DGPS Directional Signal Strength Meter

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BIOGRAPHIES

Lee Hartshorn is a 2002 graduate of the US Coast Guard Academy with a BS in Electrical Engineering. Following graduation he served as an engineer on Coast Guard Cutter *Bear* based in Portsmouth, Virginia. After a two-year tour on *CGC Bear*, LTJG Hartshorn transferred to the University of Rhode Island, where he is currently pursuing a MSEE.

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Gregory Johnson is a Senior Program Manger at Alion Science & Technology, JJMA Maritime Sector. He heads up the New London, CT office which provides research and engineering support to the Coast Guard Academy and R&D Center. He has a BSEE from the USCG Academy (1987) a MSEE from Northeastern University (1993) and a PhD in Electrical Engineering from the University of Rhode Island (2005). Dr. Johnson is a member of the Institute of Navigation, the International Loran Association, the Institute of Electrical and Electronics Engineers, and the Armed Forces Communications Electronics Association. He is also a Commander in the Coast Guard Reserves.

ABSTRACT

The U. S. Coast Guard currently operates a maritime differential GPS service consisting of two control centers and over 85 remote broadcast sites. This service broadcasts on marine radiobeacon frequencies using minimum shift keying (MSK) as the modulation method. For some time, the Coast Guard Academy has been developing hardware/software tools to assess the performance of this system.

The tool described in this paper performs DGPS beacon field strength measurements using an electronically steerable antenna array. The steerable nature of this sensor provides the ability to perform spatial filtering while analyzing the DGPS beacon spectrum. This tool is useful for validation of DGPS coverage prediction software, for site certification, and reception troubleshooting:

- Consider two DGPS transmitters that are transmitting on the same frequency. This tool would provide the capability to make field strength measurements at a location half way between the two transmitters, in the direction of one transmitter, while nulling out the transmission from the other. Such a tool would be invaluable in validating propagation prediction coverage algorithms and software. The mandated coverage required by the National Differential Global Positioning System (NDGPS) makes such propagation prediction tools critical.

- The combination of this tool with a standard DGPS receiver would provide great insight while troubleshooting receiver reception problems. This combination could provide the ability to correlate directional signal strengths from DGPS beacons with periods of non-reception.

The receiver consists of an antenna array (an H-field crossed loop antenna and an E-field whip antenna), amplifiers and filters, an analog-to-digital converter, and a MATLAB®-based, GUI driven, digital back end.

INTRODUCTION

The Coast Guard currently operates a maritime differential GPS service consisting of two control centers and over 85 remote broadcast sites. This service broadcasts on marine radiobeacon frequencies (the 285-325 kHz band with frequency reuse) using minimum shift keying (MSK) as the modulation method. For some time, the Coast Guard Academy (USCGA) has been developing hardware/software tools to assess the performance of this system. Of interest here are tools for measuring the received signal strength at specific locations for specific beacons. While measuring the signal at an antenna output is simple, what complicates matters is the frequency reuse pattern. For example, consider the case shown in Figure 1 of beacons at Annapolis, MD and Macon, GA. Both of these transmitters broadcast at 301 kHz, hence, both would be visible to measurement equipment at locations between them. Therefore it is not possible to make signal strength measurements, for individual beacons, using omni-directional antennas. The goal of a recent USCGA cadet project has been to implement a signal strength meter that can isolate one beacon in such situations by using a more sophisticated antenna system.

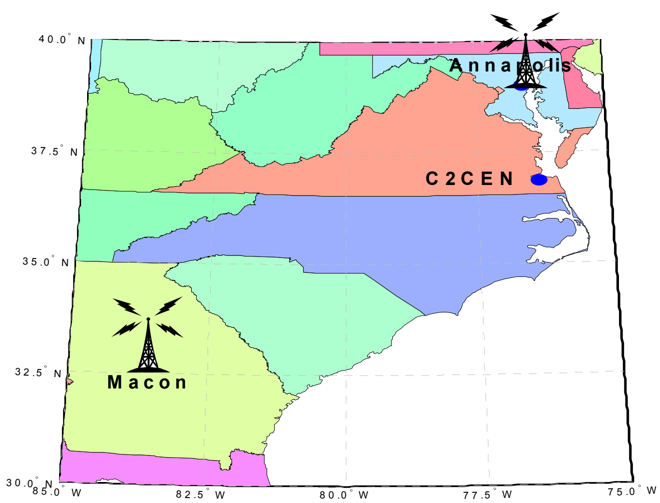

Figure 1 – Example of interfering beacons.

This tool provides the capability to make field strength measurements in the direction of one transmitter, while nulling out the transmission from the other. As such, it will be invaluable to the Coast Guard in validating propagation prediction coverage algorithms and software. The mandated coverage required by the National Differential Global Positioning System (NDGPS) makes propagation prediction tools critical. In addition, this will be an outstanding DGPS troubleshooting tool; the combination of this sensor with a standard DGPS receiver could provide great insights while troubleshooting receiver reception problems. This combination could also provide the ability to correlate directional signal strengths from DGPS beacons with periods of non-reception.

