IMPROVED UAV DATALINK PERFORMANCE USING EMBEDDED ANTENNAS

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ABSTRACT

UAVs are generally an order of magnitude less expensive and smaller than piloted vehicles, but still must possess air vehicle essentials such as propulsion, flight control, and payload. Antennas used for communication, navigation and mission function present unique challenges because they generally cannot be reduced in size without degradation in electrical performance or increase in weight. Typical UAV telemetry systems operate at UHF or L-band frequencies and employ blade antennas that mount on the fuselage exterior and protrude many inches into the air stream. These parasitic antennas degrade aerodynamics, increase drag, increase weight, usually provide less than optimal antenna performance because of blockage by surrounding structure, and are prone to physical damage due to its obstructive locations. These problems can be largely eliminated by embedding antennas into existing composite structures on the UAV, such as wings or stabilizers. Such antennas have been embedded in UAV flight control structures and have demonstrated improved RF performance, lower weight and lower total cost compared to conventional blade antennas. This paper presents results of the antenna demonstration program, including details of the design, integration, manufacture, and electrical test results.

KEY WORDS: Antenna, Radome, Unmanned Air Vehicle, Data Link

1. INTRODUCTION

The UAV industry presents a rapidly emerging market as potential users continue to understand and realize the benefits of using unmanned vehicles for carrying out dull, dirty, or dangerous missions. The cost pressures and competitive landscape in the UAV community creates new demands for advanced composite structures, and specifically new opportunities for multi-functional composites. Multi-functional composites are assemblies that simultaneously serve multiple functions, such as structural and electrical (e.g., antennas and other sensors). The antennas described in this paper demonstrate that a UAV platform is an ideal application for incorporating multi-functional composites, specifically combining structure plus electrical radio frequency (RF) functions.

1.1 UAV CHALLENGES Developers of UAVs face a number of design challenges. First, the vehicle must have many features of conventional piloted aircraft, such as flight control, propulsion and payload; however, the vehicle must also be significantly less expensive than conventional aircraft. With the numerous competing platforms in development, cost is invariably a primary design consideration.

Second, the UAV community has a background unlike piloted aircraft. Small UAV platforms resemble an evolutionary product from radio-controlled hobby planes. As such, many UAV developers have similar origins and are typically not RF or antenna experts. Antennas and payloads are vehicle afterthoughts and not primary design considerations. Consequently, antenna performance typically suffers due to interference with the airframe, non-optimum antenna location or improper selection of components. Ultimately, data link efficiency and mission success are less than optimal.

Finally, UAVs must be both light weight and damage tolerant, which are typically conflicting goals. The light duty propulsion system is only capable of carrying the essential payload components and a minimally designed composite airframe. UAVs must also be highly damage tolerant, as many of these vehicles are launched from trucks, trailers, runways, manually, and other rugged environments and can land on rough terrain or even in water. For these lightweight vehicles to sustain these operating environment loads, efforts must be made to reduce parasitic components, such as antennas. With these challenges, UAV developers require an increased level of component integration to satisfy their cost, weight, performance, and mission goals. This need has created a new application for multi-functional composites.

1.2 MULTI-FUNCTIONAL COMPOSITES The notion of incorporating multiple functions within a single composite structure has existed for many years. Piezo-electro materials, electro-rheological fluids, load monitoring devices, and many other types of sensors have been successfully embedded within composite structures. Applications have included structure health monitoring, shape altering, dampening, stiffening, RF integration and others. For many reasons, these embedded technologies have been slow to become qualified on production platforms and programs.

One reason for the slow acceptance of multi-functional composites on aircraft is perceived technical risk. There is a technical uncertainty with disrupting the continuity of a composite structure with an embedded device. Terminating composite plies, changing material properties across a section, and adding electrical or thermal connectivity devices to a structure all create new variables regarding structural performance and long term survivability. Significant costs must be expended to understand, quantify, and address these issues. Prior to UAVs, there have been few applications that provided sufficient justification to resolve these issues. Compared to piloted vehicles, UAVs have less stringent qualification requirements and the composite technology employed is more basic. UAV platforms are ideal applications to exploit multifunctional composites. Development of multi-functional composites on UAVs is expected to accelerate their acceptance on piloted vehicles and for other harsh environments.

2. CURRENT TECHNOLOGY

To fully appreciate the benefits of a multi-functional UAV composite structure with an embedded antenna, a full assessment of the current technology is necessary. The current technology is explained by first considering blade antennas that are routinely employed in data link applications. Next, a detailed explanation of the composite construction of a typical UAV is provided. The explanation pertains to flight control surfaces, such as wings and stabilizers, as these are the components from which the embedded antenna demonstrator units were produced.

The specific processes and materials are presented with the mechanical integration issues associated with the antenna.

