Army Research Laboratory

Reproducibility Measurements on Two-plate Transverse Electromagnetic (TEM) Horn Transmit Antennas

by Steven Wienecke

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Steven Wienecke
Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

The performance of the U.S. Army Research Laboratory's Synchronous Impulse Reconstruction (SIRE) radar is dependent on the performance of the antennas and baluns that make up the radar system's physical aperture. We measured the S11 parameters of six different antenna configurations to find the most suitable transverse electromagnetic (TEM) antenna for our application in the 300 MHz−3 GHz frequency range. In this memorandum report, we show that these TEM transmit antennas can be reproduced consistently with a fairly high degree of accuracy, even when constructed by hand. We accomplished this by comparing the measurements for two fabrications of six antenna configurations, one fabricated by Gregory Smith and the other fabricated by the author. Most of the comparisons between two antenna fabrications are very close. For those antenna configurations for which discrepancies exist, we highlight the discrepancy and provide a potential explanation for why the difference occurred.

15. SUBJECT TERMS

Wideband, radar, antenna, TEM horn

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1. Background Information on SIRE

Detection of concealed weapons and explosives is critical to the Army's mission in both Iraq and Afghanistan. To address this problem, the U.S. Army Research Laboratory has developed the Synchronous Impulse Reconstruction (SIRE) radar system, which has wall-, ground-, and foliage-penetration capabilities. SIRE is an ultrawideband (UWB) synthetic aperture radar (SAR) imaging system, which can be mounted on top of a vehicle. The frequency range of operation is 300 MHz–3 GHz, which is a low enough frequency range to provide good penetration through lossy materials and a wide enough frequency band to achieve high downrange resolution.

The aperture size of the SIRE system is constrained by the size of the vehicle upon which it is mounted. This physical aperture, created by placing a horizontal array of receive antennas side by side on top of the vehicle, provides the cross-range resolution. A synthetic aperture, formed by the forward motion of the vehicle, provides the height resolution. This allows the two-dimensional aperture to give the cross-range resolution (from the physical aperture) and the height resolution (from the forward motion of the vehicle), resulting in a three-dimensional image. The bandwidth provides the downrange resolution ($\Delta r = c/(2*B)$, where Δr is the downrange resolution, c is the speed of light in free space, and B is the bandwidth).

2. Construction of Physical Aperture

The performance of the SIRE radar system is dependent on the S11 parameters of the antenna array used to create the physical aperture, as the only losses of the system result from the losses in the antennas and baluns. The basic structure of these antennas consists of a two-plate transverse electromagnetic (TEM) horn that is open lengthwise on two of its four sides, where a resistive plate is attached to its emitting end. The feed end is cut short of a perfect point so that the TEM horns are electrically divided and the drive wires can be separately attached to the top and bottom of the feed. A balun connects the radar transmitter to the antenna. The antenna's characteristic impedance must be 200 Ω in order for it to match the balun and prevent undesirable reflections. Figure 1 provides a side view of the basic construction of these antennas and figure 2 provides a rear view.

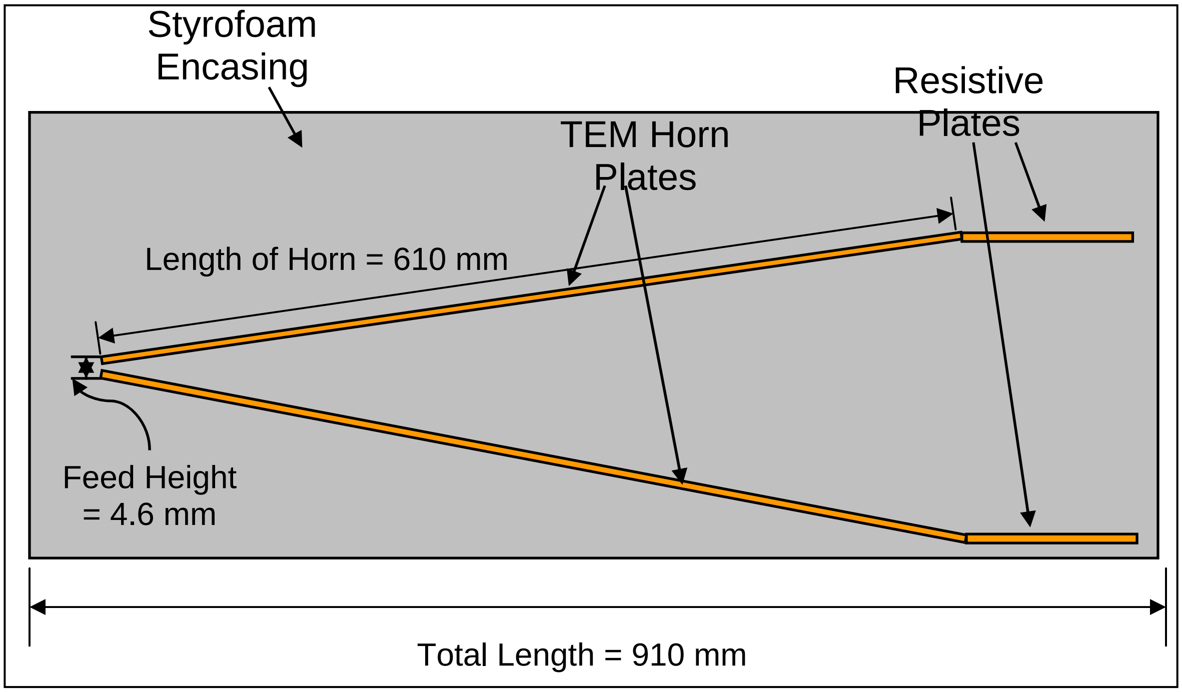

Figure 1. Basic structure and dimensions of the ARL TEM horn (side view).

