

# GPS Jammer Localization Using Unmanned Aerial Vehicle

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## **ABSTRACT**

The aviation industry has and continues to benefit tremendously from the efficiency and safety improvements provided through the prevalence of GPS technology. However, as GPS technology becomes more ubiquitous and relied upon for all phases of flight, the potential risk posed by GPS jamming devices increases. In an effort to combat these risks and mitigate the effects of interference in the vicinity of an airport, this paper presents the design of a system called Jammer Acquisition with GPS Exploration and Reconnaissance (JAGER) which is an multirotor unmanned aerial vehicle (UAV) sensor platform capable of rapidly and autonomously localizing the source of a jamming device.

The urban environment near many major airports poses a challenge for quickly localizing a jammer through ground based methods. Our approach to localization uses a UAV as a mobile sensor platform operating well above the noise and multipath rich environment near the ground to make bearing observations of the jamming signal at dynamically chosen positions in order to optimally locate the source of the jammer.

The three main elements making up the system to localize a GPS jammer described in this paper are the sensing and measurement system, the path planning system and the navigation system. For sensing and measurements, JAGER relies on the maneuverability of the multirotor platform to be able to use simple antenna configurations, such as a directional antenna, to determine the bearing to the signal source from specific locations. Using the bearing observations, a closed loop

navigation controller determines the next action to most quickly locate the source of the jammer.

Using bearing observations, JAGER is able to use different path planning methods to determine the best route for localization of the jammer. In this paper we will describe and show experimental results of the use of two different path planning methods: a simple greedy method following the direction of strongest signal and a more complex approach that models the problem as a partially observable Markov decision process (POMDP) which results in a near optimal path for localization. The benefits and challenges faced by each of the different methods will be explained for different jamming scenarios including multiple or moving jammers.

In addition to localizing the GPS jammer, the navigation system must be able to successfully navigate in the GPS denied environment. Our approach to denied navigation with JAGER is to leverage vision, low cost inertials and the many signals of opportunity present near an airport to navigate in the denied environment in and around the jammer.

JAGER is a fully integrated mobile sensor platform capable of autonomously locating the source of a GPS jammer in the urban environments present near many major airports designed to quickly mitigate the risks posed by a GPS jammer placed in the vicinity of an airport.

## INTRODUCTION

The concern over radio frequency interference (RFI) of safety critical applications is not a new one. The vulnerability of GPS to jamming has already led the Federal Aviation Administration (FAA) to pursue different technologies for RFI detection and localization [1].

To help mitigate the risks posed by GPS jammers, we are developing an unmanned aerial vehicle (UAV) capable of autonomously localizing the source of a GPS jammer. The system we are developing, JAGER (Jammer Acquisition with GPS Exploration and Reconnaissance), is being designed with a target application of supporting airports in localizing sources of jamming that could interfere with airport operations and pose a threat to the safety of commercial aviation.

## Existing Solutions

An existing solution of note to localizing RFI sources is the Aircraft RFI Localization and Avoidance System (ARLAS), which used a small, manned airplane with a patch GPS antenna on the roof [2]. Using this antenna, and the banking motion of the aircraft, ARLAS was capable of creating a bounding area of the source of RFI from determining at what regions the roof mounted GPS antenna picked up the interference.

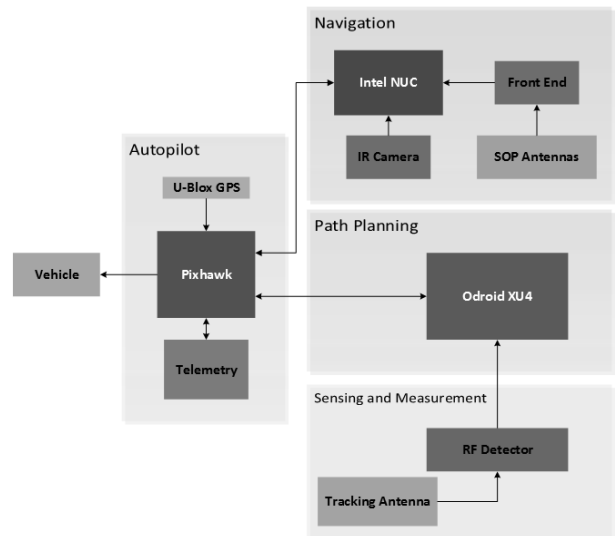
ARLAS unfortunately suffers from coupling between sensing and navigation, meaning that in order to make a measurement, the plane needed to bank and therefore change the trajectory of the aircraft. This coupling leads to tradeoffs between trajectory and sensing, leading to longer search times.

