Antenna Design for Small UAV Locator Application

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Abstract

An antenna design problem is presented for a small UAV application. A UAV locator system must include an on-board transmitter with the capability to provide a beacon signal, in the event of a crash, and a receiver that is tailored for a transmitter hunt. This specific context for applying antenna theory allows a variety of design constraints, technical approaches, performance measures, and required results. The paper provides a structure for organizing the material, example approaches that illustrate possible design choices, and recommendations on educational implementation.

Introduction

Antenna theory is a core subject within electrical-engineering education. However, the abstract concepts may be difficult for students to comprehend. Specific application examples and hands-on experimentation can aid student understanding. Antenna projects that are included in electromagnetics courses can reinforce principles in design and measurement. These activities may even incorporate competition, along with an element of fun, as in the case of a long-running exercise used by the United States Air Force Academy. In their antenna theory course, engineering students design, simulate, and construct VHF direction-finding antennas that they use for a transmitter-hunt exercise [1]. Amateur radio clubs conduct similar transmitter or “fox” hunt activities for their members to improve their technical knowledge and to practice their operator skills [2,3]. Amateur radio can be a convenient tool for supplementing engineering education in many areas, including antenna theory [4]. These antenna-locating activities can be applied to the emerging proliferation of UAVs in modern society.

Unmanned aerial vehicles (UAVs), or unmanned aircraft systems (UASs), have been developed and purposed for civilian, military, and recreational activities [5]. The technology is interdisciplinary with the incorporation of aerospace structures, electronics, telemetry, etc. UAV development and application require the integration of systems to satisfy performance and mission requirements. Related educational activities are becoming common as well. For instance, competitions and open-source projects encourage student design and operation of UAV technology [6-8]. The efficient retrieval of a crashed UAV is an ongoing concern for operators, as the UAV and perhaps its payload may be quite expensive. While typical operation of small UAVs is limited to line of sight during flight, a search for a downed UAV could be difficult in rugged terrain. The design of a locator system is an interesting technical problem that is significantly constrained for the case of a small UAV (sUAV). These constraints include size, weight, power, and performance of the system.

This paper describes a flexible context for exploring topics in antenna design. A UAV locator system requires both an on-board transmitting antenna for the beacon signal and a ground-station receiving antenna for the transmitter-location exercise. The UAV context introduces realistic constraints and performance measures for a communication system, including antenna design. The locator task introduces issues of how the system will be used. The project description includes design constraints and objectives for the small UAV application, a discussion of antenna approaches and trade-offs, and example antennas that illustrate possible design choices. Recommendations are given for the educational implementation of the project.

Small Unmanned Aerial Vehicles as an Application

Small UAV Constraints

A small UAV for non-commercial purposes is defined as weighing between 55 lbs. and 0.55 lbs [9]. The FAA has established operational limits and registration. (Commercial operations have more extensive operational protocols and such operations require licensing.) These UAVs include fixed wing, helicopter, and multi-rotor designs. Figure 1 shows an example of a popular quadcopter design.

Figure 1. Model F450 Flame Wheel Quadcopter by DJI.

Any extra on-board system must be tailored to the host UAV and its intended usage. The UAV platform introduces constraints for the size, weight, and power needs of extra components and electronics. The UAV usage determines the required payload, e.g. a camera, which further constrains what can be added. Small UAVs have limited load capacity. The antenna choices must be compatible with this application area. The transmitting antenna must be installed in or on the UAV without adversely affecting its operation. For a fixed-wing UAV, the antenna could be mounted on the wing or in the fuselage. For a quadcopter UAV, the antenna could be mounted along the vehicle arms.

