NEAR-FIELD TEST FACILITY DESIGN

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ABSTRACT

Lesson learned in the design of large, planar near-field ranges used at millimeter wavelengths are described. Specific issues include facility design, RF equipment, scanner design, dynamic position measurement, servo control and software requirements.

INTRODUCTION

In the development and flight qualifications of advanced, multibeam spacecraft antennas, it is necessary to determine the radiation pattern, gain, axial ratio, and other antenna parameters rapidly and to a high degree of accuracy. In the past these types measurements have been primarily with far-field ranges.

Far-field measurements have several disadvantages which have encouraged the development of antenna measurement techniques in the near-field. The advantages of near-field techniques include:

1. Complete characterizations of the antenna.
2. Minimal real estate requirements.
3. Convenient test site locations.
4. Minimal multipath problems.
5. Improved security.
6. Elimination of weather effects.
7. Stationary antenna (planar near-field configuration)
8. Improved weightless spacecraft antenna simulation.
9. Faster measurements.
10. Simple modification to support shape measurements.

Near-field ranges operate by measuring the electromagnetic field near the antenna and then mathematically transforming the data to any arbitrary location. Near-field operations are a form of microwave holography. The wave front measurements are normally made on a planar, spherical or cylindrical surface. This paper discusses primarily the planar configurations as used in the measurement of large, millimeter wave spacecraft antennas.

TRW has had a large (20’ x 20’) near-field range in operation since 1982. This near-field range has been highly successful and is currently in very heavy use, resulting in the construction of three additional near-field ranges.

NEAR-FIELD THEORY

The foundation of near-field testing is based on Huygens principle which states that every point in an electromagnetic field or wave front can be considered to be the source of a secondary spherical wavelet which spreads out uniformly in all directions. The far-field angular response of an antenna can be determined by measuring the electromagnetic field distribution near the antenna and using Huygens principle to compute the far-field response. The far-field energy is computed by summing all of the near-field spherical wavelet contributions to the desired point in the far-field region.

If energy from an ideal antenna measured in a plane has a constant amplitude and phase, all of the energy will be going in direction normal to the plane. If the measurement plane or antenna is tilted, a linear phase slope will be introduced to the measured phase at a right angle to the axis of tilt. The linear phase slope is directly related to the amount the beam is steered off axis. The phase slope can be measured in units of spatial frequencies which are cycles of phase shift per unit distance. The relation between the phase slope (d) and the beam steering angle (phi) is:

sin (phi) = d/lambda
where: lambda = wavelength

The minimal spatial frequency (0 cycles/lambda) occurs when the beam is pointed normal to the scan plane. The maximum spatial frequency (1 cycle/lambda) occurs when the beam is parallel to the scan plane. Since the scan plane is two dimensional, the spatial frequency includes an X and Y component or alternately a magnitude and orientation. If the antenna were simultaneously steered to two different angles, energy at two different spatial frequencies would result which could be sorted by a Fourier transform. Real antennas send energy in many different directions implying the existence of many spatial frequencies. The near-field range measures the RF phase front and then uses a two dimensional Fourier transform to convert the phase front to a set of spatial frequency coefficients. The spatial frequency coefficients are then normalized by the previous equation to convert the data to the equivalent far-field angles. There is a one-to-one correspondence between energy at a given spatial frequency in the near-field and at a specific angle in the far-field.

The computed far-field angular response is invariant to the distance at which the planar phase front measurements were acquired. The spatial phase front measurements can be acquired at any distance, including the far-field, and be transformed to the angular far-field domain without any knowledge of the probe to antenna separation. This is a direct consequence of the transform relationship between the spatial phase front domain and the far-field angular domain.

NEAR-FIELD RANGE DESIGN

The near-field range is comprised of the following systems:

1. RF Signal Source - The RF source provides the excitation to the antenna under test.

2. Probe Antenna - The probe antenna samples the electromagnetic field distribution of the antenna under test.

3. Phase Coherent Receiver - The receiver measures the complex value of the phase front samples by the probe.

4. Probe Positioning System (Scanner) - The scanner is a robotic system which precisely positions the probe at the required point for the electromagnetic field measurement. The scanner is comprised of three subsystems: the mechanical gantry, the probe position measurement system and the servo controller.

