EOS Aura MLS, First Year Post-Launch Engineering Assessment

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ABSTRACT

The Microwave Limb Sounder (MLS) instrument, launched in July of 2004 on NASA's EOS Aura satellite, has been in its nominal science operating mode since August 2004. The objective of EOS MLS is to obtain measurements of atmospheric composition, temperature and pressure through observations of millimeter- and submillimeter-wavelength thermal emission as the instrument field-of-view is scanned through the atmospheric limb. The MLS instrument has completed activation, in-orbit calibrations have been performed leading to adjustments to radiometric calibration (Level 1) algorithms, a software upgrade was implemented for more robust operation of the laser local oscillator, and engineering performance trends have been established. This paper discusses the current status of the MLS instrument which now continuously provides data to produce global maps of targeted chemical species as well as temperature, cloud ice, and gravity wave activity. Performance trends are assessed with respect to characterization during initial on-orbit activation of the instrument, and with data from ground test verification prior to launch.

INTRODUCTION

The Earth Observing System Microwave Limb Sounder (EOS MLS) instrument was launched into Earth orbit on 15 July 2004 on the EOS AURA satellite. Scientific objectives of the MLS instrument include determining if stratospheric ozone is recovering, quantifying atmospheric composition and its affect on climate, and studying aspects of pollution in the troposphere. Measurements of molecular spectra are achieved by microwave limb sounding [1], a technique that has been successfully applied previously on NASA's Upper Atmosphere Research Satellite (UARS). EOS MLS is the follow-on to UARS MLS [2] and expands the global mapping capability to include many more molecular species. A more detailed description of the experiment is given in [3].

THE MLS INSTRUMENT

EOS MLS is a passive microwave radiometer, sensitive to thermal emissions in five bands centered around 118 GHz, 190 GHz, 240 GHz, 640 GHz, and 2.5 THz. The EOS MLS measurements are summarized in Table I. The instrument is comprised of three modules (see Figure 1): the GHz module houses the 118 through 640 GHz radiometers, GHz calibration targets, the GHz antenna, and switching mirror; the THz module contains the two 2.5 THz radiometers, the THz telescope, THz calibration target, and the THz scan/switching mirror; within the Spectrometer module are 19 filterbank spectrometers (25 channels each), 5 narrower spectrometers (11 channels each), four digital autocorrelator spectrometers, the command and data handling subsystem, and the power distribution subsystem.

The 1.6-m x 0.8-m GHz antenna scans the atmospheric limb from 0 km to 80 km every 24.7 s (major frame, or MAF). EOS MLS is a total power implementation, with radiometric calibration performed every MAF by views to a calibration target and cold space reference during the scan retrace. The THz module's scan/switching mirror scans are also repeated every MAF, with a view above the Earth's atmosphere (cold space) and a view of the internal THz black-body target for radiometric calibration. The received signals are downconverted and multiplexed into intermediate frequency bands, nominally 1300 MHz wide, centered at IF frequencies in the range 2 to 20 GHz. Each band is further down-converted and spectrally resolved in filterbank spectrometers. A simplified signal flow block diagram is shown in Figure 2.

Table I. EOS MLS radiometers and their measurements

Radiometer	Spectrometer Bands	Primary measurements for which the radiometer was included in EOS MLS	Additional measurements that are provided, or contributed to, by the radiometer
R1 (118 GHz)	1, 21,22, 32,34	temperature, pressure	cloud ice, geopotential height
R2 (190 GHz)	2-6,23, 27	H2O, HNO3	cloud ice, ClO, N2O, O3, HCN, CH3CN, volcanic SO2
R3 (240 GHz)	7-9,24,25, 33	O3, CO	cloud ice, temperature, pressure, HNO3, volcanic SO2
R4 (640 GHz)	10-14, 28-31	HCl, ClO, BrO, N2O, HO2	cloud ice, O3, HOCl, CH3CN, volcanic SO2
R5 (2.5 THz)	15-20	OH	O3, cloud ice, temperature, pressure

In this paper, we provide an engineering assessment of the EOS MLS instrument performance as MLS operation reaches its one-year anniversary, and note some significant events that occurred in this first year. MLS activation began three days following launch. Details of MLS activation are given in a companion article in these proceedings [4].

Following activation, calibrations were performed which provided the necessary updates to Level 1 software, which could only be determined from in-orbit measurements. Some of these measurements are repeated periodically to verify the calibrations are maintained. Level 1 software was updated to version 1.5 at the beginning of January, 2005, and is producing MLS data that is now made publicly available. Full science mode operation commenced on 13 August 2004, and many of the first scientific results were presented at the Fall 2004 meeting of the American Geophysical Union in San Francisco in December 2004. As of this writing, the MLS instrument has been operating in its nominal science mode for over 6500 hours, more than 75% of the time it has been in orbit (Figure 3), and has executed over 950,000 vertical scans profiling the atmosphere.

