AN IMPROVED ANTENNA GAIN EXTRAPOLATION MEASUREMENT

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ABSTRACT

An improved system for antenna gain extrapolation measurements is proposed. The improved method consists of a vector network analyzer, a pair of RF optical links, and a pair of waveguide mixers. This change in hardware equates to a system with better dynamic range and a simplified reference measurement. We present a detailed description of the new extrapolation measurement setup, discuss the advantages and disadvantages, and validate the new setup by measuring the gain of an antenna previously measured with a traditional extrapolation setup. After presenting the comparison, we will discuss applications of this measurement system that extend beyond extrapolation gain measurements (e.g., spherical near- and far-field pattern measurements).

Keywords: Antenna Gain, Extrapolation Measurement, Spherical Near-Field, Vector Network Analyzer

1.0 Introduction

There are several methods of measuring the gain of an antenna. The main difference between these methods is where the measurements take place: anechoic chamber, outdoor area test site (OATS), or extrapolation range. Regardless of the environment used, the concept is the same.

First introduced in [1], the three antenna measurement method enables the determination of absolute antenna gain and polarization given three antennas. To use the three antenna method, one need not know the gain of any of the antennas. This feature is what made the method more appealing than the older "substitution" method, where an antenna was compared to a known standard. The original three antenna method has been modified and expanded to be applicable to any of the measurement environments listed above.

The first application of the three antenna method to extrapolation gain measurements was in [2], where it was shown that if a sufficient number of measurements were taken in the near-field of the antenna, the gain data could be extrapolated to the far-field of the antenna. This "conversion" from the near-field to the far-field was accomplished using a polynomial curve fitting process. Later, in [3], this procedure was summarized and updated. Since then, the NIST extrapolation gain measurement has essentially remained essentially unchanged.

This traditional method was still used by NIST through 2010, when the system was retired. In its place, a new measurement system was developed using modern hardware. Extrapolation gain measurements made using the original hardware configuration can still provide accurate data, as the technique and mathematics behind the measurement have not changed.

The result of modernizing the measurement system is a reduced number of components, a simplified reference/calibration procedure, improved dynamic range, and improved system stability over time and distance. The key components of this measurement system are a vector network analyzer (VNA), a pair of RF optical links, and a pair of waveguide mixers.

In this paper, a detailed description of the new extrapolation measurement setup is presented after a brief overview of the original system. A WR-42 standard-gain horn that was measured on the original system is then measured on the new system. The results of this measurement are compared as a means for validating the modern measurement setup. Finally, the advantages and disadvantages of the modern setup are discussed along with potential applications to other measurements.

2.0 Original NIST Measurement Setup

The goal of any extrapolation gain measurement is to measure the received power as a function of separation distance, given a constant transmitting power. To accomplish this, the ratio of transmitting and receiving power, and the separation distance must be measured.

In the original NIST measurement setup, outlined in Figure 1, measurement of the transmitted and received power was accomplished through a dual channel receiver (denoted as RCV) that measured the difference between the two signals. Harmonic mixers were used as needed to adapt the receiver to the desired frequency range. These mixers could be either coaxial or waveguide.

A rotary vane attenuator (RVA) was placed after the coupler to keep the received signal (on the load side) in the linear range of the receiver. This RVA was adjusted for each pair of horns/frequency range. It was critical that the RVA be precisely calibrated and tuned for each

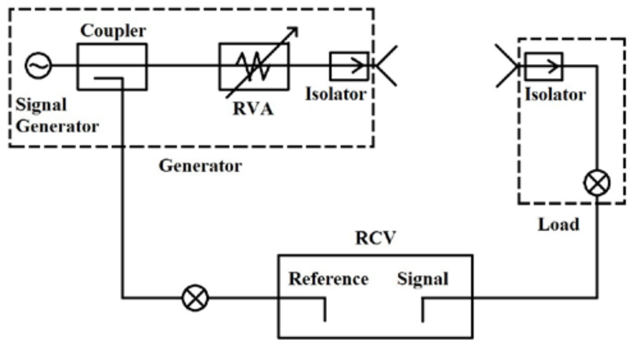

Figure 1 – Original NIST extrapolation gain measurement setup.

measurement. The uncertainty associated with the calibration of the RVA was accounted for in the final gain uncertainty, and typically added 0.05 dB to the unexpanded uncertainty.

To ensure the signal generator and receiver were working at the same frequency, they were phase-locked together. The phase locked signal was strictly a reference signal and contained no a priori information regarding the list of frequencies to be measured. This forced the measurement system to be locked to a single frequency because any sudden change in the signal generator's frequency would force the receiver to lose phase lock and measure the signal at an incorrect frequency.

