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# Structurally Integrated Antenna Concepts for HALE UAVs

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## **Introduction**

This technical memorandum describes work done in support of the Multifunctional Structures and Materials Team under the Vehicle Systems Program's ITAS (Integrated Tailored Aero Structures) Project during FY 2005. The Electromagnetics and Sensors Branch (ESB) developed three ultra lightweight antenna concepts compatible with HALE UAVs (High Altitude Long Endurance Unmanned Aerial Vehicles). ESB also developed antenna elements that minimize the interaction between elements and the vehicle to minimize the impact of wing flexure on the EM (electromagnetic) performance of the integrated array. In addition, computer models were developed to perform phase correction for antenna arrays whose elements are moving relative to each other due to wing deformations expected in HALE vehicle concepts. Development of lightweight, conformal or structurally integrated antenna elements and compensating for the impact of a lightweight, flexible structure on a large antenna array are important steps in the realization of HALE UAVs for microwave applications such as passive remote sensing and communications.

## **Background**

In recent years there has been rapidly increasing interest in Unmanned Aerial Vehicles (UAVs), also called Remotely Piloted Vehicles (RPVs), for numerous applications. These UAV applications compare extremely favorably to current technology alternatives such as spaceborne satellites, lighter than air, and piloted aircraft. The interest, mission goals and available technology developed in the last several years have spawned many mission specific subcategories of UAVs. The world has seen the high profile effectiveness of military UAVs, such as Predator®, a registered trademark of General Atomics Aeronautical Systems Inc., and Globalhawk®, a registered trademark of Northrop Grumman Corp., capable of delivering weapons to, and intelligence from, threat regions. Since the mid 1990s, however, there has been a rapidly growing niche for High Altitude Platform Stations (HAPS) and the use of UAVs to support such missions. NASA has been involved with HAPS concepts in the Environmental Research Aircraft and Sensor Technology (ERAST), HALE programs and of course the record breaking Helios Prototype (see Figure 1).



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Equipped with an experimental fuel cell system to power the aircraft at night, the solar-electric Helios Prototype is shown during a checkout flight prior to its long-endurance flight demonstration in the summer of 2003.

Figure 1. Helios prototype test flight.

After several generations of HAPS – UAVs starting back in 1997 with the Pathfinder, the Helios Prototype in August 2001 exceeded the altitude record for fixed wing jet or propeller aircraft by reaching 96,000 ft. Being solar powered and above weather systems the plane could remain at altitude indefinitely during daylight hours. Currently research is being conducted at NASA and elsewhere to develop lightweight electrical energy storage devices such as hydrogen fuel cells and lightweight batteries to extend the capability to stay aloft through the nighttime hours. The impact of a success would be far reaching, and future mission goals of HAPS would be to maintain the UAV at 60,000 ft for up to 6 months. No piloted aircraft could perform such a mission.

### **Potential mission areas for microwave HAPS-UAVs**

This section identifies three broad areas where appropriately designed microwave HAPS-UAVs could have huge impacts in the immediate future. The mission areas are environmental, communications and military.

*Environmental* – Microwave passive remote sensing instruments are vital to understanding numerous ecological, meteorological / climatological and agricultural phenomena.

*Communications* – broadband wireless technology is today currently limited by the ability to deliver the high capacity data and other information to potential users. Examples of these current needs are in 3G mobile, direct broadcast (radio, TV, HDTV), fixed and mobile broadband (internet) and high capacity narrowband (mobile voice).

*Military* – Ground Penetrating Radar (GPR), Foliage Penetrating Radar (FPR), Synthetic Aperture Radar (SAR), C3 (Command, Control and Communications) / Airborne Warning and Control Systems (AWACS).

The GPR technology also has many commercial / research uses such as environmental and archeological.

The above applications all have one important thing in common. They all rely heavily on the UHF / L-Band microwave frequency range.

### **Antennas for microwave HAPS-UAV applications**

To achieve the desired performance characteristics for HALE UAVs, the overall vehicle weight must be minimized. When designing the various subsystems which must be included on the vehicle, one approach is to attempt to reduce the weight and aerodynamic impact of each subsystem independently. A more holistic approach is to combine functionality between the vehicle structure and various subsystems in order to eliminate unnecessary components and thus reduce weight. This approach is particularly beneficial for applications where long wavelengths and high spatial resolution are required. Since required antenna apertures can be very vehicle intrusive, optimizing the sensor/vehicle concept to meet the mission requirements may lead to substantially improved performance

In support of the Multifunctional Structures and Materials Team under the Vehicle Systems Program's ITAS Project, ESB developed several antenna concepts integrable with HALE UAV vehicle configurations. The antennas were designed to be either very lightweight and thin (the first approach described above) or to have part of the vehicle structure providing either physical support for the antennas, electromagnetic functionality, or both (the second approach described above).

The frequency ranges required for HALE UAV antennas will vary according to the specific application. The biggest challenge, however, will be the design of antennas for the lower frequencies. Higher frequency antennas are inherently smaller and would have less impact on the overall vehicle weight. In some cases (L-band soil moisture measurements, for example) the antenna array might need to span the entire vehicle. Unless the weight of the elements is carefully considered during the design, including such an array on a HALE UAV might be impossible.