2.1 BLADE ANTENNAS Most blade antennas are variations of a monopole radiator, one of the most fundamental of all antenna types. Typical monopoles are quarter-wavelength long at the frequency of operation and must be installed on a conducting groundplane. The groundplane acts as an image plane for the monopole, resulting in a vertically polarized dipole-like radiating mode with maximum gain at the horizon for very large groundplanes. For finite sized and electrically small structures such as UAVs, where the vehicle skin acts as the groundplane, maximum gain occurs at lower elevation angles. See Figure-1 for an example of a monopole blade antenna and typical radiation patterns.

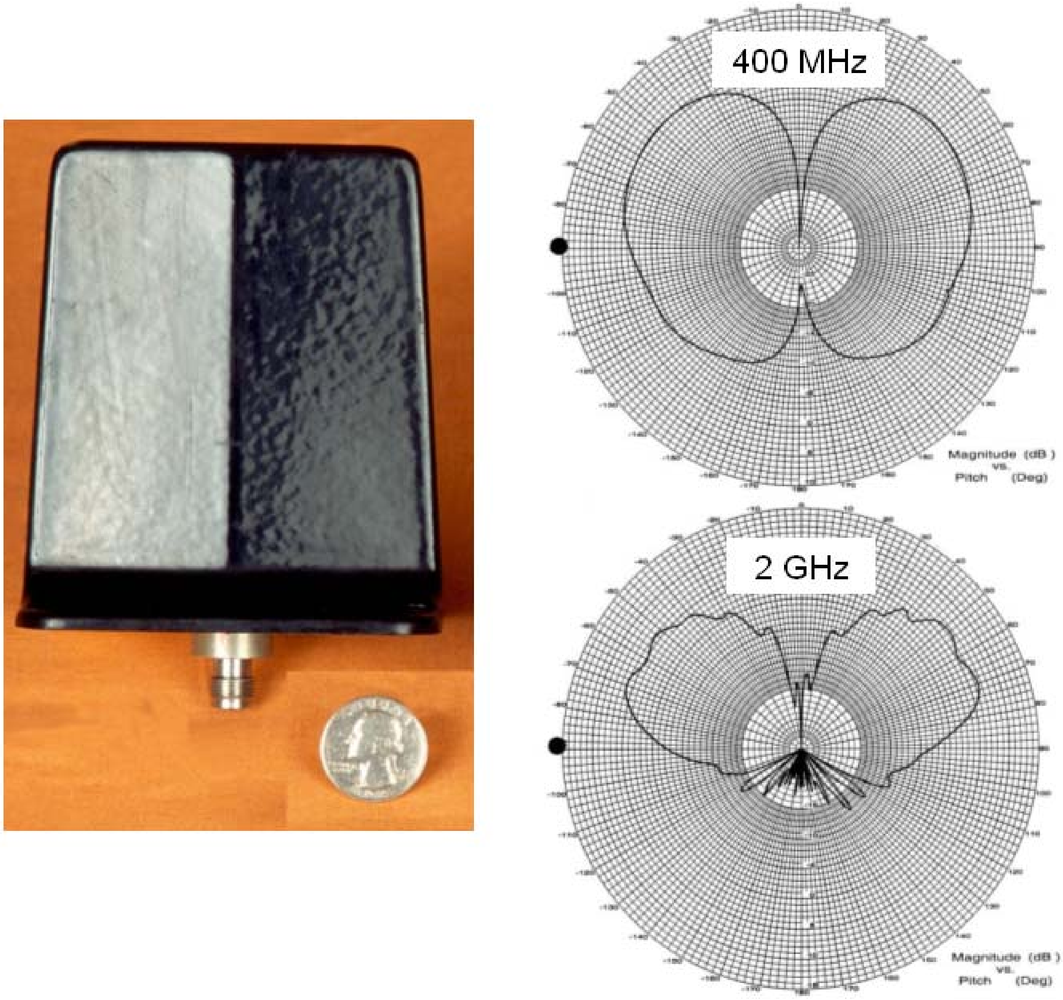

Figure-1: Blade Antenna for 400 MHz to 2000 MHz Operation

A common blade manufacturing process is to first creating the antenna element by photo-etching an antenna circuit pattern onto one side of a copper clad glass/epoxy laminate substrate. The etched laminate is then mounted to a metal base plate and a coaxial RF connector is threaded into the base plate and soldered to the printed circuit board element. The element is covered with an aerodynamically shaped composite radome. The base plate has mounting holes to secure the antenna to the vehicle using nuts and bolts or other similar mechanical hardware. After mounting, the connector passes through an opening in the aircraft skin and the radome protrudes away from the vehicle and into air stream.

2.2   UAV FABRICATION AND MATERIALS The materials and processes used for typical UAVs are consistent with the overall low cost vehicle design goal. Material composition is generally foam or balsa core wrapped with composite skins. The skins are glass or carbon fiber cloth impregnated with epoxy resin. In some designs, glass fiber is used for a majority of the structure and carbon is used for local stiffening, such as for a wing spar. The skins are either prepreg or dry cloth impregnated via a wet lay-up method. An alternative to using core as a light density filler is using an assembled structure of composite spars and ribs.

