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Resistively Loaded Discones for UWB Communications

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Abstract

An Ultra-Wideband (UWB) antenna is required for UWB communications systems, such as the Joint Tactical Radio System (JTRS). In this case, the desired antenna must cover a bandwidth of 20 MHz to 4 GHz, be omnidirectional, be convenient to transport and deploy, and be able to transmit 200 Watts of power. Conventional discone antennas are candidates for such systems, but they have insufficient bandwidth for the required application. To improve their bandwidth, we added resistive loading to the conical elements and to the ground plane, and we increased the size of the ground plane. We built several models of the resistively loaded discone, and we observed a dramatic reduction in VSWR when compared to a commercial off-the-shelf (COTS) discone. We also simulated the antenna pattern using the NEC computer code, and we used the antenna with an amateur radio. The resistively loaded discone has clear advantages for UWB communications when compared to the COTS discone.

Table of Contents

I. Introduction.

Ultra-Wideband (UWB) antennas are a critical component of UWB communications systems, such as the Joint Tactical Radio System (JTRS). For this particular system, the antenna must cover a bandwidth of 20 MHz to 4 GHz, be omnidirectional, be convenient to transport, and be able to handle 200 Watts of transmitted power. A leading candidate for such a system is a discone, due to its very wide bandwidth.

Discones of a reasonable size are available commercially that have a nominal range of 100 MHz to 1.3 GHz. Such devices could be enhanced to reach as high as 4 GHz by using more care at the apex of the cone. But if one wanted to extend the frequency range of such devices down to 20 MHz, they would become too large to be convenient. We investigate here extending the frequency range at the low end by adding distributed resistive loading to the antenna, while keeping the size constant. This reduces the return loss without increasing the antenna size.

We investigate here improving the low-frequency response of a commercially available discone antenna, a Diamond model D-130J. The bandwidth given in the Diamond catalog for this antenna is 25 to 1300 MHz in reception and 80 to 1300 MHz in transmission, with the vertical element attached. The vertical element with the loading coil can be removed if 25-50 MHz reception is not required. Our measurements showed satisfactory performance only as low as around 100 MHz before the VSWR became too high. With the vertical element attached, there was an additional useful band near 50 MHz.

In this study, we investigated reducing the VSWR of the discone at low frequencies by adding resistive loading, based on work by T. T. Wu and R. W. P. King [1]. We built and tested a number of modifications to the standard unmodified D-130J. The five versions of the D-130J discone antenna were the following:

(a) Commercial Off-The-Shelf (COTS) discone
(b) same as (a) but with resistive loading in the conical section
(c) same as (a) but with the ground plane enlarged to match the diameter at the base of the antenna
(d) same as (c) but with tapered resistors in the conical section (loaded like (b))
(e) same as (c) but with tapered resistors in both the conical section and the ground plane

The five cases are summarized in Table 1. We studied each of the configurations both with and without the vertical element attached. By progressing through these five modifications we are able to see the effect of each modification and evaluate its effect on the performance of the discone antenna. The experimental data are reported in Section II. In Section III we report the results of some radio tests of case (e).

We also analyzed cases (a) through (d) numerically using NEC-Win Plus, a Method-of-Moments (MoM) wire antenna analysis code. This allows us to predict antenna patterns as well as VSWR. We begin now with a description of our experiments.

Table 1. Discone versions built and tested.

Case	Loaded Cone?	Enlarged Ground Plane?	Loaded Ground Plane?	Comments
(a)				COTS version
(b)	X			
(c)		X		
(d)	X	X		
(e)	X	X	X	

II. Modifications and Experimental Results.

We describe here our discone modifications and measurements. Our starting point in the development is the Diamond Model D-130J discone antenna, shown in Figure 1. The D-130J is about 1.71 m (67.2 inches) high, including the vertical element, and is rated at 200 Watts. The bandwidth given in the Diamond catalog for this antenna is 25 to 1300 MHz receive, 80 to 1300 MHz transmit. The vertical element with the loading coil is optional and can be removed if 25-50 MHz reception is not required. The COTS version is referred to as Case (a) in our measurements.

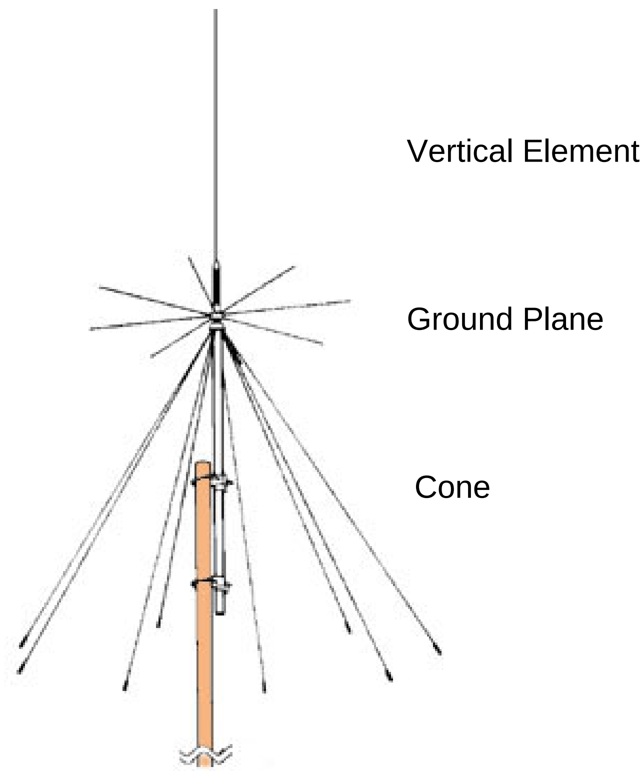

Figure 1. The Diamond D-130J Discone antenna.

For Case (b), we replaced the stainless steel elements in the conical section with G-10 fiberglass rods, to which resistor strings were attached. We show this version of the discone in Figure 2.

To calculate the resistor values, we used the formulas given in Appendix A, based on the Wu-King model. These formulas have a singularity at the last segment, so we used twice the previous value for the sixth (last) resistor. The resistor values are given in Table 2. The resistor values for case (e) are simply half of the values used for case (b) since the loading is distributed evenly between the ground plane and conical elements. Columns 3 and 4 of Table 2 give the actual resistance values used in the experiments.

