Measurement Uncertainties in Outdoor Far-field Antenna Ranges

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***Abstract*— Consolidated methodologies have long been established to assess measurement uncertainties in near-field antenna measurements. More recently, similar detailed approaches have been developed for compact ranges and adopted as standard practice. However, currently there is no analogous methodology for outdoor far field measurement facilities. This paper presents a framework for assessing the measurement uncertainties on an outdoor far-field elevated range. Various sources of uncertainty in an outdoor far-field range are identified, using the industry standard 18 term analysis for near-field range assessment as a baseline. An example analysis based on an actual outdoor far-field range is presented. The uncertainty terms are quantified by analysis, observation, or measurement, and finally combined by the root sum squared method to arrive at the gain uncertainty and the -30 dB sidelobe level uncertainty.**

I. INTRODUCTION

Since the advent of compact antenna test ranges, and somewhat more recently near-field antenna test ranges, the number of newly built indoor test facilities has far surpassed the number of outdoor test facilities constructed. Outdoor far-field testing requires suitable real estate, is subject to interference from external transmissions, and requires favorable weather conditions. However, the measurement of very large or very low frequency antennas sometimes precludes a suitable indoor configuration.

While the antenna measurement methodology for outdoor far-field direct illumination ranges is well established, and there are several references to estimates of specific uncertainty terms [1]-[3], there are no comprehensive recommended practices for the estimation of measurement uncertainty. This is in contrast to the existing recommended practices for near-field [4] and compact antenna range measurements [5].

In this paper, key uncertainty terms for an outdoor elevated far-field antenna range are identified and a procedural methodology for predicting and evaluating the measure of uncertainty is developed. The method for analyzing each term is described in detail in accordance with [6], commonly referred to as the Guide to the Expression of Uncertainty in Measurement (GUM). All uncertainty terms are then accumulated into a single value and example uncertainty budgets are presented for the antenna's peak gain and -30 dB sidelobe measurements.

II. RANGE DESCRIPTION AND COORDINATE SYSTEM

The range considered in this uncertainty analysis has a total range length of R = 1,086 m spanning a valley containing woodland, asphalt roads, and several buildings. The range operates in the antenna under test (AUT) receive configuration. Referencing Figure 1., the height of the transmit source and AUT are h_t = 143 m and h_r = 71 m above the lowest point in the valley floor, respectively. A reference antenna, used to provide a phase reference for the measurement, is co-located just below the AUT. The valley slopes up toward the source and AUT location gradually.

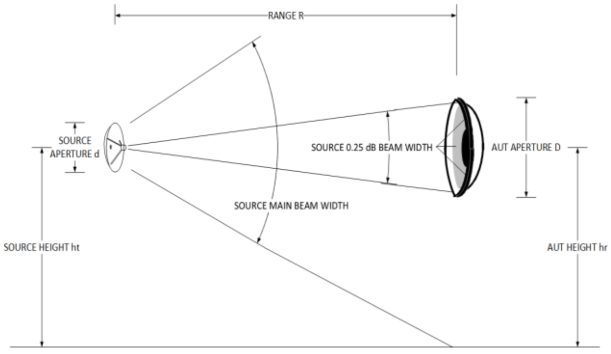

Figure 1. Range geometry.

The source antenna is a 0.935 m linearly polarized parabolic reflector antenna, the AUT is a 1.2 m circularly polarized parabolic reflector, and the frequency of operation for the analysis is 7.5 GHz.

The AUT positioner stack-up, shown in Figure 2, is configured as roll/slide/azimuth/elevation. It allows full polarization control of the AUT as well as translation along the z-axis. The conventional spherical coordinates are used to define the AUT coordinate system, also depicted in Figure 2. Here, the z-axis is defined as perpendicular to the AUT aperture plane, which may or may not coincide with the antenna electrical boresight.

The source antenna is mounted on a polarization positioner so that it can transmit two orthogonal polarizations for reconstruction of the circularly polarized response of the AUT. The source antenna and source polarization positioner are affixed to a squint mount and positioned such that the z-axes of the source and AUT can be made coincident.