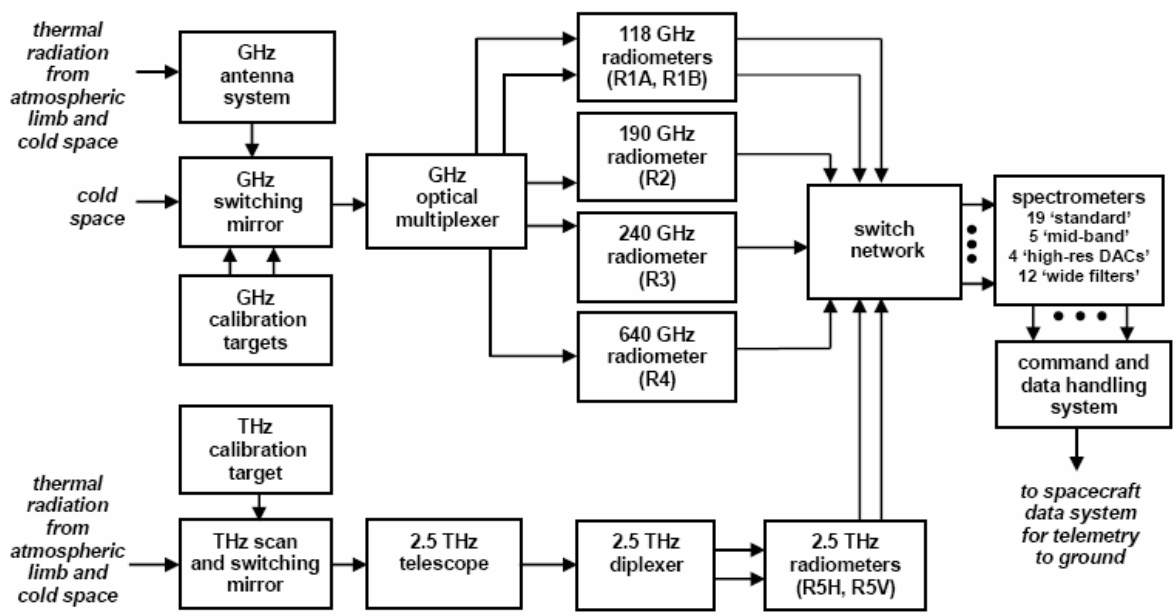

Figure 1. Signal flow diagram of the EOS MLS instrument.

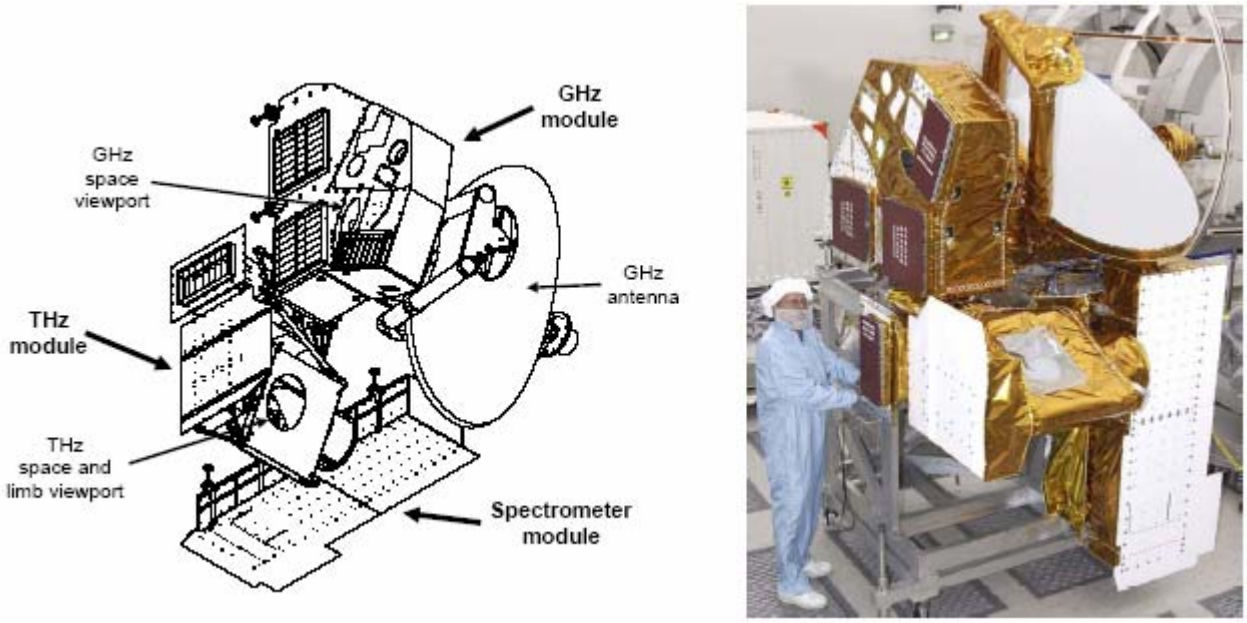

Figure 2. Drawing and photograph of the EOS MLS instrument.

