On Orbit Commissioning of the Earth Observing System Microwave Limb Sounder (EOS MLS) On the Aura Spacecraft

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ABSTRACT

The Microwave Limb Sounder instrument was launched aboard NASA's EOS AURA satellite in July, 2004. The overall scientific objectives for MLS are to measure temperature, pressure, and several important chemical species in the upper troposphere and stratosphere relevant to ozone processes and climate change. MLS consists of a suite of radiometers designed to operate from 118 GHz to 2.5 THz, with two antennas (one for 2.5 THz, the other for the lower frequencies) that scan vertically through the atmospheric limb, and spectrometers with spectral resolution of 6 MHz at spectral line centers. This paper describes the on-orbit commissioning the MLS instrument which includes activation and engineering functional verifications and calibrations.

1. INTRODUCTION

In August of 2004 after the successfully completion of Commissioning Activities the EOS MLS instrument began its five year science mission. The EOS MLS[4] instrument was designed, assembled and tested at the Jet Propulsion Laboratory in Pasadena with several key sub-systems procured from commercial contractors and vendors. The instrument was integrated to the Aura spacecraft[1] at the Northrop Grumman Space Technology Facility in Redondo Beach. Aura was launched atop a Delta-II (7920) launch vehicle from Vandenberg AFB on 15 July 2004. This paper will focus on the on-orbit commissioning of EOS MLS with references to the pre-launch spacecraft interface and mission tests. These tests were conducted from the EOS Aura control center at the Goddard Space Flight Center against the spacecraft at both the spacecraft contractor facility in Redondo Beach and the Astrotech launch preparation facility at Vandenberg Air Force Base. The on-orbit activation sequence will be outlined with discussion of the successful and anomalous events that occurred.

Microwave limb sounding obtains remote measurements of atmospheric parameters from space by observing millimeter- and submillimeter-wavelength thermal emission (radiances) as the instrument field-of-view (FOV) is scanned through the atmospheric limb. By measuring the spectra of the received signals from an array of tangent heights, the local atmospheric temperature, pressure, humidity, and concentration of many trace gasses can be measured with high vertical resolution. To obtain the required spectral resolution, the incoming signals are filtered and downconverted through several steps then fed into 1.5 GHz wide filterbanks each with an array of filters from 6 to 96 GHz wide. Each spectral band requires gain control and local oscillators locked to a common 5 MHz ultra-stable oscillator (USO). The system gain, which is modulated by the physical temperature of the instrument electronics, is calibrated every 25 seconds using a spectrally flat calibration load and a view to cold space. This is accomplished by rotating a mirror in the optical path. Two additional motors rotate the two antennas to scan the limb. The angular range of the antenna scan varies during an orbit, due to the elipticity of the spacecraft orbit and the earth's oblateness.

The EOS MLS instrument consists of three separate modules. They are the GHz module, the THz module and the spectrometer module. Figure 1 shows a line drawing and photograph. The spectrometer module houses the Command and Data Handler (C&DH), the power distribution assembly (PDA), the 19 standard filterbank spectrometers (25

[1] The Aura satellite carries three instruments in addition to MLS: OMI, HIRDLS, and TES. Information about each of these and the Aura mission can be found at http://aura.gsfc.nasa.gov

channels each), 5 midband spectrometers (11 channels each), and four digital autocorrelator spectrometers. These various types of spectrometers are used to digitize the radiometric signals. The GHz module houses five heterodyne receivers at 118, 190, 240, and 640 GHz frequencies, the two calibration targets, the second intermediate frequency (IF) down converter assemblies, an IF switch network, the necessary optical elements for the multiple receivers, two sets of mechanism control electronics for the GHz antenna and switching mirror, and the GHz switching mirror assembly. The THz module houses two 2.5 THz receivers, one calibration target, the gas laser local oscillator, the second intermediate frequency down converters for the THz bands, an IF switch, the necessary THz optics and the scan and pointing mechanism along with its control electronics [4]. The THz radiometer uses a methanol gas laser for its local oscillator. The 2.5 THz heterodyne receiver requires that the laser local oscillator (LLO) maintain frequency stability at 2522.782 GHz for nominal operation [5]. Three of the GHz radiometers use Gunn diode oscillators with phased lock looped electronics to maintain frequency stability. With more than 500 spectral channels, a varying scan sequence, and more than 1000 telemetry points, the commissioning of EOS-MLS was a complicated process requiring extensive planning and careful execution.

