PRACTICAL GAIN MEASUREMENTS

Marion Baggett
MI Technologies
1125 Satellite Boulevard
Suwanee, GA 30022
mbaggett@mi-technologies.com

ABSTRACT

Collecting accurate gain measurements on antennas is one of the primary tasks for our community. One of the primary concerns in making gain measurements is choosing one of the well known gain measurement techniques to make the measurement. Each gain measurement technique has an inherent accuracy limit based on the measurements made, the measurement environment and the equipment required. The frequency band of interest may also have an impact on the gain measurement scheme employed. In addition, each technique can affect the throughput of the range in question. Balancing the cost of obtaining the gain versus the required accuracy of the gain measurement is a difficult task. This paper will discuss the basic accuracy limitations for several of the standard gain measurement techniques and will catalog the accuracy limitations of the various gain measurement techniques versus the cost associated with obtaining that quality of measurement.

Keywords: Gain Measurements, Error Analysis

1.0 Introduction

In their paper "What's a dB Worth?" [1], Sanchez and Connor described how judicious application of specifications could significantly reduce the cost of an anechoic chamber by approximately $10,000 cost savings per dB relative to the original specification. This paper takes a similar approach to obtaining the accurate gain for an antenna under test (AUT). The position for this paper is that most well designed modern antenna ranges can obtain gain accuracies approaching those of the national testing laboratories, but at a cost in time, labor and additional test equipment. For example, Francis et al [2] has reported gain errors from 0.07 to 0.15 dB for several gain measurement methods at NIST. However, the same report stated that measurement times to obtain these results ranged from 1 to 3 weeks for a single antenna tested. This amount of time and effort may be justified for calibration of a gain standard or "golden antenna" to be used as a system reference on multiple ranges or to qualify an initial prototype, but usually cannot be justified in a production or antenna repair environment. The question to be addressed is how much effort is needed to achieve a gain accuracy of +/- X dB.

2.0 What Is Gain?

The ANSI/IEEE Std 145-1993, Definitions of Terms for Antennas [3] gives the following definition:

"Power Gain of an Antenna – In a given direction, 4π times the ratio of the radiation intensity in that direction to the net power accepted by the antenna from the connected transmitter.
Note 1: When the direction is not stated, the power gain is usually taken to be the power gain in the direction of its maximum value.
Note 2: *Power Gain does not include reflection losses arising from mismatch of impedance.*
Note 3: *Power gain is fully realized on reception only when the incident polarization is the same as the polarization of the antenna on transmission*."

The ANSI/IEEE Std 149-1979, Test Procedures for Antennas [4] give the following definition:

"12.1 The power gain of an antenna in a specified direction is 4π times the ratio of the power radiated per unit angle in that direction to the net power accepted by the antenna from its generator. This quantity is an inherent property of the antenna and *does not involve system losses arising from a mismatch of impendence or polarization.*"

These definitions highlight the difficulty in accurate gain measurements. The italicized parts of the definitions show that mismatches to the environment are not included in the definitions. However, antennas connect to the real world and a measurement that includes mismatches is commonly termed "realized gain", while a measurement that corrects for these mismatches is commonly termed "IEEE gain". The first decision for a test engineer or researcher is to determine which gain is needed. Most users of antennas want to know the gain of the antenna assembly or line replaceable unit, but the designer has likely modeled the gain "at the flange".

3. Types of Gain Measurements

Section 12.5 of [4] lists the common methods of gain measurement and divides the types into absolute gain measurements and gain transfer methods.

- Absolute gain methods
  - 2 and 3 antenna comparison method in the far-field
  - 2 and 3 antenna comparison method with extrapolation in the near-field
  - Directivity measurement plus antenna loss measurements by other means
- Gain transfer methods
  - Gain transfer in the far-field
  - Gain transfer in the far-field from data on the gain standard and the AUT transformed from the near-field
  - Gain-insertion-loss measurements applied to near-field measurements of the AUT that are then transformed to the far-field

All of these methods have advantages and disadvantages ranging from the size of range required, number and duration of measurements needed to the requirement for additional equipment. For example, 3 antenna comparisons in the near-field with extrapolation require an accurately aligned longitudinal slide of sufficient length to provide the necessary distance to project the readings into the far field [2] [5] [6] [7]. The near-field methods require more time to complete than far field measurements. In all the methods, making a statistically significant set of measurements to gauge repeatability and minimize connection and noise errors is always possible but requires significantly more test time.