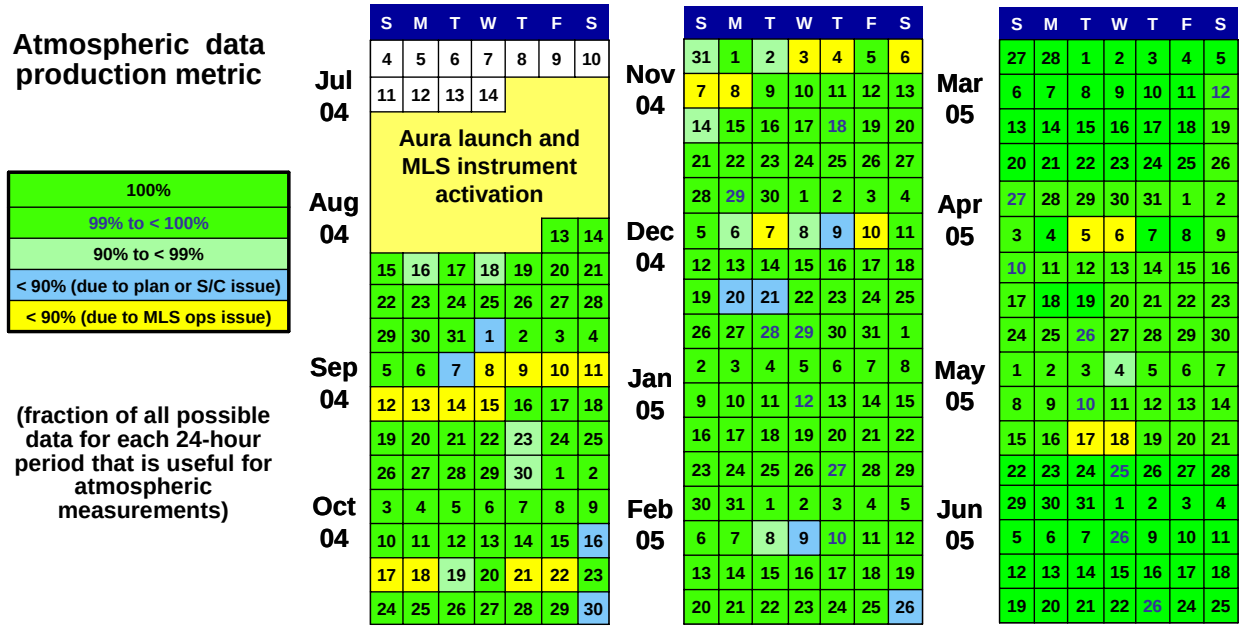

Figure 3. Metric of raw data used for production. The EOS MLS instrument has been operating in its nominal science mode (all GHz and THz radiometers and spectrometers operational and scanning the atmosphere) for over 75% of its time in orbit, including "down" times for activiation, calibrations, and operational issues.

ENGINEERING DIAGNOSTICS

Radiometric calibration is an integral part of the MLS measurement sequence. In the GHz module, the switching mirror directs the receivers' fields-of-view to one of four ports: the limb (via the GHz antenna), cold space, an ambient-temperature blackbody target, or a passively-cooled blackbody target. In the THz module, the scan/switching mirror directs the receivers' fields of view to the limb, to a space view 3.2° above the nominal limb, or 180° from the limb view to the enclosed ambient-temperature THz calibration target. Key diagnostics in the radiometric calibration algorithms are derived from the raw data during Level 1 data processing, including channel gain, system noise temperature (the spectrally-varying component of noise in each channel, T_{sys}), and χ^2 (from which the spectrally-averaged component of noise can be determined). For a more complete description of the MLS radiometric calibrations, see [5,6]. The THz radiometric calibrations take into account local oscillator power variations, measured through mixer bias telemetry. Plots of the GHz and THz diagnostic parameters for each day of operation in-orbit, along with the engineering telemetry and the raw science data from space and target reference views (counts from each channel) are reviewed to provide an engineering assessment of the MLS instrument's status. The calibration diagnostics have generally been stable since activation was completed and are in agreement with performance measured during ground testing. T_{sys} and gain for the standard GHz bands from 22 June 2005 are compared with the same parameters from 02 August 2004 (activation) and 17 April 2004 (pre-launch comprehensive performance test) in Figures 4 and 5, respectively. The spectral shape of Tsys remained constant from pre-launch testing through the first year. The increase in noise temperature from the pre-launch values is a consequence of the calibration target temperature refinement and not a degradation of the receivers' performance. Of the calibration diagnostics, the gains have seen the greatest change over the past year, with all channels in all radiometers slightly but steadily decreasing (see Figure 6). Temperature variations along the signal chains affect the gains; the time period where the optical bench was commanded to step up in temperature shows the expected commensurate steps down in gain. However seasonal temperature changes do not explain why the radiometer's gains continue to decrease. Aging of the low dropout voltage regulators used to bias the signal chain components in the spectrometer may cause some of the decline in gain, and this is under investigation. Three measurements bands of the 640 GHz radiometer are declining at a faster rate than all the other bands. A special test that switched the bands to an alternate spectrometer determined that a second cause for the gain decrease is present in the radiometer. This, too is under investigation. However the declines are small, they have had no adverse affect on the science data, and if they persist, the gain of each measurement band can be adjusted to compensate for the aging effects.

