Abstract—Airborne high frequency (HF) direction finding is difficult due to wavelengths on the order of the aircraft size resulting in inefficient apertures and limited azimuthal resolution. This research effort focuses arrays of magnetic field sensors in a simulated airborne array. The MGL-S8A is a magnetic sensor developed for frequencies above 5 GHz and does not offer adequate sensitivity, but a larger MGL-5 sensor does offer efficiencies equivalent to previous research. Eight and ten-element airborne array designs prove to have limited azimuthal resolution, but addition of sensors increases null depth and reduces sidelobes improving the direction finding potential of the array.

I. INTRODUCTION

In the current saturated telecommunications environment, the Federal Communications Commission (FCC) requires radio frequency (RF) systems to limit bandwidth and power levels in order to maximize the number of users in the spectrum. Systems, such as the High Frequency Global Communications System (HF-GCS), used for long distance communications, international broadcast stations, Standard Time and Frequency, and emergency distress beacons operate in the high frequency (HF) band, 2-32 MHz. As the number of users of the HF band increases, the need for an airborne HF direction finding (HFDF) capability also increases.

There has been much research in DF algorithms, methods, and arrays. DF capabilities in the HF band are difficult due to the long wavelengths (10-100 meters), resulting size of resonant antennas, and the spacing required for adequate phase difference between individual elements. DF requires azimuthal resolution. Classical phased array processing requires linear array lengths of multiple wavelengths to achieve azimuth resolution. The differences in phase between individual elements allow beamforming to determine angle-of-arrival of a signal of interest.

The overall goal of this research is to design a sensor array that can be included on a large body aircraft and is capable of performing HFDF. Because an array of classical HF antennas is not possible on an aircraft, this research investigates smaller sensors whose output voltage changes as the magnetic field changes. These sensors are often referred to as B-dot sensors. The MGL-S8A B-dot sensor was developed in the 1970s by the Air Force Weapons Laboratory [1], and an example is shown in Figure 1. The MGL-S8A is a half-loop magnetic field sensor designed for frequencies above 5 GHz, but is attractive for airborne applications because of its small profile. This research investigates a cluster of four MGL-S8A sensors to improve sensitivity and their potential usefulness in an airborne HFDF array.

An array for four-sensor clusters is simulated on a simple, large aircraft design based on the dimensions of a Boeing 707. The array layout is based on maximizing directivity and eliminating any possible grating lobes. A non-linear array approach is used in order to minimize sidelobe levels. Though the proposed array design uses the sensor clusters at each simulated location, in order to minimize simulation time a single sensor is used to represent the overall effect of the array. Simulations are evaluated to understand the effectiveness of the airborne array for direction finding in the HF band.

II. SENSOR ANALYSIS

A. B-dot Sensor

A single B-dot sensor is simulated to determine the farfield characteristics and sensitivity of the sensor. The MGL-S8A B-dot sensor is designed in CST Microwave Studio in order to understand the sensor effectiveness in the 2-32 MHz band. Sensor design is simulated based on the Air Force Weapons Laboratory specifications [1]. To validate the sensor design, radiation efficiency and directivity patterns of the sensor are simulated over an infinite perfect electric conductor (PEC) ground plane [3].

Fig. 1. MGL-S8A B-dot sensor [2]
The theoretical radiation efficiency of a simple loop of equivalent radius is used to validate the sensor design. Radiation efficiency evaluates conduction and dielectric losses within a radiating structure [4]. Radiation efficiency is defined by the loop antenna loss resistance,

\[ R_L = \frac{a}{b} \sqrt{\frac{\omega \mu_0}{2\sigma}} \]  

(1)

where,

- \( R_L \) - loss resistance (ohms),
- \( a \) - radius of loop (m),
- \( b \) - radius of wire (m),
- \( \sigma \) - conductivity of wire (S/m),

and the radiation resistance,

\[ R_r = \eta \frac{\pi}{6} (k^2 a^2)^2 \]  

(2)

where \( R_r \) is radiation resistance and \( \eta \) is intrinsic impedance [4]. The radiation efficiency, \( e_{rad} \), can be found by

\[ e_{rad} = \frac{R_r}{R_L + R_r} \]  

(3)

The efficiency quantifies how well an antenna radiates at a given frequency based on its physical design. Radiation efficiency only takes into account conduction and dielectric losses (antenna losses only), not reflections due to a mismatch between the antenna and the transmission line. Since a direct comparison is done based on the radiating structure, reflections will not be considered.

