The Design of an Automated, High-Accuracy Antenna Test Facility

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Abstract—**This paper presents the step-by-step application of proven far-field range and instrumentation design techniques to a specific antenna measurement problem, describes the resulting facility design, and presents the predicted measurement uncertainty. Fundamental electromagnetic design criteria for an outdoor, far-field facility establish minimum dimensional requirements for the range design and limiting values of source-antenna directivity. Electromagnetic compatibility of the facility is assured by frequency coordination with existing and planned services in the area surrounding the available site. Additional design constraints for this facility included restricted measurement time, reduction of spurious test enclosure effects, limited available terrain, and required data quality. In this case, the required range length is in excess of 6500 ft, and paraboloidal source antenna diameters up to 23 ft are required. The frequency coordination problem was solved by exploiting the natural terrain features and configuring the measurement system as "test-on-transmit." Signal and reference paths share the same range cable. The quantity of data that must be handled in the available measurement interval required the use of a computer-based measurement system.**

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INTRODUCTION

THE IN-ORBIT FAR-ZONE operating characteristics of communications satellite antennas must be carefully tailored to provide the best spatial coverage in order to facilitate the full usage of the satellite's capacity. Ideally, the measurement system used to determine satellite antenna performance would be an antenna range that is constrained to operate within the bounds of the same electromagnetic environment as the operational satellite, thus the ideal antenna range would have a reflection-free plane wave of constant amplitude over the test zone. The quality of the information gathered on an antenna range is determined by how closely this ideal electromagnetic environment is simulated. Range instrumentation measurement speed determines the quantity of data collected. Range instrumentation quality should preserve the integrity of the range, not degrade it.

The free-space antenna range models the ideal electromagnetic environment over the test zone by using a source antenna with appropriate directivity and by having adequate source-test antenna separation, and by suppressing the effects of all surrounding surfaces and extraneous sources of energy. The degree to which this can be done is discussed here in terms of 1) amplitude taper over the test zone, 2) phase variation over the test zone, 3) spatial variations over the test zone produced by reflections, 4) interference from spurious sources, and 5) inductive and radiation coupling [1]. Range instrumentation and measurement system configuration are discussed here in terms of 1) source antenna directivity and sidelobe suppression, 2) range profile, 3) antenna under test protective enclosure, and 4) phase and amplitude measurement bridges.

DESIGN FACTORS

The basic geometry chosen for the range and the choice of source antenna size are the principal design factors that will determine the uniformity in amplitude and phase of the illuminating wavefront over the test zone. The measured pattern of the antenna under test is distorted when compared to the infinite range length pattern if there is amplitude taper in the illuminating field. The effect on the measured pattern level caused by this amplitude taper is determined by the amount of this taper and by the characteristics of the antenna under test (AUT). For example, the approximate decrease in measured peak pattern level of paraboloidal reflector antennas due to a 0.25-dB taper is 0.1 dB for typical illumination functions. The amplitude taper over the transverse projection of the AUT test zone was specified to be 0.25-dB worst case for this facility. This criterion along with range length will set an upper bound on the size of the source antenna [2].

In the far field of a paraboloidal transmitting antenna, the phase front of the approaching wave deviates very little from a section of a sphere centered on the transmitting antenna over a major portion of the main lobe. At an angle from boresight corresponding to the 0.25-dB beam width, the phase deviation from spherical is much less than 1 ° for range lengths of $2d^2/\lambda$ or greater, where d is the source antenna diameter. For the range length and source antenna diameters specified on this test range, the illuminating phase front can be considered to be spherical with negligible error. However, the source antenna produces a spherical phase front over the test aperture rather than the ideal planar wavefront because the range length is finite. This difference between the spherical and planar wavefronts is the phase variation that must be considered in terms of range quality [3], [4]. The far-field criterion chosen for this test range is that the range length be greater than $10D^2/\lambda$ where D is the AUT diameter. A review of antenna patterns that were calculated for the infinite and $10D^2/\lambda$ cases for antennas that are to be tested on this range, showed no difference between the patterns over the bulk of the main beam and peak areas of the sidelobes.