In addition to the weight issue, another aspect of HALE UAVs must be considered if they are to support missions which require large antenna arrays with elements which are distributed over the entire vehicle. The flexibility of such a large, lightweight structure will induce errors in the antenna array pattern as the elements move relative to each other when the vehicle aeroelastically flexes during flight. For some applications, the errors in the array pattern will cause unacceptable errors in the data. Some correction technique must be used to mitigate the effects of the vehicle flexion.

In the following sections, three antenna designs are described which have potential for use on HALE UAVs. In addition to being lightweight, two of the designs are envisioned as structurally integrated antennas, and one is envisioned as a very thin conformal surface mounted element. Following the discussion of the antenna elements developed for the program, a description of a computational phase correction technique to mitigate the effects of vehicle distortion on a large antenna array is given. Such a correction scheme will be necessary for passive remote sensing applications using large, flexible antenna arrays such as the one envisioned here.

## **Design assumptions**

The goal of this work is to develop antennas which are compatible with a HALE UAV platform. The approach taken was to address the most challenging technology development issues. Also, it was desired to develop specific antennas which could be modeled, fabricated and tested. Certain design assumptions about the frequencies of interest and the HALE UAV vehicle configuration were made a priori to achieve these goals. This section describes these assumptions.

*Frequency:* As explained in the previous section, the lowest frequencies of interest are seen as the biggest challenge for the HALE UAV antenna design, due to the physical size requirements for these frequencies. For this reason, this research concentrated on UHF / L-Band frequencies. Interest in UHF / L-Band frequencies for many applications is due to a number of reasons. For communications, low frequency RF has the unique ability to penetrate and “bend” around buildings’ topography. UHF and L-Band are at the upper end of what would be considered low band, and to gain the maximum bandwidth for data capacity this is the obvious choice. The FCC has designated a number of frequency bands in this range for mobile telephone and other communication uses. Sometimes the frequency is dictated by physics as in the case of radiometry, GPR and FPR. L-Band happens to contain a strong water emission line.

*Vehicle configuration:* This section explains some of the rationale for the UAV configuration chosen for this study. The UAV as outlined in this paper is designed to fly at extraordinarily high altitudes for great lengths of time. Because of this the high altitude, extremely high lift and low velocity requirements of the mission, AeroVironment Inc. and other air framers have not only considered but also built actual prototypes of flying wings. The flying wings have been either of single wing element or bi-plane design. The bi-plane design was primarily considered



for structural reasons, but it was the single wing element design which was actually used in the Helios and Pathfinder missions. Since there is no fuselage on these candidate aircraft we have considered only wing surface and some potential wing volumes as possible locations for antennas.

Figure 2 shows the vehicle and a potential wing cross section design. This cross section is based on a few assumptions made following structural and onboard power needs discussions. As can be seen there is a forward and rear span-wise structural member assumed to run along the length (span) of the wing. With the possibility of a hydrogen fuel cell electrical power storage system, it has been envisioned that the hydrogen would be stored in a metallized bladder (tank) between these 2 structures. This tank may itself be this structure. The metallization creates antenna ground plane possibilities for the antennas described in the following sections, as well as other potential designs. Chord-wise structural elements and a thin volume between the lower surface and the tank create ideal locations for the Vivaldi and reduced surface wave (RSW) antennas described in detail in the following sections.

