BROADBAND GAIN STANDARDS FOR WIRELESS MEASUREMENTS

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Abstract

Total Radiated Power (TRP) and Total Isotropic Sensitivity (TIS) are the two metrics most commonly used to characterize the over the air (OTA) performance of a wireless device. Measurement of these quantities requires a reference measurement of the loss from the origin of the spherical coordinate system to the power measurement device. Calibrated dipoles are typically used as gain standards for the reference measurement. These narrow bandwidth dipoles can provide low uncertainty reference measurements, but numerous dipoles are required to cover all of the wireless frequency bands. Since typical wireless measurement systems must be calibrated from 700MHz to 6GHz, calibration of the measurement system with narrow bandwidth dipoles becomes a tedious and time-consuming exercise. Broadband gain standards can be used, but due to the uncertainty in their absolute gain and their interaction with the measurement system, these add uncertainty to the reference measurement. This paper reports on a broadband gain standard and a measurement procedure that allow an extremely fast reference measurement while at the same time does not appreciably increase the uncertainty of the reference measurement.

Keywords: **gain standard, OTA, TIS, TRP, wireless, CTIA, reference measurement, EIRP**

1. Introduction

Total Radiated Power (TRP) and Total Isotropic Sensitivity (TIS) are the two metrics most commonly used to characterize the over the air (OTA) performance of a wireless device. Measurement of these quantities requires a reference measurement of the loss from the origin of the spherical coordinate system to the power measurement device.

Calibrated dipoles are typically used as gain standards for the reference measurement. These narrow bandwidth dipoles can provide low uncertainty reference measurements, but numerous dipoles are required to cover all of the wireless frequency bands. Since typical wireless measurement systems must be calibrated from 700MHz to 6GHz, calibration of the measurement system with narrow bandwidth dipoles becomes a tedious and time-consuming exercise. A broadband gain standard would have obvious advantages, but the issue is how to gain the advantages of a broadband gain standard without giving up the inherent low gain uncertainty of a calibrated dipole.

2. The Range Reference Measurement

The range reference measurement is used to convert the measured power values into values of EiRP from which the Total Radiated Power (TRP) can be calculated.

TRP is defined as

$$TRP = \oint U(\theta,\phi)\,d\Omega$$

Where U is the radiation intensity in watts per steradian. With some mathematical manipulation TRP can also be expressed as

$$TRP = \frac{1}{4\pi}\int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} EiRP(\theta,\phi)\sin(\theta)\,d\theta\, d\phi$$

What is actually measured is a relative power that must be corrected to get EiRP. The received power P_r in the measurement can be expressed as

$$P_r = P_o G_t(\theta,\phi) G_r(\theta,\phi)\left(\frac{\lambda}{4\pi R}\right)^2$$

Where

- P_0 is the transmitted power of the DUT
- G_t is the gain of the DUT
- G_r is the gain of the measurement antenna
- λ is the wavelength at the measurement frequency
- R is the separation of the DUT and the measurement antenna

EiRP can be expressed as

$$EiRP = P_o G_t(\theta,\phi)$$

And we will define path loss PL as

$$PL = G_r(\theta,\phi)\left(\frac{\lambda}{4\pi R}\right)^2$$

Therefore

$$EiRP = \frac{P_r}{PL}$$

Thus it is possible to convert the relative power measurements into EiRP measurements if one knows the path loss from the origin of the measurement system to the input of the power measurement device. Determining this path loss is known as the range reference measurement. This measurement typically consists of placing an antenna of known gain at the origin of the measurement system and measuring the power input to the antenna and the power received by the power measurement device. The path loss, or range reference measurement, is then

$$PL = Pt + G - Pr$$

Where

- Pr is the received power by the measurement receiver in dBm
- Pt is the power input to the gain standard in dBm
- G is the absolute gain of the gain standard in dBi

It is important to note that the range reference measurement is used to convert each measured data point to EiRP. A measurement uncertainty in the reference measurement translates to a measurement uncertainty in the measured TRP.

3. The Effect of Finite Range Lengths

Wireless devices are measured at finite range lengths. This introduces the possibility of measurement uncertainties due to the range length. There are two major contributors to measurement uncertainty due to range length. These are

1. Uncertainties due to phase taper across the aperture of the gain standard
2. Uncertainties due to the position of the phase center of the gain standard relative to the origin of the measurement system.

