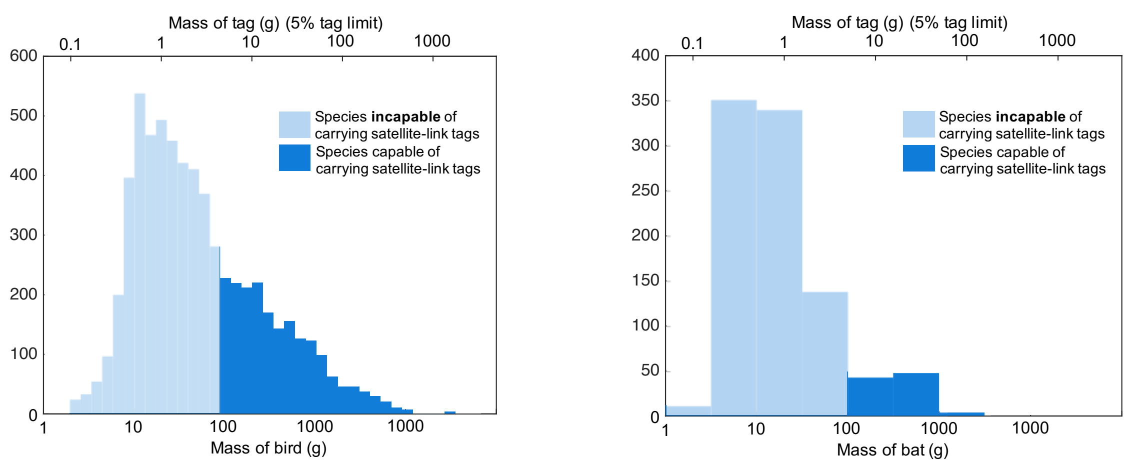
IDBR: Type A - An unmanned aerial radio tracking system for monitoring small wildlife species

1 Needs assessment

Small unmanned aerial systems (UAS) have the promise to revolutionize a number of ecological research paradigms due to their low-cost ability to sample at previously infeasible locations and spatio-temporal resolutions. In this research program, we will expedite this revolution in field data fidelity for small-animal biologists through the development and open-source publishing of a pre-engineered low-cost unmanned aerial vehicle (UAV) mounted radio telemetry system that significantly reduces technical barriers to adoption.

Despite advances in technology, wildlife telemetry for small species continues to be a major challenge. The power and lifetimes required by wildlife telemetry tags continue to require that tag mass be dominated by energy storage. Moreover, a large fraction of species are very small, with approximately 70% of bat, bird, and terrestrial species weighing less than 15 g, 88 g, and 251 g, respectively (Blackburn 1998 and 1994, Brown 1991). With tag mass limits of less than 3-5% of the host (Naef-Daenzer 2001, Aldridge and Brigham 1988, U.S. Geological Survey 2011, Reinert 1992), tag functionality is extremely limited and prohibits fine-scale monitoring of the majority of terrestrial, avian and Chiropteran species. Approximately 64% of avian species require tags less than 3 g, while the approximately the same percentage of bat species require tags less than 630 mg (figure 1). These mass constraints are the reason that the extremely small, but technologically archaic, Very High Frequency (VHF) radio tags continue to be the standard method of real-time localization for small wildlife species. While more modern tags exist, employing both ARGOS and GPS technology, their energy requirements make them too massive for a large number of species. The smallest ARGOS-enabled tags weigh 5 g (Microwave Telemetry^{TM}), and the proposed ICARUS system has a target tag mass of less than 5 g (ICARUS Space project technical overview 2011). Even if these systems could halve their tag masses, they would still be precluded from use on 88% of bats, 60% of birds, and 43% of terrestrial (North American) species. Thus, small VHF transmitters remain the only option for real-time tracking many species.

Satellite tags are also approximately an order of magnitude more costly than their VHF telemetry alternatives. A 5 g ARGOS satellite-enabled tag from Microwave Telemetry Inc. currently costs $3450, whereas VHF tags range in price from $180 to $370 (Microwave Telemetry 2015, Holohil Ltd. 2013). This difference can make ARGOS-enabled tags less attractive on small animals where the likelihood of tag recovery is low. Other tags known as ‘data-loggers,’ measure and store the animal’s location using GPS or light measurements. Although these tags can weigh less than satellite-communicating tags, the animals must be re-captured to offload data, making data-loggers unattractive or infeasible in many studies.



(a) Avian species

(b) Chiropteran species

Figure 1: Histograms of species mass (lower x-axis) and allowable tag mass (upper x-axis) delineating animals capable of carrying satellite enabled tags. Species mass data from (Blackburn 1994) and (Blackburn 1998).

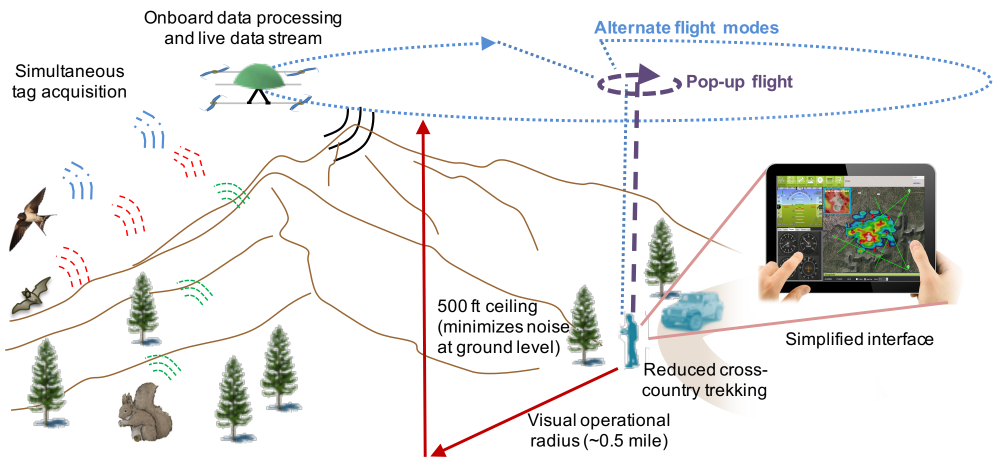


Figure 2: Operational overview including limits on flight based on proposed Federal Aviation Administration (FAA) regulations, as well as expected flight paths for various search types.

Current methods of position acquisition via radio telemetry are extremely inefficient, especially for remote locations, requiring many hours of cross-country hiking, driving, and/or manned aerial flights for each collected data point. Energy density restrictions will continue to couple and limit transmission power and lifetime of small telemetry tags. We believe that a systems approach, using a mobile aerial platform with a receiver system where mass and power are less constrained, will dramatically improve wildlife monitoring capability while using tiny, commercially-available, and inexpensive VHF tags.

This IDBR research program will develop an unmanned aerial vehicle-radio tracking (UAV-RT) system that includes a UAV-mounted antenna and receiver, as well as the associated data processing system for efficient reception and localization of VHF telemetry tags. An operational overview of this system is provided in figure 2. The system will dramatically increase detection and localization performance via aerial mobility and pulse combining, and improve researchers' ability to locate and track multiple subjects through concurrent detection of multiple tags. Automated flight will be accomplished via on-board autopilots with ground station software allowing for mission planning in office, at the deployment site, or during flight. Unlike commercial UAV systems, the mechanical system design considerations will reflect the targeted field research applications. The system will be collapsible for field deployments, allow for rapid assembly and repair by field biologists, and will include design features that minimize electromagnetic interference between the vehicle, communication systems, and the radio telemetry system. Fire-safe design features will be incorporated to reduce the risk of wildfire ignition in the event of a hard landing or crash.