There are spatial variations over the test zone on practical earth-based antenna ranges caused by extraneous reflection and diffraction of the signal transmitted by the source. The field at a point in the test zone is the phasor sum of the desired and extraneous fields. This may be viewed as if there were many propagation paths between the source and the test zone. The primary propagation path is the desired direct path, while the secondary paths involve reflection and diffraction from other surfaces or transmission through media different from the primary path. These variations are often referred to as multipath effects. This test problem required measurement of -30-dB sidelobe levels to an accuracy of ±1.1 dB. This means that the total extraneous signal level must be 18 dB below the direct path signal. Note that if the extraneous signal is incident along the main beam axis of the test pattern, then the extraneous signal must be 48 dB below the direct path signal.

TABLE I
RANGE LENGTHS, TEST ZONE DIAMETERS, AND MAXIMUM SOURCE ANTENNA SIZES

MAXIMUM FREQUENCY FOR EACH ANTENNA (GHZ)	TEST ANTENNA DIAMETER (FT)	MINIMUM ALLOWABLE RANGE LENGTH (FT)	TEST ZONE DIAMETER (FT)	MAXIMUM SOURCE ANTENNA DIAMETER (FT)
4.1	12.5	6508	13.7	50.9
6.3	8.0	4252	11.1	40.9
11.7	3.3	1294	8.1	30.2
14.5	3.3	1604	7.3	27.0

The test frequency bands, especially the 4- and 6-GHz common carrier bands, are well used. Energy from spurious sources must not affect the information collected on this range. Likewise, this facility cannot interfere with the operation of the various telecommunications systems that are located in the same general area. Range location and instrumentation signal processing techniques are the tools available to the range designer to insure sufficient suppression of spurious signals.

Inductive coupling effects are often considered to be negligible when the range length is greater than or equal to 10X because this means that the induction field level is at least 36 dB below the radiation field level. At range lengths of several thousands of wavelengths, which is the case here, the inductive field coupling effects are negligible.

Mutual (radiation) coupling caused by scattering and reradiation of energy by the test and source antennas must be considered. If the mutual coupling loss for this test range is 60 dB or greater, then mutual coupling effects will be negligible.

RANGE PARAMETERS

The minimum allowable range length which will satisfy the $10D^2/\lambda$ criterion, is listed in Table I for each value of actual test antenna diameters and the corresponding maximum frequency (minimum wavelength). The test range length chosen is 7850 ft, which is greater than any of the minimum range length values. Since the range length is greater than the minimum, then the test zone diameters are greater than the required test diameter which satisfy the $10D^2/\lambda$ criterion. The calculated test zone diameter is listed in Table I.

Application of the 0.25-dB amplitude taper criterion to the calculated test zone dimensions yields a set of maximum allowable paraboloidal source antenna diameters. Since the 0.25-dB beamwidth, d/λ_4, of a paraboloidal antenna of diameter d is very nearly

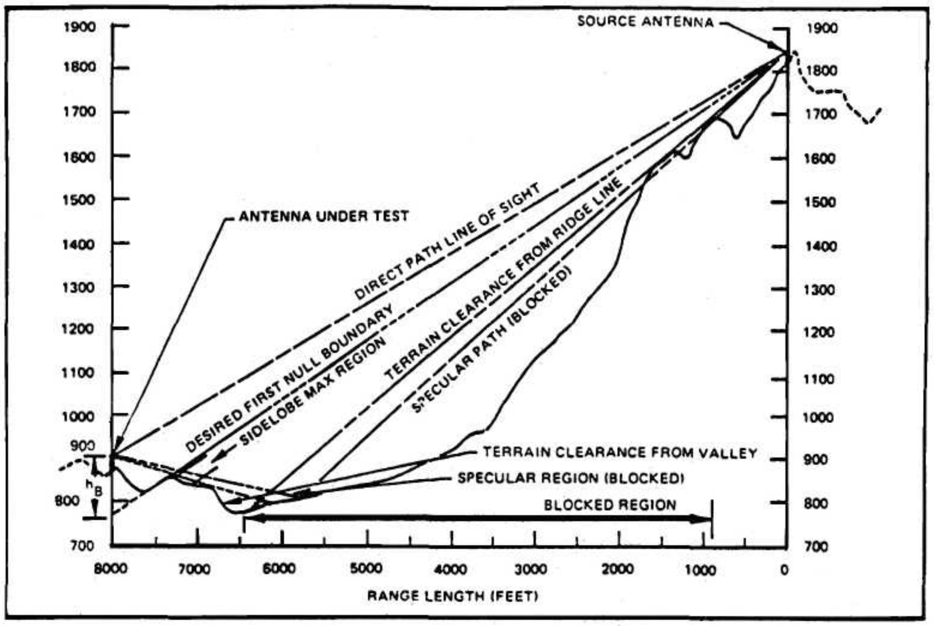

Fig. 1. Test facility—range profile.

