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# Experimental Evaluation of a Low-Cost UAV-based System For Locating Ground Transmitters

Boris Galkin<sup>1</sup>, Lester Ho<sup>1</sup>, Paul Brophy<sup>2</sup>, and Holger Claussen<sup>1,3,4</sup>

<sup>1</sup> Tyndall National Institute, Ireland; <sup>2</sup> Civil Defence, Ireland;

<sup>3</sup> University College Cork, Ireland; <sup>4</sup> Trinity College Dublin, Ireland

*E-mail: boris.galkin@tyndall.ie, lester.ho@tyndall.ie,  
paul.brophy@defence.ie, holger.claussen@tyndall.ie*

**Abstract**—Unmanned Aerial Vehicles (UAVs) are becoming an indispensable tool in civilian and military data-gathering and reconnaissance tasks, due to their ability to freely fly over a mission area and collect data. In this paper, we experimentally demonstrate how off-the-shelf Software-Defined Radio receivers can be used as part of a UAV payload, to create a cost-effective system to locate the origin of a radio transmitter. A uniform linear array of antennas is used to measure the angle-of-arrival of the signal, which is then combined with the GPS coordinates of the UAV and processed with an Unscented Kalman Filter algorithm to estimate the location of the transmitter. We demonstrate this system in field conditions, and show that the system can accurately estimate the angle-of-arrival. We demonstrate that a low-power handset can be located to within 100m from over 1.5km away within several minutes of flight. While our experiment is based around a search and rescue scenario, this localisation approach has wider applicability for wireless communications applications.

**Index Terms**—UAV, Angle-of-Arrival, Software-Defined Radio, Localisation, Experimental Measurements

## I. INTRODUCTION

With every passing year, Unmanned Aerial Vehicles (UAVs) are becoming increasingly common as platforms for carrying out mapping and surveying tasks, as used by commercial, law enforcement, and emergency organisations. While remotely controlled aircraft have been in use for decades among the leading militaries, innovations in electronic motors, battery technology, and miniaturised processing capabilities have increased the capabilities of these devices, while significantly reducing the cost-of-entry. As a result, organisations that previously relied on helicopters and airplanes to carry out aerial mapping and surveying tasks are turning to UAVs to support their operations. While UAVs bear a lot of fundamental similarities to their manned counterparts, they also have unique strengths and weaknesses which will determine how they will be used, and their limitations. The new opportunities and challenges offered by UAVs have spurred research in the areas of telecommunications, robotics, and AI [1].

The Irish Defence Forces (DF), as part of the GUARD [2] and MISTRAL [3] projects, are currently developing their own UAV capabilities, to support their missions at home and abroad. In their role as United Nations (UN) peacekeepers, DF personnel carry out humanitarian missions in some of the most

remote parts of the world, where reliable long-distance communication is challenging to achieve and maintain. UAVs are seen as a suitable alternative to High Frequency (HF) radio or satellite communications to provide communication support. At home, the DF assist civilian emergency organisations, such as Civil Defence, in dealing with critical situations.

Civil Defence is a volunteer-based emergency response organization under the Department of Defence. Their remit is to support the frontline emergency services in dealing with severe weather or Search and Rescue (SAR) missions. In 2022, Civil Defence engaged in almost 100 missing person searches across the territory of Ireland [4].

While Civil Defence has access to camera-equipped UAVs for their SAR missions, there is a lack of means to detect someone based on their electromagnetic (EM) emissions. Unlike optical or thermal tracking, EM signals are less impacted by the time of day or the weather, and depending on the environment these signals can be detected across large distances. This makes EM signal detection and localisation a valuable tool for emergency and law enforcement organisations.

To illustrate, we can consider a scenario where a person suffers a medical emergency in a remote area, and requires immediate assistance. If the cellular network is unreliable (or unavailable), their only method of calling for help would be a radio transmitter. This transmitter would not only alert the emergency services, but also allow them to locate the person.

