HF Radar Antenna Principles 101

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- **<u>Ground Rules</u>:**
  - Transmit antenna must be efficient. Who wants to draw 400 watts of power only to radiate 40 watts and see 360 watts converted to heat? Low radiated power directly impacts SNR and therefore radar range.
  - Receive antenna need not be efficient. External noise dominates internal noise, meaning that if echo signal is reduced by inefficiency, so is noise. No impact on SNR or radar range.
  - Both antennas must have broad enough bandwidth to pass the signal. Narrow radar bandwidth (or frequency sweep width) means poor range resolution.

- **<u>Antenna Impedance</u>:** When a transmission line is connected to an antenna, it looks into an input impedance. This means the antenna looks like a resistor and inductor/ capacitor, i.e., two elements in series.
  - The impedance real part, or resistance, is called "radiation resistance." Current flowing through this radiation resistance accounts for radiated power, by the familiar law $P_R = I^2 R$, where I is the current and R is the resistance.
  - The impedance imaginary part is called the reactance. It can be either positive (inductive reactance), negative (capacitive reactance) or zero. It is zero only "at resonance."

- **<u>Why Should I Care about Antenna Impedance</u>:** A transmission line has a real impedance of 50 ohms. A fundamental theorem of electrical engineering says that maximum power is transferred if the load (in this case, the antenna) has an impedance whose real part is 50 ohms and reactive (imaginary) part is zero. At HF this "matched" condition means all the power available coming down the cable goes into the antenna and gets radiated, i.e., a good thing.
  - If the real part of the antenna impedance is not 50 ohms (i.e., it is mismatched), then power gets reflected, i.e., a bad thing. This can be remedied by a lossless RF transformer that matches 50 ohms to the antenna resistance.
  - If the imaginary (reactive) part of the antenna impedance is not zero, it is also mismatched, and power gets reflected, a bad thing -- even worse if both real and imaginaries are mismatched. This is remedied by tuning; e.g., if the antenna's reactive impedance is capacitive (negative imaginary), including an inductor in series cancels the capacitive reactance, getting back to zero.

- If these two things are not done and the antenna is mismatched, then much of the power generated and sent down the line does not get radiated. It's as though it is being burned up and turned to heat in a non-radiating resistor -- not a good thing!

- **<u>Antenna At and Below Resonance</u>:** Pluck a guitar string of a given length and you generate a specific frequency: it "resonates" at this frequency based on its length. You'll also generate weaker harmonics of this frequency (higher resonances). Same with an antenna of a given size: there is a lowest frequency at which it resonates. A half-wave dipole or quarter-wave monopole is a resonant antenna (just as a half-wave guitar string experiences its lowest resonance). A quarter-wave monopole is resonant because there is a mirror image of itself below the ground plane, making it act like a full dipole.
  - At resonance, the antenna has zero imaginary impedance. The real part (radiation resistance) of a monopole/dipole may be between 36 and 72 ohms.
  - This is close enough to the 50 ohm line resistance that it is almost matched (90% of the power gets radiated), but if an even better match is desired, use a transformer.
  - At frequencies below resonance, the real part (radiation resistance) drops and imaginary part increases precipitously, constituting an unacceptable mismatch.
  - This can be transformed/tuned so you're back to 100% efficiency. So great! What's the problem? Well, read on --

The Small Antenna Tradeoff Quandary

Small antennas are nice and inexpensive at HF. If they can be made efficient also just by tuning/matching, maybe we are home free! But why then do we see these huge towers for AM radio transmitter stations? Why don't they use 18-inch high whip monopoles to pump out their megawatts of power? They could be put on top of a car. Like "perpetual motion machines", a never-ending stream of would-be inventors has come forward with their own ultimate compact transmit-antenna "solution", only to be laughed off the stage.

There are three factors at play here that must be considered that represent tradeoffs, around which one cannot escape.

- **<u>Antenna Size</u>:** Small is good. We define "electrically small" as one whose dimensions are quite short with respect to the wavelength.