The gain of the AUT is determined using the gain substitution method, where a gain standard antenna with a known gain value, in this case a calibrated standard gain horn, is used to determine the absolute gain of the AUT. The standard gain horn had previously been calibrated by the manufacturer in a compact antenna test range and had been issued a certificate of calibration.

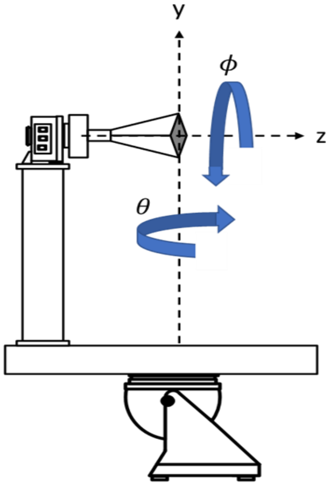

Figure 2. AUT positioner configuration and AUT coordinate system.

III. UNCERTAINTY ANALYSIS AND EXAMPLE

The following assessment leverages the industry standard 18 term analysis for near-field ranges [1], [8], as well as historical and modern literature relevant to far-field and compact range assessments [2], [9]. Each of the identified uncertainty terms is evaluated, by analysis, observation, or measurement, for their effect on boresight gain and the -30 dB sidelobe level. Each term is also classified as a Type A or Type B uncertainty and its relevant divisor assigned, such that the standard uncertainties may be combined. Finally, the terms are collected and combined by the root sum squared method and a coverage factor is assigned to bring the confidence level to 95% (k=2).

A. *Source polarization purity (Type B)*

When measuring a circularly polarized AUT with a linearly polarized source antenna, the imperfect axial ratio of the source has a significant impact on the measurement error [5]. On outdoor ranges, it's often desired to have broadband source antennas with relatively high gain. This requirement often comes at the expense of source polarization purity.

The source polarization purity term can be estimated by the following equation [2]:

$$U_1 = \frac{1+\rho_w^2\rho_A^2+2\rho_A\rho_w\cos 2\theta}{\left(1+\rho_w^2\right)\left(1+\rho_A^2\right)} \tag{1}$$

where $\rho_w = \left(r_w+1\right)/\left(r_w-1\right)$ and $\rho_A = (r_A+1)/\left(r_A-1\right)$. Here r_w is the axial ratio of the transmitting antenna, r_A is the axial ratio of the receiving antenna, and θ is the angle between the source and receiving polarization vectors. Assuming an ideal linearly polarized standard gain antenna (SGH), a purely circularly polarized AUT, and a Tx antenna axial ratio of 30 dB, the gain uncertainty can be estimated as $\pm 0.279/\sqrt{3} = \pm 0.161\,dB$

B. *AUT alignment (Type B)*

This error term concerns the AUT azimuthal errors with respect to the range axis. Assuming that the AUT pattern is approximately parabolic around the 3dB point, and using the standard quadratic function, the associated error can be estimated as:

$$U_2 = -3\left(\frac{\theta_{err}}{\theta_{3dB}}\right)^2 \tag{2}$$

where θ_{err} is the stated accuracy of the positioner and θ_{3dB} is the 3dB beamwidth of the AUT. This term may also be evaluated experimentally.

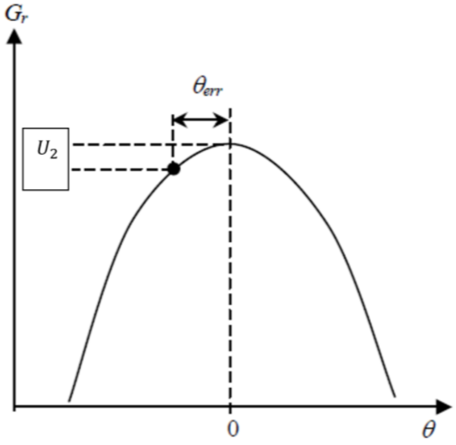

Figure 3. Model for the estimate of Azimuthal errors.

Assuming a standard positioner accuracy of 0.03 degrees, and an AUT 3 dB beamwidth of 2.5 degrees, the estimated error for this term is approximately ± 0.0004 dB and is therefore negligible.