To produce the UAV flight control surfaces, the cavity filler can be either CNC machined or prefabricated and assembled. For prepreg composite skins, the skins are pre-cured and subsequently wrapped around the light density filler and bonded in place. Wet lay-up skins are either pre-cured or laminated directly around the machined foam. The skins are generally 2-4 plies in thickness.

Blade antennas are typically mounted to the top or bottom of the vehicle after the UAV airframe structure is produced. To accommodate antenna integration, channels and holes are cut into the structure to allow for cable routing and mounting, bolts are used to attach the antenna to a conducting ground plate and UAV, and an access hole is created in the composite skin at the antenna mounting location. Typical installations are shown in Figure-2.

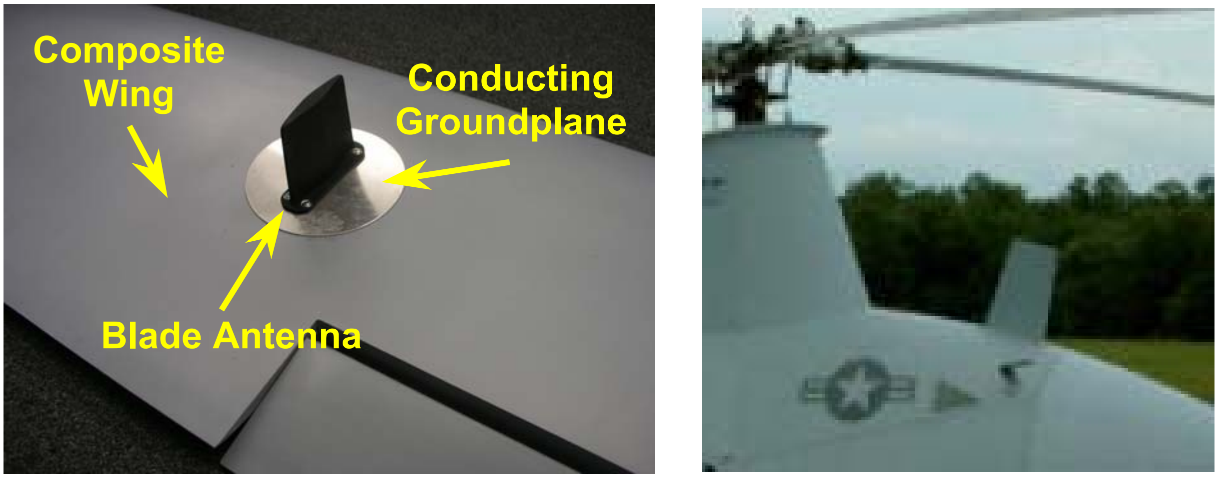

Figure-2:   Conventional Blade Antennas on UAVs

All of these changes degrade the basic UAV design by adding weight, increasing aerodynamic drag, interrupting the continuity of the composite structure and reducing the structural integrity and efficiency. Additionally, the parasitic antennas create a damage prone feature.

Since blade antennas on UAVs are usually incorporated after the vehicle is produced, antenna performance is generally less than optimal. Antenna gain and radiation pattern are degraded by the air vehicle, particularly if carbon fiber is used on the UAV. The pattern orientation relative to the target may not be optimal due to the location of the antenna on the vehicle. Considering antenna location at the end of the design process limits the possible locations for the antenna, which compromises RF system performance.

All of these issues associated with current UAV antenna integration and technology suggest that the antenna functions should be included as an initial design consideration and designed into the composite structure. These issues are the motivating factors that lead to the development of the two demonstration units described in the next sections.

3. MULTI-FUNCTIONAL UAV WING

The first multi-functional composite structure demonstrator presented consists of a UAV wing with a slot antenna integrated into the wing underside. A UAV wing was modified by removing the existing blade antenna, installing a flush mounted slot antenna in the same location, and then testing the antenna for RF radiation pattern and gain performance. Descriptions of the antenna and these processes are described below.

3.1 SLOT ANTENNA The slot antenna consists of an annular slot in a conducting groundplane, backed by a machined or stamped conducting cavity, and connected in some manner by an RF transmission line. In the case of the demonstration unit, the slot is circular and backed by a cylindrical cavity and is electrically fed through a connector in the center. This type of annular slot radiator is widely used in airborne applications as flush-mounted alternatives to monopole blade antennas. Annular slot radiation patterns are very similar to blades, providing omni-directional azimuth coverage, vertical polarization and maximum gain at or near the horizon (dependant on groundplane size). Figure-3 shows the annular slot antenna built for UAV wing integration.