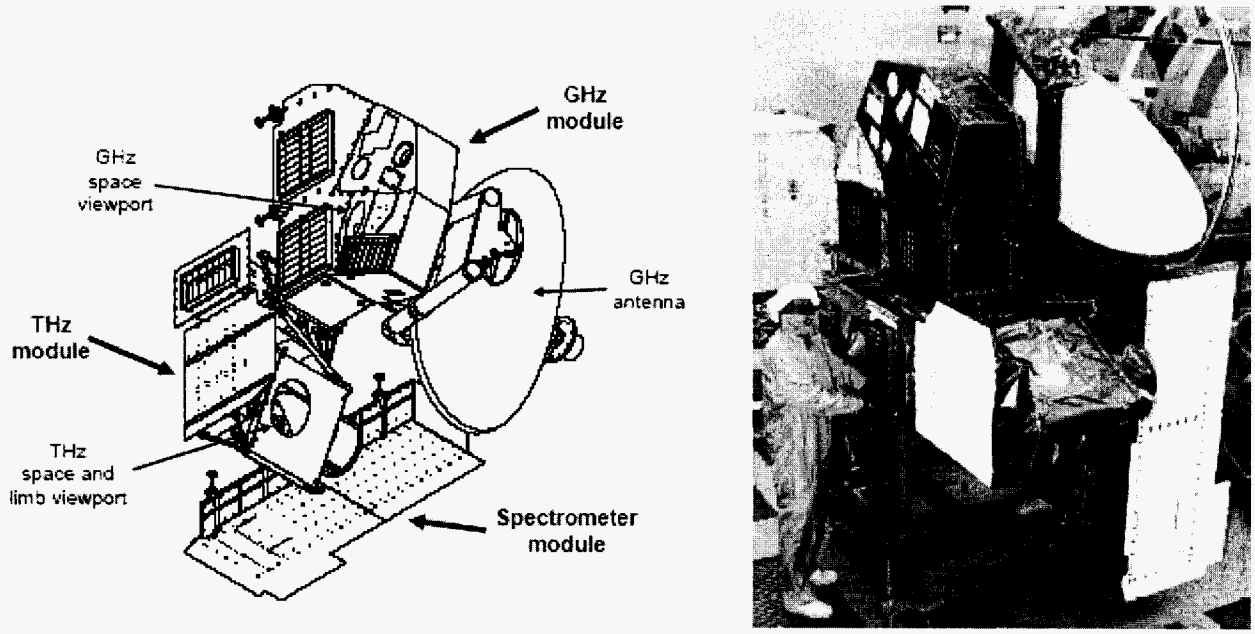

Figure 1 EOS MLS Line Drawing and Photo

2. METHODOLOGY

The MLS activation plan had three primary objectives. The first was to successfully power on all primary assemblies and verify functionality. The second was to characterize the on-orbit performance of the seven radiometer signal chains. The third objective was to collect the on-orbit calibration data needed for Level 1 and Level 2 science processing software. In order to complete these objectives a detailed activation plan was created. This plan detailed the sequence, commands, and timing constraints needed for the successful instrument commissioning. The sequencing, commanding and timing were verified and refined during the pre-launch testing activities discussed in section 2.2.

2.1 Management Principles

The MLS activation was managed by developing a plan including the staffing, training, and tools needed to accomplish the three primary objectives. People to staff the on-orbit commissioning were chosen from the team utilized during the initial instrument I&T, and the AURA spacecraft I&T. Training of these people was accomplished via simulations performed on the instrument ground station at JPL and participation at a minimum of two of the tests identified in the next section.

There were four guiding principles for MLS on-orbit commissioning: 1) Always ensure the instrument is safe; 2) Attention to the real time data takes priority over all other activities during ground contacts with the spacecraft; 3) Prior to taking action to rectify an anomalous condition understand the telemetry available, and also the telemetry needed to develop an understanding; 4) Do not hesitate to call in the necessary resources needed to address any anomaly. These principles were applied during the pre-launch mission testing and rehearsals, as well as the commissioning phase. The application of these continues throughout the flight operations.

2.2 Pre-launch tests and rehearsals

Prior to launch the Aura mission conducted five spacecraft interface (SCIF) tests, two mission tests, and five mission rehearsals. The first of these tests were SCIF tests 1 thru 3. This suite of testing and rehearsals served four purposes: 1). Exercise the communication link between the control center and the spacecraft; 2) Step through the entire spacecraft on-orbit activation plan; 3) Introduce the multiple instrument teams to the control center; and 4) Practice potential anomalous conditions during flight. SCIF tests 4 & 5 served as a means to resolve issues discovered in earlier testing. The mission tests served to demonstrate the nominal and contingency operational procedures and tools. The mission rehearsals tested personnel readiness and anomaly resolution procedures. These pre-launch activities had to be conducted in conjunction with the spacecraft integration activities, which required careful planning of shared personnel resources. Since the activation team had extensive hands on experience with the instrument, training focused on the ground system and the specifics of the on-orbit operational environment.

All of the pre-launch tests and rehearsals were accomplished by first developing a detailed activation plan which defined the command sequences, scan profiles, timing constraints and success criteria. This plan identified the command procedures and microprocessor files needed to properly commission the EOS MLS instrument. This plan evolved from test to test, such that lessons learned from one test were incorporated into the plan and applied to the next test.

2.3 Anomaly resolution

JPL Flight Project Practices and AURA requirements dictated the need for an anomaly resolution procedure and a crisis response plan to be in place prior to launch. This plan and procedure were developed during testing and implemented prior to launch. The anomaly procedure, coupled with a crisis response plan, governed the reaction and resolution of all anomalies encountered. During the pre-launch testing, all anomalies were recorded by the GSFC and NGST Discrepancy Reporting (DR) system, as well as JPL's Problem/Failure Reporting (P/FR) system. Each DR and/or P/FR was initially categorized as being either flight system or ground system related, then reviewed and resolved by a team which included the relevant instrument, spacecraft, and mission assurance personnel. All DRs and P/FRs resolutions were presented to the JPL and GSFC management during the pre-launch Mission Readiness Reviews.

The MLS on-orbit commissioning activities encountered anomalous situations of varying degrees. During the initial on-orbit commissioning period there were seven anomalies documented in the JPL Incident Surprise Anomaly (ISA) reports and GSFC DRs. Details of these events are available through the JPL P/FR or GSFC DR systems.

2.4 Aura Instrument Planning Group (IPG)

The Instrument Planning Group (IPG) was formed by the Aura Project to aid in the interface of the instrument teams with various aspects of the Aura Project and GSFC Flight Operations Team. Based on lessons learned on the Terra and Aqua missions, a resident at GSFC for instrument support is important to mission preparedness.

The IPG's role with the instrument teams evolved over the phases of the Aura project's mission. In the early stages of the project, the IPG gathered available information through MLS mission documentation, holding Mission Operation Working Group meetings with the MLS and spacecraft teams, and participating in Integration and Test activities at JPL. Through this working knowledge of the instrument and inherent knowledge of the services and products used by the GSFC operations teams, the IPG was able to aid in the early stages of simulation and spacecraft test planning and support, ground system requirements, database development support, on-board spacecraft services development (telemetry monitors and supporting stored command sequences), and flight dynamics product development. Project management relied on the IPG for instrument operations expertise for various activities and decisions. Closer to launch,

the IPG's role shifted to support activities such as ground system and database testing, integrated launch activity timeline planning, flight product development, and training of the MLS team on the flight ground system and protocols.

