A 550 GHz NEAR-FIELD ANTENNA MEASUREMENT SYSTEM FOR THE NASA SUBMILLIMETER WAVE ASTRONOMY SATELLITE

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ABSTRACT

This paper describes a 550 GHz planar near-field measurement system developed for flight qualification of the radio telescope carried onboard the NASA submillimeter wave astronomy satellite (SWAS). The very high operating frequency required a new look at many near-field measurement issues. For example the short wavelength mandated a very high precision scanner mechanism with an accuracy of a few microns. A new thermal compensation technique was developed to minimize errors caused by thermally induced motion between the scanner and spacecraft antenna.

Keywords: Near-Field, Antenna, Submillimeter Wave, SWAS, Thermal Compensation

1. INTRODUCTION

This paper describes a submillimeter planar near-field antenna measurement system developed for flight qualification of the radio telescope carried onboard the NASA submillimeter wave astronomy satellite (SWAS). This telescope will produce high resolution radio maps of molecular cloud chemistry in the Milky Way galaxy. The SWAS satellite is part of the NASA small explorer (SMEX) satellite program, a series of small and inexpensive spacecraft. The SWAS will be placed into orbit by a Pegasus launch vehicle.

The SWAS radio telescope consists of an off-axis elliptical Cassegrain antenna coupled to a dual channel submillimeter wave receiver that operates at 490 and 548 or 553 GHz. The receiver outputs are simultaneously processed in an acousto-optic spectrometer and transmitted back to earth. The radiotelescope antenna is electrically quite large, providing a beamwidth less than 5 arcminutes wide. (See Figure 1.)

The SWAS telescope operates in a wavelength region from 0.54 to 0.61 millimeters. Even though the near-field scanner is physically small, it is electrically very large, as the scanner aperture width is greater than 1400 wavelengths. The SWAS telescope was designed to a 25 micron phase-front accuracy.

2. DESIGN REQUIREMENTS

The SWAS near-field measurement system required a 15 micron or better phase-front measurement accuracy. This paper will concentrate on the technology needed to provide a high phase measurement accuracy in this application. Three elements will be discussed in detail: the scanner design, phase reference system design and thermal compensation.

SWAS near-field antenna measurement system design constraints:

1. The scan area was to be 0.8 by 0.8 meters.

2. The system would require an rms Z planarity of 15 microns or better. The error budget was allocated as follows:
   a. Scanner Z planarity .... 5 microns rms
   b. Phase reference arm...................... 12 microns rms
   c. Other errors.................................... 6 microns rms

3. The system would be shipped to several facilities. The scanner Z planarity needed to be easily checked.

4. The system would need to be operationally and thermally compatible with the spacecraft assembly area.

5. A vertical scan plane orientation was required for compatibility with the flight article handling fixture.

3. SCANNER DESIGN

Four basic scanner design elements were used to provide the extreme precision needed in this application. These elements were:

1. Granite structure - The scanner was built from granite. Granite provides several advantages in this application, including excellent long term mechanical stability and compatibility with precision surface lapping methods. Lapped surfaces were necessary to produce the required planarity.

2. Air bearing carriages - Air bearings were used to provide a better planarity than can be provided by conventional ball or roller bearings. Air bearings have a large surface area which minimizes the effect of local surface errors.

3. Sideways H scanner geometry - A sideways H scanner geometry using a vertical surface plate reference was selected as the method to provide the best planarity.

4. Reference surface plate - The scanner would include an integral surface plate to be used for checking scanner Z planarity.

A vertically oriented surface plate at the back of the scanner served both as the foundation and as a Z planarity reference when probed with a precision dial indicator. Two horizontal granite rails separated vertically by several feet were attached to the vertical surface plate. An air bearing carriage rides on each of the horizontal granite rails. The two air bearing carriages are interconnected with a vertical granite rail. A third air bearing carriage rides on the vertical rail. Both the horizontal and vertical axes are positioned by precision stepper/leadscrew drives. The scanner as delivered had a Z planarity of 1.2 microns rms (2 wavelengths of red light). See Figure 2 for a photo of the SWAS scanner.