An aircraft such as a UAV is ideal for this role, as it can leverage its aerial position and 3D mobility to detect, identify, and localise the signal.

### A. Related Work

Prior works have used simulations to demonstrate how UAVs carrying wireless receivers can be used to locate a ground transmitter. In [5], the authors show how a UAV with a single receiver antenna can create a virtual antenna array in the sky to locate the direction of a received signal. In [6], the authors simulate a UAV flying in a rectangular back-and-forth flight pattern over a search area, and demonstrate how a linear least-squares algorithm can be used to approximate the transmitter location. In [7] the authors apply an Extended Kalman Filter (EKF) algorithm to localise the transmitter.

In recent years, there has been a revolution in the area of Software-Defined Radios (SDRs), which has enabled relatively low-cost hardware to be used for specialist radio communication and monitoring tasks. RTL-SDR USB dongles have been used for everything from spectrum analysis [8], to aircraft [9] and ship tracking [10], to monitoring cellular network control traffic [11]. Other hobbyist-grade SDRs like the HackRF One have been used to determine a signal's Angle-of-Arrival (AoA) across a large room via an antenna array [12].

An advantage of many of these SDR platforms is their small size and low power consumption, which makes it feasible to mount them on consumer UAVs. In this work, we demonstrate how a low-cost SDR can be mounted on a commercially-available UAV platform (of the same sort already used by Irish emergency organisations) to be used for locating signals of interest across large distances in an outdoor environment. Unlike the works cited above, we use neither simulations nor experiments in laboratory conditions to demonstrate this, but actual UAV flights in remote areas where real SAR missions occur. Our contribution is to show that such a prototype can be used to successfully locate the origin of a transmitter signal, and thereby assist with SAR operations.

This work is structured as follows. In Section II we describe the experiment location, equipment, and methodology. In Section III we provide the experimental results. In Section IV we conclude, and propose future directions for this work.

## II. EXPERIMENT DESCRIPTION

### A. Location

The Wicklow mountains national park is chosen as the location for carrying out the experimental measurements. As one of Ireland's six national parks, the Wicklow mountains are a popular destination for tourists, hikers, campers, and other outdoorsmen. As a result, it inevitably sees its share of missing person cases. The location of the experiment consists of a valley covered in heath and grassland, used primarily for cattle grazing. Individual trees below 5 meters in height and shrubs are found alongside several roads, but the terrain is largely devoid of tall vegetation. Single and two-storey farmhouses are found in clusters in the experimental area. The shape of the valley acts as a shield from RF emissions arising from the nearby city of Dublin. The transmitter is positioned in the middle of an empty car park to minimise the impact of nearby obstacles on signal propagation. A substantial body of water in the form of a reservoir is found in the valley, however this reservoir is positioned far behind the transmitter when sending signals to the receiving equipment, and is therefore not expected to impact the communication channel. Given the above environmental conditions, we assume that the UAV is able to establish an unobstructed Line-of-Sight (LOS) channel to the transmitter when it is flying in the air.

### B. Equipment

The AoA localisation equipment consists of a Kraken SDR platform [13] connected to a Raspberry Pi 4 and a USB powerbank battery that powers both devices, shown in Figure

2. The Raspberry Pi 4 is a miniature single-board computer running a Linux-based operating system on a quadcore ARM processor with a 1.8GHz clock speed and 4GB of RAM. The Kraken is an array of five RTL-SDR parallel circuits running on the same internal clock, whose signals are further synchronised to create up to five phase coherent IQ streams. Each RTL-SDR uses an analog-to-digital converter (ADC) to digitize the received signals into 8 bit IQ samples at a rate of 2.56 megasamples/sec. Because it uses the low-power, small-size RTL-SDR circuits, the Kraken platform can offer a sufficiently lightweight payload that can be powered by a portable USB power supply, which motivates the use of the device on our UAV.

