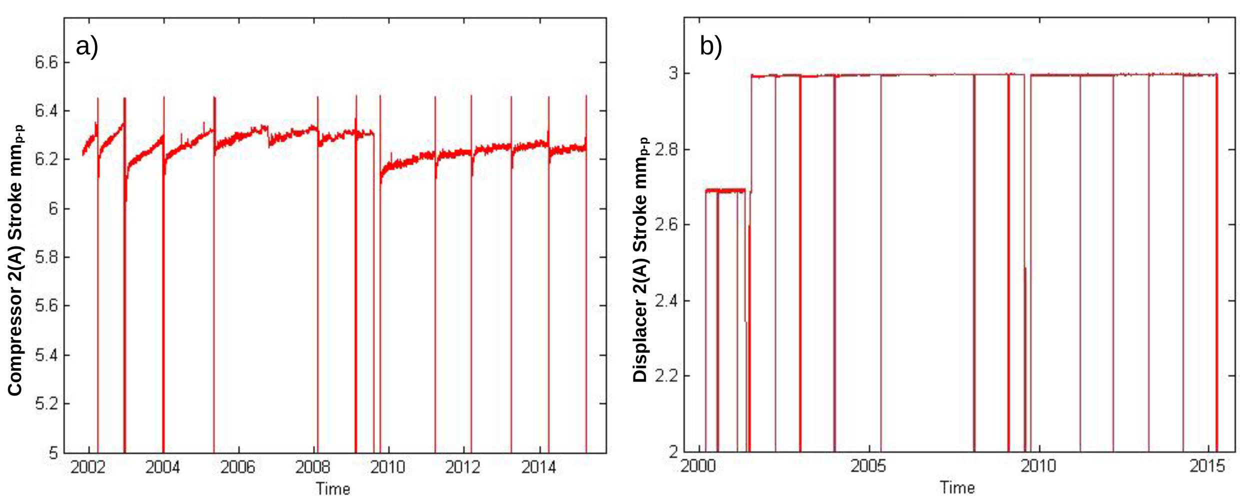

Figure 10. Cryocooler Displacer and Compressor Displacement Over Lifetime

The detector temperatures as maintained by the coolers are shown in Figure 11. Normally, the detector temperature on the non-cooling side B is stable around a warm temperature of 326 K and not varying more than 0.2 K (occasionally ~0.5 K). The detector temperature on side A (coolers working with nominal amplitudes) is stable at ~84.0 K. It continues to demonstrate a lessoning of the rates of change of temperature after each decontamination cycle, as the cold-enclosure continues to be freed of moisture. However, the presence of contamination build-up (condensation) on the cold-tips is still noticeable, even after 16 years in orbit and many decontamination cycles.