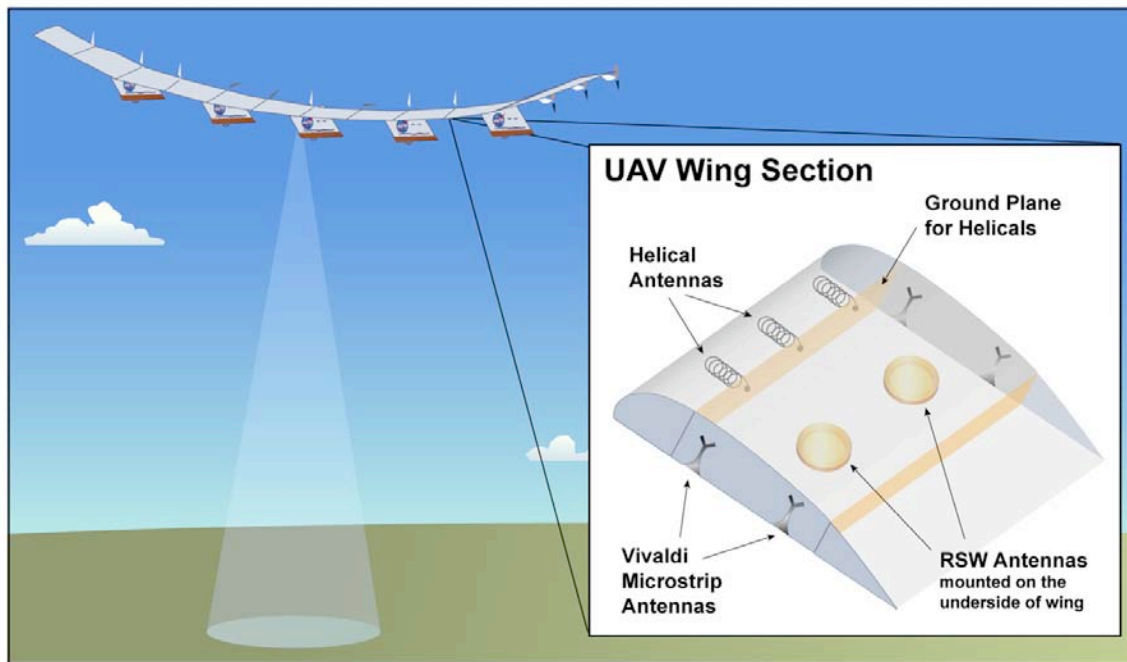


Figure 2. Potential antenna locations on HALE UAV wing section.

The leading edge has been identified as a potential free zone for antenna elements also. There would unlikely be any flight control surface or flight system requirements for this volume and would be covered by the antenna community. This volume is perfect for helical antennas described in the next section. If appropriately designed, these antennas could potentially serve as

structural elements themselves. The size of this volume as indicated by the structural designs would be compatible with helical antennas from UHF to microwave frequencies.

## **Antenna designs**

### **Helical antenna**

The first antenna concept developed under this program is an extremely lightweight helical antenna operating in the axial mode. A working one third scale model of the proposed helix antenna is described here. At one third scale, the actual working L band frequency of 900 MHz scales to 2.7 GHz. As can be seen in Figure 2, the concept for incorporating this antenna into a UAV wing involves using the forward spar as a ground plane, and it is envisioned that the leading edge of the wing would be filled with a lightweight, low dielectric constant foam material which would support the helix and also provide some structural stiffness for the wing.

The design goals for this antenna, in addition to light weight, were to have the broadest possible bandwidth and beam width of 60 degrees. This helical design was accomplished using the following guidelines for optimal performance:

The circumference of the helix (C) must be equal to a wavelength ( $\lambda$ )

The number of turns (N) must be greater than 3 (4 were used in this case)

The total length of the helix (L) must be equal to  $(\lambda/4) * N$

From these guidelines, the following design parameters were obtained:

$D = 3.56 \text{ cm} = \text{helix diameter}$

$L = N * (\lambda/4) = \lambda = 11.0 \text{ cm}$

$S = 2.75 \text{ cm} = \text{spacing between turns}$

From Equations 1 and 2 (Reference 1) we can compute the predicted axial ratio and half power beamwidth of the helical antenna.

$$\text{Axial Ratio} = (2 * N + 1) / 2 * N = 1.125 \quad (1)$$

$$\text{Half Power Beamwidth} = 52 / (C/\lambda) * (N * S/\lambda)^{(0.5)} = 60 \text{ degrees} \quad (2)$$

As stated above, the antenna's center frequency of 2.7 GHz scales to 900 MHz, the center frequency for the full size antenna. It is constructed on a 3.56 cm diameter polystyrene foam cylinder, which provides mechanical support. Four turns of 0.00254 cm thick copper tape 0.305 cm wide were helically wound on the surface of the cylinder. The center to center spacing of the tape on the cylinder is 2.75cm. The tape was wound in a counter clockwise direction, as viewed from the top, and produces right hand circularly polarized radiation. The foam cylinder was

mounted in the center of a 30.5 cm ( $2.77 \lambda$ ) square aluminum ground plane. The helix is fed using an SMA connector mounted in the ground plane and has the center conductor connected to the bottom of the helix at the level of the ground plane. In order to improve the impedance match, it was necessary to add a small triangle of copper tape near the feed point of the helix at the ground plane. The shape and location were empirically determined. The final antenna is pictured in Figure 3.

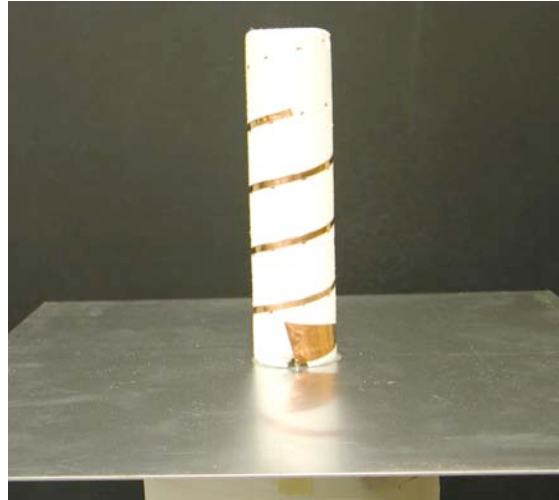


Figure 3. Foam and tape helical antenna

The antenna’s performance characteristics were measured in LaRC’s Low Frequency Antenna Chamber. Test results exceeded the requirements envisioned, and are summarized in Table 1 below:

Parameter	Measured Value
Bandwidth	1.9 to 3.5 GHz
Gain (circularly polarized)	8 dBi at band edges, 9 dBi at the center
Beamwidth	60 degrees
Axial Ratio	On axis band center: 0.5 dB 30 degrees off axis band center: 3.0dB 30 degrees off axis band edge: 6.0 dB
S11	-10 dB or better across the band
Weight excluding ground plane and connector	3.8 grams

Table 1. Foam and tape helical antenna performance summary.

