A Large Aperture 650 GHz Near-Field Measurement System for the Earth Observing System Microwave Limb Sounder

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ABSTRACT

This paper describes a large aperture, 650 GHz, planar near-field measurement system developed for field of view characterization of the Earth Observing System Microwave Limb Sounder (EOS MLS). Scheduled for launch in 2003 on the NASA EOS Aura spacecraft, EOS MLS is being developed by the Jet Propulsion Laboratory to study stratospheric chemistry using radiometers from 118 to 2500 GHz. The combination of a very high operating frequency and a 1.6-meter aperture, coupled with significant cost and weight restrictions, required a new look at near-field scanner design approaches. Nearfield Systems Inc. (NSI) developed a planar scanner that provides a planar accuracy of 4 microns RMS over the entire 2.4 x 2.4 meter scan area. This paper presents an overview of this system including the sub-millimeter wave RF subsystem and the ultrahigh precision scanner. Representative measurement results will be shown.

Keywords: Near-Field, Antenna, JPL, Microwave Limb Sounder, MLS, EOS, Microwave Inter-ferometry, THz, Sub-millimeter

1. Introduction

An emerging technology is the design, production and testing of large aperture sub-millimeter wave antennas. These antennas are often used in space research as part of radiometer systems. One such antenna is the Earth Observing System Microwave Limb Sounder (EOS MLS). The MLS GHZ antenna has a 1.6 meter aperture and operates at frequencies as high as 640 GHz. There is a separate THz antenna operating at 2500 GHz.

The MLS instrument consists of an off-axis elliptical Cassegrain antenna coupled to a multi-band sub-millimeter wave radiometric receiver operating at a number of frequencies between 118 and 640 GHz. The receiver outputs are simultaneously processed in spectrometers with the resultant spectra being transmitted back to earth. The MLS antenna is electrically quite large, providing a beamwidth only a few arcminutes at 640 GHz.
astronomy satellite (Slater 1994) and Rosetta comet orbiter satellites (Koch 2001). This system, while having the necessary accuracy, did not have a sufficiently large scan area. The technology used in this scanner was not readily adaptable to the cost and weight requirements necessary for the EOS MLS project. As a result, a new second generation system called the SubMillimeter Wave Scanner (SMWS) was designed and fabricated for JPL by NSI.

2. Submillimeter wave near-field system requirements

The EOS MLS sub-millimeter wave near-field measurement system had a system wide axial wave front measurement uncertainty limit of 16 microns RMS. The final system exceeded this significantly with a delivered accuracy of less than 10 microns RMS. This paper will concentrate on the technology needed to provide high phase measurement accuracy in this application.

JPL MLS near-field antenna measurement system design constraints were:

1. The scan area was to be 2.8 by 2.8 meters.
2. The system would require a system wide Z planarity of 16 microns RMS. The error budget was allocated as follows:

<table>
<thead>
<tr>
<th></th>
<th>Contract requirement</th>
<th>As delivered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanner Z planarity</td>
<td>10 microns rms</td>
<td>4 microns rms (measured)</td>
</tr>
<tr>
<td>Phase reference cable</td>
<td>12 microns rms</td>
<td>8 microns rms (measured)</td>
</tr>
<tr>
<td>Phase reference thermal</td>
<td>3 microns rms</td>
<td>3 microns rms (estimated)</td>
</tr>
<tr>
<td>Receiver phase noise</td>
<td>1 microns rms</td>
<td>1 microns rms (estimated)</td>
</tr>
<tr>
<td>RSS total</td>
<td>16 microns rms</td>
<td>9.5 microns rms (calculated)</td>
</tr>
</tbody>
</table>

3. A vertical scan plane orientation was required for compatibility with the EOS MLS flight article.
4. The entire near-field measurement system would need to be operationally and thermally compatible with a class 1000 clean room spacecraft assembly area.
5. The scanner weight was limited to 10,000 pounds and the system would need be moveable for storage between projects.