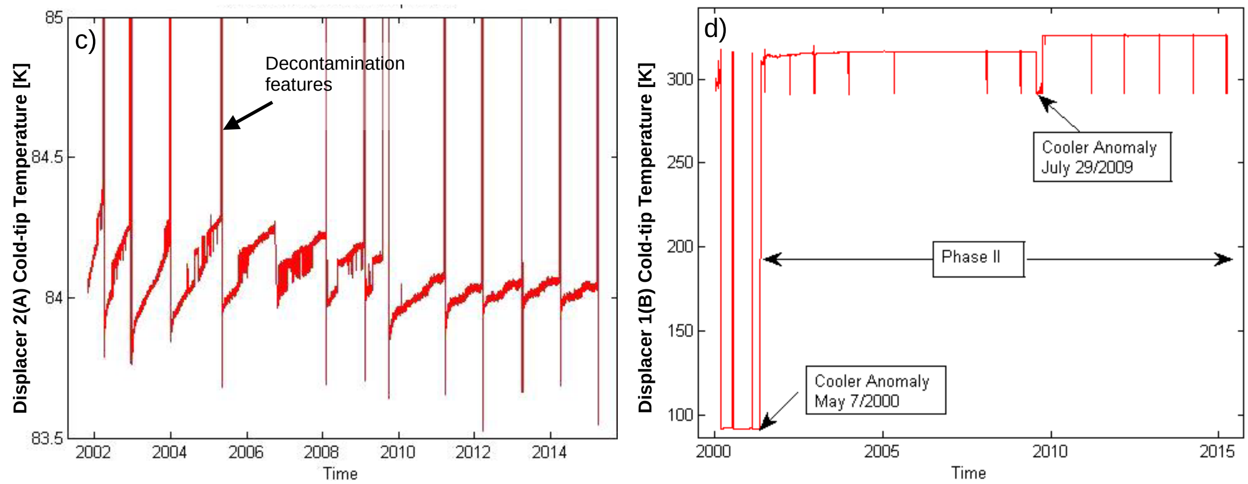

Figure 11. Detector Temperatures Over Lifetime

The 'PDECs' (position control) mode had been preferred prior to the failure as this mode was less sensitive to drifting than the 'ADECS' (accelerometer feedback) mode. Axial vibration levels were reduced to below 0.12 N_{rms} in PDECs prior to the failure [9]. After the anomaly, the compressors were intentionally run at imbalanced strokes to allow the active detectors to cool, while keeping the failed displacer from being driven into its end stops. As a result, the unit has operated in this manual mode with temperature control on the active side for most of the mission. Variations of the axial induced vibration (Z) are driven primarily by seasonal parameters, but overall they are very stable. Increasing displacement (Figure 10) has little impact on residual axial vibration, as seen in Figure 12. Considering the overall situation, the vibration cancellation of the system is considered to be exceptional for the improvised balancing situation which needed to be adopted.

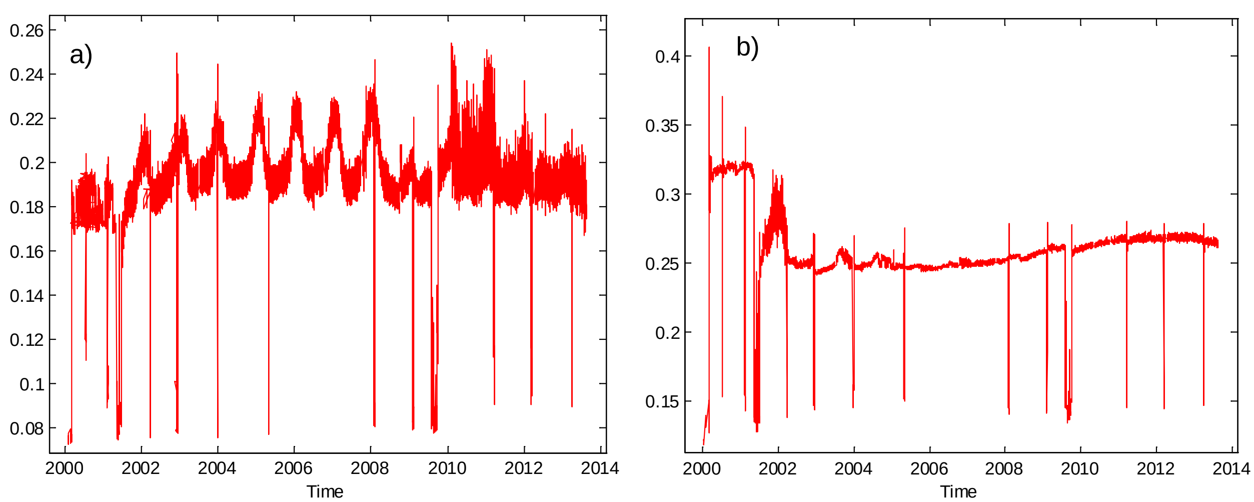

Figure 12. Cooler Accelerometer Readings [N_{rms}] a) Axial – Z axis, b) Lateral – X axis (Lateral Y-axis is very similar to X axis)

Two further minor anomalies were recorded for the cooler system. On December 13, 2002 there appeared to be a transient transition to the ‘door-bell’ mode of the cooler (when the displacer B piston repeatedly strikes the end-stop of the body). The displacer being driven by the pressure wave was very near to full stroke and a small change in the amplitude resulted in this behavior. This could have been initiated by ambient temperature changes or small changes in fill pressure, etc. Telemetry was triggered by the displacer B amplitude which automatically turned off the coolers. The cooler was restarted after some testing and has continued to operate successfully.