4. The Gain of a Gain Standard

The most time efficient gain measurement technique is the gain transfer method in the far field using a "known" gain standard. In many cases, this is a "standard gain horn" (SGH). This means a single polarization rectangular horn built to the dimensional requirements of the 1954 NRL report on these antennas. However, employing one of these standards can introduce significant error in the gain measurement. Looking at errors inherent in the SGH itself, without addressing its interaction with other equipment or the range:

1. The gain standard curves published by the SGH manufacturers match the NRL report calculations. Most manufacturer's specify a +/- 0.3 dB tolerance for the gain of any one horn to the standard curves for horns used above 3 GHz and +/- 0.5 dB for horns below 3 GHz. This tolerance is due to manufacturing tolerances fabricating the horn.
2. Bodnar [8] showed that modeling of the traditional SGH indicates frequency dependent variation in the gain that is based on the interactions at the aperture. These variations can be up to +/-0.25 dB, as opposed to the smoothness of the traditional NRL curves. This variation is also described elsewhere [4].
3. The NRL curves give the "IEEE gain" for the SGH, since only the waveguide section is included. Most SGH's less than 40 GHz are fitted with a waveguide to coaxial adapter so that the SGH can be connected to common microwave cabling. This adapter can have from 0.2 to 0.3 dB of insertion loss and present normally a 1.25 to 1.5 VSWR.

Taking the root sum of squares (RSS) of the error terms above, the composite error contributed by the SGH in a simple gain transfer measurement can be up to 0.45 dB for a SGH used above 3 GHz and 0.61 dB for lower frequency horns. The range probe in a near-field range has essentially the same error contributors as the SGH when using the gain-insertion loss gain measurement technique in the near-field. The probe does not contribute these errors when gain transfer on transformed near-field data is performed, since the probe is identical for both the SGH and AUT near-field measurements.

Many examples exist in the literature on measurement techniques that result in highly accurate calibrations of gain standards. Looking at the common methods of calibration:

- Have the antenna calibrated at a national standards laboratory such as NIST, NPL or TUD. Available accuracies are published by the various laboratories and can be as good as < 0.1 dB [2]. The penalty is the cost for the laboratory to perform the calibration and the time that the gain standard will be at the laboratory.
- Have the antenna calibrated at an AL2A certified test facility. Generally, the offered accuracies are 0.1 to 0.2 dB higher than the national laboratories, but costs are generally lower and turn around times faster than the national laboratories.
- The antenna can be calibrated on the range in which it will be used by measuring with the "best practices" techniques described later in this paper. For any local calibration, at least one week of range time should be devoted to calibrating the gain standard.

5. Gain Measurement Errors

The gain errors listed below are the ones that occur on a measurement to measurement basis and can be mitigated. This paper does not address range design issues such as alignment of the range or quality of absorber treatment.

These errors are assumed to have been addressed and mitigated as much as possible. For example, the absorber treatment is assumed to provide the normal industry maximum of 50 dB attenuation by the absorber. For each error, a "minimal effort", "moderate effort" and "best practices" mitigation or calibration technique is listed. Errors given are estimates for Ku band operation and positioning systems with dual speed synchro accuracies. Transmission from the range antenna to AUT is assumed in all cases.