We use four of the five SDR circuits, which are connected to four dipole whip antennas arranged in a Uniform Linear Array (ULA) configuration. The antenna elements in the ULA need to be spaced apart, with the inter-element spacing being between 0.2 and 0.5 of the wavelength of the signal we are trying to measure. The closer the spacing is to 0.5 the better the measurement resolution will be. If we wish for our localisation system to be useful for detecting a variety of different signals at different frequencies, we should choose an inter-element spacing that covers a range of frequencies commonly used for communication. In Ireland, consumer walkie-talkies use the PMR446 channels at 446MHz and LPD433 channels at 433MHz, while emergency organisations such as Civil Defence, the Garda Síochána (police service), the fire brigades and ambulance service use TETRA radios on the 390MHz band. These correspond to wavelengths of 0.67 meters, 0.69 meters and 0.76 meters, respectively. Given these wavelengths, the inter-element spacing should be between 0.15 meters and 0.33 meters, corresponding to a total ULA length of between 0.45 meters and 1 meters. Bigger ULA sizes can create stability issues for the UAV during flight, so we opt for an inter-element spacing of 0.225 meters (0.68 meter total length).

The connected Raspberry Pi processes the IQ samples from the Kraken, performs a squelch operation to determine if a signal is present on the frequency of interest, and then estimates the AoA of the signal (if present). The antenna array,



Fig. 1. Wicklow mountains national park.



Fig. 2. Powerbank-powered Raspberry Pi 4 with the Kraken receiver, and Motorola handset.



Fig. 3. DJI Matrice 350 UAV, with the dipole antenna ULA and electronic payload.

Kraken, Raspberry Pi and powerbank are attached to a DJI Matrice 350 UAV [14], as shown in Figure 3. This quadcopter UAV is capable of lifting up to 2.7 kg of payload, which is more than sufficient for our localisation system whose total mass is roughly 1.9 kg. The Matrice 350 is currently adopted by Civil Defence as well as volunteer mountain rescue teams in Ireland for SAR operations, which further motivates our choice of this system for the experiments.

In addition to the UAV payload equipment described above, we use a laptop to process the data from the payload after landing the UAV to estimate the transmitter location. For our experiments we use a Dell Latitude 5500 with an Intel Core i7-8665U CPU with a clock speed of 1.9GHz, and 32GB of RAM.

The transmitter used is a Motorola 1.5 W handset operating on the TETRA network [15]. The spectrum plot of this waveform is given in Figure 4.

### C. Methodology

1) *Signal Processing and Localisation:* To estimate the coordinates of the transmitter of interest, we first need to estimate the direction of the transmitter to the UAV at multiple different positions, by estimating the AoA of the received signal. This signal is received by the Kraken SDR during flight,

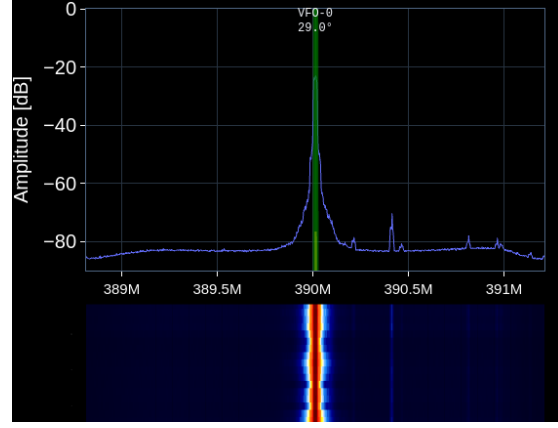


Fig. 4. Spectrum plot of the handset waveform.

and is digitised into IQ phase-coherent IQ samples across the antennas of the ULA. Once a second, 400 milliseconds of IQ samples are recorded, squelched (that is, discarded if no coherent signal is detected) and pre-processed using Forward-Backward Averaging [16] to improve measurement accuracy. After this, we can determine the AoA of the signal from the recorded IQ samples. This is achieved using the Multiple Signal Classification (MUSIC) algorithm [17], which returns an angle estimate with respect to the ULA boresight. These AoA estimates are recorded alongside the timestamp corresponding to when the IQ sample was recorded. These timestamps allow us to pair the AoA recordings with the flight logs of the UAV, which contain the GPS positions and the UAV orientation (the compass direction of the ULA boresight) at each moment of flight.