**JAGER**

Our approach to the jammer localization problem uses a multirotor UAV to be able to quickly navigate and sense its environment for rapid localization. JAGER is built on a commercially available octocopter platform, the DJI S1000, which has been modified to be a test platform for various systems, including the one presented in this paper [3]. For localization of a GPS jammer, the vehicle is equipped with several different subsystems, illustrated in Figure 1.

At the autopilot system's core is the open source Pixhawk autopilot system running the PX4 firmware that has been modified to work with the path planning and navigation systems to autonomously execute the desired path and measurements [4]. The path planning system is comprised of an Odroid-XU4 ARM based computer that is the decision making heart of the system. It processes all the sensor measurements, makes the high level decisions for the next observation location and reports the location of the jammer when finished. Finally, the navigation system will be using infrared imaging and signals of opportunity processed by an Intel NUC computer at its core. This system processes all the imaging and signal of opportunity to

determine an estimate for JAGER's location, which is fed to the autopilot system to assist with the autonomous navigation.



**Figure 1. JAGER System Diagram.**

Through the use of an agile, multirotor UAV, we hope to overcome the limitations posed by existing RFI localization techniques. The airborne nature of a UAV allows it to fly well above the noise that can plague ground based systems, and the ease of rotation of a multirotor can be leveraged to make measurements and observations without having to alter its flight path. This solution also aims to be easier to deploy, have a lower cost, and provide faster response times than a manned system.

## SENSING AND MEASUREMENT SYSTEM

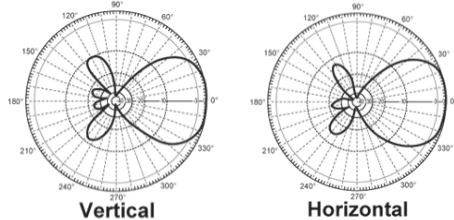
The primary observation that is used in the path planning system is the bearing to the jammer, however in order to determine bearing, we need signal strength measurements. Therefore the primary sensor onboard JAGER is a directional antenna and radio capable of measuring signal strength at a given heading. With a collection of signal strength measurements generated by rotating at a specific location we can recreate the gain pattern of the antenna, which can then be used to determine the bearing to the signal source.

In this section, the antenna configuration and sensing equipment will be described along with several different bearing calculation methods and their different advantages and drawbacks.

## Sensing

Signal strength measurements of the jamming signal are made with a directional antenna and a radio frequency (RF) detector. In flight testing, due to legal constraints, a Wi-Fi router has been used a proxy for a GPS jammer, therefore in this case the antenna is a directional WiFi antenna and the signal strength measurements are being

made with an RN-XV WiFly module capable of returning the received signal strength indicator (RSSI) value. However, the frequency of operation makes no difference to the resulting methods of calculating bearing from a set of measurements, therefore when JAGER will be tested with GPS jammers, the same methods will be used. Currently, the directional antenna being used has a beamwidth of about 60 degrees and a true gain pattern as shown in Figure 2.



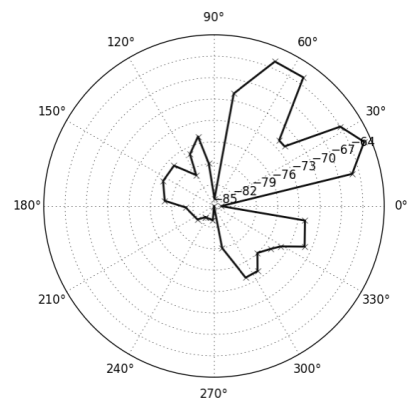
**Figure 2. Directional Antenna Gain Pattern [5].**

The antenna is mounted like shown in Figure 3 on JAGER. This allows maximum forward field of view, but does create an empty region just below the vehicle. However, this void below the vehicle is not a concern as one of the goals of the navigation system is to avoid approaching the jammer more than is necessary to minimize operational time in the GPS denied environment, therefore getting a maximum field of view outwards is more advantageous.