The IPG provided various functions during launch and activation. Launch support included the management of the instruments integrated mission launch activities, anomaly resolution support, interface with the flight team, and general operations support.

2.5 MLS commissioning activities on orbit

The MLS activation plan included the staffing, training and tools needed to accomplish the three primary objectives. Each shift during the commissioning period was staffed with 3 MLS team members, a shift lead, and instrument operator and an analyst. The shift lead's primary responsibility was to maintain oversight on the activities and the objectives for the shift as well as to interface with the Spacecraft Flight Operations Team. The instrument operator's primary responsibility was to communicate with the Spacecraft Operations Conductor, monitor instrument real time telemetry, and to approve the execution of the activation scripts. The analyst was responsible of analyzing data between spacecraft contacts and backing up the instrument operator during real time passes. During the pre-launch testing and rehearsals, all operations team members acted in each of these capacities so that the team had depth in staffing, and could withstand the unexpected loss of any of the team members. This proved to be quite a useful feature in the execution of the plan, as it allowed for changes due to the unexpected events. The end result of the commissioning activities was that the MLS team met all objectives successfully, and did so approximately 10 days earlier than planned. The data collected and analyzed will be discussed in the next section.

3. DATA

After the Delta-II launch vehicle successfully placed the Aura spacecraft into the desired insertion orbit of approximately 680 Km the first priority for all the instruments was to turn on the survival heaters. All of the EOS MLS survival heaters are thermostatically controlled and powered by two spacecraft power buses referred to as Survival bus A and B. Thermal models showed that EOS MLS would reach a non-operationally temperature lower limit at approximately 200 minutes mission elapsed time (MET). The Aura launch script had the instrument survival bus activation planned such that the different instrument survival buses would be powered on within the various thermal models predicted limit violation times. The EOS MLS survival heater bus was activated at the scripted time of 140 minutes MET and the first thermostat closed at 205 minutes MET, thus validating the thermal model prediction.

The first MLS alert message occurred shortly after 15 hours MET when the survival temperature on the THz Receiver Control Assembly reached -21.52 C. The thermostat set point for this survival heater is -22 C ± 2 C and the database yellow alert limit was set to -20 C. This short coming in the alert limit value was noted and action was taken to update the limit for this telemetry point.

3.1 Initial MLS activation

The MLS Command & Data Handler (C&DH) Turn on and flight software configuration were scheduled and occurred on mission day 4. Prior to MLS C&DH turn on the spacecraft format multiplexing unit (FMU) and solid state recorder (SSR) write precedence had to be enabled for MLS data. A relay on the MLS power distribution assembly (PDA) was added early in the instrument design phase because the MLS distributed power design has the potential of excessive inrush current when spacecraft power is applied. This relay and the soft start characteristics of the Aura spacecraft's secondary converter electronics (SCE) allows MLS to be turned on safely with a spacecraft stored command sequence. The stored command sequence insures all MLS assembly power relays are off and a controlled current ramp up to the MLS power supplies occurs. The stored command sequence was initiated by ground command and when it completed the MLS C&DH was on and running its boot version of flight software. The boot version of the C&DH flight software (version 323) is incompatible with the nominal spacecraft communication protocol and an updated version of flight software has to be selected from EEPROM. This was accomplished with a scripted command procedure executed during a real time spacecraft contact. This C&DH configuration update procedure commands the C&DH to reboot using an updated version (version 349) of flight software stored in one of 4 EEPROM slots. After the C&DH reboot completed the additional patches identified during ground testing were loaded.

The next available spacecraft contact was used to power on and configure the Spectrometer modules remaining assemblies and the 5 MHz Master Oscillator. This activity powered on the GHz assembly controlling the MLS 5 MHz USO and the 14 remaining spectrometer module assemblies. The MLS power consumption increased from 14.5 watts to 145 watts. This power on activity completed with one of the 15 MLS assemblies failing to boot correctly. The GHz module which controls the USO did not boot to the nominal RAM code state. When the initial power on cycle completed status indicators reported it was in ROM code state indicating it failed to boot the RAM code which is broadcasted by the MLS C&DH. This condition had been observed during ground testing on multiple occasions. The corrective action defined was to power cycle the assembly and determine if it boots to the RAM code on the second power up attempt. This procedure was executed and the assembly successfully booted to the nominal RAM state.

The initial configuration steps for the spectrometer module are to enable the 5 MHz USO, set the 1100 MHz spectrometer local oscillator frequency, and set multiple third local oscillator frequencies. This activity also commanded the MLS instrument to generate the first on orbit science type data packets and raise the MLS data rate to its full nominal 100 K bits/sec.

Now in an operational state several operational temperatures were initially in the red low alarm state. These were monitored and as expected most of these temperatures rose above the alert limits. After four hours we determined that the single powered GHz assembly was not likely to rise above the red low alert limit without additional heat. The remaining GHz second IF assemblies, located in the within the same GHz module electronics bay, were powered earlier than planned in order to generate more heat. All temperatures in the SIF electronics bay rose above the low alert limit within the next 2 hours.

There was one deployment activity on MLS. A launch latch was used to prevent possible damage to the GHz antenna drive actuator from launch stresses. This was a mission critical event and required a command authorization meeting (CAM) to proceed. The standard Aura policy is to convene a CAM the day before the critical action is to be executed. The MLS team convened the MLS Antenna Launch Latch Release CAM on day 6 with the scheduled deployment on day 7. The CAM was used to describe the shaped metal alloy actuator, the captive notched bolt and the heater element used to snap the bolt. The command sequence was described in detail. Abort and success criteria were defined. Contingency plans and redundancy components were also explained and described. The outcome from the meeting was a GO to proceed as planned.