Work on this system has been ongoing by cadets at the Coast Guard Academy for the past several years [2-3 and 5-6] with initial results reported at ION in 2002 [4]. Initial work on the beam-forming algorithm was done in 1997 [1]. This year, the project has been advanced to completion of a functional prototype.

SYSTEM DESCRIPTION

A photo-based system diagram of the DGPS Signal Strength Meter is provided in Figure 3, a photo of the complete system in its weatherproof enclosure appears in Figure 2. The basic system consists of three parts: the antenna array, the analog front end, and the digital/software component.

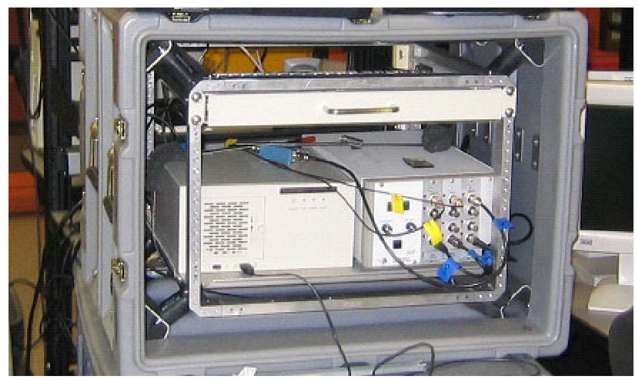

Figure 2 – The complete system.

The antenna array consists of three antennas: a pair of orthogonal loops and one co-located whip. While earlier incarnations of this system used two distinct loops, the current system employs an H-field crossed loop antenna designed for Loran-C (100 kHz) use by Megapulse Corp. which has separate outputs for each loop. Both antenna packages (loops and whip) include active low noise amplifiers.

The analog front-end subsystem consists of three parallel channels of amplification and bandpass filtering and is implemented on a Frequency Devices Inc. 90IP instrumentation platform. This unit is able to provide up to 60 dB of pre-filtering gain and 20 dB of post-filtering gain. Anti-aliasing bandpass filters are implemented in the 90IP. Both the gain and filter parameters are programmable on this device and can be stored in memory for reuse. Each of the three bandpass filters is implemented as a cascade combination of a lowpass filter and a highpass filter that are set to pass the DGPS beacon band (285-325 kHz) and attenuate all signals that would alias into this band. Each of these filters is an 8^{th} order elliptic filter.

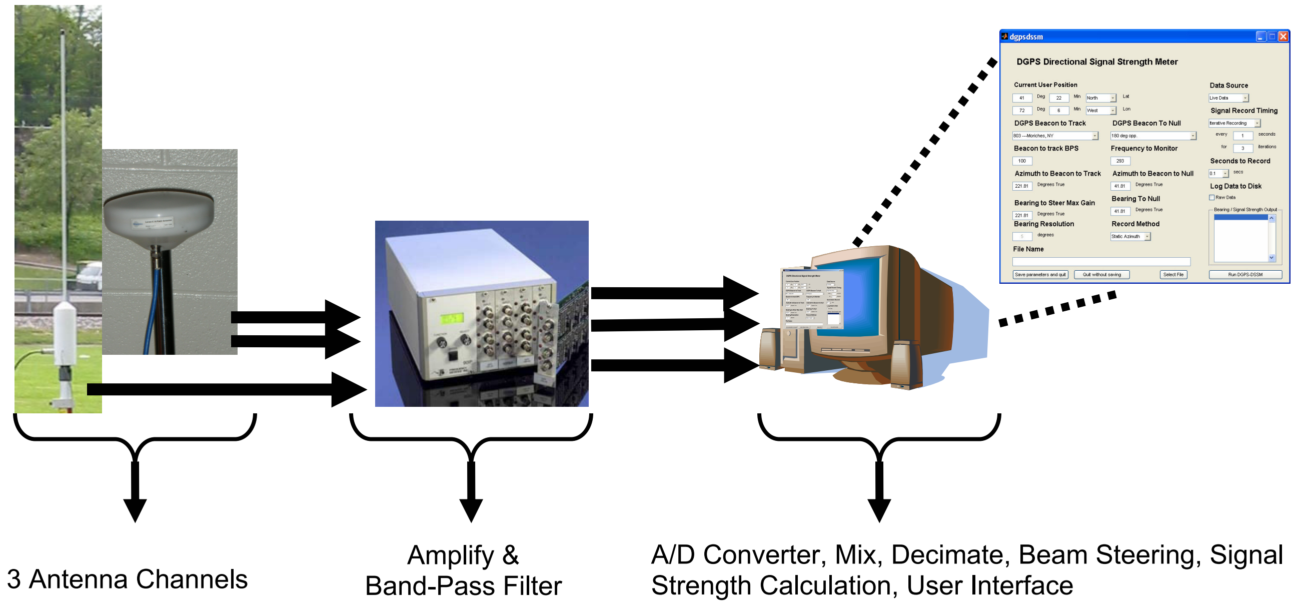

Figure 3 – System Diagram of Directional DGPS Signal Strength Receiver

The performance of each of the three filters is shown in Figure 4 (only magnitude responses shown). With an A/D sampling rate of 1 MHz, frequencies of 675-715 kHz are those that would alias into the 285-325 kHz band thus it is necessary for the bandpass filter to attenuate these frequencies sufficiently. With the filters used, we observe at least 75 dB of attenuation (this is the noise floor of the measurement device used) for frequencies greater then 580 kHz. In addition, the filter provides at least 80 dB of attenuation for frequencies less then 150 kHz. Figure 5 contains a magnified version of this frequency response plot focusing on the DGPS beacon frequency band. The magnitude response is relatively flat in the passband, with about 6 dB of attenuation per channel; this attenuation as well as the small variation in magnitude is corrected in software prior to beam/null steering and signal strength measurements.