Consequently, the size of the UAV imposes limits on the antenna size, which in turn constrains the choice of operational frequency. Regardless of the specific type of transmitting antenna, its efficient radiation typically requires its size to be on the order of one-fourth to one-half wavelength, which is inversely proportional to frequency. The receiving antenna must be sized so that an operator can easily transport it to the search area and orientation it to determine the direction from which the signal is emitting. In addition to size constraints, antenna polarization can also influence the design choices. The receiving antenna's orientation can be manipulated by the operator, in order to match the polarization and position of the transmitting antenna. However, the transmitting antenna's polarization will tend to be randomly oriented, depending on the nature of the crash. Therefore, the designer will need to consider antenna designs that tend to be robust to the transmitters orientation, ranging from simple monopoles to loop antennas, or perhaps a transmitting turnstile antenna, made from orthogonal dipoles fed ninety-degrees out of phase. Alternatively, the student-designer may choose to compensate for the suboptimum transmitting signal by designing a more robust receiving antenna instead. These design choices allow for a wide trade space for system optimization.

Locator System

A UAV locator system consists of on-board components and operator components. The on-board components are the transmitting antenna, the transmitter, and supporting electronics. This antenna must be omnidirectional since the orientation of the UAV after a crash is unknown. The transmitter must come on in the event of a crash and should have its own power supply. For instance, the system could be configured to transmit when the UAV experiences loss of power or when an accelerometer senses an impact. The operator components are the receiving antenna and receiver. A highly discernable antenna pattern is needed for the receiving function. The on-board power needs for the transmitter are defined by the search limits. Power concerns are related to the maximum distance between the operator and the crashed UAV and to the desired search time. The procedure for the transmitter hunt is influenced by the antenna characteristics, the supporting electronics, and the environment. For instance, direction finding is complicated by obstacles or terrain that block line of sight and introduce multipath reflections.

An appropriate frequency of operation determines many of the subsequent design choices. For high operating frequencies, the cost of components and the precision of antenna construction are problems. For low operating frequencies, antenna dimensions may be too large for the transmitting antennas on the UAVs, as well as for convenient handling of the receiving antennas on the ground. A convenient frequency choice for ease of construction is the VHF band. The amateur "2-meter" wavelength band allows relatively easy antenna construction from material that can be readily purchased at the local home-improvement store. However, an efficient antenna will be in units of feet, not inches, which could present a problem for the size constraint put on the onboard transmitting antenna. This size constraint might drive the frequency choice to be in the UHF band, or even one of the microwave ISM bands. Although the antenna size can be drastically reduced at these bands, the electronics and construction techniques become more demanding at these smaller wavelengths. These constraints provide a trade space for the student's design-optimization task. For instance in comparison to UHF, the more diffractive nature of VHF frequencies is beneficial in hilly areas. Furthermore, VHF tends to travel farther than UHF, for the same transmit power. The "2-meter" amateur-radio band is ideal for this frequency, due to the availability of high-quality transmitters and receivers. Also, during a transmitter hunt, a single operator can easily handle a directional antenna for the 2-meter band as shown in Figure 2 [1]. (An instructor or volunteer with an amateur radio license will be required to operate the transmitter.) The disadvantage of VHF over UHF is the transmitting-antenna size. An efficiently radiating dipole would be over three feet long. In contrast, a dipole in the "70-cm" amateur band would be slightly more than one foot long, which is attractive for a small UAV wing span. However, the need for an efficient transmitting antenna is simply another element in the designer's trade space. The inefficiency of the transmitter could be compensated by the minimum gain requirement demanded of the receiving antenna.

