Demonstration of UAV-Based GPS Jammer Localization During a Live Interference Exercise

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BIOGRAPHIES

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ABSTRACT

To assist in the mitigation of the effects posed by Global Navigation Satellite System (GNSS) jammers, this paper demonstrates the use of an unmanned aerial vehicle (UAV) capable of autonomously localizing the source of Global Positioning System (GPS) jamming in a live jamming exercise hosted by the Department of Homeland Security (DHS).

Developing an autonomous UAV for jammer localization in a real-world environment needs to address three main challenges: accurate measurements of the jamming signal, rapid localization steps and reliable navigation in the presence of interference. Our system, Jammer Acquisition with GPS Exploration and Reconnaissance (JAGER), has been developed to address those main challenges for rapid localization and has been previously tested with localizing Wi-Fi signals. This paper outlines the modifications to JAGER required to be able to move from localizing Wi-Fi sources to localizing GPS jammers. Modifications include new sensing equipment for determining the bearing to the jammer and additional navigation systems to fly while the jammer is active.

The main goal for the testing was to demonstrate the feasibility of JAGER to localize a GPS jammer at realistic distances and the performance of several different localization methods. The second goal was to explore possible GPS-denied navigation solutions.

INTRODUCTION

GPS has become a critical element in many different industries ranging from commercial aviation to telecommunications and even the power grid. The ubiquitous nature of GPS today has brought with it a growth in commercial jammers that, while illegal, are used for personal privacy and pose a threat to today's industries, especially in the wrong hands. In addition to efforts to toughen and augment GPS to combat jammers, the ability to quickly interdict and eliminate an interfering jammer is important. To address the protection against jammers, this paper discusses the development and testing of Jammer Acquisition with GPS Exploration and Reconnaissance (JAGER), an autonomous multirotor unmanned aerial vehicle (UAV) capable of localizing commercially available GPS jammers, in the presence of on-air Global Navigation Satellite System (GNSS) jamming during the Department of Homeland Security (DHS) First Responder Electronic Jamming Exercise (FREJE) conducted at a Department of Defense (DOD) test range in 2016.

Our prior work demonstrated the capability of the UAV to localize a Wi-Fi proxy jammer over a short distance [1]. Several major changes had to be made to enable localization of a GPS jammer in a more typical operational area including new sensing subsystem, faster algorithms and navigation systems capable of operating in a GPS-denied environment. We will describe these modifications as well as the equipment changes and testing needed to ensure safe and reliable test operations.

To ensure rapid localization of the jammer, measurements of the jamming signal need to be accurate and therefore robust to jamming signal variations and radio frequency interference (RFI) not directly coming from the jammer. This may be RFI from the other equipment in the vicinity, noise from the vehicle and signal reflections from the jammer. For the UAV presented in this paper, the sensor used and configuration onboard the vehicle reduced effects from the signal variations and RFI, and algorithmic methods are used to determine bearing through the noise. The primary measurement for localization is the bearing to the GPS jammer, determined from a directional antenna and leveraging the ease of rotation of a multirotor. To contend with RFI noise, a robust algorithm to extract bearing has been developed and is demonstrated through flight-testing.

To handle the larger search area for these tests, instead of using the computationally expensive Partially Observable Markov Decision Process (POMDP) methods used previously [1], the rapid localization of the jammer is performed through several one-step optimal (greedy) solutions that minimize a specified information-theoretic objective.

Navigation in a GPS-denied environment is essential for a system searching for a GPS jammer. For testing during the live jamming exercise, our UAV integrated several navigation solutions including: GLONASS, Locata and GPS itself. Our equipment setup and the nature of the jamming allowed us to conduct the flight trials using GLONASS for positioning and control of the UAV. In fact, a majority of the flights were conducted using the GLONASS receiver as it provided a low weight, easy to integrate navigation package. The presence of a jammer does not mean that GPS/GNSS should be ignored, however. Our test demonstrated that it is viable to localize the jammer while maintaining a standoff distance where GPS is not degraded by the interference.

In addition to describing the methods for localization for an autonomous UAV, this paper presents the modifications of our UAV to ensure safe and reliable operations of the UAV in a live interference exercise. In assembling the system, RFI was a significant challenge for all antennas in close proximity onboard the UAV and care was taken to minimize the interference between all systems onboard the UAV. Furthermore, all flight-testing was performed at night at long range so reliable visual markers and communication systems were required.

TEST SETUP / CONFIGURATION

During the DHS FREJE both first responder groups and academia where invited to participate in an exercise with live interference across many different frequencies that can affect first responders. For our testing, we focused exclusively on jamming in the GPS L1 band with a DHS provided commercial off-the-shelf (COTS) jammer.

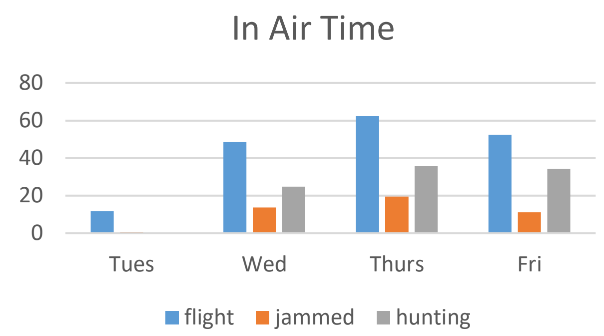


Figure 1: Minutes of in air time for each night of testing

The exercise was a weeklong event, with flight-testing occurring during the nights of Tuesday through Friday. An outline of the overall flight time for each night of our testing is shown in Figure 1. The figure shows the overall total flight time, the amount of time GPS was unavailable due to jamming and the amount of time JAGER was flying autonomously in jammer hunting mode. For our test campaign, the first two nights were spent on final integration, ensuring RFI mitigation was properly taken care of, and safety testing, both on the ground and in the air. On the final two nights, Thursday and Friday, we almost exclusively tested the various localization algorithms and navigation systems. Hence hunt mode represents a high percentage of the total flight time.

For each test, the COTS jammer was placed at a known location and the UAV was started at another known position to execute its search.

Jammer

DHS provided COTS handheld GPS jammer similar to the one depicted in Figure 2.