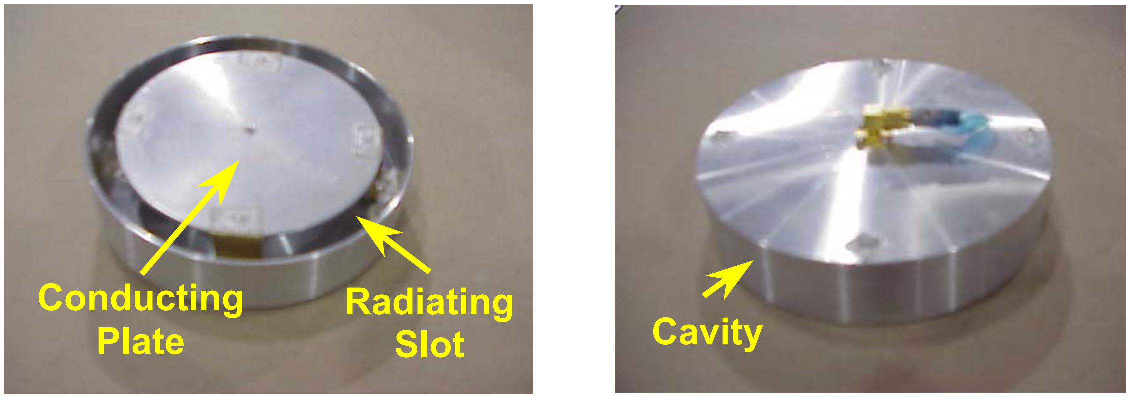

Figure-3: Annular Slot Antenna

3.2 FABRICATION AND MATERIALS To install the slot antenna into the wing, a recess was created in the underside of the wing at the blade antenna location. To create the recess, a circular piece of the composite skin was first removed. The diameter of the removed section was slightly larger than the antenna and the location was centered on the location of the existing blade antenna. With the skin removed, a circular recess was machined into the foam core to allow the antenna to seat into the core just below the surface of the skin. As a parallel task, a circular composite radome was produced to cover the antenna after installation. The radome simultaneously protects the antenna from environmental conditions and allows RF transmission with very little attenuation. Since the embedded slot antenna was installed at the same location as the existing blade antenna, a channel already existed to route the antenna cable from the antenna to the transceiver. The recess, antenna and radome are shown in Figure-4.

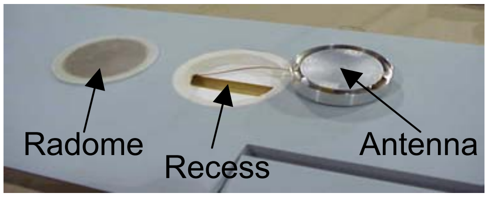

Figure-4: Antenna Recess, Radome and Slot Antenna Prior to Installation

The antenna was positioned into the recess and bonded in place with epoxy. The radome cover was positioned over the antenna and also secured with epoxy. Figure-5 shows the antenna in the recess and then covered with the radome.

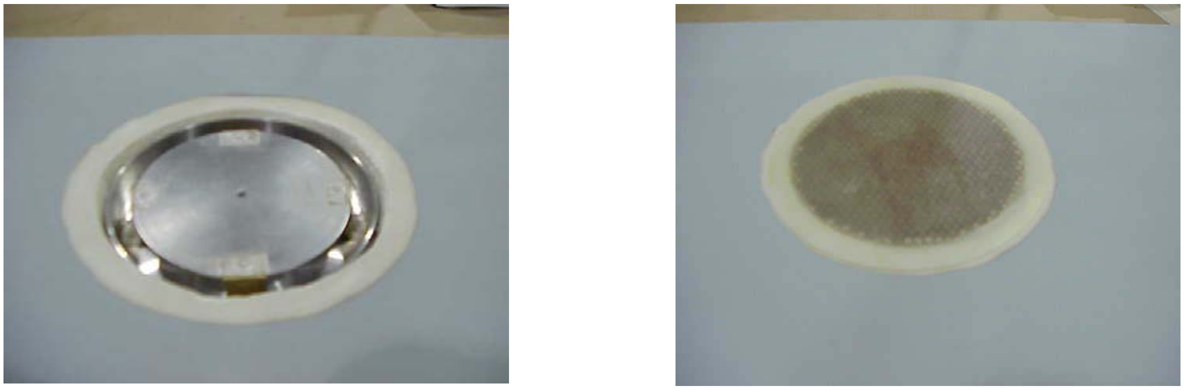

Figure-5: Annular Slot Antenna Installed in Recess and Covered with Radome

One layer of fiberglass was laminated over the radome and extended over the existing wing surface. After curing, the area was sanded, primed and painted. After painting, the antenna was visually undetectable. No antenna ground plane was incorporated into this demonstrator. The finished product is shown in Figure-6 (compare to blade installation in Figure-2).

This antenna demonstrator was produced by embedding the antenna into an existing UAV wing rather than into a new one. All of the process steps pertaining to the antenna integration could be carried out more efficiently during the production of a new wing. A new wing would be produced by machining a recess into the foam prior to the skin placement. The skin and radome would then be laid up in a continuous fashion over the entire wing surface including the antenna. The result would be continuous fibers (structure) with an underlying antenna (RF function), which is a pure multi-functional structure. This demonstrator was intended to prove that an antenna of this type could be embedded within the wing and still provide adequate RF pattern and gain performance as explained in Section 5.