A representative S11 plot and endfire pattern at the band center of 2.7 GHz are shown in Figure 4. The input impedance for the helical antenna is seen to correspond to an S11 of less than -10 dB from 2 to 3.5 GHz.

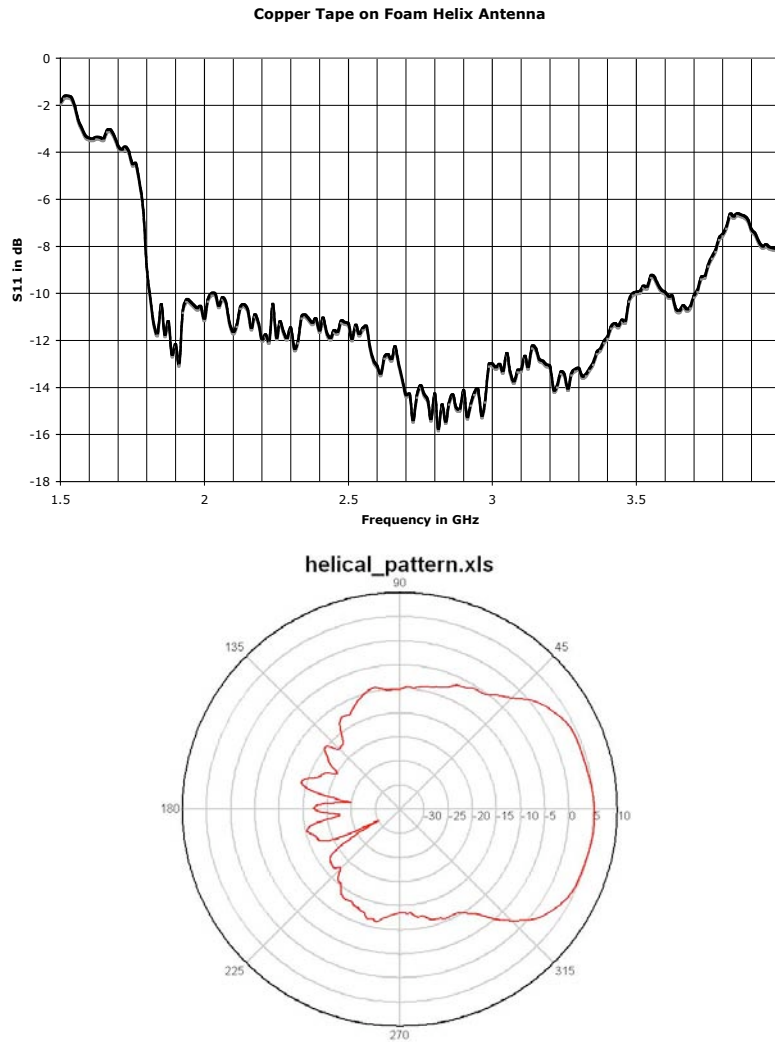


Figure 4. S11 and endfire pattern for foam and tape helical antenna.

For comparison purposes a free standing helical antenna had been constructed. This version was made using 10 gauge copper wire and has the same dimensions and ground plane size as the foam version. This antenna is pictured in Figure 5. Performance characteristics were comparable to the foam and tape helix.

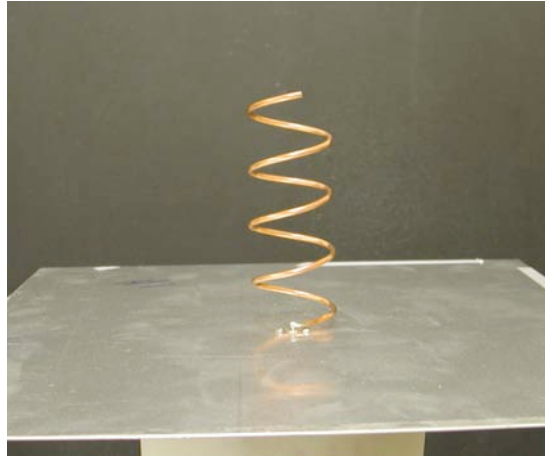


Figure 5. Free standing helical antenna.

### Vivaldi antenna

The second antenna concept proposed for HALE UAVs is a balanced antipodal Vivaldi (BAV) antenna. Vivaldi antennas are inherently very broadband and therefore could be potentially useful for a wide range of applications. BAV antennas avoid some of the disadvantages of regular Vivaldi antennas (high cross polarization, complicated feeding structure) by providing a simple stripline input and low cross polarization (Reference 2). A BAV antenna consists of two dielectric layers sandwiched with three metallic layers. The top and bottom metallic layers are identical. They form the left side of the radiating element and the ground planes for the stripline input (shown in gray in Figure 6). The middle metallic layer forms the right side of the radiating element and the strip for the stripline (shown in darker blue in Figure 6). The dielectric material is shown in lighter blue in Figure 6.