On day 7 the operational heater on the antenna position encoder was adjusted and a the successful release of the antenna launch latch was completed. The antenna position encoder heater was set to 50% duty cycle in order to expedite warm up. The notched bolt "broke" as expected after the heater on the shaped metal alloy actuator was commanded on. Movement of the GHz antenna was confirmed by the antenna position encoder and a change in micro-switch status.

Following the completion of the spacecraft's X-band transmitter activation and checkout, the THz Module activation began. Due to concerns raised during vibration testing the MLS team was directed to activate and checkout the THz gas laser "as soon as possible." Vibration testing showed that the menthol cavity of the THz gas laser local oscillator might leak during launch. It was decided that if the laser cavity did leak that efforts would be made to start the THz science mission and collect as much atmospheric data as possible before the laser local oscillator power was insufficient. This activity had to follow the X-band transmitter activation because the engineering and status telemetry for the laser electronics is only available in the MLS X-band telemetry. The procedure to power on the THz module assemblies was completed successfully which brought the MLS instrument power to 287 Watts. The THz signal chain and scan electronics were than configured to their operational state. The THz gas laser local oscillator heater was powered on to warm the laser cavity to an optimal start temperature. These activities were executed while waiting for the X-band data to become available. The X-band telemetry is not available during Aura real time contacts, but is available within typically two hours when expedited.

The Gas Laser local oscillator start command was issued after the laser's x-band data was verified. The laser start command turned off the LLO heater and ignited the laser. Ground testing often required the start command to be repeated to achieve a successful laser ignition. The on-orbit activation only required one start command for a successful ignition. The instrument power consumption with the laser ignited was 406 Watts. The laser power is measured continuously and reported in the X-band telemetry. The initial power reading showed the menthol cavity did not leak

during the launch phase. A stutter is used to prevent the laser output, which is typically unstable when first ignited, from driving the 2.5 THz receiver mixer. The shutter was opened 12.5 hours after laser ignition in order to allow the laser output power to stabilize and avoid the small possibility of damaging the mixer by overdriving it.

The remainder of the GHz Module A-side assemblies was the final power on step. During this turn on sequence one "recoverable" error was reported by the MLS C&DH, and the telemetry reported 34 red alerts and 10 yellow alerts for MLS. The operators noted and monitored these telemetry points. Most of these alerts were expected to end as power dissipation warmed the several electronics bays. When all the GHz modules receivers were powered on it was also noted all the receiver front end temperatures were below the red alert threshold. It was decided to power on the GHz optical bench operational heater in an effort to warm the receiver front ends more quickly. The instrument power consumption was 530 watts.

On day 9 was when the GHz receiver and the second IF initialization were started. The receivers and their second IF VCO frequencies were all successfully set. Each VCO is sequentially set for each IF band and the receiver local oscillators. The MLS receiver design includes automated initialization, but the bias setting for the receiver Gunn diodes must be commanded to achieve phase lock. The On-orbit performance at startup matched the ground test performance. As the temperatures within the GHz module stabilized all telemetry alerts ended except the 640 GHz Tripler voltage which was stable but remained below the yellow low alert threshold.

The local oscillator for the EOS-MLS 640 receiver depends on a frequency tripler that generates the necessary power at 321 GHz to drive the mixer. During the detailed design phase for the receiver, the only existing technology that provided the required performance were the delicately assembled point contact diodes which depend on electrically contacting a microscopic metallic whisker onto an anode "dot" on the semiconductor chip. Assembly of such components requires nearly-artistic skills acquired by many years of experience. Still such components are difficult to qualify and are prone to problems over time. After the 640 GHz receiver had been delivered to the instrument, an intermittent behavior with this tripler was observed. Over a period of 2 days the tripler exhibited no signs of electrical functionality and then, for no known reason, the tripler suddenly returned to a functional state essentially identical to that before this incident.

A review board was called to investigate this incident and to explore options for resolving the issue. One option that was to be considered was the implementation of a planar diode multiplier to replace the whisker-contacted tripler. During the later stages of the MLS instrument assembly, development planar diode multipliers had gained much momentum due to advances in device processing. Planar device components are generally more robust than their whisker-contacted counterparts and are much simpler to assemble with a higher level of control and repeatability.

JPL had already processed a batch of multipliers that included a design applicable to the MLS 640 GHz receiver for the very purpose of providing the option of an emergency replacement for the whisker-contacted device in the case of a late failure. A waveguide mounting circuit was fabricated and a planar tripler was assembled using an existing device to demonstrate that the required performance could be met. In February 2003 it was decided that although the whisker-contacted tripler had returned to a seemingly fully functional state, the correct course of action was to replace it with the newly developed planar tripler. This switch was made and the 640 GHz receiver has been fully operational without problems since.

The 640 GHz receiver has a number of telemetry points for monitoring the health of the subsystem. Included in this was the bias voltage associated with the tripler. When the whisker contacted tripler was installed this telemetry point was generally in the positive 3-5 Volt range and was a measure of the voltage across the tripler diode. However, the configuration of the planar tripler circuit was somewhat different, and although a voltage was still measured, it now represented the magnitude of the current flowing through the tripler diode and was generally in the -50 to -80 mVolt range. Because our experience with operating this tripler was so new, alert limits were set at conservative levels to alert us to even minor changes in the operating point of the tripler. The yellow low alert was initially set to -0.024 V. After launch of Aura, as the receiver reached a stable equilibrium we quite often experienced "yellow" low limit alert on the tripler voltage. Over time, however, we gained valuable experience with the tripler and understood the normal operating points in the space environment. After review, we relaxed the yellow limits to account for the normal orbital

and seasonal variations in operating parameters experienced by the tripler. It was decided to reset the yellow limit to -0.028 V.