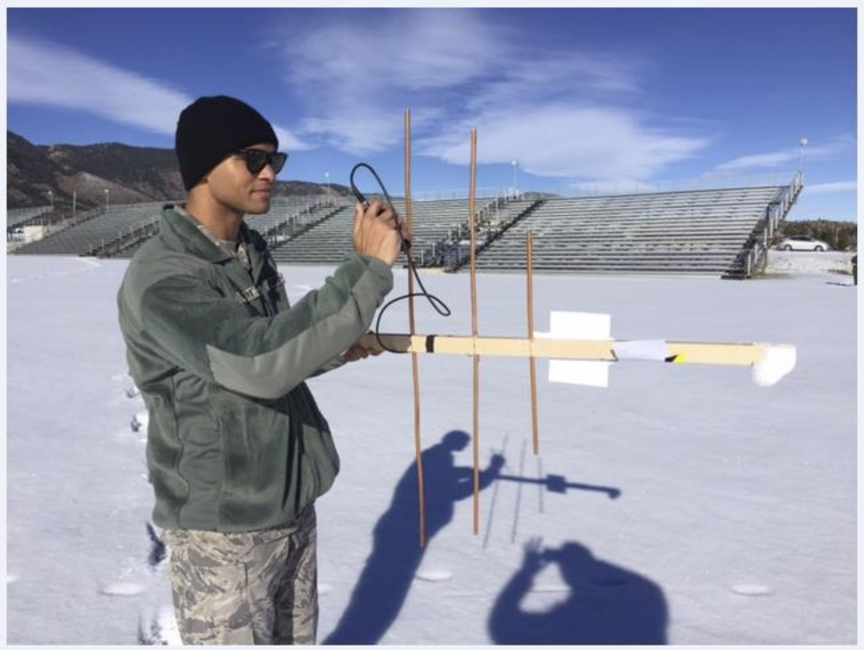


Figure 2. Transmitter Hunt with Directional Antenna in Two-Meter Band [1].

The effectiveness of the locator system will depend upon successful integration of the technological components and the user procedure. During the transmitter hunt, the user must understand the characteristics of the transmitting antenna with an unknown orientation and the possible influences of a complex propagation environment. The user must choose a receiver design and a search procedure with an understanding of the limitations of each system component.

Design Problem

Target Concepts in Antenna Theory

The UAV locator context is interdisciplinary with aspects related to antenna theory, communication techniques, electronics, system integration, etc. The concern of this paper is antenna design and performance, but the antenna topics can be discussed in relation to these other areas. Some antenna topics that can be explored with a locator project are as follows:

- Directional properties of various antenna types
- Propagation characteristics of various frequencies
- Antenna iterative design procedure
- Antenna construction
- Antenna simulation techniques
- Antenna testing procedures
- Transmitter and receiver electronics
- Spectrum regulations

Since a key issue is directional properties, common directional and omnidirectional approaches can be highlighted. Even for a given antenna type, considerable tailoring of the design can be done; students have many opportunities to explore trade-offs. Also, simple changes in antenna types, constraints, etc. can vary project work from one semester to the next.

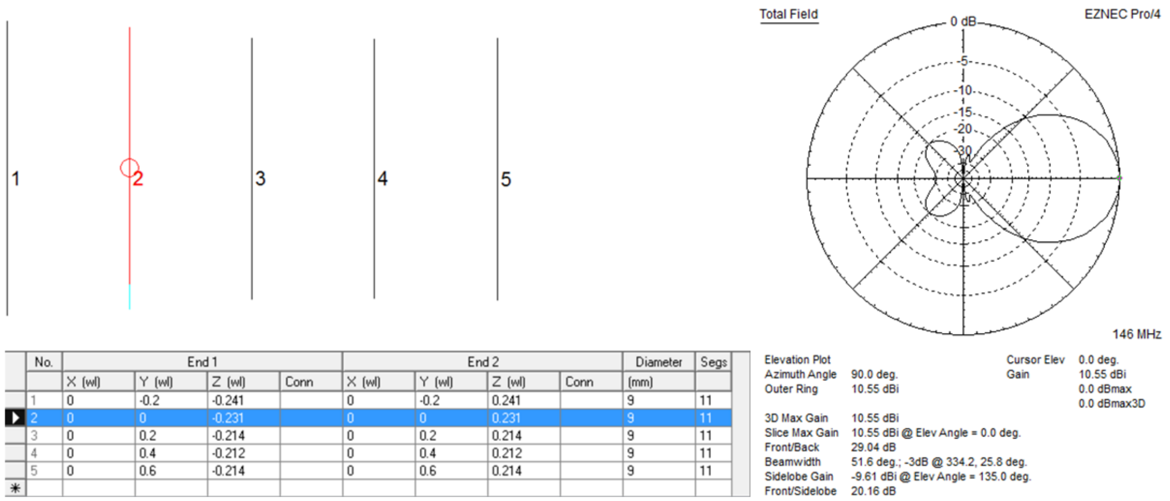
Resource for Education

The UAV locator problem can support education objectives in several different contexts. The material could be used to the basis for an assignment or case study in a core electromagnetics, communications, or systems engineering course to emphasize the interrelation among technologies in a specific application. A design project or activity could be used in an elective antenna course to emphasize desired performance differences among antennas. A locator system design could be the focus project for a capstone design team in which team members with backgrounds in electromagnetics, communications, electronics, etc. must interact. An extra-curricular activity or competition could use this design problem for students with interests in UAVs, amateur radio, etc.