5. Data Acquisitions Computer - The data acquisitions computer controls the real time data acquisition process. Major functions include scanner position control, receiver control, data acquisition, task sequencing, and fault monitoring.

6. Far-Field Transformation Computer - The transformation computer converts the near-field phase front measurements to the far-field.

7. Test Antenna Mount – The test antenna mount provides a means to support and align the antenna under test to the scanner geometry.

RF SIGNAL SOURCE

The source provides the excitation of the antenna aperture. Frequency synthesizers are generally the preferred source because of reduced cable length matching requirements. With unmatched cable lengths, a frequency change also results in a phase change.

The signal source must provide sufficient power to insure an adequate signal to noise ratio in the receiver. Higher power levels are required with larger, higher gain antennas due to the aperture mismatch loss between the probe and test antennas.

PROBE ANTENNA

The correct probe antenna selection can significantly improve the near-field data accuracy and through-put probes operate as spatial filters on the near-field phase front just as they work as angular filters in the far-field. A higher gain probe accepts energy over a small angle in the far-field filtering out off-axis energy. The same probe in the near-field “averages” the higher spatial frequencies corresponding to off-axis energy.

High gain probes are recommended when the far-field responses will be computed over small angles around five degrees or less. This is a very common case for spacecraft antenna measurements. High gain probes provide four significant advantages for near-field measurements.
First, the high gain probe decreases the aperture area mismatch ratio, resulting in an increased signal noise ratio. This is especially significant with large antenna apertures where the energy density becomes extremely low. Unlike far-field ranges, the loss increases with antenna size because a given amount of energy will have to cover a larger area.

The second advantage of a high gain probe is to spatially prefilter the measurements allowing a lower sampling density. With a low gain probe, sampling should be performed at less than ½ lambda spacing to satisfy the Nyquist criteria. With high gain probes a sampling density of .2 samples per wavelength or lower can be achieved. This results in an order of magnitude lower data requirement on each axis or 200 times fewer points for a 2 dimensional raster transform.

The third advantage of the high gain probe is to reduce the effects of off-axis multi-path energy by the spatial filtering technique. Increased mutual coupling between the probe and antenna is counteracted by the lower sampling density. The mutual coupling can be further reduced by placing an isolator in series with the probe. The isolator reduces reflections due to mismatch. Mutual coupling and multi-path can be completely eliminated by the use of radar range gating techniques.

Fourth, the X and Y positioning requirements in the scan plane are less severe. This is because the high spatial frequency components with rapidly changing phase as a function of scan position have been eliminated. The positioning requirement is based on maximum allowable phase error. The axial or Z positioning requirements are unaffected.

Typically high gain probes have gains from 15dB to 25dB. The probe is normally a scalar horn, providing good sidelobe suppression. The use of an orthomode transducer will allow the simultaneous measurement of both polarizations.

Low gain probes (gain = 6dB) are required if the far-field pattern needs to be computed over a large angle. The low gain probes do not significantly spatially filter the data. Typical probes are open ended waveguide sections.

For high quality measurement of deep sidelobes, a probe with an axial null is preferred. This type of probe operates as either a high pass or band spatial frequency rejecting the main beam. The result is a reduced receiver linearity requirement since the overpowering main beam contribution is not present. The physical probe design is similar to a monopulse (auto track) feed horn design.

The spatial frequency filtering of the RF probes modify the far-field pattern. Probe gain correction can be applied prior to or after transformation to the far-field to eliminate gain errors.

SCAN PATTERN DESIGN

The scan pattern design can significantly affect the data quality and data acquisition time. Most facilities use a ½ lambda XY raster scan which provides relatively poor through-put.

The selected scan pattern should meet three requirements. First, the pattern should be designed to sample all significant near-field energy. This is accomplished by slightly over scanning the aperture. Excessive over scanning will result in poor data quality since most of the over scanned measurements are noisy. The correct scan width can be determined by the geometry or by measuring the amplitude drop off at the scan edge. Normally, measured near-field data is truncated at about -20dB relative to the peak value.