To facilitate wide-scale adoption of the technology, the entire UAV system, from mechanical designs to data processing code, will be open-sourced. We will develop and host a website where detailed plans, part lists, software, firmware, assembly instructions, training modules, and regulatory information can be obtained. The UAV system will be designed to enable field researchers to build and fly their own research vehicle without engineering support. To assure maximum usability, the open-source system will be developed and tested at Northern Arizona University (NAU), followed by construction, deployment, and testing by a collaborating wildlife biology team at Cornell University in the third year of the program. This partner will build their UAV based on the published open-source plans and provide feedback about the system design, user interface, and assembly/operational plans provided on the website. This will allow for additional testing of the system, as well as testing and feedback on the instrument dissemination methods. Feedback will allow for modifications to be made to the system design and/or published development and operational plans to improve ease of access to and adoption of the technology.

In addition to the technical development effort of this program, we will incorporate a significant outreach and dissemination effort beyond that provided by the website to engage both researchers and the public. We have budgeted funds for dissemination, with results presentations and demonstrations at well attended annual conferences such as The Wildlife Society and the American Ornithologists' Union. This project has the potential to excite a broad spectrum of individuals due to its multidisciplinary nature.

We plan to work with the Upward Bound Program at NAU, which helps to guide first-generation and low-income rural area high school students from the Four Corners Region toward a successful college career. We also plan to develop booths for the Flagstaff Festival of Science and the NAU Community STEM night. Finally, we will continue our engagement with the regional public radio station and other media outlets.

The Northern Arizona University development team is uniquely positioned and qualified to pursue the development of this novel telemetry system for the following reasons:

- We have high-level expertise in the planned research area of wildlife radio telemetry (Chambers). The team also has strong engineering expertise in wireless communication (Flikkema) and in system and hardware design, as well as flight-vehicle development (Shafer).
- NAU has a baseline system prototype (see figure 5 inset) being used for initial testing.
- NAU has vigorous, long-standing, and internationally recognized research programs investigating wildlife, forest ecology and water resources in the arid southwest.
- NAU has experience working with the FAA certification of UAV flight programs, and has already been granted two Certificates of Authorization (COA) to fly small UAVs: *UAS COA 2013-WSA-62 and UAS COA 2014-WSA-90* (Investigators: T. Hoisch and T. Sankey).
- NAU's location offers ample and diverse testing environments. Meadows, lakes, deserts, dense forests, deep canyons, and mountains up to 3650 m (12000 ft.) are all less than a one hour drive from Flagstaff. Additionally, the NAU Skydome is a large (97,000 ft^2/9000m^2, 142 ft/43m ceiling) indoor athletic arena, allowing for year-round indoor testing of small UAS.

A leading manufacturer of wildlife telemetry equipment summarized the distinct benefits and risks of manned aircraft-based radio wildlife tracking prior to the advent of UAV systems:

> *If you're ground tracking a medium-sized animal wearing a collar with a state-of-the-art telemetry receiver...the range performance on level ground can be anywhere from 2 to 5 miles. By getting up on a hill and overlooking the animal, ranges can be extended to 5 to 10 miles. However, if it is possible to take your telemetry receiver up in an aircraft, the range is extended even further—typically from 10 to 30 miles. For many studies, regular aircraft tracking...extends the line-of-sight range and reduces signal attenuation due to vegetation. These two factors, combined with aircraft speed and mobility, provide significant advantages…Conducting research from aircraft is recognized in our field as a dangerous operation. Over the years far too many friends and colleagues have been injured or lost in aircraft accidents.* ***Therefore anything that increases efficiency, and reduces the time spent conducting low level flights, should have a positive influence on our actuarial statistics.*** (Beaty 1997)

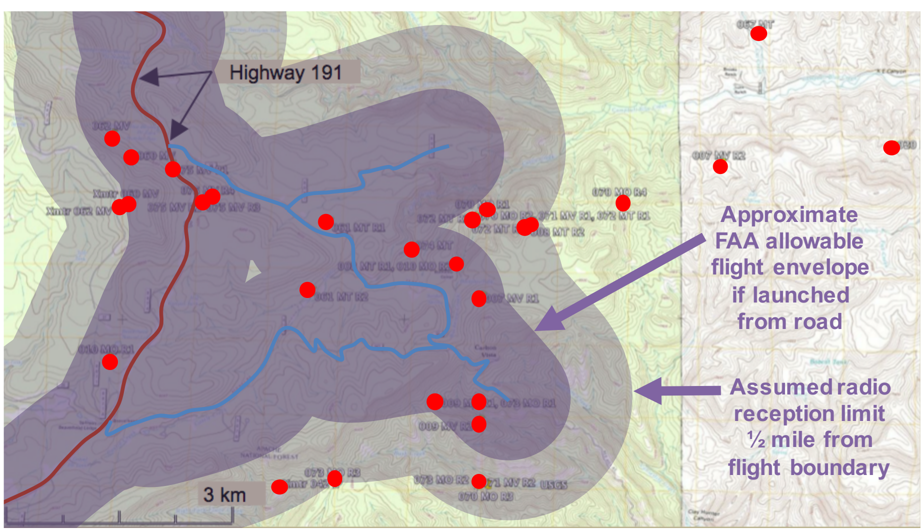


Figure 3: Red pins show bat roosts found on the Apache-Sitgreaves National Forest, 2014. Rugged topography with elevation from 2000-2500 m and one paved road (red line in figure), limits or prevents VHF signal reception, requiring trackers to access high points by climbing to tops of hills or mountains. The large landscape (1000 km^2) and rough terrain created poor ground access with some roosts 5 km from nearest road. Dark purple region shows approximate boundary of UAV flight based on FAA-required "see and avoid" requirement, if launched from a road. Light purple region shows conservative VHF tag reception region of 0.8 km (0.5 mi) from flight boundary limit.

Although the technology for tracking larger animals has changed significantly since the advent of satellite-based systems, tracking small animals will still require manned aircraft searches, that are both costly and a risk to human life. These flights are the most significant cause (66%) of the work-related mortality for wildlife workers in the U.S. (Sasse 2003). Our proposed solution integrates modern micro-UAV and radio technologies to significantly improve the performance and reduce the cost and risks of wildlife tracking.

Many species could be better studied and benefit from the development and introduction of a UAV-RT system. Wildlife research poses significant challenges to field ecologists, especially when study areas are remote and difficult to access or focal species are costly to study. Relatively few wildlife studies have used UAVs and the potential for their use has tremendous advantages over current methods. Some potential applications for small wildlife research include locating animals, conducting animal counts, identifying species, surveying landscapes for potential habitat, and monitoring reproductive success (Jones et al. 2006, Watts et al. 2009). This technology has been applied in wildlife conservation only recently. Researchers in Hawaii recently used a large (20 m wingspan), fixed-wing UAS to monitor the endangered Hawaiian monk seal (*Monachus schauinslandi*) (Iacurci 2014). In Montana, small 2.3 kg UASs are being tested for their effectiveness in surveying osprey (*Pandion haliaetus*) nests to determine nest success and disturbance (Averett 2014). These platforms indicate the tremendous potential of this technology to monitor wildlife while minimizing environmental disturbance and replacing costly and dangerous airplane or helicopter surveys (Martin 2014). Initial studies have suggested minimal disturbance to animals when the UAV vehicles is kept above 100 m (330 ft) (Jones et al. 2006). We have outlined potential use-cases of a novel UAV-RT system in the following sub-sections.

1.1 Use case: Bat habitat relationships

We envision using a UAV-RT to assist in radio telemetry studies of bats (Chiroptera) in remote and difficult terrain in northern Arizona. Although satellite transmitters can relay precise location information from a radio tagged animal to the researcher, the smallest transmitters of this kind weigh 5 g (e.g., the solar-powered Platform Terminal Transmitter PTT-100, Microwave Telemetry, Inc. Columbia, MD). Scientists generally cap the weight of a transmitter to ≤3-5% of the body weight of flying animals (Naef-Daenzer 2001, Aldridge and Brigham 1988, U.S. Geological Survey 2011), limiting satellite-link enabled transmitters to animals larger than 100 g.