The analog to digital converter (A/D) is a NuDAQ PCI-9812 card which provides four simultaneous channels of A/D at up to 20 MHz sampling on each channel with a 128K-word buffer. For this application, the sampling frequency is set to be 1 MHz. The A/D interface, mixing, decimation, beam/null steering, signal strength calculations and graphical user interface are all performed on a 1.5 GHz Pentium M computer in the MATLAB® programming environment. The mixing operation shifts the desired center frequency down to baseband, which permits decimation by a factor of 100 or a reduction of the sampling frequency to 10 kHz. The beam/null steering routine then performs spatial filtering. This allows the user to measure the signal strength in one direction while nulling out a signal in a different direction (greater than 90º away) that is at the same frequency. The beam/null steering algorithm is discussed in detail below. Finally the signal strength at the frequency of interest is determined and displayed to the operator. The details of the signal strength calculations are also discussed in a later section.

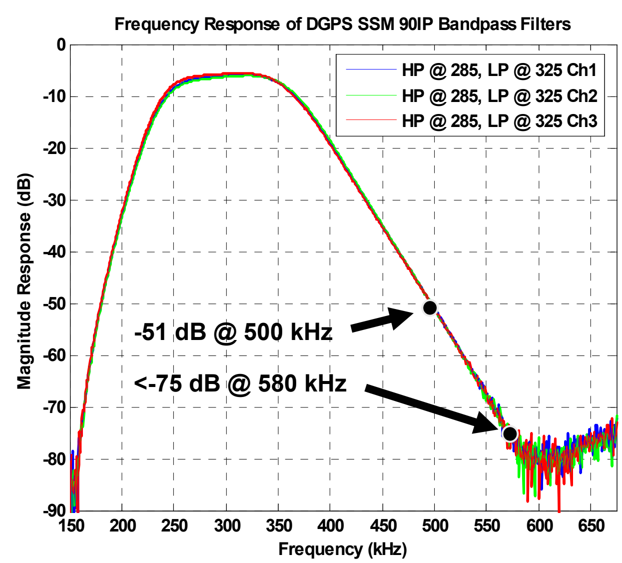

Figure 4 – Frequency responses (magnitudes) of the three anti-aliasing/bandpass filters.

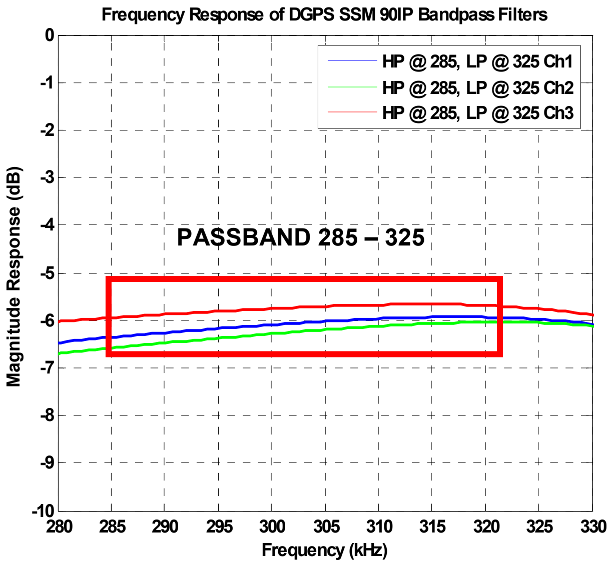

Figure 5 – Detailed look at the DGPS passband.

BEAM/NULL STEERING - THEORY

Our antenna system consists of the combination of two orthogonal loops (without loss of generality, we assume one oriented north-south, the other east-west) and one co-located whip antenna. In a perfect world, for a signal *s(t)* arriving at angle θ with respect to the positive horizontal axis (000° T), we would see antenna outputs:

$$x_{loop1}(t) = \cos\theta \; s(t),$$

$$x_{loop2}(t) = \sin\theta \; s(t), \text{ and}$$

$$x_{whip}(t) = s(t).$$

In other words, the loop antennas are sensitive to the angle to the signal (the second loop has a 90º offset from the first antenna, hence the sine function) while the whip is omnidirectional. It is common to show these multipliers for *s(t)* as antenna patterns on polar axes as in Figure 6. This figure is interpreted by selecting the angle of arrival of the signal (from 0 to 360º); the corresponding blue, green, and red values show the magnitudes of the responses of the antennas with respect to the original signal. For example, at an angle of 45º, both loops have a multiplier of 0.707 while the whip maintains full signal. Further, this plot shows magnitude only; the loops would show a sign change (polarity reversal) on the left and bottom patterns.