C. *Gain Standard (Type B)*

This error is due to the gain uncertainty of the standard gain antenna itself, and only impacts the gain measurement uncertainty. It is often one of the largest contributors to the total uncertainty budget and can be somewhat mitigated through careful gain calibration. For a typical standard gain horn, the manufacturer's analytical gain curves are accurate to within about ±0.3 dB to ±0.5 dB, which may be sufficient depending on the required value for total uncertainty budget.

Other types of antennas used as gain standards must generally be calibrated in a separate measurement. Common gain calibration types, in order by increasing levels of uncertainty (k=2):

- 3-antenna extrapolation ranges (~± 0.1 dB)
- 3-antenna ranges without extrapolation (~± 0.25 dB)
- Substitution method (~± 0.5 dB)

The calibration certificate for the range SGH states that the k=2 uncertainty is, as measured at the manufacturer, ±0.570 dB. Therefore, the standard gain uncertainty for the SGH is U_3=±0.285 dB

D. Connection Repeatabiltuy (Type A)

This error term is due to mating/de-mating the cable connections to the AUT, which may induce errors due to improperly torqued connectors and excessive flexing in the cabling. Care should be taken to properly torque the connectors using a calibrated torque wrench and to avoid unnecessary cable flexure and strain. Still, there will be a small but finite variation in signal level. This error affects the gain but does not affect sidelobe measurements.

The associated uncertainty is estimated by taking 10 measurements of the peak of beam RF signal after de-mating and then mating the cable to the AUT. The standard deviation of the measured signal is the estimate of the gain uncertainty, which was determined to be U_4=± 0.058 dB.

E. Source and AUT Coupling (TypeB)

The coupling between the source antenna and the AUT can be divided into two terms: inductive coupling and mutual coupling. For an outdoor FF range, the inductive term is generally insignificant, unless the AUT is electrically small and the source to AUT separation is approaching the $2D^2/\lambda$ far field criterion. Likewise, the mutual coupling (or mutual reflection) term, which is due to radiated energy being reflected back and forth between the source and AUT, is typically quite small when the range length is much greater than the size of the source aperture. Nonetheless, both terms will be described below for completeness.

1) Inductive Coupling:

The ratio of inductive field to the radiating field between the source antenna and AUT is given by [7]:

$$\rho_{\varepsilon} = \frac{\lambda}{2\pi R} \qquad (3)$$

where R is the range length and λ is the wavelength of operation. At 7.5 GHz, with a range length of 1086 m, the stray signal level due to inductive coupling on the considered outdoor FF range can be estimated at -105 dB and can therefore be ignored.

2) Radiation Coupling

Radiation coupling occurs when the receiving antenna re-radiates the transmitted signal back to the source antenna and the source antenna then re-radiates that signal back to the receiving antenna. The antenna will re-radiate an amount of energy equivalent to the return loss of the component attached to the antenna terminals. For example, if the VSWR seen by the receiving antenna is 3.0, the return loss will be 6 dB. If the amplitude taper for the source antenna across the AUT aperture is significant, ripples in the main beam of the AUT will be created.

The normal error allocated for this problem is 0.05 dB, meaning that the ratio of the re-radiated signal at the receiving antenna to the original signal should be at least -45 dB. Reference [2] derives the equation for the ratio of the power seen by the AUT from the re-radiated signal from the source antenna to the original power transmitted by the source antenna when both are parabolic reflectors as:

$$\frac{P_r'}{P_r} = k_t k_r \left(0.92\epsilon_t \epsilon_r\right)^2 \left(\frac{\alpha_D}{\theta_s}\right)^4 \qquad (4)$$

where $\alpha_D = D/R$ is the angle subtended by AUT diameter is:

P_r' = re-radiated power seen by the receiving antenna

P_r = desired power seen by the receiving antenna

k_t = linear value of the reflected signal at the transmit antenna (example, a return loss of 6 dB is a linear k = 0.25)

k_r = linear value of the reflected signal at the receive antenna (example, a return loss of 6 dB is a linear k = 0.25)

ϵ_t = efficiency of the transmit antenna = 0.5 (assumed)

ϵ_r = efficiency of the receive antenna = 0.5 (assumed)

α_D = the angle subtended at the source antenna by the aperture of the AUT

θ_s = the HPBW of the source antenna

Assuming a 3 degree HPBW for the source antenna, and an AUT diameter of 1.2 meters, and antenna efficiencies of 50%, the equivalent stray signal is -92 dB, and therefore negligible. The calculation of the coupling term for the gain standard will result in similarly negligible values.