**Figure 3. Directional Antenna Mounted on Underside of UAV with Antenna Main Lobe Shaded.**

The orientation of the antenna creates three different classes of measurements based on the distance to the jammer: near, ideal and far. When near the jammer, measurements are very noisy and therefore the resulting gain patterns are nearly unusable. In the ideal case we get gain patterns that look almost identical to the true gain pattern, which result in very good bearing estimates. Far from the jammer, we are limited by which of the bearing calculation methods we can use, and the precision is also reduced. Finally, beyond the sensitivity of the sensor, we get no valid measurements.

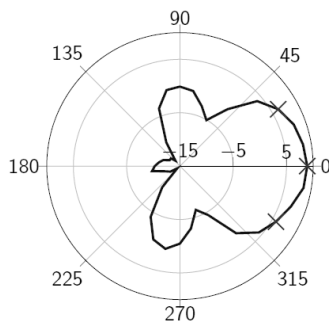




**Figure 5. Signal Strength Measurements at Various Bearings and Distances.**

### **Bearing Calculation**

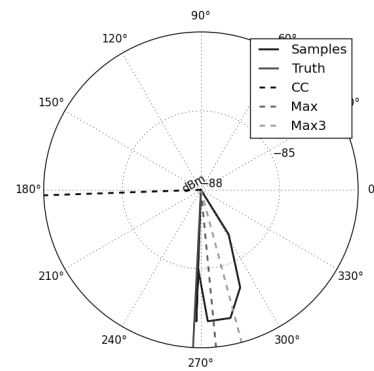
Given a recreated gain pattern, two different techniques have been used to be able to calculate the bearing to the signal source. The first method is a modification of simply using the heading of the maximum received signal strength as the bearing, which has been used on UAVs in prior research [7]. The modification used here, a method we call Max3, smooths out noise along the main lobe of the gain pattern by determining the bearing to be the halfway point between the two -3dB crossing points of the gain pattern (this is the point where the main lobe begins to drop off quickly) [8]. These points are illustrated in Figure 6.



**Figure 6. Depiction of Max3 Bearing Method.**

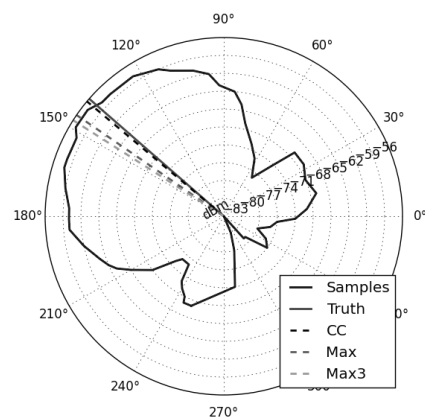
The second method used is cross-correlation, which compared the measured pattern with a known “truth” pattern for the antenna. This method has also been used previously to determine bearing on a rotating robot in previous research [9].

The main disadvantage of cross-correlation is that the reliance on a known gain pattern makes it more difficult to get accurate bearings very far from the signal source. Far from the jammer, the gain pattern created, shown in Figure 7, no longer resembles the true gain pattern. At these distances the Max3 method performs significantly better.



**Figure 7. Measured Gain Pattern Far from Signal Source.**

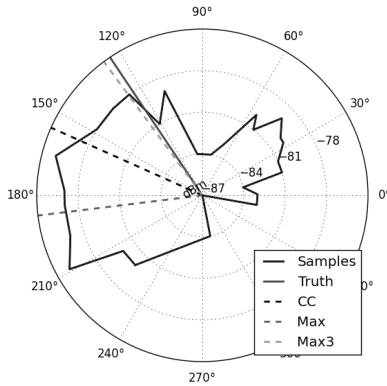
However, at ideal distances from the signal source, both method perform very well, an example which is shown in Figure 8. In this case the advantage with cross-correlation is that it is able to provide a cross-correlation coefficient which is a measure of confidence in the calculated bearing. This provides additional information that can be used in the path planning system.