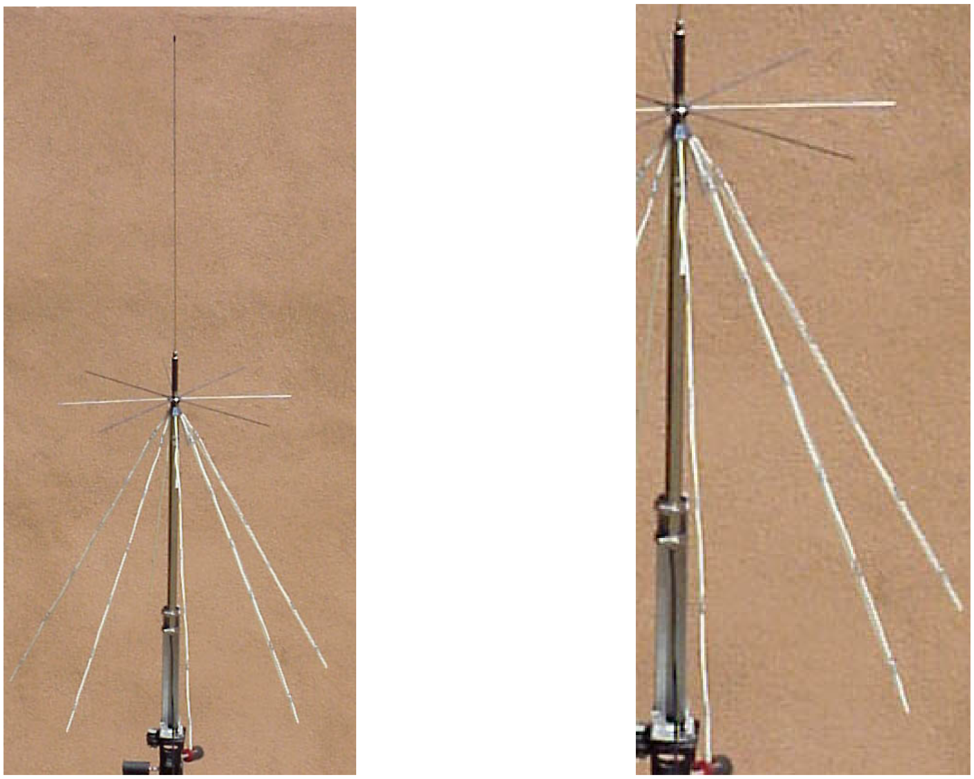

Figure 2. Diamond D-130J with loaded conical elements (Case (b)) (left), detail (right).

Table 2. Resistor values for loaded discone.

Segment	Calculated Resistance (b)	Standard Resistors (b)	Standard Resistors (e)
1	240 Ohms	240 Ohms	120 Ohms
2	294 Ohms	300 Ohms	150 Ohms
3	379 Ohms	390 Ohms	180 Ohms
4	534 Ohms	510 Ohms	240 Ohms
5	914 Ohms	910 Ohms	430 Ohms
6	1827 Ohms	1800 Ohms	910 Ohms

For Case (c), we welded extensions onto the ground plane elements to make the diameter of the ground plane approximately the same as the conical section at the base of the antenna. We could have extended the ground plane somewhat further, but this would have made the antenna more difficult to transport and more awkward to deploy.

We show the VSWR for each of the 5 cases below, both with and without the vertical element, in Figures 3 through 7. These measurements were made at 2 MHz intervals with a MFJ HF/VHF SWR Analyzer, Model MFJ-259B.

We begin with the data for Case (a), the COTS version of the antenna. The data is shown in Figure 3, where we see a sharp dip in the VSWR at approximately 52 MHz. This dip is due to the coil at the base of the vertical element. This coil is probably intended to improve reception on the 6 m Amateur Radio band that extends from 50 to 54 MHz. The vertical element reduces the VSWR substantially at the low end, but not enough to meet the present requirements. The VSWR at most frequencies below 100 MHz is too high for use with most transmitters.

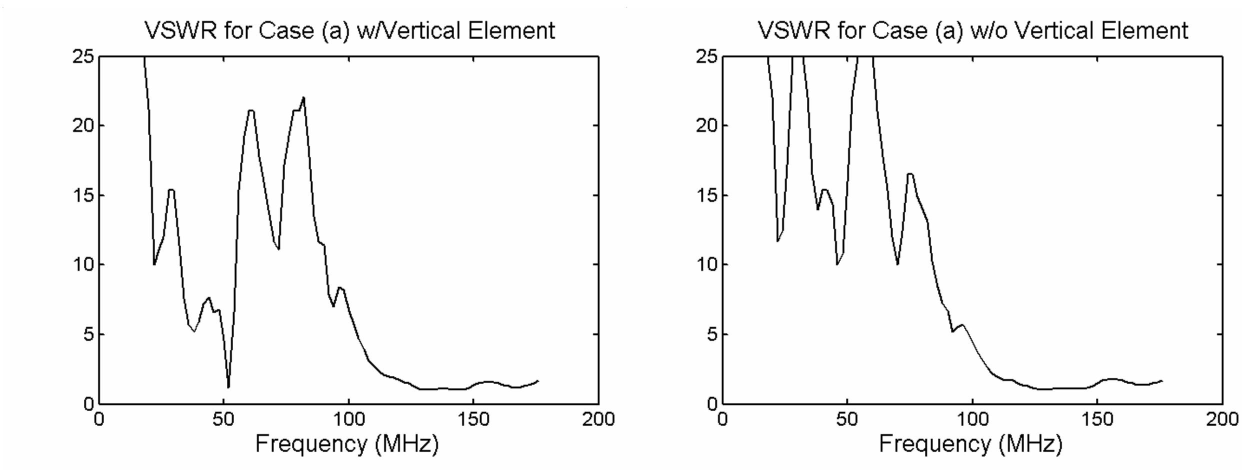

Figure 3. Case (a), Standard D-130J discone antenna.

Next, we measured Case (b), in which we replaced the stainless steel elements in the cone section of the antenna with resistor strings. A photo of this configuration is shown in Figure 2, and the resistor values are given in Table 2. The VSWR for this case is shown in Figure 4, where we see the VSWR is dramatically improved. We also see that the resistive loading smoothes the VSWR considerably.