Having a set of direction estimates to the transmitter at several known UAV positions, we can estimate the coordinates of the transmitter. For this we use the Unscented Kalman Filter (UKF). The UKF algorithm begins with an estimate of the transmitter position, and using an estimate and measurement model it refines the position based on repeated input measurements. The UKF is an improvement over the EKF used in the related works above in that it allows for more accurate estimations in non-linear systems. In [18] the authors use the UKF to track the movement of multiple aircraft based on time-of-arrival. Although we track a ground object using AoA, the algorithm is applied in a similar manner. Starting with an initial location estimate (a random guess) we use each AoA measurement to gradually refine the location estimate and converge on the true location of the transmitter. To achieve this, we require knowledge of the mean and variance of the AoA measurement errors of our system. These are obtained by calibrating the UAV before carrying out the transmitter search.

2) *Calibration Flight:* The calibration flight involves obtaining a set of AoA measurements for a transmitter at a known location, and determining the AoA error mean and variance parameters to be used for the UKF. We expect that these parameters will depend on the distance between the transmitter

and the receiving UAV; however, we assume not to know a priori the distance to the transmitter to be located, therefore we choose a relatively short distance (but one sufficiently large to ensure far-field signal behavior). We position the transmitter at the UAV take-off point. The Raspberry Pi and Kraken are activated and begin taking IQ samples, as the UAV is manually flown away from the transmitter, while the ULA boresight is pointed towards the transmitter location by flying the UAV in such a manner that it faces the transmitter location. The quadcopter design allows the UAV to fly sideways to its facing direction, as such the UAV is flown at a speed of 15 km/h approximately perpendicular to the direction of the transmitter, to maximise the parallax of the AoA measurements.

During this flight a signal is transmitted, which is processed by the UAV equipment and a timestamped list of AoA measurements is recorded on the Pi. After several minutes of flying, the UAV is returned to the take-off point and transmissions stop. The AoA recordings are retrieved from the Pi, and the flight logs are retrieved from the UAV. Given the known GPS position of the transmitter, these flight logs are used to obtain the true AoA of the signal to the UAV at each timestep, which we then compare to the estimated AoA to obtain the mean and variance of the AoA measurement errors. These parameters are then used in the UKF.

It is very important that during the flight the ULA boresight is pointed towards the direction of the transmitter to minimise errors, as for a ULA its highest measurement resolution is for angles close to its boresight [19]. Any unexpected misalignments or tilts of the array can cause measurement errors. For a quadcopter UAV, these tilts can be caused by rotation along the three principal axes of movement: in aviation this is referred to as yaw, roll and pitch. Yaw is the horizontal rotation that we can directly account for by manually rotating the UAV to face the transmitter. Roll and pitch are caused by horizontal movement of the UAV as well as incoming wind which the UAV compensates for. For DJI quadcopters, roll and pitch angles are determined automatically by on-board avionics to ensure a smooth flight and compensate for wind effects. We can reduce the amount of roll and pitch by ensuring the UAV does not fly at high speeds, although the amount will still depend on wind in the area, which we cannot control for in a real-world environment (especially in a mountainous one). For the selected speed of 15 km/h, the UAV is able to maintain less than 5 degrees of roll and pitch on the antenna array. An investigation into the impact of UAV speed on measurement performance is left for a future work.