**Figure 8. Measured Gain Pattern at Ideal Range from Signal Source.**

Overall these methods of determining bearing from a set of measurements have proven to be sufficiently accurate to be able to quickly localize a signal source. Both of these methods, at an ideal distance, have standard deviations of about 13 degrees, and far from the signal source, the Max3 method still fairs decently with a standard deviation of about 22 degrees.

Near the signal source, both bearing determination techniques suffer greatly due to the noise of the measurements, shown in Figure 9. As will be shown later in the path planning section, this greatly affects the decisions made by the POMDP based path planner, as it strives to avoid the areas near the signal source, where it will not be able to get reliable measurements.



**Figure 9. Measured Gain Pattern Near Signal Source.**

## **PATH PLANNING SYSTEM**

JAGER's path planning system focuses on determining, in real time, the next best location for making a bearing observation. Given that each observation provides information to the location of the signal source, getting the right collection of observations allows JAGER to localize the signal source as quickly as possible.

In this section of the paper, the partially observable Markov decision (POMDP) based method used by JAGER will be demonstrated and motivated by the performance of a simple greedy method for path planning.

### **Greedy**

In order to establish a baseline for comparison, a simply greedy method was used as a path planner. This method is the closest approximation to how a human might do localization: keep moving forward in the estimated bearing direction until you pass the signal source and the bearing becomes the other way around. Now because we don't have continuous bearing observations, and JAGER must stop to make those measurements, we take this approach and discretize it into a set of steps. To make some slight improvements in the method to speed things up, we used a variable

step between the observations. This means that the algorithm will move in the direction of the calculated bearing with a variable step size. The step size used is determined using equation 1. In this equation,  $\delta$  is the tolerance in bearing similarity,  $\alpha$  is the step increase factor,  $s$  is the step size and  $b$  is the calculated bearing.

$$s_{i+1} = \begin{cases} \alpha * s_i & \text{if } |b_i - b_{i-1}| < \delta \\ s_0 & \end{cases} \quad (1)$$

As can be seen, this effectively increases the step size by a factor of  $\alpha$  if the current and previous observations are within some tolerance. Or more intuitively, if the signal source is still in the same direction last time we checked, then keep going in that direction and go even further before making another measurement as we are surely on the right track.

The baseline was able to successfully localize the signal source consistently in all of the flight tests performance. An example flight path taken can be seen in Figure 10. This method takes on average 4 steps to reach the vicinity of the jammer, and then another 4 or 5 steps to be able to crisscross the signal source's location to have a reasonable certainty that the signal source is at that location.



**Figure 10. Flight Path of Greedy Path Planning.**

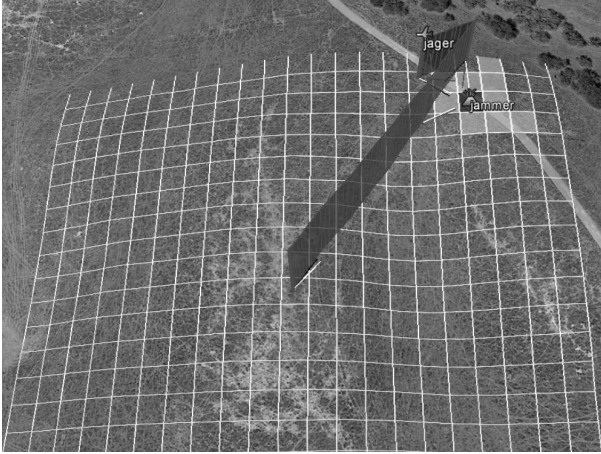
## **Partially Observable Markov Decision Process**

The more optimal method of localization is based on a partially observable Markov decision process (POMDP). The POMDP takes in a set of observations, and from that create a belief distribution for where the signal source could be. From here, the algorithm determines the optimal action, which in this case is where to make the next observation. This process is repeated online until the jammer has been successfully localized.