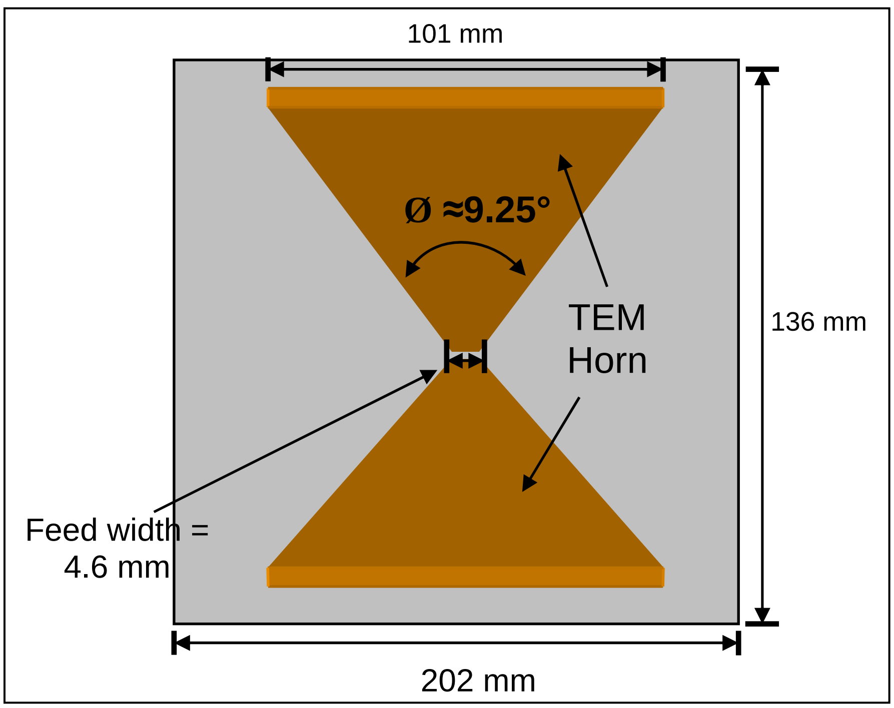

Figure 2. Basic structure and dimensions of the ARL TEM horn (rear view).

We explored six configurations of this basic antenna structure in order to achieve the best S11 parameters for our frequency range. In this report, we confirm the reproducibility of these six antenna configurations by comparing equivalent measurements for a set of these antennas constructed by Greg Smith to those of the same set of antennas constructed by the author. Good correlation in the measurements suggests that the antenna can be consistently reproduced. For those antenna designs for which discrepancies exist over certain frequency bands, a potential explanation for the discrepancy will be proposed. All measurements were taken with a Rhode & Schwartz ZVB4 Vector Network Analyzer.

The first five sets of measurements were taken for antennas that shared the same basic physical structure, i.e., the same TEM horn printed circuit boards or plates (will be referred to as TEM#1), the same Styrofoam encasing, and the same balun (balun#1). Moreover, the only differences in these antenna configurations were the resistive plates, the arrangement of the TEM horns (copper plate facing inside or outside), and the addition of some external components to the basic structure of the antenna. The sixth antenna configuration, however, was made with a different TEM horn plate (TEM#2) and balun (balun#2). Both the TEM horn plates and the balun were constructed with the intent of making them identical to the TEM horn plates and balun found on the first five antennas, but because the intent of this report is to show that these six antennas can be consistently reproduced, it is important to point out that the sixth antenna configuration was designed on a reproduction of the original basic physical structure of the antenna. Since the antenna/balun was handmade, the antenna's dimensions had an error bound of 3 mm for each measurement and the measured S11 parameters of balun#2 differed slightly from that of balun#1. The S11 parameters for balun#1 and balun#2 are compared in figure 3.

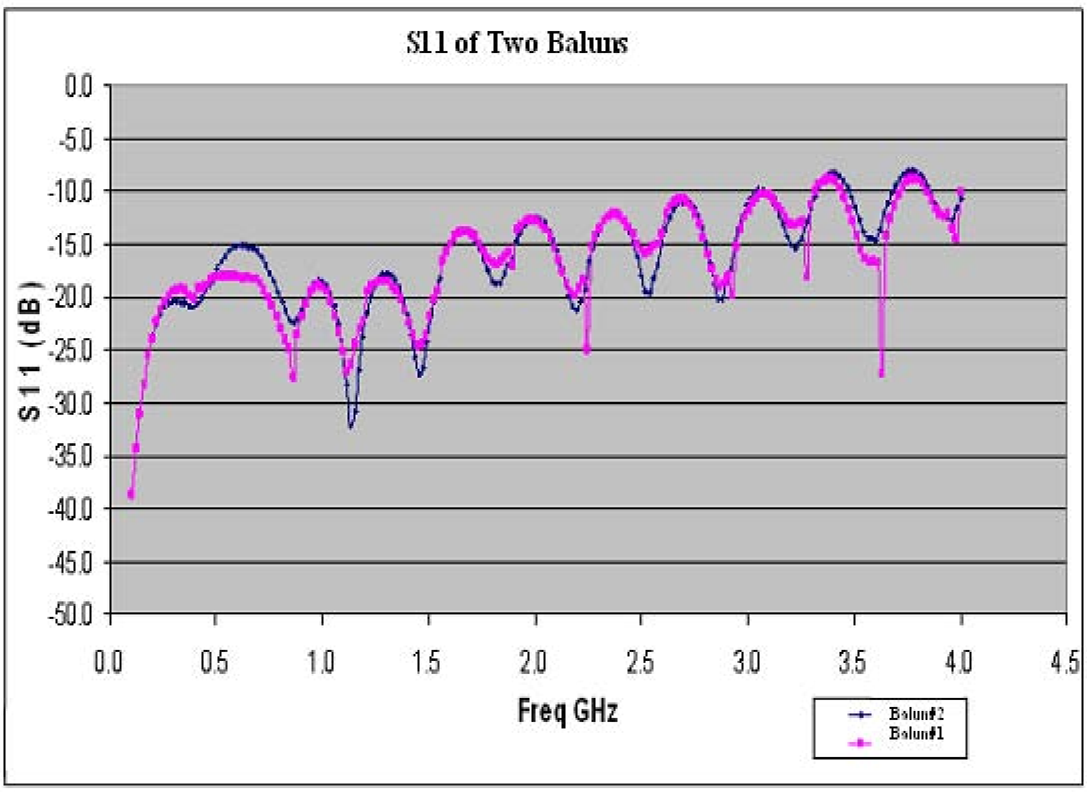

Figure 3. S11 Comparison of similarly constructed baluns.

3. Description of Each Antenna

The dimensions of each antenna configuration (except the sixth whose dimensions were slightly off as explained previously) are given by figures 1 and 2.

The characteristics of each antenna are as follows:

- **Antenna #1:** The first antenna measured had a 441 Ω resistively loaded parallel plate transmission line (shown in figure 4) connected to each TEM horn, as well as a 6-cm radius, 180° cylindrical flare. The TEM horn plates were ascribed with the copper surface on the outside of the antenna (the other side simply being the dielectric substrate).
- **Antenna #2:** In the second antenna measured, the same 6-cm radius, 180° cylindrical flares was kept, but the resistive plates were replaced with copper plates, which only had a resistance of 0.2 Ω. The copper surface of the TEM horns faced outwards.
- **Antenna #3:** In the third antenna, the copper plates remained, but the 6-cm cylindrical flare was replaced by a 3-cm, 180° cylindrical flare. The copper surface of the TEM horns faced outwards.
- **Antenna #4:** The fourth antenna only contained the copper plates, and all cylindrical flares were removed. The copper surface of the antennas faced outwards.
- **Antenna #5:** The fifth antenna had the 441 Ω resistively loaded parallel plate transmission line, as well as the same 180°, 6-cm radius flares, but in this antenna the copper surface of the TEM horns faced inwards and the dielectric substrate faced outwards.
- **Antenna #6:** It is important to reiterate that the final measurement was taken on the second antenna structure using balun #2. In this antenna, the parallel plate resistive sheets were replaced by the three contiguous resistive sheets shown in figure 5. These contiguous resistive sheets were created using a special dielectric ink spread over top each of the plates. The thickness and concentration of this ink determined the actual resistive values obtained. Because there was no uniform way to spread the ink and control the thickness of each coat, the resistive values of the plates were not uniform (although the concentration of the ink used was consistent).