To establish a reference for the received signal, the horns were removed and the generator and load sides were directly connected. This is commonly referred to as a "generator-load measurement." This measurement characterized the losses in the generator, load components, and cables, allowing them to be separated from the losses associated with the antennas being measured.

As with the extrapolation measurement, the receiver had to be kept in its linear range during this reference measurement. This meant the RVA must be adjusted again to have a higher attenuation during the generator-load measurement.

Data acquisition was accomplished by a computer connected to the receiver. Software was written to query the receiver, query the laser being used to measure the distance between the two antennas, and control the motor that physically moves the antennas apart. As the extrapolation measurement took place, the motor was set to a constant speed and the software constantly queried the laser until a specified interval was reached (e.g., every 2 mm). At this time software queried the receiver for the current value of received power.

Once the extrapolation measurement was complete, the data were saved. This process was repeated for each of the three antenna pairs. Once data had been collected for each pair, it was processed through software that calculates the far-field data based on a polynomial curve fit. From this, individual antenna gains can be found. This numerical process is detailed in [3].

3.0 An Improved Hardware Configuration

RF equipment has improved significantly over the last three decades. These improvements have translated into equipment with increased accuracy, dynamic range, and faster acquisition times.

Despite the change in measurement hardware, the goal of the extrapolation measurement remains the same: transmit a signal through one antenna, measure the amplitude and phase (if desired) of the received signal through another. This measurement requires a source and receiver phase locked through a reference. These components are available individually, but also as a single unit, vector network analyzer (VNA).

Though the network analyzer consolidates some of the hardware into a single unit, gain extrapolation measurements are commonly conducted over a span of meters. Coaxial cables may be used to cross the distance between the VNA and antennas, but their inherent attenuation negatively impacts the dynamic range and phase stability. In their place, a set of optical links can be used.

As with coaxial cables, optical links are subject to drift as a function of temperature and physical movement. Care must be exercised when selecting a pair of optical links for this measurement to ensure that the laser/oscillator are temperature controlled. Any systematic losses of the optical links (or coaxial cables) will be accounted for with a generator-load measurement. Any losses or phase changes that occur between the antenna and reference measurements (e.g., change in ambient temperature) will appear in the measurement data as an error. This error is accounted for in the measurement uncertainty.

The configuration of the network analyzer will depend on the exact hardware used. For simple setups, an S_{21} (transmission) measurement may be sufficient. More complicated setups may require directly measuring the receiver monitoring the transmitter (RX_A) and the measurement receiver (RX_B).

Figure 2 shows the new extrapolation measurement setup that utilizes a VNA and optical links. The optical links are denoted as E/O or O/E, indicating electrical-to-optical or optical-to-electrical. In this measurement we also utilized a frequency mixer. The VNA was placed behind the generator with one port directly connected to it. The receiving antenna (the “load”) is located 0.5-4 m from the generator. The optical links used to span this distance do not operate at a high enough frequency to directly couple the RF in this antenna measurement. To accommodate this, a frequency mixer was used to down-convert the received signal and feed it into the optical link. After the down-converted signal is passed through the optical link the network analyzer measures the IF signal.

The use of a frequency mixer is optional. It is shown here because the frequencies of interest exceed the capabilities of the optical links. To use mixers in this setup, the VNA analyzer must be capable of sourcing and receiving from the mixers. Modern network analyzers are available with options that make this possible (e.g., frequency offset mode and a configurable test set). Alternative hardware setups for VNAs that aren’t capable of working with mixers are possible, but the number of components increases significantly. These configurations are beyond the scope of this paper.

A comparison of Figure 1 and Figure 2 reveals that the use of a RVA is no longer required. The receivers on the VNA have a linear range large enough to accommodate the wide variation in power between the generator-load measurement and the extrapolation measurement. The lack of a RVA will also have a positive impact on the uncertainty budget. This is reflected in the sample budget shown in Section 5.

The comparison also shows that the isolators have been replaced with fixed-value attenuators. This change is optional. The goal of both devices is to improve the impedance match between the measurement system and the antennas.