- While good range alignment is assumed, gain measurements dictate that the AUT or gain standard is measured at its beam peak for substitution methods and all antennas are measured at their peak for the three antenna method. Note that near-field measurements find the beam peak as part of the process.
  - Minimal effort Mount the AUT and perform several small principle plane scans to locate the peak or perform a "plunge and rotate" type bore sight alignment. Expected error is 0.1 dB.
  - Moderate effort Perform and bore sight alignment and then a small raster scan pattern to ascertain the peak. Expected error is 0.05 dB
  - Best Practices effort Perform the moderate effort multiple times. Expected error is 0.03 dB.
- Interaction of the antennas and the equipment that they are connected to can generate a significant error due to the interactions of the VSWR of both devices. For gain substitution methods, the interactions of the AUT and SGH with the receiver have an effect [4] [10]. For gain-insertion loss measurements or the three antenna method, the AUT, receiver, range antenna and signal source all interact [4] [12].
  - Minimal effort Do nothing. This error can be large. If a 2:1 VSWR antenna is connected to a receiver with a 2:1 VSWR (common input VSWR for mixers), the measurement uncertainty will be approximately 0.95 dB.
  - Moderate effort A common method to reduce the antenna to equipment VSWR interaction is to place an line matched attenuator at the antenna port. The attenuator will reduce the return loss of the antenna by twice its attenuation value, reducing the effective VSWR at the antenna. For example, adding a 6 dB attenuator in the scenario above reduces the uncertainty to 0.24 dB. A penalty for this addition is that the measurements will be 6 dB further down the receiver dynamic range. In modern VNA's and microwave receivers, the linearity error is 0.05 dB per decade [11] [13].
  - Best Practices If the reflection coefficients of the AUT, gain standard, range antenna, the receiver and the transmit source are measured, the mismatch uncertainty can be reduced to essentially the error of the network analyzer making the reflection measurement. For a representative VNA, the Agilent PNA-X N5242A, the error in a reflection measurement for a calibrated unit with basic reflection coefficients in the 0.2 to 0.4 class is approximately 0.02 [11]. For each antenna/equipment pair measured, the uncertainty will reduce to the RSS of the 2 VNA measurements or 0.03 dB and the gain insertion loss/three antenna method uncertainty is the RSS of the 4 VNA measurements or 0.05 dB.
- As stated above, modern receivers exhibit a linearity error of approximately 0.05 dB per decade of dynamic range. Therefore, the antenna in the gain measurement with the highest gain is set to be a close to the top of the receiver dynamic range as possible and the same system drive level is used for all measurements. The measurement of each antenna will have a linearity error driven by this configuration. In many circumstances, such as millimeter wave measurements, the system may not be able to place the antenna peak responses high in the receiver dynamic range. This error term can not be mitigated other than by moving the peak antenna response higher in the receiver dynamic range with additional amplification or a higher gain range antenna.
- As described in [4], the error due to near-field effects in placing an antenna exactly at $2D^2/\lambda$ is approximately 0.05 dB. Increasing the range reduces this error. For a compact range, or near-field data transformed to the infinite radius far field, this error is not present.
  - Minimal effort Ignore the error in far field or 3 antenna method. This leaves the error in place.
  - Moderate effort Adjust results with the 0.05 dB rule of thumb for far field methods that do not use a compact range.
  - Best Practices Measure/calculate the aperture to aperture distance and adjust results with an actual distance error.
- In far field measurements, the amplitude taper from the range antenna pattern can affect the measurement [4] [14]. The nominal case is a range antenna presenting a 0.25 dB taper across the AUT aperture, resulting in a 0.1 dB error in the measurement. In near-field measurements, probe pattern correction can take out the effects of the probe pattern, but the error in the measurement is the error bounds for the probe pattern. Most compact ranges are specified to have a 1 dB taper across the quiet zone, leading to an error

term of 0.3 dB. However, the AUT may only encompass a part of the quiet zone.