F. Multipath reflections (type A)

Based upon the range geometry, it is possible to estimate the effect of specular reflections on gain measurements [2],[3]. The geometry for the analysis is shown in Figure 4.

The path to the AUT via the specular reflection is:

$$R_{reflection} = \left[R^2 + \left(h_r + h_t \right)^2 \right]^{1/2} \tag{5}$$

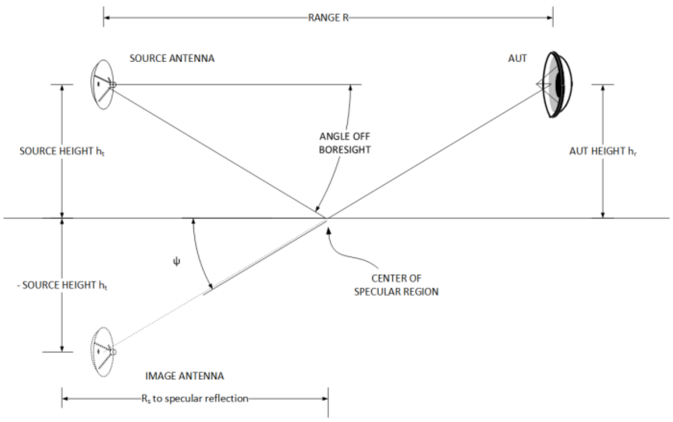

Figure 4. Range geometry for multpath reflection analysis.

The grazing angle Ψ is given by:

$$\psi = \tan^{-1} \left[\frac{h_r + h_t}{R} \right] \tag{6}$$

Note that the grazing angle should be less than the Brewster angle. The Brewster angle is the incident angle at which energy that is polarized normal to the reflecting surface will have almost no reflection. For air over ground, the Brewster angle is approximately 14 degrees [2].

The range from the source to the center of the specular region is:

$$R_S = \frac{h_t}{\tan \psi} \tag{7}$$

The magnitude of the specular reflection signal at the AUT represents a stray signal that combines with the direct ray signal that is desired. The reflected signal will be below the desired signal by:

$$\begin{aligned} 10\log_{10}\left(\frac{E_R}{E_D}\right) &= dB\ down\ on\ the\ source\ pattern\ @\ \psi \\ &+20\log_{10}\left(\frac{R}{R_{ref}}\right) + 20\log_{10}\left(k\right) \end{aligned} \tag{8}$$

Here, E_R and E_D are the magnitudes of the direct and reflected signals and k is the reflection coefficient of the ground. Assuming that the specular region is covered by low grass, a typical value is k =0.3[3]. Using this, and the geometry of the range, we find the stray signal level to be -41dB, leading to an estimated uncertainty of ±0.080dB.

While the above analysis gives a useful approximation of the level of uncertainty due to reflections, the real outdoor range surface is far more complicated than the model. There are likely to be several points of reflection that will contribute to the error, along with several types of ground surface. Therefore, we use measurement to establish the reflection contribution.

The example range is equipped with an offset slide along the AUT z-axis. Measurements were taken as a function of slide position and the maximum to minimum variation of the signal in the quiet zone was recorded. Finally, the maximum deviation from the RMS value of the measurement set is used to estimate the error due to reflections. The uncertainty in AUT gain is estimated to be U_{13}=±0.033 dB while the uncertainty in the -30 dB sidelobe level is estimated to be ±1.127 dB. When repeated for the gain standard the measurement set resulted in a gain uncertainty of U_6=±0.08 dB and has no effect on the sidelobe levels.