Beam steering implies that we combine the antenna outputs in such a way as to enhance the response to signals arriving from certain spatial angles while simultaneously attenuating signals at other angles. With one whip and two orthogonal loops it is possible to aim (or enhance) the combined response toward one direction, say to angle ϕ, and to provide a null (or zero) response to signals at angles $\pm\lambda$ relative to ϕ (note that λ must be at least 90º otherwise the loops are aimed in the opposite direction). The linear combination of antenna outputs to achieve this is:

$$r(t) = k_{loop1}x_{loop1}(t) + k_{loop2}x_{loop2}(t) + k_{whip}x_{whip}(t)$$

where:

$$k_{loop1} = \cos\phi,$$

$$k_{loop2} = \sin\phi, \text{ and}$$

$$k_{whip} = -\cos\lambda.$$

Assuming perfect antennas, this expression can be simplified to:

$$r(t) = [\cos(\phi-\theta) - \cos\lambda]\, s(t).$$

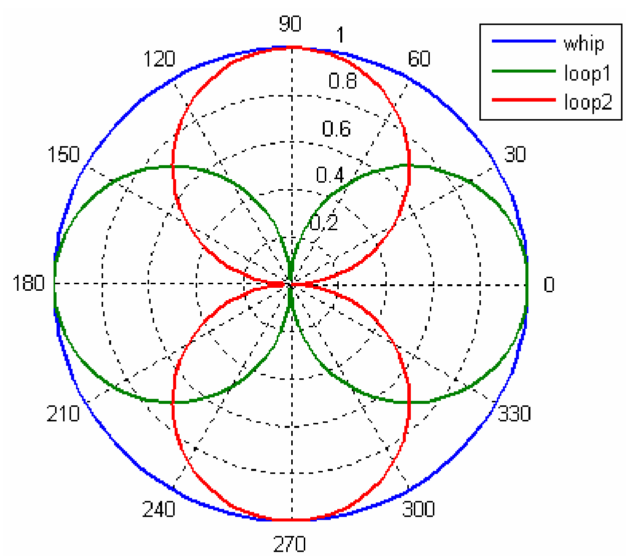

Figure 6 – Ideal antenna patterns.

Figure 7 shows the beam steering responses to signals arriving at angle θ for $\phi = 45$ and different values of λ. In each case, we see a pattern aimed or steered to 45º with a null λ away:

- at λ= 90º, (the magenta curve), the whip is effectively disconnected ($k_{whip} = 0$) and the resulting figure eight pattern is just the combining of the two loops with equal weights.

- at λ= 110º (the green curve), we start to see some cancellation of signals out the back of the antenna (toward 215º) and the nulls properly located.

- at λ= 135º (the red curve) and λ= 160º (the blue curve), we observe more and more cancellation out the back, but at a cost of widening the front lobe.

- finally, at λ= 80º, we see the limits of this simple steering/nulling scheme – it is impossible to set the null closer than 90º, angles smaller than 90º result in a beam looking 180º away from the desired heading.

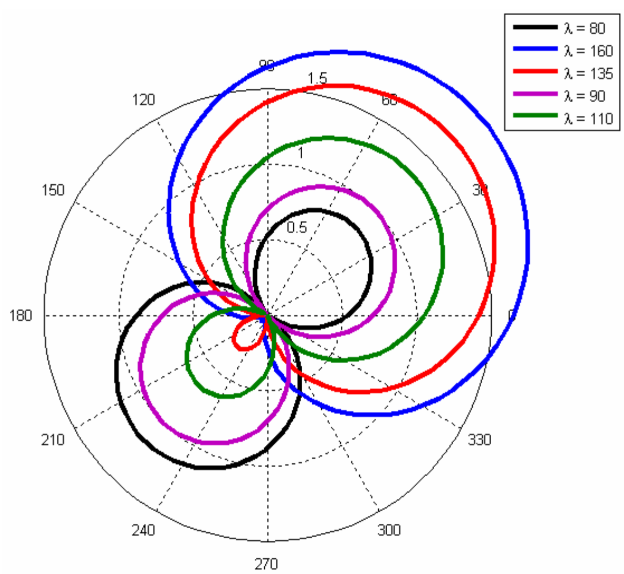

Figure 7 – Ideal steering to φ=45º with various angles to the null.

BEAM/NULL STEERING – REAL ANTENNAS

In reality, our antennas are not perfectly matched:

- the maximum gains are not each equal to unity.

- each antenna/amplifier channel may exhibit different amounts of time delay (which exhibits itself as phase delay in our sinusoidal signals).

- the loops may not be orthogonal.

- the nulls for each loop are small, but non-zero.