4. RF SUBSYSTEM

The RF subsystem design was primarily driven by the need to use the internal receiver in the SWAS payload. For this reason, the near-field scanner probe was configured as a transmitter. A frequency multiplier on the probe carriage converted a 5.11 GHz phase reference signal to the submillimeter wave test frequency. All submillimeter hardware for the system was developed by Millitech.

The 5.11 GHz phase reference path to the moving probe carriage was required to be extremely phase stable, since any phase error at 5.11 GHz would be multiplied approximately 100 times by the frequency multiplier. A two arm mechanism interconnected with three specially selected rotary joints was used to meet the performance requirement of a 12 micron rms path length stability. The arm design used a thermally shielded exoskeleton that enclosed a low temperature coefficient SiO_2 cable. The phase accuracy of the rotary joint arm system was verified by an S11 measurement of the phase delay to a short mounted at one end of the phase reference cable.

The SWAS telescope receiver IF output was at S-band. A standard Hewlett-Packard 8753C network analyzer was used to convert the S-band IF signal into digital form for sending to the NSI near-field measurement software. The SWAS telescope receiver also provided the phase reference signal for the network analyzer.

5. 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 SWAS telescope, the near-field measurement system has a 15 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 and thermal drift will result in less than a 15 micron rms change in RF path length. Temperature changes in a near-field test facility will cause the following thermal effects:

1. Thermally and time dependent 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 an 8 ppm/°C temperature coefficient and 1°C temperature change will have an electrical path length change of 8 microns.

2. The SWAS payload is mounted onto an aluminum handling fixture which can differentially expand. In general, any Z axis motion components of the SWAS telescope hves the same effect and magnitude as any Z errors in the NFR scanner.

   Thermal changes in the test antenna mount can cause the antenna location (X, Y, Z) and orientation (yaw, pitch, roll) to drift unpredictably. The SWAS 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 .1 arcsecond pointing change of the antenna mount would move one side of the SWAS aperture 15 microns closer to the scanner than the other side of the antenna. This would use up the entire error budget.

3. 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 are often thermally stabilized to a ±0.5°C range or better.

2. Low temperature coefficient materials can be used. Granite has a low temperature coefficient (5 ppm/°C) and a high thermal inertia. The SWAS RF components are interconnected with specially selected RF cables that have a very low thermal coefficient.

3. Thermally induced cable phase errors can be reduced by minimizing the length of the RF cables and other mechanical elements.

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 the receiver phase reference cable was internal to the SWAS payload, this method could not be used.

5. The tie scan technique can be used to measure cable drift and the component of relative motion aligned with the beam boresight direction.

6. A new thermal compensation technique called motion tracking interferometry (MTI) was developed for the SWAS near-field measurement system. This method measures several thermal drift components including multiaxis solid body motion and time varying low order distortions of the AUT and scanner.

6. 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 multidegree of freedom 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 measurement uncertainty.

The MTI processor measures the relative azimuth, elevation and Z motion between the scanner and SWAS antenna. Measurements of other degrees of freedom (X, Y, roll) are not needed because the significant SWAS antenna energy is aligned with the scanner boresight axis. The MTI data is acquired by periodically interrupting the normal data acquisition process and then scanning four spatially separated points. The MTI scan is performed at a single frequency with an unsteered beam, even in the case of multifrequency and multipolarization 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 SWAS antenna. Even though the MTI measurements were made at a single frequency, polarization and beam steering, the results apply to all polarizations and frequencies.

Because the solution is overdetermined, the measurement uncertainty can be readily estimated. The measurement uncertainty is a function of the RF signal to noise ratio, scanner repeatability and unmodeled nonsolid 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. First, the MTI measurements can be nulled by periodically rotating and translating the scan plane. Second, the MTI Figure 3measurements can be interpolated over the duration of the scan to estimate the relative solid body motion history. A postprocessor is used to perform a time varying derotation and translation of the phasefront that effectively nulls the drift. The second technique was used in the SWAS system as the scanner did not include a motorized Z axis.

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

7. RESULTS

See results illustrated in Figures 3 through 5.

8. CONCLUSIONS

The operation of an electrically large submillimeter wave near-field antenna measurements 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 development of an RF based motion tracking (MTI) system. The new phase reference and MTI systems are being applied to other electrically large near-field measurement systems operating at lower frequencies. The MTI system provides a simple and highly accurate alternative to autocollimator, tiltmeter, and other mechanial referencing methods. The need for the customer to provide a thermally stable test article mount is reduced. The MTI system is patent pending.