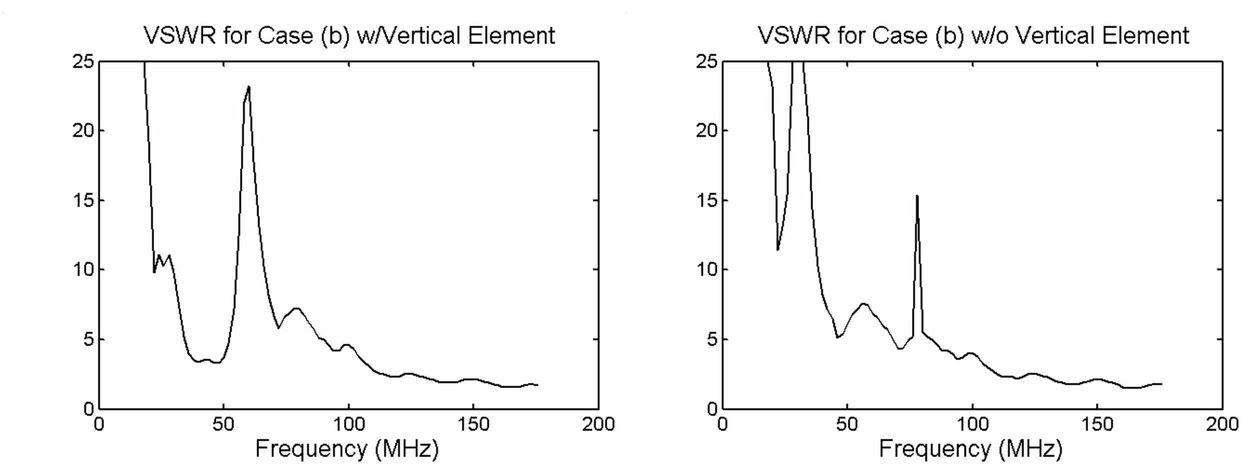

Figure 4. Case (b), Loaded cone elements.

Next we consider Case (c), which has an enlarged ground plane with all unloaded elements. This also improves the VSWR of the antenna, as seen by comparing Figures 3 and 5.

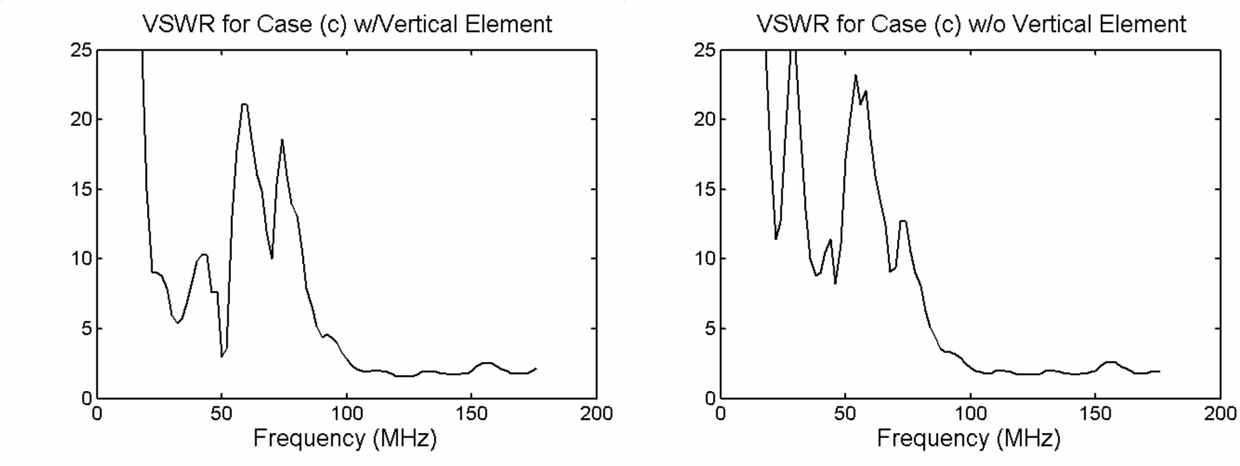

Figure 5. Case (c), Extended ground plane.

Next we consider Case (d), in which we replaced the cone elements from case (c) with the loaded elements from case (b). The results are shown in Figure 6, where we see a marked improvement in the VSWR.

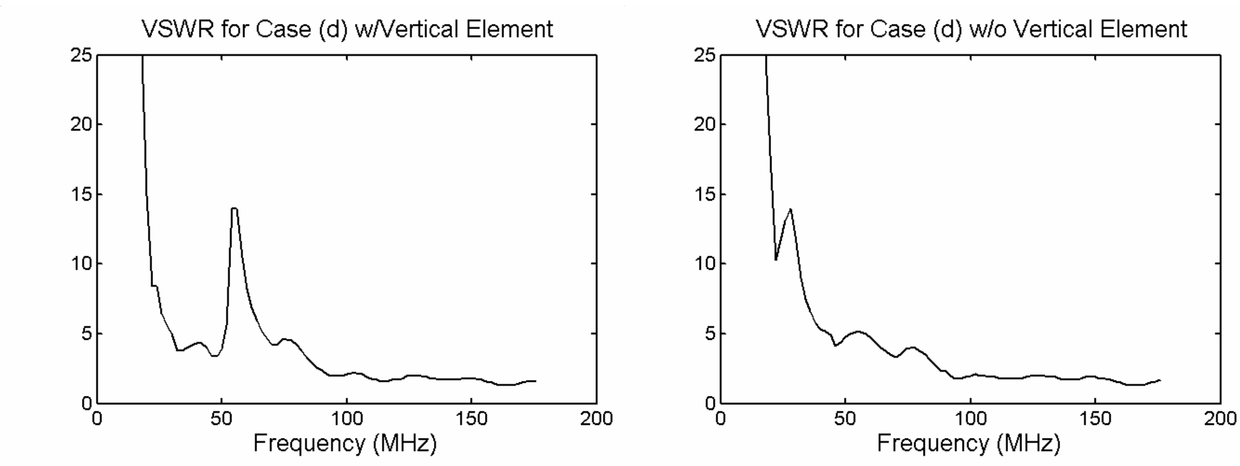

Figure 6. Case (d), Extended ground plane with loaded cone elements.

Finally, we provide the results for Case (e), which has an enlarged ground plane and resistive loading on both the conical elements and the ground plane. The results are shown in Figure 7, where we see that this case has the best performance of all the cases studied so far.