3. Submillimeter wave near-field measurement system design

3.1 Thermal design

Thermally induced phasefront errors become an important issue when the near-field scanner is electrically large, that is when the scanner dimensions are large when measured in wavelengths. Because of the high operating frequency of the EOS MLS instrument, the near-field measurement system has a system wide 16 micron RMS phase measurement accuracy requirement. This specification requires that the RMS phase error from all sources including mechanical scanner errors, phase reference cable systematic errors, receiver errors, test article support fixtures and thermal drift will result in less than a 16 micron RMS change in RF path length. Temperature changes in a near-field test facility will cause the following thermal effects:

1. Thermally induced time varying changes in the electrical length of the probe antenna phase reference cable, test antenna cable and receiver phase reference cable will cause phase changes that appear to be along the antenna boresight direction. A one meter long RF cable with a 10 ppm/deg C temperature coefficient and 1 deg C temperature change will have an electrical path length change of 10 microns.
2. The EOS MLS instrument is mounted onto an aluminum handling fixture which will differentially expand due to facility thermal variations. In general, any Z axis motion component of the MLS telescope has the same effect and magnitude as any Z error in the planar near-field scanner.
3. Thermal changes in the test antenna mount can cause the antenna location (X, Y, Z) and orientation (yaw, pitch, roll) to drift unpredictably. The MLS antenna near-field region is similarly quite sensitive to unmodeled azimuth and elevation changes as these include a differential Z motion of reflector. A Z component of motion is present for relative Z, azimuth and elevation motion. A 10 microradian (2 arcsecond) pointing change of the antenna mount would move one side of the projected 1.6 meter MLS antenna aperture 16 microns closer to the scanner than the other side of the antenna. This would use up the entire Z error budget.
4. Temperature changes can warp both the scanner and antenna under test.

A number of techniques can be used to reduce the effects of thermally induced phase errors. These techniques include:

1. Thermally stabilizing the environment minimizes all error terms. Electrically large systems generally need to be thermally stabilized to a +/- 1 deg F range or better. Both the JPL spacecraft assembly clean room and the NSI fabrication facility were thermally stabilized to this value.

2. Low temperature coefficient materials are used where possible. Granite has a low temperature coefficient (5 ppm/deg C) and a high thermal inertia.

3. Thermally induced cable phase errors are reduced by minimizing the length of the RF cables and other mechanical elements. The phase reference cables have a relatively high thermal coefficient. Errors here are minimized by a combination of facility temperature control, cable thermal inertia and MTI processing.

4. As the RF subsystem of the near-field range is a form of a two arm interferometer, a differential thermal drift cancellation technique can be used. In this technique, the receiver phase reference cable is made equal in length to the sum of the probe and AUT cable lengths. The assumption here is that all cables have the same temperature environment, coefficient and time constants. This would minimize the first error term only. Because much of the receiver phase reference path was internal to the EOS MLS instrument, this method could not be used.

5. Motion Tracking Interferometry (MTI) uses submillimeter wave phase tracking in conjunction with least squares computations to estimate the time varying solid body azimuth, elevation, and Z motion between the near-field scanner and the MLS antenna. MTI also compensates for phase reference cable thermal errors.

4. Motion Tracking Interferometry

The Motion Tracking Interferometer (MTI) system is an extension of the tie scan concept sometimes used for thermal drift compensation of near-field measurements. Unlike the tie scan, MTI provides a multiple degree of freedom of measure of the relative rigid body motion between the scanner and test antenna during the test. Additionally, the MTI system provides an estimate of the differential motion measurement uncertainty.

The MTI processor provides a measure of the relative azimuth, elevation and Z motion between the scanner and MLS instrument antenna. Measurements of other degrees of freedom (X, Y, roll) are not needed because the significant MLS antenna energy is aligned with the scanner bore sight axis. The MTI data is acquired by periodically interrupting the normal data acquisition process and then measuring the complex (S21) transmission at four spatially separated points. The MTI scan is performed at a single frequency with a co-polarized unsteered beam, even in the case of multi-frequency and multi-polarization measurements. The MTI measurements are phase unwrapped and distance normalized to remove frequency dependence. A series of least squares solutions to the plane orientation provides a time history of the relative Z, azimuth and elevation motion between the scanner and MLS instrument antenna. Even though the MTI measurements are made at a single frequency, polarization and beam steering, the results apply to all polarizations and frequencies.