The design and analysis aspects can be tailored for the educational venue. A possible assignment could be for students to perform the simulation and/or testing for the antenna transmitter and receiver pair. A case study could guide students to analysis the trade-offs among the system components. A capstone project could produce an optimized locator system for a given UAV platform. A key aspect of the UAV locator problem is the interrelation among the various technologies and the realistic design constraints and objectives.

Antenna Design Example

A comparison of the Yagi-Uda antenna and the phased-array antenna illustrate the opportunities for significant design work in the receiving antenna. Here the directional properties are critical. Both the Yagi-Uda antenna and the phased array antenna are constructed of half-wave dipole antennas. Figure 3 gives an example of the structure and radiation pattern for a five-element Yagi-Uda antenna. Figure 4 gives an example of the structure and radiation pattern for a two-element phased-array antenna. In both cases, the dimensions are given in wavelengths and the pattern is simulated for 146 MHz, using EZNEC. The Yagi-Uda antenna has a more complex structure, but it can provide more gain and has a pronounced directional pattern. As a high gain antenna, it is better for receiving weak signals. However, it must be electrically large. The phased-array antenna has a more compact structure. Its more omnidirectional pattern makes it easier to initially acquire stronger signals. However, it requires a precise ninety-degree phase shifter not required for the Yagi-Uda. Other differences are in the precision and tuning required for construction. The phased-array antenna must be constructed to tighter tolerances than the Yagi-Uda antenna. Both antenna types can be used to discern the direction of a transmitter, but they would be operated differently. The high gain Yagi-Uda would indicate the transmitter direction based on the maximum received signal strength, likely requiring the use of attenuation as the distance decreases. The lower gain phased array would indicate the transmitter direction by the null or lack of signal strength.



No.	End 1				End 2				Diameter	Segs
	X (wl)	Y (wl)	Z (wl)	Conn	X (wl)	Y (wl)	Z (wl)	Conn	(mm)	
1	0	-0.2	-0.241		0	-0.2	0.241		9	11
2	0	0	-0.231		0	0	0.231		9	11
3	0	0.2	-0.214		0	0.2	0.214		9	11
4	0	0.4	-0.212		0	0.4	0.212		9	11
5	0	0.6	-0.214		0	0.6	0.214		9	11

```
Elevation Plot                                   Cursor Elev   0.0 deg.
Azimuth Angle    90.0 deg.                       Gain          10.55 dBi
Outer Ring       10.55 dBi                                     0.0 dBmax
                                                               0.0 dBmax3D
3D Max Gain      10.55 dBi
Slice Max Gain   10.55 dBi @ Elev Angle = 0.0 deg.
Front/Back       29.04 dB
Beamwidth        51.6 deg.; -3dB @ 334.2, 25.8 deg.
Sidelobe Gain    -9.61 dBi @ Elev Angle = 135.0 deg.
Front/Sidelobe   20.16 dB
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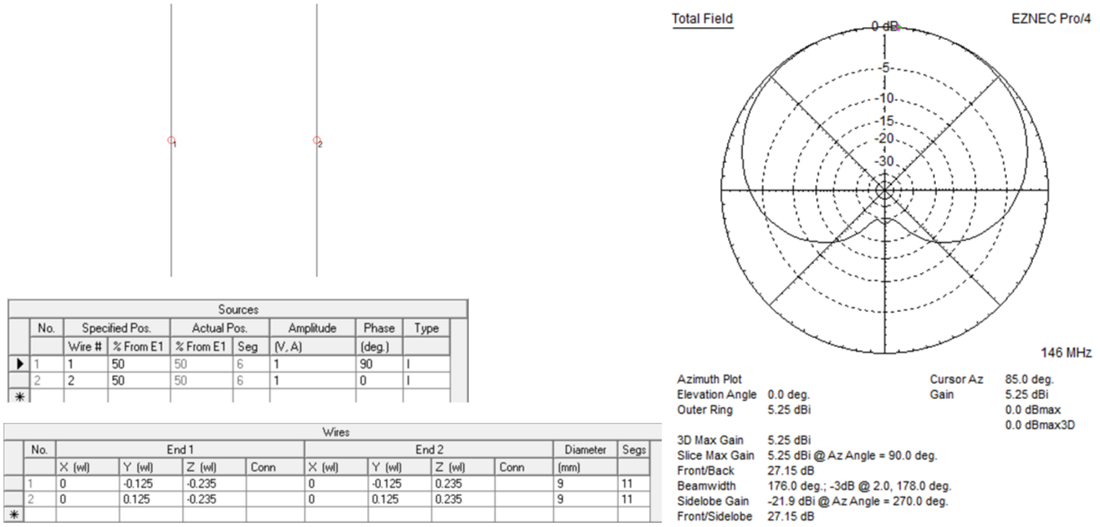
Figure 3. Five-element Yagi-Uda antenna (dimensions in wavelengths) with radiation pattern. Wire 2 is the actively fed driven element; Wire 1 is the reflector, and Wires 3-5 are the directors.



Sources							
No.	Specified Pos.		Actual Pos.		Amplitude	Phase	Type
	Wire #	% From E1	% From E1	Seg	(V, A)	(deg.)	
1	1	50	50	6	1	90	I
2	2	50	50	6	1	0	I

Wires										
No.	End 1				End 2				Diameter	Segs
	X (wl)	Y (wl)	Z (wl)	Conn	X (wl)	Y (wl)	Z (wl)	Conn	(mm)	
1	0	-0.125	-0.235		0	-0.125	0.235		9	11
2	0	0.125	-0.235		0	0.125	0.235		9	11