In order to determine the radiation efficiency of the simulated sensor, an impulse signal is introduced into a 50 Ω port on the sensor, and the radiation pattern is determined from 2-32 MHz with steps of 1 MHz. The 50 Ω port is used to simulate the SMA connector on the sensor. The impulse signal is a approximated by a Gaussian excitation from 0-32 MHz. Though it is not required to analyze the sensor below 2 MHz, simulation times are reduced by using a Gaussian pulse compared to a sine wave required for 2-32 MHz excitation.

To accurately evaluate the sensor performance in the farfield, the simulations are designed to assess the sensor with the correct boundaries and constitutive parameters surrounding the sensor. To measure the farfield, open boundary conditions are used in all directions around the sensor excluding at the base of the sensor. The open boundary conditions have space added between the sensor and the boundary in order to measure the farfield, because the field must be evaluated at a distance far enough away to be considered in the farfield. Due to the long wavelengths, the large boundary box increases the computational space of the analysis.

The bottom of the sensor is simulated with an electric field boundary in order to simulate an infinite PEC ground plane. The electric field boundary condition is used for initial characterization of the sensor. A full understanding of the array’s farfield pattern in an airborne HFDF application requires the aircraft to be simulated as the ground plane.

Quantifying the impulse response of the array in CST Microwave Studio requires a hexahedral mesh to evaluate the current distribution across the surface of the sensor. The mesh defines the spatial step for evaluating the model, which affects the farfield of the signal excitation on a small facet of the sensor. Due to the small curvature of the sensor and small conducting wires, the mesh must be concentrated over the detailed areas of the sensor to accurately define the electromagnetic response. Computational runtime increases exponentially with number of mesh cells; therefore, the mesh cells must be optimized. Local mesh grids are applied to the sensor that allow minimized meshing over larger flat areas on the sensor. Based on the fact that the boundary box is large (minimum of 38 m across) and the mesh is defined across the entire boundary, much of the computation is a calculation of the field interactions in free space.

The MGL-S8A B-dot sensor the pattern, as expected, is nearly isotropic for the 2-32 MHz band. The B-dot sensor functions as a magnetic dipole. At HF the sensor functions much like a Hertzian dipole; therefore, the pattern should be isotropic. The radiation efficiency of the sensor varies from -104 to -66 dB from 2 to 32 MHz respectively. In comparing the efficiencies of the B-dot sensor to previous research, the efficiency is reduced between 10 and 40 dB compared to a structurally integrated monopole design [5]. Additionally, considering the direction finding system, using an expected receiver noise floor of 107 dBm and at best a total efficiency of -87 dB, the incident signal would have to be -10 dBm to attain a 10 dB signal-to-noise ratio (SNR).

Based on the expected SNR, the comparison to previous research and a field test, the MGL-S8A B-dot sensor is too inefficient for application in an airborne HFDF array. To assess the capability of the general B-dot sensor design a larger MGL-5 B-dot sensor is simulated in CST Microwave Studio. The MGL-5 B-dot sensor is designed for 700 MHz and above [6]. Based on initial simulations the efficiency improvement is 30 dB across the entire HF band. Though the MGL-S8A B-dot sensor is ineffective, the MGL-5 appears to have equivalent radiation efficiency as the structurally integrated antennas [5].

