Ground System Measurements on a 160 M Vertical

Rudy Severns N6LF

Over the summer I've been designing and building a new 160 m vertical phased array. In process I asked myself: how many radials should I use on each element? Given the present very high cost of copper wire this is a critical question. At 1.83 MHz, 64 quarter-wave radials require 7,600' of wire, doubling that to 128 radials, means you need 17,200' for each element. In a 3 or 4 element array, that becomes an awful lot of wire!

The conventional wisdom is that the point of vanishing returns should set in by 64 radials but I wondered how good would a 64 radial system be and how much difference doubling that number of radials would actually make. Would it be worth the time and trouble in my situation?

One could approach this question with either modeling or calculation but I chose to make a very careful set of measurements on an actual vertical, at my site, while varying the number of λ/4 radials. The measurements include both base impedance and relative field intensity at a point 700' from the antenna. The measurements were done using good instrumentation: a vector network analyzer for base impedance and a spectrum analyzer for field strength.

Because my site is not a flat open field and ground characteristics are specific to my location, one cannot apply these measurements universally but they should still be a useful example of the measurement process and illustrate trends to be expected.

The following discussion is in three parts: a brief description of the antenna and ground system, a discussion of the measurements and then details of the measurement equipment and techniques.

Test antenna

The test antenna was a 125' length of #12 insulated copper wire suspended from a triatic midway between two 150' wooden poles. The radial system consisted of #12 insulated (THHW) wire lying on the ground surface. Radials were put down in the sequence of 4, 8, 16, 32 and 64. The ground system was elevated about 2" over the soil, being spaced away from the soil by closely mowed dry weeds. The ground around the antenna is not flat but is a narrow ridge about 40-50' wide. The result is that many of the radials are bent down at about a 45 degree angle as they run down the steep slope on either side. Along the ridge however, the radials are more or less level.

Figure 1 is a photo of the base of the antenna.

Figure 1, antenna base.

Besides the radials, two ground rods are also connected to the hub as shown.

Ground characteristics were measured using both monoprobe and open wire line (OWL) probe techniques. By averaging the measurements over the area of the radial field, I get $\sigma = 0.006$ S/m and $\varepsilon_r = 65$.

Measured data

At the base of the antenna, $Z_{in} = R_s + jX_s$. A graph of R_s over the entire 160 m band for different numbers of radials is given in figure 2.

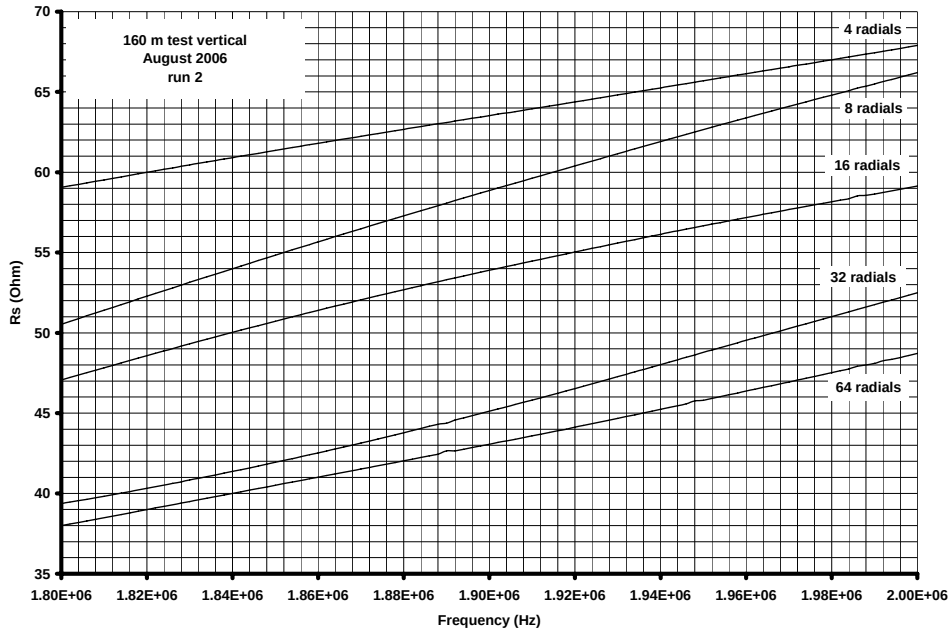

figure 2, measured base resistance over the 160 m band.