```
Azimuth Plot                                    Cursor Az   85.0 deg.
Elevation Angle   0.0 deg.                      Gain        5.25 dBi
Outer Ring        5.25 dBi                                  0.0 dBmax
                                                            0.0 dBmax3D
3D Max Gain       5.25 dBi
Slice Max Gain    5.25 dBi @ Az Angle = 90.0 deg.
Front/Back        27.15 dB
Beamwidth         176.0 deg.; -3dB @ 2.0, 178.0 deg.
Sidelobe Gain     -21.9 dBi @ Az Angle = 270.0 deg.
Front/Sidelobe    27.15 dB
```

Figure 4. Two-element phased-array antenna (dimensions in wavelengths)
with radiation pattern.

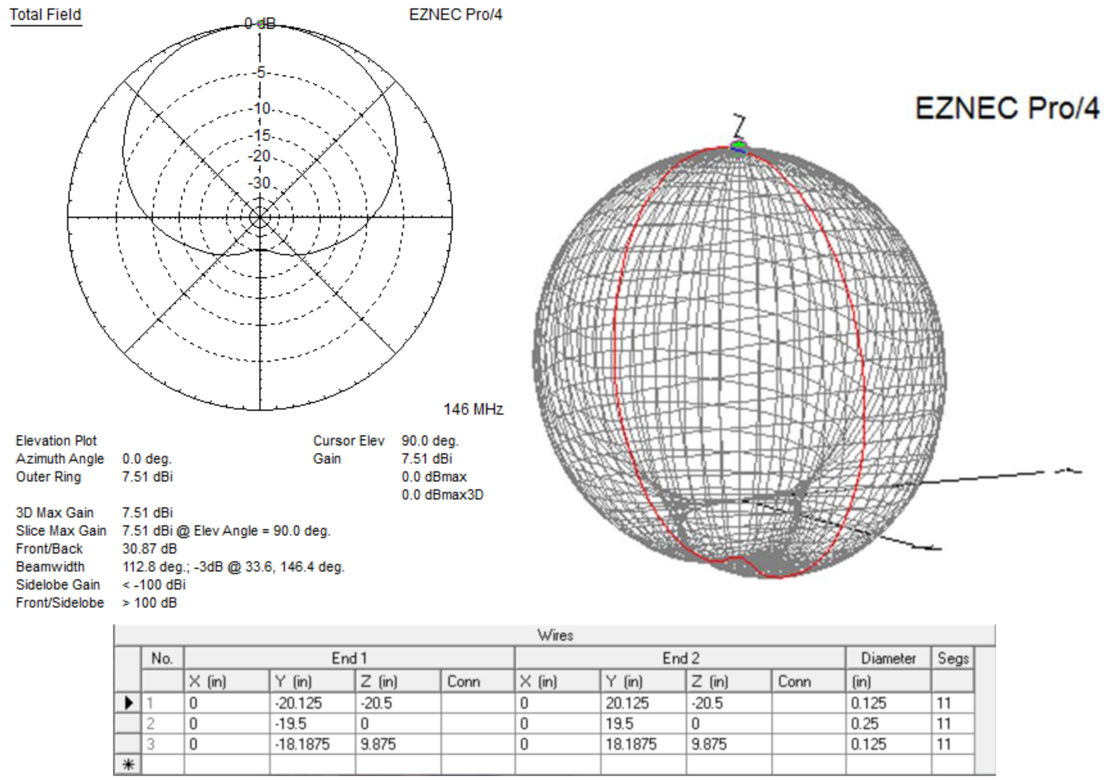
Consider the design details for these antenna types. The advantage of the Yagi-Uda antenna is that the increased gain reduces the required transmit power needed at a certain distance. This advantage could allow a more inefficient transmitting antenna. It is also relatively easy to construct, with a single feed point at the active element, while the passive elements are simple unfed conductors. The inter-element phasing is dictated by the relative lengths of the elements along with their inter-element spacing. The main disadvantage is the larger size, if high gain is desired. The advantage of the two-element phased-array antenna is its compact size and its near-omnidirectional pattern. If the transmitter is close enough, the signal can easily be acquired across a range of angles, unlike the narrower range for the Yagi-Uda antenna. Then the operator only needs to rotate the antenna in azimuth until the deep null points in the direction of signal. The operator would then notice the abrupt signal dropout, indicating the direction of the transmitter. The disadvantage of the phased-array antenna is that the radiation pattern greatly depends on construction variations.

Consider the differences in simulation, construction, testing, etc. The design of the phased-array antenna is fairly straightforward. The spacing is one-fourth of a wavelength, the phase shift is 90 degrees, and the elements are half-wavelength dipoles tuned to resonance. However, the construction-testing-tuning iteration procedure tends to be much more involved for the phased-array antenna than that for the Yagi-Uda antenna. The radiation pattern is extremely sensitive to subtle errors in element length, element spacing, and the 90-degree phase shift. Therefore, the phased-array performance requires iterations to adjust construction details. In contrast, the Yagi-Uda's iteration cycle tends to be more involved in the simulation/design phase of the project, and the Yagi-Uda construction is fairly straightforward. The design here can prove to be as much an art as a science. This complexity is due to the secondary effects of mutual coupling between the various elements, each of which is a different length. The “reflector” in Figure 3 is slightly longer than the driven element, in order to make it more inductive. The lagging current, and thus the re-radiated field, combines with the incident field from the driven element in such a phase that it tends to cancel the total field away from the driven element, and reinforces the incident field toward the driven element and directors. Likewise, the shorter “director” elements are more capacitive and the leading re-radiated field tends to reinforce the total field away from the reflector. The difference in these lengths is very nuanced. While changing the length and spacing might improve one parameter, such as front-to-back ratio, it tends to degrade another, such as impedance mismatch at the feed point. Therefore, the Yagi-Uda design is often an iterative approach relying heavily on simulations; however, the construction is straightforward.