TABLE II
MINIMUM SOURCE ANTENNA SIZES, SELECTED SOURCE ANTENNA SIZES, AND TEST ZONE DIAMETERS

MINIMUM FREQUENCY FOR EACH ANTENNA (GHZ)	MINIMUM SOURCE ANTENNA DIAMETER (FT)	SELECTED SOURCE ANTENNA DIAMETER (FT)	TEST ZONE DIAMETER (FT)	RATIO OF ¼ DB TEST ZONE TO TEST ANTENNA DIAMETER
3.7	22.4	23.0	30.3	2.4
5.9	14.0	16.4	27.7	3.5
10.9	7.6	10.0	24.4	7.4
14.0	5.9	6.0	32.9	10.0

$$\theta_{1/4} = 0.37\lambda/d \text{ rad}$$

while the angle θ_Z, subtended at a 7850-ft range length by a test zone dimension D_z, is

$$\theta_z = D_z/7850 \text{ rad}$$

the criterion is equivalent to the relation

$$0.37\lambda/d \geq D_z/7850 \text{ or}$$

$$d \leq 2905(\lambda/D_z)$$

where λ, d, and D_z are expressed in feet. The resulting values for the maximum allowable source antenna diameters are also shown in Table I.

The minimum limit on source antenna diameter is dependent on the geometry of the range since the combination of source antenna directivity and range profile determine the level of ground illumination. Ground illumination and the subsequent diffraction and specular reflection of the transmitted signal is of major concern in the design of a free-space antenna test facility. After studying several different transmit and receive sites for this facility, two were selected. The range profile for the selected sites is shown in Fig. 1. There is no ground illumination on the range between 900 and 6500 ft because of natural terrain blockage. This screened region includes the theoretical specular reflection area centered at a range distance of 5900 ft. Potential reflections from the range surface area between 7000 and 7500 ft are effectively suppressed by ensuring that only sidelobe energy from the source antenna be allowed to illuminate this area. This requirement defines a first null boundary for the source antenna pattern.

Projecting the desired first null boundary line through to the test site defines an equivalent null boundary height h_B. The angle θ_B, subtended at the source antenna by h_B, is very nearly

$$\theta_B = h_B/7850 \text{ rad}$$

for this selected range. The angle θ_N from main-beam axis to first null for typical paraboloidal source antennas of diameter d is about

$$\theta_N = 1.5\lambda/d \text{ rad.}$$

Now the restriction of interest is equivalent to

$$\theta_N \leq \theta_B$$

or

$$1.5\lambda/d \leq h_B/7850$$

which may be written as

$$d \geq 11775(\lambda/h_B).$$

For the profile of Fig. 1, h_B *is* approximately 140 ft.

The resulting values for minimum allowable source antenna diameters, as calculated for the minimum test frequencies are shown in Table II. The selected source diameters are also shown in Table II. Since the selected values are intermediate between the allowable maximum and minimum limits, the resulting test zone diameters which will fall within the 0.25-dB amplitude taper criteria are correspondingly increased beyond those defined in Table I. The design test zone diameters become those shown in Table II, as calculated at the maximum frequency in each band. The ratios of these 0.25-dB test zone sizes to the test antenna sizes are also listed. The smallest ratio is 2.4:1.

The region of the range surface which will be illuminated through the first sidelobe maximum of the source antenna pattern lies within 500 to 1000 ft of the test site over the full test frequency band; see Fig. 1. The range topography is such that the specular efficiency is no greater than 5 percent over this area. The nominal first sidelobe peak levels for the source antenna patterns will be at least 18 dB below the main-lobe peaks. Thus the nominal level of the range surface reflections will be at least 40 dB below the direct-path signal.

