

Experimental Determination of Ground System Performance for HF Verticals

Part I

Test Setup and Instrumentation

This description of the test setup used by the author for a series of experiments sets the stage for a series of articles describing his results.

HF verticals located on or near ground are a perennial topic among amateurs. Over the past several years this discussion has been illuminated (and in some cases obscured!) by the advent of really good modeling software based on NEC (numerical electromagnetic code). This has resulted in a vast literature on antennas using the results of modeling. However, these results are not without some controversy. In particular the relative merits of a large number of buried radials versus a few elevated radials has been especially contentious. What has been missing from the discussion are careful field measurements done with good instrumentation and technique to see if the NEC predictions actually hold up in the real world. To address this problem I performed a series of field experiments, over a period of a year, to examine how different ground system arrangements affected the behavior of a vertical antenna and to see if field measurements on a real antenna would correlate with NEC modeling.

The results of these experiments will be presented in a series of *QEX* articles. There is no pretence that these experiments will answer all questions or even definitively settle some of the arguments, but at least they should give us something to think about.

In Part 1, I will discuss the test range, test instrumentation and test procedures used for all the experiments. Part 2, which is included in this issue of *QEX*, discusses an earlier and apparently overlooked prediction from NEC,

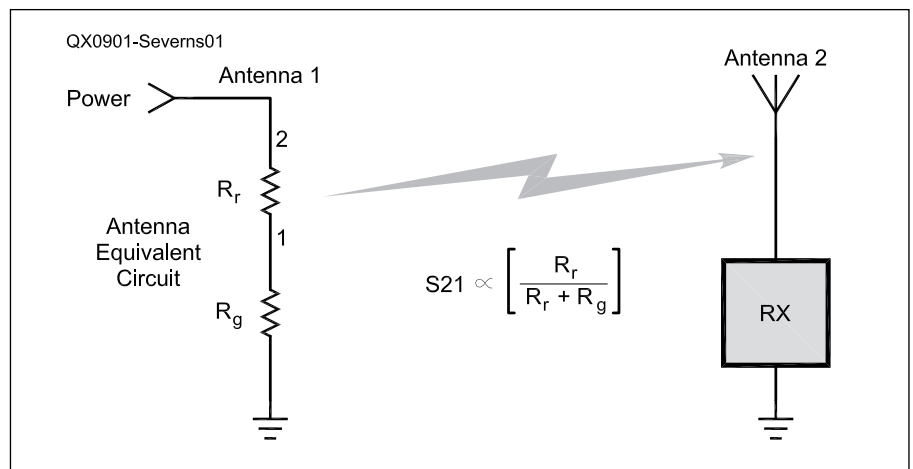


Figure 1—This drawing illustrates the traditional measurement scheme.

that in sparse (<10 radials) radial systems lying close to ground, there can be a substantial increase in ground loss when the radials are made much longer than $\frac{1}{8}$ wavelength. This is a case of more copper = more loss, which is not at all intuitive! Part 3 will compare verticals with a large number of ground surface radials to verticals with four elevated radials. This part will directly address the elevated radial controversy. Part 3 will also have comparisons between several different elevated radial configurations. Part 4 will

look at the effect of radial numbers on the characteristics of $\frac{1}{4}$ wavelength and several shorter loaded antennas. Part 5 will take a look at the problems of ground systems for multiband verticals, where a range of 7 to 30 MHz must be accommodated. Finally in Part 6, I will report on some experiments with a full size $\frac{1}{4}$ wavelength vertical on 160 m. In addition, because this series will take many months to be published, there will be lots of time for feedback. I plan to include some of this in Part 6.

Test Setup

The physical layout of the test range, the instrumentation employed and the test procedures were all key elements in obtaining reliable results. The following discussion provides descriptions of these elements which remained essentially constant for the experiments. The majority of measurements were done at 7.2 MHz although there was some work at 160, 30, 20, 17, 15 and 10 meters. The information given here is intended to provide information common to all the experiments.