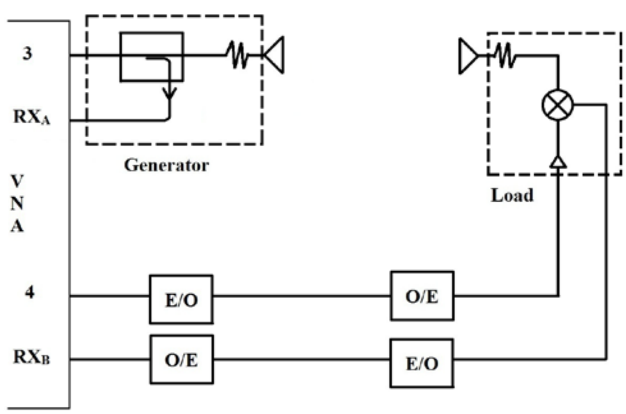

Figure 2 – New extrapolation measurement setup.

As with the original measurement system, there is a laser that measures the distance between the two antennas, a motion control system that automatically moves the load antenna, and a computer that interfaces with these systems.

The technique for completing the extrapolation measurement remains largely unchanged from the original system. Software is used to control the motor that separates the two antennas, and query the laser that measures the separation distance. The software also controls the VNA.

As the two antennas are separated at a constant speed, the software constantly queries the laser until a predefined distance interval is reached. At this point, the VNA is triggered; and both the generator and load receivers (RX_A and RX_B, respectively) are measured at all frequencies of interest. All of these values are saved for processing.

Even though both receivers are measured, a reference generator-load measurement is still required. This measurement will characterize the losses in the generator and load so they can be separated from the antennas being measured.

Once all three antenna pairs have been measured, the data are fed into the same processing software used in the original measurement setup to calculate the far-field polynomial fit and individual antenna gain, as shown in [3].

4.0 Validation

Before the system can be used to calibrate unknown antennas, it must first be validated using antennas that have been calibrated on another system. We chose to validate the system in the WR-42 band (18.0-26.5 GHz). In this band, NIST has several well characterized horns. In particular, the measurement history on the horn used in this validation dates back to 1982.

The validation process consisted of measuring the gain of three antennas, in order to complete a standard three antenna gain calculation. The three horns used in this validation were all WR-42 standard gain waveguide horns. Two of the horns were nearly identical in size, but with no previous information on their individual gain.

After the data have been processed and the individual gains have been calculated, the gain of the NIST horn can be compared to historical data. This is done in Figure 3.

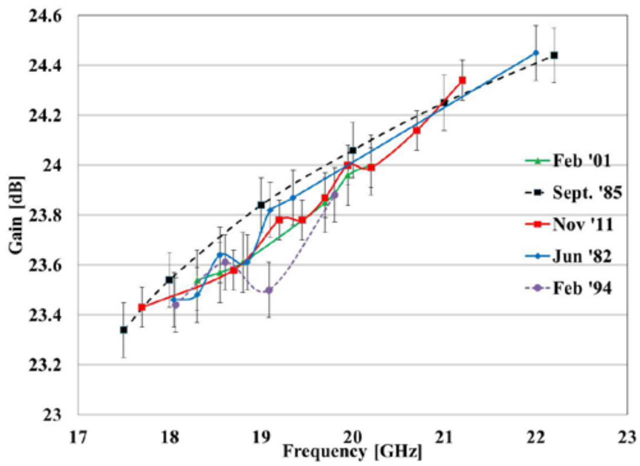

Figure 3 – Historical antenna gain data compared with data from the new hardware configuration.

Included in the plot of historical data are the data taken with the new extrapolation hardware setup described here. These data are labeled as “Nov ’11.” Though not all of the historical data sets are at exactly the same frequencies, there are enough in close proximity that a fair comparison can be made. Uncertainty bars for each data point are shown, and range from 0.08 dB to 0.12 dB, depending on the set. The uncertainty bars for the 1982, 1985, and 1994 data sets have a coverage factor of k=3. This is because the international standard governing uncertainties was not adopted until 1995. Data sets after 1995 use a k=2 coverage factor.

It should be noted that while the data points for each respective set shown in Figure 3 are connected with a line, this line is for illustrative purposes only. This line should not be read as an approximation of the actual gain between measured frequency points.

From the plot, it can be seen that the data taken with the new hardware configuration fall in line with the historical data. The only exception to this lies in the data from February 1994. At 19.085 GHz, there appears to be a statistically significant difference between the other four data sets and the 1994 set. This difference is most likely caused by an artifact of the coax-waveguide adapter used for that particular measurement.

5.0 Discussion

The biggest advantage of the new hardware setup is that the measurement time has been significantly reduced. Because the signal generator and receiver were physically separate pieces of equipment, the measurement system was limited to capturing a single frequency. If the antenna gain needed to be calculated at multiple frequencies, one measurement run was required for each frequency point.