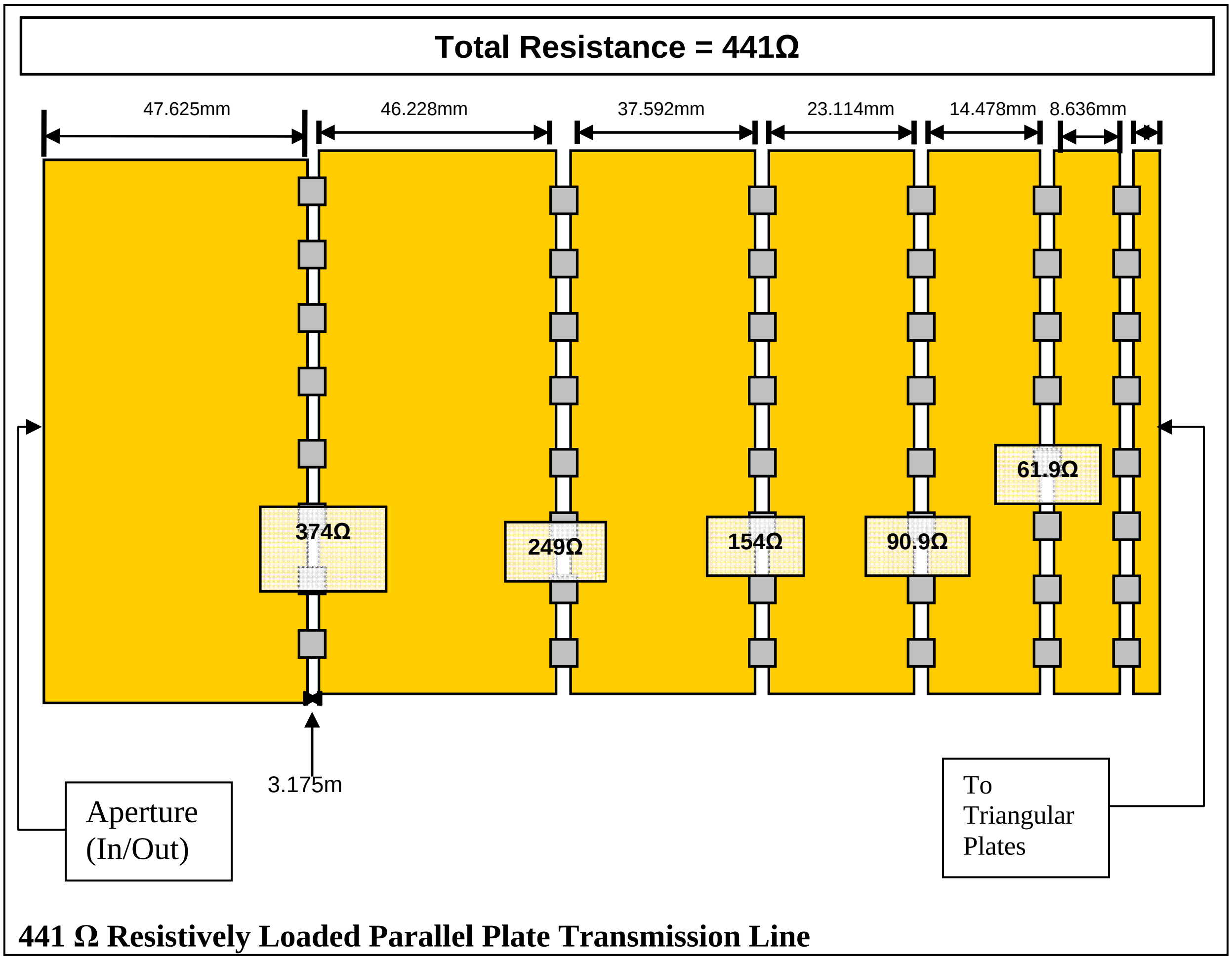

Figure 4. Dimensions, resistor locations, and values for the resistively loaded plates of Antenna #1 and Antenna #5.