3) *Signal Localisation Flight:* Having obtained the AoA measurements and calibrated the UKF, we can carry out the localisation experiment. The transmitter is moved to a distant location away from the UAV take-off point; this location is assumed to be unknown to us and needs to be estimated. The receiver equipment is activated, and the UAV is launched directly up into the air. The transmitter then begins transmitting its signal. When the UAV is high enough in the sky to detect the signal over the noise floor, the receiver payload instantly begins determining the AoA via the MUSIC algorithm. At this

stage, we do not have an estimate of the transmitter location; however, these AoA estimates do provide an approximate direction to the transmitter from the UAV's position. This direction estimate is used to rotate the UAV so that the antenna array boresight is approximately aligned with the signal direction, to ensure accurate AoA estimates. As with the calibration flight, we wish to fly the UAV perpendicular to the estimated direction of the transmitter, to maximise the parallax. We fly the UAV in a straight line away from the take-off point, until we reach a distance of 350 meters, which is the legal limit for the UAV distance to its pilot. The UAV is then flown in the opposite direction back towards the take-off point. This is repeated several times. The UAV is then landed at the take-off point, with the AoA measurements and the flight logs retrieved. These are then passed into the UKF algorithm which is implemented in MATLAB running on a laptop. The UKF algorithm returns the estimated positions of the transmitter.

### III. EXPERIMENTAL RESULTS

Both sets of UAV flights were carried out from a launch location at 53°13'14.41"N, 6°19'29.67"W. Figure 5 shows the flight path of the UAV for the short-range calibration flight. The UAV was flown for 7 minutes and 40 seconds at approximately 30 meters above the take-off point, with the antenna array pointing approximately towards the transmitter location. The on-board equipment monitored the spectrum for the presence of the signal, and during moments that it was transmitting it would estimate the AoA once a second. The histogram of the AoA estimation errors is given in Figure 6. Note that we use compass bearings, with positive values referring to angles clockwise from the boresight of the antenna array. The mean error (or bias) is 1.83 degrees, with a standard deviation of 14.86 degrees. We attribute these measurement errors to fluctuating pitching and rolling of the UAV due to wind (as discussed in the previous section), as well as reflections of the signal coming off of the terrain.

Figures 7, 8 and 9 show the result of the long-range localisation flight and the AoA localisation. The UAV was flown for 14 minutes approximately 50 meters above take-off point, which corresponds to approximately 210 meters above the transmitter location. Figure 7 shows the flight path of the UAV, along with the estimated locations of the transmitter, numerically labelled according to the order of estimation. The initial estimate is a randomly selected location approximately 1.2 kilometers away from the true transmitter position; the UKF takes this initial position estimate, the measured AoA values along with their known mean and variance taken at multiple points by the UAV, and refines the estimates. The blue line in Figure 8 shows how the estimate position error changes as more and more AoA measurements are processed by the UKF. We can see that with 2 minutes worth of AoA estimates (given 1 measurement per second) the UKF can estimate the transmitter position to within 200 meters, with estimates being between 50-100 meters once we have more than 3 minutes of measurements to process. While the calibration flight was carried out to observe the behavior of the AoA estimation

errors, for the sake of comparison we can also apply the UKF algorithm to these estimates to localise the transmitter across the short distance; these results are shown with the red line. We observe that the estimate accuracy is within 50 meters by the end of the flight. It is interesting to note that the UKF algorithm appears to have more difficulty converging on an estimate for the calibration flight than the localisation flight, despite the fact that the former occurs over a much shorter distance. This is explained by the next figure.