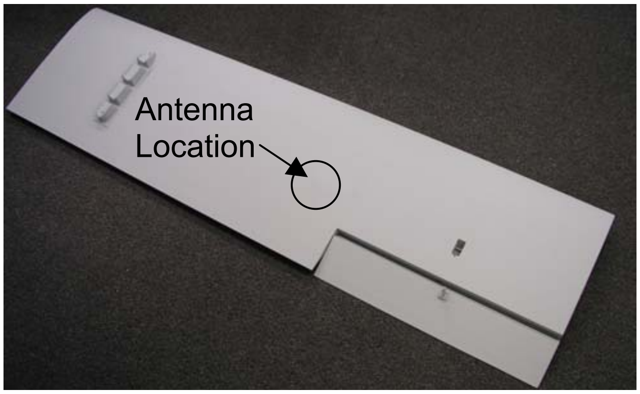

Figure-6: Painted UAV Wing with Embedded Slot Antenna

4. MULTI-FUNCTIONAL UAV STABILIZER

The second multi-functional composite structure demonstrator presented consists of a UAV vertical stabilizer with a dipole antenna embedded into the outboard side. Descriptions of the antenna and the processes used to embed the antenna are described below.

4.1 DIPOLE ANTENNA A dipole antenna is a fundamental antenna configuration consisting of a half-wavelength long resonator, similar to the monopole discussed in Section 2, but with the key distinction that a conducting groundplane is not needed. Instead of imaging in the groundplane as is accomplished with the monopole, the dipole is a full length radiator that provides maximum gain at the horizon without requiring a large groundplane.

The dipole antenna used for the demonstration unit was produced from a glass/epoxy laminate substrate with copper cladding on one side. The cladding was selectively removed through a photo-etching process such that only the dipole elements remained. As shown in Figure-7, A coaxial RF connector and cable were attached to the antenna elements to provide the RF signal.

Figure-7: Dipole Antenna

4.2 FABRICATION AND MATERIALS To install the dipole antenna into the stabilizer, a recess was required in the stabilizer. For electrical reasons, the antenna location was chosen to be near the top of the stabilizer to minimize signal reflections from the rudder servo motor and other vehicle components. With the location established, the outer two-ply skin was removed and the foam core was recessed to accommodate the thickness of the antenna. A groove was made into the core to accommodate the antenna cable. The antenna positioned into the recess is shown in Figure-8.

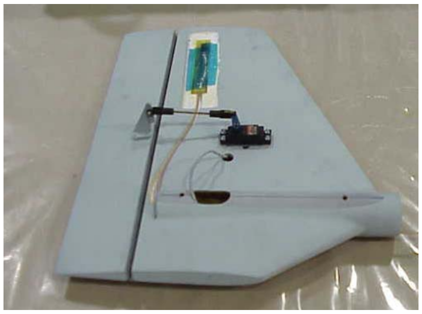

Figure-8: Dipole Antenna Installed in Recess

To secure the antenna in the stabilizer, the antenna was first bonded to the foam core with epoxy. Next, two layers of fiberglass were laminated over the antenna and extended over the existing stabilizer surface. After curing, the area was sanded, primed and painted. After painting, the antenna was visually undetectable. Figure-9 shows the embedded antenna in the stabilizer both before and after final painting.