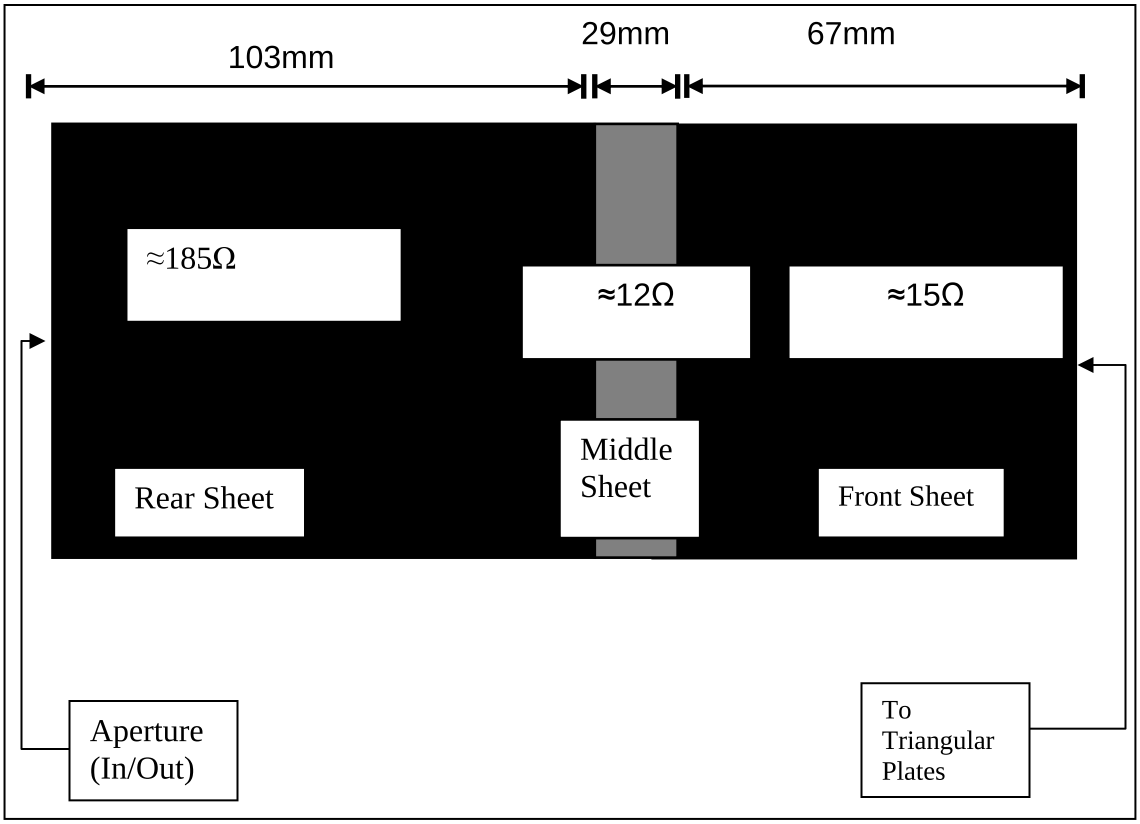

Figure 5. Contiguous resistive ink sheet used for the parallel plates of Antenna #6.

4. Comparison of Antennas

This section compares the measurements made by Greg on each particular antenna to the measurements I made on the same antenna. Both measurements were taken with a Rhode & Schwartz ZVB4 Vector Network Analyzer in the same room, under generally the same conditions. The only difference in our measurements was that Greg took 400 samples of data within the 300–30000 MHz frequency range, whereas I used 800 samples.

4.1 Comparison of Antenna #1

Figure 6 shows the comparison between Greg's and my measurements for Antenna #1. As can be seen, the two plots are nearly identical, and thus it is safe to conclude that Antenna #1 can be consistently reproduced.

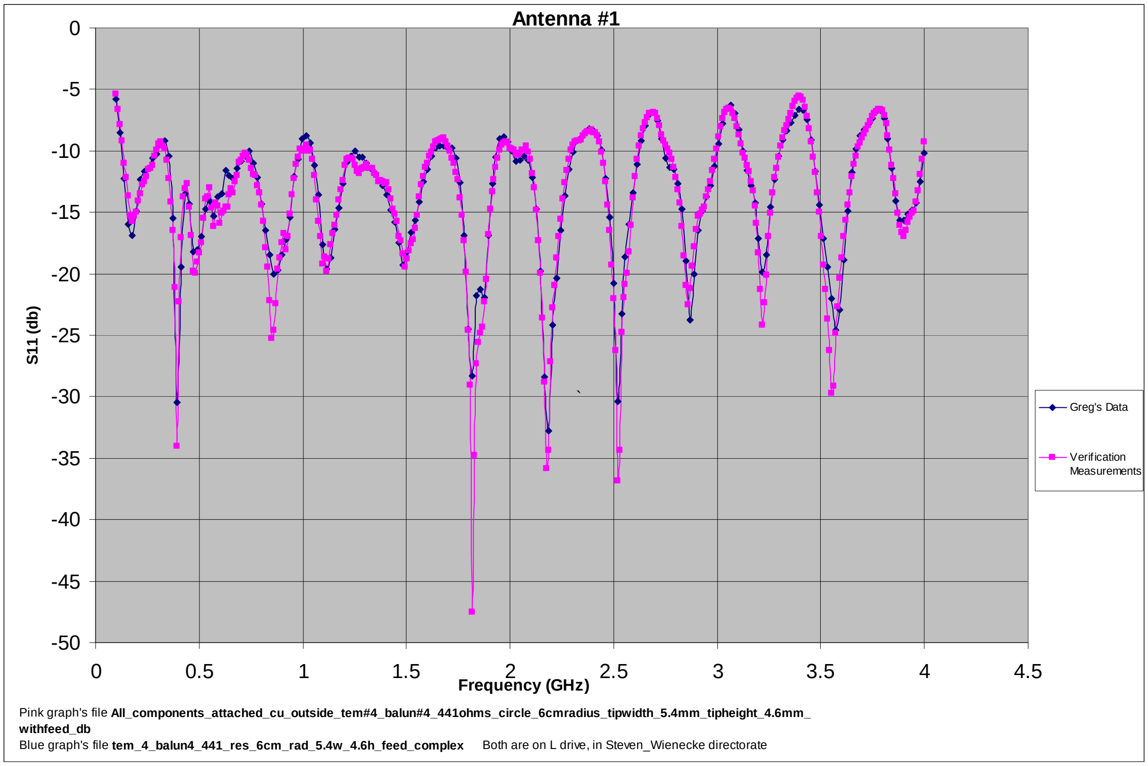

Figure 6. Comparison of S11 measurements taken on Antenna #1 (441 Ω resistively loaded parallel plate transmission line with 6-cm flares and copper TEM horns faced outwards).

4.2 Comparison of Antenna #2

Figure 7 shows the comparison for Antenna #2, where the 6-cm radius flares were kept, but the resistively loaded plates of figure 4 were replaced by copper plates with a resistance of 0.2 Ω. There were a few minor deviations between our recorded data, but as the figure shows, the two sets of data are extremely close to one another. Where differences did exist, my measurements were consistently higher than Greg's measurements. The places in the graph where at least four points on Greg's plot differed from the corresponding eight points of my plot by at least 1 dB are marked with ellipses. The rest of the comparisons throughout this report hold to the same criteria.