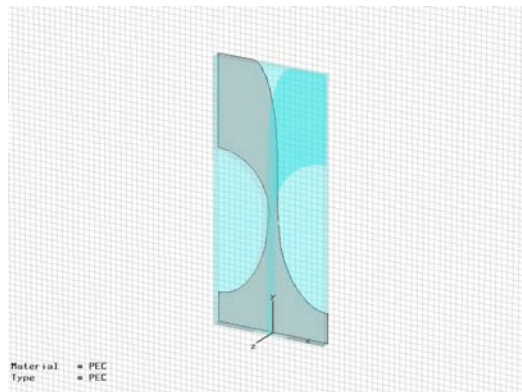


Figure 6. MWS model of BAV antenna.

In Figure 2 was shown an artist's concept of how the BAV antenna might be incorporated into a UAV's wing strut. In order to realize a design like this in practice, antenna designers and structural engineers would have to work closely in choosing materials which met both structural and electromagnetic requirements.

To design a BAV which operates down to the desired L-band frequency range, a commercial electromagnetics software modeling tool called CST-Microwave Studio was used. A commercially available thin, lightweight, copper clad foam material called Foamclad<sup>R/F</sup> 100, manufactured by Arlon, was investigated as a potential material for use in this application. The specific material used in the design is 1.8796 mm thick, clad on both sides, and has a relative dielectric constant of 1.23. For an antenna size of 92 mm by 207 mm, Microwave Studio gives the input impedance plot shown in Figure 7. The design has an acceptable S11 of approximately -8 dB or lower above about 1.5 GHz. By scaling the design slightly larger, acceptable performance at lower frequencies could be obtained. Figure 7 also shows antenna patterns at 2 and 3 GHz. The pattern cut is in the plane of the antenna, with the phi component having the E vector in the plane of the cut and the theta component having the E vector perpendicular to the plane of the cut.

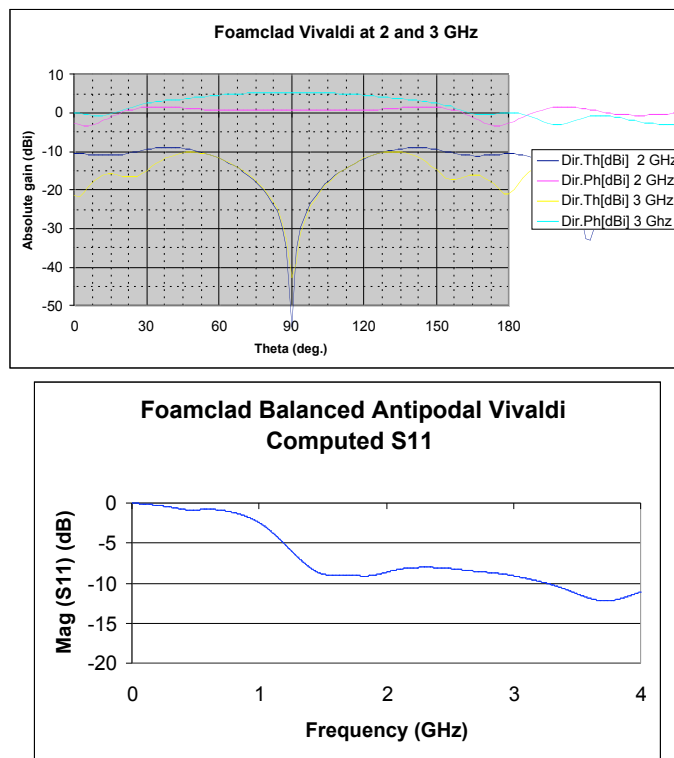


Figure 7. Computed S11 and patterns for Foamclad<sup>R/F</sup> 100 BAV.

## Reduced surface wave antenna

As discussed earlier in this paper, one important application for large, lightweight UAVs is passive remote sensing of the earth. A concept which has been investigated in the past for this application utilizes array elements along an aircraft fuselage and wings to emulate a much larger antenna array [reference 3]. However, this Scanned Thinned Array Radiometer (STAR) technique requires well-characterized antenna array performance. Therefore, changes in mutual coupling between elements and edge effects from the structure caused by the bending and flexing of a STAR instrument mounted on a HALE UAV can cause large errors in the final radiometric image. These errors must be corrected by some numerical technique in order to obtain a usable image. Even if the relative positions of the elements are known at any given time, these mutual coupling and edge effects are very complex, and a numerical correction would be very difficult to obtain. Thus, an antenna element was sought which would eliminate or reduce the need for these complex correction schemes and enable the use of a STAR instrument on a large, flexible structure such as a HALE UAV.