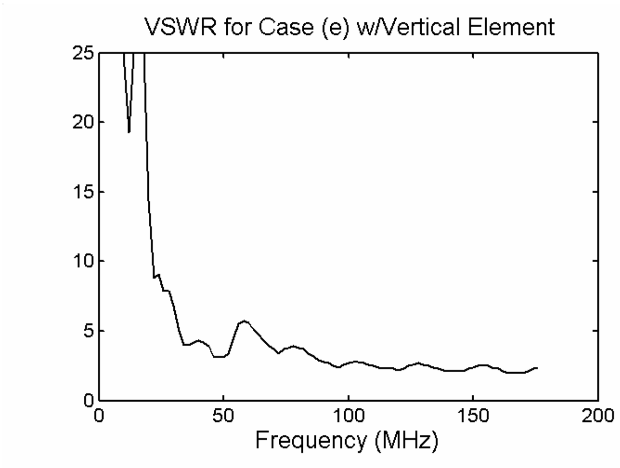

Figure 7. Case (e), Extended ground plane with all elements loaded.

We have shown a steady improvement in the VSWR with each progressive modification. In Figure 8 we overlay cases (a) and (e) to emphasize the improvement in the VSWR brought about by the modifications. Comparison of the measurements with and without the loaded vertical element indicates that the vertical element does improve the VSWR at low frequencies. However, the loading coil will have to be redesigned for use in transmit as well as receive mode.

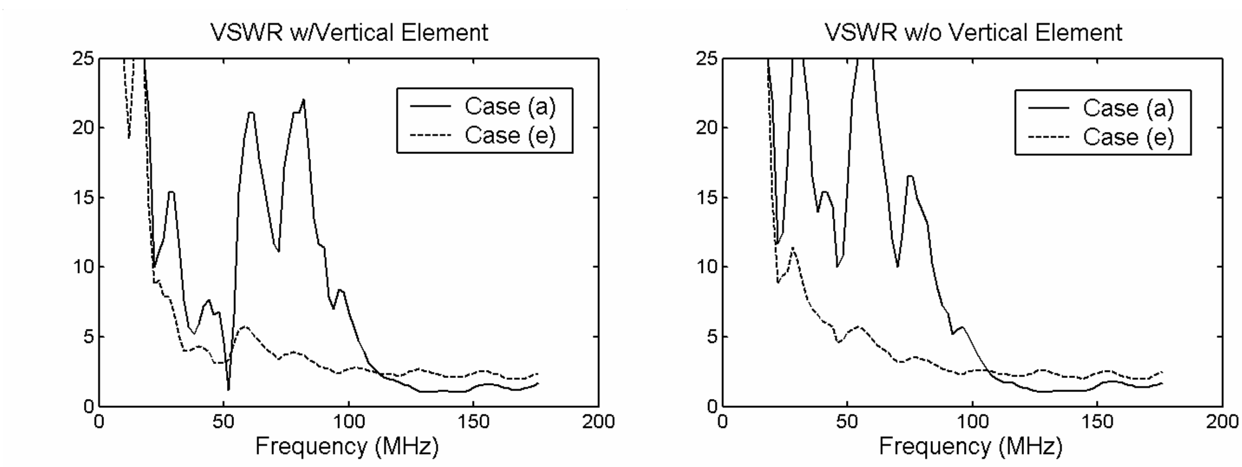

Figure 8. Comparison of Case (a), COTS version, and Case (e), with enlarged ground plane and loaded ground and conical elements.

As a check on our measurements, we measured the return loss, or S_{11}, of the antenna for Cases (a) and (e) using time domain techniques. The TDR of the antenna was measured using a Tektronix TDS 8000 digital oscilloscope with an 80E04 sampling head. The TDR can be converted to reflection coefficient, which is related to VSWR by

$$|S_{11}| = \frac{VSWR - 1}{VSWR + 1} \tag{1}$$

The reflection coefficients for Cases (a) and (e) as measured by SWR meter and TDR are shown in Figure 9, where we observe that the two methods agree quite well.

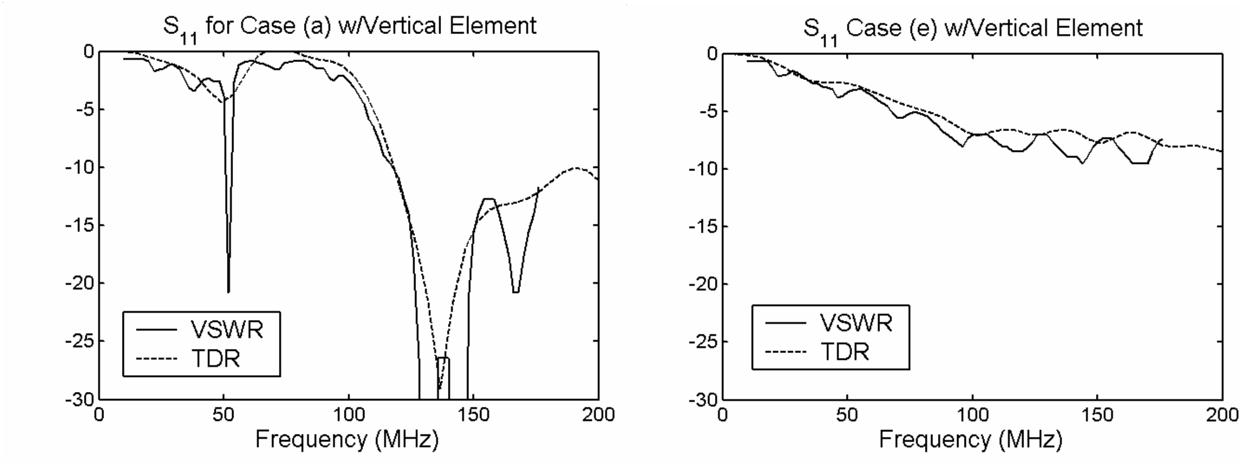

Figure 9. Reflection coefficient S_{11} calculated from the VSWR and the TDR.

Finally, we provide reflection coefficient data over a larger frequency range. In Figure 10 we extend the frequency range of Figure 9 by plotting it on a log frequency scale. The TDR measurements reach as high as 4 GHz, but our VSWR meter is capable of measurements only as high as 750 MHz. We see that S_{11} for the standard antenna is quite noisy at high frequencies. The S_{11} for case (e); however, is reasonably smooth out to nearly 1 GHz. This demonstrates that the approach using resistive loading on a discone antenna is very promising. At this point, we have done nothing to improve the high-frequency response, so some problems at high frequencies might be expected.