Second, the scan pattern should not result in any data aliasing. The scan density is established by the Nyquist sampling theorem which states that the phase of any spatial frequency component must shift by less than 180 degrees between samples. Violating this constraint will result in some energy being transformed to an incorrect angle in the far-field. This is guaranteed by sampling at less than ½ lambda or more desirably by spatial prefiltering.

Third, the scan pattern should not over sample. Over sampling results in a long measurement and data reduction time. A substantial gain in through-put can be obtained by an optimal selection of the scan pattern. By using a high gain probe as a spatial antialiasing prefilter, a two order of magnitude reduction in data collection and processing requirements can be obtained for XY raster scan patterns for some antennas.

For radially symmetric antennas a further sampling reduction can be obtained by using a starburst scan pattern. If the spatial frequencies for a radially symmetric antenna in a cartesian reference frame are converted to a polar reference frame, the higher order circular Fourier coefficients very rapidly approach zero. This implies that only very low circular spatial frequency components are significant. A high efficiency can be obtained by acquiring the data in a polar coordinate system as a set of rays emanating from a common center. The sampling density along a ray is determined by the probe antenna spatial filter cutoff frequency and usually varies between .5 and 10 lambda. The number of rays is determined by the far-field radiation symmetry of the antenna under test. Typical values are 16 to 32 rays corresponding to a Fourier truncation of 8 or 16 circular harmonics.

By using these techniques with typical high gain microwave spacecraft antennas, a complete pattern can be acquired and processed in 15 to 60 minutes. The short scan time results in reduced receiver and thermal drifts. Further drift reduction is accomplished by remeasuring the starburst central point at the end of every other ray. The drift measurements are linearly interpolated and used to normalize the raw near-field data.

RECEIVER REQUIREMENTS

The correct selection of a receiver can greatly enhance the accuracy and through-put of the test facility. Receiver considerations for near-field data acquisitions include:

1. Phase Coherent Measurements: For most near-field configurations, the receiver must provide the phase of the received signal in addition to the amplitude. Typical accuracy requirements vary between 0.1 to 5 degrees. The receiver output should ideally be in complex (IQ) form rather than the more common amplitude/phase form. Some receiver phase converters introduce glitches near the 180 degree phase crossover point. The IQ output electronics are generally simpler and more convenient for computer interface.

2. Remote Phase Reference: The receiver phase reference signal is provided by the transmitter and sent to the receiver front end mounted near the probe. The receiver and transmitter are in relative motion resulting in motion of the phase reference cable. Most flexible phase reference cables will not pass millimeter wave frequencies requiring additional receiver complexity. Any phase error due to cable flexing will result in degradation of the near-field data. Cable phase error is equivalent to Z plane errors.

3. Good Linearity: Receiver linearity requirements are established by the required quality of the sidelobe measurements. Poor linearity is equivalent to a non-linear transfer function and results in the generation of spatial frequency intermodulation (IM) products. The spurious spatial frequencies due to the IM products results in spurious and incorrect sidelobe levels.

4. Two Channel Operations: Higher through-put is obtained by acquiring both polarizations simultaneously with an orthomode transducer (OMT).

5. High Speed Operation: The receiver should be capable of high speed operation to minimize data smearing during continuous path motion. A fast receiver also allows multiple frequency data acquisition. As an example, a millimeter wave receiver with a 100 microsecond integration time will smear data over 0.001 inch at a scan velocity of 10 inches per second.

6. High Sensitivity: Large antennas with low power density and short integration times demand good low noise performance.

7. Range Gating: Reflections in the near-field region can be minimized by a variety of techniques including absorber, probe selection and range gating. Range gating can be implemented by pulse or swept frequency techniques.

Most near-field ranges use commercially available test range receivers or network analyzers. These units are expensive and because they were designed for other applications, do not provide first rate performance in near-field test applications. Particular problems include slow measurement speeds and poor real time computer compatibility. For example, a typical receiver has a measurement uncertainty time of 10 milliseconds or more. The measurement position needs to be known to an accuracy of 0.001 inch limiting the maximum scan speed to slow 0.1 inch per second.