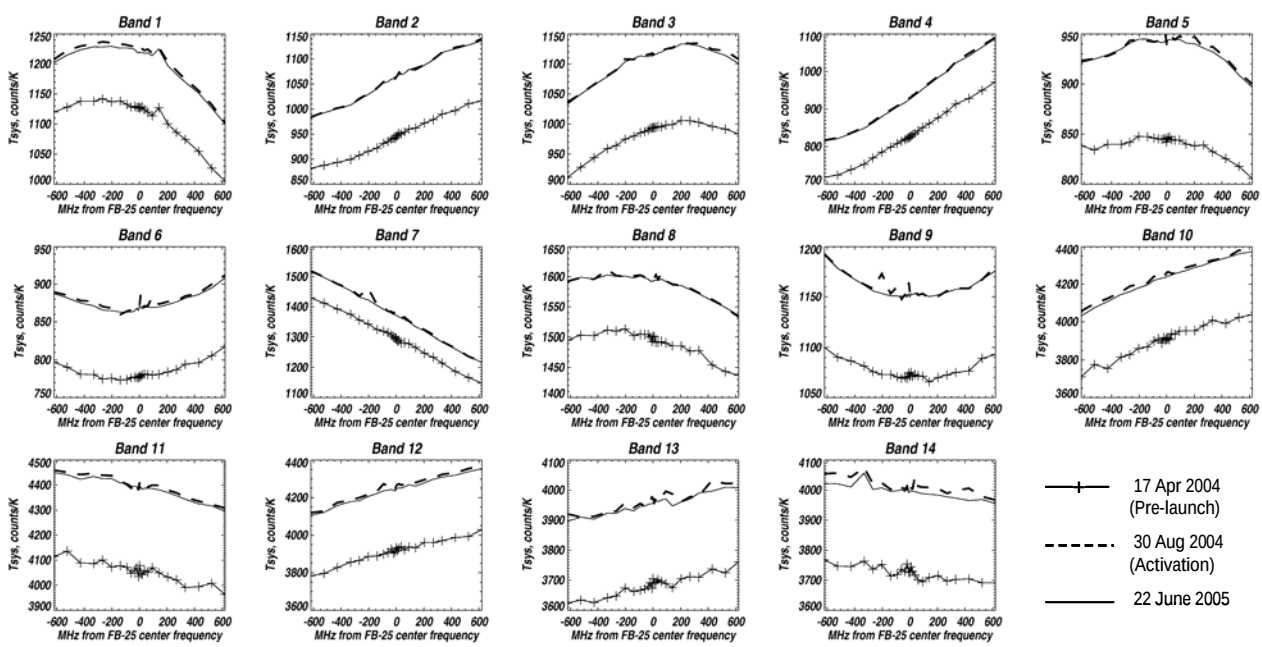

Figure 4. System noise temperature, Tsys, of the standard 25-channel bands from the GHz radiometers measured at three different times: pre-launch, soon after activation and initial in-orbit calibration, and 11 months after launch.

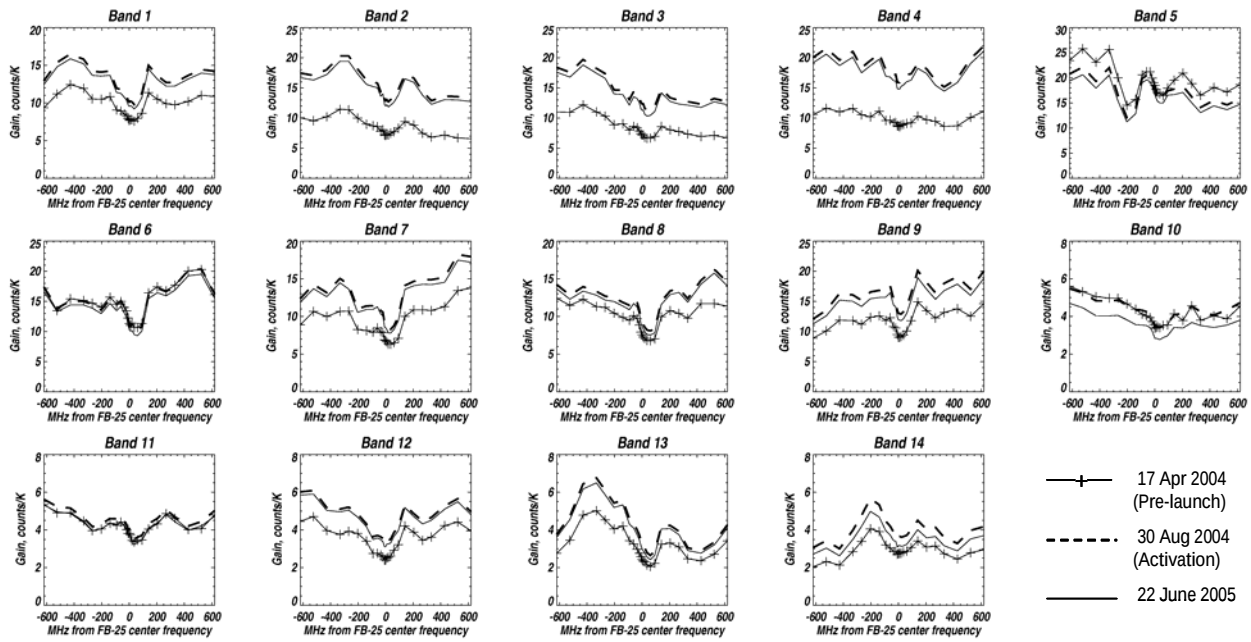

Figure 5. Gain of the GHz standard spectrometer bands measured at three different times: pre-launch, soon after activation and initial in-orbit calibration, and 11 months after launch.