Test Concept

The traditional test procedure for these kinds of measurements is well known. As shown in Figure 1, a test antenna is excited with a known power, and the resulting signal is measured at a remote point. A change is then made in the test antenna and the measurement is repeated. The difference between the two measurements is a measure of the effect of the change in the antenna and/or ground system on performance. The signal transmission to antenna 2 from the excitation of antenna 1 (S_{21}) will be proportional to the radiation efficiency of the antenna. In other words, $S_{21} \sim \text{input power} \times R_r / (R_r + R_g)$ where R_r is the radiation resistance and R_g is the ground loss. For our purposes we can assume that losses due to conductors are small. Both R_r and R_g will vary as we change the ground system but the final goal is to see the effect on the transmitted signal.¹

The standard way to make these measurements is to use a transmitter combined with forward and reflected power meters to excite the test antenna (antenna 1) with a known power. A calibrated receiver is connected to a remote receiving antenna (antenna 2) to measure the resulting signal. In my initial tests I used both an HP3586C and an HP3585A spectrum analyzer for the receiver. I wished to measure the performance differences between configurations to within 0.1 dB if possible, and these instruments were capable of that. However, the limiting factor turned out to be my ability to measure the excitation power; 0.1 dB corresponds to about 2%. To make repeatable measurements to 0.1 dB you would need to measure power to better than 1%.

To get around that problem I decided to use the instrumentation scheme illustrated in Figure 2. I chose to make the measurements with a vector network analyzer (VNA) in the transmission mode (S_{21} is the response at port 2 due to the excitation at port 1). The transmission path was from the VNA output port, out to the test antenna via a transmission line, from there to the receive antenna and back to the VNA input port via

¹Notes appear on page 25.

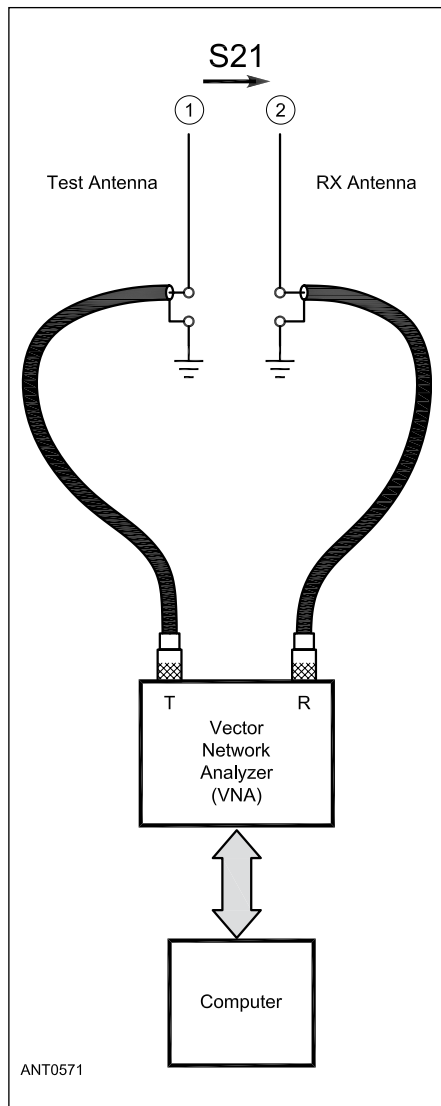


Figure 2 — This diagram shows the vector network analyzer approach for measuring antenna performance.



Figure 3— A view of the test antenna area and test equipment shelter. The receiving antenna is at the far end of the pasture.

another transmission line.

Amplitude measurements with a professional VNA are typically displayed to 0.001 dB, but of course nothing else in the system is stable to that level. In practice I found that measurements made over a short period of time (2-3 hours) were repeatable to within 0.05 dB. That is more than adequate for these experiments. A weakness of this measurement method is that as the separation between the test antenna and the receiving antenna is increased, the attenuation around the transmission loop becomes quite large, -40 to -60 dB. For instrumentation and a physical setup with a noise floor and stray coupling below -110 dBm, this is acceptable but it did limit the separation distance on 40 m to about 2.25 wavelengths for the particular receiving antenna employed. This is in the far field but not by much. Another limitation was that ± 0.05 dB repeatability was possible only when the antenna under test and the receive antennas were actually stable to that level. This usually meant that measurements had to be made in early morning when the test range was in the shade or late in the day when things had reached thermal equilibrium. It was very easy to detect a cloud passing over by the small changes due to temperature changes in the antennas. I could readily detect the effect of the wind on the vertical, causing it to move slightly. In the end the A-B comparison measurements were probably within a few tenths of a dB but only when I carefully attended to all the details.