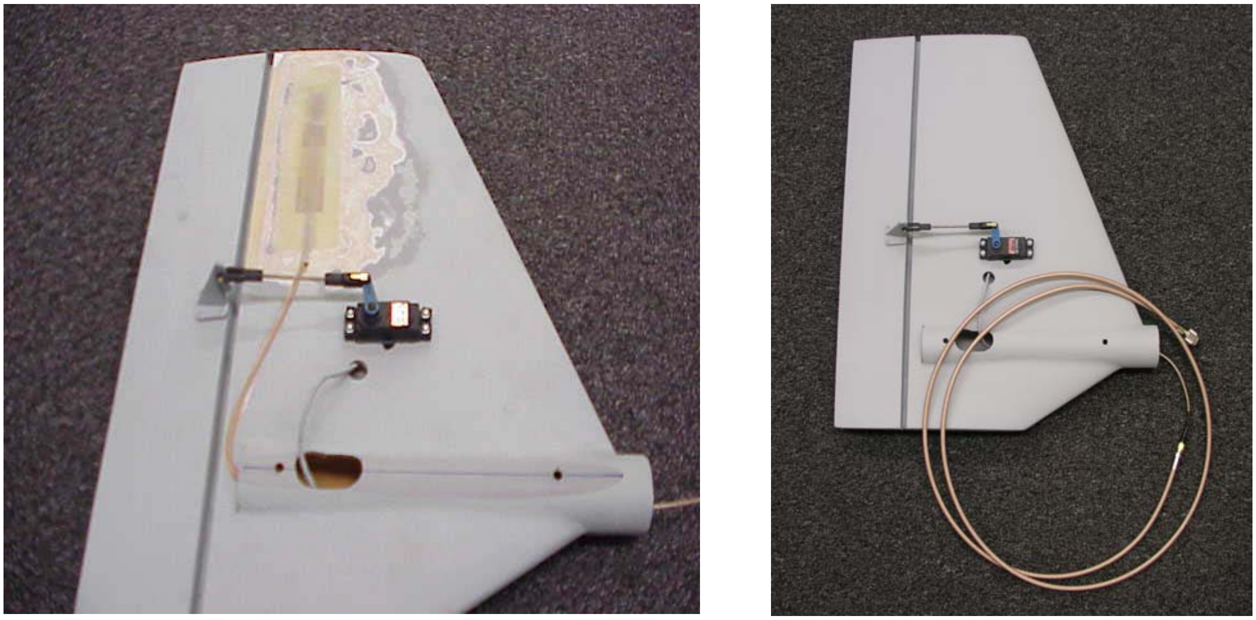

Figure-9: Embedded Dipole Antenna Before and After Paint

Some of the benefits of this embedded alternative became very apparent during the fabrication process. The dipole antenna is significantly lighter and less expensive than the blade antenna. Also, no separate radome or ground plane are needed.

This demonstrator was also produced by embedding the antenna into an existing UAV stabilizer rather than into a new one. All of the process steps pertaining to the antenna integration could be carried out more efficiently during the production of a new stabilizer. A new stabilizer would be produced by machining a shallow recess into the foam prior to the skin placement. The skin and antenna would then be laid up in a continuous fashion over the entire stabilizer surface including the antenna. The lay-up process would include embedding the antenna between composite plies. The result would be continuous fibers (structure) surrounding an embedded antenna (RF function), which is a pure multi-functional structure. This demonstrator was intended to prove that an antenna of this type can be embedded in the stabilizer and still provide adequate RF pattern and gain performance as explained in Section 5.

5. ANTENNA PERFORMANCE

The primary goal of this project was to demonstrate that data link antennas can be embedded within various UAV structures and that RF performance can be equal to or better than their traditional blade antenna counterpart. After fabrication, the embedded antennas were tested for pattern and gain and the results were compared to the blade antenna. The antenna testing and results are described in the following sections.

5.1 ANTENNA TESTING

The antennas evaluated in this project were L-Band antennas designed to operate from 1700-1900 MHz for Line-of-Sight (LOS) communications of voice or data. To support this, the antenna radiation pattern must be omni-directional in the azimuth plane and provide maximum gain at or near the horizon.

To perform the tests, the antennas were mounted on an outdoor far-field antenna range suitable for testing these low frequency, electrically small, broad beam antennas. This is an elevated far-field range instrumented with equipment that enables measurement of gain-referenced radiation patterns, including roll, pitch and yaw cuts.

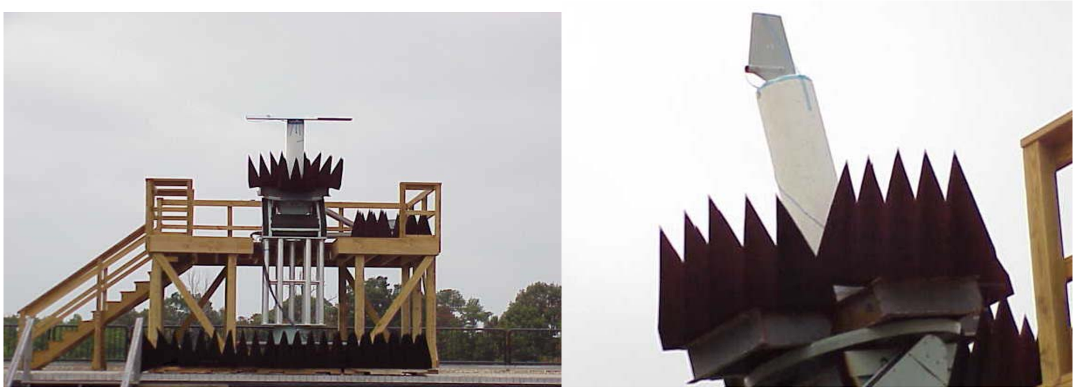

Figure-10: Antennas Being Tested for RF Pattern and Gain

5.2 ANTENNA PERFORMANCE RESULTS Although data was taken at several frequencies, only the data at the nominal frequency of 1800 MHz is included. All other plots show similar trends. Figure-11 shows antenna gain plotted versus roll angle for each of the three antennas. On this polar radiation pattern, higher radiation intensity (gain) is represented by higher polar amplitude. Each pattern displays the typical dipole radiation pattern, with maximum gain at the horizon (horizontal) and nulls at the zenith (top) and nadir (bottom).