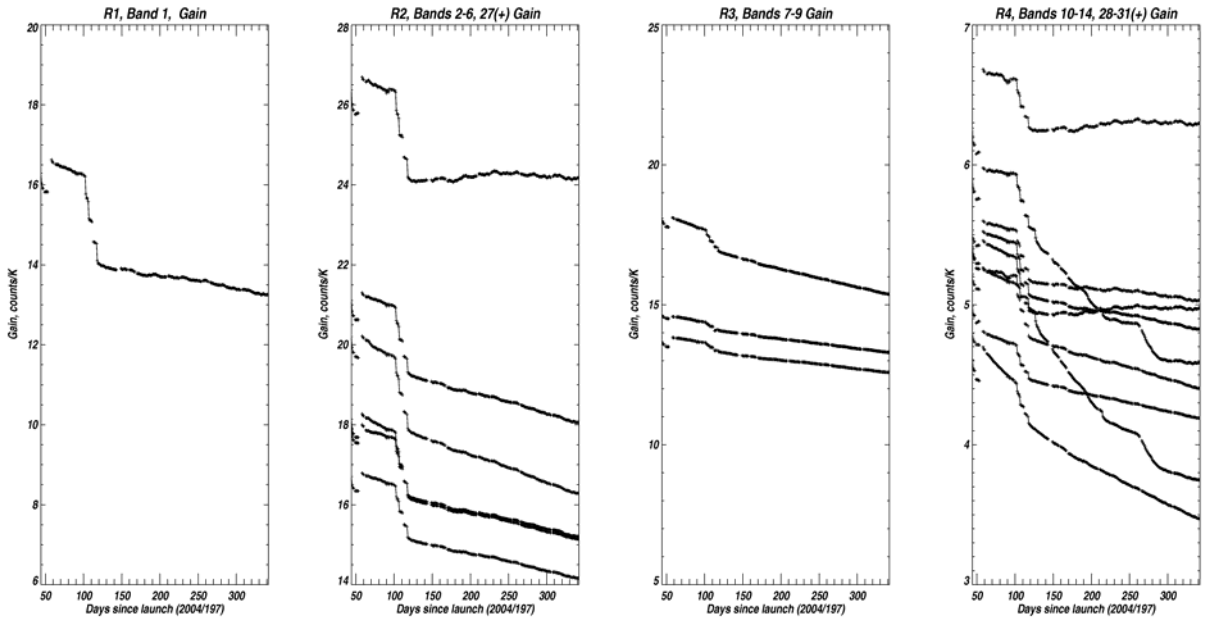

Figure 6. Trends of the gains for each GHz radiometer, since launch. The significant drop in gains around 100 days after launch resulted from operational temperature increases on the optical bench. Subsequent declines are less significant, except for three anomalous trends in the 640 GHz radiometer.

Analog engineering telemetry (voltages, currents, and temperatures) are used to monitor the state of MLS instrument. In typical daily plots of engineering telemetry data (Figure 7, for example), the variations in the telemetry and raw data are dominated by orbital variations. Telemetry from the UARS MLS experiment performed in a similar fashion that lasted over six years in orbit. Other small, unexpected changes in their values have appeared in engineering telemetry on only a few occasions in the past year. Generally these anomalies have coincided with high solar activity. One daily plot review had revealed one telemetry point, a voltage monitor for the 640 GHz phase-locked local oscillator, had significantly decreased. Within a few days it had recovered to its nominal value, and despite this anomaly, science data from the 640 GHz receiver during that period was unaffected. All other engineering telemetry has been nominal each day and indicates the MLS instrument is operating as expected. From the set of daily engineering data files, long-term trends of daily means are plotted. The long-term trends allow assessment of the instrument in the context of seasonal variations (temperature telemetry in Figure 8, as an example) and aging. Many voltage-controlled oscillators in the MLS receivers have exhibited an aging effect which manifests a shift in tuning voltage. In all of the oscillators affected, the tuning voltage telemetry appears to be leveling off as expected (see Figure 9).