With the new hardware configuration, the signal generator and receiver are within the same piece of equipment the VNA. The VNA has the ability to lock its signal generator and receiver together, thus allowing the frequency of both to be changed quickly and accurately.

For the particular system described in Section 3, we were able to acquire up to 10 evenly spaced frequency points across a single waveguide band. This number may change based on several factors including: antenna separation speed, VNA capabilities, and the spacing of frequency points.

The new hardware configuration also has the advantage of being able to capture both magnitude and phase of the transmitted and received signals. This advantage is only available in situations where harmonic mixers are not used. The phase of the signals is not required for a gain extrapolation measurement, but it does have other applications. See Section 6 for details.

The use of a VNA also allows for calibrating the power into the antenna (or into the mixer, if used) to help ensure that power is constant with frequency. These power calibrations are done with a power meter connected to the VNA and their data stored locally on the VNA. This power calibration helps to improve the overall system stability across the frequency band of interest.

By performing the proper one-port calibration on the VNA, one could also measure the reflections of the generator and load systems in place, before or after the gain extrapolation measurements. This eliminates the need to disassemble and reassemble the system elsewhere to perform these measurements.

An interesting point of the new hardware configuration is that it does not do much to decrease the measurement uncertainties. This is a result of the RVA not being a large contributor to the overall uncertainty. Table I shows the uncertainty budget calculated for the WR-42 validation measurement presented in the previous section.

These uncertainties are estimates generated for each known source of uncertainty. All components are Type B unless otherwise noted, and are assumed independent of other uncertainties. The expanded uncertainties use a coverage factor of k=2. The Ui (Kx) values are calculated by dividing the uncertainty by the positive square root of the variance of the distribution [4].

An examination of the uncertainty budget reveals that the only significant hardware dependent term is the non-linearity of the receiver. For gain extrapolation measurements, we are not necessarily concerned about the absolute accuracy of the receiver. Rather, we are concerned about the receiver’s relative accuracy as it

Table I – Uncertainty Budget

Source	Value (+/- dB)	Probability Distribution	Ui (kx) +/- dB
RX non-linearity	0.02	Rectangular (1.73)	0.0116
Impedance Mismatch	0.05	Rectangular (1.73)	0.0289
Antenna Alignment	0.02	Normal (3)	0.0067
Data Curve Fit	0.02	Rectangular (1.73)	0.0116
Connector Repeatability	0.03	Normal Type A (3)	0.0100
Residual Multipath	0.03	Rectangular (1.73)	0.0173
Random Uncertainties	0.03	Normal (3)	0.0100
Combined Uncertainty		Normal	0.0406
Expanded Uncertainty		**Normal (k=2)**	**0.08**

measures a signal of decreasing amplitude (as distance between the antennas increases).

In the measurements with the original hardware configuration, the receiver non-linearity was 0.05 dB, and there was an additional term for the uncertainty of the RVA. The unexpanded uncertainty of the RVA was 0.04 dB. Both of these terms together raised the total expanded uncertainty to 0.12 dB, with a k=3 coverage factor. If a k=2 coverage factor is used, the uncertainty becomes 0.08 dB. This uncertainty is approximately the same for the new hardware configuration.

6. Additional Applications

This new hardware configuration need not be limited to extrapolation gain measurements. Depending on how one's antenna range is setup, it may be possible to mount this hardware in such a way that a spherical near-field antenna measurement can be accomplished with this hardware configuration. When mounted on a spherical range, this hardware setup will still provide the same benefits and suffer from the same drawbacks discussed in the previous section.

As mentioned in Section 5, it is possible to measure the phase of the transmitted and received signals using the proposed hardware configuration. This is only possible if harmonic mixers are omitted from the system. Measuring the phase of the signals as the distance between the antennas increases provides a good check of the system. Processing the phase information can provide information on how well the system is performing since the phase change vs. distance is well known for a standard gain horn antenna.

Measurement of the phase information allows one to easily calculate the group delay of the antenna under test. The group delay can be calculated using a method similar to the three antenna method. Except in this case, instead of received power vs. distance, phase vs. frequency is the desired quantity.

7. Conclusions

The traditional NIST gain extrapolation measurement system has been updated to include a revised hardware configuration is presented. The new measurement method consists of updated hardware (including a VNA, and optical links). This change in hardware has been shown to significantly reduce the measurement/acquisition time, but does not have a significant impact on the overall measurement uncertainty. The new method was validated by comparing antenna gain measurements taken over the past 30 years. The data acquired with the new hardware configuration matches the historical data within the measurement uncertainties.

8. REFERENCES

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