In terms of potentially significant off-axis reflection areas along the range, the shallow ridge at 1400 ft lies at a nominal source pattern level which will vary from approximately -24 dB at 14 GHz to -26 dB at 3.7 GHz relative to the source pattern maximum. This region will have the greatest specular efficiency of the off-axis regions. The nominal value of this reflection efficiency is expected to be about 5 percent due to area truncation and reflection coefficient. Thus the off-axis reflection levels will be no greater than —50 dB relative to the direct-path signal level.

The specified mutual coupling loss for this test range is >60 dB. The level of the signal arriving at the test antenna due to retransmission from the source antenna can be estimated by using [5]

$$10 \log (P'_r/P_r) = -24.7 + 40 \log (\alpha/\theta) \text{ dB}$$

where

P'_r reradiated power

P_r radiated power

α plane angle subtended at the source antenna by the test antenna

θ 3-dB beamwidth of the source antenna.

Scattering and efficiency values for typical parabolic antennas were assumed in order to develop this relationship. Using the source antenna diameters listed in Table II with the selected range length, the mutual coupling loss is calculated to be -60 dB at 4.16 GHz, -66 dB at 6.3 GHz, -78 dB at 11.7 GHz, and -83 dB at 14.5 GHz. Thus coupling effects are negligible on this antenna range.

Considering these contributions, the overall extraneous signal level for this range, exclusive of the range termination, will have a maximum value of -37 dB relative to the direct-path signal level which is almost 20 dB better than the required value.

MEASUREMENT SYSTEM

The measurement system is configured as phase and amplitude bridges. The test and reference arms have been arranged to be nearly the same length. The test and reference signals are propagated through the same space and travel through the same range cable; see Fig. 2. Consequently, changes in range temperature, index of refraction, and cable length cancel out and the measurement system records changes in phase and amplitude that are a function of the position, frequency, etc., of the antenna under test.

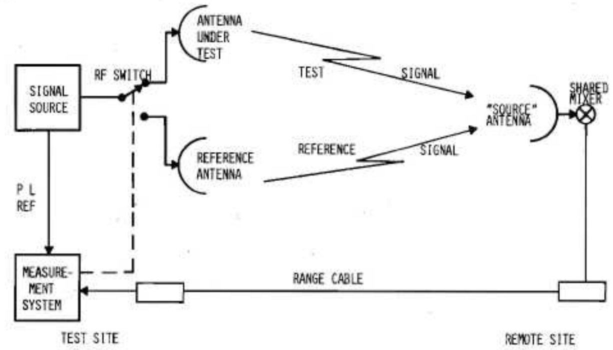

Fig. 2. Functional block diagram of test-on-transmit system.

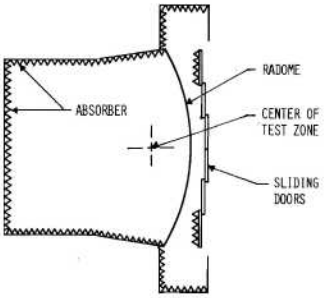

Fig. 3. Simplified floor plan of rigid test cubicle.

The antenna measurement system is a Scientific-Atlanta antenna analyzer, comprised of signal sources, display units, phase/amplitude receiver, and a Hewlett-Packard 1000 minicomputer and associated terminal equipment. This measurement system converts RF signals to 5-kHz signals by means of dual-stage, phase-locked superheterodyne instrumentation, where a one-to-one correspondence between the test and reference signals and the corresponding 5-kHz signals is maintained. The magnitude and phase of the 5-kHz signals are then measured with low-noise fixed-frequency circuits for a wide range of input signal levels before being processed, stored, and presented by the data system. The receiver linearity error for a 30-dB dynamic range is ±0.25 dB.

This measurement system and range have been discussed here in terms of the "standard antenna range" configuration where the AUT is the receiving antenna. Ordinarily, this configuration is easier to implement and operate. After the signal source is turned on and the transmitting or source antenna is aligned, all the measurement activity takes place at the receiving site where the instrumentation, AUT, and positioning system are located. The direction of propagation on an antenna range has no bearing on the data collected for reciprocal antennas. The antennas to be tested on this range are reciprocal and the direction of propagation is from the valley site up to the remote hilltop site. Transmitting signals from the valley will not interfere with other communications systems. Access to the remote hilltop site is difficult.