To model the real system, we choose the following parameterization:

- loop 1: oriented north-south, with magnitude constant α and null magnitude ε so that:

$$x_{loop1}(t) = \left(\alpha\cos\theta + \varepsilon\right) s(t)$$

- loop 2: oriented almost east-west, off by angle δ, with magnitude constant β and null magnitude ε so that:

$$x_{loop2}(t) = \left(\beta\sin\left(\theta - \delta\right) + \varepsilon\right) s(t)$$

- whip: with magnitude constant γ so that:

$$x_{whip}(t) = \gamma\, s(t)$$

Note that to include the phase delays, we just make the gains α, β, and γ complex; we will consider this further below. In the mean time, Figure 8 shows such a set of antenna patterns for parameter values: $|\alpha| = 0.96$, $|\beta| = 1.05$, $|\gamma| = 0.65$, $\delta = 5°$, and $\varepsilon = 0.1$. It's obvious that to be able to beam steer, we must first correct for the gains (complex gains; equivalently a gain and time delay term) for the three antennas; the corresponding patterns appear in Figure 9 and are quite close, although slightly different than Figure 6. The significant difference is the angular offset different from 90º.

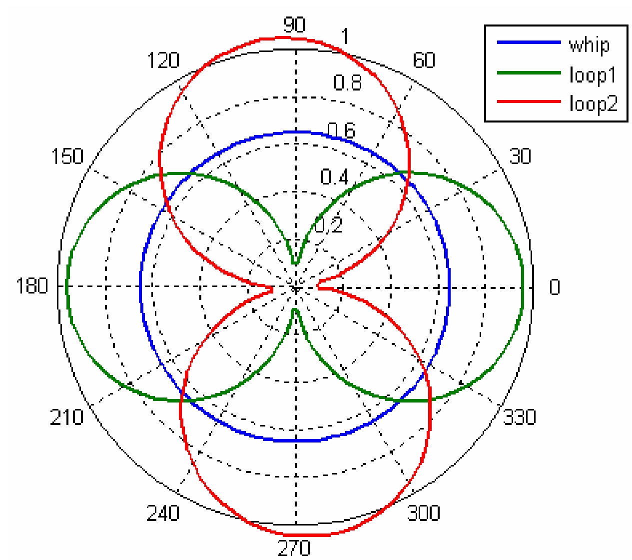

Figure 8 – Realistic antenna patterns.

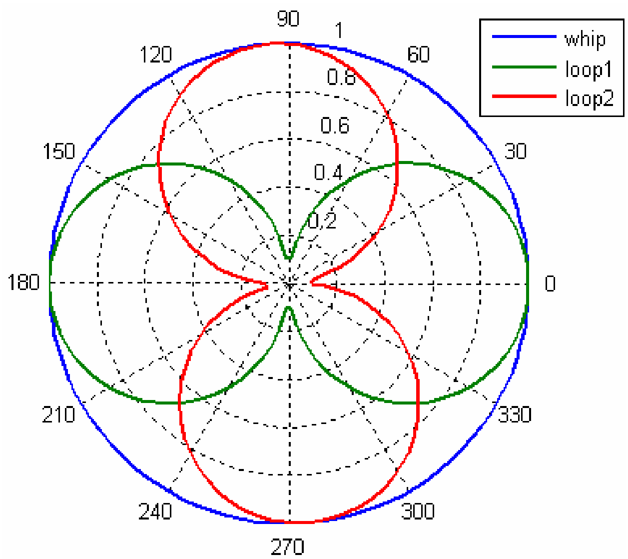

Figure 9 – Gain adjusted realistic antenna patterns.

At this point we still cannot apply the steer/null results above; the non-orthogonality of the loops results in incorrect steering and nulling. In order to achieve the desired steering/nulling we must correct for the angular offset. To present the method, let's assume that the loops have true nulls (i.e. $\varepsilon = 0$) and that the separate gains have been corrected for. Using tilde's to represent the scaled inputs, we have signals:

$$\tilde{x}_{loop1}(t) = \cos\theta\, s(t)$$

$$\tilde{x}_{loop2}(t) = \sin(\theta - \delta)\, s(t)$$

$$\tilde{x}_{whip}(t) = s(t)$$

and want to combine them using new coefficients (again with tildes):

$$\begin{aligned} r(t) &= \tilde{k}_{loop1}\tilde{x}_{loop1}(t) + \tilde{k}_{loop2}\tilde{x}_{loop2}(t) \\ &\quad + \tilde{k}_{whip}\tilde{x}_{whip}(t) \\ &= \left(\begin{array}{c} \tilde{k}_{loop1}\cos\theta + \tilde{k}_{loop2}\sin(\theta-\delta) \\ + \tilde{k}_{whip} \end{array} \right) s(t) \end{aligned}$$

Comparing to the ideal case above, we want to match the terms in brackets, or:

$$\tilde{k}_{loop1}\cos\theta + \tilde{k}_{loop2}\sin(\theta - \delta) + \tilde{k}_{whip} = \cos(\phi - \theta) - \cos\lambda$$

Matching the constant terms, we use:

$$\tilde{k}_{whip} = -\cos\lambda$$

and work on solving:

$$\tilde{k}_{loop1}\cos\theta + \tilde{k}_{loop2}\sin(\theta - \delta) = \cos(\phi - \theta)$$

