Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Computer Science

Toni Vucic, Christian Axell

Tracking sheep by radio tags and UAV

A field study of Bluetooth round-trip time ranging and multilateration

Master's thesis in Computer Science: Computers and System Software
Supervisor: Svein-Olaf Hvasshovd
July 2022

NTNU
Kunnskap for en bedre verden

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Abstract

Locating grazing sheep for both inspection and gathering is traditionally a time-consuming process that may require several days of searching on foot in challenging environments. Every summer, almost 2 million sheep are released on open pasture, and 12 % are lost.

In our thesis we perform field trials on the third iteration of a sheep localization system consisting of custom made lightweight radio tags on sheep, an automated UAV and custom Ground Control Station software. The goal is to evaluate the feasibility of such a system in the real world. The radio tags are placed on the collars or ears of grazing sheep and utilize Bluetooth Low Energy hardware. Localization is performed using Round Trip Time (RTT) ranging and multilateration. The RTT distance estimates are collected using an automated quadcopter.

We located stationary sheep tags in a farm environment with an average error of 15m, and showed that the system can detect tags in a thick forest up to 226m away. Together with results from earlier iterations of the system, it has now been shown that the system works in open fields, in thin vegetation and around a farm in a valley. It seems that the system works well for locating sheep, however our literature study showed that a system based on a 865MHz radio technology like LoRa might perform even better.

Sammendrag (Abstract in Norwegian)

Å lokalisere beitende sau for både tilsyn og sanking er tradisjonelt en tidkrevende prosess som kan kreve flere dagers leting til fots i utfordrende naturmiljøer. Hver sommer slippes nesten 2 millioner sauer på utmarksbeite, og 12 % går tapt.

I oppgaven vår utfører vi feltforsøk på tredje iterasjon av et sauelokaliseringssystem som består av egenbygde små radiomerker festet til sauer og lam, et automatisert kvadrokopter og en videreutviklet Ground Control Station-programvare for ruteplanlegging og visualisering av saueposisjonene. Målet er å evaluere hvor godt et slikt fungerer system i den virkelige verden. Radiomerkene er plassert på halsbåndet eller ørene til beitende sauer og bruker Bluetooth Low Energy-maskinvare. Lokalisering utføres ved hjelp av Round-Trip-Time (RTT) og multilaterasjon. RTT-avstandsestimatene samles inn ved hjelp av det quadcopteret.

Vi lokaliserte stasjonære sauemerker i et gårdsmiljø med en gjennomsnittlig lokaliseringsfeil på 15m, og viste at systemet kan oppdage merker i tett skog opptil 226m unna. Sammenlagt med resultater fra tidligere iterasjoner av systemet har vi nå vist at systemet fungerer i åkrer, i tynn skog og rundt en gård i en dal. Det ser ut til at systemet fungerer bra for å lokalisere sauer, men vår litteraturstudie har vist at et system basert på en 868MHz radioteknologi som LoRa kan yte enda bedre mtp. rekkevidde og signalpenetrasjon.

Preface

This thesis is a collaboration between two master's students at NTNU, Christian Axell and Toni Vucic. Christian is currently studying Information Technology, while Toni is studying Computer Science. We both have a background from Computer Engineering with a specialization of Software Engineering for our bachelor's degree. Our main motivation for choosing this thesis was that it was a hands-on task related to radio technology and UAV. During our master's Toni has been taking elective courses related to radio waves, robotics and communication technology, while Christian has focused on empirical methods and has an interest in building RC planes and hardware in general. Together this has allowed us to take on a thesis requiring knowledge of radio technology and hardware that is not typical for students of Computer Science and Information Technology. Still the work has been challenging, in particular in regards to use of the drone we inherited from Trygve Nerland. We have crashed and rebuilt probably 5 times, delaying many of our practical experiments by 2 months due to having to wait for parts.

We have been working very closely throughout the preparatory project and thesis, and being two people has been valuable when performing many of the experiments. Our knowledge and interests have been complimentary and the thesis could never have become this good without each other. We are leaving our improvements to Radio Sheep Ground Control Station open-source and hope you as readers find the thesis results and discussions valuable for further work in sheep localization.

Acknowledgements

We want to start by thanking our supervisor Svein-Olaf Hvasshovd who have been an excellent supervisor providing us with his expertise, words of encouragement and access to research funds.

