Choice of Locations and Interpretation of Data from Low Frequency Field Strength Measurements

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The first two papers in this series described the equipment the author has used for field strength measurements in the 135.7 - 137.8 kHz (2200 meter) amateur/experimental band. This paper covers the measurement and analysis process. Some of the advice may be contrary to what has been published elsewhere, but I will do my best to back it up!

How close to my antenna should I make measurements?

In the 2200 meter band, I recommend taking measurements no closer than 3 km from the transmitting site. Others have suggested that 1 km is sufficient, but that advice is probably based on MW broadcast practices at wavelengths several times shorter than 2200 meters. Consider the fields produced by a short monopole at a distance *r*, wavelength λ, and with a power *p*:

$$E = j1.51 \cdot \sqrt{p} \cdot \left[\frac{2 \cdot \pi}{r} - \frac{j\lambda}{r^2} - \frac{\lambda^2}{2 \cdot \pi \cdot r^3} \right]$$

$$H = \frac{j\sqrt{p}}{249.7} \cdot \left[\frac{2 \cdot \pi}{r} - \frac{j\lambda}{r^2} \right]$$

For the *E* field, the $1/r^3$ term dominates near the antenna, explaining the large electric fields we find around such antennas. In taking field measurements, we really want to quantify the radiation terms given by $1/r$, where absent attenuation from low ground conductivity, the field strength will drop linearly with distance. If you attempt measurements too close to the source, there are two principal errors:

- The vector sum of the various fields will be greater than the radiation terms alone.
- The relationship of $E/H = 377$ will not hold, as the electric fields may be out of proportion to the magnetic fields.

An analysis of the *E/H* relationship shows errors of +12% at 1 km, dropping to +1.3% at 3 km. The *H* field alone will be about 6% low at 1 km, and 0.7% low at 3 km. The *E* field will be high by 6% at 1km, and by 0.7% at 3 km. Beyond 3 km, the errors drop quickly. It is for this reason that I suggest staying at least 3 km from your transmitting antenna.

For those using a large loop for transmitting, the situation is similar, but the *H* field dominates near the antenna. *E/H* is 11% low at 1 km, and 1.4% low at 3 km. As expected, the *H* field is 6% high at 1 km, and 0.7% high at 3 km, and the *E* field is 5.5% low at 1 km and 0.7% low at 3 km. Again, getting no closer than 3 km will help your measurement accuracy.

How far away should I go?

The meter described in the earlier papers should produce accurate readings down to -90 dBm, which corresponds to 55 uV/m. A station producing 1 watt ERP could be measured out to 127 km over perfect ground. But if your goal is to demonstrate the radiation efficiency of your antenna system, it makes no sense to go anywhere near that far. If you confine your readings to the 3 to 20 km range, you should be able to prove almost anything you need. The only reasons I can imagine for going farther afield would be to prove to a friend that you *do* have a decent signal at his location, or possibly to do research on local ground conductivity. Otherwise, stick within the 3 to 20 km range, and you should have excellent results.

In what direction(s) should I take my measurements?

Any loaded vertical antenna, whether the loading is done as a T, or an L or as an umbrella, should have a fairly omnidirectional pattern. In that case, it probably doesn't make much difference which directions you pick for measurements. If you know the topography of your local area, you might want to avoid directions with intervening large hills (or mountains), or large bodies of water. Such things would affect the normal smooth drop-off of the signal with distance. Of course, you might want to prove the effectiveness of your station in a particular direction, and that would be as good a reason as any for making measurements there.

A loop antenna used for transmitting will have a fat "figure-8" pattern in the horizontal plane. If you don't know the exact orientation of the antenna, you can probably locate the nulls easier than the maxima, which should be at right angles apart. In trying to measure your ERP, you should stick to directions of greatest signal. If you want to depart from those by say, up to 45 degrees, you can normalize the readings to the maximum by dividing by the cosine of the angular separation from maximum signal. I'll have an illustration of this later in this paper.