Note that this equation has two unknowns that we desire to find, $\tilde{k}_{loop1}$ and $\tilde{k}_{loop2}$, and that they appear linearly in the expression. Further, we want equality for all θ, $0 < \theta \le 360^o$. To proceed, we consider two values for θ and solve the resulting simultaneous equations. We use $\theta = \phi$ and $\theta = \phi + 90^o$. The resulting equations are:

$$\tilde{k}_{loop1}\cos\phi + \tilde{k}_{loop2}\sin(\phi - \delta) = 1$$

and

$$\tilde{k}_{loop1}\cos(\phi + 90^o) + \tilde{k}_{loop2}\sin(\phi + 90^o - \delta) = 0$$

With solutions:

$$\begin{aligned} \tilde{k}_{loop1} &= \frac{\sin(\phi + 90^o - \delta)}{\cos\phi\sin(\phi + 90^o - \delta) - \sin(\phi - \delta)\cos(\phi + 90^o)} \\ &= \frac{\cos(\phi - \delta)}{\cos\delta} \end{aligned}$$

and

$$\begin{aligned} \tilde{k}_{loop2} &= \frac{-\cos(\phi + 90^o)}{\cos\phi\sin(\phi + 90^o - \delta) - \sin(\phi - \delta)\cos(\phi + 90^o)} \\ &= \frac{\sin\phi}{\cos\delta} \end{aligned}$$

Figure 10 shows the result of using these gains on the example antenna patterns. While there are slight bumps due to the non-zero nulls, the direction of the beam and the locations of the nulls are perfect. With these gains, the overall system response is:

$$\begin{aligned} &\frac{\cos(\phi - \delta)\cos\theta}{\cos\delta} + \frac{\sin\phi\sin(\theta - \delta)}{\cos\delta} - \cos\lambda \\ &= \frac{\cos(\theta - \phi + \delta)}{\cos\delta} - \cos\lambda \end{aligned}$$

At the beam direction, $\theta = \phi$, this is just $1 - \cos\lambda$ which ranges from unity at a 90º null to two at a null 180º behind the beam. This gain must later be compensated for when computing the signal strength.

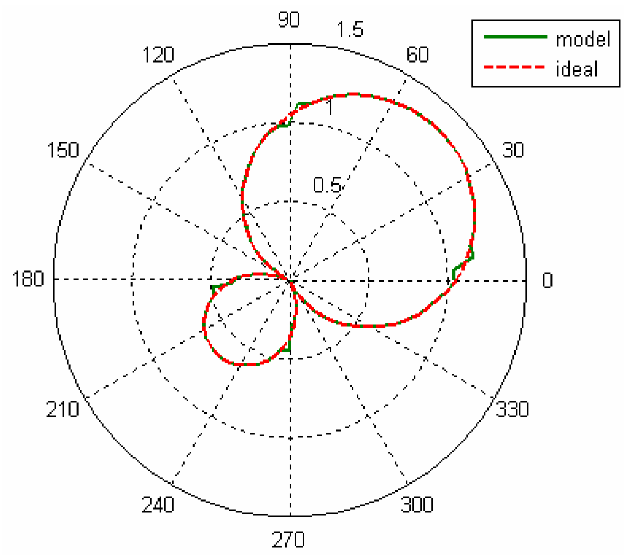

Figure 10 – Correcting for the angular shift.

BEAM/NULL STEERING – OUR ANTENNAS

Figure 11 shows measured antenna patterns for our H-field loop antenna and whip prior to any compensation. As can be seen, we did not align the loops north-south or east-west. More significantly, the loops show a slight mismatch in maximum magnitude, an angular offset from orthogonal of approximately 7º, and the whip magnitude is significantly below that of the loops. Correcting the magnitudes results in the pattern shown in Figure 12.

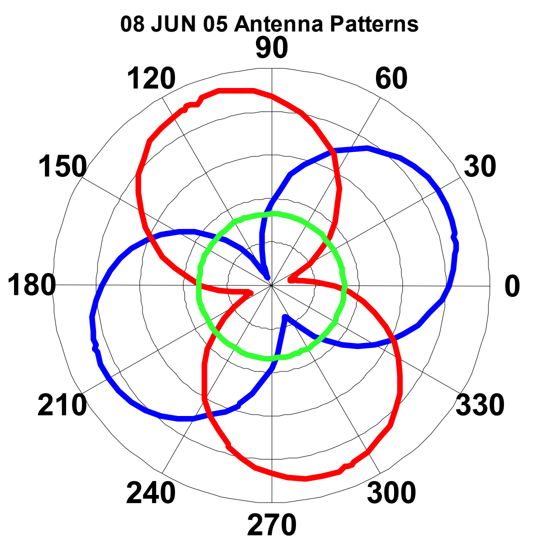

Figure 11 – Antenna patterns for our loops and whip.

We also need to adjust the phase of two of the antennas. For example, Figure 13 displays the phase angle (wrapped to the range [$-\pi$, π] radians) of the output of the whip and one of the loops as a function of time (sample number with 10 kHz sampling of the decimated signal). We adjust the time delay offset of the channels to get these phase plots to line up as shown in Figure 14.