Of last year's students who helped us with our thesis we would first like to thank Trygve Nerland for providing us with his personally made drone from his thesis which we managed to destroy. We would also like to thank him for his continued support during the semester as we inquired him a lot and he was kind enough to provide us detailed answers regarding drone construction and multiple other parts of the project. Secondly we would like to thank Gard Steinsvik as he provided us with the source code for his Radio Sheep Ground Control System that we used and built upon in our work. He also went out of his way to patch his code to make it work properly for our computers so we could conduct tests without errors. Lastly we would like to thank Gregorz Swiderski for providing us with the source code for his excellent distance estimation implementation that we used in our thesis. We would also like to thank him for helping us debug the code for the microships, and ultimately fixing it so we could perform the proper tests in time for the sheep release.

We also wish to give a huge thanks to Bente Sagberg and Odd Brevik for allowing us to perform experiments on their farm and with their sheep and lambs. Their help in mounting the tags on the sheep has also been invaluable.

Furthermore we would like to thank Terje Mathiesen for giving us access to NTNU's "echo-free" room and instructing us in how to use it. We also wish to thank him for answering our questions about radio technology. Additionally we would like to thank Aleksander Elvebakk, Gard Steinsvik, Trygve Nerland, Grzegorz Swiderski, Elias Brattli Sørensen, Elisabeth Axell and Tijana Gajic for helping with review of our thesis and providing valuable feedback on structure, content and proofreading and new interpretations.

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Acronyms

AoA Angle of Arrival. ix, 6, 9–12, 23

BLE Bluetooth Low Energy. 13, 25–29, 31, 32, 94, 96, 100

COTS Commercial off-the-shelf. 11

GNSS Global Navigation Satellite Systems. v, 4, 6, 13, 14, 25, 29, 30, 68, 97

LoS Line of Sight. x, 8, 9, 11, 14, 27, 39, 48, 79, 94, 95, 98

NTNU Norwegian University of Science and Technology. 50

PDR Package Delivery Ratio. 22, 83, 84

ROI Region of Interest. 23

RSSI Received Signal Strength Indicator. x, 2, 6–11, 14, 21, 25, 26, 38, 39, 43, 45, 51–56, 81, 96

RTL Return to Land. 67, 85, 86

RTT Round Trip Time. v, viii–xii, 1, 2, 6, 8, 9, 13, 14, 22, 23, 25, 29–33, 38, 45–47, 49, 50, 52, 56, 57, 59–62, 65–68, 70–76, 78–81, 83–88, 90–92, 94–96, 100, 111–113

SoC System on Chip. 9, 22, 34

TDoA Time Difference of Arrival. 6, 13

ToF Time of Flight. 6, 8, 9, 14, 25

UAV Unmanned aerial vehicle. iii, v–vii, xi, 1–3, 6, 10, 11, 13, 14, 19–21, 24, 25, 27, 29–31, 50, 56, 60, 65, 66, 69, 77–80, 83–86, 90, 92, 95–100

UWB Ultra-wideband. 9, 12–14, 24, 27

WUR Wake-up radio. 27, 96, 98, 101

Chapter 1

Introduction

2 million sheep in Norway graze in the country's wild nature. Checking up on them and collecting them in the fall is a strenuous process that can take days of searching on foot before all the sheep are found. Recently GPS-enabled tags have entered the market giving farmers regular updates on the location of their sheep. However they are expensive relative to the value of the sheep and sometimes unreliable. This is evident as they are only used for 5-10% of Norway's sheep. There is a need for a low-cost alternative that can also be mounted on growing lambs, for example as a part of their identification ear tag. The technology could also be generalized to locating objects, livestock or people, provided they have a radio tag that can interface with the UAV.

In our thesis we aim to evaluate through field trials the feasibility of a system developed by 3 master's students as a part of their thesis work in 2021. The system utilizes small radio tags mounted on sheep, and an automated quadcopter UAV flying a generated route covering the area of interest. The UAV performs range measurements using Round Trip Time (RTT) when the tags are in range. These range measurements are then used to create a location estimate using a multilateration algorithm in a custom Ground Control Station software developed in [1]. We built a custom UAV based on the frame from [2] that performs the ranging with the sheep tags using a custom RTT ranging implementation developed in [3]. We have evaluated this ranging implementation against the state of the art from Nordic Semiconductor released spring 2022.

