SELECTION CRITERIA FOR NEAR-FIELD GAIN TECHNIQUES

Gregory Masters, Patrick Pelland
Nearfield Systems Inc.
Torrance, CA, USA

***Abstract*— Several gain measurement techniques exist for near-field antenna ranges. These include Comparison-gain, Direct-gain and 3-antenna gain methods. Each technique has its own unique advantages and disadvantages in terms of accuracy, cost and measurement time. Range operators must understand the differences between these techniques in order to properly configure their test system to best suit their requirements. This paper surveys each of the gain techniques and identifies the relative advantages of each. As part of the survey, all three techniques were performed on three types of near-field antenna measurement systems: Planar, Cylindrical and Spherical. The results of this paper provide the reader with a practical understanding of each technique, the formulas required, and real-world examples for the trade-offs needed to outfit a range for fast and accurate gain measurements while balancing cost and schedule.**

Keywords: Near-field, gain, planar, cylindrical, spherical, comparison, direct, Three-antenna.

I. Introduction

Gain is an important parameter to be measured on most antennas. Since the gain value is of little use if the accuracy is either unknown or poor, it is important to understand how gain errors contribute to gain accuracy and how to assess them. Range operators are often approached by project engineers to achieve high accuracy with little resources of time or money. Many papers have been written on estimating the accuracy of gain and pattern measurements [1] but little is discussed on the subject of accuracy vs. gain method. In this paper, we assume the reader understands how to assess range errors and we devote the study here to understanding how the various gain measurement techniques can affect results. Understanding the tradeoffs of accuracy, cost and schedule becomes a valuable skill to the efficient use of resources.

Accuracy requirements change based on antenna type. Often high gain satellite antennas require very accurate gain measurements with accuracies typically < 0.2 dB. Low gain cell phone antennas often require peak gain measurement accuracies no better than 0.7 dB. The expense required to obtain a 0.2 dB gain accuracy is typically 10 to 50 times greater than a 0.7 dB accuracy. Some of the tradeoffs include:

1) Gain standard calibration vs. cost
2) Far-field peak accuracy vs. measurement time
3) Automation vs. set up time

II. Gain Calibration Requirements

Certain types of gain measurements require a calibration standard. When only a few narrow-band frequencies are required the cost of calibration can be minimal. When a wide bandwidth of frequencies is required, the cost of calibration rises significantly. For these reasons the range operator should understand how gain calibration affects accuracy and how the selection of a particular type of gain measurement affects calibration needs. Cost, schedule and accuracy are interdependent in the case of antenna gain measurements. Table I shows typical cost and schedule impacts on accuracy based on three types of calibration standards. While this table gives only rough estimates, it is clear that accuracy significantly affects cost and schedule.

TABLE 1. Cost and Schedule Tradeoff with Calibration Accuracy

	Calibration method and accuracy		
Tradeoff	NRL curve (0.3-0.5 dB)	Self-Cal (0.2-0.3 dB)	Lab-Cal (0.1-0.2 dB)
Cost	1x	3x	>5x
Schedule	Days	Weeks	Months

III. Overview of Gain Techniques

Some types of gain measurements require pre-calibrated gain standards. These standard gain antennas (SGA) can become the costliest element of the measurement in achieving high gain accuracy. The advantages of SGAs are that once calibrated, the gain measurement can be done in a quick, repeatable and efficient manner. Each gain method uses slightly different techniques. Three of the most common techniques are discussed here: Direct gain, Comparison gain and Three-Antenna gain.