A simple, high performance millimeter wave receiver can be constructed using largely off-the-shelf hardware. This approach is being used for TRW's three new near-field ranges.

MECHANICAL SCANNER

The planar scanner is required to accurately position the probe antenna in three dimensions. The existing TRW near-field scanner which covers a 20 foot by 20 foot region with an accuracy of 0.001 inch was designed and built by TRW.

The existing near-field scanner operates in a vertical plane. The probe is attached to a Z axis positioner with a one foot travel range. The Z axis is attached to the vertical axis which stands on the horizontal X axis. The Y axis rails are attached to a secondary structure to eliminate any stress coupling in the Y axis support tower. The gantry structure is based on kinematic design principles to insure long term stability.

Recently, several vendors have developed the capability to produce high accuracy scanners. One vendor, LK Tool of Tempe, Arizona, has experience in constructing large granite based, coordinate measuring machines. This company has been selected to provide three additional near-field scanners to TRW. The scanners are very similar to the vendor's existing coordinate measurement system hardware. The primary modifications are the addition of a higher performance control system, a different control program and special cabling provisions. Because of the similarity, the near-field ranges also fully support general coordinate measurement applications. The three new near-field scanners are being built to scan horizontally. The horizontal orientation of the antenna under test eliminates certain gravity induced distortions.

High accuracy measurements require careful thermal and seismic control. The scanner operates in a thermally and humidity stabilized (two degrees F.) and de-stratified environment. The scanner is attached to a vibration isolated four foot thick concrete foundation supported by piles driven 40 feet into the ground. The data acquisition system incorporated seismic monitoring capabilities.

PROBE POSITION MEASUREMENT SYSTEM

The accurate measurement of the probe position in three degrees of freedom is of critical importance in high quality near-field measurements. At millimeter wave frequencies, the probe position needs to be known to an absolute accuracy of 0.001 inches. The existing TRW near-field system uses a Hewlett-Packard 5501 laser interferometer system to determine the probe position. The three new systems under construction will use low maintenance optical scales.

SERVO CONTROL SYSTEM

The servo system controls the positioning of the probe. For stop or single axis motion as used in raster scanning, the control system can be quite simple.

The heart of most near-field servo systems is a rate servo. The rate servo operates by comparing the output of a tachometer attached to the motor shaft to a commanded velocity signal. The difference is a velocity error signal which is used to correct the speed of the motor.

A basic servo control system for stop motion scans operates by subtracting the measured position from the commanded position. The difference is a position error signal which is used to command the velocity of that axis. When the position error signal and velocity both get to zero, the axis is at the commanded position.

Single axis continuous path systems operate by commanding the axis to move at a constant rate. When the servo crosses over a desired measurement point, the receiver is triggered. Any timing jitter or latency in the receiver or position trigger can lead to errors in the measurement point. For example, if an axis is moving at 10 inches per second, a 0.001 inch error will occur for each millisecond of timing error. High performance millimeter wave near-field systems require control of timing errors to less than 100 microseconds.

Coordinated multi axis motion control with timing latency management as required by starburst scans is more difficult. In the millimeter wave near-field facilities developed at TRW, a largely software-based control system is used. The system operates as follows: The output of a starburst scan generator is transformed in 6 degrees of freedom into the antenna coordinate reference frame. The coordinate transformation allows simple, high accuracy alignment with the article under test. The coordinate transformed scans are then processed by a non-linear motion filter which applies position, velocity, and acceleration limits in an optimal (minimum position and timing error) manner. The filter also applies a timing correction to compensate for control system desampling delay and other related timing errors. The scan generator and filter operate at a 15Hz sampling rate. The filter output is desampled (interpolated) and used to drive a conventional digital servo loop using both feedback and feed forward compensation. Residual timing and other errors are estimated by a Kalman filter. The Kalman filter output is fed back to the non-linear motion filter to drive the timing latency to zero. The current TRW near-field can maintain a 200 microsecond RMS timing error at 2.5 ips.