While [1–3] have demonstrated that the system can locate stationary tags in an open field, they did not test it on real sheep or more challenging sheep grazing environments like valleys or forests. They proposed a small prototype tag, but building a well performing prototype tag required a more thorough investigation of antennas and radiation patterns than done in their thesis. In our thesis we have experimentally evaluated different antennas and orientations in order to build a well performing prototype tag, as well as testing it on real sheep in a real sheep grazing environment and in thick forest.

The previous choice of Bluetooth for the radio technology might not be ideal due to the limited range and foliage penetration capabilities. Thus we have also performed a literature study into alternative radio technologies for sheep localization using an UAV.

With this thesis we hope to discover through experiments and our literature study if the system functions well in a real world environment, and how it can be improved.

1.1 System requirements

The system modified for the purpose of the creation of this thesis should:

- Provide sheep position estimates with a maximum localization error of 19 meters. No worse than 2021's NTNU papers[1, 2].
- Have a Line of Sight range of at least 500 meters.
- Have an UAV that can fly far enough to perform several medium scale survey flights.
- Assist in actually locating by eye specific sheep in a real sheep grazing environment.

1.2 Research questions and how they will be answered

1.2.1 RQ1: How well does a UAV-based sheep localization system function in a real world environment?

We define "How well" the system functions primarily based on how accurately it can locate sheep, but also if the method proposed is practical and useful in real world use. Other metrics are system reliability and availability.

To answer this research question we have performed a real-world trial of an iterated version of the sheep localization system proposed in [1–3] in a real sheep grazing environment on real sheep. The system consists of new custom radio prototypes attached to the sheep, running RTT software from [3], a modified version of Radio Sheep GCS[4] originally created for [1] and a modified version of the UAV created for [1, 2]. Then evaluated all parts of the system compared to alternative solutions found through a literature study.

This necessitated the creation and testing of miniaturized radio tags for sheep that support Round Trip Time (RTT) distance estimation, which we have experimentally evaluated, partly as a part of Research Question 2.

1.2.2 RQ2: What kind of antenna and orientation is best for sheep localization?

To answer this research question we will experimentally evaluate the impact antenna type and orientation has on Received Signal Strength Indicator (RSSI) for a subset of small lightweight antennas suitable for attachment to drones or sheep.

1.2.3 RQ3: What is the best radio technology for localization of sheep using UAVs?

To answer this research question we performed a literature study. We also hope that our experimental results linked to RQ1 will contribute to the knowledge base regarding this.

1.3 Outline

Chapter 2: "Background" introduces sheep localization, radio localization concepts, antenna theory, previous work, as well as a litterature study into the best radio technology for sheep localization.

Chapter 3: "Our chosen localization method" specifies our method for locating sheep tags, as well as the hardware and software in use for other experiments.

Chapter 4: "Investigation" presents all of our experiments chronologically. The experiments build upon each other and contain their own methods, results, discussions and conclusions.

Chapter 5: "Discussion of research questions" discusses and somewhat concludes all 3 of our main research questions.

Chapter 6: "Future work" consists of a summary of the future work discussed in our experiments and literature study discussions.

Chapter 7: "Conclusion" is a overall conclusion for the whole thesis, presenting key findings.