Currently, tracking bats with masses of 3 to 60 g requires VHF transmitters. Tags on these animals are limited to 0.15 to 3 g, necessitating small batteries and short life spans (12 to 21 days). Given this, obtaining information for all animals on a daily basis is important to meet sample size needs. During a 2013-2014 study of summer habitat use, we radio tagged 69 bats in the White Mountains of eastern Arizona (see figure 3). To locate 80% of these bats, we used field crews of 4 to 5 people each year, and supplemented their efforts with manned aircraft flights for animals we could not find using ground-based radio tracking. With these resources, we were still unable to find 20% of tagged bats. The lost transmitters and time spent tracking bats represented a substantial cost to the project. In addition, some animals were located up to 5 km from the nearest road in wilderness areas, requiring extended periods of tracking over extremely rough and difficult terrain by field crews (figures 3 and 4). Using conventional radio telemetry tracking techniques, 592 person-hours of field labor were required to find these roost sites after initial tagging, or approximately 19.7 person-hours of tracking per data point. Similarly, a 2013 roost-finding effort required approximately 21 hours of tracking per roost site.

While tracking these animals, we use topographical features to improve signal reception from transmitters; we have found even a 15 m elevation increase with clear surrounding views can improve detection of transmitters by reducing attenuation of the signal through trees and reducing effects from signal bounce. Triangulating on the transmitter signal (using three locations to record compass bearing to signal) can more precisely locate a transmittered bat. Hiking to the tops of hills or mountains is thus required, as it can extend the distance a signal can be detected; however, it is time consuming and may be fruitless if adjacent taller mountains block a signal. A UAV capable of carrying a receiver and antenna that could fly over the forest canopy and local topographic features would greatly enhance the ability to locate the tags. If a UAV-RT system had been available at the time that this study was conducted, the time and cost associated with the determination of each roost site would have been substantially reduced.

In addition to depicting the roost sites collected from this tagging event, figure 3 shows an estimate of where a UAV-RT system could fly if launched from the road, based on current and proposed

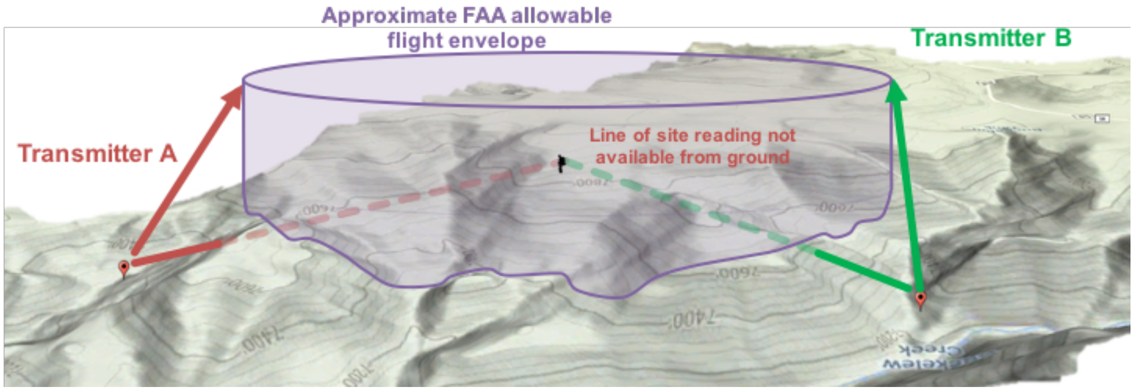


Figure 4: Two roost locations and approximate flight envelope showing coverage of transmitters not available from the ground. Transmitter locations shown are a subset of roosts shown in figure 3. UAV flight envelope allows for measurements of transmitters in a single flight otherwise not available from the ground.

FAA regulations (dark purple region). The figure also shows a conservative estimate for a signal reception boundary based on this flight envelope (light purple region), assuming a half mile reception radius. We have used this conservative estimate due to the extremely rough terrain in the region. Despite this, 85% of the roost sites collected from this tagging event would likely have been accessible from a UAV-RT system launch from a road, which would have drastically reduced the required time and monetary costs. Two of the roost sites from figure 3 are also shown in figure 4, which illustrates how the flight radius and altitude of a UAV-RT system would allow for improved line of sight reception of transmitter signals. This figure also shows how in a single flight, a UAV-RT system could detect multiple tags separated by a significant distance and over rough terrain.

Currently, there is no commercial UAS available for this type of work. Use of a UAS can be safer for biologists (e.g., reduced risk of injury or death from vehicle, plane, or helicopter crashes) as well as less costly and more efficient (i.e., able to cover more terrain quickly and access terrain that is unsafe or impossible to navigate) (Jones et al. 2006). Substantial information can be obtained from UAS flights as low as 120 m above ground; this provides height needed to detect a signal and keeps the receiver in close proximity to the ground. Telemetry locations are more accurate when taken closer to the source (i.e., 120 m vs 300 to 600 m from low-flying airplanes). Though we will use bat localization and tracking as the focal application for testing the UAV-RT instrument, it will greatly improve field studies in a number of other wildlife field research applications.

1.2 Use case: Small avian species studies

The TABER (Technology for Avian Biology and Environmental Research) group at Cornell University has a strong interest in the development of a UAV for detecting wildlife tags, and will be participating in this research program as a collaborating partner, building and testing a UAV-RT system based on the open source plans. As a members of the team, they have provided the following use case for a UAV-RT system.

TABER manufactures small solar-powered (battery-free) tags that emit a short (2.5 ms pulse) digital ID whenever an on-board capacitor is charged (typically once every second). These tags currently transmit at 434 MHz (a frequency dictated by the current RF chip being used), but are being re-designed to run at the more typical 150-165 MHz used by most wildlife tags. Much of the work with these tags is envisioned to occur where fixed base stations are deployed in areas with concentrations of tagged birds, but one of the most promising new deployments is in the detection of dispersing birds: because these tags last for a very long time, it is possible to follow dispersing juveniles that were tagged in the nest, to the sites where they first breed. Finding these dispersed juveniles poses considerable challenges. Much of this work can be performed with classic manned fixed-wing aircraft and crews equipped with yagi antennas on the ground, but the lower altitude and repeated deployment capabilities envisioned for the UAV-RT system offers the advantage of searching for birds in densely forested and highly dissected terrain. Cornell researchers are working on a preliminary plan for work in the rainforest of Kauai on endangered Hawaiian land birds, and the UAV-RT system would be an excellent instrument for this application.

1.3 Use case: Herpetology studies

The Colorado Plateau Research Station is one of four research stations within the U.S. Geological Survey's Southwest Biological Science Center and has a core research effort in wildlife ecology. A member of this group (Dr. Erika Nowak) provided the following use case for a UAV-RT system.

The northern Mexican gartersnake (*Thamnophis eques megalops*) and narrow-headed gartersnake (*T. rufipunctatus*) are federally threatened species for which only three radio-telemetry studies have been attempted (Nowak 2006; Emmons and Nowak 2015; Young, Boyarski, and Cotten 2015). Results from these studies (i.e., winter retreat site use, maximum distance from water) are being used to determine critical habitat requirements. However, these highly aquatic and cryptic species are currently challenging or impossible to locate when foraging in deep or swift water, because researchers are required to wade, swim, or boat to the animal's location. Telemetered adult female northern Mexican gartersnakes were found in water during 8-32% of their locations over a two-year period at two sites along the Verde River, Arizona (Emmons and Nowak 2015); 30% of these locations were in water >50 cm deep, and some locations were in water >2 m deep. Adult female and male narrow-headed gartersnakes were found in water during 18% of their locations over a one and a half-year period in Oak Creek, Canyon, Arizona (Nowak 2006).