The next phase of the activation plan was to set the input power levels to the spectrometers. The ground testing provided the initial settings for the attenuators on the second IF outputs, but as expected these needed to be iterated on orbit. The more complicated digital autocorrelators spectrometers (DACS) were also expected to need on orbit adjustments.

In the initial aliveness check, the total power channel, four state counters and correlator lags of each of the four DACS bands were inspected to see that values and their variances were roughly as expected. The DACS attenuators were adjusted to give between optimal counts in the respective total power channel when viewing the internal target. Each DACS has a 2-bit digitizer which consists of three comparators which define four input states. The four state counters, Di, return the instances of each state in an integration period:

- D_0 = 2-bit state 01 = below the negative threshold.
- D_1 = 2-bit state 00 = between zero and the negative threshold.
- D_2 = 2-bit state 10 = between the positive threshold and zero.
- D_3 = 2-bit state 11 = above the positive threshold.

The noise input is modeled as a Gaussian random variable. The optimal correlator performance is obtained when half of the digitizer counts are negative and when the positive and negative thresholds are at ±0.9 sigma. There are three trims on the digitizer; (M)agnitude of the positive and negative threshold, (P)ositive trim to balance D_0 and D_3 and (Z)ero to balance D_0+D_1 and D_2+D_3. With the settings for M, P and Z commanded to known values and the values returned from the state counter new values were determined for M', P' and Z'. The new values are rounded to integers and packed into a control word which was sequentially written to the DACS remote interface unit.

The final initialization activity is the initialization of the scan mechanisms. The three MLS scan mechanisms are initialized in similar fashions. The mechanisms are commanded to perform their "wakeup" sequence, a scan profile is uploaded, and the fault protection is enabled. The mechanism wakeup sequence is initiated by a single command which indexes the encoder and moves the mechanism to its home position. The scan profile is loaded and started after the completion of the wakeup sequence. The scan profile is uplinked via the CLOAD process. The CLOAD process is a process at Aura control center used by the MLS team to uplink flight software tables, scan profiles or large command sequences. The scan profile is executed after the mechanism assembly is set to issue scan "start" commands at the beginning of each engineering frame. The MLS mechanisms have three levels of fault protection. The first is a crowbar circuit on the drive power supply which will cut power if the drive current rises above selected set point of 900 milliamps. The second level fault protection is a status monitor in the flight software which will power off the mechanism assembly if an undesired status value is returned to the MLS C&DH by the mechanism control electronics. The third level is a predefined ground command sequence executed by the spacecrafts operations controller at the Aura control center. This command sequence is started if a NOAA issued S5 proton flux alert is received by the Aura FOT or at the direction of the MLS instrument operations team.

3.2 MLS Characterization

With instrument power up, the receiver functional checkout and the assembly initializations complete, the commissioning activities proceeded on to the Mechanism Characterizations. The GHz switching mirror characterization started by executing a scan profile used during ground test which views the two internal calibration targets. This was followed by a second scan profile that slowly slews the mirror around 360°. The GHz antenna characterization started with a "trapezoidal" scan used to confirm smooth operation and if the gain parameters used in the control electronics needed adjustment. Since no adjustment was needed the GHz antenna started a nominal science scan profile without the correction for the earth's oblateness. This scan was used to determine the correct offset to the scan start position. Next the nominal scan profile with the correction for the earth's oblateness was executed. The THz scan mirror characterization was an extended version of the nominal scan used to determine scan start position offset.

The GHz switching mirror characterization started on day 10. The first scan profile was loaded but at the completion of the command activity an error was reported by the mirror control electronics. This error message triggered the flight software status monitors and power down the GHz mirror system. An investigation was initiated and a recovery plan to

return the GHz switching mirror to operational state was created. This investigation determined the fault was caused by a known idiosyncrasy of the mechanism control electronics, in which the loading of a new scan table while a scan table is executing can cause a command collision within the electronics, and disrupt the currently executing scan table. The resolution of this anomaly was change the procedure such that the control electronics was put into a mode that will suspend scanning prior to uploading a new scan table. On day 11 the GHz switching mirror was returned to operational state and the two calibration target scan and slow slewing scan was completed successfully.

During the GHz mirror characterization activity, the THz scan control electronics were powered down by the flight software status monitor due to an error in the remote interface unit software. An investigation was started and the commissioning activities on the GHz switching mirror and GHz antenna continued. We decided to continue on with the commissioning activities because the THz scan did not impact on the upcoming GHz activities. This anomaly was noted after the stop for the THz scan, the THz Mechanism did not report a status check as expected when in a non-scanning mode. The Fault Management system considers lack of a status response from the control electronics an error and powered off the assembly. The corrective action was to create a new software upload for the control electronics so that the Request for Status was included in the Stop Scan Mode.

The GHz antenna characterization started on day 13. The "trapezoidal" scan was loaded and executed successfully. This scan data showed that the gain parameters being used by the control electronics were correct. The nominal scan profile table was loaded and after the "start" commands were enabled the antenna control electronics issued an anomalous status. The flight software status monitor again triggered and this time powered down the GHz antenna system. The previous calibration scan profile left the Antenna Actuator close to its stow position. The subsequent usage of the nominal scan caused the actuator to move towards stow position mechanical hard stop and subsequently issue a 'servo lost lock' error message. The corrective action was to implement an operational constraint that the operator must ensure the actuator position is consistent with the startup of the planned scan program.

After the THz scan and GHz antenna anomaly investigations were completed both assemblies were powered back on and returned to their nominal state. The GHz antenna characterization resumed and the oblateness processing was enabled for the first time. The oblateness processing uses attitude information from the spacecraft to compute a pointing correction by updating the scan table starting positions for the GHz antenna and THz scan mirror.