The base reactance (X_s) is shown in figure 3.

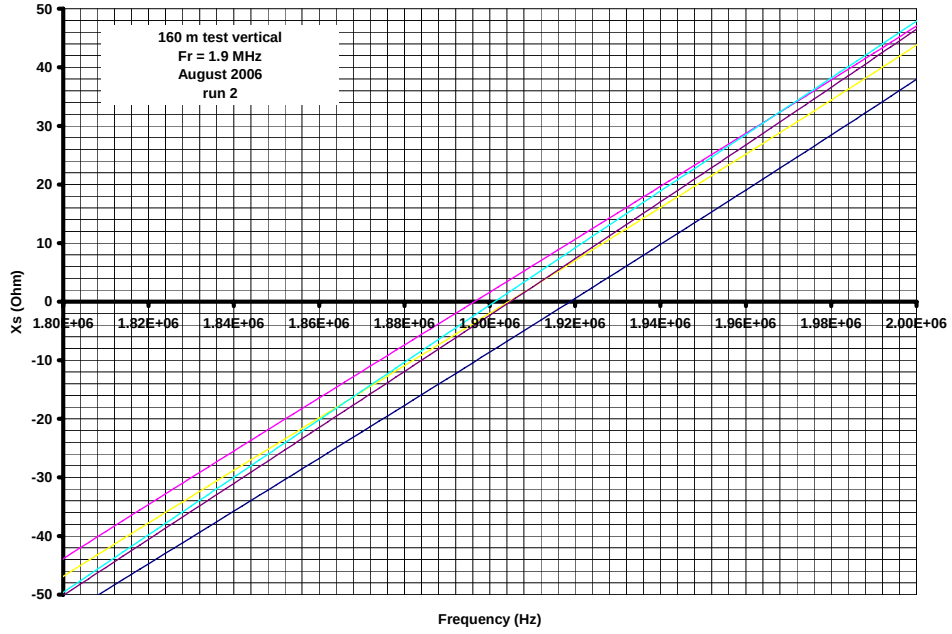

Figure 3, measured base reactance over the 160 m band.

To get a better idea of what's happening to R_s as we vary the number of radials, we can regraph the data in figure 2 as shown in figure 4. The resonant frequency varies somewhat with the number of radials but is close to 1.9 MHz.