Figure 2: Example handheld COTS GPS jammer

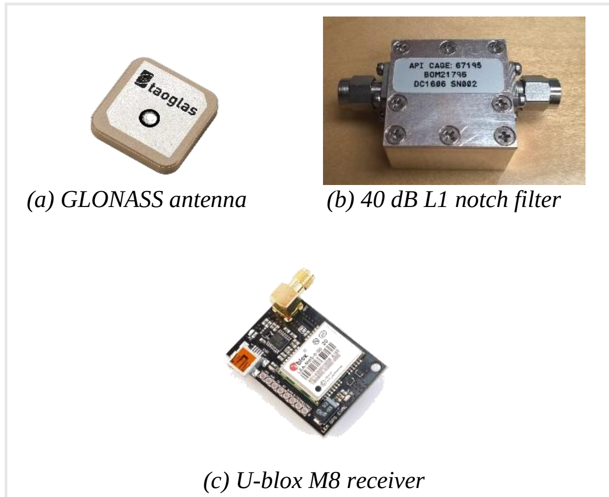
The online specifications for the jammer state a power of 2 Watts (W) in the L1, L2 & L3, L4 and L5 bands, resulting in an effective 0.5 W of interference in the GPS L1 band. Since the localization sensor onboard the UAV senses jamming in the L1 band, this is effectively a 0.5 W jammer for flight-testing. However, it is not clear that this is the actual radiated power as the jammer had several settings that could be enabled through dual in-line package (DIP) switches. The online specifications also state an effective range of 5-15 meters (m) whereas analysis such as those from [2] would suggest a range of approximately 20 nautical miles without mitigation. Our test experience indicated something a range closer to several hundred meters. This is discussed in the Jammer Performance section below.

JAGER

JAGER consists of a modified DJI S1000 airframe with a Pixhawk flight control computer and flight control code customized to the platform and the mission [3]. The Pixhawk also contains low-cost microelectromechanical systems (MEMS) accelerometers, gyros and magnetometers. A configuration of JAGER is shown in Figure 3. For navigation, JAGER has several different units that it can carry. There are separate navigation units for GPS, GLONASS and Locata. For radio frequency (RF) direction finding, JAGER carries a directional antenna that is connected to a RF log detector that determines the received signal strength in the targeted frequency. Rotation of the JAGER platform results in determination of an antenna gain pattern. Navigation and jamming signal reception information is passed to an onboard small form factor computer – an Intel i7-based Next Unit of Computing (NUC) to perform jammer direction finding and localization algorithm.

Figure 3: Fully equipped UAV used during flight tests

Several navigation systems are carried onboard JAGER. The GPS receiver is based on an U-blox chipset. The GLONASS receiver utilized a similar chipset. As a result, it was reasonably easy to integrate with the Pixhawk flight controller. The GLONASS receiver was the primary source of navigation during jamming. The system (Figure 4) is comprised of a GLONASS antenna connected to an U-blox M8 receiver through a 40 deciBel (dB) L1 band reject filter. The U-blox M8 receiver was configured to only take and use GLONASS measurements to create a position solution. Hence no GPS measurements are used as these could adversely affect the solution. The 40 dB band reject filter helped limit the effect of L1 jamming on elements, such as the automatic gain control (AGC) and low noise amplifier (LNA), used to support both GPS and GLONASS as these could affect the GLONASS position solution performance.



(a) GLONASS antenna

(b) 40 dB L1 notch filter

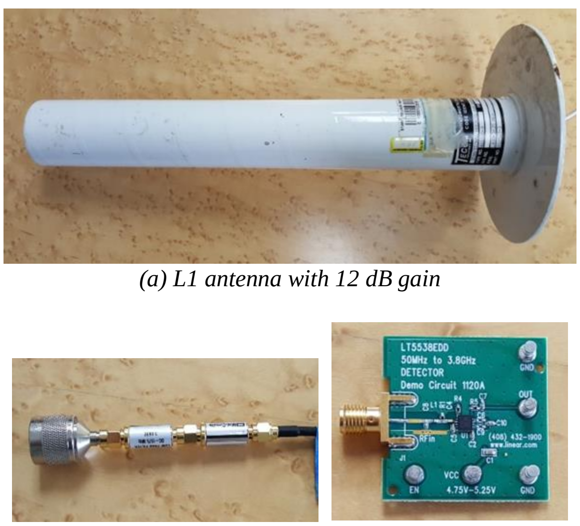
(c) U-blox M8 receiver

Figure 4: GLONASS receiver

A Locata receiver (Figure 5) was also carried for navigation. The benefit of the system is that it operates on 2.4 GHz, significantly far from GPS interferers, and it could provide millimeter level truth [4]. We tested integration both at the GPS laboratory and at the test site. This is important as RFI and other integration issues pose a big challenge for a multirotor platform. From testing with live on air signals, we found that RFI from the command and control data links affected Locata reception. Not surprisingly, this was most strong on the ground while next to the command radio; it dissipated into the air as the vehicle was farther away from the ground radio. The form factor of the current Locata receiver also posed an integration challenge. The metallic housing seemed to affect the onboard magnetometers. Also, it weighs approximately 2 kilograms (kg) which reduced our flight time by half. The testing with Locata diagnosed and resolved most of these integration issues, however, opening the way to fully operating JAGER with Locata. This is potentially important for tests involving more complex jammers that make a multi-frequency / multi-constellation solution difficult.

Figure 5: Locata receiver mounted to underside of JAGER

To localize the source of the GPS jammer, the sensor being used is a directional TECOM L1 antenna with 12 dB of gain and a beamwidth of 35 degrees, depicted more closely in Figure 6 [5]. In the same figure, the rest of the components for the sensing can be seen: a bandpass filter to reduce outside noise and a Linear Technology RF detector. The RF detector converts signal strength to voltage, allowing the system to directly measure incoming signal strength [6].



(a) L1 antenna with 12 dB gain

(b) L1 bandpass filter *(c) RF detector*

Figure 6: GPS localization signal strength sensor

JAGER carries many radios for navigation, communications and operations. Radio navigation sources are passive and operate on various frequencies: Locata on 2.4 GHz and GPS/GLONASS around 1.6 GHz. Communication sources are generally two way and operate at several frequencies including 5.8, 2.4 and 0.9 GHz. Finally, several sources of RFI exist including the power system, rotor motors which can draw up to 2 kW of power and the NUC. The radios are indicated on Table 1.

To mitigate the many sources of RFI onboard JAGER, copious amounts of copper tape were used for shielding. This is shown in Figure 7. The shielding helped minimize the interference from the power sources of the vehicle with the navigation antennas, minimized interference into the sensor and reduced interference from the Intel NUC onboard. Most of the copper shielding was placed on the platforms between our navigation systems on the top and our communications on the bottom. This reduced interference between our 2.4 GHz and Locata and likely also helped attenuate jamming from the ground to our GPS and GLONASS receivers.