For a reduced surface wave (RSW) antenna, mutual coupling and edge effects can be largely neglected, since most of the energy which propagates along the surface and contributes to these undesirable quantities for many other antenna types is not present. There are various methods available to reduce surface waves, including surface treatments for the antenna substrate, but for this study a Shorted Annular Ring (SAR) RSW configuration was used. The geometry for a SAR-RSW antenna is shown in Figure 8. It is a standard circular microstrip patch antenna with a circular cutout in the center. The cutout is metalized to connect the patch with the ground plane beneath. For a given resonance frequency, the SAR-RSW is slightly larger in diameter than a standard circular patch. The dimensions of the SAR-RSW can be calculated from (Reference 4):

$$b = x_{11}' / k_{TM0} \quad (3)$$

$$J_1(k_1 a) / Y_1(k_1 a) = J_1'(k_1 x_{11}' / k_{TM0}) / Y_1'(k_1 x_{11}' / k_{TM0}) \quad (4)$$

where  $x_{11}'$  is the first zero of  $J_1'(x)$ ,  $k_1$  is the wavenumber for the dielectric of the substrate, and  $k_{TM0}$  is the wavenumber for the  $TM_0$  surface wave. Equation (3) for outer patch radius  $b$  is the condition for eliminating the  $TM_0$  surface wave. Equation (4) for inner short circuit radius  $a$  is the condition for resonance at the desired frequency (see Figure 8).

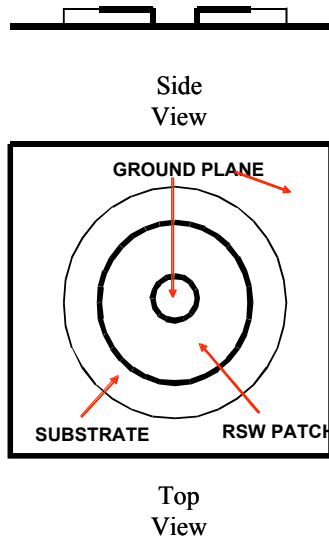


Figure 8. SAR-RSW antenna geometry.

To achieve a conformal configuration for mounting on the surface of a UAV wing (see Figure 2), a SAR-RSW antenna was designed using a very lightweight, thin material. The material used was double clad Arlon Foamclad<sup>R/F</sup> 100 which was described in the previous section on Vivaldi antennas. The design was achieved using CST-Microwave Studio. A test article was also fabricated for this case. The circular patch was fabricated using conventional circuit board etching techniques, and copper tape was soldered to the cutout to achieve the center short. Figure 9 shows the test article which has a mass of 19.8 grams excluding center metallization and coaxial connector. The test article was evaluated in LaRC's Low Frequency Antenna Chamber.

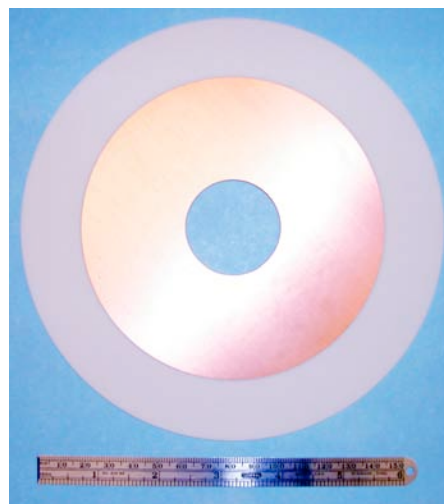


Figure 9. Foamclad<sup>R/F</sup> 100 RSW antenna



Figure 10 shows a plot of computed and measured antenna patterns, as well as the computed pattern for a conventional circular patch designed to resonate at the same frequency. The plane of the antenna pattern cut is perpendicular to the plane of the antenna. As can be seen from the figure, the level of the RSW antenna pattern is much lower at the sides and back of the antenna as compared to the conventional circular patch. The conventional circular patch diffraction lobes (in the back half plane), resulting from energy which interacts with the ground plane edges, are much lower in the RSW case. The measured and computed RSW patterns agree quite well.

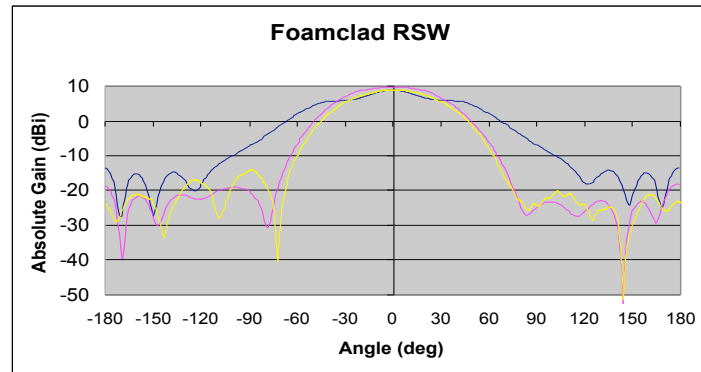


Figure 10. Measured and computed patterns for Foamclad<sup>RF</sup> 100 RSW antenna at 1.41 GHz.

Computing a pattern for an electrically large antenna array whose elements are moving relative to each other, and accounting for all the element-element and element-ground plane interactions is a daunting task. However, by using a RSW antenna with a simple approximation for its antenna pattern, and neglecting edge and mutual coupling effects (which should be valid for the RSW case), a fast computer program has been developed which calculates the array pattern for various array deflections (Reference 5). In the next section, results from this computer program will be presented and a simple phase correction technique developed at NASA Langley will be described which could be used to correct images obtained by a remote sensing array composed of RSW antennas.