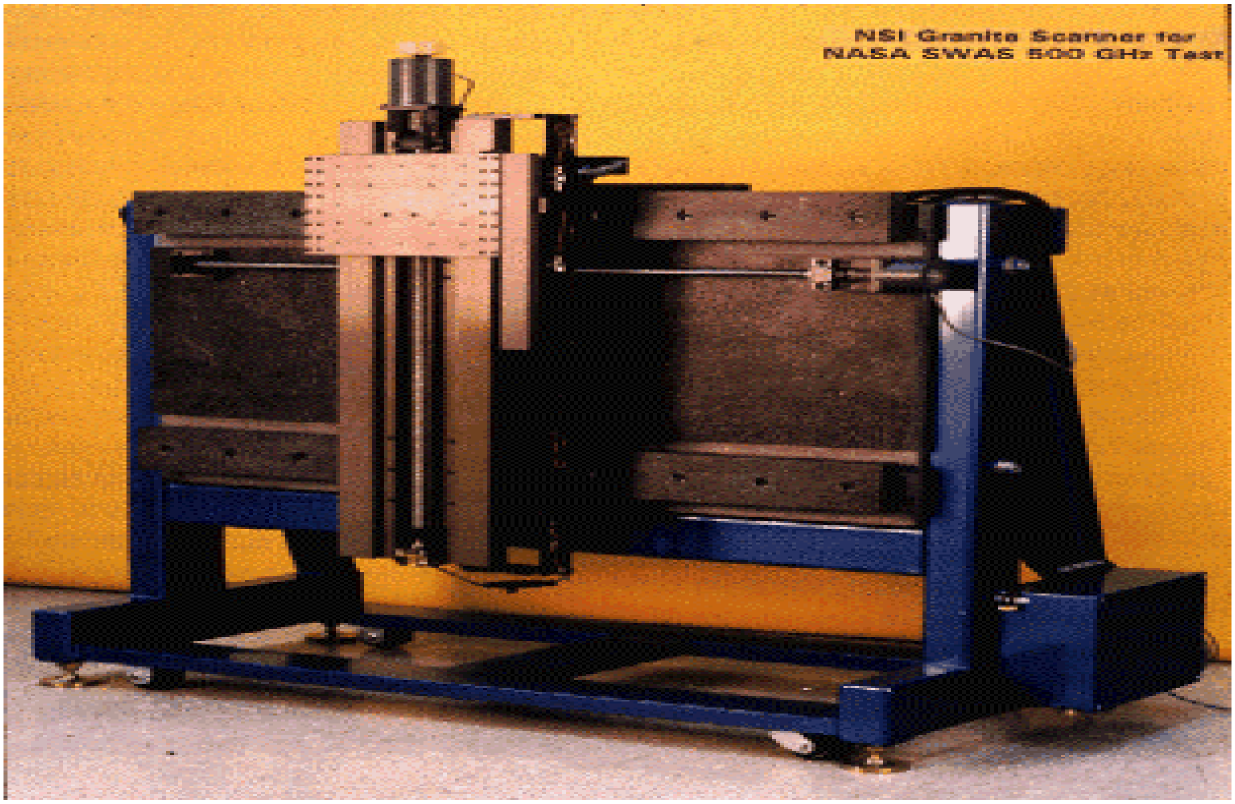

Figure 1 SWAS Scanner

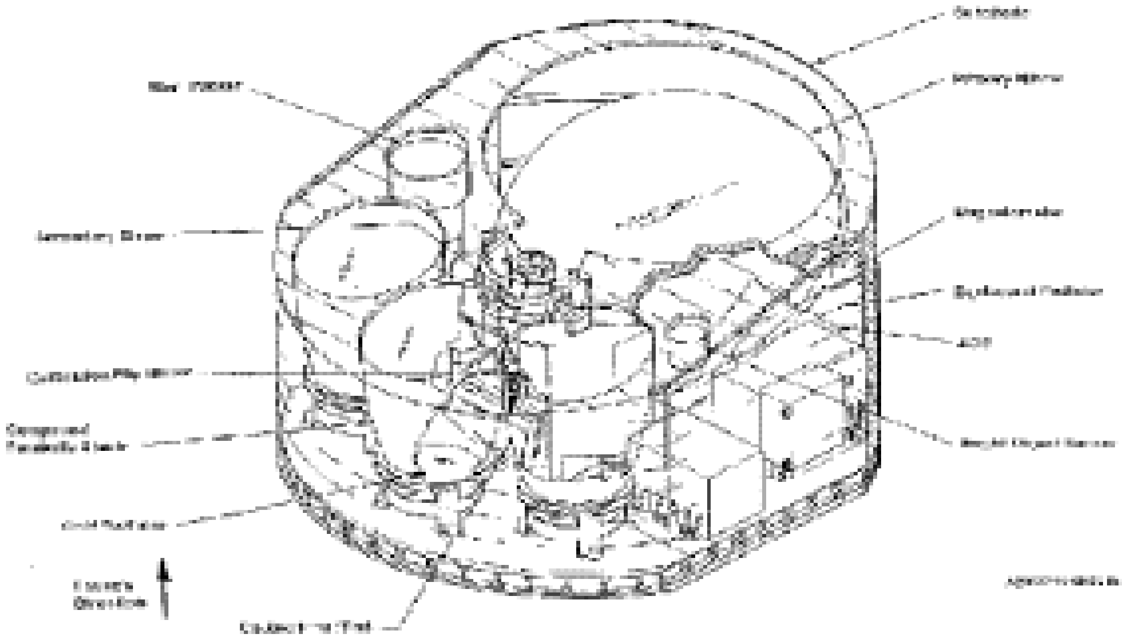

Figure 2 SWAS Satellite Payload Drawing