Table 1: Radio frequencies and RFI sources onboard JAGER

Source	Transmit Frequency
Command/Control	2.4 GHz
Telemetry	900 MHz
Datalink	5.8 GHz
Electric Motors	RFI
Intel NUC	RFI

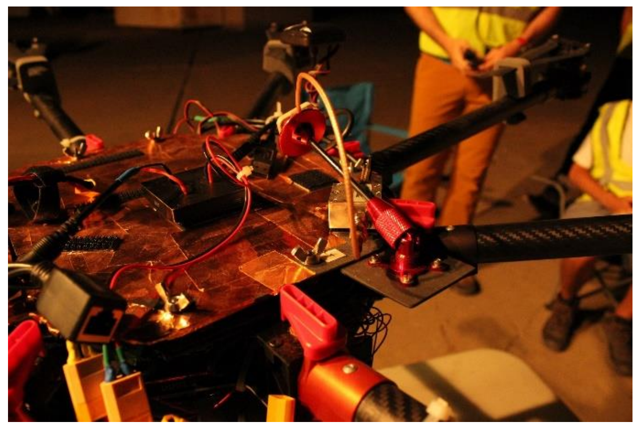


Figure 7: Copper shielding onboard JAGER to minimize RFI

Safety

Due to the nighttime testing that was performed, in addition to the normal safety features of the autopilot, the UAV was augmented with many light emitting diodes (LEDs) (Figure 8) to assist the pilot in maintaining visual observation of the UAV in case manual control needed to be taken at any time during the flight.

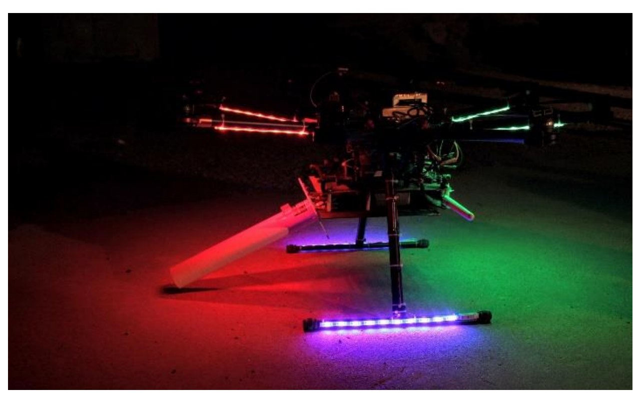
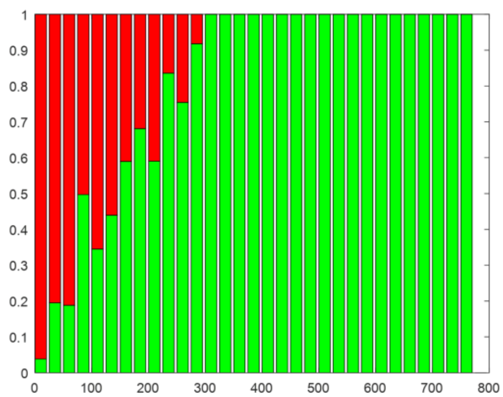


Figure 8: LEDs on vehicle for pilot visibility

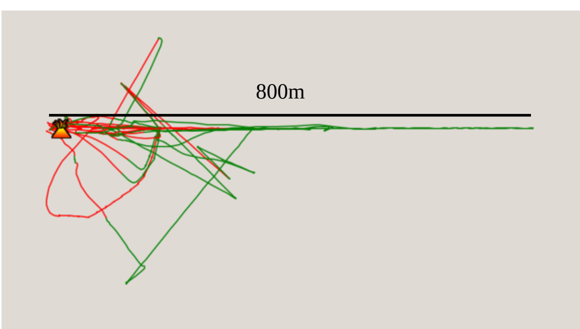
JAMMER PERFORMANCE

The source of jamming for these tests was a COTS GPS jammer provided by DHS and operated by the test support personnel at the testing site.

The advertised specifications for the jammer was 0.5 W in the L1 band with a range of 5-15 m. The jammer range experienced during flight testing was significantly larger and differed depending on setting. The jammer performance over two nights of testing is shown in Figure 9 and Figure 10. In these figures the red lines are where we did not have a solution output from the U-blox GPS receiver, and green lines are where we did have a position solution from the U-blox GPS receiver.



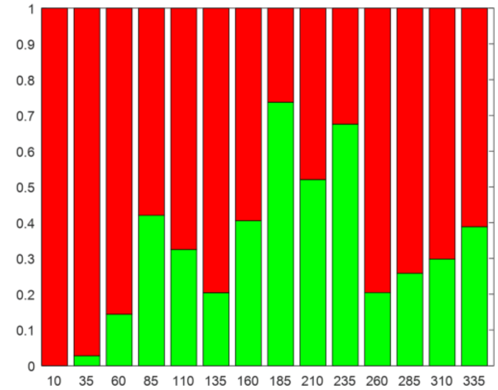
(a) Percentage of measurements with (green) and without (red) a GPS position solution as a function of distance



(b) Map of GPS performance

Figure 9: Thursday night GPS jammer performance

In each of these figures, the jammer's effectiveness is depicted both on a map and as a percentage of the measurements with and without a GPS position solution for specific distances from the jammer. As can be seen, the effective range of the jammer (the maximum distance where the GPS receiver was unable to return a position solution at least once) was approximately 300 m for Thursday night (Figure 9) and at least 350 m for Friday night (Figure 10).



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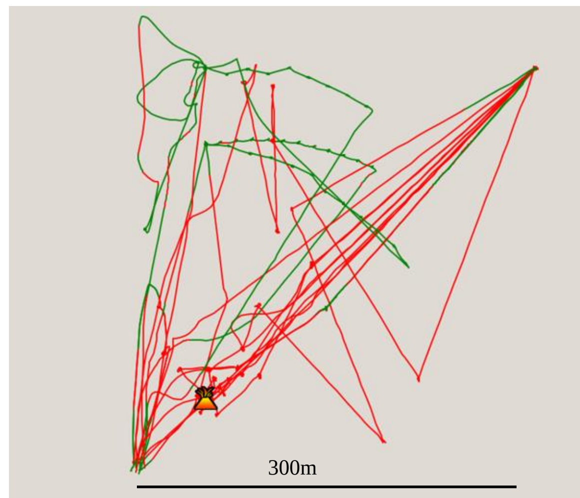


(b) Map of GPS performance

Figure 10: Friday night GPS jammer performance

The results suggest a difference in jammer power during the different nights. One difference was that the jammer was operated on battery power on Thursday and plugged into a power source on Friday. Our measurements suggest that battery powered operation provided less jamming power than plugged-in operation.

SENSING PERFORMANCE

Previously, JAGER has demonstrated an ability to localize a Wi-Fi router [1], but for these tests the sensor had to be changed to be sensitive to the L1 band. With a new sensor came a new set of challenges, especially with integration onboard the system and RFI mitigation, which were discovered during the first nights of testing. While the sensor measures received signal strength at L1, we leveraged the rotational motion of a multirotor platform to generate a sequence of signal strength measurements at various azimuth angles. This collection of signal strength measurements was then used to recreate the antenna's gain pattern to the jamming source. From there, the bearing to the jammer was determined and used in the navigation systems [1].

