Broadband and Portable Electrically Short Transmitters in the VLF/LF Band via Time-Variation

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***Abstract*—Electrically-short antennas often have a very narrow bandwidth as a consequence of standard frequency-domain impedance matching techniques. Here, we present a time-domain technique for improving impedance matching via reflection suppression. We detail initial results of a low-power prototype and its efficiency gain compared to a traditional dipole antenna. Our focus is on the VLF/LF band from 1-500 kHz, where conventional beacons require top hats that can span thousands of acres, and yet deliver very small bandwidths.**

Keywords—wideband antennas, electrically short antennas, transmitting antennas, VLF, impedance matching

I. Introduction

Fixed-length electric dipole antennas are generally operated at frequencies at which the length of the antenna is within an order of magnitude of the wavelength. This is because for a fixed antenna length well below a wavelength and without employing any matching technique, the radiated power will decrease by a factor of f^4 as the frequency is decreased. While one f^2 factor is an inescapable law of physics, another f^2 factor can be eliminated through careful engineering. This inefficiency is due to impedance mismatch, as the input impedance increases by f^2 for a given decrease in frequency. One can view the antenna as a transmission line stub terminated by an open circuit. As the stub's length decreases relative to the wavelength, its impedance increases. Applying this framework, if there were a way to make it such that the feed point saw the antenna as an infinitely long transmission line, its termination type would be irrelevant, the input impedance would be matched, and the output power would decrease by only one factor of f^2.

Previous frequency-domain impedance matching efforts have come at the expense of bandwidth. For instance, top hat antennas currently operating in the VLF band (3-30 kHz) can achieve at best 1% bandwidth, as they rely on resonance over a narrow range. Furthermore, these systems are physically massive, often covering several square miles.

Radio waves in the VLF spectrum have a unique set of properties that make them uniquely suitable for a wide range of applications including global communications, navigation systems, subterranean imaging, and over-the-horizon radar among others. The ability to generate these waves with a transmitter that is both compact and efficient would be extremely valuable to these fields and beyond.

II. A New Approach

Our method for controlling the input impedance involves suppressing reflections at the end of the antenna via rapid variation of the conductivity of the antenna in time. Revisiting the transmission line model, the open circuit at the end of a standard dipole antenna has a current reflection coefficient of -1. Thus, if the wavelength is much longer than the propagation path, most of the feed current will be cancelled out by the nearly equal and opposite reflection current. If we can stop these reflections from travelling back to the feed, we can increase the total current on the antenna and thus the radiating power. This time-domain technique is inherently frequency independent and therefore broadband in nature. As shown in Figure 1, the lower the transmitting frequency, the greater the relative gain of reflection suppression compared to a standard whip antenna.

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[1] Now at SpaceX, Inc

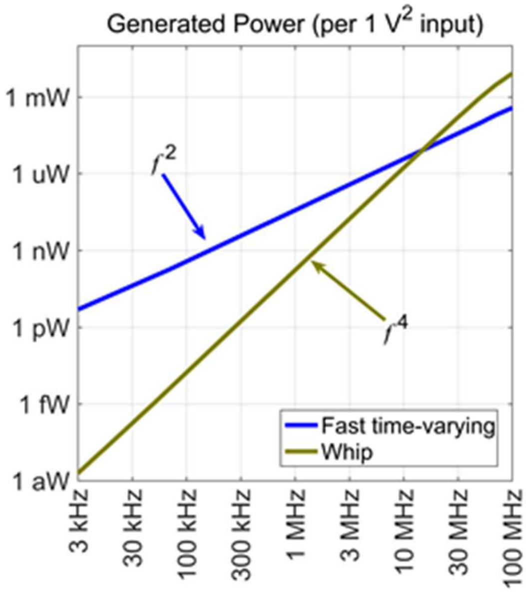

Figure 1. FDTD simulations of our antenna compared to a standard whip

The first step is to break the signal of interest into a series of pulses, i.e. by switching the input on and off. As each pulse travels down the length of the antenna, it sees a matched impedance until it reaches the end, where it is reflected. However, on its return path, a segment of the antenna is switched to a high impedance, so that the pulse is again reflected toward the end, and cannot cancel out the next incoming pulse.