The performance of servo systems is often limited by the mechanical design of the motor to load to position sensor coupling. Virtually the only techniques capable of providing extremely high dynamic multi-axis positioning accuracy are direct and friction drive technologies. In the TRW near-field ranges, the motor to load coupling is accomplished by friction drives. The friction drive power transmissions provide high bandwidth control with zero cogging and backlash. Friction drives are mechanically simple and low cost. The drives on the near-field are configured as motor driven steel pinch rollers pulling on a steel bar. The position sensors are attached directly to the load.

DATA ACQUISITION SYSTEM

The data acquisition computer consists of a PDP 11/73 computer with two RX02 floppy disks and four RL02 compatible Winchester disks, two color graphics terminals, a printer and a plotter.

The data acquisition software controls the robotic scanner and records the resulting phase front measurements. The software is written in a heavily modified version of polyFORTH. The FORTH language provides the virtually unmatched real time multitasking capabilities required for the software based real time control system.

The data acquisition program operates in a multitasking environment with critical timing requirements. The servo positions are time tagged by a quartz clock triggered interrupt processor. Measurement latency is estimated on a real time basis by a Kalman filter. The primary control task computes a trajectory synchronized to a 15Hz clock. The same task triggers the receiver and preprocesses position measurements. A second task operates at a variable rate up to 15Hz performing receiver measurement processing, measurement queuing and Kalman updating. A third task dequeues the measurements to local disk storage or transmits the measurements to the transformation computer in real time. Two additional tasks are used to support the system integrity monitor and two real time color graphics displays for communication with the operator.

Because of the real time nature of the control program, measurements can be plotted as they are being acquired. This capability allows the operator to align the antenna by viewing an antenna phase cut in real time while simultaneously changing the scan plane orientation.

Operator communications are handled by a tree structured menu system. The menu system establishes a top down structural design of the users problems. The software supports both English and metric units. As an alternative the data acquisition program can be operated by voice control. This is particularly useful for hands free operation during antenna alignment operations such as sighting through a theodolite.

The data acquisition program uses AI expert system techniques to monitor the health of the data acquisitions hardware and software and to provide recommended fault recovery procedures. During unattended operation, some automated recoveries can be performed. The user can enter a description of the antenna under test and the software will use a set of rules to provide recommendations and warnings relating to the test setup and execution.

TRANSFORMATION COMPUTER

The near- to far-field transformation is performed on a separate computer. The current TRW near-field test facility uses a DEC VAX 11/780 which can transform a starburst scan in a few minutes. The three new near-field ranges will use the MicroVAX II.

TEST ANTENNA MOUNT

The current near-field ranges uses a Scientific Atlanta positioner to coarse and hold the antenna under test. No adjustable mounts are planned for the three horizontal near-field ranges. Instead, the antenna will be aligned by a simpler and more precise method of transforming the scan plane into the antenna reference frame.

VALIDATION

Validation of the near-field test facility can be difficult. The patterns produced by a near-field range are often of higher quality and therefore different than patterns measured in a far-field range. The near-field range is normally verified by a combination of techniques.

The mechanical accuracy of the scan plane is normally verified using optical tooling or laser interferometer techniques. Tiltmeters and levels are also useful. Correct operations of the RF system is verified by swept frequency tests. Fourier transforming the swept frequency RF data results in a radar capability which can be used to track down multi-path reflections. Additional RF tests with the probe terminated are performed to check for RF leakage. Drift checks are performed to verify the RF link stability.

ANCILLARY APPLICATIONS

The near-field scanner is really a precise robot which can be used to position items other than RF probes. As an example a laser ranging probe can be installed allowing the direct measurement of the surface shape of a parabolic antenna or any other object. Antenna surface shape measurements can also be determined by 3D ISAR techniques using the RF measurements. A cutter can be installed to modify the shape of an out of tolerance antenna.

CONCLUSIONS

The basic principles behind near-field testing have often been clouded in mystery. This paper has attempted to show that the physical principles can be straight forward. Using a spatial frequency model, optimal probe and sampling considerations have been explained. The design and implementation of a high performance millimeter wave near-field test facility has been described.