The use of the collection of signal strength measurements to obtain a bearing provides some initial robustness to the effects of unwanted noise in the sensor, which is described in this section.

Noise

The signal sensor measured periodic noise spikes. This resulted in gain patterns such as the one depicted in Figure 11. Despite the noise, an accurate determination of bearing is still achievable through processing. The cross correlation (cc) method was particularly good at resolving an accurate bearing despite the noise. It did make bearing estimation more challenging for some of the methods employed.

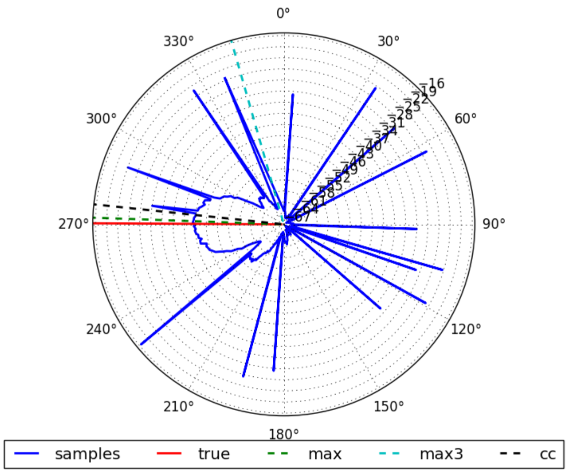


Figure 11: Raw measured gain pattern with noise

These patterns could be filtered out in real time through thresholding and a nearest neighbor analysis resulting in the smoother pattern in Figure 12. Note that once the noise is removed, each of the bearing calculation methods previously used performs as expected [1].

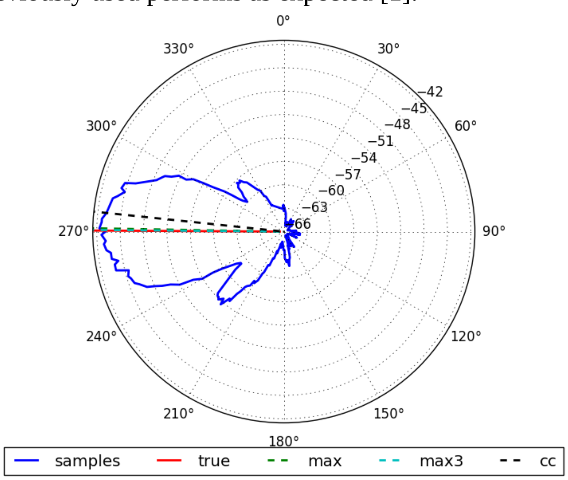


Figure 12: Filtered gain pattern with sensor noise removed

Compared to our previous testing with Wi-Fi in [1], the employed sensor and antenna setup has a smaller beamwidth. The tighter beamwidth improved the accuracy of the calculated bearing.

Range

Using a very high gain antenna also meant that the system was able to detect the GPS jammer from great distance.

The sensor clearly detected the jammer at a range of 150 m from the jammer (Figure 13) with a pattern that was good enough to have bearing extracted from any one of the bearing calculation methods used.

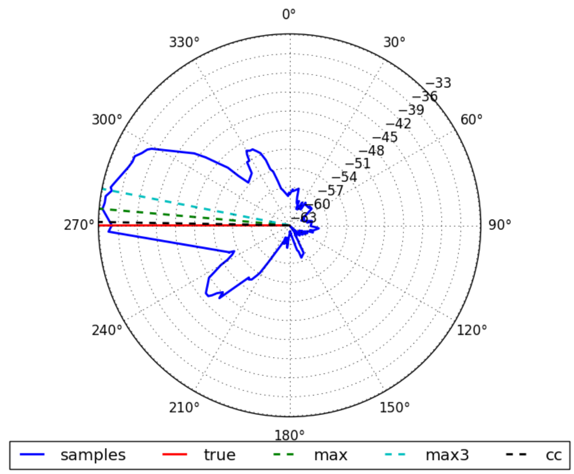


Figure 13: Filtered gain pattern at 150 m from jammer

We were able to test the sensor to a distance of 800 m from the jammer, resulting in the pattern shown in Figure 14. Note, in this pattern much more noise is present and the pattern no longer clearly resembles the expected gain pattern. Therefore several of the methods are unable to determine bearing correctly, however the more basic method (using maximum value) is still able to perform well and determine the bearing. The cross correlation method provides a correlation coefficient that indicates how well of a correlation was performed. For the measurements far from the jammer, the cc coefficient is very small and allows the system to use one of the more basic methods [1].

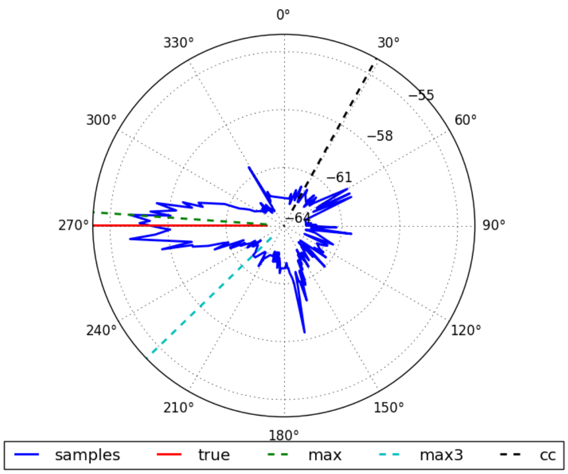


Figure 14: Filtered gain pattern at 800 m from jammer

Due to battery limitations on JAGER for these tests we were not able to perform range tests beyond 800 m, however the RF detector is sensitive down to -65 dB relative to a milliWatt (dBm), leaving approximately 7 dBm of margin left at 800 m. Therefore we are confident this system would be able to detect the jammer from beyond 800 m; however, the ability to extract accurate bearing would be more limited.

LOCALIZATION

For localizing the GPS jammer, our goal was to not only test our algorithms with a GPS jammer, but also to test at longer ranges than we have previously tested. For these tests, the initial start point was 350 m away from the jammer and the search area used was a 500 m x 500 m search area more representative of a possible scenario than the 100 m x 100 m search areas previously used [1]. We represent the square search area as an n by n set of discrete cells. JAGER maintains a belief or probability distribution over these cells. The weight of each cell is the probability the jammer is in that cell. Every time JAGER rotates and makes a bearing measurement, this belief is updated using Bayes' rule and a measurement model. This type of filter is called a discrete Bayes' filter or sometimes a histogram filter [7].