These antenna approaches offer a great deal of trade space for the student. One approach is not better than the other; they are just different. In fact, a clever student might combine the advantages of both, while minimizing the disadvantages. For example, it is possible to design a Yagi-Uda antenna with a low-gain, near-omnidirectional pattern, with a deep null similar to the phased-array antenna but without of the construction difficulties. An example of such a Yagi-Uda antenna is shown in Figure 5. So, even the Yagi-Uda antenna design by itself offers a great deal of design tradeoffs. If the signal-to-noise ratio is expected to be very weak at the distances of interest, a higher gain Yagi-Uda antenna might be preferred despite its large size. However, if the transmitter is powerful enough or close enough, then a more omnidirectional lower-gain antenna would be easier to deploy, as well as construct.

Discussion

The UAV locator context provides a rationale for constraints in an antenna design project. Design choices can be made with regard to realistic performance measures. Consequently, this context adds to traditional transmitter hunt activities. The multiple technologies give an interesting systems engineering aspect to the design. Optimization must be done with constraints ranging from technical performance to user search procedures. If the system is used in an actual transmitter hunt, then issues of theoretical performance verses as-built performance are introduced. Also, students with strong interests in UAV applications may be more attracted to the course and more engaged with the activity. The scope and difficulty of assignments can be easily changed. For instance, different UAV platforms, which have different constraints for size, payload, etc., will change the design space. A possible approach for an initial educational implementation is to design a transmitting antenna system for a particular UAV platform. The set of frequency, transmission, and power characteristics along with distance and environmental constraints will give an interesting target situation to be addressed by the receiving system design. Of course, the design and construction activities can culminate in a fun transmitter hunt competition.



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Elevation Plot                              Cursor Elev   90.0 deg.
Azimuth Angle    0.0 deg.                   Gain          7.51 dBi
Outer Ring       7.51 dBi                                 0.0 dBmax
                                                          0.0 dBmax3D

3D Max Gain      7.51 dBi
Slice Max Gain   7.51 dBi @ Elev Angle = 90.0 deg.
Front/Back       30.87 dB
Beamwidth        112.8 deg.; -3dB @ 33.6, 146.4 deg.
Sidelobe Gain    < -100 dBi
Front/Sidelobe   > 100 dB
```