This temporal variation in impedance along the antenna can be achieved in several ways. One proposed method is to use a plasma as the conducting channel. The plasma channel could be ionized and deionized to control impedance. This method would allow for very high currents in theory. However, in practice, controlling plasmas on nanosecond time-scales is an incredibly challenging engineering task. A second method involves replacing a portion of the antenna with a reflective switch. This method is limited by the power capacity and transition time of the switch. However, it provides a reasonable method for demonstrating this concept at low powers.

III. Implementation

A proof of concept was constructed using a single transistor switch for reflection suppression. The radiating element took the form of a single-wire transmission line similar to that described by Goubau [1]. Using a 3-meter transmitting antenna (extremely short electrically at these frequencies), we were able to measure a >20 dB improvement in magnetic field strength if a 30 kHz signal at 25 meters when using the reflection suppression method as compared to a conventional antenna, as shown in Figure 2. As predicted, the relative gain provided by this method increased as the transmitted frequency decreased.

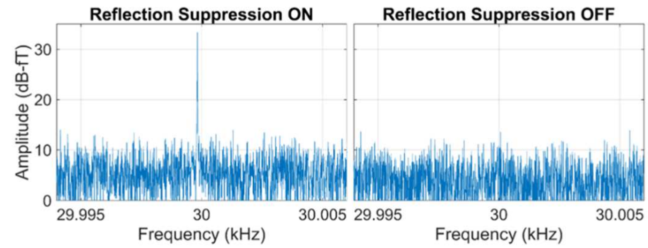

Figure 2. Measured field strength at 25 meters shows 20 dB improvement using reflection suppression compared to conventional antenna.

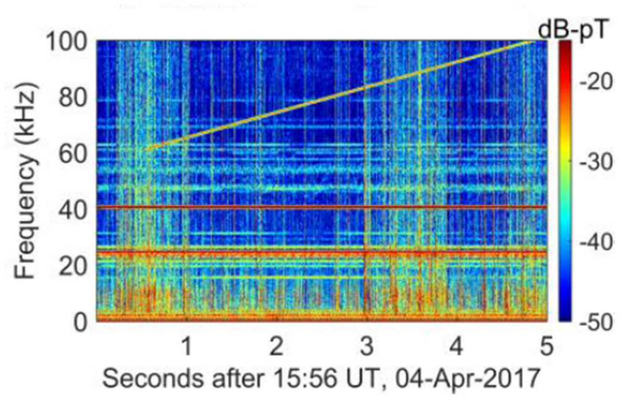

Figure 3. Measured frequency sweep transmitted using frequency suppression highlighting broadband nature of the technique.

Figure 3 shows a spectrogram of the measured magnetic field a chirp sweeping from 60 kHz to 100 kHz. This demonstrates the broadband capability of this method. It's worth noting that in an unmatched configuration, in the near field, the magnetic field could be expected to be constant with frequency if the current moment is constant with frequency. This matches our observations and indicates that our technique for matching is working as intended, albeit at low powers for now. All measurements were taken using the AWESOME VLF receiver, which is capable of greater than 1 fT/rt-Hz sensitivity [2]. With this sensitivity and recent improvements in our system allowing for greater output power, we believe that we should be able to detect signals at km-scale distances.

IV. Future Plans

We are currently pursuing several methods to increase the output power of our transistor-based system. This includes optimizing the impedance match of the single-wire transmission line, improving our timing algorithm, and applying novel switching technologies. We will detail these improvements and further results in this presentation.

References

[1] G. Goubau, "Single-Conductor Surface-Wave Transmission Lines," Proceedings of the I.R.E, pp. 619–623, Jun. 1951.

[2] Cohen M. B., U. S. Inan, and E. W. Paschal (2010), Sensitive Broadband ELF/VLF Radio Reception with the AWESOME Instrument, *IEEE Trans. on Geoscience and Remote Sensing*, 48, 1, 3-16, doi:10.1109/TGRS.2009.202833