Although the AoA measurement errors are assumed to be unknown for the long-range flight (as the "true" location of the transmitter is not known and needs to be estimated), for completeness we also include the histogram of these AoA error measurements in Figure 9. We observe that the AoA measurements were less noisy for the long-range flight, with a significantly smaller standard deviation of 7.54 degrees. We attribute this to the longer range between transmitter and

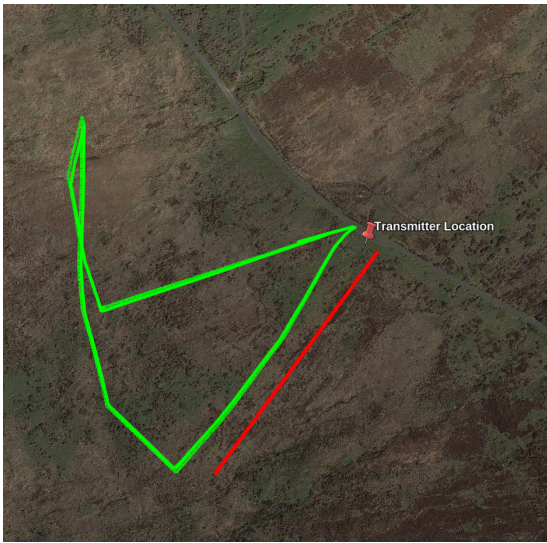


Fig. 5. GPS trace of the short-range UAV flight. 250 meter line shown for scale.

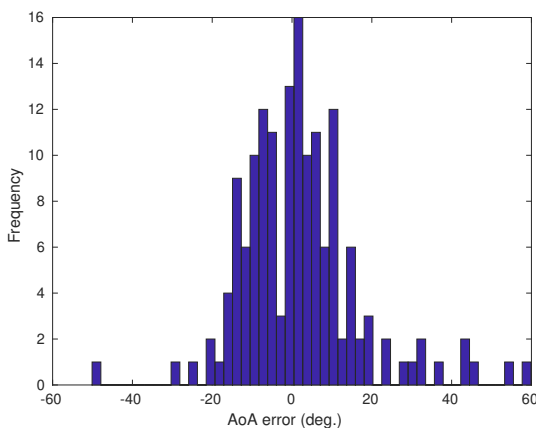


Fig. 6. Histogram of the AoA errors for the short-range flight. Mean is 1.83 degrees, standard deviation is 14.86 degrees.

receiver, which results in less impact caused by multipath reflections of the signal of interest. As a result, the localisation algorithm appears to work better for this set of measurements.

We report that it takes less than one second for the MATLAB implementation of the UKF algorithm to process the full set of AoA measurements and generate the results shown in Figure 8. Therefore this algorithm could be run in real-time and estimate the location as more measurements are obtained during flight.

As mentioned above, AoA errors can be caused by signal reflections from the terrain, as well as UAV tilting. Outside of a controlled lab environment it is very challenging to compensate for reflections, and the tilting along the roll and pitch axes are caused by wind, which is very unpredictable in a mountain environment. However, we have direct control over the horizontal yaw rotation of the UAV, that is the compass azimuth (mis)alignment of the ULA to the transmitter. Therefore we can measure the impact it has on the AoA error. We carried out a separate flight and had the UAV hover in the air, while rotating around its vertical axis. AoA measurements were taken for different azimuth orientations of the UAV (and therefore the ULA) relative to the transmitter direction. These results are shown in Figure 10. We can clearly see that the lowest errors are found when the ULA boresight is directly pointed towards the direction of the transmitter, and that the measurement errors increase with larger boresight offsets. This reveals one of the bigger drawbacks of the ULA design, in that it requires the array to be pointed approximately towards the signal of interest for the measurements to be accurate. This is not an issue with quadcopter-style UAVs (such as the one used in this experiment) that are freely able to rotate around their own axis independently of their direction of travel, but it can be a serious limitation for other types of aircraft, such as fixed-wing UAVs. Once we have an understanding of the measurement error distribution across the angle offsets for a given antenna array, it should be possible to determine if an offset is present for a given UAV orientation by having the UAV remain static in place and observing the distribution of the AoA measurements. This alone would not tell us exactly what the true azimuth of the transmitter is, but it will inform us if there is an angle offset present, and if it is significant enough to skew the measurement results. This can help us decide to change the UAV orientation given an unknown "true" location of the transmitter. We leave the exploration of this to a future work.