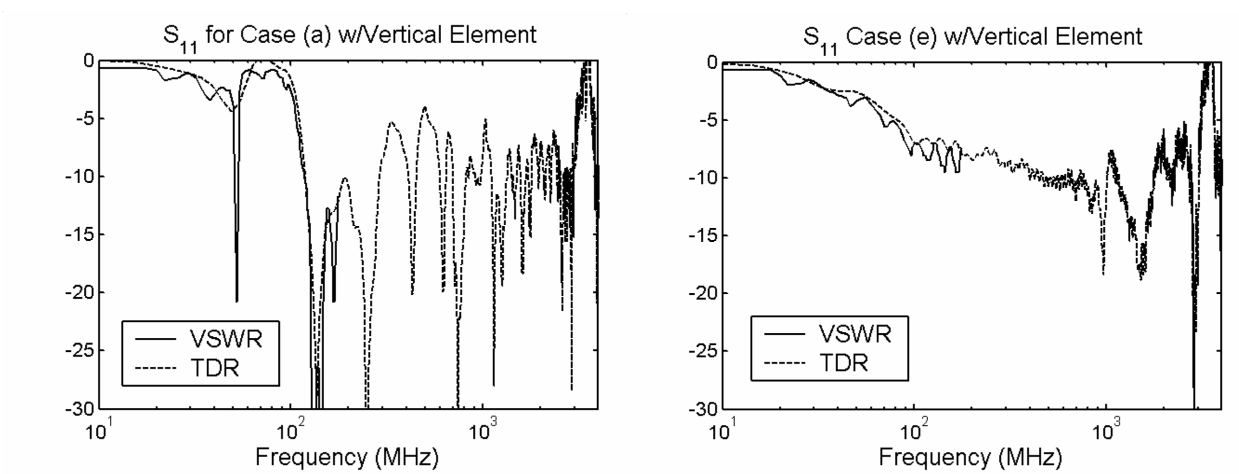

Figure 10. Reflection coefficient S_{11} calculated from the VSWR and the TDR.

III. Radio Experiments with the New Antennas

In this set of experiments, we compare the reception of our loaded discone to that of two other Commercial Off-The Shelf (COTS) antennas. We do so in order to test the validity of our loaded discone concept in a "real-world" environment.

Testing at 50.125 MHz Amateur Band

We compared the performance of an COTS version of the Diamond D-130J discone, case(a), to that of our best resistively loaded discone, Case (e). The loaded version of the discone had an enlarged ground plane, and it had resistive loading on both the ground and conical elements. Both antennas included their original vertical element, in order to extend the useful frequency range at the low end.

Our technique was to mount both antennas onto the roof of FRI's central facility using two antennas. An A/B switch was placed at the antenna output of our radio, a Yaesu FT-847. By manually flipping the switch, we could compare signal levels received by either of the two antennas. The signal level was measured on the S-meter of our radio. The radio was operated in Upper Sideband (USB) mode.

The COTS version of the discone only works well continuously down to around 100 MHz, based on its VSWR. However, because we included the vertical element, the discone has a null in the VSWR near 50 MHz, to allow good operation near the 6-meter ham band (50-54 MHz). For that reason, the unloaded COTS version of the antenna worked better in this band than the loaded version. Received signals were about 2 S-units stronger than received signal with the loaded discone.

It is reasonable to assume that the COTS discone would have been much worse than the loaded version just outside the 6-meter ham band, based on its VSWR, and based on the fact that the radiation mechanism is resonant (only) in that band.

At this point, it would be appropriate to comment on the precision of our measurements. It is widely known that the S-meters on ham radios are grossly inaccurate. One S-meter level is nominally 6 dB, but the actual measured range varies widely, depending on the make and model of the receiver. So a measurement based on ham radio S-meters is crude, at best. A better approach would be to transmit a low-level CW signal from a nearby location, and use stepped attenuators to compare signal levels with different antennas.

Testing at 28.185 MHz Citizen's Band Channel 19

Next, we compared the reception of three antennas on CB Channel 19, which is at 28.185 MHz. The three antennas used were the two discones described above, and a quarter-wave resonant whip. We chose channel 19, the road channel, because it seemed to have the most activity.

Because AM modulation is used on this frequency, the signal level varies rapidly during the course of a transmission. This makes it difficult to obtain a reading from the S-meter of a single transmission. Nevertheless, it seemed possible to visually average the signal levels.

The results of our measurements are as follows. The quarter-wave whip provided the best reception, being about 2 S-units above the loaded discone. The COTS discone came in third, about 2 S-units below the loaded discone.

Discussion

In both experiments, we observed the best performance with an antenna that was resonant at the desired frequency. However, our loaded discone always had reasonable performance, and it has the advantage that it does not depend upon resonance, so it works well over a very broad frequency range. In the future, it will be necessary to carry out more accurate measurements using stepped attenuators.

IV. Numerical Analysis of Discone Antenna.

We used the Method-of-Moments (MoM) wire code, NEC-Win Plus, to analyze the Diamond D-130J discone antenna in configurations (a) through (d). In this analysis, we used 18 segments on the conical portion and 4 segments on the ground plane. The vertical element was not included in the numerical model.

We plot the VSWR for the four configurations in Figure 11 on two vertical scales. We can see that as we progress from configuration (a) to (d) we obtain progressively better VSWR performance at the low end of the frequency band. So both large ground planes and resistive loading are helpful to the VSWR.

It is interesting to observe that there is a knee in the VSWR of the simple discone that occurs at around 110 MHz, below which the VSWR quickly becomes unacceptable. For an element length of 33.5 in, this knee occurs at a frequency where the length of the conical elements is about one-third of a wavelength.

Next, we plotted the elevation patterns for the four configurations at four frequencies – 50, 100, 150, and 200 MHz. Note that the azimuth patterns are nearly uniform, so there is little point in plotting them. The elevation patterns for the two unloaded configurations, (a) and (c), are shown in Figure 12, and the patterns for the two loaded configurations, (b) and (d), are shown in Figure 13. The unloaded configurations both have gains around 1 dBi for the entire frequency range, whereas the loaded configurations have gains that range from a high of –6 dBi at 200 MHz down to –14 dBi at 50 MHz. This is a disadvantage that is offset by the lower VSWR.