Both of these two uncertainty contributions have encouraged the use of dipoles as the gain standards of choice for wireless measurements. With a dipole one has a physically small antenna thus minimizing the phase variation across its elements, and also a very well defined phase center thus minimizing errors due to the location of the phase center relative to the measurement system origin. Another advantage of the dipole is that its theoretical gain can be calculated and its actual gain can be expected to be within a few tenths of a dB of its theoretical gain. Offsetting these advantages is the fact that a dipole is a narrow bandwidth device and hence multiple dipoles must be used to determine the path loss in a wireless measurement system, and this results in an onerous and time-consuming range calibration process.

4. Difficulties in Using Broadband Antennas as Gain Standards

Two broadband antennas that might be used for gain standards in wireless measurements are log periodic antennas and dual ridged horn antennas. Both of these antennas are physically larger than the dipole, have phase centers that are not clearly defined and move with frequency, and whose actual gain can deviate significantly from the theoretical gain. However, these antennas have one very attractive feature. Because of their bandwidth it is possible to complete the range reference measurements very quickly.

The purpose of this paper is to define how to minimize the uncertainty contributions due to these effects so that the advantages of the high speed reference measurement can be obtained without significantly increasing the uncertainty of the reference measurement.

5. The Concept of “Apparent” Gain

In order to facilitate this discussion, we will define the apparent gain of the broadband gain standard (BGS) as the gain that would be measured in a gain transfer measurement from a gain standard dipole to the broadband gain standard. In order for this apparent gain to be useful, it must be measured in a configuration identical to the actual measurement configuration being calibrated. In practice this means that the measurement must be made using the actual measurement antenna and maintaining its distance from the center of the coordinate system.

The apparent gain of the broadband gain standard will be the absolute far-field gain of the broadband gain standard modified by any effects due to the

1. The finite range length
2. The offset of the phase center of the broadband gain standard from the origin of the measurement system coordinate system

3. Measurement of Apparent Gain

As mentioned previously the apparent gain would be measured using a gain transfer measurement from a gain standard dipole to the broadband gain standard. Given that the calibration configuration for the gain transfer must be identical to the measurement configuration for the chamber in which the gain standard is to be used, the most expedient approach would be to perform the gain transfer measurement in the actual chamber where the gain standard will be used..

4. Additional Uncertainties in Apparent Gain

There are numerous potential contributors to measurement uncertainty that must be considered when using the concept of apparent gain.

Measurement Repeatability – The repeatability of RF connectors and the effects of cable flexing make it impossible to exactly repeat any measurement. However, by using high quality phase stable coax cables and high quality connectors tightened to their specified torque, these uncertainties can be kept to less than 0.05dB.

Extraneous Signals – Reflections from the chamber surfaces, standing waves between the BGS and the measurement antenna, and interactions between the BGS and the DUT support structure all result in extraneous signals received by the BGS. However, because we are making a gain transfer measurement from the dipole to the BGS, and we are not trying to determine the absolute gain of the BGS, these effects can be minimized by careful positioning of the BGS prior to making a measurement.

Positioning Uncertainty – It is important to carefully and accurately position the BGS on the peak of its main beam prior to making a measurement. However, it is not the actual pointing direction of the BGS that is important. Rather it is the repeatability of the positioning that is important.

Effects of Temperature – All RF measurements tend to vary with temperature so controlling the temperature to reasonable levels is simply good measurement practice.

Receiver Linearity – Because the difference in gain of the BGS and the dipole is only 6-8dB, the effects of non-linearity in the receiver are negligibly small.

Mismatch – Because we are making a gain transfer measurement of apparent gain, the match into the BGS is not critical. However, it was determined that placing a 10dB attenuator at the calibration point made a significant improvement in the repeatability of the VNA calibration.

Beam Skew vs Frequency – The direction of maximum gain of broadband antennas tends to change with frequency. However, since we are making a gain transfer measurement, this change in gain is not important so long as it is repeatable.

Because we are using the apparent gain rather than the absolute gain of the BGS, the largest uncertainties associated with a typical gain measurement are reduced to the positioning uncertainty of the BGS.

5. Measurement Procedure

The measurement procedure was to first determine the range loss using calibrated dipole antennas and then to measure the range loss using a log periodic antenna (LPA). The difference between the two different range loss measurements is the difference between the absolute gain of the dipole and the apparent gain of the LPA, and the apparent gain of the LPA is this difference plus the gain of the dipole.