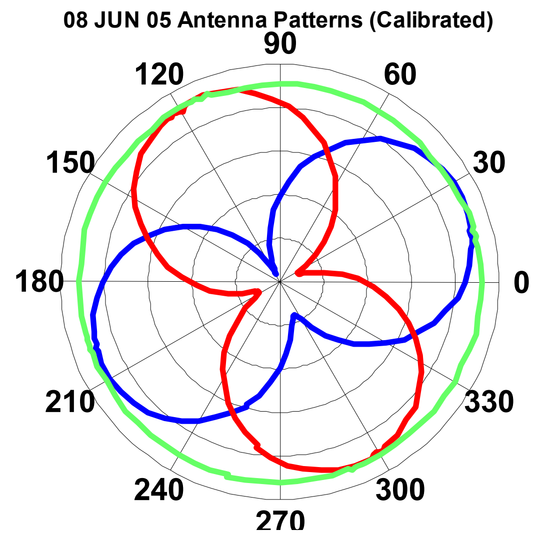

Figure 12 – After correcting the gains.

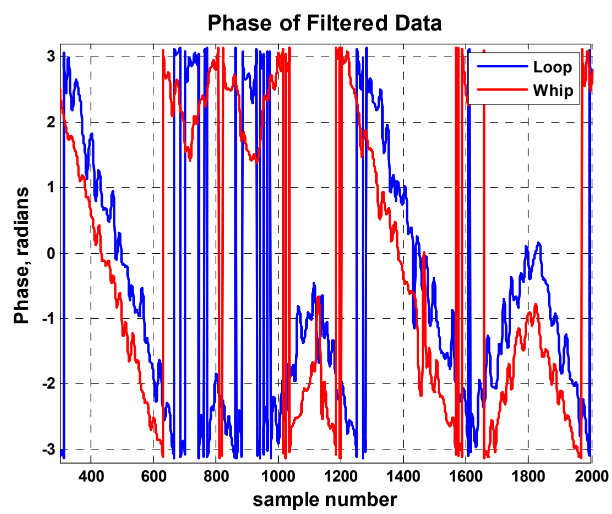

Figure 13 – Antenna outputs prior to phase adjustment.

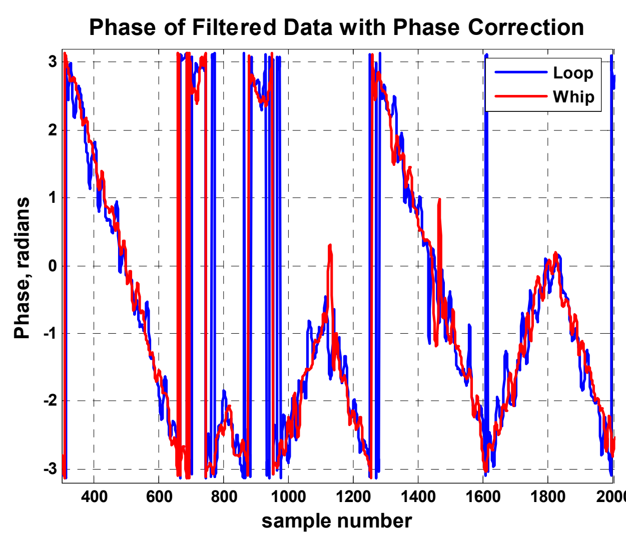

Figure 14 – Antenna outputs after phase adjustment.

SIGNAL STRENGTH MEASUREMENTS

The final stage is to calculate the signal strength. That is, calculate the signal strength (dB relative to 1µV/m) for a particular frequency, with a specific orientation of the antenna beam/null steering algorithm.

We have been considering two different methods to estimate the power: direct MSK and MSK-to-FSK conversion. Direct MSK refers to directly computing the power in the MSK band of the beacon of interest. A typical MSK spectrum for the beacon at 293 kHz appears in Figure 15. This single center lobe is typical of MSK. Taking an FFT of the beam steer/null output, with bin width of 100 Hz (matching the bit rate of the beacon), our estimate of signal strength is the value resulting from the bin at the beacon frequency. This is a fast estimation method if we can assume that there are no other signals interfering in the band of interest.

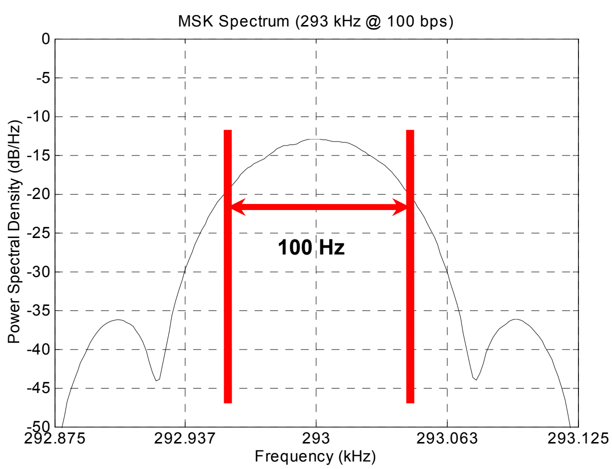

Figure 15 – Spectrum of an MSK signal.