#### IV. CONCLUSION AND FUTURE WORK

In this work we detail the performance of a localisation system using a commercially-available UAV and low-cost, consumer-grade SDR receiver. We have demonstrated that the AoA measurements obtained by the receiver are accurate enough to be usable in signal localisation tasks, with our UKF-based localisation approach managing to estimate the transmitter location to within 100 m. As we used a ULA antenna array for this experiment, the alignment of the antenna boresight with the approximate direction of the transmitter

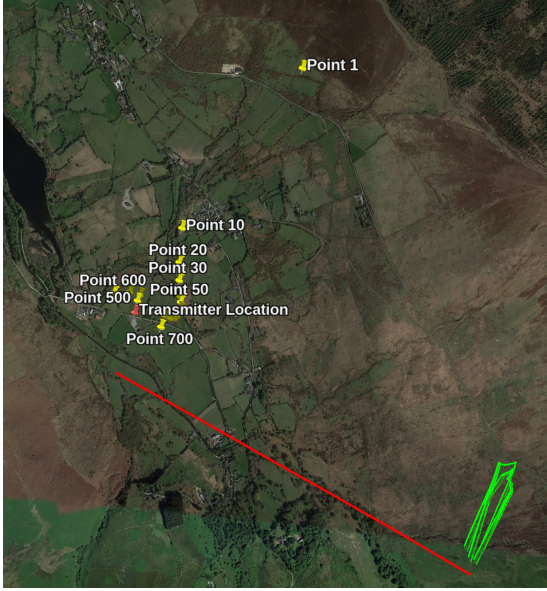


Fig. 7. GPS trace of the long-range UAV flight, along with estimated locations of the transmitter. 1.55 kilometer line shown for scale.

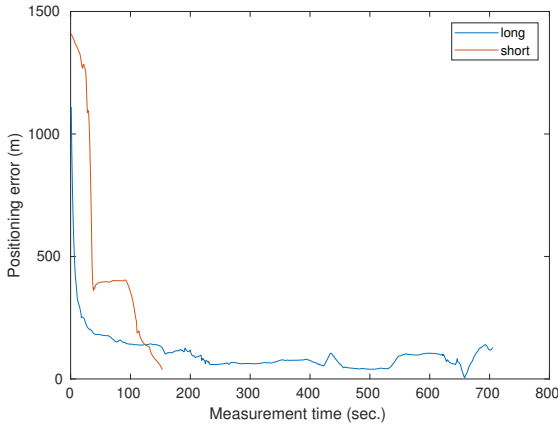


Fig. 8. Positioning error of the UKF algorithm over time.

during UAV flight was critical, and we demonstrated the impact of boresight misalignment on the resulting measurement performance.

It should be noted that, although for this experiment we focused on a SAR scenario, the AoA methodology shown here can be used to locate the origin of any detectable radio signal, provided it is in the tunable frequency range of the SDR. The system presented in this paper has applicability to the broader area of communication system localisation. In future works, we intend to explore localisation of transmitters using other frequency bands, including devices using the cellular network.

The work presented in this paper represents a preliminary set of trials carried out as part of the larger MISTRAL and GUARD projects that are currently underway with the Irish DF, with the ultimate goal of creating a fleet of communication and reconnaissance UAVs for the DF. While the current results

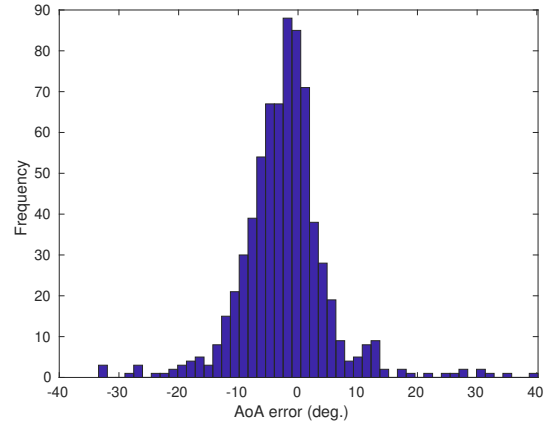


Fig. 9. Histogram of the AoA errors for the long-range flight. Mean is -2.2 degrees, standard deviation is 7.54 degrees.