A Vector Network Analyzer (VNA) was used to make both sets of measurements. Figure 1 shows the measurement setup.

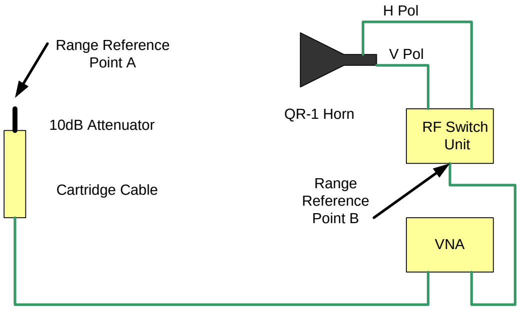

Figure 1

Measurement Setup Block Diagram

An S_{21} calibration was first performed. A long phase stable RF cable was connected from Port 2 of the VNA to the output of the 10dB attenuator. This measurement setup is shown in Figure 2.

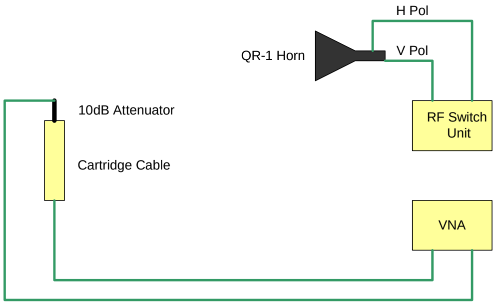

Figure 2
VNA Calibration Block Diagram

The calibration was performed at increments of 5MHz from 710MHz to 2655MHz. This provided a cal data set that could be used in the measurement of all the dipoles and the LPA.

Next the RF cable was disconnected from the 10dB attenuator and connected to the output of the RF Switch. A calibrated dipole was attached to the output of the 10dB attenuator and the height of the dipole adjusted to place its phase center on the intersection of the phi and theta axis. An S_{21} measurement was then made at the low, mid and high frequencies of the dipole. This procedure was repeated until a total of 13 dipoles had been measured. A block diagram of this measurement is shown in Figure 3.

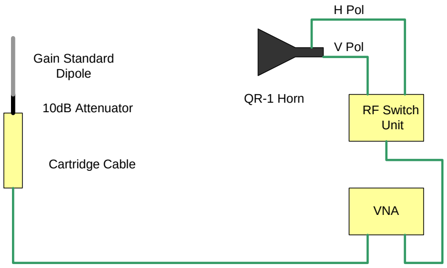

Figure 3
Dipole Measurement Block Diagram

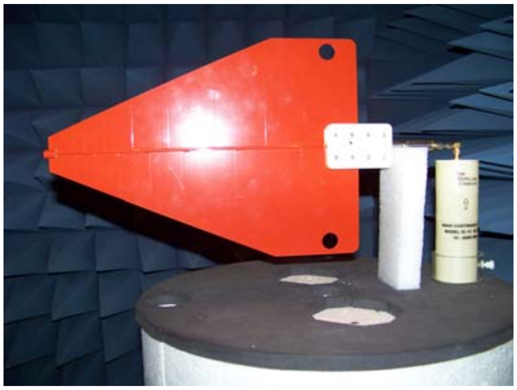

Figure 4
LPA Vertical Polarized Configuration

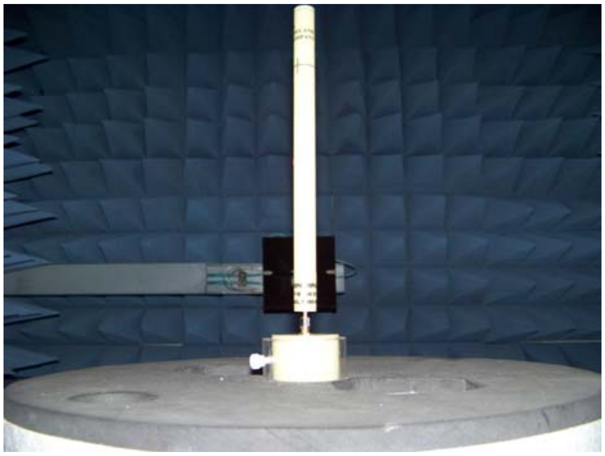

Figure 4
Dipole with QR-1 in Background

Next the dipole was removed and replaced with the LPA. The LPA was vertically polarized and a dual axis laser was used to precisely align the LPA axis along the range axis. The dual axis laser was used to obtain repeatability in the placement of the LPA rather than to achieve any specific alignment. A picture of the LPA installation is shown in Figure 4.