This brings us to an important point. The purpose of the experiments was to determine the effect of different ground system arrangements from their effect on S_{21} . All the measurements were relative A-B comparisons. In other words, they were comparisons between two different configurations. There was no



Figure 4 — This photo shows a typical test antenna and center post support.

attempt to measure absolute signal strengths or radiation patterns. The separation distance between the test antenna and the receiving antenna was sufficient to place the receiving antenna outside the reactive near field but the groundwave was still significant. This was not a problem for the type of measurements being made. The presence of a metal pump house and a travel trailer, both of which are small in terms of a wavelength might have had an impact on pattern measurements but should not have affected the type of A-B measurements being made in this series of experiments.

Physical Arrangement

The test range was set up in a field as shown in Figure 3, with an area for the test antennas (including ground systems), a remote receiving antenna (in the far distance) and a small travel trailer to provide shelter for the instrumentation.

The eight poles, in an 80 foot diameter circle around the test antenna, were used to support elevated radials as needed. When more than eight elevated radials were needed, a ½ inch Dacron line was stretched around the posts at the desired height and tightened with a turn-buckle. Each post has a backstay to a buried deadman anchor so the radials could be well tensioned. Radial heights on each post were located using a laser level to keep the radial fan flat around the circle.

In the center of the circle there is a support post (PVC pipe) as shown in Figure 4, with Dacron support lines attached to the top. This post is intended to hold the antenna under test and allow it to move up and down to vary the height for elevated radial tests. An example



Figure 5 — Here is the test antenna base at ground level, with 64 radials.



Figure 6 — The base plate is in position for elevated radials.

of the base plate at ground level with 64 radials attached is shown in Figure 5.

The base plate is isolated from ground but there are three ground stakes (4 foot copper-clad steel rods) close to the plate for those tests where grounding is desired. The ground stakes have short pig-tail leads to connect to the base plate when desired.

Figure 6 shows an example of the base plate positioned for elevated radial tests. The base plate, the radials and the entire test antenna are elevated by sliding them along the support pipe. This arrangement made it very easy to change the height of the radials in small increments up to 4½ feet above

ground. The radials lying on the ground in Figure 6 were *not* present during elevated radial tests!

As shown in Figures 5 and 6, a coaxial common mode choke (balun) was used to isolate the transmission line from the test antenna. This was done for all measurements whether or not ground stakes were engaged. The choke has an impedance of >3 kΩ at 7.2 MHz. For those tests in which the SteppIR vertical was employed, the balun that comes with that antenna was used in lieu of the choke shown in the photos.

The receiving antenna was a 3-turn diamond loop with a diagonal dimension of

24 inches, as shown in Figure 7. The loop was resonant at 8.2 MHz. This loop was installed at the top of a 40 foot mast, as shown in Figure 8.

The distance from the base of the test antenna to the receiving loop is a little over 300 feet, about $2\frac{1}{4}$ wavelengths at 7.2 MHz. The elevation angle from the base of the test vertical is about 8° .

The coax from the VNA output port to the base of the test antenna was $\frac{1}{2}$ inch Andrews Heliax with N connectors. The coax from the receiving antenna back to the VNA was LMR400. Low loss coax was used because it provided better shield attenuation to reduce coupling and in the case of the heliax running out to the test antenna, the very low loss removed the need for an additional correction



Figure 7 — This photo shows the loop receiving antenna.



Figure 8 — Here is the receiving antenna atop a 40 foot mast. N7MQ assisting!

factor for the change in cable loss with variations in SWR.

Test Instrumentation

Feed point impedance, transmission gain (S21) and radial current measurements were all made using a VNA. Two analyzers were available: an HP3577A with an HP35677A S-parameter test box and an N2PK analyzer with dual fast detectors. Figures 9 and 10 are photos of these instruments.

Note the organic automatic heating unit

on top! Critical for maximum accuracy! The common mode choke in the photo is undergoing characterization for transmission loss and series impedance at 7.2 MHz. It turned out however, that the impedance of the choke was much greater than the $50\ \Omega$ reference impedance of the VNA. Above about $2\ \text{k}\Omega$ even an HP VNA becomes inaccurate for a direct measurement. For choke measurements, I used an HP4815 analyzer, which is well suited for high-impedance measurements.