On average, we estimate that it takes most researchers 30 minutes to one hour to locate each gartersnake, and longer if swimming or boating is involved. However, especially in deep water, swimming or boating usually results in disturbance of the telemetered individual, biasing assessment of habitat use. Researchers at the Colorado Plateau Research Station are currently conducting microhabitat analyses of northern Mexican gartersnakes at Bubbling Ponds Fish Hatchery (Page Springs, Arizona); they need to locate 20 telemetered snakes every few hours to obtain fine-scale microsite use to aid in future hatchery development and creation of habitat for gartersnakes. Like many other studies, given the resources available, this level of temporal resolution for the required number of individuals has proven to be infeasible with current methods of tracking. Moreover, researcher disturbance to the animal when locating at this frequency is likely to alter snake movements and habitat use, biasing results. Jones et al. (2006) reported no disturbances to wading birds when their internal combustion powered UAV was >100 m (330 ft) above birds; thus this UAV-RT technology has exceptional potential in telemetry studies as a means of obtaining unbiased locational fixes in areas that are challenging or impossible for researchers to reach, and/or in situations where multiple animals must be tracked frequently.

2 Development Plan

The challenges in time, cost, and physical exposure, associated with standard radio tracking methods result in low sample sizes for many field tracking studies. Therefore, we plan to use sample size normalized tracking hours as the performance metric for this instrument development. We expect this system to drastically decrease the time required to initially acquire a radio tracking signal, as well as the time required to triangulate the beacon. This metric is tightly coupled to the ease of use and design simplicity; an instrument that is hard to build, operate, and maintain is antithetical to increasing data collection. Thus system operational simplicity will be a goal for the instrument development as well.

We expect reductions in the size of the error polygons associated with triangulated positions given the improved vantage of a UAV mounted antenna and the ability to move quickly to acquire additional measurements. The accuracy of the position measurements could be an additional metric, but time and cost associated with tracking is currently a more significant barrier to research. The design of the UAV-RT system will therefore be primarily driven by increasing the number of tracking measurements per hour spent tracking.

2.1 Aerial platform selection

The scientific objectives for a UAV-RT system can be met with multi-rotor type UAV. We made this decision by considering mission requirements and payload, in conjunction with vehicle capabilities. Multi-rotor vehicles have a number of distinct design and functional advantages over fixed-wing platforms.

- Fast launch and recovery: Vertical landing and takeoff without the need for runways.

- Payload protection: Many small fixed wing vehicles employed hard/crash landings, dissipating kinetic energy with a frangible vehicle. This would jeopardize antenna systems and is thus not feasible.
- Design/fabrication simplicity: Multi-rotor vehicles are easier to design, build, and repair. Reductions in development time and deployed service costs are critical given the expected user community.
- Loiter/Hover: A radio telemetry system mounted on a UAV would benefit from the ability to spin in place, taking signal bearings and allowing for multiple pulse acquisitions from a fixed location.

In addition to these considerations, we have conducted a comparison of critical performance metrics between fixed wing and rotorcraft. We have compiled performance characteristics of 32 small UAVs, both fixed wing and rotorcraft, similar in scale to the vehicle required here, to assess which platform would be more likely to meet the needs of the research goals. We considered as performance metrics vehicle size (span) vs. payload, vehicle weight vs. payload, and vehicle weight vs. covered distance. The first two metrics are critical for this application; remote field deployments require a vehicle that the flight crew is capable of carrying and deploying by hand. The compiled performance data showed multi-rotor vehicles tend to outperform the fixed wing vehicles in payload per unit span, but are similarly matched for payload per unit vehicle mass. The data also showed that fixed wing aircraft do outperform a similarly scaled rotorcraft in covered distance performance, by about 4.8:1. This advantage of fixed wing aircraft is not needed in our system given the relatively short duration of expected flights and the fact that current and pending FAA regulations require the vehicle to remain close enough to the operator to be visible without the need for supplementary equipment like binoculars. If needed, persistence can be accomplished by landing and exchanging batteries.

2.2 Integrated radio/platform system development

Recent work has elucidated the potential of of UAV platforms for animal tracking, including sequential Bayes approaches for on-line vehicle flight planning (Posch and Sukkarieh 2009, Korner et al 2010) and the evaluation of phased arrays and entropy-based algorithms for searching (Cliff et al. 2015). These research efforts focused on fully autonomous approaches. The instrument we propose here instead complements the knowledge and insights of experienced ground-based human trackers, extending their reach into the aerial domain but without the risks, expense, and logistical complexity of airplane-based tracking. Moreover, our system has operational flexibility with different flight modes and capabilities that allow users to integrate the system as part of their existing operational paradigms.

The proposed UAV-RT instrument carefully integrates three capabilities: the three-dimensional aerial mobility of a multi-rotor UAV, wideband radio front-end integrated circuit technology, and a software radio architecture enabled by high-speed digital processing hardware. In this section we detail an integrated design that exploits the new capabilities made possible by combining a UAV, modern telemetry receiver technology in the UAV-RT, and new vehicle flight modes.

Optimization of bearing estimation. In a typical localization and tracking expedition, trackers drive and hike around the search area. Stops are required so that the receiver antenna can be raised in an attempt to reduce the effects of vegetation and topography on the received signal strength. In many such efforts, trackers hike up local hills in hopes of getting a better signal, at the cost of time and safety.

In the first subtask of this effort, we will perform comprehensive testing of a prototype UAV platform that we have already designed and built (figure 5 inset). The payload of the platform includes a standard handheld telemetry receiver whose audio output is stored and relayed to a ground receiver. We will develop a pop-up flight mode in which the UAV effectively becomes a variable-height virtual pole of up to 150 m (500 ft) that enables the same user control as the baseline hand held system. Using tags distributed in a forest environment, we will perform A/B testing comparing the standard on-the-ground and handheld pole measurements to the new UAV based system to quantify the bearing improvement.

The second sub-task targets significant improvements in performance and usability. A major source of bearing estimation errors is multipath propagation, where radio waves arrive at the receiver antenna via multiple paths due to reflection, diffraction, and scattering. Working in canyons or mountainous areas greatly exacerbates the problem. The paths differ in physical length and thus the signals arrive with different phases. The result is both destructive and constructive interference that changes with antenna location, causing fading (variation) of the received signal strength (RSS) even when the antenna is moved a meter or less (depending on the signal wavelength). The result is that moving closer to the tag can degrade, rather than improve, the RSS, and can significantly affect the time required to locate a tag.