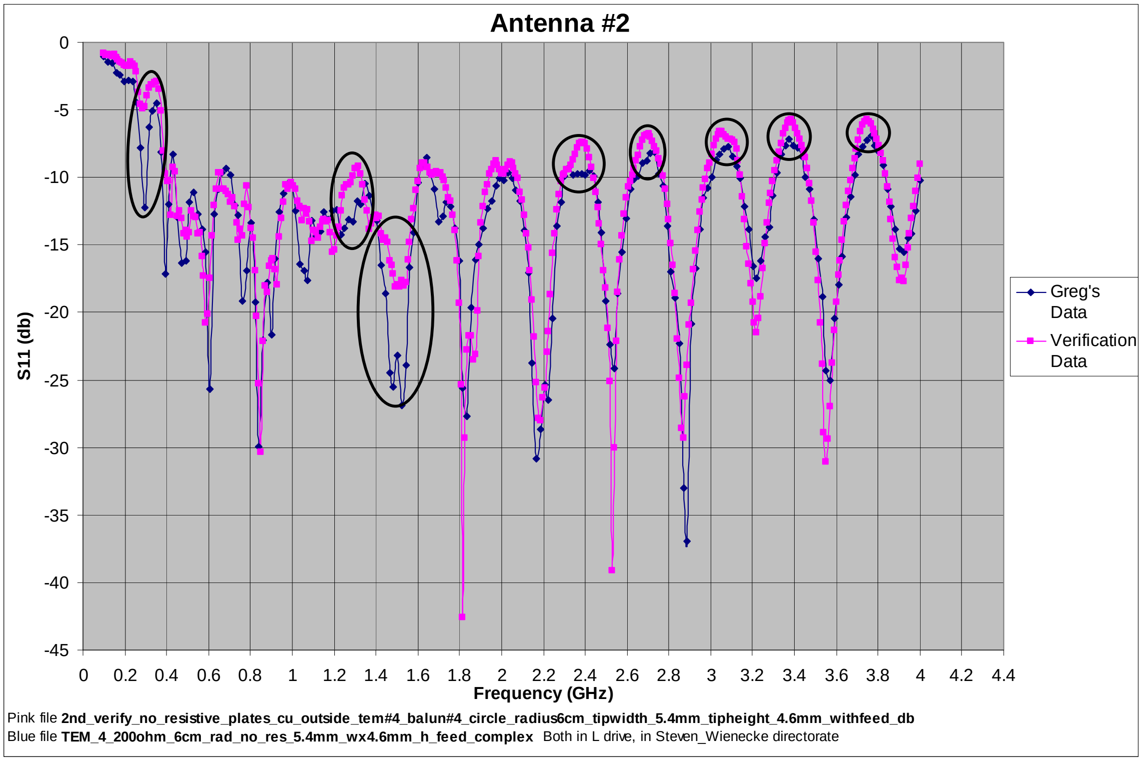

Figure 7. Comparison of S11 measurements taken on Antenna #2 (copper plate transmission line with 6-cm flares and copper TEM horns faced outwards).

All but one of the circled differences for the data on Antenna #2 were less than or equal to 2.5 dB. The largest difference (in terms of dB) occurred around 1.5 GHz, with an 8-dB difference in our measurements. However, both measurements at this frequency had an S11 less than –17 dB, indicating that this relatively large dB difference corresponds to a very small difference in terms of actual percentage of power reflected at 1.5 GHz (roughly a difference of 1.5% of the total supplied power).

The small differences seen in our graphs may be attributed to a number of different factors, one of which being the sensitivity of the Vector Network Analyzer. Greg and I assumed that any reflections from the room would produce negligible differences in the S11 data, so we did not time gate the measurements. However, of course, reflections from the room did occur. Moreover, the measurements were performed on different days, so it is conceivable that certain objects in the room may have been moved around during the time lapse from whence the two measurements were taken. Thus it is possible that differences seen at the lower dB values (since at the lower dB values a larger difference in dB corresponds to a smaller percentage of total reflected power than at higher dB values) may have been caused by the differences in the reflections received from the room as measured by the Vector Network Analyzer. This is a likely explanation of the deviation seen at 1.5 GHz.

Additionally, any time the coaxial cables are bent to attach/detach the cable to/from the balun of the antenna, the tension and compression exerted on the dielectric in the cable will change the impedance of the cable. This can cause a slight impedance mismatch between the cable and the balun of the antenna, resulting in a higher value of the measured S11. Thus, if Greg and I were to have made the measurements of the antenna with the cable oriented in different positions, there is a strong possibility the measured S11 parameter would be different due to different degrees of mismatch between the cable and balun. Furthermore, before conducting any of my own measurements, I detached and subsequently reattached the two TEM horns to the balun, and in the process slightly changed the feed height from what Greg had. This difference, coupled with the variation in the amount of solder used in the antenna/balun configuration, may have been a contributing factor as well.

Despite these minor disparities, the fact that our plots have identical shape and very close dB values verifies the reproducibility of Antenna #2. As will be seen, this holds true for Antennas #3–#5 as well. Because the causes of the small differences in these antennas are the same as for Antenna #2, the proposed explanation for these discrepancies is omitted for Antennas #3–#5 in the coming comparisons.

4.3 Comparison of Antenna #3

Figure 8 shows the comparison for Antenna #3, where the copper plates were kept, but the 6-cm radius flares were replaced by 3-cm radius, 180° cylindrical flares. This graph clearly indicates the reproducibility of Antenna #3.

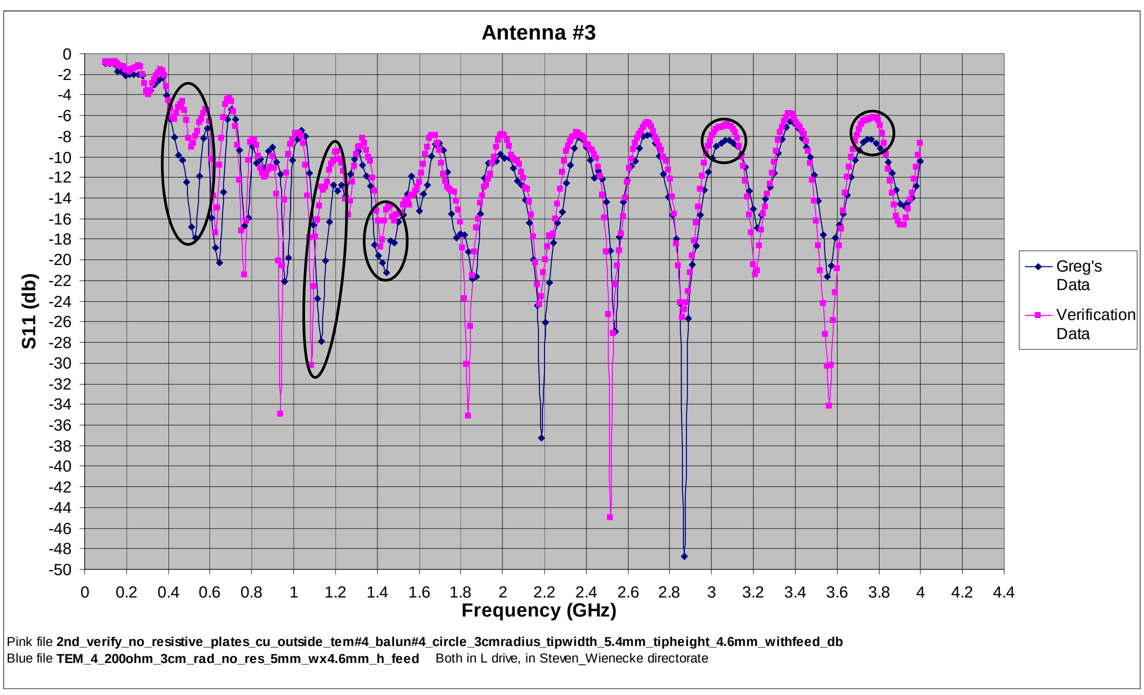

Figure 8. Comparison of S11 measurements taken on Antenna #3 (copper plate transmission line with 3-cm flares and copper TEM horns faced outwards).