  - Minimal effort Do nothing
  - Moderate Effort Adjust the results with the rule of thumb error of 0.1 dB for far field or the assumed probe pattern accuracy in near-field.
  - Best Practices For a far field or compact range, use field probe data to determine the actual taper across the test antenna aperture and adjust the results with this value. For near-field measurements where probe pattern correction is employed, actual probe patterns can be used.
- As described in the definitions of gain [3] [4] presented above, polarization mismatch is another contributor. For test ranges that can rotate either the range antenna or the AUT, the primary polarizations of the range antenna and AUT can usually be aligned to the same quality as finding the beam peak for the AUT, or approximately 0.05 dB. Error due to the finite axial ratio of the range antenna can be a much more significant factor. Tables in Std 149-1979 [4] show error terms for finite range antenna axial ratio for linear and circular AUT's. The contamination for circular AUT's can be significant and Kolesnikoff [15] has reported even higher errors in measuring circular antennas. An axial ratio of 40 dB or better in the range antenna is normal for most commonly used single polarized range feeds. However, if range throughput or other considerations dictate the use of dual polarized range feeds, the feed axial ratio probably is in the 20 dB class, significantly increasing the error term.
  - Minimal effort Align the range antenna and the test antenna with a polarization scan and do nothing about the range antenna axial ratio
  - Moderate effort Align the range antenna and the test antenna with multiple polarization scans and adjust the results for the error caused by the nominal axial ratio of the range feed. Residual error should be about half the original error.
  - Best practices Accurately measure the axial ratio of the range feed and adjust the results for the measured axial ratio. Residual error is the accuracy of the axial ratio measurement of the range feed.
- Two errors affecting gain measurement accuracy that are randomly distributed are the error introduced by the connecting various antennas and the S/N error of the measurements. The variability of a connection to an antenna can be estimated at around 0.1 dB and with multiple operations and measurements; this error can be reduced to around 0.05 dB [9]. The measurements for gain are normally high in the receiver dynamic range, so S/N levels are relatively high, with associated small errors. However, S/N ratios of less than 40 dB can introduce errors of 0.1 dB or more.
  - Minimal effort take all measurements once
  - Moderate effort take all measurements three times
  - Best Practice take all measurements ten times
- For near-field gain by insertion loss, the uncertainty of the S_{21} value of the shorting cable and attenuator and the reflection coefficient of the combination will affect the measurement.
  - Minimal effort Assume nominal S_{21} value for the attenuator and assume ideal reflection coefficients
  - Moderate effort Assuming that matching attenuators are used for the AUT measurements; leave these attenuators in place for the shorting measurement.
  - Best practice Measure the attenuator and cable combination on a VNA and adjust the results by these values [12].
- The gain technique of measuring directivity and measuring losses by other means introduces the error in directivity measurement. Hansen [16] showed that for an adequately aligned spherical near field range, directivity can be found to within 0.1 dB when a full 4π steradian pattern is acquired. A full sphere directivity pattern in the far field should provide comparable accuracy. For planar or cylindrical near field techniques, the error will be increased proportionally for the amount of coverage that can not be obtained with that geometry.
  - Minimal effort measure directivity once and loss components on a VNA once
  - Moderate effort measure directivity three times and loss components on a VNA three times
  - Best practice measure directivity ten times and loss components on a VNA ten times

6. Time versus Accuracy

No one rule of thumb can provide a succinct guideline of error versus time invested. However, it is instructive to go through a hypothetical set of measurements on a real antenna and observe the time required for minimal, moderate and best effort gain measurements. Times used in the tables that are located at the end of the paper were the actual times needed to perform these types of tasks on either the MI Technologies' compact range or spherical near-field range. For entries that are marked "X2" or "X3", the individual errors for two like operations are combined via RSS. For the entries that are marked "$$"

or "$$$", these represent one time or periodic costs such as calibrating a gain standard.

- AUT :
  24" diameter reflector with prime focus feed
  Ka band (26.5 – 40 GHz)
  lossy components connected to the feed: waveguide to coax adapter, 22" coaxial cable and a bulkhead "k" connector
  nominal gain of 40 dBi, mid band
  VSWR at bulkhead connector is 2:1
- SGH when used:
  MI-12-26.5 with MI-11-26.5 waveguide to coaxial adapter
  nominal mid band gain = 26 dBi
  VSWR at the WCA = 1.5:1
- Three antenna gain was performed with 2 MI-12-26.5 SGH's and the AUT
- The VSWR of the source is 1.8:1 and the VSWR of the mixer at the front end of the receiver is 2.3:1.
- Far field measurements made on a compact range with MI-33 single polarization feeds with 40 dB axial ratio and VSWR of 1.7:1.
- Near field and three antenna measurements made on a spherical near-field range with MI-6970 OEWG probes with 40 dB axial ratio and VSWR of 1.9:1. The three antenna measurements were in the far field.
- For all measurements, the AUT peak signal was within 10 dB of the top of the receiver dynamic range
- Reflectivity measurements made with an Agilent 8362B VNA after SOLT calibration
- When making multiple measurements, the antennas are disconnected and re-connected for both antenna measurements and reflectivity measurements with the VNA.

7. Summary

For all the gain measurement techniques evaluated, the expected errors for minimal effort, moderate effort and best practices track across the techniques. Minimal effort errors ranged from 1.3 to 1.7 dB, Moderate effort errors ranged from 0.4 to 0.5 dB and best practices ranged from 0.12 to 0.22 dB. The exception is the gain by directivity and direct measurement of the loss components. This method has the potential for the most accurate gains in minimal time except that the uncertainty of the mismatch error between the AUT and the loss components is a relatively large unknown in the calculations. The time required for moderate effort compared to minimal effort varied from 2 to 3.5 times, while the best practices time compared to minimal effort varied from 4 to 12 times.