The analysis of the MLS pointing with the oblateness enabled confirmed the need for updates to the orbit table. During the uplink of the new orbit tables both the GHz antenna control assembly and the THz scan control assembly went to an anomalous state. The resulting action from the flight software's fault management system was a cascade turn off of all MLS assemblies. This put a hold on all MLS activation activities until the remote interface unit communication issue could be explained. While there is not conclusive evidence, the most probable cause was determined to be a change command from the C&DH to update the scan table starting positions for the GHz antenna and THz scan mirror coincided with a command to not execute the scan table. This caused a communications failure between the mechanism control electronics and the RIUs connected to the C&DH. The corrective action taken to avoid this anomaly was to change the procedure such that the oblateness processing was suspended prior to updating orbit tables or scan languages. This investigation resulted in a two-day hold.

A full power on recovery was started on day 17. During the assembly power on the GHz antenna assembly failed to power on and multiple errors were reported by the C&DH indicating the cause. Occasionally an assembly will not turn on when it is selected by the C&DH. This idiosyncrasy was accepted pre-launch and the documented procedure for recovering from this anomaly was to power cycle the affected assembly. In this case execution of that procedure was successful. There is an ongoing investigation using the MLS Flight Software Testbed to understand the nature of this anomaly. MLS was returned to full power successfully.

3.3 On-orbit calibration

The final on orbit activities were radiometric characterizations and spectral calibrations to assess instrument performance and gather the radiometric and spectral calibration data needed for Level 1 and Level 2 science data processing software. The first activity in the suite of calibration measurements was the Receiver Radiometric Characterizations. This activity was to verify that pre- and post-launch noise performance was consistent. This was

indeed the case except for R4 which exhibits lower spectrally-varying but higher spectrally-averaged noise than anticipated. The lower spectrally-varying noise arises from the tripler change out, and the higher spectrally-averaged noise was masked in pre-launch data because it is only readily evident when viewing low radiances (and we didn't look at cold scenes very often during pre-launch testing). The increased spectrally-averaged noise has been `taken care of' in Level 2 processing by subtracting a MIF-dependent baseline. This is possible because most measurements in R4 depend on spectral contrast (rather than absolute radiances), and overall noise performance for R4 meets pre-launch expectations.

This calibration sequence was followed by a series of radiometric characterizations. This began with two separate target view scan activities. The purpose of these activities was to look for any unexpected behavior in target radiances such as could arise from sneak paths of reflecting sunlight into the GHz switching mirror cavity. There were none seen for either of the two internal calibration targets. This was followed by the space view characterization. This was also to look for any unexpected behavior in target radiances such as could arise from sneak paths of reflecting sunlight into the GHz switching mirror cavity. Again there were none seen. Each of the two targets and space port viewing data provide more than two continuous orbits of staring data suitable for analysis (by Fourier transforming) to determine gain variation characteristics (1/f noise) and any periodic orbit thermal signatures.

The last characterization activity was the Radiometric Antenna Space View test. This test parked the antenna at a scan angle high above the atmosphere and performed the nominal calibration reference views. This test provided information on the orbital dependencies of spectrally-averaged and spectrally-varying differences between views to cold space via the routine switching mirror view and the antenna. The results of this measurement are used in the `antenna offset' correction in the Level 1 processing. The Level 1 software uses the 17 reflector temperatures, measured every engineering frame, to compute calibrate radiances. The data set measured here showed a ripple in the calibrated radiances having a shape similar to the average primary reflector temperature, suggesting that reflectivities in flight differed from the values measured before launch, by statistically significant amounts for 240 and 640 GHz receivers. Using this high-altitude view data set, we retrieved new values for ohmic loss, relaxing the Fresnel constraint between the primary and the other reflectors, by making the average calibrated radiance match the Planck value [1].

The first of two calibration data sets was from the Target Radiance Calibration. The MLS instrument implements two ambient radiometric calibration targets in the GHz module, one at the temperature of the structure (approx. 20 C), the other radiatively cooled by approx. 40 C. Pre-launch analyses indicated that the warmer of these targets would be briefly illuminated once every orbit by solar reflection from a strut (part of the antenna structure). The decision was made to use the radiatively-cooled target for nominal radiometric calibration. The UARS MLS experience indicated that small thermal gradients through the absorbing material would result in a small discrepancy between the target temperature reported by temperature sensors and that observed radiometrically. This gradient was measured by comparing the radiances of the two targets, and a ~0.5 C correction was applied in Level 1 processing to compensate.

At the completion of the target radiance calibration and the beginning of the spectral baseline measurement the GHz antenna electronics reported an anomalous status and was powered off by the flight software's status monitor fault management. This anomaly was caused by a failure of the instrument operator to recognize that a prior scan program had left the mechanism in a non-nominal position that was not compatible with the new scan being started. During the stand down of MLS activities to investigate the GHz antenna anomaly, the THz scan control assembly was powered off by the flight software's status monitor fault management during a "back orbit." The THz mechanism control electronics shutoff due to an invalid stop bit. This anomaly was a re-occurrence of a problem noted during I&T where the cause is thought to be a timing error on the interface between the RIU and control electronics. The occurrence rate of this anomaly is very low, and it was decided to fly with this idiosyncrasy. After both mechanism anomalies where understood the control assemblies were powered back on and the mechanisms were initialized and configured to begin the spectral baseline calibration sequence.

The last calibration activity was the Spectral Baseline measurement. This is a key calibration measurement for instruments of this type. The views to space via the different optical paths (i.e. switching mirror and antenna) exhibit a spectral difference of ~0.3 C in the GHz bands. It is necessary to measure these spectral signatures, and verify that they are stable and exhibit no scan dependence. This was done by performing extended limb scans well above Earth's limb, and by performing "limb scans" with the spacecraft in a pitched up attitude. This measurement characterized the GHz

spectral baseline to ~0.02 C, and verified its stability and lack of scan dependence to the same level. Because of the importance of this parameter, we plan to measure the spectral baseline approximately twice per year for the duration of the mission. The THz optics uses the same mirror for both limb and space views, and so is not subject to the same baseline issues as the GHz module.