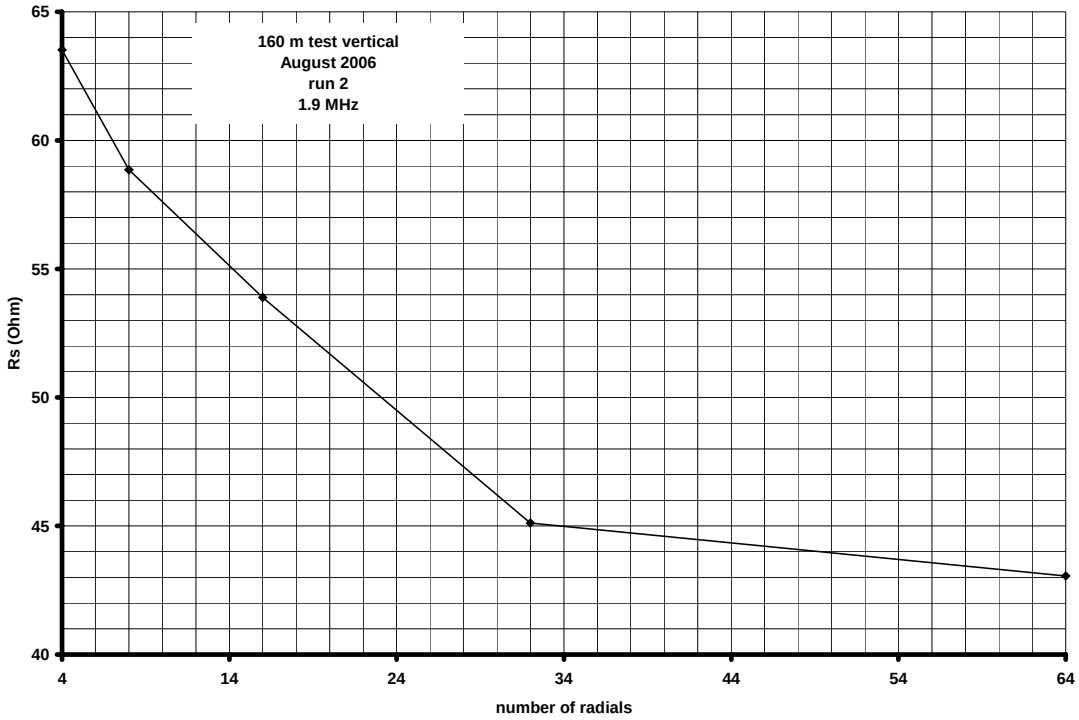

Figure 4, R_s at 1.9 MHz for different numbers of radials.

From 4 through 32 radials R_s drops rapidly but then flattens out at about 43 Ohms when you reach 64. Extrapolating the curve to 128 radials suggests that R_s will probably only drop to about 42 Ohms.

42 Ohms is clearly not the classical value of 36 Ohms. Does this mean that my ground system resistance is really 6 Ohms? Probably not. Remember the example of the ground-plane antenna (in free space) where the radials are sloped away from the base. In that case the base resistance, even when there are no losses, rises significantly. In my case, a good portion of the radial system slopes away from the base at a steep angle as the radials go down into the canyon on either side of my ridge.

The object of the experiment was to determine the point where adding more radials gave only a small additional benefit in the context of my soil and terrain. The best way to see this is to measure the field strength, for a given power. After all, more field strength for a given input power is what we're after. The effect of radial number on field strength is shown in figure 5. There are measured data points at 4, 8, 16, 32 and 64 radials. A trend line has been has been fitted to the data.