4.4 Comparison of Antenna #4

Figure 9 is a comparison of Antenna #4, where the copper plates were kept, but all cylindrical flares were removed. Again, the graph confirms the reproducibility of this antenna.

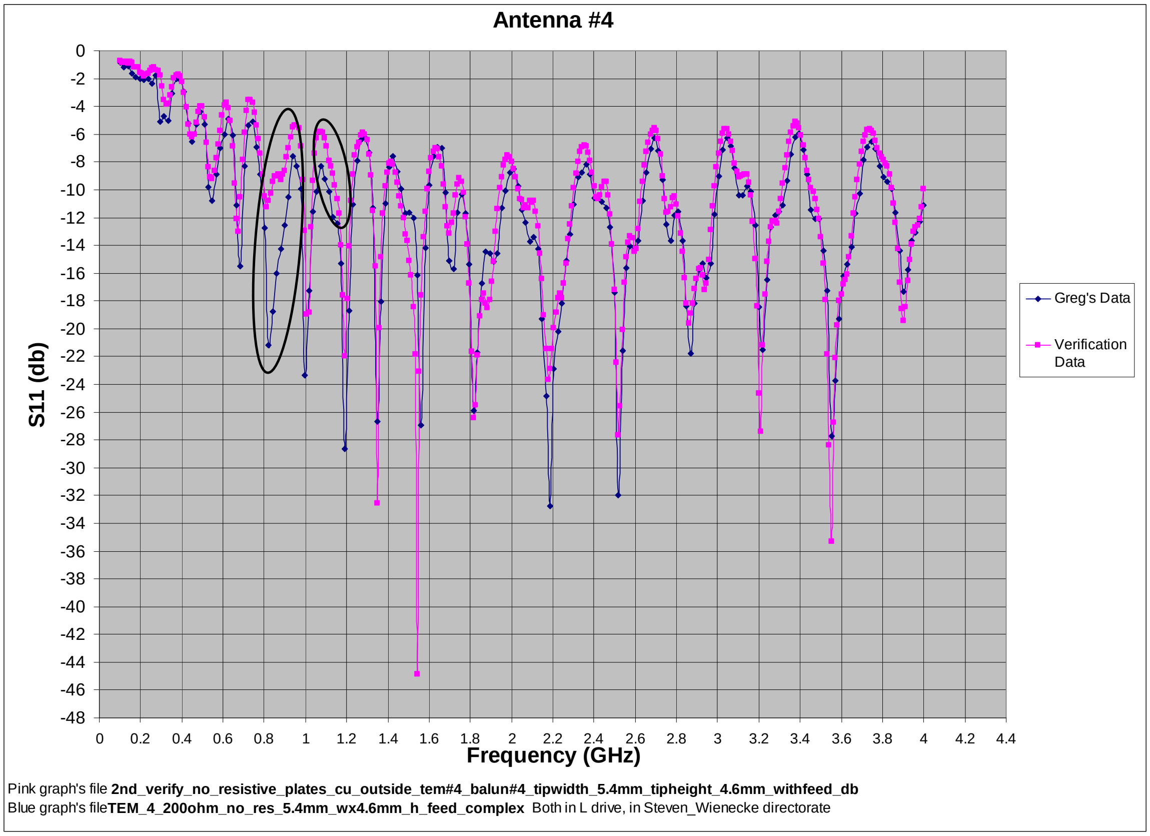

Figure 9. Comparison of S11 measurements taken on Antenna #4 (copper plate transmission line, no flares, and copper TEM horns faced outwards).

4.5 Comparison of Antenna #5

Figure 10 is a comparison of our measurements for Antenna #5, which was very similar to the first, in that it had the 441 Ω resistively loaded parallel plates, as well as the 180°, 6-cm radius cylindrical flares. However, in this antenna the copper face of the TEM horns faced downward. The graph verifies the reproducibility of Antenna #5.

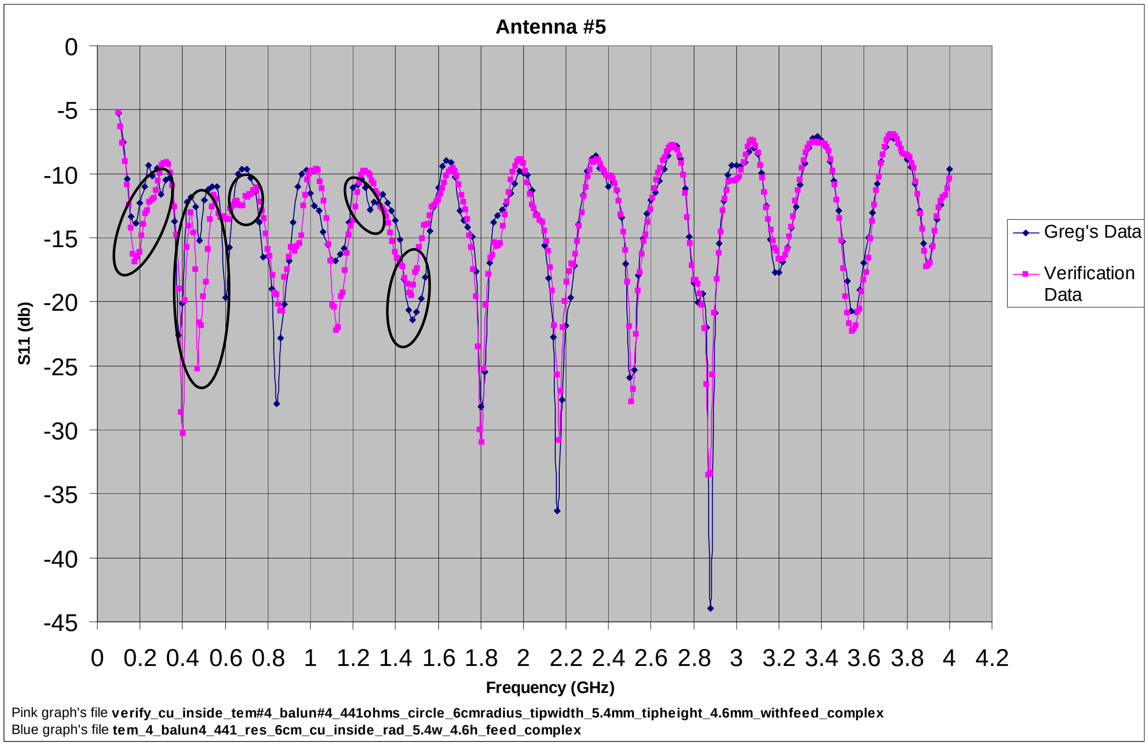

Figure 10. Comparison of S11 measurements taken on Antenna #5 (same as Antenna #1 with copper TEM horns faced inwards).