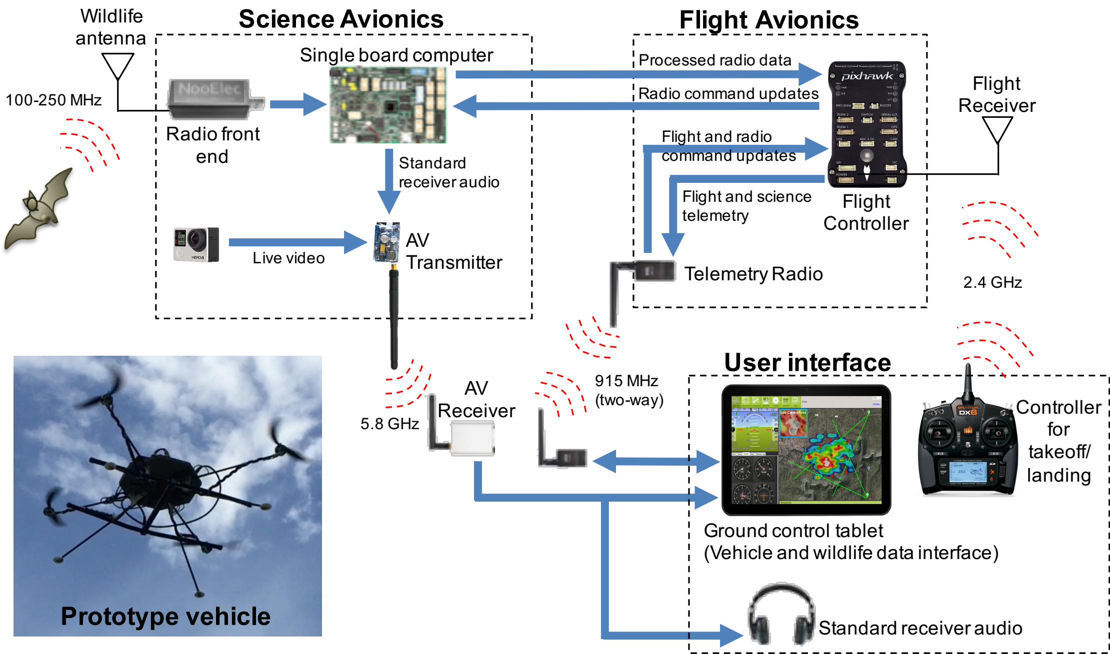


Figure 5: System avionics block diagram showing planned science and flight systems. User interface includes standard receiver audio feedback, UAV controller, and a ground control station for vehicle and wildlife telemetry feedback. Note that ground control station will allow for on-the-fly waypoint adjustments. Inset shows current vehicle prototype with H-configuration wildlife antenna in flight.

The ability of the platform to move in 3D space creates an opportunity to exploit the well-known technique of spatial diversity in wireless communication to mitigate multipath fading. To accomplish this, we will develop new UAV flight control modes in two steps. We will first develop a loiter with stepped yaw (LSY) mode in which the UAV will stabilize at an operator-set position and then dwell at nominally eight different compass directions. While the dwell time at each compass direction will be programmable, we will use a baseline of 5 s to ensure capture of multiple pulses (most tags use an inter-pulse interval of 0.5-1 s). Thus the details of scanning are managed by the UAV, and the received telemetry pulses are now tagged with GPS position and yaw (using an on-board GPS receiver and magnetic compass). In the second step, we will use LSY as a sub-mode in a 3D scan mode where the platform stops at each corner of a cube and invokes LSY. Since the true bearing will change negligibly, the total of 8 spatially-separated samples at each of 8 potential bearings will give a much richer dataset on which to estimate bearings to tags. To refine the estimate, we will employ a two-phased approach, where the first estimate is derived from a classical multiple hypothesis test (one for each of the yaw steps), followed by maximum-likelihood estimation using a slow scan about the winning yaw steps to pinpoint the bearing.

Through experiment, we will optimize performance parametrically, including selection of the number of compass directions, dwell time, and cube size, and again compare performance with the baseline tracker/pole/antenna system. Further refinements will follow, including development of variable-length pole mode that uses the LSY and 3D scan modes at a programmable set of heights.

Multi-tag pulse detection. Typical animal localization and tracking missions deploy a set of tags that transmit pulsed sinusoids at a set of fixed radio frequencies such that the frequency uniquely identifies the tagged animal. Commercially available handheld telemetry receivers are programmed to receive transmissions at the frequency of a specific tag, requiring a serial ('one at a time') strategy for detection and bearing estimation. Our instrument will incorporate a compact and lightweight wideband telemetry receiver that enables simultaneous pulse reception from multiple tags. The receiver consists of two components based on recent technological developments. The first is a flexible radio front-end that covers any desired frequency band for a tag deployment. This radio front-end utilizes single-chip technology that has only become available in the last few years. We emphasize that the particular band is flexible: the wideband radio front end we are planning to use can receive a bandwidth of up to 10 MHz in the range of 24 to 1800 MHz, enabling use with any known VHF tag. As an example, we will cover the 148-152 MHz VHF band in our testing with tags for bat and small bird applications. Initial tests have confirmed that the flexible radio front-end we have selected for use on the vehicle is able to detect standard wildlife tags (see figure 6).

The wideband radio front-end converts radio frequency energy in the desired band to a much lower frequency that can then be processed using the second component, a small single-board computer (SBC) that implements a 'software radio' consisting of programs that together perform the same function as handheld telemetry receivers, but with two important differences. First, because the processing is performed in software, it enables rapid refinement of algorithms for tag reception. The second difference exploits the powerful processing now available in these computers to enable simultaneous capture of pulses from multiple tags. Software based on established signal processing algorithms for this application (Flikkema et al. 1988, Flikkema et al. 1989) can be tuned to the properties of different manufacturer's tags, such as pulse width and pulse repetition rate, an additional advantage.

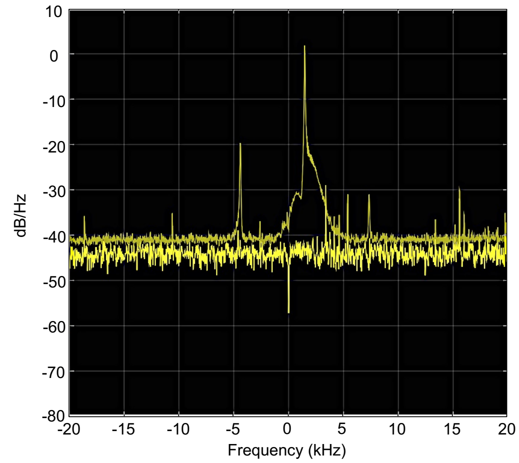


Figure 6: Snapshot of radio-frequency power spectrum of a Holohil 150.327 MHz tag pulse using proposed wideband RF front-end and software-defined radio (SDR). Frequencies are translated to zero (aka baseband) so that 150.327 MHz is shown as 0 kHz. Upper trace (green) shows strong peak at 1.5 kHz containing most of the pulse energy, along with spurious spike (specific to this tag) at -4 kHz. Tag frequencies can drift with age and temperature, shown here as offset of peak by 1.5 kHz to the right of 0 kHz; this drift can be tracked and compensated in software to improve detection performance. Lower trace is power spectrum (of noise) in absence of pulse.

Keeping the human tracker in the loop is a core component of the software pipeline; our design will output audio signals familiar to trackers, so they can quickly assess qualitative performance and compare it with traditional tracking receivers. The conversion of energy from radio to audio frequencies will be functionally equivalent to the hardware used in handheld receivers, but with the additional flexibility (e.g., for tuning and data-stream storage) only available in a software implementation.

We have already demonstrated the core functionality of the approach with a handheld radio and audio capture using a Raspberry Pi SBC on-board the UAV. The wideband radio front end will plug into the SBC via USB. We will use a single-board computer that is significantly more powerful than hobbyist SBCs (e.g., Raspberry Pi) that do not have enough processing power for this application. The selected SharksCove SBC also eases development with its full complement of software needed for the project (see Budget Justification).

Omnidirectional Scanning. After determining the error polygon from multiple signal bearings, researchers are often required to then manually search that region with an omni-directional antenna to determine a more precise location for the tag. The speed, 3D flight capabilities, and range of a small UAV make the integration of multiple measurements possible, allowing a UAV-RT system to effectively scan a triangulated error polygon for the precise animal location. We plan to allow users to exchange directional yagi-type antennas for omnidirectional antennas, and deploy a "signal-localization" flight mode. This flight mode will stream tag signal intensity to the ground control station, which will process and graphically display signal intensity to users (see conceptual interface in figure 7). This operational mode will allow users to visualize signal hotspots during flight to identify likely areas of tagged location. This basic functionality will allow for novel search algorithms to be deployed as part of the automated vehicle flight modes, such as gradient search methods for highly accurate automated tag localization.