The nulls (valleys) on the top and bottom indicate the lack of gain at the vertical axis of the antenna and are characteristic of monopole and dipole antennas. As the plot shows, all three antennas have a similar radiation pattern. The dipole antenna clearly has the highest overall gain and will provide improved performance independent of the aircraft attitude. The slot antenna and blade antenna are very similar; however, the slot antenna has slightly better overall performance.

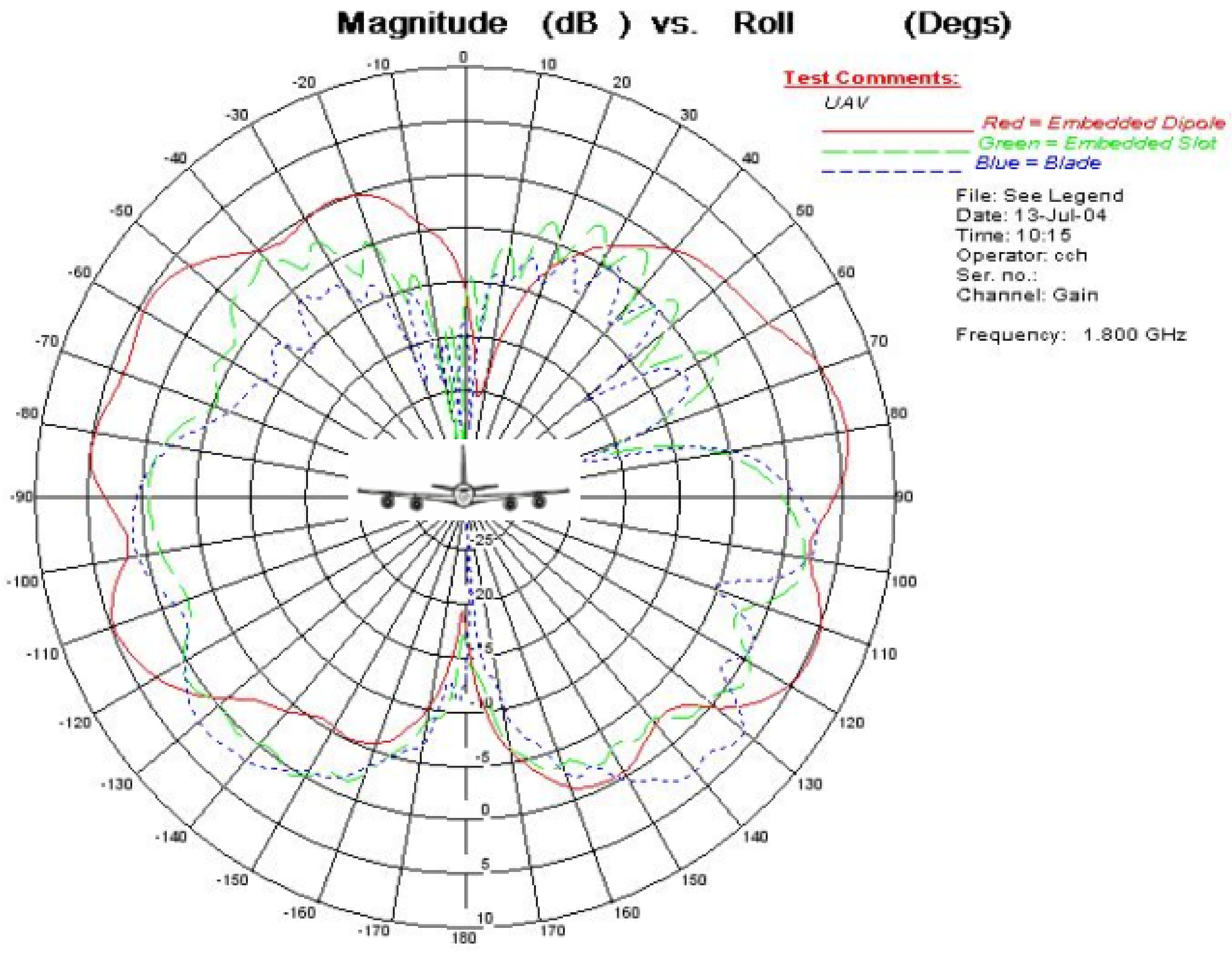

Figure-11: Antenna Gain versus Roll Angle

Figure-12 shows antenna gain versus yaw, which reveals the omni-directional radiation pattern on the plane of the antenna. The first observation from the plot is that all three antennas show very good omni-directional coverage. One inference from this is that embedding the two types of antennas in a composite structure did not inhibit the required omni-directional performance. Typical UAV composite structures made with glass fiber based composites act as effective radomes at typical data link frequencies. As the plot indicates, RF transmission does occur efficiently through the composite structure of the wing and vertical stabilizer in all directions relative to the embedded antenna. The second observation is that the overall comparison between the three antenna types is similar to the previous plot. The dipole antenna has the best performance and slot antenna and blade antenna are very similar in performance.