G. Leakage – (Type A)

Unwanted radiation, usually caused by improperly torqued cable interfaces, broken cables, improperly sealed mixers, multipliers, sources, and isolators, is deemed leakage. Additionally, there can be crosstalk within the RF system itself, due to poorly designed internal circuitry that permits leakage. These two terms are tested separately. Internal crosstalk can be measured by terminating the output of the signal source and the input of the receiver and taking a frequency dependent sweep. External leakage is first measured by disconnecting the source antenna, terminating the cable, and taking a frequency dependent sweep. Finally, external leakage on the AUT side can be measured by disconnecting the AUT, terminating the cable, and taking a frequency dependent sweep. Typical levels should be near the system noise. The uncertainty in AUT gain is estimated to be U_{14}=±0.000 dB while the uncertainty in the -30 dB sidelobe level is estimated to be ±0.006 dB. Similarly, the gain uncertainty of the standard gain horn is estimated to be U_7=±0.002 dB.

H. Impedance Mismatch Error (Type B)

Impedance mismatch errors occur because of non-perfect impedance matches between the AUT and its cable network and between the SGH and the same cable network. This term affects the absolute gain measurement only.

The estimated uncertainty may be obtained by evaluating the following equation [10]:

$$U_8(dB) = 20Log_{10}\left(1 \pm \Gamma_{AUT}\Gamma_{Rx}\right) + 20Log_{10}\left(1 \pm \Gamma_{SGH}\Gamma_{Rx}\right) \tag{9}$$

where $\Gamma_{AUT} = 0.126, \Gamma_{Rx} = 0.130,$ and $\Gamma_{SGH} = 0.069$ are the measured reflection coefficients of the AUT, receiver, and gain standard, respectively. It should be noted that the mismatch uncertainty is different to all other type B uncertainties in that it has a U-shaped distribution whereas the rest are assumed rectangular [11]. The error due to mismatch can therefore be calculated as $U_8(dB) = 0.222/\sqrt{2} = \pm 0.157dB$.

I. *Receiver Amplitude Linearity (Type B)*

The non-linearity of modern digital receivers typically has very little impact on the measurement accuracy of an antenna's peak of beam. However, the error induced may become significant when measuring an antenna's low sidelobe levels where the dynamic range is large. The linearity of a receiver is usually given in its manufacturer's specification sheet in units of dB/decade.

The receiver used in the example test campaign was an MI-750 Advanced Digital Receiver with stated amplitude linearity of 0.05 dB/10 dB. The effect on the gain uncertainty is assumed to be near zero while the effect on the -30 dB sidelobe level measurement accuracy can be calculated as $(0.05 \cdot 3)/\sqrt{3} = \pm 0.087dB$.

J. *Receiver Dynamic Range (Type A)*

The dynamic range of the RF subsystem is referred to as the receiver dynamic range in the standard near-field 18-term error analysis. However, it is truly due to a combination of factors including system cabling, AUT and source antenna gain, attenuation used to mitigate mismatch loss, and the dynamic range of the receiver, amongst other items.

Similar to the receiver amplitude linearity, errors for this term tend to be negligible on the peak of the AUT beam and more significant on the sidelobe measurement accuracy. In practice, the RF subsystem dynamic range can be determined by measuring the signal level at the AUT peak of beam, disconnecting the source antenna and terminating the cable with a 50 Ω load, and comparing the difference between the two signals. The dynamic range was found to be 107.5 dB and therefore has almost no impact on the gain uncertainty and only ± 0.02 dB on the -30 dB sidelobe levels.

K. *Phase Error (Type B)*

The phase error on a far-field range is due to the imperfect "plane wave" impinging on the AUT. There will necessarily be a finite error due to the variation of the phase over the aperture of the AUT. Assuming a flat aperture, and using the common criterion of 22.5° of phase variation, the far field criteria can be found by [1]:

$$R = \frac{2D_{AUT}^2}{\lambda} \tag{10}$$

where R is the range length, λ is the wavelength at the frequency of operation, and D_{AUT} is the diameter of the AUT. At 7.5 GHz, the range length is more than 15 times longer than the far field criterion and the uncertainty due to phase error can be estimated to be 0 dB for both the gain and -30 dB sidelobe levels.