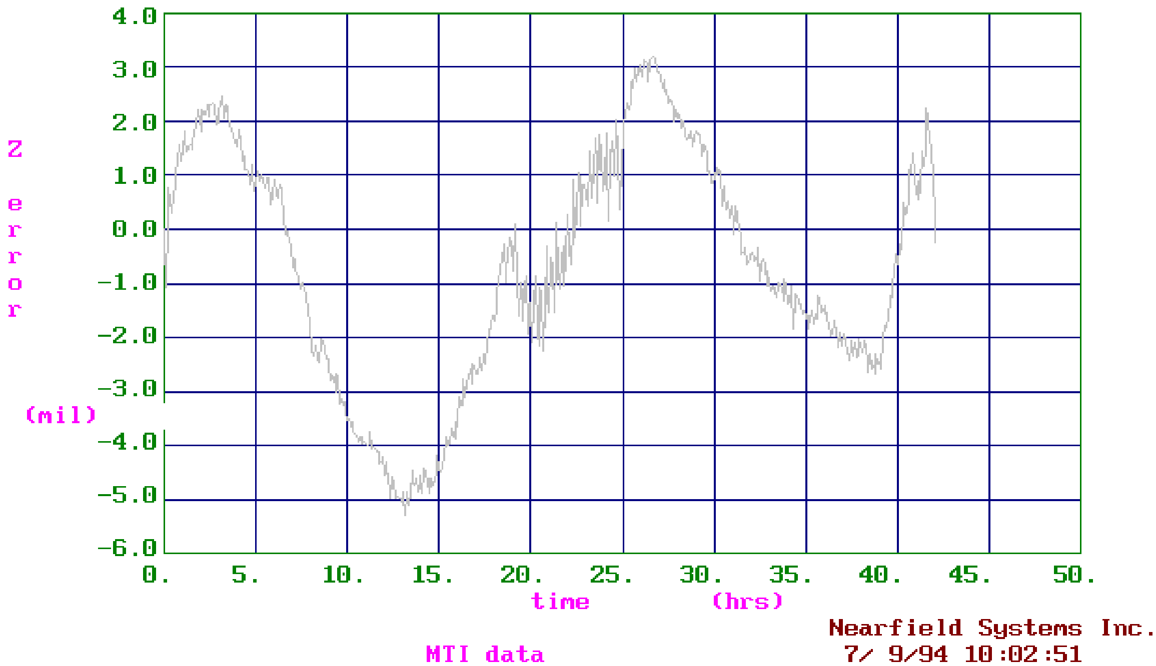

Figure 3 Z Drift as a Function of Time

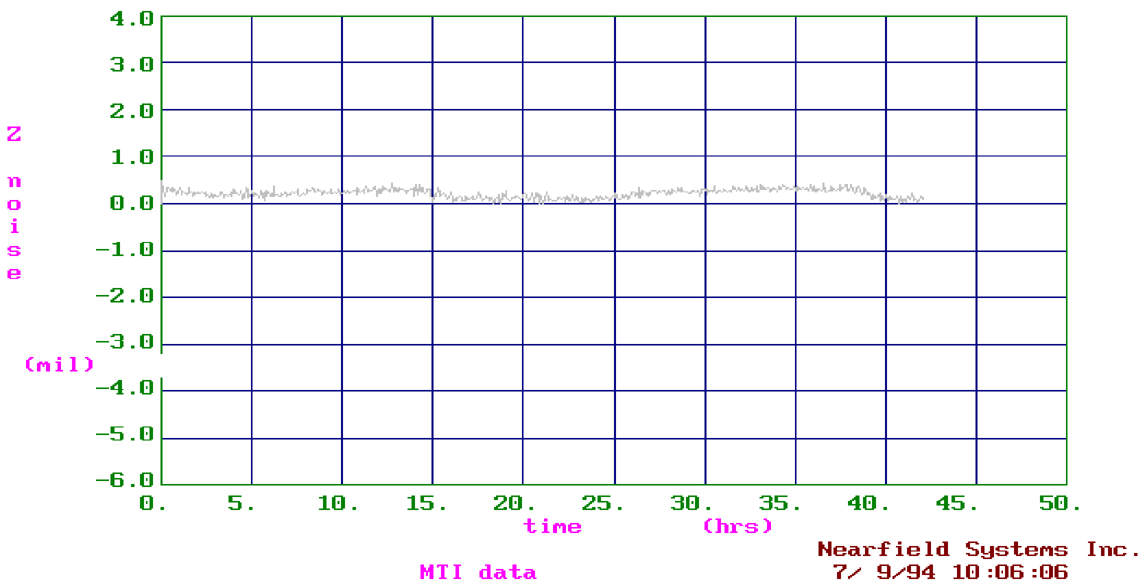