B. B-dot Sensor Cluster

To achieve an increase in sensitivity a four-sensor cluster is simulated. Due to long wavelength at HF, four closely spaced sensors can be summed coherently due to the minimal phase difference between the sensors, increasing the sensor efficiency by approximately 6 dB. The 6 dB increase assumes negligible mutual coupling between the sensors. With an improvement in efficiency the SNR is improved increasing the detection capability of the array using B-dot sensors as array elements.

To assess the expected mutual coupling within the MGL-S8A B-dot sensor cluster, the radiation efficiency of a theoretical loop may again be used. Mutual coupling is the impact of the reradiated fields on adjacent loops; therefore, the incident signal must be received at a given radiation efficiency and then reradiated, which doubles the effect of the sensor efficiency. To define the coupling of the sensors, a 0 dBm incident signal is compared to the reradiated fields from a single sensor. Due to a -73 dB radiation efficiency at 32 MHz, a 0 dBm signal would have a -147 dBm reradiated field strength; therefore, the coupling between the sensors does not have to be
considered when deciding the layout of the four-sensor cluster. The radiation efficiency comparison is only accomplished at 32 MHz because the mutual coupling effects are the greatest at shorter wavelengths. Based on reduction in phase difference and minimizing the impact of mounting the sensors on the aircraft, the sensor cluster design shown in Figure 2 is used.

Figure 3 is a plot of the radiation efficiency of the single B-dot sensor, an equivalent loop, and a four-sensor cluster. Comparing the efficiencies, the MGL-S8A B-dot sensor design has the same frequency response as a theoretical loop of equivalent radius with an increased efficiency of 8.5 dB above the theoretical loop. The four-sensor cluster has an increased radiation efficiency of 6 dB above that of a single sensor, as expected due to the sum of the four-sensor detections. Based on the simulation, mutual coupling between sensors in the cluster is correctly assumed to be negligible. Additionally, the sensor cluster pattern is still isotropic, also validating the interaction is negligible. Based on the cluster improvement and the sensor simulation, eight and ten-element airborne arrays are simulated to determine the airborne HFDF capability.

III. AIRBORNE ARRAY DESIGN AND ANALYSIS

An airborne HFDF array on a Boeing 707 [7] is simulated in CST Microwave Studio. The aircraft is on the order of a wavelength at the lower frequencies in HF; therefore, each sensor location must be simulated separately and then combined. Due to the negligible mutual coupling, the individual fields can be summed based on separate simulations of each sensor location. The MGL-S8A dimensions are on the order of millimeters, but the simulation boundaries are on the order of hundreds of meters making the simulation space large. To simulate an array, ten sensor locations are simulated in separate projects, and then the fields are coherently summed to assess the array capability using eight and then ten sensors. The eight and ten-sensor arrays are compared to determine the effect of additional sensors on reducing sidelobes and increasing null depth. Figure 4 shows the sensor locations for the two simulated array designs. Sensor locations nine and ten are used only in the ten-element array design.

A. Eight-Element Array

As a starting point for an array design, an array of eight MGL-S8A sensors are simulated. The array factor of the design presented in Figure 4 provides an initial estimate of the array pattern. The array factor only shows the expected shaping based on the phase information in the array element spacing without including effects of the individual installed sensor patterns.

Basic linear array concepts can be applied to the HFDF array, but in many ways this array is different. The array will function much more as a planar array of non-uniform spacing, and therefore a detailed estimation of the pattern is not as easily accomplished. Additionally, classic array theory makes the assumption that all array elements have identical radiation patterns; therefore, the effect of the array design defines the operation of the array, as shown by,

\[
AF = \sum_{n=1}^{N} e^{j(n-1)(\vec{k} \cdot \vec{r} + \beta)}
\]

where,

- \(N\) - number of array elements
- \(\vec{j}\) - \(\sqrt{-1}\)
- \(\vec{k}\) - vector from the array origin to an observation point,
- \(\vec{r}\) - vector from the array origin an individual element,
- \(\beta\) - phase excitation [4].