Chapter 2

Background

2.1 Sheep localization: What and why?

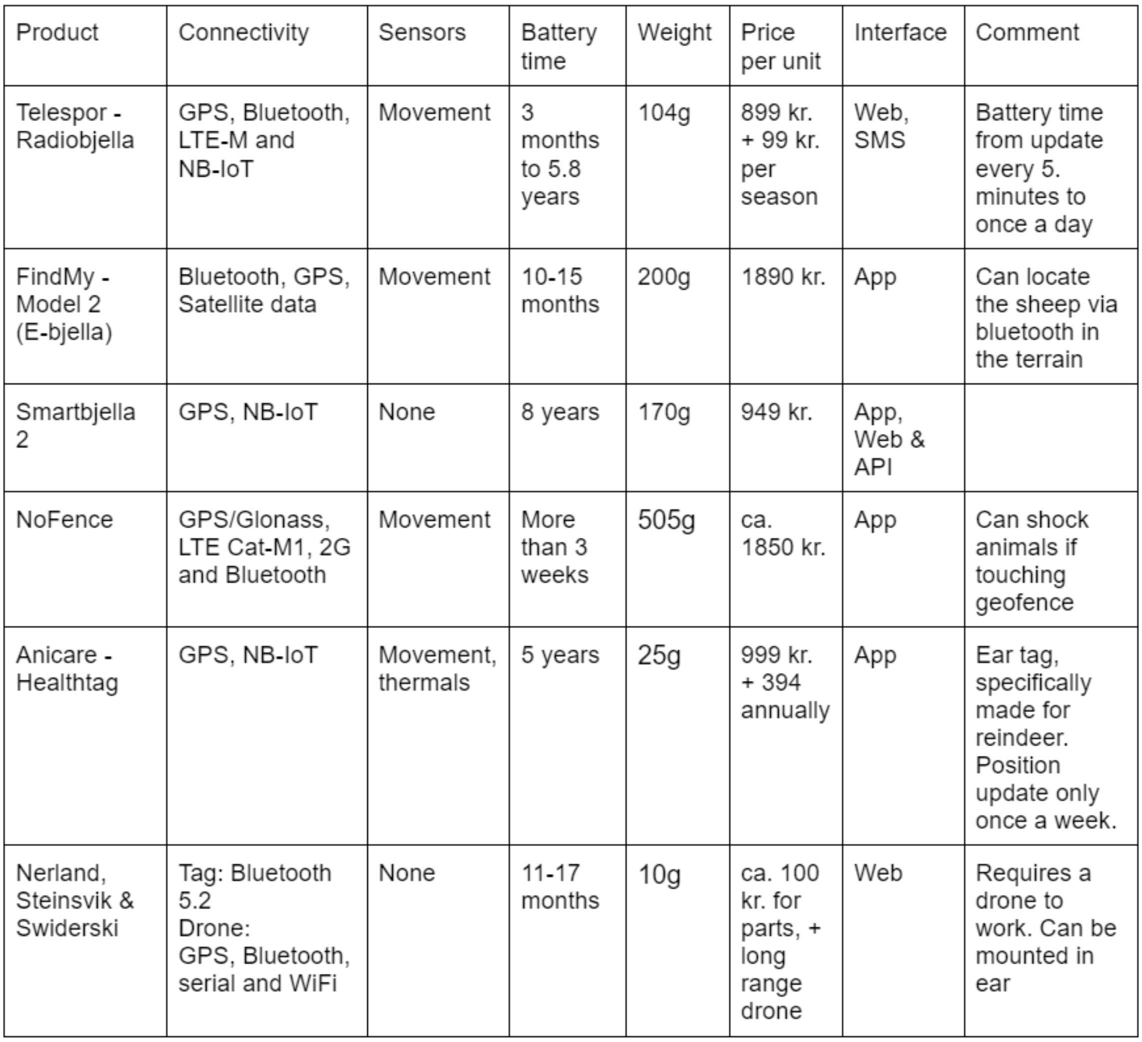
There are approximately two million sheep grazing in the Norwegian rangelands every summer[5]. Of these, 12% die or are lost while grazing, where most of these losses occur while the sheep are grazing in the rangelands. These rangelands where sheep graze are sometimes called outlying fields or outfield pastures. The sheep are released in the spring and collected again in the fall, mostly for slaughter. Norwegian law requires that the sheep are checked up on once per week to ensure animal welfare.[6] Both checkups and sheep collection in the fall require that the sheep are localized. Locating and retrieving sheep in the fall typically takes several tens of hours when using the traditional method of going by foot and attempting to locate the sheep by sight and sound.[7]

In Norway, only 3% of the area can be used for farming, while 45% can be used as grazing grounds for livestock.[8] Areas suitable for sheep grazing vary in vegetation type, but are everything from the edges of thick pine forests[9] to half-barren islands[10], wherever there is enough grass, shrubs or herbs for the sheep to gain weight. The value of grazing in these areas corresponds to about 1 billion NOK annually in sheep feed for the whole country.[11]

2.2 Sheep localization technologies available today

As a part of the preparatory work for this thesis we did an internet search of technology-enabled sheep localization techniques where a an overview is presented in Figure 4.2. This section is based on that work.