The simplest explanation of a gain measurement can be seen by using the log form of a modified Friis transmission equation which relates the gain and separation between two antennas to the signal power transmitted and received:

$$\mathbf{P_r - P_t = G_r + G_t + 20\log_{10}(\lambda/4\pi R)} \qquad (1)$$

where:

- Pr-Pt is the ratio of power received to power transmitted
- Gr and Gt are the gains of the receive and transmit antennas
- 20log10(λ/4πR) is the space loss as energy spreads out over a sphere of radius R

Note that (1) ignores losses due to mismatch of the two antennas, which is assumed to be zero for the purposes of this paper. In practice, losses due to mismatch should be accounted for when performing gain measurements. Assuming that the gains in the formula represent peak gains and that the antennas are aligned such that their pattern peaks are pointing at each other, the peak gain of the receive antenna G_r can be written as:

$$\mathbf{G_r = (P_r - P_t) - G_t - 20\log_{10}(\lambda/4\pi R)} \tag{2}$$

A. Direct Gain

If the transmit or receive antenna gain is known, the gain of the other can be computed from the formula, as in (3):

$$\mathbf{G_r = M - G_t - 20\log_{10}(\lambda/4\pi R)} \tag{3}$$

where: M is the measurement ratio $\mathbf{(P_r - P_t)}$.

The gain uncertainty for Direct gain measurements is based on the accuracy of the far-field peak measurement (**M**), the accuracy of the transmit gain $\mathbf{(G_t)}$ and the accuracy of the computation of the space loss: $\mathbf{20\log_{10}(\lambda/4\pi R)}$.

A variant of the direct gain measurement can be made if the transmit and receive antennas are not known but are identical. Then the gain formula becomes:

$$\mathbf{G_r = 0.5\{M - 20\log_{10}(\lambda/4\pi R)\}} \tag{4}$$

B. Comparison Gain

Another gain method that is useful is called the Comparison gain method. In this method two Direct gain measurements are made and then subtracted from each other; one with an SGA and the other with an antenna of unknown gain. The result is that the transmit antenna gain and space loss subtract out so that knowledge of their values are not required in the gain calculation. As long as the antenna gain of one of the measurements is known (G_2 = SGA), the gain of the other antenna can be computed as:

$$\mathbf{G1 = (M1 - M2) + G2} \tag{5}$$

where: $\mathbf{M_1}$ and $\mathbf{M_2}$ are the measurement ratios for the two measurements.

The gain uncertainty is based on the accuracy of each far-field peak measurement ($\mathbf{M_1}$ **and** $\mathbf{M_2}$) and the accuracy of the SGA's pre-measured or calculated gain $\mathbf{(G_2)}$.

C. Three-Antenna Gain

Another extremely useful method is called the Three-Antenna gain method. This method has the advantage that none of the antenna gains must be known to calculate the gain. The method uses three direct gain measurements under different conditions to create a set of three equations with three unknown gains. The difference between the measurements is that one of the three antennas is either the transmit or receive antenna and each new measurement has a different combination of transmit and receive antennas. An example is shown in Table II.

TABLE II. THREE-ANTENNA FAR-FIELD MEASUREMENT CONFIGURATION

Meas. #	Tx Ant	Rx Ant	Transmission Equation
1	Ant-1	Ant-2	$\mathbf{M_{12} - 20\log_{10}(\lambda/4\pi R) = G_1 + G_2}$
2	Ant-1	Ant-3	$\mathbf{M_{13} - 20\log_{10}(\lambda/4\pi R) = G_1 + G_3}$
3	Ant-3	Ant-2	$\mathbf{M_{32} - 20\log_{10}(\lambda/4\pi R) = G_3 + G_2}$

The three simultaneous equations can be solved and thus give the following results:

$$\mathbf{G1 = 0.5\{M12 + M13 - M32 - 20\log10(\lambda/4\pi R)\}} \tag{6a}$$

$$\mathbf{G2 = 0.5\{M12 + M32 - M13 - 20\log10(\lambda/4\pi R)\}} \tag{6b}$$

$$\mathbf{G3 = 0.5\{M13 + M32 - M12 - 20\log10(\lambda/4\pi R)\}} \tag{6c}$$

The gain uncertainty is based on the accuracy of each far-field peak measurement ($\mathbf{M_{12}, M_{13}, M_{32}}$) and the accuracy of computing the space loss: $\mathbf{- 20\log_{10}(\lambda/4\pi R)}$.