Because the solution is over determined, the MTI measurement uncertainty can be readily estimated. The measurement uncertainty is a function of the RF signal to noise ratio, scanner repeatability and unmodeled nonrigid body motion. For example, if the scanner or antenna became thermally warped, the MTI measurement uncertainty would increase. Thermal drift in the phase reference cable appears as a solid body motion aligned with the MTI reference antenna beam direction, in this case, aligned with the Z axis.

The MTI measurements can be used to correct for the unwanted solid body relative motion in two ways. The MTI measurements can be nulled by periodically rotating and translating the scan plane, so as to maintain a constant orientation relative to the drifting test article. Alternatively, the MTI measurements can be interpolated over the duration of the scan to provide an estimate of the time varying relative solid body motion history. A postprocessor is used to perform a time varying derotation and translation of the phase front that effectively nulls the drift. The second technique is used in the EOS MLS near-field measurement system as the SMWS scanner did not include a motorized Z axis.

MTI, as used in the SMWS near-field measurement system does not measure X, Y or roll motion nor does it explicitly separate out the cable thermal term. MLS antenna near-field measurements are relatively insensitive to these motions because the antenna beam is directed along the scanner Z axis.
5. RF subsystem

The RF subsystem design was primarily driven by the need to use the internal receiver within the MLS payload. For this reason, the near-field scanner probe was configured as a transmitter. A microwave reference signal is passed through a phase reference cable to a probe mounted varactor multiplier.

The MLS receiver IF output is passed to an Agilent 8530A microwave instrumentation receiver, which produces a measure of the complex (S21) transmission between the probe and MLS payload.

6. Scanner design

Six basic scanner concepts were used to provide the extreme precision needed for the MLS antenna test. These elements are:

1. T scanner design – The scanner is built in a T configuration with two horizontal granite beams and one vertical column. This approach minimizes the weight of the scanner, improves the portability and simplifies the scanner interface to the facility foundation.

2. Granite beams – Granite beams are used to provide a structure with deformations having predominant low spatial frequencies. Granite provides several advantages in this application, including excellent long term mechanical stability and compatibility with precision surface lapping methods. Lapped surfaces are necessary to produce the required planarity. Center column support – The Y (vertical) axis granite column is supported at its center of mass. This reduces the magnitude of certain structural deformation errors that increase as the square of the support distance.

3. Triple vertical carriage – The scanner Y axis uses 3 separate carriages, the probe carriage, the counterweight carriage and a drive carriage. This combination provides a minimum set of disturbance forces to the probe carriage.

4. Active heat control system – Heat produced by the motors and sub-millimeter wave up-converter is extracted in a manner that does not allow thermal plumes to impinge upon the scanner structure or test article.

5. Clean room compatibility – Constant attention was paid to the need to operate in a class 1000 clean room with significant out gassing restrictions.

7. Submillimeter wave scanner (SMWS) validation

The very high precision of this scanner required a new look at the construction and validation technologies. NSI constructed a thermally controlled facility that was used both during the construction and validation of this scanner. Temperature within this facility was stabilized to within +/- 1 deg F. At JPL, the SMWS scanner is operated in a clean room spacecraft assembly area that is also thermally stabilized to +/- 1 deg F.

Conventional optical tooling and laser planarity measurement techniques do not provide sufficient accuracy for this application. Planarity was instead determined by
integrating a series of auto collimation and biaxial tilt meter measurements. The measured planarity of the delivered system was less than 4 microns RMS over the entire 2.4x2.4 meter scan area.

8. Representative measurement results

This section shows a few of the early measurement results of the JPL MLS breadboard antenna made with the NSI SMWS near-field measurement system.

9. Conclusions

The SMWS near-field measurement system has met all project requirements. The scanner Z planarity was better than 4 microns RMS and the system planarity was less than 10 microns RMS over the full scan plane. The operation of an electrically large sub-millimeter wave near-field antenna measurement system required several extensions to normal near-field test methods. These extensions included a very
high precision granite scanner mechanism, a highly stable phase reference system, and the RF based Motion Tracking (MTI) system. The MTI system provides a simple and highly accurate alternative to autocollimator, tiltmeter, and other mechanical referencing methods. The need for the customer to provide a thermally stable test article mount is reduced. Elements of this system are patented or patent pending.

10. References


Waters, J.W., “An Overview of the EOS MLS Experiment”, JPL report D-15745, Jet Propulsion Laboratory, Pasadena