The final days of the MLS commissioning involved the fine tuning of the various orbital parameters, small adjustments to the intermediate frequency attenuation settings and the first use of the orbit synchronization software. In nominal operation the MLS limb scans are synchronized to the orbit and phased such that limb scan tangent point loci occur near the equator on each equator crossing [4]. Multiple iterations to the oblateness and orbit sync parameters were made by updating the "orbit tables" which reside in C&DH memory. The final update could not be computed until the Aura spacecraft reached its final orbital altitude on mission day 25. The attenuation controlling the input power to the spectrometers was fine tuned to optimize the response on the receiver signal chains. The MLS entered Mission Mode on August 12, 2004.

4. RESULTS

The EOS-MLS commissioning was the successful completion of all objectives. Although several aspects of the instrument's behavior were not learned until on orbit, we gained the knowledge to avoid these pitfalls in the future. When developing a commissioning plan it is important to consider many factors. Adequate staffing with experienced individuals allowed for easy recognition of instrument idiosyncrasies. A flight alert limit policy that is consistent with instrument design and planned configurations needs to be identified. Configuration states will typically last longer on orbit than during ground tests. A more difficult issue to avoid is to match ground test procedures with the on-orbit procedures. The MLS flight software and internal communication interface complexities proved to be difficult to diagnose during ground testing and often issues which could not be fully identified were closed when a procedural workaround was identified. This was easily acceptable for ground test but proved to complicate on-orbit command scheduling. The limited duration contacts and scripted command sequences make it difficult to alter or repeat indefinitely instrument commands. The Instrument Planning Group (IPG) was a key element to the implementation and testing of the activation plan. Their familiarity and presence at the control center during the development and testing phases expedited the products and tools the instrument team needed at the control center.

The Instrument checkout showed no unexpected behavior of the instrument systems. The laser power matched the ground test data. The scan mechanisms functional performance also matched ground test performance. The radiometer signal chains exceeded the science measurement requirements. Most notably a procedural solution was development to avoid the limits within the flight software's fault management.

The calibration data collected on orbit was incorporated into the Level 1 and Level 2 science data processing and is being used to improve the initial science results. A ripple in the calibrated radiances having a shape similar to the average primary reflector temperature, suggesting that reflectivities in flight differed from the values measured before launch. The spectral baseline measurement characterized the GHz spectral baseline to ~0.02 C, and verified its stability and lack of scan dependence to the same level.

4.1 Documented Anomalies

A brief summary of the seven documented anomalies with the JPL Incident Surprise Anomaly (ISA) reports and GSFC DRs references is listed here:[2]

1. JPL ISA Z84338 & GSFC DR Spcrft_R0249: Mechanism electronics 'Servo Lost Lock' error. A 'Servo Lost Lock' error is a flag set by the mechanism control electronics when the difference between the actual position of the mechanism and the expected position differ greater than a pre-set value. This error flag can have several sources. This particular instance was caused by a known idiosyncrasy of the mechanism control electronics, in which the loading of a new scan table while a scan table is executing can cause a command collision within the electronics, and disrupt the currently executing scan table. The resolution of this anomaly was change the

[2] Details of these events are available through the JPL P/FR or GSFC DR systems.

procedure such that the control electronics was put into a mode that will suspend scanning prior to uploading a new scan table.

2. JPL ISA Z84359 & GSFC DR Spcrft_R0254: Mechanism electronics 'Servo Lost Lock' error. This anomaly was caused by executing a nominal scan program on the linear actuator (GHz Antenna Actuator) following the use of a special calibration scan program. The calibration scan program left the Antenna Actuator close to its stow position. The subsequent usage of the nominal scan caused the actuator to move to the stow position mechanical hard stop and subsequently issue a 'servo lost lock' error message. The corrective action was to implement an operational constraint that the operator must ensure the actuator position is consistent with the startup of the planned scan program.
3. JPL ISA Z84369 & GSFC DR Spcrft_R0255: MLS received error status on GHz and THz scan control electronics. This anomaly occurred during the instrument re-configuration for oblateness parameters via the upload of an orbit table. The previous orbit table active at the time of the event, and while there is not conclusive evidence, the most probable cause was determined to be a change command from the C&DH processing of the orbit table coincided with a Select Command to use a scan table. This caused communications failure between the mechanism control electronics and the Remote Interface Units connected to the C&DH. The corrective action taken to avoid this anomaly was to change the procedure such that the oblateness processing was suspended prior to updating orbit tables or scan languages.
4. JPL ISA Z84411 & GSFC DR Spcrft_R0251: Mechanism electronics (non-status) error. This anomaly was noted during up-link commanding of the Stop Scan Mode for the THz module, the THz Mechanism did not report a status check as expected when the non-scanning RIU language was selected. The Fault Management system considers lack of a status response from the control electronics an error and responded by configuring the electronics into safe (off) state. The corrective action was to create a new software upload for the control electronics so that the Request for Status was included in the Stop Scan Mode.
5. JPL ISA Z84415 & GSFC DR Spcrft_R0265: This anomaly was a re-occurrence of ISA Z84359 and was caused by a failure of the instrument operator to recognize that a prior scan program had left the mechanism in a non-nominal position that was not compatible with the new scan being started.
6. JPL ISA Z84416 & GSFC DR Spcrft_R0256: THz mechanism control electronics shutoff due to an invalid stop bit. This anomaly was a re-occurrence of a problem noted during I&T where the cause is thought to be a timing error on the RS-232 interface between the RIU and BEI electronics. The occurrence rate of this anomaly is very low, and it was decided during the I&T phase to fly with this idiosyncrasy.
7. JPL ISA Z84513 & GSFC Spcrft_R0256: Mechanism control electronics did not power-on in recovery on DOY 214, 1 August 2004. This anomaly was another re-occurrence of a known idiosyncrasy of the MLS instrument. Occasionally an RIU will not turn on when it is selected by the C&DH. This idiosyncrasy was accepted pre-launch and the documented procedure for recovering from this anomaly was to power cycle the affected assembly. In this case execution of that procedure was successful. There is an ongoing investigation using the MLS Flight Software Testbed to understand the nature of this anomaly.