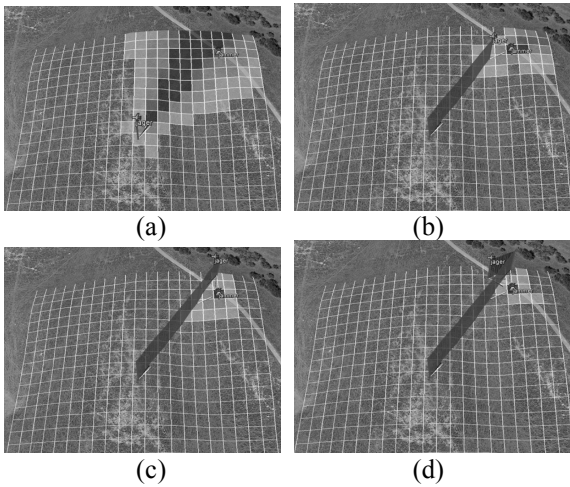
For this method, the world that the vehicle is operating in needs to be discretized into a grid. The grid that is used is one with cells 10 meters on a side, as being able to localize the signal source within a 10x10m square is

enough to be able to greatly minimize the search for the ground team.

When the POMDP approach was executed from the same starting location as the greedy method, the localization took a mere three steps and four measurements to find the signal source, as can be seen in Figure 11. The final belief state is overlaid with the location accurately determined to be the darkest cell. There are a handful of light cells, but those all had negligibly small probabilities.



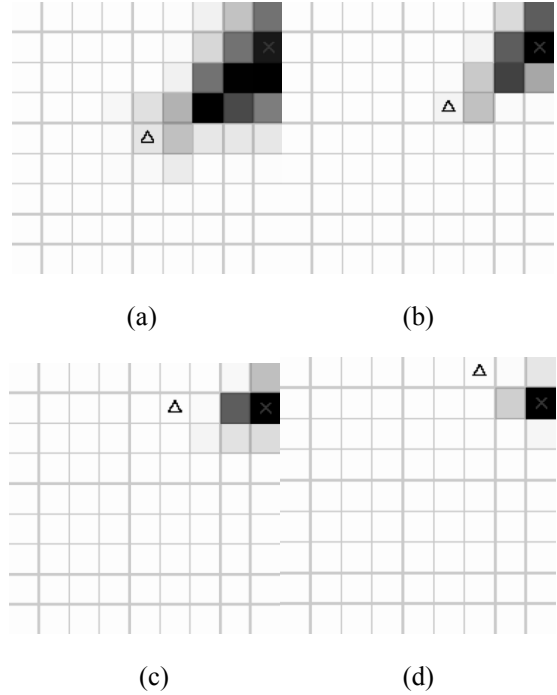
**Figure 11. Flight Path of POMDP Path Planning with Overlay of Final Belief State.**



**Figure 12. POMDP Belief State at Each Step.**

Figure 12 shows the internal belief state of the location of the jammer between all of the observations made by JAGER during the localization. The cells with the highest probability are in dark red and then fade from there. Notice that with the POMDP based path planner, JAGER makes much larger steps than seen in the greedy method and does not always move towards the signal source. This is due to the fact that in order to minimize the spread of the belief, a measurement that is to the side of the belief distribution can be a lot more effective than going towards the jammer itself. When the measurement model with the additional noise near the jammer is taken into account, the resulting effect of

maintaining enough distance from the signal source, shown in Figure 13, is much more pronounced.



**Figure 13. Path Planning with High Noise Near Jammer.**

## NAVIGATION SYSTEM

As with most autonomous systems, the open source hardware that powers JAGER by default relies on GPS position for navigation, which will need to be substituted for the duration of time that JAGER find itself in the jammed environments. The navigation system being developed will provide an approximate location of the vehicle in the environment using signals of opportunity and vision.