A third cooler anomaly was similar to the previous one, having occurred on July 28, 2009. In this case, it was not possible to reactivate the cooler at the same unbalanced pre-anomaly setting (amplitude ratio of 82.5%). A slight modification was made to allow the cooler to continue to run with the B side compressor at 77.5% of normal amplitude; avoiding end-stop contacts (with ~0.5-mm margin) with the side B detectors heating at a slightly higher rate. The cooling rate on the working side (A) was unchanged. This mode of cooler operation induces a little more vibration but with a negligible impact on the spacecraft. Only the MISR instrument has reported a vibration induced effect and this was at a very low level.

Over the past 16 years, the Kistler AG piezoelectric accelerometers have recorded vibration outliers as short, high intensity signals, strongly correlated with the high energy radiation environment. Previously noted by Nichitiu [8], the accelerometers integrated into the cooler system have been demonstrated to provide a bonus measurement of space radiation. As a multi-component force transducer, the tri-axial accelerometers consist of a stack of quartz discs or plates and electrodes, with quartz discs cut in an appropriate axis. The orientation of the sensitive axes coincides with the axes of force components to be measured. An internal charge-to-voltage converter provides a low impedance output. During normal operation, there are short fluctuations (spikes lasting for only one telemetry sample), which appear as an increase in the level of vibration exceeding 4 sigma [8]. The sensor typically records a normal level within 8 seconds afterwards, the time between two consecutive telemetry samples. These spikes, or accelerator outliers, occur most often for the z-direction compressor vibrations. Outliers occur for other directions and for the displacer accelerometer, but their rate is very low.

The occurrence of the z-direction compressor transducer outliers is well described by a decreasing power-law as a function of magnitude. The spatial distribution of these observations is provided in Figure 13, showing accelerometer readings correlating significantly with the South Atlantic Anomaly (SAA) [8]. The high energy particles - the source of anomalous accelerometer signals - are localized mainly in the SAA region, while the polar regions, particularly the southern pole, are associated with a higher risk for satellites during intense solar proton events.

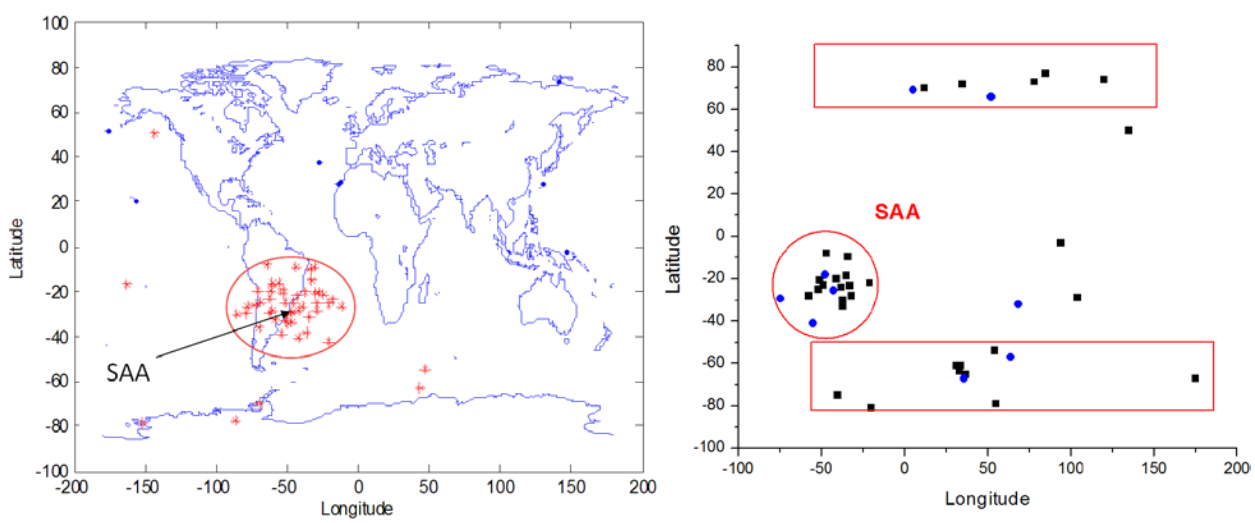

Figure 13. Accelerometers Anomalies Due to Space Radiation (Incl. SAA)