S_{21} measurements were then made at 5MHz intervals from 710MHz to 2655MHz.

Next the LPA was rotated 90 degrees on its axis so that it was horizontally polarized. Again it was carefully aligned using the dual axis laser so that it could be precisely repositioned in future measurements. The horizontal orientation is shown in Figure 5. S_{21} measurements were repeated at 5MHz intervals from 710MHz to 2655MHz.

Three complete sets of measurements were made using the LPA antenna to determine how repeatable the measurement procedure was. For each set of measurements the LPA was removed, a new calibration of the VNA performed, and then new S_{21} measurements made for both polarizations.

6. Measurement Results

The measurement results of the dipole calibration and the first set of LPA measurements are shown in Table 1.

Table 1
Dipole Calibration Results

Freq (MHz)	Dipole Gain (dBi)	S_{21} Dipole VP (dB)	S_{21} LPA VP (dB)	S_{21} LPA HP (dB)	LPA Apparent Gain (dBi)
715	1.90	-31.02	-25.26	-24.74	7.66
720	1.93	-30.85	-25.00	-24.50	7.78
725	1.93	-30.78	-24.85	-24.41	7.86
820	1.85	-30.30	-24.45	-24.24	7.70
835	1.86	-30.01	-24.37	-24.32	7.50
850	1.86	-29.84	-24.29	-24.39	7.41
870	1.89	-29.79	-24.15	-24.39	7.53
880	1.91	-30.19	-24.13	-24.40	8.08
885	2.02	-29.75	-24.59	-24.31	7.17
895	2.01	-29.92	-24.76	-25.01	7.18
900	2.02	-30.24	-25.80	-26.12	6.45
915	1.99	-30.90	-24.40	-24.57	8.49
925	1.92	-30.97	-24.60	-24.69	8.30
945	2.02	-30.93	-24.48	-24.24	8.46
960	2.05	-31.25	-25.32	-24.90	7.98
1560	1.60	-35.94	-30.10	-30.01	7.44
1585	1.59	-36.06	-30.14	-30.16	7.50
1610	1.71	-36.20	-30.23	-30.25	7.68
1710	1.59	-36.69	-30.63	-30.56	7.65
1750	1.91	-36.94	-31.03	-30.80	7.81
1785	1.77	-37.34	-31.40	-31.10	7.71
1805	1.72	-37.63	-31.30	-31.01	8.05
1840	1.82	-37.71	-31.39	-31.36	8.15
1850	1.62	-37.90	-31.48	-31.47	8.04
1880	1.84	-37.86	-31.74	-31.79	7.96
1910	1.70	-38.21	-32.19	-32.28	7.73
1930	1.73	-38.70	-32.56	-32.53	7.87
1960	1.70	-39.04	-32.76	-32.69	7.98
1990	1.63	-38.95	-33.01	-33.00	7.57
2110	1.75	-39.27	-33.50	-33.34	7.52
2140	1.82	-39.33	-33.59	-33.23	7.56
2170	1.76	-39.38	-33.54	-33.18	7.60
2400	1.90	-39.90	-34.63	-34.44	7.17
2440	1.94	-39.85	-34.28	-33.94	7.51
2485	1.93	-39.89	-34.04	-33.68	7.78
2630	1.60	-40.17	-34.89	-34.74	6.88
2640	1.55	-40.08	-34.90	-34.84	6.73
2655	1.44	-40.02	-34.99	-34.98	6.48

The calibration factors determined from this first set of measurements are shown in Table 2.