The range control and ease of operation features have been retained in this system by keeping the instrumentation at the AUT test site. The phase/amplitude receiver in this system

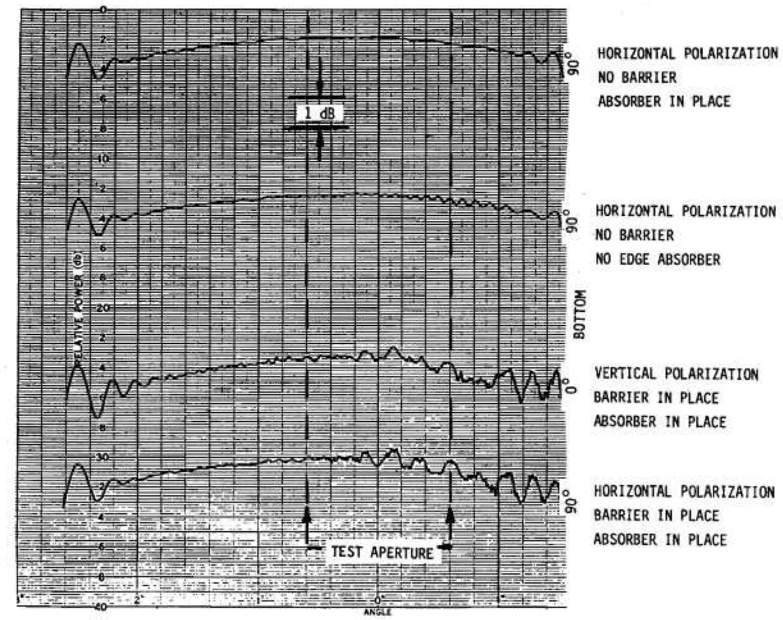

Fig. 4. Example of diffraction edge effects in a test enclosure.

is operated in the shared mixer mode. Test and reference signals use the same mixer. The Scientific-Atlanta receivers all use remote mixers to improve operating range and flexibility of operation. In this case the mixer has been remotely located 7850 ft away at the other end of the range. The test signal, reference signal, and range control signals in an IEEE-488 bus format are all carried on the broad-band range cable (the range cable is a CATV cable system with a T1 group of channels in addition to the test and reference channel signals of the instrumentation system). Since the signal source and measurement system are located at the same site, the system can easily be configured to measure individual outputs from a multibeam feed assembly or to perform component measurements.

TEST ENCLOSURE

A rigid test cubicle, Fig. 3, will be used to terminate this range. It has been designed by considering both logistic and measurement system factors [5]. The test terminal equipment will be housed in this building. The protective cover for the range aperture will be open for testing. A single-wall low-pressure radome curtain will complete the environmental enclosure during tests. Fig. 3 shows the floor plan of the test facility. Energy reflected and diffracted by the radome edge and range aperture door edge will be reduced by installing serrated absorber panels on these edges. The test antenna is to be placed as far forward in the cubicle as is practical. This is done to place the AUT in front of as many of the test cubicle related reflected signals as possible.

Fig. 4 presents some data from a test enclosure that shows the effects of edge diffraction and aperture blockage. The bottom two traces show an extraneous signal level of -25 dB, caused by a nylon-strap safety barrier covering the lower quarter of the test cubicle aperture. When the barrier was removed, the level dropped to -39 dB. The residual interference was caused by straight-edge diffraction at the bottom front edge of the cubicle. Placement of a pyramidal absorber along this edge produced the field recorded in the top trace of the figure, which has an extraneous signal level less than -45 dB. All cubicle reflections will be suppressed by at least 30 dB in this test facility.

SUMMARY

An antenna test facility that can be operated in the 4-, 6-, 11-, and 14-GHz common carrier bands and that meets the $10D^2/\lambda$ criteria to ensure adequate beam formation to model the infinite range length pattern over the main beam and peak areas of the sidelobes has been designed. Summation of range instrumentation systematic uncertainty with range surface and test enclosure random uncertainties produces a test facility uncertainty of ±0.6 dB when measuring -30-dB sidelobe levels.

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