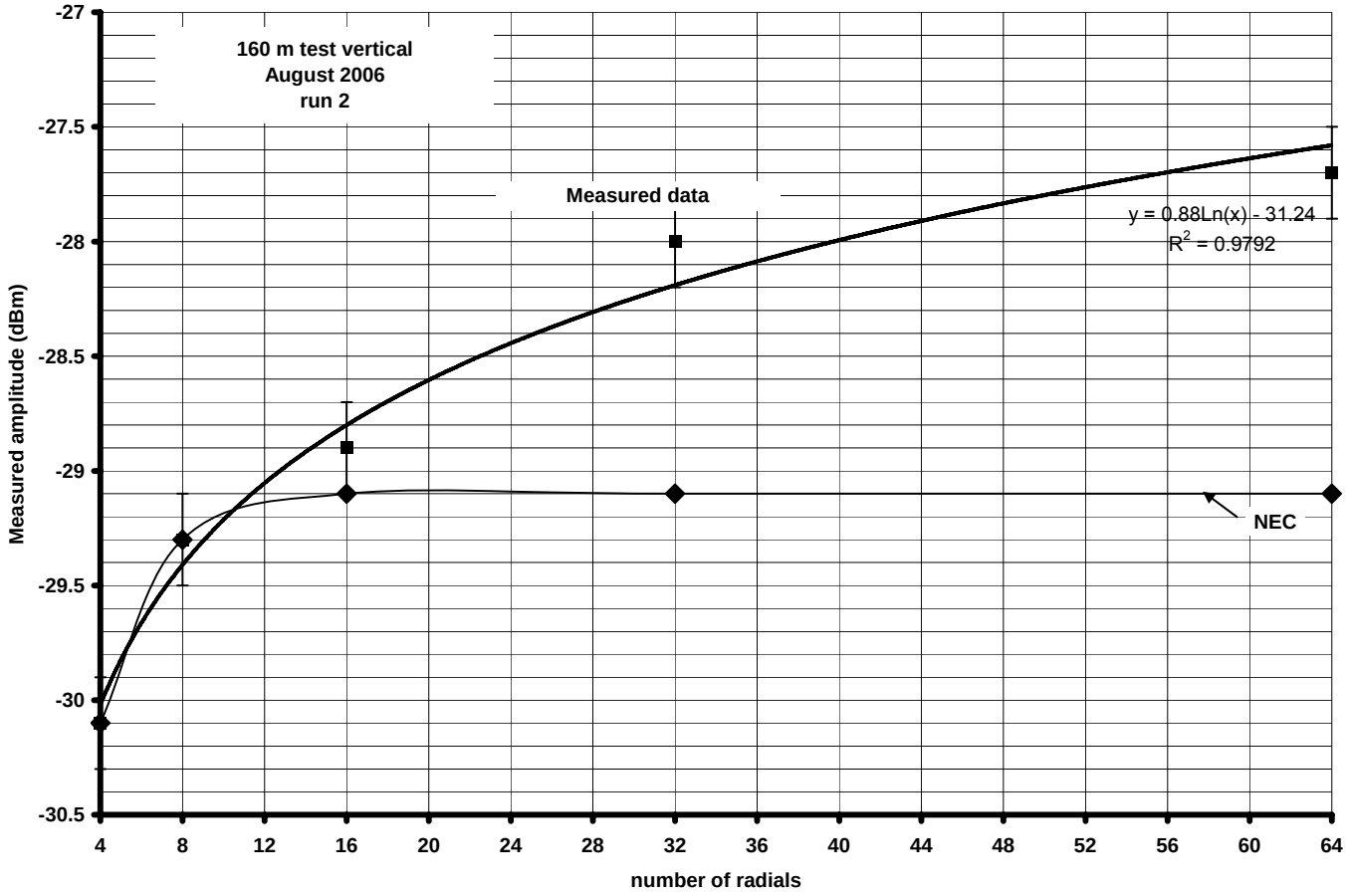

Figure 5, Measured voltage at the receive antenna
as the number of radials are varied.

The change in field strength between 4 radials and 64 radials is only 2.5 dB but this is equivalent to going from 50% efficiency to over 90 %. Certainly a worthwhile improvement.

While R_s may have pretty much flattened out by 64 radials, it is clear that the field strength is continuing to rise. Extrapolating the curve to 128 radials, I would probably pick up 0.3 dB or a bit more. Not insignificant but certainly not worth adding another 1.5 miles of wire to the radial system of each element!

I also modeled the antenna using EZNEC with the NEC4-D engine. I couldn't model the exact shape of my terrain so I used a flat field approximation but kept the ground constants, wire size, insulation, etc, the same as the actual antenna and ground system. Figure 5 has a curve of this data which was normalized to the 4 radial case. NEC shows one dB less improvement and is flat above 16 radials. That's really not a very good fit for my experimental data. The lack of any change for 16 or more radials just doesn't fit my personal experience and I think that of many others.

Measurement procedure

Measurements were repeated in two runs to provide a crosscheck. The first set of measurements were taken as the radials were laid down in the 4, 8, 16, 32, 64 sequence. The difficulties of laying down the radials on my steep terrain spread the first run over several days. Fortunately the weather was constant without any rain. Once the entire ground system (64 radials) was in place, I made a second run by progressively cutting the radials near the hub and pulled the cut end of the radial back from the antenna 30' or so. The radial number sequence was then 64, 32, 16, 8 and 4. This set of measurements was made within an hour. The differences between run 1 and run 2 were insignificant but it did provide a good check for any errors. At the end of the tests, all the radials were reconnected.