Table 2
Calibration Factors

Freq (MHz)	Calibration Factor HP (dB)	Calibration Factor VP (dB)
715	32.43	32.92
720	32.31	32.78
725	32.30	32.71
820	31.95	32.15
835	31.83	31.87
850	31.81	31.70
870	31.93	31.68
880	32.50	32.21
885	31.48	31.76
895	32.21	31.94
900	32.60	32.26
915	33.08	32.89
925	33.00	32.89
945	32.73	32.95
960	32.89	33.30
1560	37.47	37.54
1585	37.68	37.65
1610	37.95	37.91
1710	38.23	38.28
1750	38.62	38.85
1785	38.83	39.11
1805	39.08	39.35
1840	39.53	39.53
1850	39.53	39.52
1880	39.77	39.70
1910	40.02	39.91
1930	40.41	40.43
1960	40.68	40.74
1990	40.58	40.58
2110	40.88	41.02
2140	40.81	41.15
2170	40.80	41.14
2400	41.63	41.80
2440	41.47	41.79
2485	41.49	41.82
2630	41.65	41.77
2640	41.59	41.63
2655	41.49	41.46

Table 3 summarizes the results of the three sets of measurements. For any frequency and any polarization, the worst case spread of the measurement is 0.09dB.

7. Summary & Conclusions

As the data in Table 3 shows, it is possible to repeat a calibration using a broadband log periodic antenna to within 0.09 dB. Thus using the LPA to perform the calibration rather than the set of precision dipoles will increase the uncertainty of the range calibration, but by less than 0.1dB.

The advantage of using the LPA as the gain standard is the speed with which the calibration measurement can be performed. Using a vector network analyzer and the broadband gain standard, it is possible to determine the cal factors for both polarizations in less than 30 minutes. Using the narrow bandwidth dipoles to make the same calibration takes a minimum of several hours to generate the same set of data.

The reason for periodically repeating the range calibration measurement is to determine if the path loss from the center of the test zone to the measurement receiver has changed. As components in this path age and wear, it is realistic to expect changes in the path loss. Through periodic calibration the effects of these changes can be eliminated from the measurement results. However, the longer the calibration interval, the more measurements will be affected before the cal factors are corrected. This calibration procedure could easily be performed once a week, and thus greatly reduce the likelihood of a change in range path loss causing problems in the measurement results.

Ultimately the uncertainty of the path loss measurement is limited by the accuracy of the gain standard used in the measurement. However, these measurements show that it is possible to transfer the accuracy of the narrow bandwidth dipole gain standard to a much more desirable broadband gain standard with less than 0.1dB increase in the measurement uncertainty.

8. References

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Table 3

Results from Three Calibrations w/ LPA

Freq (MHz)	Average		Spread	
	VP S_{21} (dB)	HP S_{21} (dB)	VP S_{21} (dB)	HP S_{21} (dB)
715	-25.26	-24.77	0.03	0.07
720	-25.00	-24.53	0.05	0.08
725	-24.85	-24.44	0.06	0.09
820	-24.45	-24.25	0.02	0.01
835	-24.37	-24.33	0.02	0.04
850	-24.29	-24.40	0.02	0.04
870	-24.15	-24.40	0.02	0.03
880	-24.13	-24.41	0.02	0.04
885	-24.14	-24.50	0.01	0.04
895	-24.76	-25.03	0.01	0.06
900	-25.80	-26.15	0.04	0.09
915	-24.40	-24.59	0.01	0.07
925	-24.60	-24.70	0.01	0.04
945	-24.99	-24.82	0.02	0.02
960	-25.32	-24.91	0.02	0.05
1560	-30.10	-30.03	0.01	0.06
1585	-30.14	-30.17	0.02	0.04
1610	-30.23	-30.27	0.02	0.06
1710	-30.63	-30.58	0.02	0.05
1750	-31.03	-30.81	0.02	0.04
1785	-31.40	-31.12	0.00	0.06
1805	-31.30	-31.04	0.03	0.07
1840	-31.39	-31.38	0.01	0.05
1850	-31.48	-31.48	0.01	0.05
1880	-31.74	-31.80	0.01	0.05
1910	-32.19	-32.29	0.01	0.04
1930	-32.56	-32.54	0.02	0.02
1960	-32.76	-32.71	0.01	0.05
1990	-33.01	-33.02	0.02	0.05
2110	-33.50	-33.37	0.02	0.07
2140	-33.59	-33.25	0.02	0.06
2170	-33.54	-33.20	0.02	0.08
2400	-34.63	-34.46	0.02	0.06
2440	-34.28	-33.96	0.01	0.08
2485	-34.04	-33.71	0.00	0.06
2630	-34.89	-34.77	0.03	0.08
2640	-34.90	-34.86	0.03	0.07
2655	-34.99	-35.01	0.01	0.09