IV. MEASURING FAR-FIELD GAIN FROM NEAR-FIELD MEASUREMENTS

Gain measurements using near-field techniques are only slightly different from those of far-field and do not depend on the distance between antennas. For near-field, a measurement is made of the fields over a surface surrounding the antenna and the plane wave spectrum is computed. The computation includes a correction for the effect of the probe's pattern and the far-field peak of the antenna under test is then determined. It is interesting to note that the near-field gain equations do not require any knowledge of the distance between the antennas. While the near-field to far-field formulation is beyond the scope of this paper, it is well understood and has been formalized in many technical papers [2]. For the purposes of formulation, far-field measurements usually speak of transmit and receive antennas where the transmit antenna is fixed and the AUT is the receive antenna which has the ability to be rotated. In fact, which antenna is actually transmitting or receiving makes no difference to the formulations. This is also true for near-field formulations.

V. NEAR-FIELD GAIN SETUP AND EQUATIONS

A. Direct Gain

Direct gain near-field measurements require knowledge of the probe gain and a measurement that represents the computed far-field peak. In addition, normalization is required to relate the far-field peak to the input power. This normalization is done by connecting the probe cable directly to the antenna-under-test (AUT) cable to "bypass" the probe and antenna. Thus, the computed far-field peak and bypass measurement represent a measured power ratio (FF peak-Bypass) = $(\mathbf{P_r - P_t})$. The near-field Direct gain equation is thus:

$$\mathbf{G_{AUT} = M - G_{probe}} \quad \mathbf{(8)}$$

where: **M** is the computed far-field peak - bypass.

The sequence of operations is:

1) Connect the AUT cable to the probe cable and make a bypass measurement.
2) Reconnect the AUT and probe cables and make a near-field scan.
3) Compute the far-field peak and adjust by the value of the bypass measurement.

The gain uncertainty is based on the accuracy of the computed far-field peak **(M),** the bypass measurement and probe gain $(\mathbf{G_t})$.

B. Comparison Gain

Comparison gain near-field measurements require two measurements; one of the SGA and the other the AUT. The gain formula is thus:

$$\mathbf{G_1 = (M_1 - M_2) + G_2} \quad \mathbf{(9)}$$

where: $\mathbf{M_1}$ and $\mathbf{M_2}$ are the far-field peaks for the two measurements. Since the quantities $\mathbf{M_1}$ and $\mathbf{M_2}$ are subtracted from each other, the bypass measurement is subtracted out and thus not required.

The sequence of operations is as follows:

1) Connect the AUT cable to the AUT and make a scan.
2) Compute the far-field peak of the AUT $(\mathbf{M_1})$.
3) Connect the AUT cable to the SGA and make a scan.
4) Compute the far-field peak of the SGA $(\mathbf{M_2})$.
5) Calculate the AUT gain by computing: $\mathbf{G_1 = (M_1 - M_2) + G_2}$

The gain uncertainty is based on the accuracy of the computed far-field peaks $(\mathbf{M_1, M_2})$, and the SGA gain $(\mathbf{G_2})$.

C. Three-Antenna Gain

The Three-Antenna gain near-field measurement requires three measurements and is typically done using an open-ended waveguide (OEWG) probe and two other antennas as shown in Table III. Each of the three measurements requires a bypass measurement but if the system is stable the bypass measurement should be the same for all three.