For JAGER, we have three main goals for our navigation system: low cost, robustness to time of day, and robustness to weather. These conditions come out of a need to be able to operate at any point in time. Since we are designing for operation at an airport, where the impact of a GPS jammer would need to be taken care of immediately to be able to minimize the impact to flight operations, it is important for JAGER to have a robust navigation system.

This navigation problem is defined as a simultaneous localization and mapping (SLAM) problem, a problem that has become increasingly popular for autonomous navigation. Some examples are indoor and outdoor rover navigation [10], indoor UAV navigation [11], and outdoor UAV navigation [12]. The SLAM problem is one of both creating a map of the environment the vehicle is moving within and determining the location of the vehicle within that map. While JAGER is not necessarily explicitly trying to map the environment, it

does indeed need to generate a map of key features that can be used to then localize JAGER within that map.

A lot of research recently has focused on the visual SLAM (vSLAM) problem with the use of both stereo-vision cameras [13] and monocular vision cameras [11]. For JAGER, we will have a visual sensor, but we will also leverage signals of opportunity that come in great variety near airports. We have previously shown the ability to post process the location of a UAV to within 10s of meters [3].

The SLAM problem we are solving is better known as bearing only SLAM. The traditional SLAM definition has both range and bearing to features in the map as an observation, but in this case, bearing will be the only observation. This again is due to the fact that we can very easily rotate the vehicle and get bearing estimates to features around the vehicle, while range requires stereo-vision cameras and a ranging metric for the signals of opportunity. As we have seen for the WiFi measurements, signal strength, the simplest metric, is not the best indicator of range. While there are other possible techniques for determining range, most add unnecessary complexity to the system.

Of the vSLAM techniques, the majority use visual-spectrum cameras, which suffer performance loss at night and in inclement weather conditions (e.g. fog). For this reason JAGER will be equipped with an infrared (IR) camera. IR cameras will give the navigation system the necessary robustness to be able to operate day or night and are able to provide more detail than visible spectrum cameras in other low light conditions such as fog and rain [14].

For the specific target environment and application of JAGER, there are very useful simplifications that can be made. For example we can leverage the fact that we can take off from a known point that is ideally far from the jammer such that we have GPS when we start. This means that for the duration of time that JAGER is operating outside of the denied environment, the system is able to build a map more reliably and accurately. Therefore, once in the denied environment, JAGER can rely heavily on features that are very well known within the map, while at the same time continuing to build the map.

Furthermore, the path planning algorithms can be tuned to tradeoff some optimality for navigation support by keeping JAGER far enough from the denied environment to be able to maintain a GPS position for as long as possible.

## **CONCLUSIONS**

With JAGER, we have successfully demonstrated, through flight testing, the ability to autonomously rapidly localize a signal source using a UAV and a POMDP based path planning algorithm.

We have demonstrated the capability of determining bearing from a set of signal strength measurements reliably and accurately enough to successfully and rapidly localize a signal source.

Finally we have outlined the development of a navigation system that represents the problem as a bearing SLAM problem that will use IR vision and signals of opportunity to both build a map of the environment and localize JAGER when in the denied environment around a GPS jammer.

## **FUTURE WORK**

So far all JAGER flight tests have been performed with the goal of localizing a WiFi signal at no more than 150m away. However, in the coming months, JAGER will be tested with GPS jammers at significantly greater range.

JAGER is an ongoing project and we are continuing to refine the sensing modality to be able to reduce the time for a measurement and observation. Currently we only use the measurements during a rotation, however the localization process can be sped up by being able to also use the measurements being made while traveling from one observation location to another. In order to do this, we are working on estimation algorithms that will provide bearing estimates given the measurements in flight.

The navigation system being developed is also still heavily being tested and refined. The biggest challenge is the ability to robustly track features in IR imagery in real time. There are many existing methods for visual imagery, however IR imagery poses additional challenges that are still being explored.

## **ACKNOWLEDGMENTS**

The authors would like to gratefully acknowledge the Naval Postgraduate School for providing an unmatched space to be able to perform test flights of the JAGER system at the Joint Interagency Field Experimentation events.

The author would also like to thank the Stanford Center for Position Navigation and Time (SCPNT) and its members for supporting this work.

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