- **<u>High Efficiency</u>:** When transmitting, we don't want to waste power. For example, no one wants to generate 4000 watts if only 40 watts gets radiated. That would be 1%

efficiency (or -20 dB expressed another way). But when one tunes and matches, then we're back to 100% efficiency, right? So what's the problem? Well, read on --

• **Antenna Bandwidth:** Here's where the impedances and tuning come into play. Remember that electrically small means that initially we were terribly mismatched because we were well below the antenna's natural resonance. There's a very simple fundamental theorem of electromagnetics (like $E = mc^2$ was for Einstein), and we don't even need to consider what kind of antenna we are talking about (e.g., monopole, dipole, loop, corrugated, horn, zigzag, spiral, etc.). Fractional bandwidth cannot exceed the value $fBW = (ka)^3$, where $k = \frac{2\pi}{\lambda}$ with λ being the wavelength; and a is the radius of the smallest sphere that can circumscribe the antenna[1]. (For both monopole and dipole, it's the half-height.) ***That's right, the cube of size/frequency!*** Reduce the size, and bandwidth collapses like a balloon shot out of the sky. What does this mean?

- This ironclad law has already assumed that the antenna is tuned and matched in the manner described earlier when we were discussing impedances. In other words, we artificially resonated it, making it 100% efficient at that one frequency.
- The reciprocal of the fractional bandwidth fBW is called its Q, which is a more familiar term to antenna and electrical engineers.
- If we go back to the impedance concepts earlier, then another alternative representation of bandwidth is $fBW \equiv \frac{R}{|X|}$, where R and X were the antenna radiation resistance and reactance ***before any matching was done***.
- This means that the smaller electrically was the antenna -- and therefore badly mismatched (i.e., very small radiation resistance and very large imaginary reactance) -- the smaller the bandwidth. But the "cube law" above gives us a less roundabout but still exact alternative estimate of the fractional bandwidth in terms of antenna size with respect to frequency below resonance.

• **Radar Bandwidth Required:** Remember, in ***any*** radar, the bandwidth determines the range cell size, and *vice versa*. For instance, at 13 MHz, a lot of people need 2 km range cell, and so sweep the frequency over 75 kHz, which becomes the radar bandwidth. On the other hand, a typical voice channel only requires 3 kHz bandwidth. So suppose you push a 75 kHz radar signal through a filter, i.e., an efficient, electrically small, tuned antenna with a 3 kHz bandwidth, why is that so bad? Well, your range resolution has

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[1] McLean, J.S. (1996), A re-examination of the fundamental limits on the radiation Q of electrically small antennas, *IEEE Trans. Antennas & Propagation*, vol. 44, pp. 672-676.

now gone from a cell 2 km to a 50 km cell. That's not too good! So let's read on and see how really bad it is for a practical example.

Examples: Come On, Surely We Can Get Around This!

- **Let's Go for Tuning and 100% Efficiency:** Let's start with a monopole whip 18" high that is meant to operate at 12 MHz (the radar frequency used in Hawaii). Wavelength is 25 m; circumscribing sphere radius is 18/2 = 9" = 0.2286 m. Using the formula above, we see that fractional bandwidth is $fBW = 0.00019$. Applying this to 12 MHz, the actual bandwidth of the antenna "filter" is 2.3 kHz. But we needed to get 75 kHz through the antenna. Not good! As an independent check, the impedance of an 18" monopole from textbook formulas and exact calculations is $Z = 0.1534 - i1646.3 \text{ ohms}$. From this, the fractional bandwidth after tuning is the ratio of the real divided by the imaginary part, i.e., ~0.0001. This is close, but smaller than the previous value of 0.00019 by about a factor of two, suggesting that this bandwidth estimate is 1.2 kHz. So take your pick. The bandwidth is somewhere between 2.3 and 1.2 kHz. Let's say 2 kHz. Range cell resolution has thereby been destroyed, so that what we started out wanting -- 2 km -- has been smeared out to 75 km. That's unacceptable!

- **How Much Do We Have To Sacrifice Efficiency to Get Back Bandwidth?** The short antenna's radiation resistance was 0.15 ohms. Let's add enough resistance in series to get back to the 50-ohm transmission-line value, so there is no mismatch at this load plus antenna. Now the power gets split between the antenna radiation resistance of 0.15 ohms (this bit gets radiated, that's good) and the resistor we added of 49.85 ohms (this larger portion gets burned up in heat, that's bad). So the efficiency dropped from 100% by the ratio 0.15/49.85 = 0.003, or 0.3% efficiency (a drop of 25 dB in transmitted signal). Meaning, to get 40 watts out of the antenna, we need to generate and burn 12,000 watts of power! How about that, anyone want to do this? The good news is, we can get our 75 kHz signal through the antenna and the resistances. But what a price to pay!

- ***Sorry, there just isn't any way around this conundrum. If we want adequate bandwidth and good efficiency on transmit, we need a bigger antenna. You don't go to jail if you try to break fundamental laws of electromagnetics and radio physics, you just waste money and time, and end up looking stupid.***