TABLE III. THREE-ANTENNA NEAR-FIELD MEASURMENT CONFIGURATION

Meas. #	Probe	AUT	Transmission Equation
1	Ant-1	Ant-2	$\mathbf{M_{12} = (FF_{12}\text{-}Bypass) = G_1 + G_2}$
2	Ant1	Ant-3	$\mathbf{M_{13} = (FF_{13}\text{-}Bypass) = G_1 + G_3}$
3	Ant-3	Ant-2	$\mathbf{M_{23} = (FF_{23}\text{-}Bypass) = G_3 + G_2}$

As an example, the three antennas could be:

1) Ant-1 is an NSI-WR90 OEWG
2) Ant-2 is an NSI-SG90 Standard gain horn
3) Ant-3 is a Narda-WR90 horn.

The sequence of operations is as follows:

1) Measure Ant-2 (NSI-SG90) with the probe as Ant-1 (OEWG) and compute $(\mathbf{M_{12}})$.
2) Measure Ant-3 (Narda-WR90) with the probe as Ant-1 (OEWG) and compute $(\mathbf{M_{13}})$.
3) Measure Ant-2 (NSI-SG90) with the probe as Ant-3 (Narda-WR90) and compute $(\mathbf{M_{32}})$.

Compute the gains using the formulas:

$$\mathbf{G1 = 0.5\{M12 + M13 - M32\}} \quad \mathbf{(10a)}$$

$$\mathbf{G2 = 0.5\{M12 + M23 - M32\}} \quad \mathbf{(10b)}$$

$$\mathbf{G3 = 0.5\{M13 + M32 - M12\}} \quad \mathbf{(10c)}$$

The gain uncertainty is based on the accuracy of each far-field peak and bypass measurement $(\mathbf{M_{12}, M_{13}, M_{32}})$.

VI. AUTOMATED GAIN MEASUREMENTS

Often it is desired to automate gain measurements to improve speed and reduce operator intervention. Automated measurements can reduce measurement drift and allow multiple measurements to be averaged. In addition, mounting the SGA permanently so as to allow automatic switching between AUT and SGA can reduce operator intervention. Unfortunately, automated measurements typically require additional cables and RF switches which can increase measurement errors. Mismatch losses and cable calibration cannot be ignored and can add significant error to the gain measurement if not handled properly. Additionally, permanently mounting an SGA on the range may introduce unwanted interaction with the AUT causing errors in the computation of the AUT's far-field peak. It is good practice to experiment with several automated techniques before settling on one so that the best tradeoff between automation and accuracy can be achieved.

VII. Real-World Gain Measurements and Accuracies

A set of measurements was made at 10 GHz on three types of near-field ranges to compare the results of each. To reduce overall test time and user intervention the combination planar, cylindrical, spherical near-field test system from Nearfield Systems Inc was used for all measurements (see Fig. 1). This allowed all three near-field scan geometries to be acquired on each antenna in an automated fashion. This system used two linear motion axes (X axis, Y axis) and three rotational axes (theta axis, phi axis, polarization axis). Using the probe's polarization axis and two of the remaining three axes allowed planar, cylindrical and spherical measurements to be performed on the same test system.

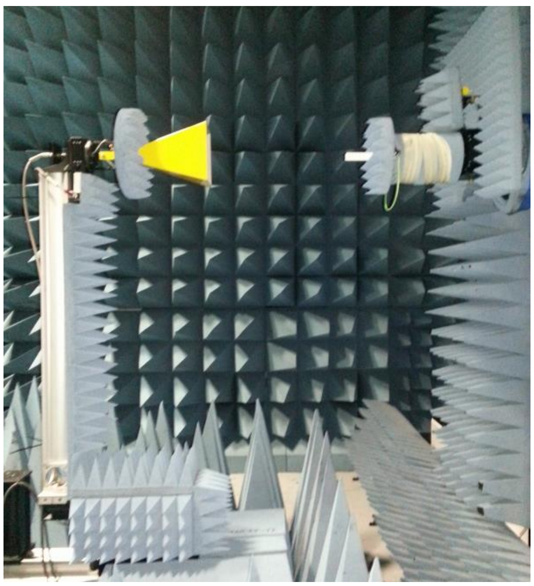

Figure 1. NSI-SG90 AUT Mounted on an NSI Combination Planar, Cylindrical, Spherical Near-Field Test System with OEWG Probe.