The measurement model for our system is the true bearing from JAGER to the jammer with additive Gaussian noise. This noise and errors result in the bearing accuracy having a standard deviation of roughly 10 degrees [1].

The planning problem consists of selecting a new rotation/measurement location given the belief. In our previous work, we explored multi-step planning with POMDPs [1]. Although POMDPs offer a principled approach to decision making under uncertainty [8], they are computationally intractable in the general case [9]. In previous work, we used small search areas (100 m x 100 m) that were coarsely discretized (11 x 11 grids) [1], so we could apply approximation techniques yielding good solutions.

In these experiments, we used more realistic search areas. This requires grids larger than 11 x 11 so individual grid cells are not too large, giving us the precision we desire. Therefore, we explore one-step optimal also known as greedy solutions that minimize some information-theoretic objectives over a planning horizon of one. The following subsections describe different greedy planners used.

Entropy Minimization

A common method for localization is minimizing the expected entropy after the next measurement [10]. Entropy is a measure of spread in a distribution. A uniform distribution maximizes entropy and one in which all weight is concentrated in a single cell has zero entropy.

One way to compute expected entropy is to discretize the observation space into a discrete number of observations. Given JAGER's position and the jammer's position, we can assign probabilities to each observation. Each observation yields a new belief whose entropy we can compute. Because we do not know which observation we will receive, we take an expectation over all possible observations. We also do not know the jammer's location, so we take an expectation over our belief. This provides the entropy given a position for JAGER. To find the best new position, this process is repeated for every position to which JAGER can travel. The set of possible JAGER positions contains the center of every cell in our search area. That is, JAGER moves to a new position $x_{v,t+1}$ according to the following equation:

$$x_{v,t+1} = \underset{x_v}{\operatorname{argmin}}\ E_{x_j \in b_t} E_{y_{t+1}} H(b_{t+1})$$

where b_t is the belief at time t, xj denotes a possible jammer location, and $H(b_t)$ is the entropy of belief b_t. This computation requires iterating over all grid cells twice, leading to computational complexity of $O(|Y|n^4)$, where $|Y|$ is the number of discrete observations. These computations become intractable when the number of grid cells per side, n, increases.

We computed controls online for 25 x 25 grids on a 500 x 500 m search area, yielding reasonable 20 x 20 m grid cells. Any discretization more fine was difficult to compute in less than one second during flight. Figure 15 shows an example of a localization run carried out using this method. After each measurement, the belief concentrates around the jammer location (red triangle).

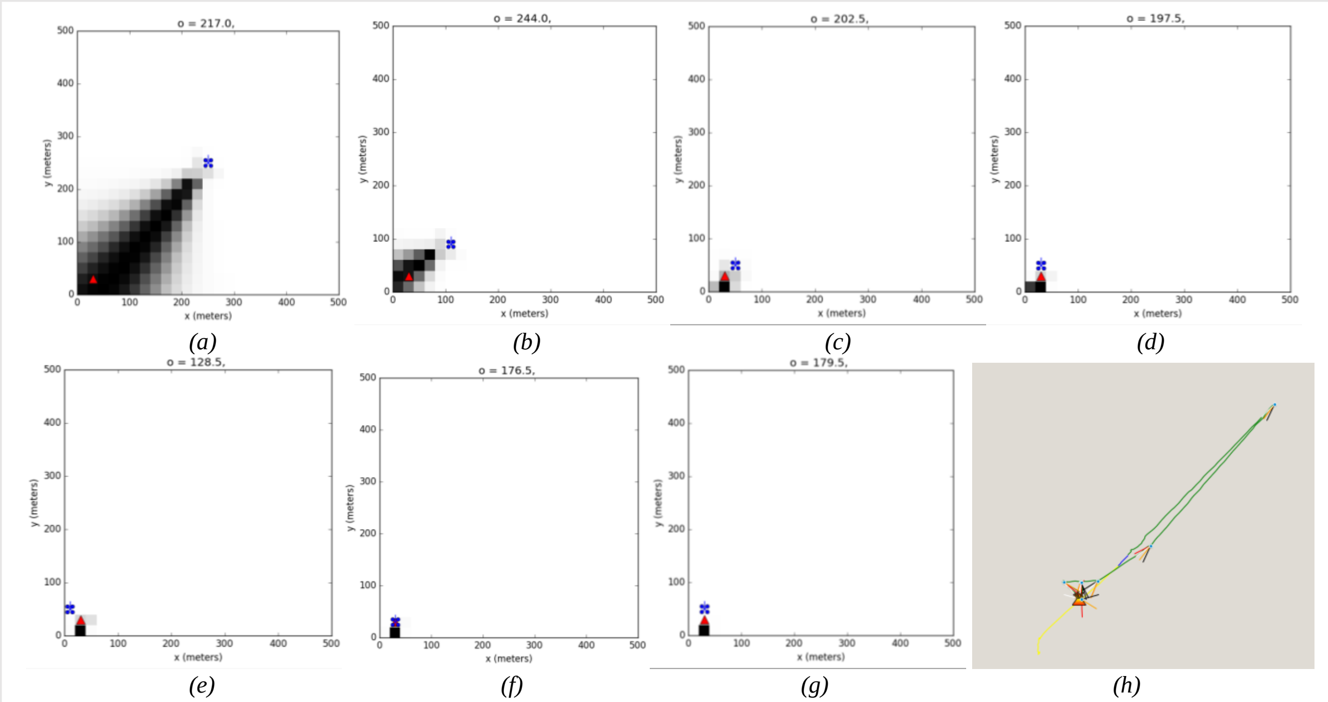


Figure 15: Entropy minimization belief distribution at each step (a) through (g) and overall flight path of search (h)

Determinant Minimization

As mentioned in the last subsection, computing entropy minimization can become intractable as the number of grid cells in a discrete filter increases. If we want very fine cells, for example half a meter per side, we need to make some approximations.

A common approximation in estimation is linearizing the measurement model and assuming beliefs are roughly Gaussian. Filtering is computationally inexpensive with these approximations. More importantly, estimating the covariance after future measurements becomes far more tractable. Kalman filters struggle in bearing-only localization schemes because the measurement function is very nonlinear, however. Our solution is to maintain a discrete filter for localization, but fit a Gaussian approximation after each step. This approximation can be calculated from the mean position and covariance of cells in our discrete belief.

An interesting feature of Kalman filters is that future covariance can be estimated easily given future measurement locations and the estimate mean. This feature becomes most apparent when using the information filter – a Kalman filter that uses the canonical form for Gaussians:

$$\xi = \Sigma^{-1}\mu$$
$$\Omega = \Sigma^{-1}$$

When using the canonical form, the update step in the Kalman filter becomes:

$$\Omega_{t+1} = \Omega_t + \frac{C_t^T C_t}{\sigma^2}$$

where C_t are the linearized measurement dynamics for the target mean at time t and σ is the bearing error standard deviation (10 degrees in our case). This gives us the inverse of our covariance matrix at future step, without discretizing the observation space and iterating over it. This is not a true expectation over jammer locations, because the mean estimate is used, but the computational trade-off is favorable. Computing the covariance for a measurement from a future measurement location is now $O(n^2)$, a great reduction from the entropy reduction.