(a) Location during period of December 2014 to February 2015

(b) Locations of accelerator anomalies (4 day periods): Black = Cooler Off 2002/084, 2003/359, 4 days each; Blue= Cooler ON 2004/024 (indicated as year/day of year)

Lessons Learned & Conclusions

The billions of rotations achieved for 7 rotating mechanisms demonstrates that the lubricant screening methods based on heritage with polyalphaolefin (PAO) oils were effectively transferred to the Nye 2001T oil. In the case of the LMC, there was a heightened concern for the presence of these additives, which exhibit much higher outgassing than the base oil. It was thought that the additive could provide benefits during the run-in process, so the screenings were all done similarly, but with the LMC bearing sub-assemblies baked prior to final installation in the housings. This approach did not appear to have any detrimental effects in terms of optics or lifetime for these units. Optical cleanliness continues to meet specification after 16 years in-orbit, where the gain of the system has remained very stable. Despite one cell having been gas-filled and the compensating cell being evacuated, there has been no significant difference between the paired rotors.

By current space mechanism standards, it may be viewed as fortunate that so much success has been achieved for such customized rotating mechanisms without pre-launch life testing. The schedule had precluded life testing at representative speeds, and accelerated life tests would have misrepresented the situation with an increased film thickness of lubricant. Without the desired life testing option, alternative measures were taken to increase the probability of long-life being achieved. The risk management strategy included:

- Sourcing the experience of Draper Laboratories involving design consultation, lubricant formulation, and implementing a screening process for the duplex bearings (resulting in as many as 5 iterations of run-in, cleaning and re-lubrication)
- TiC coatings implemented for scan mirror motor bearings
- Screening tests performed on the new lubricant formulation (Nye 2001T) for LMCs and choppers, which was a worthwhile quality measure. (4-ball tribometer screening test successfully identified a degraded batch of tricresyl phosphate additive prior to the new formulation being applied in the flight mechanisms, saving a great deal of cost, time and potential investigation efforts)
- Provision of power during launch, so as to run choppers and length modulators at 100 rpm during launch, as well as the associated drive system provisions to accommodate this mode

Films were observed during screening of LMC and chopper bearings, representing a suspected ‘polymerization’ of the lubricant running in or near the elastohydrodynamic regime [4]. It is believed that the TiC coating employed for the scan mirror motor bearings likely limited such phenomena, given that the overall travel of three of the scan motors is equivalent to $>10^7$ rotations. The scan motors clearly operate in the boundary lubrication regime.

Significant achievements were made for both types of linear drive mechanisms, with both pressure modulated cells having performed flawlessly. A small leak in the PMC 2 system was managed using standard in-orbit calibration so as to have minimal science impact.

The cooler failure, which was abrupt in nature, may have been due to electronics, harness or the mechanism. Loss of science return was minimized for the cooler system failure case due to the partial redundancy of the optical channels of the instrument. The compressor from the impaired functional cooler has been used to compensate the vibration of the active cooler for the majority of the mission, with a high degree of success. Some adjustments in compressor settings were required to deal with minor drifts in the amplitude of the impaired (free-piston) displacer to avoid end-stop contact.

The launch configuration of the Stirling displacer without shorting (or active control), is thought to have incurred some residual risk despite having been tested at acceptance vibration levels. Where feasible, it is recommended to review such configurations closely and to ensure clamping by adequate shorting or active control to limit stroke variations during launch.

Decontamination heaters and the venting design have been vital to the ongoing reliable performance of the instrument, even after 16 years in orbit. It is emphasized that even with tight contamination controls, the system design must have adequate heater capacity to remove water vapor and other contaminants and adequate venting to ensure long life functionality. The venting design, material selection, and ground purging with dry gas were key to ensuring that the required frequency of decontamination cycles was not too high.

A capillary bonding method for sealing of germanium infra-red windows into the titanium housings showed the capability for use in a long duration mission, while the depressurization witnessed for two of the units may indicate that the related process controls could be improved.

Accelerometer anomalies continue to be caused by interaction of trapped particles from the sun with the neutral atmosphere. Other cooler applications with similar accelerometer arrangements should take note of the accelerometer phenomena cited herein for both the cooler control integrity and scientific value.

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