One significant finding is that using attenuators to reduce the VSWR mismatches in the system is much more cost effective in terms of times than measuring reflection coefficients of the antennas and components. Adding the additional attenuation may not be viable from a dynamic range perspective. The benefit of doing either the additional attenuation or reflection coefficient measurements has been well known for near field measurements, but using reflection measurement in gain by substitution schemes improves their accuracies significantly.

The data shows that for many ranges, if the time investment is made, the accuracy of the gain measurements on that range can approach national laboratory results. However, the time vs. accuracy trade-off must be made by the test engineer and their organization.

8. REFERENCES

[1] Gabriel Sanchez and Pat Connor, "How Much is a dB Worth?", AMTA Symposium, 2001

[2] Michael H. Francis, et. al., "Comparison of Gains Determined from the Extrapolation and the Far-Field Pattern Integration Methods", AMTA Symposium 2005

[3] ANSI/IEEE Std 145-1993, Definitions of Terms for Antennas, 1993

[4] ANSI/IEEE Std 149-1979, Test Procedures for Antennas, 1980, Chapter 12

[5] Katie MacReynolds and Michael H. Francis, "The Three Antenna Extrapolation Method", AMTA Symposium, 1999

[6] Katie MacReynolds, et al., "Three Antenna Extrapolation Gain Measurement System at Millimeter-Wave Frequencies", AMTA Symposium, 2006

[7] Michael H. Francis and Ronald C. Wittman, "Swept Frequency Gain Measurements from 33 to 50 GHz at the National Institute of Standards and Technology, AMTA Symposium, 1991.

[8] Donald G. Bodnar, "Numerical Calibration of Standard Gain Horns and OEWG Probes", AMTA Symposium 2009.

[9] Allen C. Newell, et al. "Planar Near-Field Gain Measurements to Verify Calibration of Probes and Gain Standards", AMTA Symposium, 2001

[10] John McLaughlin and Robert Shoulders, "Calibration of Mismatch Errors in Antenna Gain Measurements", AMTA Symposium 1992

[11] Agilent 2 and 4 Port PNA-X Network Analyzer, Data Sheet and Technical Specifications, 2011, Agilent Technologies, Inc.N5242-90007

[12] Doren Hess, "An Apparent Discrepancy between Impedance Mismatch Factors for Near-Field and Far Field Measurements", AMTA Symposium, 2006

[13] MI-750 Antenna Measurement Receiver Brochure, 2010, MI Technologies

[14] Hollis, et. al., Microwave Antenna Measurements, Scientific-Atlanta, 1970, Chapter 14

[15] Kolesnikoff, Paul, “Antenna Gain Measurement Errors due to Finite Source Axial Ratio”, AMTA Symposium, 2000
[16] J. E. Hansen, Spherical Near-Field Antenna Measurements, Peter Peregrines Ltd., London, 1988

Gain by Substitution on a Compact Range						
Error Term	**Minimal Effort**		**Moderate Effort**		**Best Practices**	
	Error (dB)	**Time (hours)**	**Error (dB)**	**Time (hours)**	**Error (dB)**	**Time (hours)**
Gain standard gain	0.45	0	0.25	$$	0.1	$$$
Antenna peak alignment (X2)	0.14	0.2	0.07	0.5	0.04	1.0
Antenna polarization alignment (X2)	0.14	0.2	0.07	0.5	0.1	$$
AUT mismatch	1.1	0	0.3	0	0.03	2
SGH mismatch	0.68	0	0.16	0	0.03	2
AUT receiver linearity	0.05	0	0.1	0	0.05	0
SGH receiver linearity	0.125	0	0.175	0	0.125	0
AUT S/N	0.009	0.1	0.0045	0..3	0.002	0.6
SGH S/N	0.045	0.1	0.022	0..3	0.011	0.6
Range Antenna Aperture Taper (X2)	0.28	0	0.14	0	0.05	$$
$2D^2/\lambda$ Distance	0	0	0	0	0	0
Range antenna axial ratio (X2)	0.013	0	0.006	0	0.05	$$
RSS Error/Total Time	**1.42**	**0.6**	**0.50**	**1.6**	**0.22**	**5.2**