4.6 Comparison of Antenna #6

Figure 11 shows the comparison for Antenna #6, where three contiguous resistive sheets were attached to each TEM horn in place of either the copper plates or the 441 Ω parallel resistive plates. Although Greg and I both used the same antenna structure (Styrofoam encasing, TEM horns, and balun) to take our measurements, it should be noted that the antenna structure and balun used were not exactly the same as those used in the previous measurements, as explained in section 3.

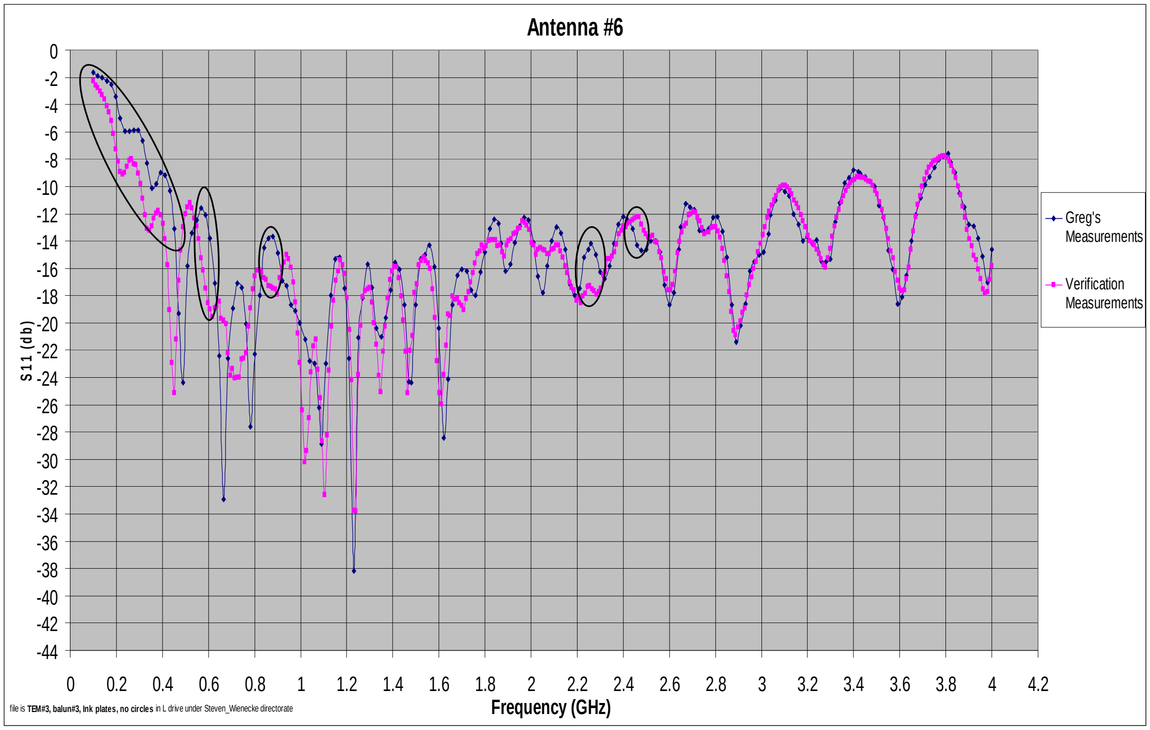

Figure 11. Comparison of S11 measurements taken on Antenna #6 (contiguous resistive ink sheet transmission line, 6-cm flares, and copper TEM horns faced outwards).

Perhaps more importantly, it must be stated that the resistive values used for the contiguous resistive sheets in the antenna I measured were not the same as those used by Greg. As mentioned previously, there was no uniform way for us to spread the special dielectric ink and control the thickness of each coating, making it difficult to create resistive plates with the desired resistance. Table 1 compares the resistances of the sheets Greg used with the values I used for the top-side of the antenna. Table 2 gives the values for the resistive sheets used on the bottom of the antenna. There was a difference in our data at the lowest part of the frequency range, but our data were almost the same at frequencies higher than 450 MHz.

Table 1. Top resistive sheets.

	My Resistive Sheets	**Greg's Resistive Sheets**
Rearmost sheet	183.5 Ω	189.5 Ω
Middle sheet	9.7 Ω	12 Ω
Front sheet	12.9 Ω	15.6 Ω

Table 2. Bottom resistive sheets.

	My Resistive Sheets	**Greg's Resistive Sheets**
Rearmost sheet	178.9 Ω	189.5 Ω
Middle sheet	10.3 Ω	12.8 Ω
Front sheet	14.1 Ω	15.6 Ω

The major difference that occurs in this graph is between 100 MHz and 450 MHz, where Greg's data were 1–3 dB worse than mine. Though it is only a few dB different, the difference covers a larger frequency range than any of the other previous comparisons, suggesting its cause may be different as well. Because the only disparity between the antennas we measured were the exact values of the ink plates, it seems reasonable to believe that they were the cause. In selecting the resistance values for our ink plates, we tried to match the values to those used in a paper written by Kurt L. Shlager, Glenn S. Smith, and James G. Maloney[1]. Although the paper states that they were restricted by the resistive values of the ink plates available to them, they were able to compute the optimal resistance value for their antenna using the finite-difference time-domain (FDTD) method.

The problem with using their values is that both the resistance and dimensions of our TEM horn antenna differ from the TEM horn antenna that they used. This means that the values we used were not the optimal ones for our antenna.

Although my measurements were only a few dB better than Greg's (and this difference was restricted to the lowest frequency range), finding the best resistance value for our ink plates may be worth exploring. For one thing, the performance of the balun is a limiting factor to the overall performance of the antenna, but looking back, figure 3 shows that our balun performs very well in this frequency range. This indicates that there is room for improvement, in this frequency range, to be made through modifications to the rest of the antenna. Another reason for optimization is the fact that within the desired frequency range of SIRE (300 MHz–3 GHz) our antenna currently performs the worst between 300 and 400 MHz, and thus it is especially important to improve our antennas performance in this area. Finally, overall, Antenna #6 performed the best out of all the antennas (as shown in figures 12 and 13), and thus more time and effort should be devoted to optimizing this antenna. Moreover, once the correct values are found, a better method must be found for uniformly spreading the dielectric ink so that a consistent resistance value of the sheets will be obtained, in turn increasing the reproducibility of the antenna.

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[1] Shlager, K. L.; Smith, G. S.; Maloney, J. G. TEM Horn Antenna for Pulse Radiation. *Microwave and Optical Technology Letters* **Dec 2 1996**, *12* (2), 86-90.