Let us consider now whether we should use an enlarged ground plane. An enlarged ground plane reduces the VSWR without reducing gain, so would normally want to use it. It does increase the antenna size near its top, however, not so much that it extends beyond the base of the antenna. So using an enlarged ground plane is strongly recommended.

A more interesting question is whether one should use resistive loading. The two loaded designs have a much better VSWR, but at a cost of reduced gain. The two effects might appear to offset each other, if it were not for the characteristics of the typical radio. Most transmitters have protection circuits that will not allow it to operate at full power unless the antenna is a reasonable match to 50 ohms. This feature prevents large reflections from the antenna from damaging the transmitter. Thus, having a low VSWR is much more important than having an optimal antenna gain. Therefore, the loaded designs are strongly preferred.

The numerical results presented here are intended to be preliminary. We have yet to analyze the effect of loading the ground plane, using inductive loads instead of resistive loads, and the effect of the vertical element. Nevertheless, the results provided so far demonstrate considerable promise for improving the standard discone over the COTS version. This work should guide us in the development of a discone antenna that will fully meet the requirement to operate from 20 MHz to 4 GHz and be able to handle 200 Watts of power.

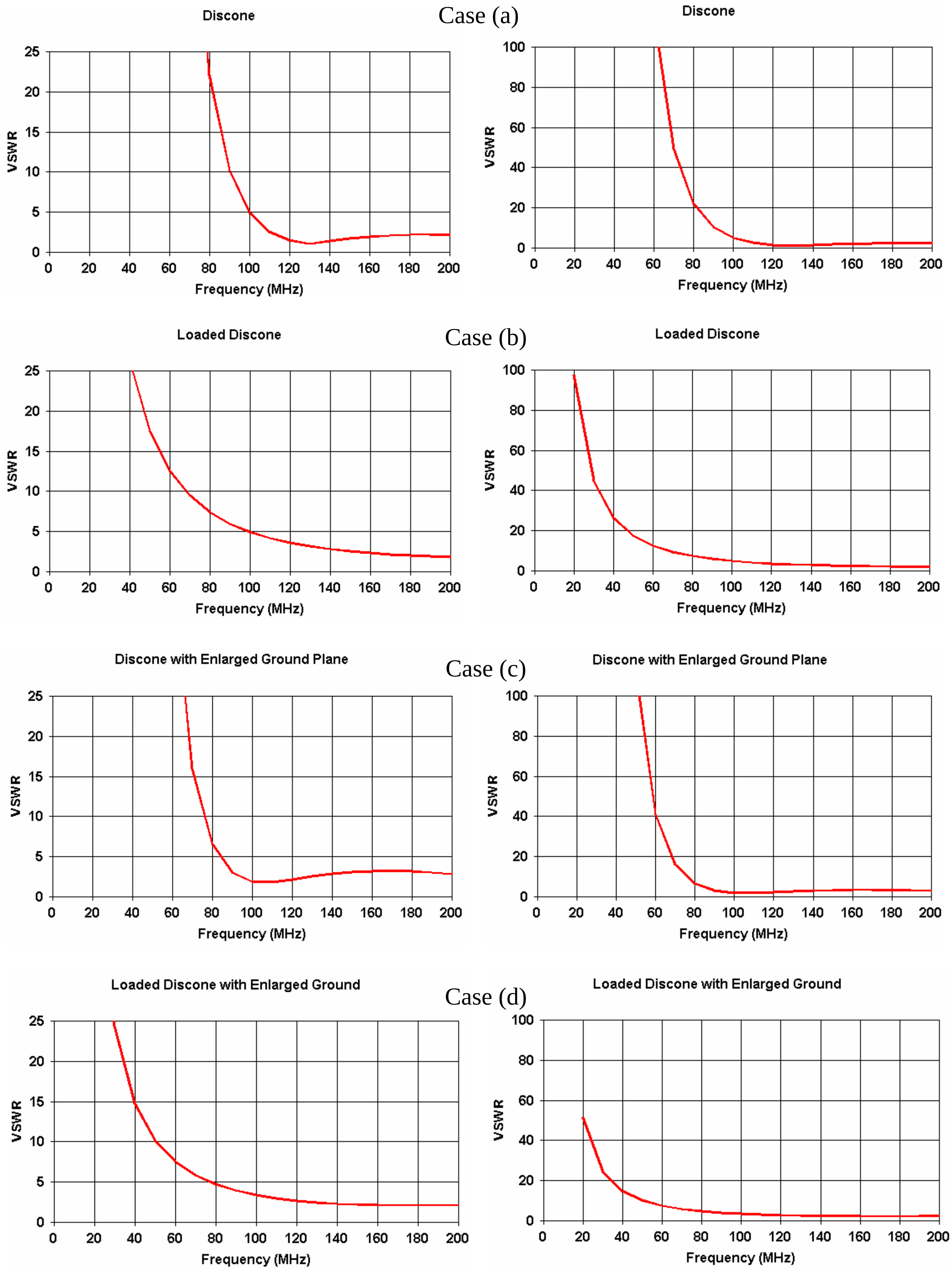

Figure 11. VSWR for four configurations of the Diamond D130J discone, Case (a) through (d).