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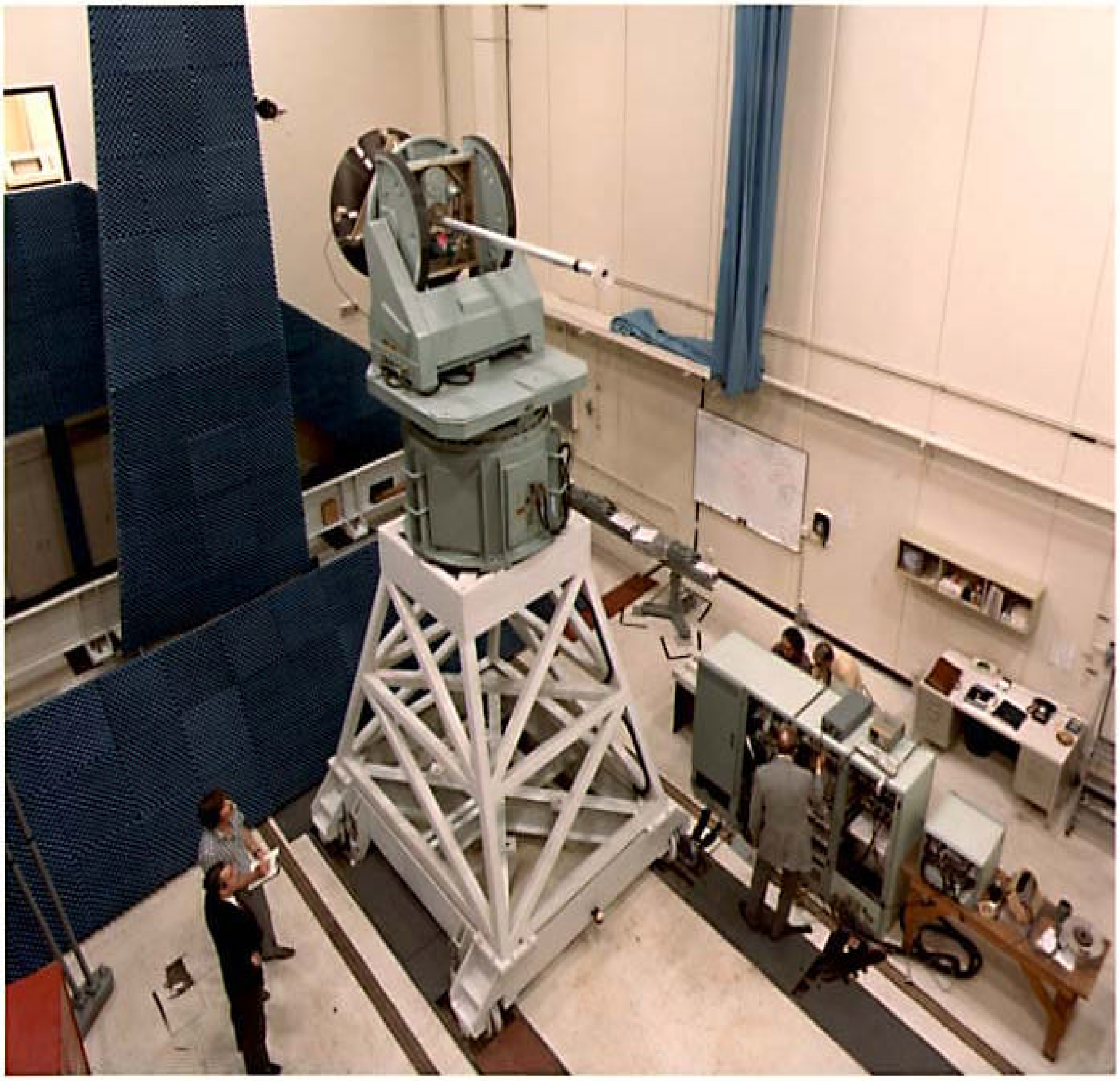

TRW 20' x 20' PLANAR NEAR-FIELD SCANNER