Radiobjella, Smartbjella 2, NoFence and Healthtag sell collars/devices that use a combination of GPS data and cellular connectivity. GPS or other global navigation satellite systems (GNSS) are used to retrieve the positions of the sheep. Then the positional data is sent periodically over low-power cellular connections like LTE-M or NB-IoT. These new cellular technologies enable longer range and



Product	Connectivity	Sensors	Battery time	Weight	Price per unit	Interface	Comment
Telespor - Radiobjella	GPS, Bluetooth, LTE-M and NB-IoT	Movement	3 months to 5.8 years	104g	899 kr. + 99 kr. per season	Web, SMS	Battery time from update every 5. minutes to once a day
FindMy - Model 2 (E-bjella)	Bluetooth, GPS, Satellite data	Movement	10-15 months	200g	1890 kr.	App	Can locate the sheep via bluetooth in the terrain
Smartbjella 2	GPS, NB-IoT	None	8 years	170g	949 kr.	App, Web & API	
NoFence	GPS/Glonass, LTE Cat-M1, 2G and Bluetooth	Movement	More than 3 weeks	505g	ca. 1850 kr.	App	Can shock animals if touching geofence
Anicare - Healthtag	GPS, NB-IoT	Movement, thermals	5 years	25g	999 kr. + 394 annually	App	Ear tag, specifically made for reindeer. Position update only once a week.
Nerland, Steinsvik & Swiderski	Tag: Bluetooth 5.2 Drone: GPS, Bluetooth, serial and WiFi	None	11-17 months	10g	ca. 100 kr. for parts, + long range drone	Web	Requires a drone to work. Can be mounted in ear

Figure 2.1: Available products compared to 2021's NTNU project

lower power consumption for the same data rate compared to previous solutions like 2G, 3G and 4G.

Anicare with their Healthtag are the only ones with a product that can be attached to the animal's ear, similar to what we are attempting.

Henrik Nyholm [12] mentions regarding Anicare's Healthtag that "while having a radio on each raindeer is probably economically feasible, it is likely not the case for sheep since the worth of each animal is significantly smaller." We investigated the number of tracking devices sold by the different vendors in Norway based on their published sales figures as of December 2021. Sold units for all brands totaled less than 100.000. There are approximately 2 million sheep grazing outside of enclosed areas in Norway[5], so the low adoption rate could indicate that the current solutions are still not attractive enough for the vast majority of Norwegian sheep farmers. A quick look at the comments section of the Facebook pages of Radiobjella[13] and Smartbjella[14, 15] indicates that several farmers are unhappy with both the price and reliability of current solutions. Nyholm[12] also mentions that the NB-IoT coverage does not yet cover several important locations for sheep farming in Norway, although this could have changed since his thesis was published in 2020.

FindMy uses satellite data communication and thus has more reliable communication capabilities, but is also the most expensive solution as seen in Figure 4.2.

2.3 UAV localization methods proposed in literature

This section gives an overview of technologies and methods used for localization of objects using Unmanned aerial vehicles (UAVs), popularly called drones. For radio localization using UAVs to work, the UAV needs to be combined with a localization method as described later in this chapter. There are terrestrial localization methods that do not involve a UAV, such as utilizing a Global Navigation Satellite Systems (GNSS) system or fixed radio anchors. They are however not a focus of this thesis.

2.3.1 Overview of UAV localization methods

Previous works have focused on either radio localization[1–3, 12], or localization using normal[16, 17] and or infrared cameras[17–21]. The focus of this thesis is radio localization.

2.3.2 Radio localization methods

There are several different approaches to locating objects using radios. In this section we will explain triangulation using Angle of Arrival (AoA) and multilateration using Round Trip Time (RTT) or Time Difference of Arrival (TDoA), with an extra focus on multilateration as it is the method in use for this thesis. There are also other techniques such as fingerprinting[22], although it is not very suitable for use with an UAV[12].

Range based localization with multileteration

For the purpose of finding a static object using a moving drone, Received Signal Strength Indicator (RSSI) or Time of Flight (ToF) (typically Round Trip Time (RTT)) are used to obtain a distance between two objects. This process is called ranging. The distance measurements are then combined using techniques like multileteration in order to find the position of the object(s) in 2D or 3D space. This process is called localization.

Multilateration

Multilateration is a localization technique that works by combining several range measurement from multiple known positions. Circles can be drawn with the radius of the range measurements. The point where the circles intersect is the estimated position output from the multilateration algorithm, as visualized in Figure 2.2.