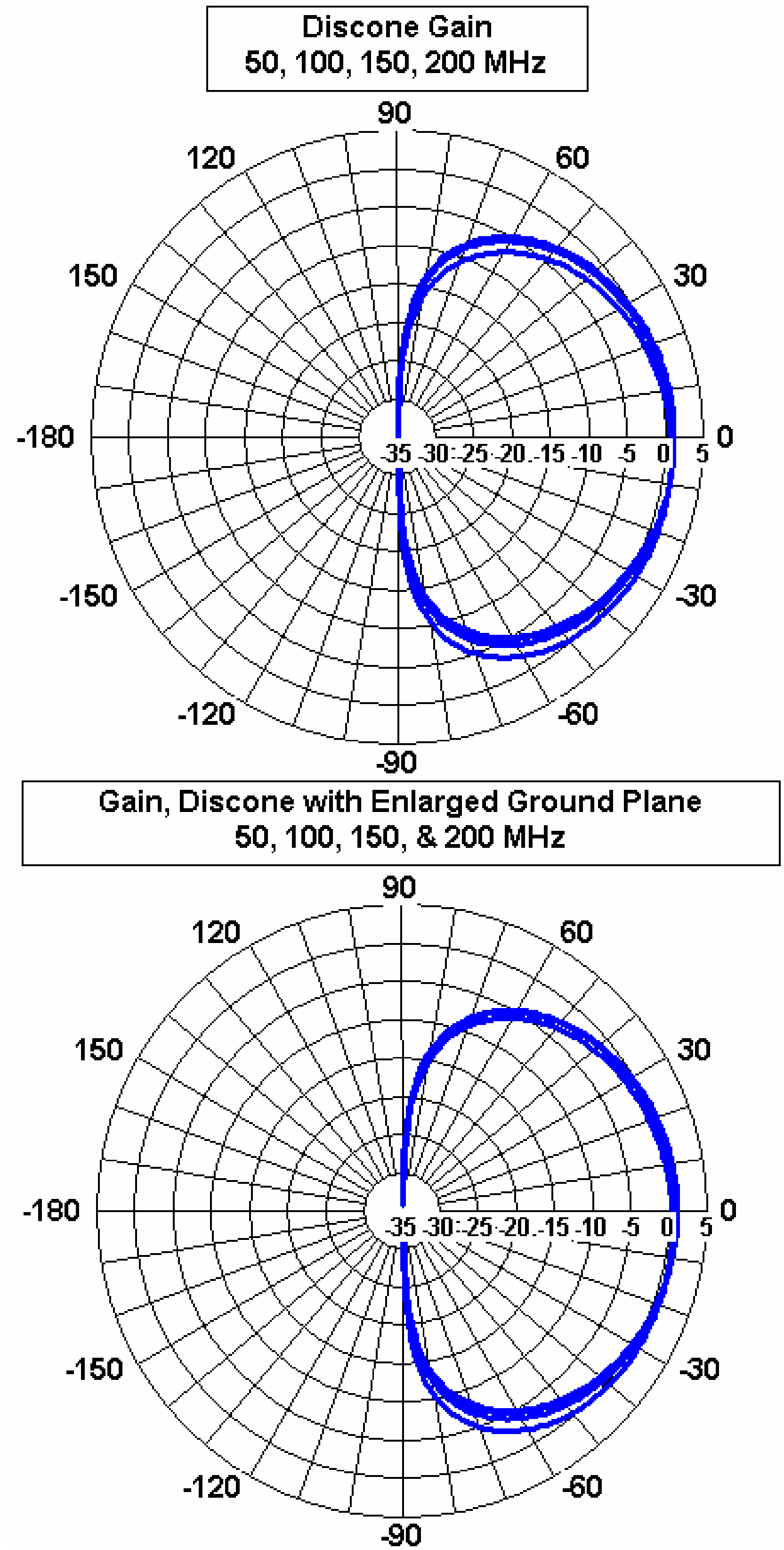

Figure 12. Elevation antenna pattern for two discones in unloaded configurations, Case (a), top, and Case (c), bottom.

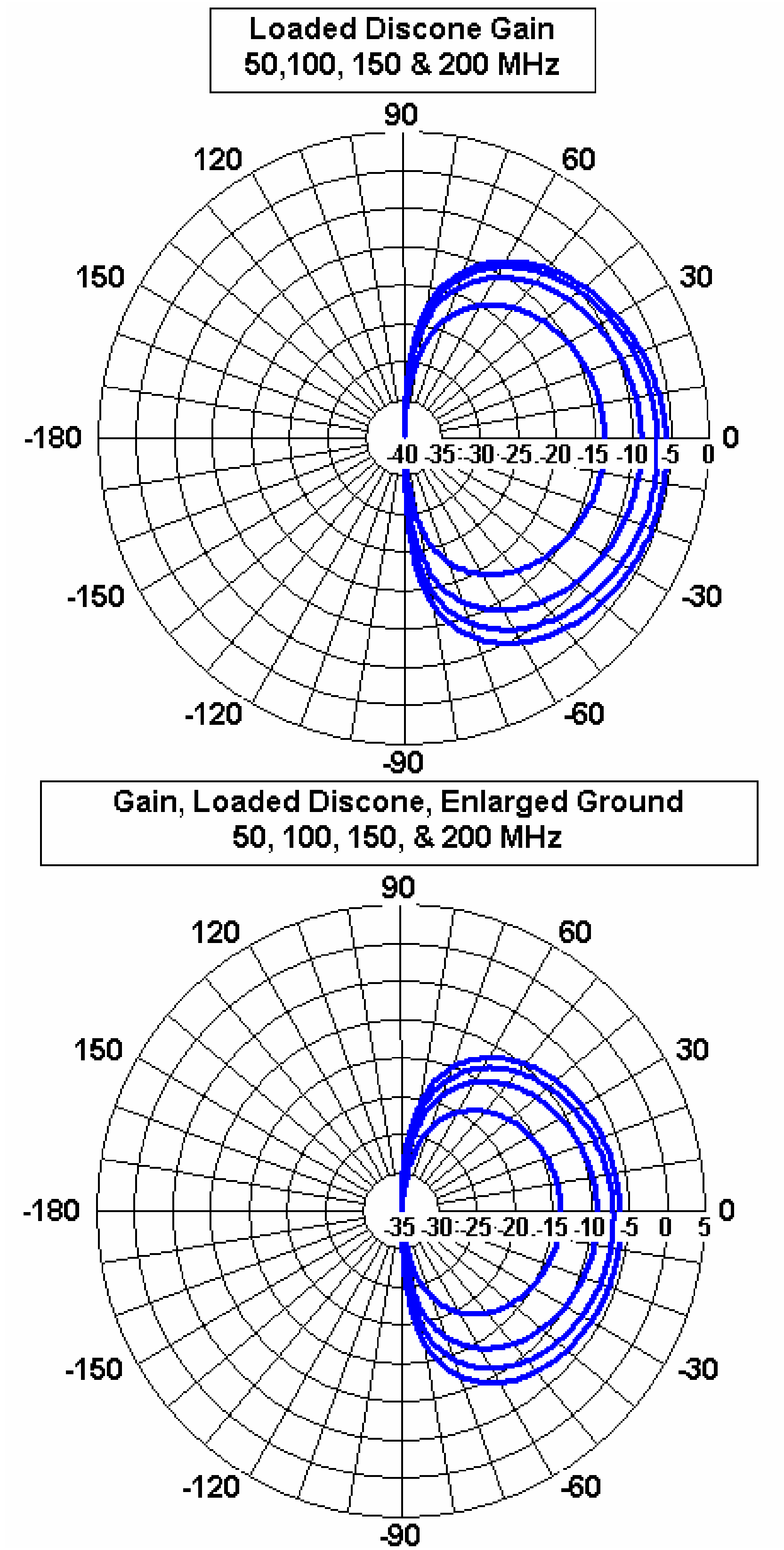

Figure 13. Elevation plots for the discones in loaded configurations, Case (b), top, and Case (d), bottom.