What are the characteristics of a good measuring location?

- The meter I have been describing is fairly bulky, and you don't want to carry it by hand too far. Consider locations within 30-50 meters of where you can park your vehicle.
- Avoid overhead wires whenever possible. They make great antennas, and are probably re-radiating your signal in some random phase relationship to what you would receive directly. This means that your results may be higher or lower than what you'd expect! In the same manner, avoid metal fences (including old barbed-wire fences that may be hard to see), roadside guard rails, railroad tracks, and so forth.
- Avoid underground metal conductors such as electrical conduits, water piping, etc. These may be hard identify, but can spoil excellent-appearing spots like cemeteries, golf courses, etc. Frequently, you'll come across them as nulls or hot spots in the readings.
- Avoid towers!
- Before you take your final measurement, rotate the antenna/meter by 90 degrees from peak, and see how the signal drops. Ideally, your measuring points should show null depths of 20 dB or more, indicating freedom from re-radiated signals. If the null is 10 dB or less, go somewhere else.
- Measurements in a wooded area are OK, but don't get too close to the trees. At MF, I have encountered some "magic trees" that seem to make excellent antennas. The presence of overhead foliage and branches doesn't seem to be a problem for a field meter with a loop antenna.
- As noted above, hills can be a problem. The usual effects of shadowing and diffraction apply, but with the very large wavelengths, the result may be subtle. You may find that an intervening hill makes little difference unless you are on the immediate downward slope. If you take a reading at such a location, don't be surprised if one at a greater distance is higher.
- Open areas are to be preferred. Do respect the property rights of the owner, however. Walking unannounced into someone's back yard is poor form, especially if they are practicing nudists.
- If you plan to visit a particular location repeatedly during the year, consider how accessible it will be in the winter months or during the "rainy season."
- Field strength measurements are best done in the daytime. Noise and interference levels will be lower, and it will be less awkward to explain your presence to curious bystanders.
- While you don't want to sacrifice accuracy for speed, the less time you spend standing there with that funny looking meter, the fewer questions will be posed by people who hate towers and think you are trying to site one in their neighborhood.

How many measurements should I take, and should they be on radial lines?

Medium wave broadcast field measurements are taken for two reasons: to prove the efficiency of a “borderline” antenna, or to prove the directional pattern of a multi-tower array. In both cases, standard FCC practice is to make measurements along at least 6 radial lines from the antenna site. Distances from 1 km (unless that’s too close for the size of a multi-tower array) to 15 km are preferred, with about 15 measurements on each radial line. Measurements of directional arrays are usually done on more than 6 radials, as they have to include bearings toward other stations being protected by the antennas. The results can be graphically or numerically analyzed for ground conductivity (and perhaps dielectric constant) effects.

That’s obviously “overkill” for the amateur/experimental LF station. On the other hand, a single measurement might not prove much, particularly if the location had re-radiation problems of which you were unaware. My sense is that 5-10 measurements would be appropriate. You can analyze the results as described later, and get a sense of whether you have any problems with locations or your LF antenna system. Those of use running transmitting loops are probably advised to take a series of measurements along the centerline of the loop, in both lobes of the figure-8. In either case, you will probably find one or two really good spots that you can revisit as you make changes to your transmitting setup. If you have an interest in researching the local ground conductivity, then MW broadcast-style measurements would be interesting.

How do I determine the distance and bearing from my QTH to a measuring site?

GPS. It has made this whole business much easier. Carry a portable GPS receiver with you, and let it provide the latitude/longitude of your measuring spot. The receiver may be able to calculate the distance and bearing to previously stored numbers for your QTH, or you can bring the data home and do the analysis with any number of computer programs. The fancier GPS units with mapping capability might be interesting to use, but are really not necessary.