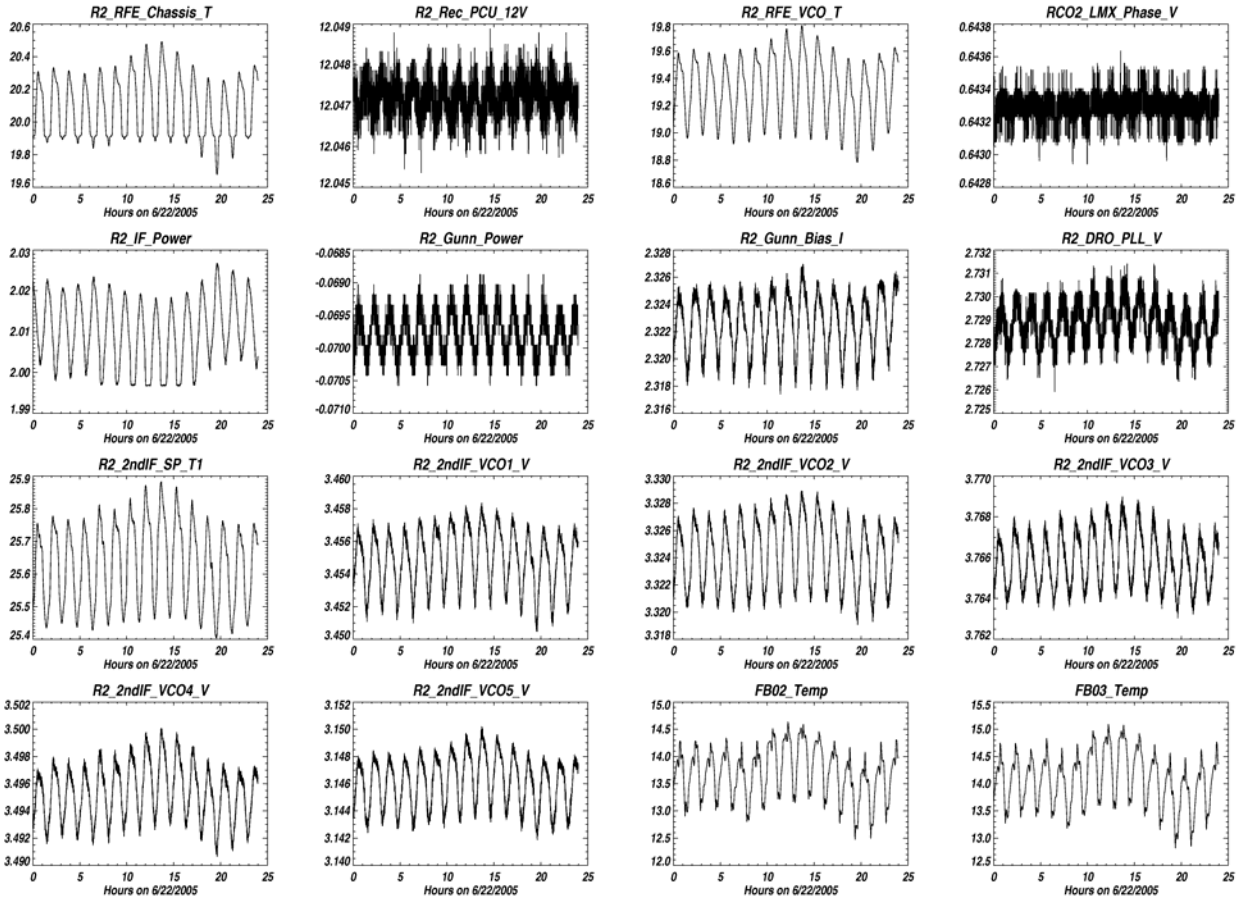

Figure 7. Typical daily plots of temperature and voltage telemetry used to monitor health and status of the R2 (190 GHz) receiver front end. Daily plots of telemetry throughout the MLS instrument show similar stability and orbital dependence.

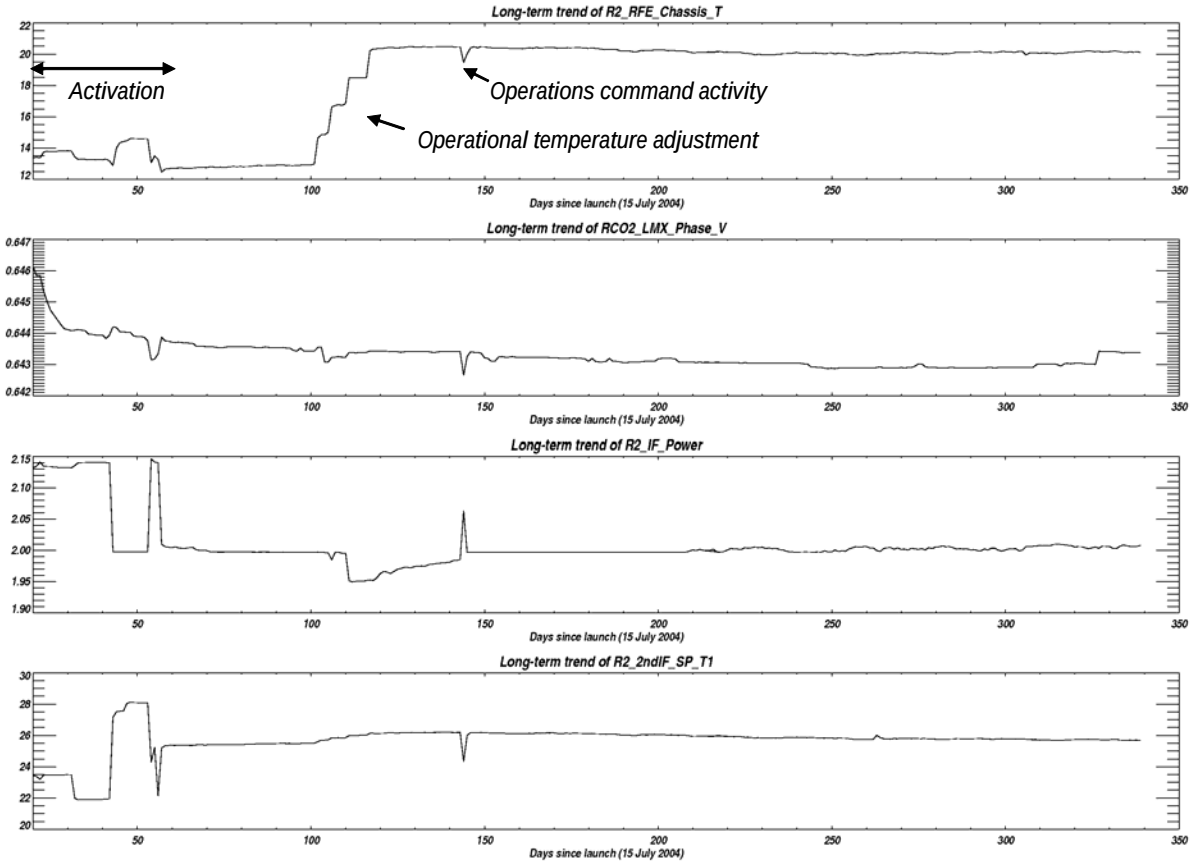

Figure 8. Example plots of engineering telemetry points' long-term trends, used to assess MLS R2 (190 GHz) radiometer's health and status. Discontinuities in the trends occur on days with planned operations activities.

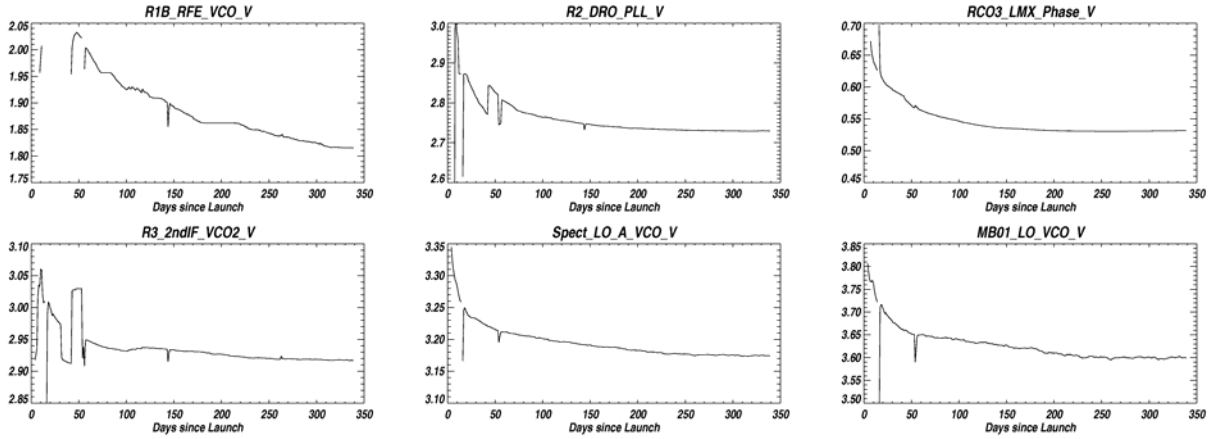

Figure 9. Trends of VCO voltages in the MLS instrument.