The impedance measurements were straight forward. These measurements were made using an N2PK vector network analyzer. Crosschecking with an HP 3577A analyzer, the measurements appear to be better than 1% which is more than adequate.

The receiver for the field strength measurements was an HP 3585A spectrum analyzer. The absolute accuracy for that instrument is ±0.4 dB but for relative measurements over a small range of amplitudes, a resolution of ± 0.1 dB is possible. I checked the amplitude calibration using an HP 3336A Synthesizer/level generator. Other (and much less expensive) instruments could be used for these measurements. An HP 312A/B selective voltmeter, which can be found on E-Bay or at swap meets for very reasonable prices (I paid about $50 for my 312B), would work very well. Another choice would be the HP 3586A/B/C Selective Level Meter. These cost $200-$400 on the used market. I have a 3586A which has an absolute accuracy of ±0.2 dB and a resolution to 0.01 dB.

The sense antenna was a 3 meter length of wire connected to a ground stake. Due to possible changes in ground impedance that is not a very good antenna for long term measurements but over the short period of the testing it proved to be very stable yielding results repeatable to ± 0.1 dB. Great care was taken to keep the analyzer settings (bandwidth, sweep time, etc) constant for all measurements.

The tricky part of field strength measurements is knowing the input power to the antenna within ±0.1 dB. You have to know the actual power dissipated which implies you have to measure both the forward and reflected power and take the difference. I used a Bird model 43 wattmeter. This is a standard instrument for this purpose but it isn't particularly accurate. It is rated for 5% of full scale although most seem to be a somewhat better than that. You can set the forward power to the same point each time (I used 50 W) but the reflected power will differ because, as can be

seen in figure 2, the feedpoint impedance and consequently the reflected power, varied with radial number. At 1.9 MHz the SWR remained relatively small, not exceeding 1.4:1, so the reflected power was small, on the order of a Watt or less. Unfortunately at 5% of full scale (2.5 W) you really can't resolve this with the Bird, at least not without changing the element. So I asked the question, "how much does it matter if when SWR is low?"

Figure 6 is a graph of the power reduction in the antenna as a function of SWR for a given fixed forward power. Because the highest SWR I saw in was of the order of 1.4:1, and that was for only the one case of 4 radials (the SWR was below 1.25:1 for the rest of the combinations) I decided to accept the possible 0.1 dB error and simply set the antenna input power very carefully to the same point on the meter scale for each test run which can be done quite closely on the Bird. This error is included in the figure 5 error bars.

Figure 6, Power reduction due to SWR.

As an alternative I could have used the impedance data to calculate the SWR and from that determine the reflected power. I didn't think that was worth the trouble but it certainly could be done. In the case where the SWR is significant but accurate measurement of power is not possible this does provide a means to determine the

relative power into the antenna, picking one point as the reference and then setting the forward power to the same point on the meter each time.

Summary

In my case, 64 radials appear to be adequate. At another site however, fewer radials might do the job or more might be needed. Overall I believe these measurements are about as accurate as is practical and certainly adequate to make a estimate on what's to be gained by adding more radials. They also show the continued increase in field strength even when R_s has very nearly flattened out.

None of this is particularly surprising or new. A lot of this kind of work has been done professionally over the past 70 years but most was done at BC frequencies and down. Not much has been published on work at HF with modern instrumentation. I found it interesting to go through the procedure for myself.

It's my intention to replace the present sense antenna with a balanced one, isolated from ground. I'll calibrate this shortly during my "dry" season and then repeat the field strength measurements over the winter to see if I can determine the effect on the soil losses of lots of rain, which we do occasionally have here in Orygun.

If you have any comments on improving the accuracy of this kind of measurement or pointing out errors I may have made, by all means pass them along:
rudys@ordata.com