Once the covariance of a measurement from a new position is estimated, it is possible to iterate over all possible new measurement locations. To convert the covariance to a scalar metric, the determinant can be used. Minimizing the determinant is equivalent to minimizing the area of an uncertainty ellipse representing the belief.

Figure 16 shows this method in a flight test. The mean and 95 percent confidence ellipse after each step is shown. JAGER selects new positions that are almost identical to the mean location. This might be because the linearized bearing measurement equation approaches infinity as the relative distance between the jammer and JAGER decreases. It is also a possible use of the determinant as a metric causes JAGER to move to the mean estimate. In bearing localization, determinant minimization sometimes moves sensors toward the estimate rather than perpendicularly, which is intuitive. This is because the determinant corresponds to the area of an uncertainty ellipse. This area can be small if uncertainty is large in one direction but very small in another.

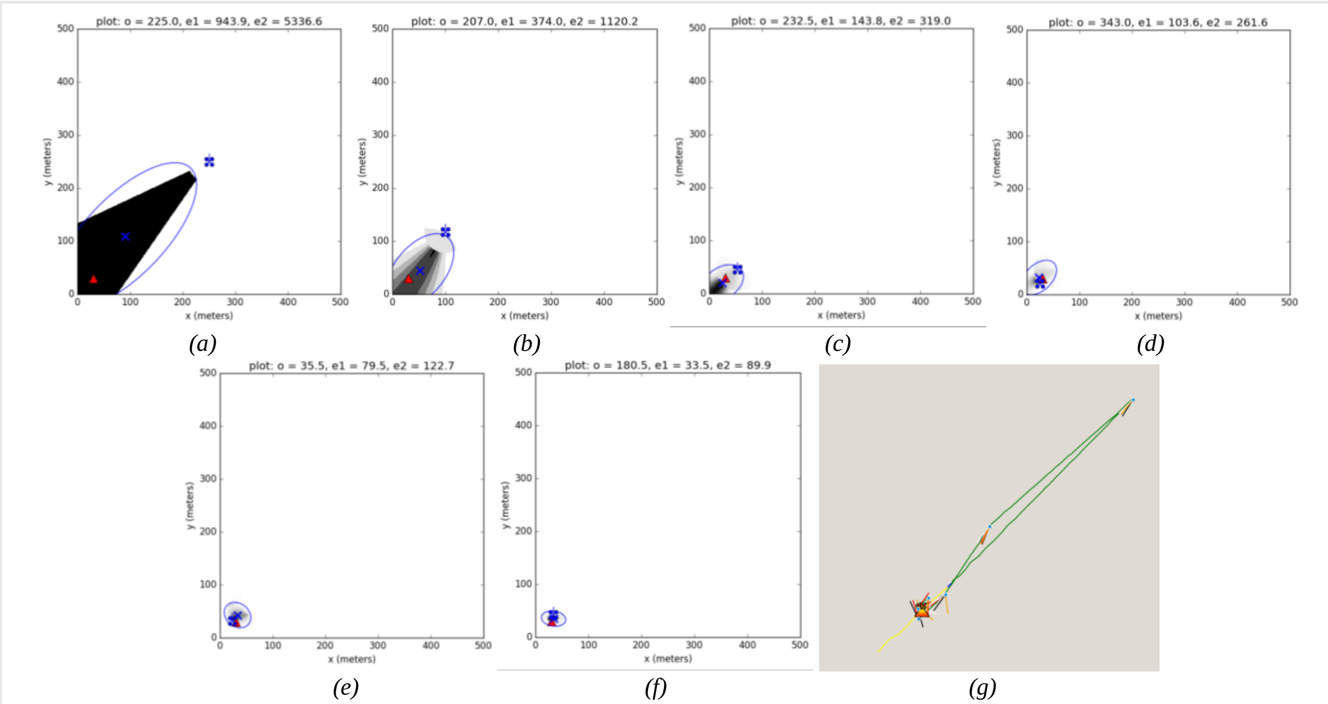


Figure 16: Determinant minimization belief state at each step (a) through (f) and overall flight path of search (g)

Maximum Eigenvalue Minimization

In some cases, it is desirable to move towards the jammer. For example, if we wanted to photograph the jammer, moving to the belief mean would make sense. However, we often want to maintain some distance from the jammer, as measurements near it can be noisier [1]. Therefore, we explore another metric using the approximation approach mentioned in the previous subsection.

Instead of minimizing the determinant, we can minimize the largest eigenvalue of the future covariance matrix. Instead of minimizing the area-like determinant, this operation minimizes the largest axis of an uncertainty ellipse representing our belief. This is often done to minimize the worst-case uncertainty along any axis.

The eigenvalue minimization approach was flown and an example trial can be seen in Figure 17. JAGER often elects to take new measurements from a position perpendicular to the largest axis of the uncertainty ellipse. This behavior makes sense in bearing localization. Interestingly, JAGER also tended to stay some distance away from the jammer. This can be desirable as perhaps GPS will be available for navigation farther from the jammer.