V. Discussion and Future Plans.

The results reported here demonstrate a dramatic reduction in the VSWR of the discone antenna over a large portion of the frequency range. We see significant improvement in the VSWR as we add resistive loading and enlarge the ground plane. Based on these results, we recommend using the enlarged ground plane and resistively loading both the ground plane and conical elements of the antenna.

Although resistive loading in discones greatly improves the VSWR of the antenna, it also reduces the antenna gain. One might therefore wonder whether the two effects offset each other, realizing little additional net radiated power. However, because of the protection circuits that are built into most radios, reducing the VSWR is much more important that maintaining the antenna gain. Most radios are designed to reduce their output power when the VSWR exceeds some threshold. So a high VSWR has the added penalty of reducing available output power, and therefore can never be a feature of an optimal design.

In future work we hope to improve the low-frequency performance of the antenna by a variety of means (other than simply increasing the antenna size). First, we will optimize the resistive loading, both by numerical simulations and by measurements. We will also experiment with inductive loading, since that is used commonly in antennas for CB and AM radio. The optimal design will have low VSWR and high antenna gain over as broad a frequency range as possible.

We also hope to improve the high-frequency performance of the antenna. The high end of the antenna response is determined by the accuracy with which the cone is built near the apex or feed point. Deviations from a conical geometry are inevitable at the apex, but they can be minimized with careful design. Building a portion of the cone and ground plane near the apex out of solid metal will help, as will the use of improved connectors. We are confident we can reach 4 GHz upper bandwidth, since we routinely build UWB antennas commercially that reach as high as 20 GHz.

Once we have optimized the electrical design, we hope to ruggedize the antenna to withstand field conditions that include rough treatment, dropping, and high winds.

Appendix A
Resistor Calculations For a Loaded Discone

We calculate here the resistive loading that is required in the discone. In order to calculate the loading, the first requirement is to find the input impedance of the cone. To find this, we measured the dimensions of the discone as follows, where the dimensions are shown in Figure 1.

a = 15.7 in
h = 29 in
L = 33 in

$$\begin{aligned} \theta_o &= \arctan(a/h) \\ &= 28.5 \text{ deg} \end{aligned}$$

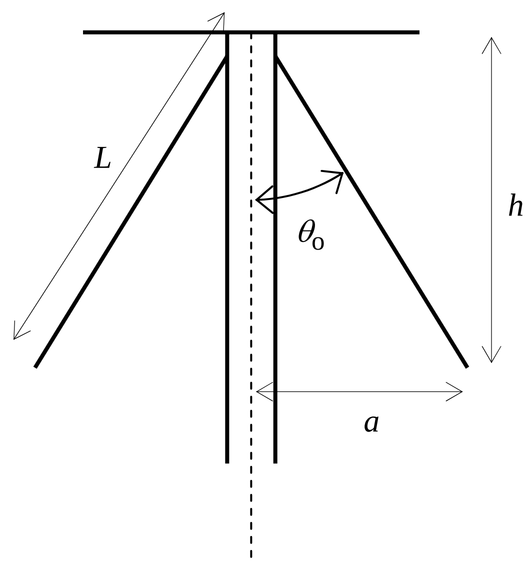

Figure A.1. Coordinates of a discone.

Now the impedance of a half-cone against a ground plane is [2, 3]

$$\begin{aligned} Z_c &= \frac{Z_o}{2\,\pi} \ln\left(\cot\left(\theta_o / 2\right)\right) \\ &= 82\,\Omega \end{aligned} \tag{A.1}$$

where $Z_o = 120\ \pi\ \Omega$. After substituting in the above value for θ_o, we find an impedance of 82 ohms. Ideally, we would prefer a 50-ohm cone, but it was easier for us to modify a pre-machined cone than to build a new device.

To calculate the resistors, we divided each diagonal arm into N segments of equal length. It seemed that $N = 6$ should be sufficient. At first, we loaded only the long diagonal element.

The impedance per unit length is specified by the Wu-King model [1, 4]. Thus, the distributed resistance for a bicone is of the form

$$Z'(r') = \frac{2Z_c}{\ell - r'} \tag{A.2}$$

where $Z'(r')$ is the resistance per unit length along the cone, and Z_c is the impulse impedance of the monocone at its apex. Furthermore, ℓ is the slant length of the cone, and r' is the distance out on the cone.

To find the total resistance to be placed at the center of a segment, we integrate the resistance per unit length over the segment length. So the total resistance for segment i, which begins at $r' = a_i$ and ends at $r' = b_i$, is

$$R_{t\,i} = \int_{a_i}^{b_i} Z'(r')\, dr' = 2Z_c \int_{a_i}^{b_i} \frac{d\,r'}{\ell - r'} = 2Z_c \ln\left|\frac{\ell - b_i}{\ell - a_i}\right| = 2Z_c \ln\left(\frac{\ell - a_i}{\ell - b_i}\right) \tag{A.3}$$

where, in the last step, we have inverted the fraction to keep the absolute value positive. Now for uniform spacing we have

$$a_i = \frac{(i-1)}{N}\ell \quad , \qquad b_i = \frac{i}{N}\ell \quad , \qquad i = 1,2,\ldots, N \tag{A.4}$$

So the expression for the total resistance becomes

$$R_{t\,i} = 2Z_c \ln\left(\frac{N - i + 1}{N - i}\right) \tag{A.5}$$

When $i = N$, we have a singularity. For this resistor, we somewhat arbitrarily set $Z_N = 2\, Z_{N-1}$.

Finally, we need to spread the resistance over the ribs, where we assume we have N_r ribs. Thus, for N_r resistors in parallel, the actual resistor values are

$$\boxed{R_i \; = \; N_r R_{t\,i} \; = \; 2 N_r Z_c \, \ln\left(\frac{N - i + 1}{N - i} \right)} \tag{A.6}$$

This is the final value of each resistor at the i^{th} position on the cone for N_r ribs on a cone of impedance Z_c.

If we add resistance to the truncated ground plane, then all resistor values are reduced by a factor of two.

Acknowledgement

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