2.3 Avionics and mission planning

The flight controller and mission planning for the UAV-RT system will be based on the open-source ArduPilot Mega (APM) platform for its ease of use, extremely low cost, and existing user community. Using open source software will reduce the upfront cost to users while allowing for customization of the

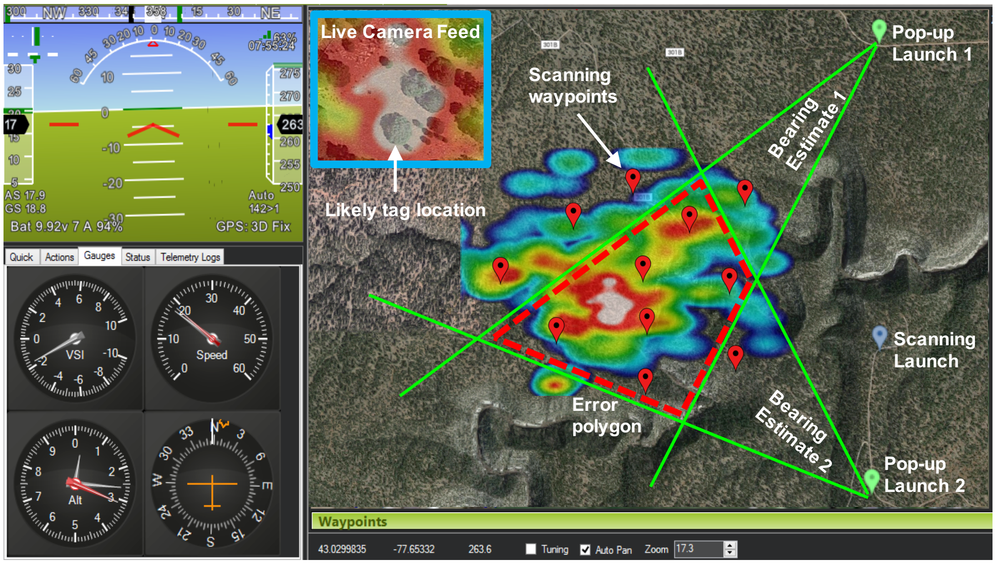


Figure 7: Planned user interface built as add-ons to open-source ground control software such as Mission Planner or APM Planner. Pop-up launch bearings plotted and heat-map from omni-directional antenna scanning flights. Live camera provides users with view of potential tag location.

system. We have previously used the commercially available PixHawk flight controller running the APM:Copter controller. The PixHawk hardware allows for the attachment of peripheral sensors and interaction with a payload computer. The firmware has a number of preinstalled flight modes such as Stabilize, Loiter, Return to Launch point, etc. Additional new flight modes that will be developed for this application, such as LSY (Section 2.2), can be easily created and added to the existing list of flight modes. In addition to meeting the basic requirements of the UAV-RT system, the APM platform could be interfaced with the payload computer to close the loop, providing semi-autonomous, and eventually, autonomous flight planning based on data received from the wildlife radio telemetry.

We will also employ an associated free and open source mission planner/ground control software such as APM Planner or Mission Planner. These software allow for mission planning (e.g., GPS waypoints, altitude selection, vehicle orientation) in the office, in the field, or during flight. Versions are available for Windows, Mac, Linux, Android, and iOS operating systems, which will allow users to deploy the system using existing computers or mobile devices. We plan to develop modules for the open-source ground control software that will allow users to visualize real time radio tracking data received from the vehicle (see figure 7). Together with the Pixhawk controller, the APM platform provides an easy to use, low-cost, flexible, and proven flight control platform suited to the requirements of the UAV-RT system.

2.4 Mechanical Design

We propose to develop a simplified, purpose-built vehicle rather than adapt a commercially available hobby-type RC aircraft. Currently available commercial vehicle designs are subject to significant design changes over time and are not designed for the unique requirements of isolated field deployments. Additionally, the risk of igniting wildfires can be mitigated by proper material selection, battery protection, and vehicle configuration not included in commercial vehicles. A purpose-built vehicle also affords the ability to integrate the science payload avionics with flight controller waypoints and vehicle operation for the deployment of closed-loop search algorithms. The cost to build a vehicle is significantly less than the cost associated with pre-fabricated systems. This may be an important factor in broad instrument adoption for university research groups that are financially constrained, but have students available for vehicle assembly. Finally, familiarity with the system design and methods of fabrication invites customization and continued innovation from the user group beyond the term of this research program.

We plan to deploy a quad- or octo-copter as shown conceptually in figure 8. Emphasis in the design will be placed on minimizing fabrication complexity, while maintaining a system that is robust to repeated field deployments. Figure 8 shows a system that is collapsible for ease of packing and

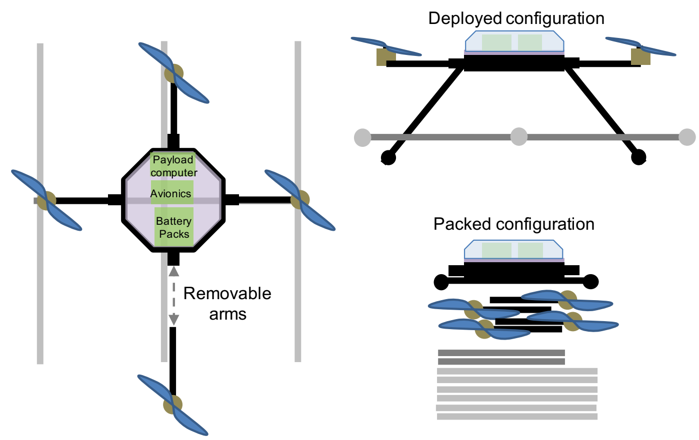


Figure 8: Conceptual vehicle configuration with break-down features for easy packing during field deployments.

deploying. The UAV-RT systems will be designed to be built and maintained by their ecologist users. Therefore the mechanical components will be designed to be easily fabricated with standard tools. The design simplicity of multi-rotor vehicles will help to ensure this design goal. The ubiquity of 3D printing machines and service providers will allow for any complex geometries to be printed rather than fabricated by the user. Any part that cannot be fabricated using standard hand tools will be designed as a 3D printed part, and the associated models will be available for download. The prototype shown in the figure 5 inset required approximately six hours to build and this will be reduced further with design refinements.

Electromagnetic interference and reflection from the vehicle structure will be minimized with shielding and material selection as needed. Although the wildlife radio tracking antenna could be incorporated as part of the vehicle frame to reduce overall configuration complexity and vehicle mass, this would couple tracking tag frequency to vehicle design, and may be infeasible for a broadly deployed design. Depending on the final configuration and selected components, flight and payload avionics may need electromagnetic shielding to reduce interference with the wildlife telemetry antenna and receiver. Initial tests on the prototype systems have shown no electromagnetic interference from the vehicle or a Raspberry Pi computer in the band from 100-250 MHz.

Small UAVs store energy within their batteries, and dissipate significant kinetic energy during a crash event, both of which create serious risk of fire. In 2012, a Navy RQ-4 UAV started a wildfire on Maryland's Eastern Shore (Whitlock, 2014). Given the intended use of these vehicles in remote and arid/semi-arid study environments, wildfire prevention must be a consideration in their design and operation. This currently is not considered in commercial systems. We plan to holistically approach the vehicle design and operational standards for this system with consideration to fire prevention and mitigation during a failure event. The design features will include a multi-tiered approach that should provide multiple levels of risk mitigation. As part of this approach, we plan to develop/incorporate the following features: Vertical/soft landing to minimize risk to batteries; Radio link failure contingencies will change vehicle flight mode to "return to base" if radio link is lost; Use of battery power will eliminate internal combustion engines; Battery protection for primary flight batteries will protect against both punctures and blunt impacts; Fast vehicle recovery in the event of a crash will be enabled by the radio link between the vehicle and the ground station, providing live vehicle GPS positions; A fail-safe parachute system will reduce energy on impact in the event of system malfunction; Material selection will reduce the likelihood of sparks during an impact event. Informed users will be created through information provided on the system website, including where to obtain fire extinguisher training and suggestions on who to inform prior to flights (i.e. local fire departments and/or wildland fire crews).