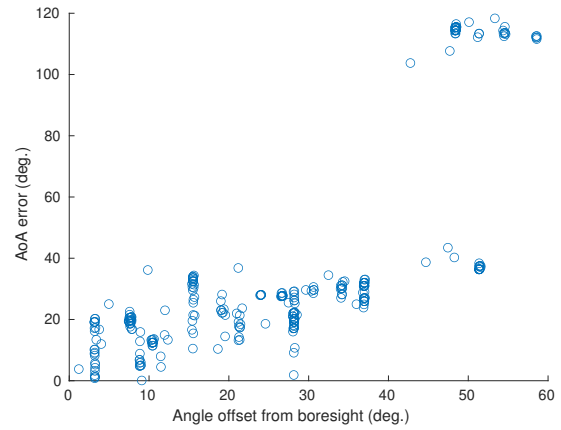


Fig. 10. AoA error under varying offsets from the boresight.

are promising, there is a number of areas where we intend to carry out further research. The ULA antenna design was shown to be sensitive to the orientation of the UAV with respect to the transmitter; this was shown to be easily avoided with a quadcopter UAV, however this would be a serious limitation for fixed-wing UAV designs. In future work we will investigate rectangular and circular antenna array configurations, which sacrifice measurement resolution in favour of consistent 360-degree performance.

The UAV was flown at a distance of approximately 1.5 kilometers from the transmitter for the long-range localisation test. This range was chosen out of practicality when organising the experiment. We have observed that an aerial UAV can detect a strong signal from very large distances, due to a lack of obstacles in the way [3]. Provided that the measurement errors remain consistent, we expect that the presented methodology could be used to localise a signal tens of kilometers away. The biggest challenge in that scenario would not be the detection or AoA estimation of the signal, but rather flying the UAV a sufficient distance to observe a

measurable parallax and change in transmitter AoA. For very large distances this could require the UAV to travel several kilometers while taking measurements, which is challenging to achieve from a regulatory perspective.

The experiments were carried out in a large, open area with a lack of obstacles that could shadow and occlude the signal, such as tree canopies. While this is a national park that sees real-life SAR missions, the environment is also particularly favourable for signal propagation. Emergencies also occur in areas with dense woodland cover or other complicated terrain, all of which could negatively impact the performance of the proposed localisation system. In subsequent experiments we will investigate the impact of vegetation around the transmitter on the localisation ability of our system. We will also carry out experiments in and around large bodies of water such as the Atlantic ocean, to examine the impact of water on localisation performance in maritime SAR.

Our experiments highlighted that the UKF algorithm is very computationally lightweight, and could run in real-time to process measurement data as it arrives. In this experiment, this was not possible as the GPS data had to be extracted from the UAV after landing; for real-time operation the computer running the UKF algorithm (such as the on-board Raspberry Pi) would require real-time GPS information, such as via a separate connected GPS module. We plan to explore this further.

Finally, in this work we have considered localisation of a transmitter that is fixed in place. The UKF approach can be used to localise a moving transmitter. The effectiveness of this will largely depend on the a priori knowledge of the transmitter and its mobility, as the UKF method relies on using a mobility model to predict the changing location of the transmitter over time, and aligning these predictions with measured values to arrive at a final estimate. Having prior knowledge about the transmitter (knowing that it belongs to a person who can only move at a walking pace, for example) will allow us to use a more accurate mobility model for the transmitter in our predictions, whereas having no knowledge of the type of device generating the transmissions will cause our prediction models to be more inaccurate. In follow-up experiments, we intend to explore this performance for a moving transmitter.

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