Wires

	No.	End 1				End 2				Diameter	Segs
		X (in)	Y (in)	Z (in)	Conn	X (in)	Y (in)	Z (in)	Conn	(in)	
▶	1	0	-20.125	-20.5		0	20.125	-20.5		0.125	11
	2	0	-19.5	0		0	19.5	0		0.25	11
	3	0	-18.1875	9.875		0	18.1875	9.875		0.125	11
✳											

Figure 5. Three-element Yagi-Uda antenna with cardioid pattern.

Summary and Implementation

A locator project for small UAVs is described that emphasizes antenna design. A UAV locator system must include an on-board transmitter with capability for providing a beacon signal in the event of a crash and an operator receiver that is tailored for a transmitter hunt. Hence, antenna topics can be discussed in relation to electronics hardware, electrical power, systems integration, and UAV technology. This specific context for applying antenna theory can highlight the relevance and trade-offs in what are often abstract topics. Such classroom design exercises can provide a background for students to directly apply their knowledge to extra-curricular activities with UAVs, amateur radio, etc. This problem can also be the basis of a case study to highlight interdisciplinary design [cf. 10].

As an educational resource, the material can be used as an assignment for electromagnetics and antenna courses, as a case analysis for a systems course, as a focus project for capstone design teams, and as a UAV-related extra-curricular activity or competition. The difficulty and scope for a student project may be varied by the specific constraints and the required results, e.g. antenna simulations or anechoic chamber testing. The locator context provides many types of paper design exercises and problems that require students to apply electromagnetic concepts. The choice of frequencies within the amateur radio bands provide good tradeoffs for availability of electronics and reasonable antenna sizes and construction simplicity. The expense for implementing a hands-on project can be minimal since the antenna construction can use readily available materials and the associated electronics can be obtained through amateur radio equipment sources. A next step in this work is to implement the material within a particular course. A transmitting antenna and system using an amateur radio band is planned for the DJ Quadcopter shown in Figure 1. This system will be a design example for the course. Associated assignments can guide students in characterizing this transmitting antenna, e.g. calculate the gain. With this background, the course project will be for student design and construction of the operator receiving antenna. The final project activity will be the transmitter "lost UAV" hunt.

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