### **Modeling EM effects of aeroelastic deformation**

The impact of aeroelastic deformation on the performance of antenna arrays mounted on flexible HALE UAV type aircraft can be considerable. The movement of antenna elements relative to each other causes errors in the radiation pattern as the antenna phases combine constructively and destructively, resulting in pattern degradation and gain loss. This pattern distortion is fairly negligible for zenith and nadir directions, but the phase errors become more pronounced with increasing scan angle and can lead to unpredictable array behavior and mission failure.

RSW antennas exhibit greatly reduced mutual coupling and edge effects compared to a regular circular patch. By neglecting these effects, an array pattern calculation for RSW elements is greatly simplified. Under the NASA Summer Faculty Fellowship Program, a MATLAB computer code (Reference 5) which computes the pattern for an array of RSW elements has been developed. The RSW element pattern may be approximated by a simple analytic expression, which allows for a reasonable and quick approximation of RSW antenna array behavior.

An array on a flexible aircraft wing can move in three directions: fore and aft ( $\psi$ ), up and down ( $\rho$ ), and rotation around pitch axis ( $\phi$ ), illustrated by Figure 11. For this study, only the up and down (i.e. “flapping” motion) is considered. The positions of the deformed array antenna elements are assumed to be known.



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The solar-electric Helios Prototype flying wing bisects the volcanic atoll of Lehua off the coast of Kauai, Hawaii, during a checkout flight on June 7, 2003. Helios is now equipped with an experimental fuel cell system to allow nighttime flight.

Figure 11. Flexible antenna array movement.

The basis of pattern correction lies in changing the phase of the individual array elements. As in beam steering, the goal is to have the transmitted or received energy from the antennas be of equal phase along a reference plane in the desired direction. The distance to this phase front, in wavelengths, is the phase correction  $D$ , given by

$$D = \beta d \cos \theta \tag{5}$$

where  $\theta$  is measured from the plane of the array and  $\beta=2\pi/\lambda$ . This relationship is illustrated in Figure 12 for a five element array with one wavelength spacing, scanned  $20^\circ$  from the array

normal. It is observed that the main lobe of the pattern, the lobe of greatest gain, has expectedly shifted by  $20^\circ$ .