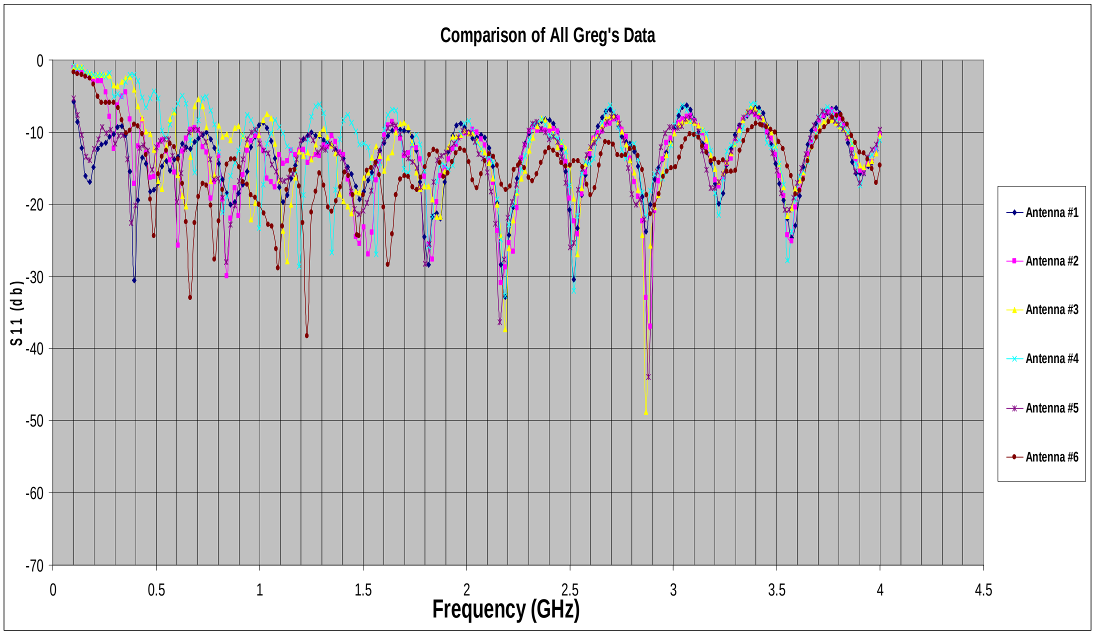

Figure 12. Comparison of S11 measurements taken on Antenna #6 with differences pointed out.

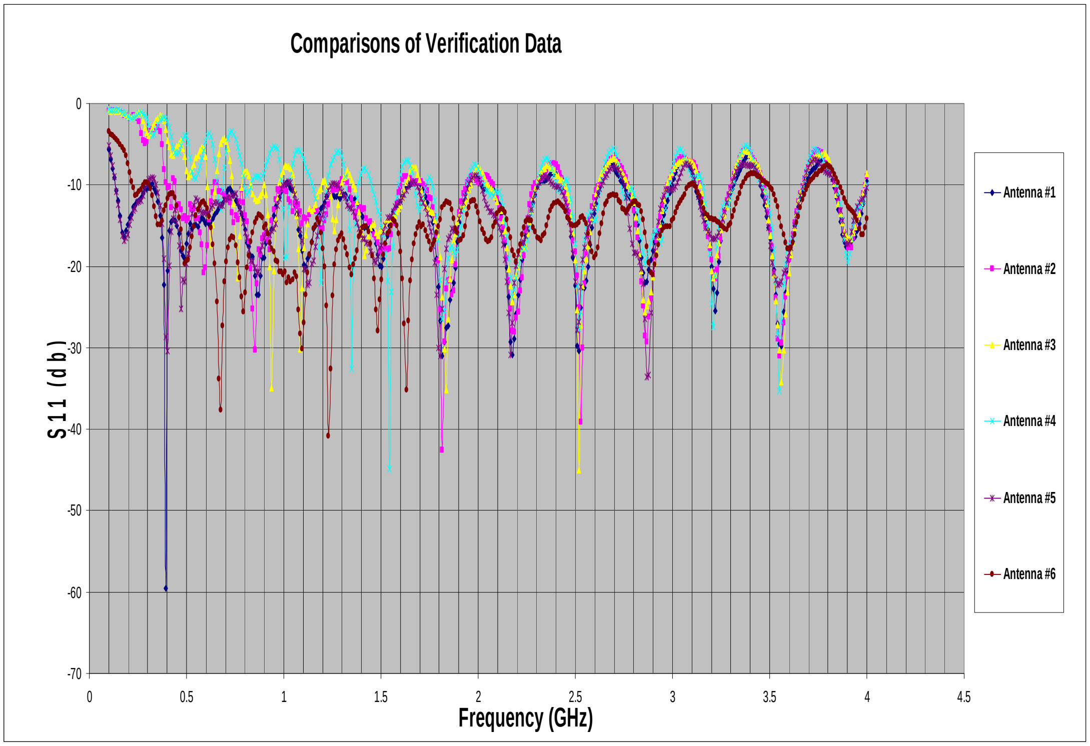

Figure 13. All of Greg's S11 measurements plotted together.

It is common to define an S11 of –10 dB at a certain frequency as the highest S11 allowed for that specific frequency to be considered within the bandwidth of the antenna. For many applications, an S11 higher than this is not sufficient. The Antenna #6 that I constructed has an S11 ≤ –10 dB from 300 MHz on up, indicating that this antenna operates adequately or better at every frequency within SIRE's frequency range. However, the antenna Greg constructed does not consistently have an S11 ≤ –10 dB until ≈430 MHz, meaning his antenna would not perform adequately over SIRE's frequency range. This suggests, at least when spreading the dielectric ink in a similar fashion to how Greg and I did, that some reproductions of the antenna may perform adequately over SIRE's frequency range, while others may not. Thus, unless a better method for spreading the dielectric ink is introduced, one cannot say with full confidence that this antenna can be properly reproduced 100% of the time.

4.7 All Antenna Measurements

Figure 12 displays all of the measurements Greg made on one graph, and figure 13 shows all the measurements I made.

5. Conclusions

After comparing the measurements taken for the first five antennas, it can be seen that antennas #1–#5 can be consistently reproduced.

For Antenna #6, the S11 improvement seen at the lower frequencies produced by a change in the values of the resistive ink plates suggests it may be worth computing the optimal values of the contiguous resistive plates in order to improve the antenna's performance in the 300–450 MHz range. As Antenna #6 performed the best out of all the antennas, it seems logical that more time be spent in optimizing it, in comparison to the other antennas. Moreover, once it is optimized, a better method must be found to spread the dielectric ink in order to obtain consistent resistance values for the resistive sheets, and in turn increase the reproducibility of Antenna #6.

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