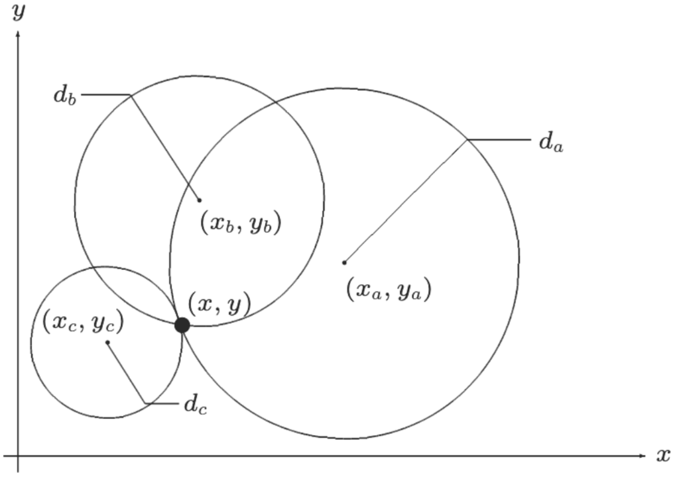


Figure 2.2: Two-dimensional multilateration problem. X and y are distance axes. From [23]

Due to inaccuracies in the measurements, or movement of the object that is being localized during the localization, there might not be an exact intersection point. In this case the radius of the circles can be increased and the area of intersection can be used instead like implemented in [12] and [1]. This is visualized in Figure 3.1. For a more in-depth explanation of the math involved we refer to [1, 12].

As an alternative to multilateration, the particle method has been considered and tested in [1], but it performed much worse than multilateration, and is thus not a focus of continued study for us.

Different ranging methods are explained below.

Received Signal Strength Indicator (RSSI)

RSSI is a measurement of the strength of the received signal, typically in dBm. dBm is a logarithmic unit used to measure power level. If one knows what distance each dBm value corresponds to, it can be used for ranging. A crude mapping between dBm and distance can be done by using models like the Free-space path loss model or the Two-ray ground-reflection model[12]. For more accurate mappings, measurements must be done at several distances. Using these measurements a propagation model can be created. Attempting to use the model in another environment than the one it was created in, leads to incorrect mappings between dBm (signal strength) and distance.[22, 24] This is because different environments have different levels of shadow fading (signal loss due to obstructions) and different levels of interference caused by the emitted radio waves reflecting off of the surrounding environment (multipath fading). For longer range transmissions than those applicable for this thesis there there are additional fading effects as described in [25, 26]. There can also be a complete lack of a direct Line of Sight path for the radio signals, making the object appear further away since the only path is an indirect one.

Time of Flight (ToF)

Time of Flight measurements are done by sending out a signal, and measuring the time it took for it to reach the target. Since it is known that radio signals travel at the speed of light, the distance the signal has traveled can be calculated from the time measured. These measurements have to be taken by the target node, and typically require synchronization of clocks[27].

Round Trip Time (RTT)

Round Trip Time measurements are done by sending out a signal, having it be picked up by a receiver node, having the node send a message back, receiving the response, and then timing the time it took for this whole interaction from start to finish. Like ToF is based the fact that we know that radio signals travel at the speed of light (299 792 458 m / s). Conceptually, if we compare the time the signal was sent with the time the signal was received, we get the distance the signal has traveled in that time.

Unlike for radar, where the signal is simply reflected immediately by the objects it hits on the way, RTT methods have to take into account that the signal is received by a node, processed, and then a response is sent back. Typically the time it takes for a device to receive, process and send a response to a received RTT package can be discovered experimentally. Due to jitter in the hardware this time is not equal every time, and thus several RTT measurements are typically performed in quick succession from the same position to average out this error[12]. Doing this we get the measured time the signal has traveled and thus can calculate the distance based on the speed of light. The method builds upon Time of Flight (ToF) and is sometimes called Round Trip Time of Flight (RT-ToF)[28].

Comparison of RSSI and RTT

When comparing RSSI and RTT the following parameters are of interest.

- Ranging performance
- Availability
- Cost

Ranging performance

Both RTT and RSSI require a model mapping measured values to real world distances to determine the range between the devices. For RSSI this means a model that maps each received signal strength value to a corresponding distance. For RTT it means mapping each round trip Time of Flight to a distance. The way the signal propagates varies based on it's environment, and using a propagation model created from one environment in another environment with different levels of fading can have a big impact on accuracy.[22].