Consider using a computer mapping program in advance to draw out any special radial lines you wish to include. The intersection of those lines with roadways will be obvious, and you can take the printed maps into the field for driving instructions. Remembering that you don’t want to carry the FSM too far, make your judgement about accessibility and local metallic conductors when you get there.

What information should I record with each measurement?

- The time and date.
- The receiver reading in dBm.
- The GPS lat/long coordinates of the location.
- A brief description of the spot to aid in finding it again.
- The depth of the null that you get by turning the antenna 90 degrees to the signal.
- The approximate air temperature. You will likely find higher readings in cold weather.

The next section of this paper will discuss the analysis of the data you collect, and will end with a couple of examples from the WD2XES operation. Let’s start with a story...

There was once a community of engineers who made field strength measurements. Like their modern counterparts, they would dutifully record all of the information, and then take it back to the office for tabulation, graphing, and so on. Their goal was to find the unattenuated field at one mile from the antenna site, because that’s what their government authorities wanted. They were a happy bunch, not only because the numbers they produced made some sense, but because the results were expressed in milliVolts per meter at one mile. Any good engineer seeing such a mixture of units would naturally giggle, leading to the perception of happiness. This tradition continued for many years.

Then along came the French...and the Germans...and the rest of the world. Such an outrageous combination of units could not stand, and the once happy engineers now frown when they calculate unattenuated fields in milliVolts per meter at one kilometer. Not only is there no mix-up of units, but the whole concept lacks some physical reality. But we're stuck with it, so you'd better put on your best unsmiling face and understand what you're dealing with. End of story...

You probably know that given a perfectly conducting ground, the electric and magnetic fields at LF will drop off linearly with distance. That is, a measurement made at 10 km should be half of one made at 5 km. You also know from this paper that at LF, measurements made at distances closer than 3 km are subject to considerable errors. But to determine the actual efficiency in a particular direction, the convention is to pick a nominal distance, 1 km, and set the standards accordingly. This is a fairly brilliant idea at higher frequencies, but not at 137 kHz. That being said, we have to deal with the convention, and just keep in mind that it lacks reality.

ERP calculations are based on the fields from a half-wave dipole in free space. The electric field is given by: $E = \frac{7.02 \cdot \sqrt{p}}{d}$, where p is the power in watts, and d is the distance in meters. For 1 watt at 1 km, E = 7.02 mV/m. At HF and above, this has some physical validity, as the various higher-order E and H fields are low at 1 km, and the radiation fields dominate. But at LF, the whole concept of half-wave dipoles is a bit strange, and the static and induction fields are considerable at 1 km. However, we are stuck with it, and should reduce our results to that form in dealing with any regulatory matters.

If we were dealing with perfectly conducting ground, we could take a field strength measurement at 5 km, and linearly scale it back to 1 km simply by multiplying by 5. For those of us with good local ground conductivity and measurements at relatively short distances, this may be a reasonable approximation. The author, however, is blessed to live in an area with very rocky soil and low conductivity. Signals, even low-frequency ones, do drop off more quickly than the $1/d$ relationship would indicate. So for accuracy, after computing the measured field strength, I must correct for the attentuation from ground conductivity over that distance, and only then multiply to its equivalent at 1 km. Fortunately, the ground conductivity is all that matters at LF; the dielectric constant of the ground is not a factor, as it is at HF.

The easiest way to determine the ground conductivity is to use published maps for MW broadcast purposes, or to get data from local MW stations that have done field measurements. In my case, I have some knowledge of the local ground conditions at 580 kHz from an earlier job. They approximately agree with the U.S. maps provided by the FCC. Presumably, regulatory authorities in other countries provide similar resources.