Figure 4 Measurement Uncertainty as a Function of Time

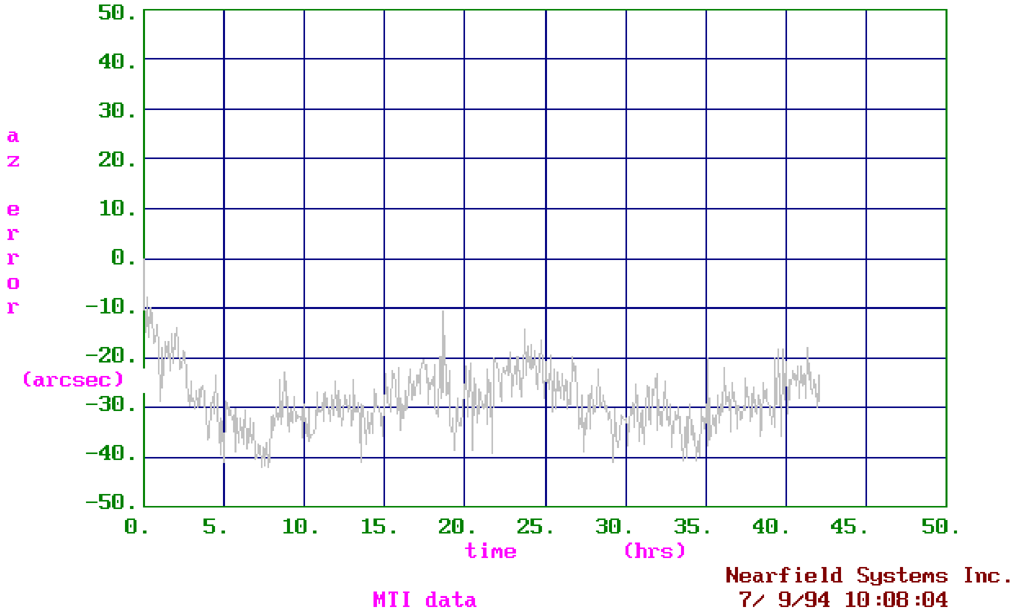

Figure 5 Azimuth Drift as a Function of Time