2.5 Regulatory environment

Within the United States, unmanned aerial systems are regulated by the Federal Aviation Administration (FAA). Depending on for whom they are being operated, the vehicle is considered to be a Public, Civil, or Model aircraft. Currently, most research using UAV platforms would be classified as Public or Civil depending on the institution carrying out the research. Under this classification, the current FAA regulations requires operators to file a *Section 333 Exemption*, *Special Airworthiness Certificate,* or *Certificate for Authorization (COA),* depending on the vehicle classification. These authorization procedures can be laborious, and are recognized as temporary measures until final rules are approved.

On April 24, 2015, the FAA closed the comment period on the new draft rules for small (<55 lbs/25kg) UAS operation within the U.S (Federal Aviation Administration 2015 - Docket No.: FAA-2015-0150; Notice No. 15-01). In summary, the rules do away with the previous methods of certifications (COAs, Section 333 Exemptions, etc.) to fly for public and civil entities, but do require a standard certification process for UAV operators. Despite the required training, the new rules will make it significantly easier to fly. We have reviewed these draft rules (https://www.faa.gov/uas/nprm/) and found that the system we plan to develop would comply. The parts of the proposed regulations that would affect the operation and/or design of the UAV-RT system include: vehicles less than 55 lbs (25 kg); operator able to maintain visual line of sight to the vehicle; day-time operation only; maximum speed of 100 mph; maximum altitude of 500 ft above ground level; operational limits depending on airspace classification.

The proposed rules include operator certification requirements. These include passing an initial aeronautical knowledge test at an FAA-approved testing center. This test would be similar in style to those test taken by manned aircraft pilots, but would be more limited in scope. The operator would also have to be vetted by the Transportation Security Administration, be at least 17 years old, and pass a recurrent aeronautical knowledge test every two years. This limited set of mandates on operator certification would make it relatively easy for research institutions operating a UAS to maintain a certified operator. The FAA currently estimates the total cost of the knowledge test, TSA and identification vetting, and FAA registration costs at approximately $4500-7000, depending on if opportunity costs are included.

Although these rules are not currently approved, the comment period on them has closed. It is extremely likely that these rules, or some derivative thereof, will be in place well before the third year of this IDBR program when the public launch of the open source plans would occur. Any outdoor operations required for development purposes after the start of this research program, but before the implementation of these new rules would require a COA. NAU has obtained two COA's in the past and we do not expect problems obtaining an additional COA for this program if necessary. Extensive indoor testing of the vehicle can occur without a COA inside NAU's Skydome arena (97,000 ft^2/9000m^2, 142 ft/43m ceiling).

3 Management Plan

The research team selected is reflected by the five major goals of this IDBR program. These goals are:

1. Vehicle design and testing
2. Radio system design and testing
3. Education and outreach
4. Instrument dissemination
5. System integration, field testing, and capability enhancement verification

Each of these tasks involves one or more members of the research team. The engineering portion of this team includes one mechanical and one electrical engineering graduate student and their advisors (Drs. Michael Shafer and Paul Flikkema). A computer science student will also be included to develop data graphics modules for the user interface. A wildlife ecologist (Dr. Carol Chambers) is also a member of the team, and will consult the team on requirements of field equipment and help to verify the system efficacy upon design completion. We also plan to incorporate a outreach and dissemination coordinator as part of the team. Ms.Karin Wadsack has an extensive background in educational outreach to the native communities on the Colorado Plateau. She will coordinate the program's outreach, as well as oversee the implementation of the open-source dissemination efforts. Finally, we have included a user testing team at Cornell University to help provide feedback on open source plans and help disseminate the UAV-RT system to a broader community. In this section we have included details of the major technology development tasks (1, 2, and 5). The details surrounding the *Education and Outreach* and *Instrument Dissemination* tasks are presented in sections 4 and 5, as per the program solicitation guidelines. A detailed schedule of tasks can be seen in figure 9.

As part of the system design, year one of this IDBR program will begin with an assessment of feature needs beyond the core functionality detailed in this proposal. We plan to meet with wildlife ecologists with research areas spanning multiple species in order to assess other design features that may further increase data collection efficacy. Core and peripheral functionality will be translated into engineering design requirements (e.g., mass, size, radio sensitivity, tag frequency targets). Depending on the state of FAA regulations, the process to obtain a COA for tests flights may be initiated during this period as well.

The mechanical team will focus efforts in year one on developing an initial prototype design for system testing in year two. To decouple mechanical design efforts from radio system development, existing in-lab vehicles (figure 5 inset) will be used for any early radio system deployment testing. Mechanical design efforts will involve propulsion system sizing and testing. Finite element analysis and mechanical proof testing of components will be conducted to ensure system performance during harsh field deployments. Rapid prototype models will be used for testing the ease of assembly and packing of the vehicle for field deployments. The mechanical engineering student charged with system design will also serve as the vehicle operator, receiving the training and certifications required to fly from the FAA. Year two of the mechanical team effort will be focused on radio system integration, vehicle testing efforts, and improving vehicle designs based on testing results. Year three will continue this effort, but efforts will be shifted toward developing assembly and operational guides for the open source system website.

Our testing will characterize the performance of the system with respect to its ability to reliably detect tag pulses and its ability to accurately and precisely estimate bearing to the tag. For detection, our testing will enable us to refine threshold values to maximize the probability of detection given a maximum false alarm rate. We will measure sensitivity and false alarm rate as a function of distance at different altitudes, with comparison to the performance of handheld receivers. We will assess the bearing estimation performance similarly, with particular attention to optimizing the parameters of dwell time and cube dimension for the Loiter with Stepped Yaw flight mode. Further testing will characterize the system's ability to find tags using the nulls in antenna directivity, as is currently used in aircraft-based tracking. For both detection and bearing estimation, performance will be compared with that of human trackers with handheld receivers.

Radio system testing will be conducted in three stages. Year 1 will be dedicated to laboratory testing, with focus on sensitivity and sensitivity/false alarms, and ensuring the capacity of the system to capture pulses from multiple tags. Multiple engineering tests will be conducted in year 2 while the final design is being refined. To enable ground truthing (e.g., true bearings will be known), these tests will use multiple tags placed in known locations in open and forested environments. In year 3, we will use our system in formal testing conducted in tandem with human trackers in bat tracking field trips, and gather both quantitative and qualitative performance measures (including feedback from trackers).

Tests of system efficacy in year 3 tests will require bats to be tagged using standard techniques. Bats will be captured at water catchments located in ponderosa pine forest and a subset of individual bats will be radio tagged. At most, 3 bats will be radio tagged from each catchment because bats can share roosts and we want to avoid locating the same roost, and maximize the number of locations to be found using the UAV-RT system. Although bats can move daily to new roosts, the mean number of roosts an individual uses is ~1 per week (Bernardos et al. 2004, Solvesky and Chambers 2009), so we can test the UAV-RT system daily or several times during the period a bat has an active transmitter. Technicians will confirm locations of roosts identified using standard tracking techniques. The ground crew will also

	Year 1				Year 2				Year 3			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Vehicle mechanical design and prototype model testing	X	X	X	X								
Science payload/radio system development	X	X	X	X	X							
Student operator training/certification or FAA COA application		X										
Vehicle/Radio system integration				X	X							
Tag search mode flight path development testing				X	X	X	X					
Outdoor beacon search testing					X	X	X					
Outdoor beacon search system efficacy testing							X	X				
Website development							X	X				
System design iteration/finalization								X	X			
Website content creation and public release								X	X			
Cornell student operator certification									X			
Cornell vehicle build and testing									X	X		
Cornell system design, fabrication, operational feedback.									X	X		
System efficacy testing (bat tagging and tracking)										X		
Website updates										X	X	X
Design, fabrication, operation plans updates										X	X	X

Figure 9: Project schedule

confirm all roosts to determine errors in location. We will compare the difference in location (latitude, longitude) between roost locations identified using the UAV-RT system versus the ground crew, and assess required person-hours per roost as a metric of system performance.