A calculation of the effect of the ground at LF is based on an article, "The Propagation of Radio Waves over the Surface of the Earth and in the Upper Atmosphere" by K. A. Norton in the I.R.E. Proceedings of October, 1936. He presents some alternatives to much more complicated expressions using error functions, and one set of them is quite suited to our relatively short distance measurements at LF. The ground conductivity, S, is expressed in units of milliSiemens/meter (formerly millimhos/meter), where S = 5000 mS/m for sea water, and 0.5 mS/m for very poor ground. Other units: f is the frequency in kiloHertz, and d is the distance in kilometers. First calculate an intermediate variable, p:

$p = \frac{\pi \cdot d \cdot f^2}{(5.392 \times 10^6) \cdot S}$. If p < 4.5, then calculate the attenuation factor $A = e^{(-0.43 \cdot p) + (0.01 \cdot p^2)}$.

If p > 4.5, then the attenuation factor is $A = \frac{1}{2 \cdot p - 3.7}$. As a matter of practicality, your typical measuring range will produce values for p that are less than 4.5. In either case, the value for A will be less than 1, and you should divide your measured field strength by it to get the unattenuated field at that point. Once you have that, you can scale the reading back to 1 km for comparison with the dipole.

Some Sample Calculations

My transmit loop antenna runs along a 70°/250° line. Here are two measurements taken on November 22, 2006, with a transmitter output power of about 420 watts:

The first was on a public watershed near a reservoir. The reservoir itself is in the opposite direction from my QTH, so the body of water was not an issue. I took the meter into a wooded area on a fire road leading away from the main road. The nearest metal conductors were in a fence about 30 meters away, and the power lines were farther than that. The GPS receiver gave coordinates that were 6.57 km from WD2XES at a bearing of 69.6° true. The Rycom meter gave an indication of -65.8 dBm, with a null of more than 25 dB when the meter was rotated.

The voltage equivalent of -65.8 dBm is $V = \sqrt{0.05} \cdot \left[10^{\frac{-65.8}{20}} \right]$ = 115 uV. Multiplying that by the calibration factor of 7.84 derived in an earlier paper, the measured field strength is 0.899 mv/m. Based on my knowledge of local ground conductivity in the MW broadcast band, I will use S = 1 mS/m. So $p = \frac{\pi \cdot 6.57 \cdot 137.779^2}{(5.392 \times 10^6) \cdot 1.0}$ = 0.0727. Since $p < 4.5$, $A = e^{(-0.43 \cdot 0.0727) + (0.01 \cdot 0.0727^2)}$ = 0.97. So the unattenuated field at that point is 0.899/0.97 = 0.927 mV/m. To scale back to 1 km, just multiply that by the distance in km: 0.927 (6.57) = 6.09 mV/m at 1 km. To determine the ERP, recall that the half-wave dipole with 1 watt produced 7.02 mV/m at 1 km, so $ERP = \left(\frac{6.09 \times 10^{-3}}{7.02 \times 10^{-3}} \right)^2$ = 0.75 watt. This would be a dangerous assumption based on one measuring point, but if you do enough of them, a pattern should appear.

The second measurement was taken earlier that day in a wooded area near a small pond close to where I work. The GPS coordinates gave a distance of 30.33 km at a bearing of 37.5° true. This is well off the 70° center-line of the transmit loop. The Rycom meter gave -80.7 dBm, with as good a null as I could read. -80.7 dBm equates to 20.6 uV. Multiplying that by the 7.84 calibration factor, the measured field strength is 162 uV/m. Since this point is not in the maximum direction of the loop, I will correct it by dividing by cos(70°-37.5°) = 0.843, so the field strength becomes 192 uV/m normalized to the plane of the loop. Doing the math for attenuation, p = 0.335 and A = 0.867. The unattenuated field strength is then 222 uV/m at that point. Multiplying by the distance in km, the resulting field at 1 km is 6.72 mV/m. Again comparing with the free-space dipole, the ERP is 0.92 watt at 1 km.

This article has given some suggestions on the choice of field strength measuring locations for the 2200 meter band, and some ways to analyze the results. The next paper in this series will detail the results of a larger number of measurements.