Gain by Substitution on an SNF Range						
Error Term	**Minimal Effort**		**Moderate Effort**		**Best Practices**	
	Error (dB)	**Time (hours)**	**Error (dB)**	**Time (hours)**	**Error (dB)**	**Time (hours)**
Gain standard gain	0.45	0	0.25	$$	0.1	$$$
AUT mismatch	1.1	0	0.3	0	0.03	2
SGH mismatch	0.68	0	0.16	0	0.03	2
AUT receiver linearity	0.05	0	0.05	0	0.05	0
SGH receiver linearity	0.125	0	0.125	0	0.125	0
AUT S/N	0.009	2	0.0045	6	0.002	20
SGH S/N	0.045	1	0.022	3	0.011	10
Range Antenna Aperture Taper (X2)	0.28	0	0.14	0	0.05	$$
Range antenna axial ratio (X2)	0.013	0	0.006	0	0.05	$$
RSS Error/Total Time	**1.40**	**3**	**0.49**	**9**	**0.19**	**34**

Gain by Gain Insertion Loss on an SNF Range						
Error Term	**Minimal Effort**		**Moderate Effort**		**Best Practices**	
	Error (dB)	**Time (hours)**	**Error (dB)**	**Time (hours)**	**Error (dB)**	**Time (hours)**
S_{21} and S_{11} of shorting attenuator and cable	0.3	0	0.05	0.2	0.02	0.6
AUT/Probe mismatch	1.34	0	0.35	0	0.04	2
AUT/shorting system/Probe mismatch	0.98	0	0.12	0	0.04	2
Probe Gain	0.45	0	0.25	$$	0.1	$$$
AUT receiver linearity	0.05	0	0.1	0	0.05	0
Shorting measurement receiver linearity	0.1	0	0.175	0	0.1	0
AUT S/N	0.009	2	0.0045	6	0.002	20
Shorting measurement S/N	0.045	.25	0.022	0.75	0.011	2.5
Range Antenna Aperture Taper	0.2	0	0.1	0	0.05	$$
Range antenna axial ratio (X2)	0.013	0	0.006	0	0.05	$$
RSS Error/Total Time	**1.76**	**2.3**	**0.50**	**8**	**0.19**	**27.1**

Gain by Three Antenna Method in the Far Field						
Error Term	**Minimal Effort**		**Moderate Effort**		**Best Practices**	
	Error (dB)	**Time (hours)**	**Error (dB)**	**Time (hours)**	**Error (dB)**	**Time (hours)**
Antenna peak alignment (X3)	0.17	0.6	0.09	1.2	0.05	3.5
Antenna polarization alignment (X3)	0.17	0.6	0.09	1.2	0.05	$$
AUT mismatch	1.1	0	0.3	0	0.03	2
Opposite antenna mismatch	0.68	0	0.16	0	0.03	2
AUT receiver linearity	0.05	0	0.1	0	0.05	0
AUT S/N	0.009	0.1	0.0045	0..3	0.002	0.6
Opposite Antenna Aperture Taper (X2)	0.28	0	0.14	0	0.05	$$
$2D^2/\lambda$ Distance	0.05	0	0.025	0	0.025	0
Range antenna axial ratio (X2)	0.013	0	0.006	0	0.05	$$
RSS Error/Total Time	**1.35**	**1.3**	**0.40**	**2.4**	**0.12**	**8.1**

Gain by Directivity in an SNF Range and Loss Measurement by Other Means						
Error Term	**Minimal Effort**		**Moderate Effort**		**Best Practices**	
	Error (dB)	**Time (hours)**	**Error (dB)**	**Time (hours)**	**Error (dB)**	**Time (hours)**
AUT Directivity	0.1	2	0.05	6	0.03	20
AUT receiver linearity	0.05	0	0.1	0	0.05	0
AUT S/N	0.009	0.1	0.0045	0..3	0.002	0.6
Lossy components measurement	0.05	0.25	0.03	0.75	0.02	2.5
Mismatch of mating lossy components to AUT (estimated)	0.2	0	0.2	0	0.2	0
RSS Error/Total Time	**0.23**	**2.4**	**0.23**	**6.8**	**0.21**	**23.1**