Figure 2. NSI-WR90 OEWG used as Ant-1 in the Three-Antenna Gain Measurement and Probe in the Other Two Gain Methods.

In order to demonstrate the uncertainties associated with the different gain measurement methods, three different antennas were selected for measurement. First, the WR90 OEWG probe shown in Fig. 2 was selected since it is well suited as the probe on all three types of near-field systems. Next, the NSI-SG90 horn shown in Fig. 3 was chosen for its relatively high gain (~22.4 dBi at 10 GHz) and usefulness as an SGA. Finally, the NARDA WR90 horn shown in Fig. 4 was chosen since its peak gain was unknown and could be computed using all three gain measurement techniques to illustrate the different uncertainties.

Figure 3. NSI-SG90 X-Band Standard Gain Horn Antenna used as Ant-2 in the Three-Antenna Gain Measurement and SGA in the Comparison Gain Method.

Figure 4. NARDA WR90 Horn used as Ant-3 in the Three-Antenna Gain Measurement and AUT in the Other Two Methods.

Table IV shows that the Three-antenna gain measurement results compare well between the three ranges.

TABLE IV. THREE-ANTENNA MESUREMENT CONFIGURATION

		3-Antenna Gain (10 GHz)		
Ant	Description	Planar (dB)	Cylindrical (dB)	Spherical (dB)
1	OEWG w/3 dB pad	2.86	2.92	3.12
2	NSI-SG90	22.28	22.14	22.17
3	Narda-WR90	16.71	16.69	16.64
	Uncertainty	±0.14	±0.14	±0.14

As part of an accuracy comparison between the different gain methods, Table V shows the results at 10 GHz for the Narda_WR90 standard gain horn using Direct, Comparison and Three-Antenna methods. The accuracy for each of the three methods is also shown. It is obvious from the results of Table V that the comparison method using the NRL gain curve gives a significantly greater uncertainty (±0.32 dB) than that of the Three-Antenna technique (±0.14 dB). It should be noted that while the Three-Antenna method had an overall accuracy much better than the other measurements, it took 4-5 times longer to complete all the required near-field scans and data processing than the other two methods.

TABLE V. COMPARISON OF RESULTS OBTAINED FROM PLANAR GAIN TECHNIQUES AT 10 GHZ

		Narda WR90 Planar Gain Techniques (10 GHz)		
Item	Description	Direct (dB)	Comparison (dB)	Three-Antenna (dB)
1	Gain	16.71	16.82	16.71
2	Gain Ref.	OEWG*	NSI-SG90	None
3	FF peak acc.	±0.10	±0.12	±0.13
	Network loss acc.	±0.04	±0.04	±0.04
	Subtotal FF peak acc.	±0.11	±0.12	±0.14
4	Gain Ref. acc.	±0.14	±0.30	None
5	RSS Uncertainty	±0.18	±0.32	±0.14

* OEWG Gain value was derived from Three-Antenna method

VIII. SUMMARY

It has been shown that gain calibration accuracy plays a significant role in the final gain accuracy of the measurement. In addition, the type of gain method used can affect uncertainty. This paper presented three types of gain methods and the formulations for them. The formulas were presented for far-field and near-field configurations. It is hoped that this paper will be a good resource to range operators and engineers as they decide how much time and money they need to spend to get the accuracy required for their gain measurements.

IX. REFERENCES

[1] A.C. Newell, *Error Analysis Techniques for Planar Near-Field Measurements*. IEEE Trans. Antennas and Propagation pp. 754-768.

[2] A.C. Newell, R.D. Ward, E.J. McFarland, Gain and Power Parameter Measurements Using Planar Near-field Techniques. IEEE Trans. Antennas and Propagation pp. 792-803.