Based on the application of (4), the frequency response of the
array can be observed. To determine the actual array pattern, the array factor must be applied to each individual sensor pattern, but general trends may be revealed by the array factor.

It is observed that significant shaping can be accomplished at 32 MHz, and with some reduction in sidelobe levels, the directionality of the main beam is vastly improved. Choosing a lower frequency and observing the overall shape reveals additional information on the bandwidth of the array. At 17 MHz, the array has a broader mainbeam and higher sidelobe levels. This is less desired for DF application, but shows enough phase difference exists that an improvement is seen over an isotropic radiator. Analyzing the array factor at 10 MHz shows the loss of any significant shaping due to the array factor. The expected results of the eight-element array simulation shows minimal direction finding capability from 2-10 MHz.

The boundary conditions from the finite aircraft ground plane perturb the isotropic pattern of the sensors. For this reason, choosing these sensors is worthy of further investigation into the DF capability. The sensor pattern has relatively equal variation below the aircraft with expected reduction above the aircraft due to the presence of the ground plane. Because the ground plane is not infinite, the patterns are only 10 dB less on average below than above the aircraft; therefore, detection capability is broad for the B-dot sensors even when taking into account diffraction effects. Observations of the DF potential are now analyzed by looking at the summed fields. Figure 5 is the XZ, YZ and waterline plane cut of the eight-element array with zero phase or amplitude progression. The XZ cut defines the array response along the fuselage, while the YZ cut describes the array in elevation while the waterline cut describes the array azimuthally. Additionally, a sampling of frequencies in the HF band are shown for pattern analysis. The black, red, and blue lines represent the eight-element array. Additionally, the additional sensors are chosen as locations nine and ten in addition to show the sidelobe reduction and effects on the pattern based on addition of two sensors.

Comparisons were accomplished from 2-32 MHz in 1 MHz steps. For all comparisons between the eight and ten-element arrays the red lines represent the ten-element array, while the blue lines represent the eight-element array. Additionally, all patterns are normalized to themselves for comparison of nadir detections are highly correlated in a 30 degree sector of the main beam at 32 MHz. In the eight-element configuration the spatial sampling in the array is reduced from wingtip-to-wingtip which increases the sidelobes; therefore, the sidelobes should be reduced in the XZ cut as has been previously shown by the 2 dB difference in first sidelobes between the XZ and YZ cuts. The difference in the first sidelobes from the nadir beam support the usefulness of additional sensors in reducing the sidelobes and increasing null depth. The right side of the aircraft has an additional sensor and the null depth is 5 dB less than the left side of the aircraft at 32 MHz. Based on the observations the ten-element array is expected to offer increased null depth and reduced sidelobes.

Finally, the waterline cut represents the azimuthal resolution of the uniform phase eight-element array. At 16 MHz the pattern shape has 10 dB reduction from the maximum value, but the nulls are broad and the individual beams are between 40 and 60 degrees wide. Additionally, at 16 MHz 90, 140, and 270 degrees are highly correlated due less than 1 dB difference in these directions at 2 MHz the pattern, as in the other cuts, is nearly isotropic the likelihood of performing DF with the eight-element array configuration. Observations of increased null depth are found above 16 MHz with -22 to -10 dB nulls. Across all frequencies the azimuthal resolution has strong correlation of multiple directions from the peaks in the patterns. Nulls provide larger differences in all directions at frequencies from 17-32 MHz, but both peak and null comparisons offer less than 10 dB differences when comparing one incident direction to another. For example, the null at 245 degrees is less than 1 dB different from the null at 125 degrees at 32 MHz. Overall, most directions are correlated with at least a single direction across all frequencies making direction finding difficult due to a lack of ambiguity resolution.