POST-LAUNCH INSTRUMENT ADJUSTMENTS

Very few adjustments to the MLS instrument have been made since launch, as performance has been excellent. All engineering parameters have remained in their nominal ranges, with the single exception of the frequency tripler voltage during a brief period early in the activation sequence. Occasions where adjustments to the flight instrument have been made are: one minor update to the flight software to mitigate problems with the THz laser local oscillator (LLO) communications, temperature adjustments of the optical bench to raise the temperature of the frequency tripler in the 640 GHz receiver, and a new scan that is executed for periodic maintenance of the GHz antenna actuator. All other adjustments have been to the ground-based Level 1 processing software that resulted from observations of in-orbit performance, discussed below.

LLO software. The THz radiometer uses a CO_2 laser-pumped methanol gas laser for its local oscillator. Data analysis requires that the laser local oscillator (LLO) maintains a frequency of 2522.782±0.001 GHz during nominal operation. To do so, mirror positions are adjusted to re-optimize laser performance periodically. This is accomplished autonomously by the LLO software. In the first months after activation, communications with the LLO were unexpectedly interrupted, telemetry from the LLO was not transmitted to the data stream, and the LLO would not relock. To reestablish LLO operation required a power off-on cycle of the THz receiver assembly, commanded from the ground. An investigation revealed a problem with the serial interface logic while in full-duplex mode, and this was corrected with an update to the software. No further loss of communication has occurred since 6 November 2004. This is the only on-board software change that the MLS instrument has required since launch.

Optical bench temperature. Operational heaters are installed in the GHz module's optical bench to enable control of the receiver front ends temperatures. Early in activation, the frequency tripler in the 640 GHz receiver front end displayed telemetry voltages beyond its nominal operating range. In order to correct the frequency tripler performance, the thermal environment for the 640 GHz receiver was changed by increasing the optical bench temperature, returning the tripler's voltage into its nominal range.

Antenna actuator conditioning. Development of the antenna actuators which drive the scan profile of the THz and GHz antennas included life test units that demonstrate the lifetime requirement of 5 years will be met. Inspection of the life test unit showed that the quantity of lubricant for the GHz antenna actuator was reduced over time and repeated cycles. As a result, a reconditioning sequence was established for the flight actuator that moves the antenna through its full range of motion (far beyond the scan profile used for nominal science mode) so that the lubricant is redistributed and any wear products are moved aside. This sequence has been performed each month, without incident, since the completion of MLS activation.

LEVEL 1 DATA PROCESSING REFINEMENTS

Level 1 data processing software converts the raw data (digitized signals from the spectrometers in "counts") into calibrated radiances. Level 1 software is described in [6]. Based on experience with the MLS experiment on UARS, Level 1 updates as result of in-orbit calibrations were expected. Since launch and activation, Level 1 refinements have included: results from the field of view (FOV) and spectral baseline calibrations, an update of relative sideband response for the 640 GHz receiver, refinement of the calibration target temperatures, offset levels of the spectrometer channels, and compensation for frequency spurs in the 240 GHz receiver.

240 GHz receiver spurs. Temperature changes in the optical bench affect all five receivers in the GHz module, and during these adjustments the performance of the local oscillator in the 240 GHz receiver also changed. The 240 GHz local oscillator exhibits sidebands, approximately 714 kHz from the LO, which are convolved with the measured atmospheric signals. Radiance retrievals for the lines in the 240 GHz band require deconvolution of these spurious tones. The sidebands were characterized prior to launch and were expected to remain stable. However, during the optical bench temperature changes their magnitude increased as the temperature increased. This phenomenon was

detected in CO spectra resolved in the digital autocorrelator spectrometers. As a result, Level 1 software has been modified to incorporate an estimation of the magnitude of the spurs, and a correction for their effects.

Calibration target temperature. The passively-cooled GHz calibration target is used for routine radiometric calibration, and exhibits a small temperature gradient through its absorbing layer. This small effect was quantified by comparing radiances from the two calibration targets, and a 0.5 C correction applied to temperature telemetry for this target to compensate.

640 GHz relative sideband response. The heterodyne receivers (except those at 118 GHz) detect signals in both their upper and lower sidebands. Their local oscillator frequencies were carefully selected to minimize contamination of atmospheric lines from the opposite sideband, and Level 2 (retrieval) software requires precise knowledge of the relative sideband responses. After delivery of the instrument to spacecraft integration, a concern arose with regard to the reliability of the frequency tripler in the 640 GHz receiver, and a more reliable, planar device replaced the one used originally delivered. Calibration of sideband response for the 640 GHz was performed at fewer IF frequencies since the test occurred at the assembly level rather than in the compete instrument. The sideband response changed by approximately 4 %, and the Level 1 parameters were changed accordingly.