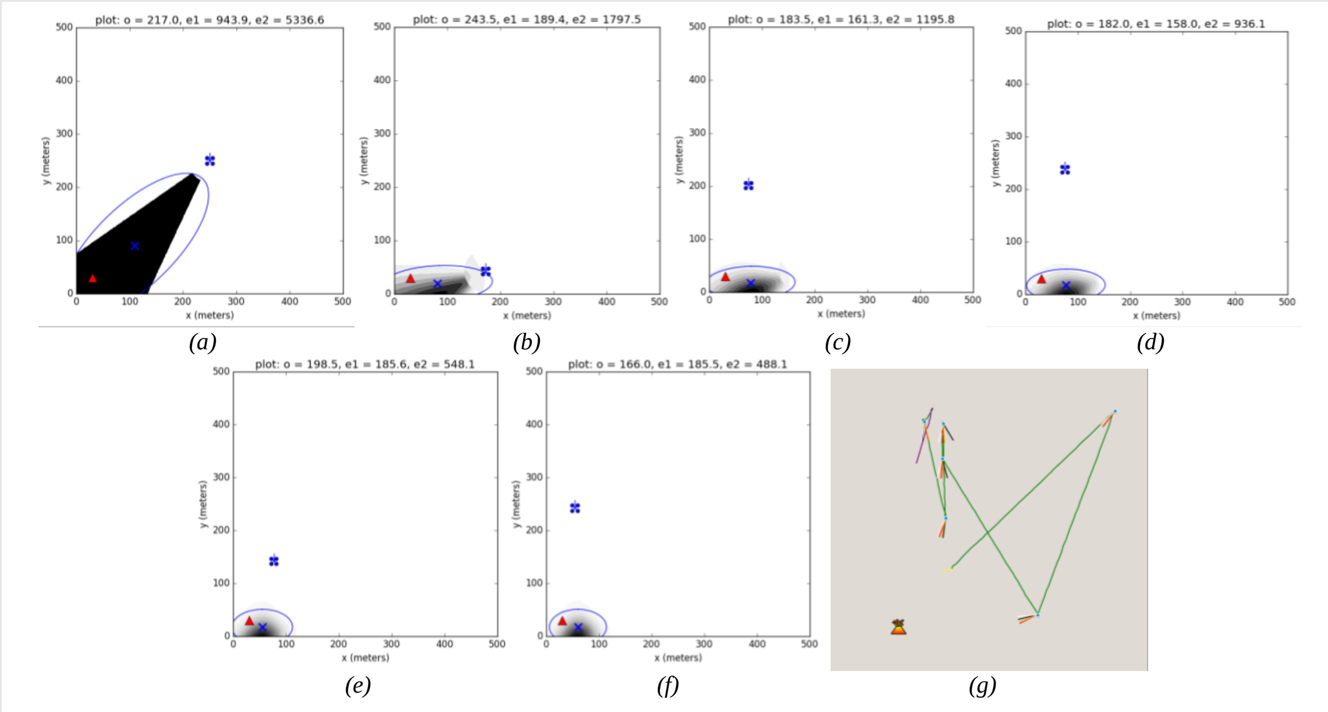


Figure 17: Eigenvalue minimization belief distribution at each step (a) through (f) and overall flight path of search (g)

NAVIGATION PERFORMANCE

Three different navigation systems were onboard JAGER: GLONASS, GPS and Locata. GLONASS was the primary navigation system used throughout all flight tests and performed very reliably. GPS was onboard to analyze both the performance of the jammer and the possibility of navigating on GPS even when attempting to localize a GPS jammer. JAGER was also equipped with Locata, a ground based positioning system, to allow for on-ground and in-air integration testing for potential future use on JAGER.

GLONASS

GLONASS was the main method used to navigate the UAV during the L1 GPS jamming exercise. Because the jammer was limited to the L1 band, and because the frequency of GLONASS was just outside the range of the jammer, GLONASS proved to be a reliable navigation system that was small and integrated easily with our flight controller. Figure 18 shows the horizontal (EPH) and vertical (EPV) position covariance for testing on Friday night. It can be seen that the horizontal covariance was almost always under 4 m, which was typical each of the nights. The only degraded performance experience with GLONASS was when the system was turned on. This occurred in close proximity to the jammer and is therefore most likely caused by the jammer.

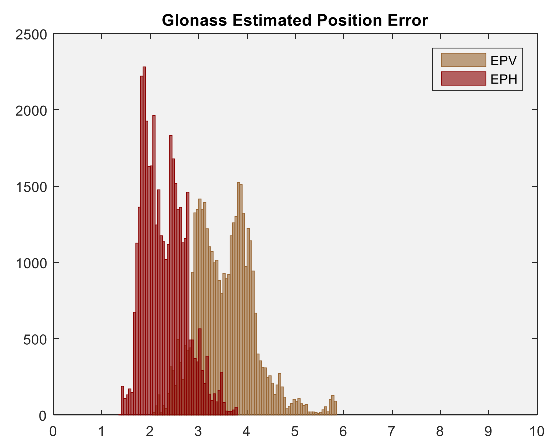


Figure 18: GLONASS horizontal and vertical position solution covariance in meters Friday night

GPS

The availability of a solution from the GPS receiver was very high despite the jammer being active (Figure 9). Further inspection showed that while a receiver solution was available, it was not necessarily of high quality and could have significant error. Figure 19 shows the GPS and GLONASS solution in blue and green, respectively. Here it can be seen that even though the system was getting a valid GPS position, the position difference from GLONASS were very large.

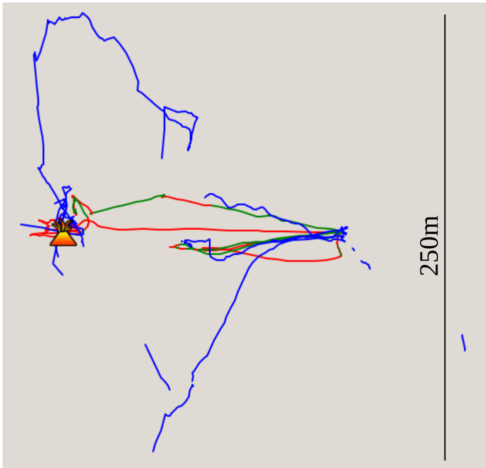


Figure 19: GPS position error in flight with GPS L1 jammer active

A plot of the GPS covariance can be seen in Figure 20. This figure shows that the covariance of the position solution for GPS was much closer to the 10 m mark than the 2-3 m seen with GLONASS. For best operation of the autopilot, the errors need to be 5 m or better.

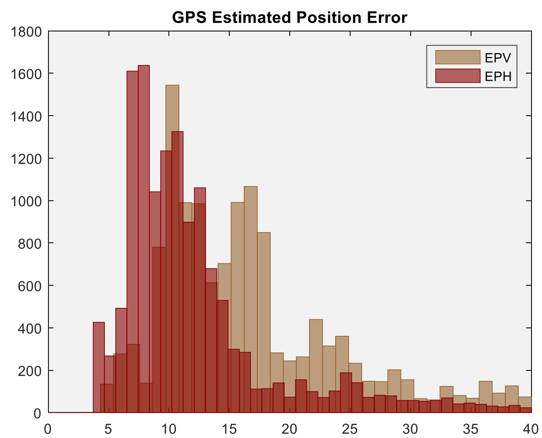
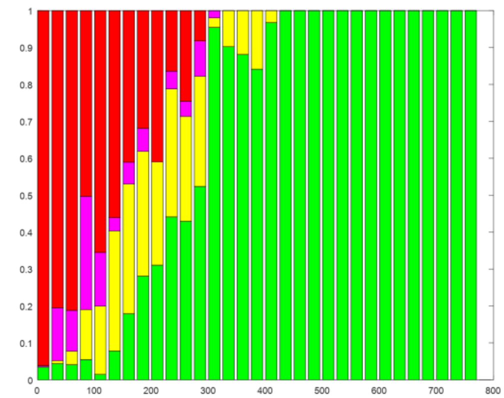
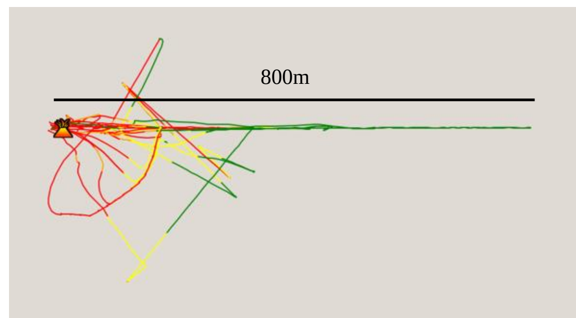