The array analysis of the pattern of the uniform phase eight-element array proves that the array is highly correlated in azimuth and elevation in multiple directions. For this reason, additional sensors may provide reduced sidelobes and increased null depth that can increase correlation with incident signals without ambiguities. The analysis of the ten-element array will be in comparing the eight to the ten-element array to show the sidelobe reduction and effects on the pattern based on addition of two sensors.

B. Ten-Element Array

The two additional sensors locations are determined by the array research accomplished by BarrieHill [5]. The structurally-integrated feeds are placed based on the highest concentration of current for a given mode. The locations are chosen by also maximizing the distance between each of the sensors. Based on these two considerations the locations of the additional sensors are chosen as locations nine and ten in Figure 4.

Comparisons were accomplished from 2-32 MHz in 1 MHz steps. For all comparisons between the eight and ten-element arrays the red lines represent the ten-element array, while the blue lines represent the eight-element array. Additionally, all patterns are normalized to themselves for comparison of
directivity. Cartesian plots are used to better observe the differences in the patterns and the sidelobe and null changes that can be difficult to decipher in polar form.

At 2 MHz the previous lack of shaping in the patterns is due to limited array extent with respect to wavelength. The added sensors do cause a difference in the pattern by merely shifting the farfield pattern. The YZ and XZ cuts have less than 1 dB difference for a given incident angle. The patterns should have minimal changes, because the largest spacing change in the x-direction is less than 0.1 wavelength at 2 MHz causing little to no change in azimuth patterns. The differences in the waterline cut are only in slight shape changes in comparison to the eight-element array. Figure 6 is a comparison of the eight and ten-element arrays at 16 MHz. The waterline cut presents two positive factors in the direction finding array, increased null depth and reduced side lobes. The nulls at 51, 105, and 240 degrees are reduced by 5, 2, and 5 dB respectfully. Additionally, the null is reduced for each of these angles. The same correlation problems exist with the ten-element array. Signals incident at 90 and 270 degrees will be highly correlated and at 30 and 320 degrees, because the differences in the patterns are less than 1 dB.

The XZ plane cut has an improvement in sidelobe level and null reduction. As discussed earlier, the impact is expected to be the greatest in this cut due to the increased spatial diversity in the x-direction by adding the two elements. A 3 dB reduction in sidelobes is seen from 60-275 degrees. Null depth changes are negligible in this cut. Though sidelobes are reduced, when comparing the shape and depth of the nulls between the two patterns they are nearly identical.

The YZ plane cut offers little change in pattern from the eight to ten-element array due to the limited spacing between elements between the wing-tips. The difference in the y-direction of the new sensors to the sensors along the fuselage is 0.08 wavelengths so the effect is less than 1 dB difference in the patterns at any given angle. Figure 7 is the normalized waterline, YZ and XZ cuts for the eight and ten-element array at 32 MHz. The waterline cut at 32 MHz has increased depth and narrowing of nulls at 50, 240, and 300 degrees. The common nulls at 300 and 50 degrees are expected in a linear type of array, but the null at 120 which in a linear array would be equal to the null at 240 degrees is increased in the ten-element array. This is due to the non-uniform spacing of the array which assists in eliminating these common angles in the pattern. Common angles lead to ambiguities so adding sensors at varying spacing will continue to reduce the ambiguity between angles. The sidelobes are increased at 190 and 170 degrees with a decreased null depth at these angles by 2.5 and 5 dB respectively. The XZ and YZ plane cuts show reduction in sidelobes. The greatest reduction in the XZ cut is at the first sidelobe, which is reduced from -5 to -9 dB by adding two additional sensors. The sidelobes are reduced at nearly every incident angle for the YZ plane cut. Additional sensors may allow more structured patterns, to a degree.