Field-of-view calibration. The GHz and THz telescope fields of view were calibrated individually before launch, but significant updates were anticipated to result from field-of-view calibrations in orbit. For the THz telescope field-of-view calibration on the ground, the radiometer response to a mercury arc infrared source imaged through a slit aperture was measured as a function of vertical scan position as the scan/switching mirror [6]. For the GHz antenna, the fields of view for each GHz radiometer were measured at several IF frequencies in each sideband on a custom near-field range. Measurements of the near-field amplitude and phase distribution were taken in each radiometer, along the signal paths from the antenna through the first intermediate frequency output. The complex field pattern was then Fourier-transformed to calculate the far-field antenna pattern. The GHz antenna, its calibration and its alignment are described in [7]. Pointing knowledge of the GHz and THz radiometers' beams is refined in-orbit using the Moon as a source, also described in [7]. Since first launched, MLS has used 6 of the bimonthly opportunities to scan the Moon for pointing calibration. Pointing offsets of the radiometers relative to the 240 GHz reference have agreed with pre-launch values to within 0.003°.

Stray radiances. The Level 1 software corrects for offsets in the GHz radiometric data that arise from stray reflections and emissions from the antenna assembly in the radiometers' fields-of-views. During activation, a special scan, extended in height above the atmospheric limb to view cold space through the antenna (limb port) as well as the space port, measured radiances differences of up to 10 K due to thermal emission and scattering from the antenna. The difference varies by up to 0.5 K orbitally. The radiance offset has been reduced for v.1.5 of Level 1 to 1—2 K by changing the parameters which describe GHz reflector ohmic loss, from the values measured during ground calibration. A repeat of the extended scan several months into the mission confirmed the stability of the spectral baseline, processed as a static correction in Level 1. The THz scan/switching mirror views the calibration targets and the limb through common optics, so Level 1 need not perform this correction for the THz radiances.

Linearity. End-to-end linearity was measured in all GHz bands prior to launch using a heated load viewed through the space port. This data set was extended in orbit by comparing data taken viewing the ambient and passively-cooled targets. These data indicate overall nonlinearity of 0.1% or better over the full range of radiances observed by MLS.

IF Zeroes. The filter spectrometer channels have a non-zero output in the absence of any input signal. This offset needs to be known by Level 1 software for accurate estimation of measurement precision (noise). Comparisons of pre-launch offsets with those measured 6 months after launch indicate negligible changes.

OBSERVATIONS IN THE FIRST YEAR

In addition to the planned limb sounding, some other noteworthy observations have been made in this first year. The HIRDLS instrument, also on the Aura platform, required the spacecraft to maneuver to a nonstandard pitch downward.

This orientation gave MLS the opportunity to observe clouds at higher spatial resolution than the standard limb scanning mode, approximately 1.2 km. These high resolution data could provide important details about cloud structure and mixed-phase clouds. A significant polarization difference has been observed using the two 118 GHz radiometers. The original intent of the second 118 GHz radiometer was to serve as a redundant pointing reference for the instrument, diplexed to the antenna with a polarizing grid and to be powered on only in the event of a failure in the primary unit. The notable difference between the two polarizations motivated the decision to have the redundant radiometer remain on as part of the nominal science mode. Model simulations indicate that particle shape and orientation will impact polarization differences, and difference measurements between the two MLS radiometers at 122 GHz are consistent with the model that simulates particles of a specific orientation [8].

A consequence of limb sounding, versus nadir sounding, is the possibility that celestial objects will appear in the fields of view. The Moon sometimes appears in the antenna beam discussed previously, and has been effectively used for calibration. The Moon also appears in the space view twice a year. When this occurs, the space reference used to calibrate the radiometers becomes invalid, and those data are flagged by Level 1. A special test with the GHz mirror scanning the space port during the lunar space view contamination in May 2005 may provide calibrations to allow these data to be recovered. The core of the Milky Way galaxy is another source of interference that has appeared in the GHz antenna field of view. Bands detected by the 240 GHz radiometer are sensitive to the CO emission line at 230 GHz, and saw a significant increase in radiance coincident with the antenna scanning past the galactic core.

The space weather environment is monitored closely for events that may affect MLS operations. Solar flares have been coincident with minor electronic circuit anomalies. The digital signal processor chips in the MLS mechanism electronics were identified as particularly sensitive to single-event upsets, and contingency plans to power off these assemblies during periods of high activity are in place, but have not been needed thus far. Science data has not been adversely affected by the solar events; however the abundances of OH, detected by the 2.5 THz radiometer, are seen to have increased during increased solar activity, as observed by other instruments in prior proton events [9].

CONCLUSIONS

The EOS MLS instrument has been successfully operating in-orbit aboard the Aura satellite for the past year. Engineering telemetry has been in the nominal range, and performance diagnostics are similar to results from pre-launch testing. Trends indicate aging effects in oscillators and possibly also in the spectrometers' low drop-out voltage regulators, and radiometer gains have declined over the past year, however the 5-year lifetime requirement is expected to be achieved. Flight software has required only one very minor change, completed late in 2004, with no flight software-related issues arising since then. Temperature of the GHz optical bench was adjusted to improve reliability of the frequency tripler in the 640 GHz receiver, and the science team will consider whether further adjustment is needed to improve overall performance. Level 1 algorithms have been (and will continue to be) updated based on in-orbit calibrations. In summary, the MLS instrument has required minimal corrections since first launched and activated, and has experienced only a very few anomalies, none of which have hampered the production of scientific results in this first year.

ACKNOWLEDGEMENTS

The authors wish to acknowledge members of the MLS instrument and science teams, especially Brian Knosp. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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