L. *Random Errors – Environmental Stability (Type A)*

This uncertainty term is a combination of all non-repeatable errors due to the receiver, cables, temperature, AUT variations, etc. It is expected that the temperature will vary greatly on an outdoor range and that the source antenna may be subject to movement due to wind loading. Additionally, scattering due to the dynamics of the forest canopy that covers the valley between the source and AUT is captured in this term.

The most direct way of estimating this quantity is to compare the far-fields of two or more azimuthal scans taken with the exact same scan parameters. Preferably, five or more repeat measurements are performed without any change in the measurement system. The far-field patterns of the repeat measurements are then averaged, and the average compared to a single measurement by complex plot subtraction. The pattern comparison and the RMS level are then used to determine the estimated uncertainty [7]

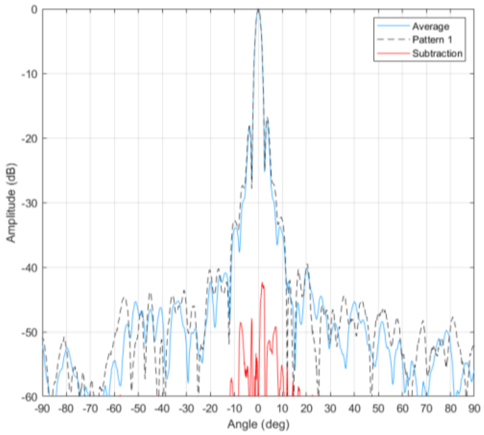

Figure 5. Pattern subtraction for estimation of random errors.

In Figure 5. , we show the average of 5 azimuthal cuts, the first of the 5 patterns, and the pattern subtraction between them. From the RMS of the pattern subtraction, we estimate error contributions to the gain uncertainty and -30 dB sidelobe levels to be U_{15}= ± 0.032 dB and ± 0.973 dB respectively.

M. *Accumulation of Errors*

Note that each term above, unless deemed negligible, has been expressed in its standard form. We now use the root sum squared method to combine the terms into a measure of total uncertainty for the gain and sidelobe levels. Strictly speaking, this requires each of the terms to be independent and uncorrelated to the other terms. A coverage factor is also assigned to increase the level of confidence. It's typically recommended that the k is in the range of 2 or 3, giving a 95% or 99% level of confidence, respectively. Here, we choose k=2 and present the final result in Table I.

IV. CONCLUSIONS

In this paper, we have described a methodology for identifying and estimating measurement uncertainties in gain and -30 dB sidelobe levels in measurements on an outdoor elevated far-field antenna range. The industry standard NIST 18 term range assessment technique for near-field ranges was utilized as a baseline for the analysis, while analysis specific to the range geometry were considered. Specific consideration was given to assigning the correct divisor to differing uncertainty types to convert the quantities to a standard distribution such that the terms could be correctly combined.

TABLE I. SUMMARY OF OUTDOOR FF RANGE ERROR SOURCES.

No.	**Error Source**	**Gain Uncertainty (dB)**	**-30 dB Sidelobe Uncertainty (dB)**
1	Source Polarization Purity	0.161	0.000
2	AUT Alignment	0.000	0.000
3	Gain Standard Uncertainty	0.165	0.000
4	Repeatability	0.058	0.000
5	Mutual Coupling - Gain Standard	0.000	0.000
6	Multipath Reflections - Gain Standard	0.080	0.000
7	Leakage - Gain Standard	0.002	0.000
8	Impedance Mismatch	0.157	0.000
9	Receiver Amplitude Linearity	0.000	0.087
10	Receiver Dynamic Range	0.000	0.002
11	Phase Error	0.000	0.000
12	Mutual Coupling	0.000	0.000
13	Multipath Reflections-AUT	0.033	1.127
14	Leakage	0.000	0.006
15	Random Errors	0.032	0.973
	Combined Uncertainty (1σ)	**0.299**	**1.492**
	Combined Uncertainty (2σ)	**0.599**	**2.983**

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