After careful comparisons between the HP and N2PK VNAs, the N2PK was selected for

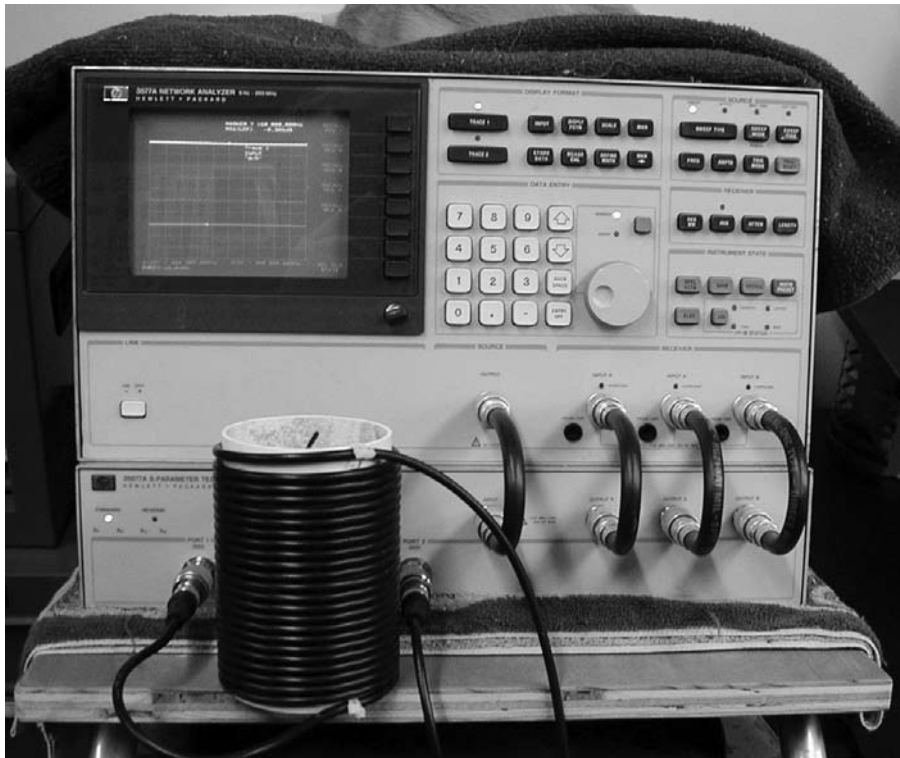


Figure 9 — HP3577A with an HP35677A S-parameter test box.



Figure 10 — Here is my test bench, showing the N2PK VNA with the associated laptop computer and HP calibration loads.

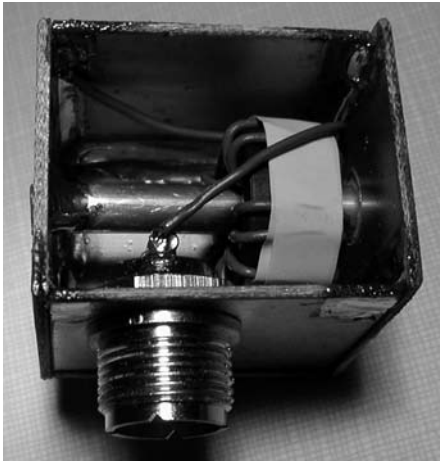


Figure 11 — This photo shows a typical shielded current transformer.

most of the measurements because its performance was very close to the HP and had the advantage of direct readout to a computer, which made data reduction much easier. The N2PK VNA was also much lighter than the HP (70+ pounds!) and much more suitable for field measurements.

On several occasions it was necessary to measure the current division ratios between the radials and in some cases, the relative current distribution along a radial. To make these measurements a set of shielded current transformers, like the one shown in Figure 11 were used.

To make a current measurement, a radial wire was passed through the current transformer, as shown in Figure 12. Current transformers were placed in the same location simultaneously on all the radials during a measurement. The transformer being used to sense current was terminated in 50 Ω by the instrumentation, so all of the dormant current transformers were also terminated in 50 Ω . This was done to compensate for any interaction introduced by the current transformer. At the very least, the effect of the current transformer would be the same on all radials. The active current transformer was isolated with a choke as shown in Figure 12.

Even with this degree of care, the current measurements were still a bit tricky because of the residual interaction between the cable from the current transformer and nearby radials. In some cases I actually used four identical cables in a symmetrical layout to try to minimize imbalance due to this interaction. I believe the resulting measurements were reasonable and useful but not especially precise!