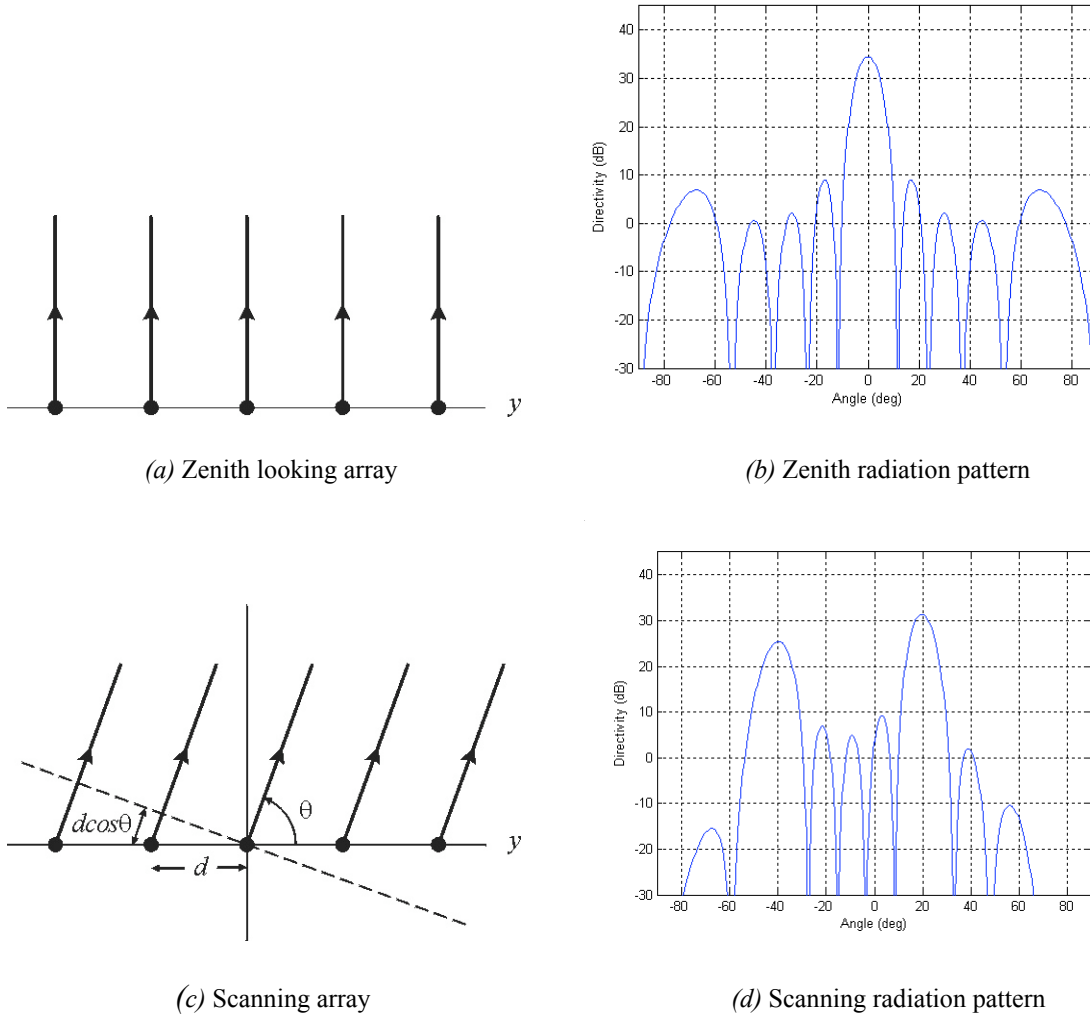


Figure 12. A planar antenna array with  $20^\circ$  scan angle from array normal.

As the array is flexed, the distance to the phase front changes and so the phase of each element must be adjusted such that

$$D = \beta(d_1 + d_2) \cos \theta \tag{6}$$

as shown by Figure 13.

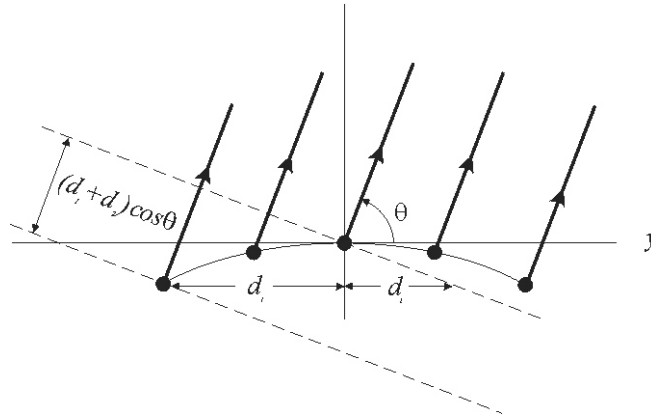
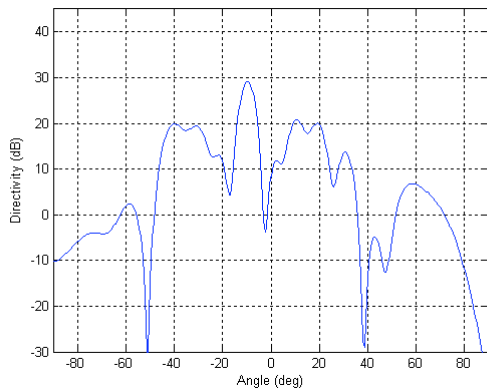
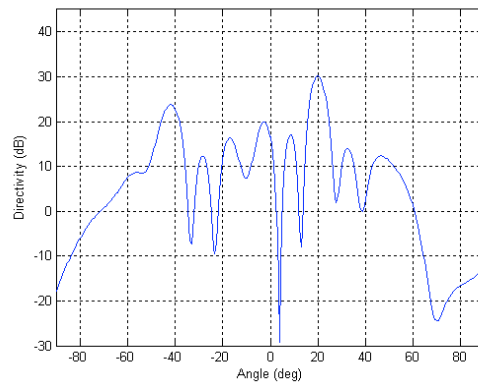


Figure 13. Flexed antenna array.

The radiation pattern for a five element array, scanned  $20^\circ$ , with parabolic deformation is simulated for 5.17 inch tip deflection, shown in Figure 14a. Phase correction is calculated for each antenna in the array and the phase-adjusted array pattern is shown in Figure 14b.



(a) Flexed array radiation pattern



(b) Flexed pattern with phase correction

Figure 14. Flexed array pattern with 5.17 inch tip displacement scanned  $20^\circ$  from array normal.

It is seen in the uncorrected pattern how array deformation has corrupted the planar pattern of Figure 12d such that the direction of maximum gain has shifted and the scan direction of interest has experienced gain loss. After correction, the main lobe is again observed at  $20^\circ$ . The entire pattern is not recreated for every angle, but this is not necessary as we are only concerned with the direction of interest. Note that although the main beam width is slightly decreased by using

this simple correction scheme, the amplitude at the beam maximum (in the direction of interest) is restored.

Calculating mutual coupling and antenna edge effects for a large antenna array is virtually impossible. Neglecting these effects simplifies the simulation and, with approximation of the RSW radiation pattern and assuming each antenna's position in space is known, results in a reasonably valid correction scheme which should compare well with test measurements.

## **Summary and Conclusions**

In support of the Multifunctional Structures and Materials Team, three antenna concepts compatible with HALE UAVs have been developed. The antennas were designed to work at L Band / UHF frequencies since those frequencies are considered to present the biggest design challenges for a lightweight, flexible structure such as a HALE UAV. Also, a phase correction technique has been presented which allows for pattern correction for an array of RSW elements, by making the assumption that mutual coupling and edge effects are negligible for these elements.

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