Table I is the integrated and average sidelobe levels for 2, 16, and 32 MHz for the eight and ten-element arrays. At 2 MHz the averages show that greatest difference in the

<table>
<thead>
<tr>
<th>Table I</th>
<th>AVERAGE AND INTEGRATED SIDELOBE LEVEL IN DB FOR A SAMPLE OF FREQUENCIES FROM 2-32 MHZ OF BOTH ARRAY DESIGNS.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eight-Element Array</strong></td>
<td><strong>Freq (MHz)</strong></td>
</tr>
<tr>
<td>2</td>
<td>-3.83</td>
</tr>
<tr>
<td>32</td>
<td>-7.93</td>
</tr>
<tr>
<td><strong>Ten-Element Array</strong></td>
<td><strong>Freq (MHz)</strong></td>
</tr>
<tr>
<td>2</td>
<td>-4.47</td>
</tr>
<tr>
<td>16</td>
<td>-6.09</td>
</tr>
<tr>
<td>32</td>
<td>-7.44</td>
</tr>
</tbody>
</table>

YZ plane cut, but the differences are less than a dB for all cut comparisons. The integrated sidelobe level comparison at 2 MHz presents little to no difference when all angles are considered. This is due to the lack of shaping in the pattern and limited change in the pattern due to the long wavelength. At 16 MHz the greatest difference for average and integrated sidelobe level is in the XZ plane cut. This is due to the limited phase difference at 16 MHz in the y-direction. Based on the observations at 2 and 16 MHz an argument can be made that elimination of one of the sensors will not change the pattern drastically due to the limited phase difference between the two additional sensors in the y-direction because the YZ plane cut is not affected at 16 MHz. The comparison at 32 MHz shows that the phase difference at higher frequencies is adequate enough to make both sensors relevant in the array performance.
due to the greatest sidelobe level change being in the YZ plane cut. Additionally, higher frequencies have reduced angular ambiguities with both sensors included in the array due to non-uniform element spacing. Overall, both sensors do assist in reducing the sidelobes at any frequency above 5 MHz based on the pattern and sidelobe level comparison considering effects on all pattern cuts.

IV. CONCLUSIONS

The MGL-S8A B-dot sensor, design for frequencies greater than 5 GHz, is not adequate for direction finding applications in the HF frequency band. Though it does offer the relatively isotropic pattern even with diffraction considerations of the aircraft ground plane, the sensor is still 30 dB less effective than the already inefficient structurally integrated design from previous research. The B-dot sensor design is valid for application to airborne HF direction finding. The MGL-5 B-dot sensor is designed for frequencies above 700 MHz and offers an increase in effectiveness over the MGL-S8A with only a two-inch vertical profile. Based on a theoretical loop comparison and a representative air gap B-dot sensor designed in CST Microwave Studio the MGL-5 sensor will be equivalent to the BerrieHill structurally-integrated antennas with slightly more vertical profile than the MGL-S8A, which is important for aerodynamic considerations for integration on an airborne platform.

The four-sensor B-dot cluster proved to increase the radiation efficiency by 6 dB. Due to the poor radiation efficiency of the B-dot sensor the 6 dB improvement does not offer an increase that makes the MGL-S8A cluster adequate for signal detection. Based on the use of the MGL-5 B-dot sensor the 6 dB increase of using a sensor cluster will improve the detection ability reducing sensitivity requirements of the HF receiver but the sensor must first be more efficient. A four-sensor cluster using the MGL-5 sensors could offer a substantial increase in detection capability due to the increased efficiency of the individual sensor. Integration considerations must be considered because the four-sensor cluster would occupy a 20-by-26 inch area on the aircraft body.

The eight and ten-element direction finding capability is limited due to the lack of sidelobe reduction from the mainlobe. The addition of two sensors does show that including additional sensors will reduce side lobes and improve the null depth for distinguishing between two different directions of incident signals. Previous research by Corbin and BerrieHill Research Corporation shows that with a reduction in phase difference between elements that direction finding is possible with eight elements within ±2 degrees [8], [5]. Based on additional phase difference added to with the presented eight and ten-element designs are an improvement in pattern capability; therefore, applying the direction finding algorithms presented by Corbin and BerrieHill the direction finding capability will be improved [8], [5].

REFERENCES