MSK-to-FSK conversion refers to first squaring the beam steer/null output which effectively produces FSK (frequency shift keying) at double the MSK frequency. Figure 16 shows a typical spectrum for such a signal for beacon frequency of 293 kHz; notice the narrow peaks due to the two instantaneous transmit frequencies. These two distinct frequency lines are located at:

$$f_{lines} = 2 * f_{carrier} \pm \frac{DataRate}{2}$$

At this point, an FFT operation with bin width of 10 Hz nicely isolates the power in the two frequency lines. These two values are summed to estimate the total power of the MSK signal. This FSK method is useful in that it focuses our attention on a narrower portion of the MSK band; useful if there is some other non-MSK interference. Remember that in either case (MSK direct, or MSK-to-FSK conversion), the gain of the beam steer/null must be corrected for.

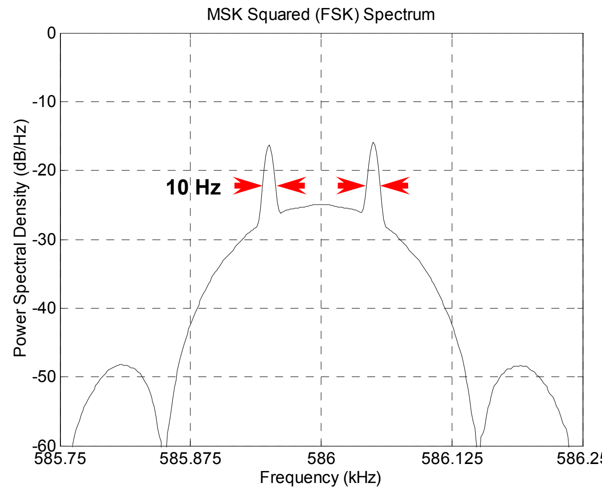

Figure 16 – Spectrum of a squared MSK or FSK signal.

USER INTERFACE

The graphical user interface screens have been developed in MATLAB; an example is provided in Figure 17. In this window the user enters beam/null steering information. To help the user determine what direction to steer the beam and/or null, there is a pull-down list of all of the DGPS broadcast beacons. If the user enters the unit's position, the bearing to the selected beacon is displayed. Furthermore, when the beacon-to-steer is chosen, the beacon-to-null drop-down menu is populated with beacons on the same frequency, or a choice for 180 degrees relative to steering angle. The bearing for the null position is also calculated and displayed for the user. In this window the user also selects whether to perform calculations on a single azimuth or repeat calculations at multiple bearings in user definable steps. All of these operations can be conducted on either live or previously recorded data.

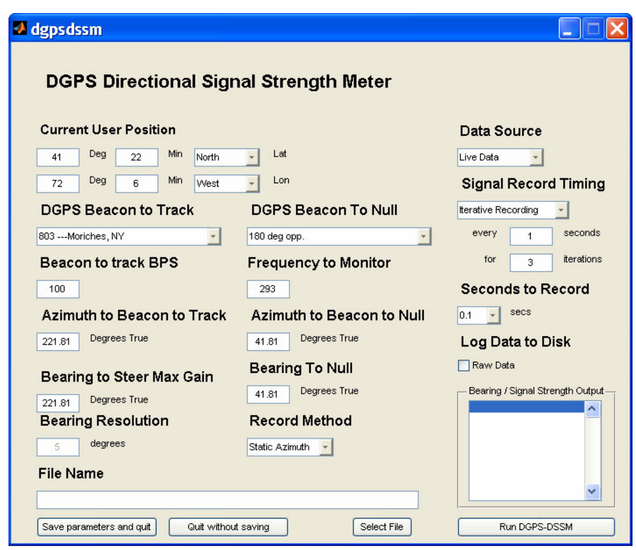

Figure 17 – MATLAB user interface.

An additional option allows the user to collect data over an extended period of time using the iterative recording function. By selecting this mode the user can choose time between iterations and number of iterations for signal strength measurements. All of this data can be saved to the hard drive for later analysis.

SUMMARY AND FUTURE WORK

Over the past four years a great deal has been accomplished in developing this signal strength meter. The system has been designed, the hardware has been assembled (through various iterations), and the software has been developed. All components have been installed in a field-ready container for portability. It is anticipated that in the near future the unit will be taken to various field locations for testing of alternate beacons, including a test of beacons on competing frequencies within range of each other. This test will likely be conducted in the Outer Banks, NC area where Annapolis, MD, and Macon, GA beacons which transmit on 301 kHz, should both be able to be received.

Future developments being considered include the capability to automatically orient the antenna array. Currently the north-south loop must be manually oriented to true north which can be difficult to do precisely and results in directional errors. Additionally, a more precise calibration of the unit must be conducted to equate the computer signal strength to the actual strength as seen by a calibrated antenna.

ACKNOWLEDGMENTS

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