The relative value of the current was determined by using the VNA in the transmission mode, measuring S21 for the loop from the VNA output port to the base of the antenna, out along the radial to the current transformer and back to the VNA input port. This was a convenient way to measure the

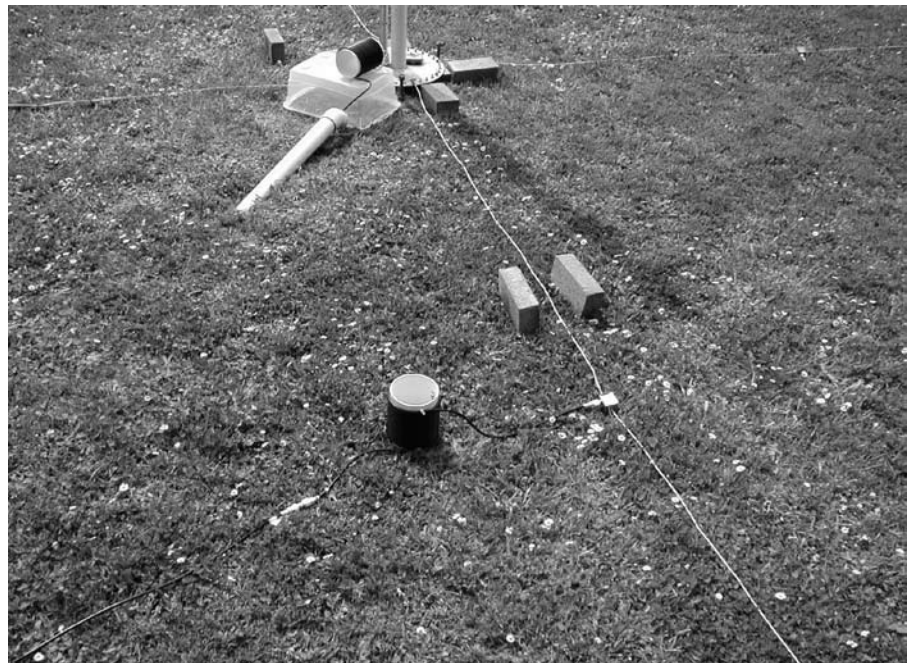


Figure 12 — Here is the test setup for a typical radial current measurement.

current division between radials and the relative current distribution along a radial.

Comments on test procedures

A good physical setup and professional instrumentation are a very good start, but to obtain reliable data great care must be exercised in using and calibrating this equipment. For feed point impedance measurements, at the beginning and end of every test run an OSL (open, short, reference load) calibration was performed with the calibration plane at the test antenna feed point. At the beginning and end of each test run a transmission calibration was also performed.

In addition, before beginning a series of measurements a measurement of stray coupling and possible interference was performed. The procedure was to disconnect the feed line from the base of the test antenna, terminate the feed line with a 50 Ω load and then measure the transmission gain of the entire system in this state. Throughout the series of experiments, this transmission level was never higher than -110 dBm and usually -115 dBm or lower, at 7.2 MHz. As a further check on results, most experiments were run several times to verify consistency and repeatability. All of this was very time consuming but absolutely necessary to assure the best possible measurements. I did not delude myself, however, into thinking the measurements were perfect and cannot be improved on. I do believe the results make sense, fit well with NEC modeling predictions, give useful insights into vertical antenna/ground system behavior, and potentially can be of practical help in optimizing a given antenna installation.

Acknowledgement

This experimental work was inspired by the earlier work of Jerry Sevick and Arch Doty.^{2, 3} Some of my experiments were a repeat of their earlier work with more advanced instrumentation. I would also like to thank Mark Perrin, N7MQ and Paul Thompson, W8IEB for the many hours of help they provided during the experiments. Without their help, I would still be out in the field taking measurements!

Notes

¹R. Severns, N6LF, "Radiation Resistance Variation With Radial System Design," Sep 2008. Available at: antennasbyn6lf.com.

²J. Sevick, W2FMI, *The Short Vertical Antenna and Ground Radial*, CQ Communications, Inc, 2003. Jerry's work also has appeared in a number of QST articles.

³A. Doty, K8CFU, "Improving Vertical Antenna Efficiency, A Study of Radial Wire Ground Systems," *CQ Magazine*, April 1984, pp 24-31. This article also has a very nice list of earlier references related to ground systems for verticals.

Rudy Severns, N6LF, was first licensed as WN7WAG in 1954 and has held an Extra class license since 1959. He is a consultant in the design of power electronics, magnetic components and power-conversion equipment. Rudy holds a BSE degree from the University of California at Los Angeles. He is the author of two books and over 80 technical papers. Rudy is an ARRL Life Member, and also an IEEE Fellow.