5. CONCLUSIONS

The commissioning of EOS-MLS was a complicated process requiring extensive planning, careful execution and the participation of many individuals. The commissioning effort was a success because of the cooperation of the MLS operations team, the Aura instrument planning group, the Aura payload manager, the Aura spacecraft deputies, the Aura flight directors and the Aura flight operations team. The staffing, training and tools used to accomplish the commissioning objectives were in place due to the coordinated effort of all these teams. The anomalies encountered were addressed, investigated and resolved in an open forum with participation from all parties. The three member instrument teams allowed for the division the MLS commissioning responsibilities. The MLS shift leads were able to maintain oversight on the activities and meet the shift objectives while interfacing with the Aura Flight Operations Team, Aura project office and JPL management. The shift lead ensured all parties stayed informed on MLS status and monitored spacecraft activities and status to properly coordinate with various groups when changes were needed. The instrument operators were able to communicate with the Spacecraft Operations Conductor without distraction, monitor instrument real time telemetry, and approve and direct the execution of the activation scripts. The MLS analysts were able to run the needed analysis on available data between contacts, to support the instrument operator during real time passes, and communicate with MLS science team for X-band data. With all team members acting in each of these capacities during the pre-launch testing and rehearsals the team had depth in staffing, and was able to withstand the

unexpected absence of team members. The Instrument Planning Group made MLS team's introduction to the Aura control center effortless and accommodating. The IPG also played an essential role in the training of MLS team members during the pre-launch testing. In Summary, the MLS activation plan met all commissioning objectives successfully, and did so approximately 10 days earlier than planned.

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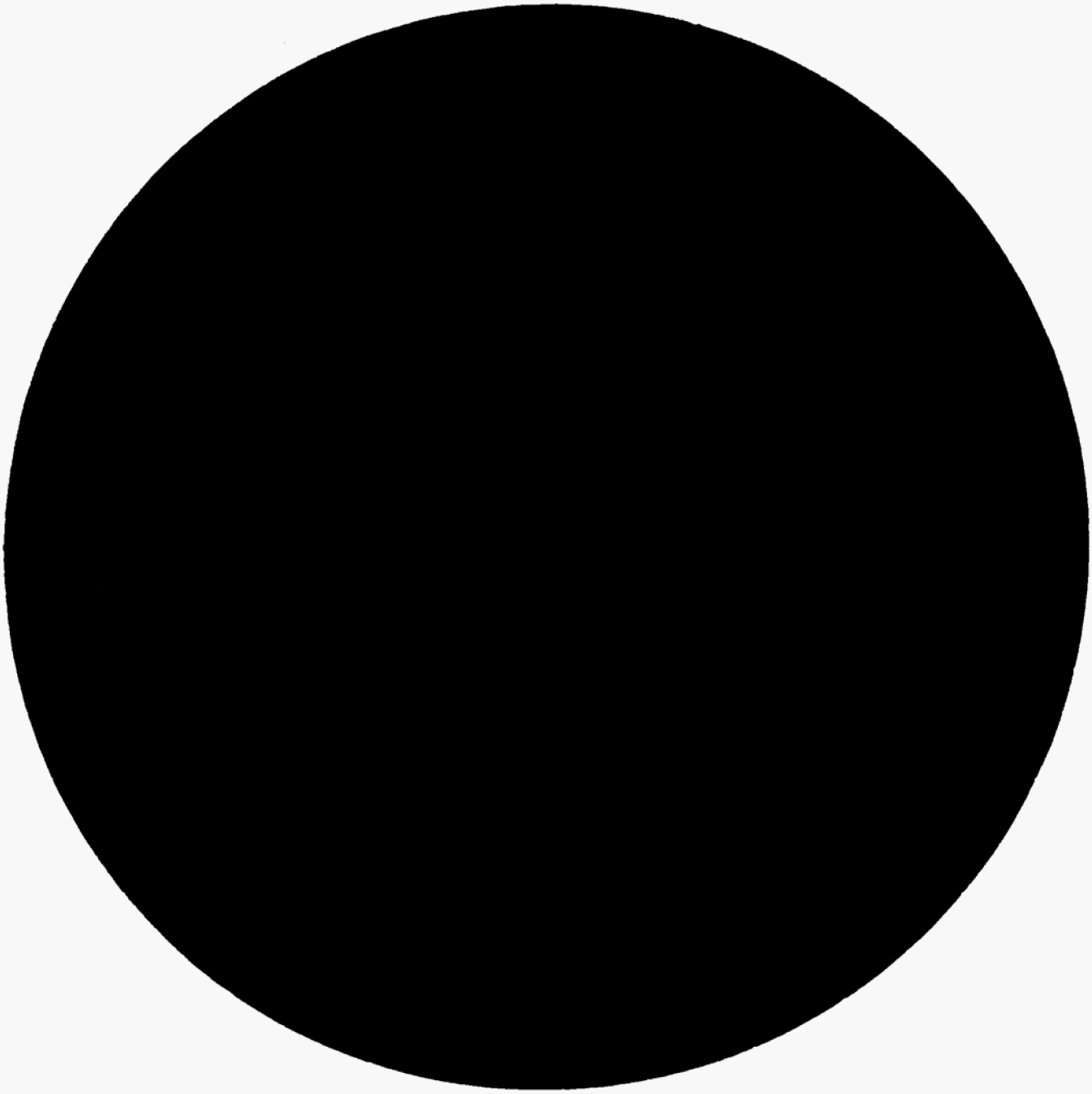
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