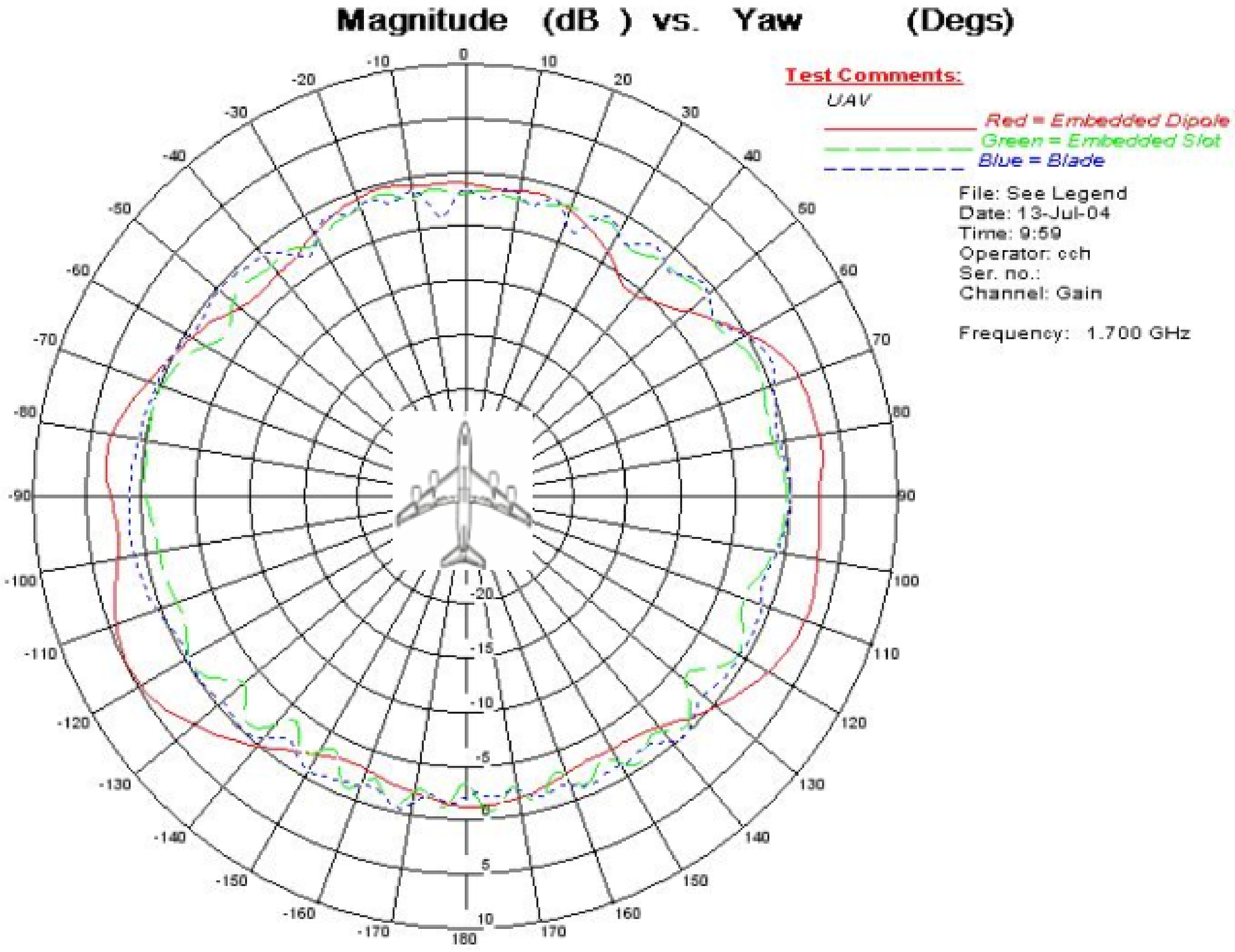

Figure-12: Antenna Gain versus Yaw Angle

7. CONCLUSIONS

This paper describes the design, development and test of two demonstration units consisting of multi-functional UAV composite structures containing embedded antennas. These demonstrators were motivated by three factors. First, UAV developers face many technical and cost challenges as the demands for their vehicles continue to accelerate. Second, multi-functional composites are structures that are intuitively beneficial, but their application and potential has only begun to be realized. Third, the current data link function on UAVs, as carried out by conventional blade antennas, is less than optimal.

The two demonstration units clearly show that there are data link antenna alternatives for UAV developers as they continue their vehicle development and design new vehicles. The first demonstrator was a UAV wing with an annular slot antenna embedded on the underside. The second was a vertical stabilizer with a dipole antenna embedded in the outboard surface of the stabilizer. The units were produced and tested. The test results were compared to the performance of a conventional blade antenna.

The antenna pattern and gain performance of the embedded antennas was equal to or better than the current blade antenna. The dipole antenna was notably superior to the blade antenna and the annular slot antenna was marginally better. The results of this paper should motivate UAV developers to consider these alternatives as they continue to develop their vehicles. The results should also help accelerate the acceptance and incorporation of multi-functional composite structures into new applications.