4 Dissemination Plan

The relative simplicity of the UAV-RT system design, fabrication, and operational methods will allow the system to be open-sourced, significantly decreasing monetary costs and time required for adoption of the instrument by the user community. Moreover, an open-sourced system encourages design modification and customization at the user level, which effectively crowd-sources future instrument innovation. We plan to sow the seeds of this technology by providing a website and user forum that will serve as a foundation for instrument dissemination and future user innovation. Additionally, we plan to present and demonstrate the system at wildlife conferences to increase system visibility among potential users.

Unlike other instruments, the UAV-RT can be built, operated, and repaired by its users. We will develop a website devoted to the dissemination of the entire vehicle, from mechanical fabrication to regulatory information. This website will be built by a professional web developer in years two and three. Core website content will be provided by the students designing and operating the vehicle. The outreach/dissemination coordinator, Ms. Karin Wadsack, will refine the content provided by students and assist the web developer to ensure the website product is a professional and useful tool for users.

On the website, we plan to offer users the mechanical and electrical assembly plans, parts lists, software and firmware downloads, operational tutorials, and information related to FAA regulations and safety. Regulatory information will include digested versions of current FAA regulations, such as airspace and altitude restrictions, and how users can get certified as UAV operators. We will also include guides to novel methods of tracking enabled by the new technology. Designs of mechanical system components will be conveyed with detailed part drawings and CAD files. The CAD files will be published as universal STL files for direct 3D printing, but the original SolidWorks files will also be available for download, which will allow users to customize the design. In addition to parts and plans, the UAV-RT website will include a user forum, wherein users can post question that can be answered by the research team or the user community. Finally, we plan to present the system with tiered functionality, allowing users to build and familiarize themselves with the most basic flight and data modes, before requiring their understanding and use of the more advanced features, such as the omni-directional scanning modes.

We recognize that the development of a website does not ensure visibility of the system among the vast potential users. A vigorous and continued outreach campaign will occur during the term of this program to users via presentations at a number of wildlife conferences. Co-PI Dr. Carol Chambers and Dr. David Winkler (Senior Personnel) regularly attend the annual conferences of The Wildlife Society and the American Ornithologists' Union. Team members will attend these or similar conferences, presenting the system design and research results, while providing attendees with information on development of their own UAV-RT system. International visibility of the system will be accomplished by the regular attendance of Dr. David Winkler at the International Ornithological Congress and Neotropical Ornithological Congress. To inform and engage regional researchers, we are organizing a conference session at the Merriam-Powell 2015 Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region. This session will focus on current and potential uses of UAVs in the region, and we plan to work with conference organizers to host a similar session at the fall 2017 conference.

5 Education and Outreach

In addition to the scientific impacts of this research, there will be a significant outreach and educational component to this project. Located in the American Southwest and near multiple Native American populations, Northern Arizona University has a diverse student population and a strong history graduating members of underrepresented communities. As such, this project has a high probability of including underrepresented populations in STEM fields. Our education and outreach efforts are three pronged, targeting the general public, underrepresented high school students, and multidisciplinary student training.

Given the novelty of the technology, the general public is not generally cognizant of the many research applications and potential benefits of scientific small UASs. We plan to engage the local and regional community through special events and popular media. We have participated for several years in the Flagstaff Unified School District STEM nights and the Flagstaff Festival of Science, which attract hundreds of participants each. We will develop an educational booth for these events to inform the public about the use of small UASs and their implications across scientific communities. We have found that in the past, topics such as ours that blend wildlife and technology are extremely popular. We will also continue our public outreach efforts through pieces in popular media outlets as we have done in the past: Popular Science (Litchman 2014); Local public radio station show “Brain Food” (Stevens 2014); Phoenix, AZ NBC news affiliate reports (Energy taking flight 2014).

We also will participate in summer residential short courses and in-school activities for high school students in the Upward Bound Math & Science program at NAU. These outreach efforts will rely upon demonstration modules and hands-on activities for students. The Upward Bound Program uses 4- and 5-week residential summer programs and in-class activities at four of the region’s rural high schools to engage low-income students and students whose parents did not earn a college degree. Dr. Shafer was an instructor for this program as an undergraduate in the summer of 2003 and has met with the Upward-Bound program directors about developing content for their programs.

Finally, this research will provide training for engineering graduate students. The electrical and mechanical students involved will be required to work closely together to develop a cohesive instrument. This interdisciplinary project will expose the students to practical and analytic research methods outside their core discipline.

6 Results from Recent Prior NSF Funding

Flikkema: **Award number** DBI-1126840**. Amount:** $2,471,913 from 10/1/11 to 9/30/15 and Supplement ($370,000 from 10/1/13 to 9/30/15)**. PI** Whitham**: co-PI’s** Cushman, **Flikkema**, Koch, & Whipple**. Title of the project:** MRI: *Development of a Southwest Experimental Garden Array for Integrating Genetics and Climate Change***.** SEGA (Southwest Experimental Garden Array) is a multi-investigator facility for examining the effects of climate change on plant communities and ecosystems. *Intellectual Merit:* Experimental garden sites along an elevation gradient with average annual temperatures from 2.4 to 14.5°C serve as temperature treatments. In this and previous NSF-funded research, we have developed self-organizing wireless sensing and actuation networks, the streaming data middleware to interconnect them, data storage/retrieval infrastructure, visualization tools, and modular software for stream processing that together support distributed real-time experimentation. This project builds on previous projects, yielding expertise in sensor/actuator network technology (Yamamoto et al. 2010) for environmental monitoring and data analytics (Clark et al. 2011, Ghosh et al. 2014) that has been further developed for SEGA (Flikkema et al. Nov. 2012, Flikkema et al. Dec. 2012). The developed CI uses open-source streaming data middleware (Shaeffer et al. 2014, Knapp et al. 2014). Supplemental award for additional development and student training in streaming middleware-based distributed real-time systems. *Broader Impact:* Undergraduate students trained on this project: Chris Porter, Nicholas Rowe, Aiden Shef, Chihiro Sasaki, James Shaeffer, JD Knapp, Michael Middleton, Jonathan Pepper, and Jeremy Anderson.

Shafer**:** **Award number** DGE0707428. **Amount:** $132k. **Period of Support**: 06-2011 through 08-2013. **Title of the project:** NSF Graduate Research Fellowship Program. **Summary of the results and accomplishments:** *Intellectual Merit:* Dr. Shafer’s NSF graduate fellowship focused on energy harvesting for wildlife biologging and tracking applications. Specifically, he worked with the Cornell Laboratory of Ornithology on assessments of how vibrational energy harvesting could be used to extend the lifetime and capabilities of avian biologging tags. He studied piezoelectric energy harvesters, with regard to their ideal design and limits, as well as avian energetics. Key findings included: -Nearly all birds have sufficient energy output to enable piezoelectric energy harvesting tags. –The flight gaits of birds are conducive to excitation of piezoelectric energy harvesters. –Analytic power and efficiency maximization methodology for piezoelectric energy harvesters. –Demonstration of negligible bird flight gait effects from attached energy harvesters. *Broader Impacts:* Dr. Shafer supervised a number of undergraduate researchers including underrepresented populations during the period of award. Additionally, he worked with the Cornell Lab of Ornithology on the development of web-based video modules on sustainable systems engineering. During the period of this award, he also presented at an elementary school on engineering design methods. **Resulting Publications:** (Shafer and Garcia 2011; Shafer, Bryant, and Garcia 2012; Shafer 2013; Shafer, MacCurdy, and Garcia 2013; Garcia, Shafer, Bryant, Schlichting, and Kogan 2013; Shafer and Garcia 2014; Shafer et al. 2015)