Figure 20: GPS horizontal and vertical position solution covariance in meters Friday night

Looking more closely at the covariance of the GPS solution and moving from simply a binary check of whether or not a position solution was calculated to a tiered analysis results in Figure 21 and Figure 22. In these figures, red again means no position solution was received, purple represents a GPS solution with horizontal covariance of more than 10 m, yellow a covariance in the 5-10 m range and finally green representing a GPS position solution with a covariance of less than 5 m.



(a) Percentage of measurements in each performance category as a function of distance

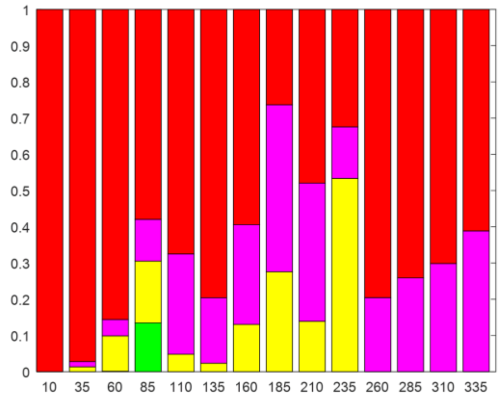


(b) Map of GPS performance

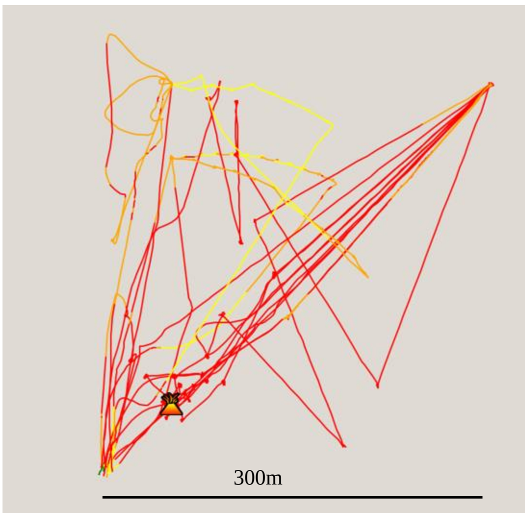
Figure 21: Tiered GPS performance Thursday night

Dividing the GPS position results into these four different categories shows that the effective range of the jammer is about 100 m more than initially observed. The results show that one needs to use GPS with care near jamming, especially with non-certified GPS receivers. For such receivers, jamming can potentially pose a more severe threat than just loss of GPS position. It could present misleading information. This is a similar experience seen by the General Lighthouse Authorities in their GPS jamming trials [11].

Because our sensor is able to "see" the jammer from such a great distance, this will help in the navigation challenge allowing us to potentially rely on GPS for part of the flight and changes the requirements of the denied navigation system.



(a) Percentage of measurements in each performance category as a function of distance



(b) Map of GPS performance

Figure 22: Tiered GPS performance Friday night

Locata

We were able to successfully integrate Locata into the open source Pixhawk autopilot system to obtain solutions both while on the ground and in the air. JAGER was able to fly the vehicle autonomously with Locata. The weight of the payload combined with the rest of the equipment reduced flight test time by half, however. Hence, it was not used as the primary positioning system used. It provides a very accurate truth measurement, however, and its frequency separation from any of the GNSS signals makes it a compelling positioning solution for future testing of a wider range of jammers.

CONCLUSION

The JAGER tests at DHS FREJE were very successful. We accomplished our major test points. Under the scenario of a single static jammer in an open field, JAGER successfully located the jammer autonomously from various distances and using several different algorithms. JAGER reliably determined the direction of the jammer from at least 800 m away, which is well beyond the effective range of the jammer tested. Despite the shorter horizon of these localization algorithms, they all very rapidly localized the jammer and consistently localized the jammer to within an appropriate distance. While we grew the search area by 25 times from previous tests, the localization algorithms only took on average approximately 1.5 times the number of steps to successfully localize the jammer, which is very promising for JAGER's ability to rapidly localize a jammer in a large search area.

GLONASS and Locata were both used for navigation. Our navigation test showed that with the jammer and the GLONASS setup used, JAGER was able to have GLONASS navigation with high availability in the air. In close proximity to the jammer, the receiver experienced difficulties quickly acquiring GLONASS. This is likely due to the jamming affecting elements used by both GPS and GLONASS, such AGC and LNA. The 40 dB band rejection is not enough when right next to the receiver leading to the jamming power affecting the LNA and/or AGC. Locata functioned both in the air and on the ground. JAGER flew autonomously using Locata. Examination of our data showed that GPS L1 solution was often available in the air. JAGER airframe likely provided some mitigation as a layer of copper tape was used to shield the top shelf with GPS and other navigation antennas from the lower two shelves as well as the ground below.

The results demonstrated that JAGER can locate a jammer from a distance that is greater than effective jamming radius on JAGER and perhaps other GNSS equipment. This result is profound in that it means that JAGER could navigate on GNSS from a standoff distance (where GNSS is not affected) and still localize the jammer given an appropriate algorithm.

FUTURE WORK

JAGER operated under very favorable scenarios at DHS FREJE. It operated in an open environment with a single static jammer. We limited the complexity of the testing as this was the first test of JAGER with actual rather than simulated jamming. JAGER will need to operate under much more complicated scenarios where there may be multiple jammers and/or moving jammers. Additionally, JAGER is meant to operate with suburban and urban environments such as near an airport. These environments have buildings and other structures that can cause signal blockages and multipath. This makes localization more challenging. We are building upon our existing research, hardware and software to develop the capability to handle these more challenging scenarios.

Navigation in GNSS denied environments is an important component on JAGER. Several possibilities exist. As demonstrated from our tests, GNSS may have some utility. There are regions where both GNSS is available and jamming is detectable. This may be coupled with a vision system to provide relative navigation should JAGER need to enter a more severely jammed region. This is one area of future work as we were not able to test the vision system. Despite being able to use GNSS, JAGER should have navigation means that is robust to GNSS RFI.

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DISCLAIMER

The views expressed herein are those of the authors and are not to be construed as official or any other person or organization.

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