A problem for both RSSI and RTT is shadow fading. Shadow fading occurs when something is in the way of the direct Line of Sight (LoS) between the two radios that are trying to communicate. When an object is in the way the signal strength is reduced. RTT ranging accuracy is much less affected by shadow fading than RSSI. This is because obstructions in the path of a RSSI measurement directly affect the measurement result, making objects appear further away as the signal is weakened by the obstruction. For RTT shadow fading does not directly affect ranging accuracy, although the signal is also weakened so that the RTT measurement's operational range is decreased.

Nyholm[12] found that RTT had significantly better accuracy than RSSI when used to perform multilateration from a drone on simulated sheep outdoors.

Availability

RSSI measurements are supported by most wireless devices, while ToF is not. However Apple devices like the iPhone 11 or later have recently received ToF support through UWB support. It is possible to implement ToF/RTT measurements in dedicated Bluetooth devices like done in [3], but this requires some upfront RD costs. With the addition of RTT to Nordic Semiconductor's distance measurement library[29] in spring 2022 it has become more accessible.

A quite strict control of the Bluetooth device hardware is needed to get accurate RTT measurements. Nyholm[12] used a seemingly hacky solution in his experiments based on interrupts and restarting the device, and proposed using the TimeSlot API provided by Nordic Semiconductor instead. He proposed removing the Bluetooth stack completely and creating a custom communication protocol in order to remove the seemingly redundant connection step of Bluetooth and thus increase efficiency.

Cost

A 2021 paper[30] stated that "Unfortunately, ToF estimation requires additional electronics (e.g. oscillators) which increase power consumption and cost." However, it was demonstrated in both [1–3] and [12] that it was possible to do without external oscillators using commercially available Bluetooth SoCs.

Angle of Arrival localization (Range-free localization)

Angle of Arrival (AoA) localization is a technique that does not require the range between nodes. Instead, two measurements producing an intersection point are enough to get an estimate of a node's location. This can be done using moving directional antennas or an array of antennas.[31] Antenna arrays are known to increase cost and complexity[32]. However recently cheap off-the-shelf devices have appeared offering the functionality. For example AoA is supported by Bluetooth since Bluetooth 5.1 released in 2019, although the accuracy at range is limited.

Conceptually, AoA is shown in Figure 2.3. Here two directional antennas are sweeping an area until they detect a signal that they then hone in on. Uncertainty in the angle measurements leads to the position being within an intersection area instead of a fixed point.

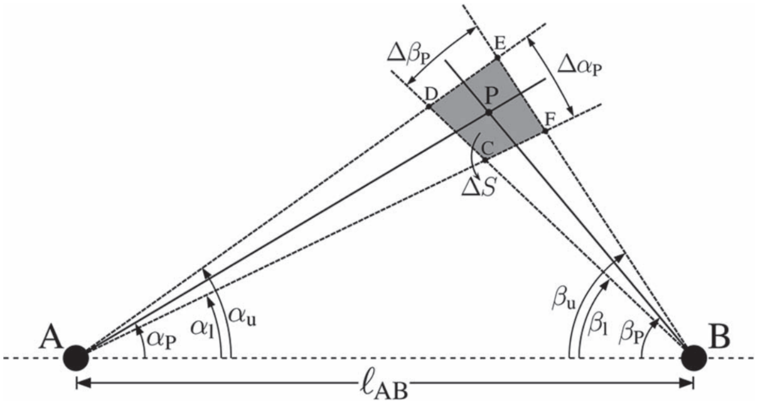


Figure 2.3: Angle of Arrival (AoA) localization. From [33, Fig. 2]

We investigated the sources used by [2] and [12] to gain a better understanding of the feasibility of using Angle of Arrival (AoA) localization together with an UAV. Key points are presented below with a summary at the end.

[34] used a grid of monopole antennas sampled sequentially (called Pseude Doppler) to estimate the Angle of Arrival (AoA) of incoming radio signals. They achieved an estimated AoA within 10 degrees of the ground truth. The receiver and transmitter were positions 20 meters away from each other. They concluded that pseduo Doppler can be a good candidate for UAV based animal tracking.

[35] used Yagi Rotation to find the AoA of nodes in an open field within at distances between 0.75 and 1km. Their drone carrying the directional antenna flew between 20 and 60 meters above the ground depending on the test. Their tests demonstrated an accuracy of -+20 degrees. The maximum range of their proof of concept system was 1km. They also found that detection became easier as they increased the height from 35 to 60 meters.

[36] used a directional Yagi antenna on a drone to determine the location of a radio tag within a circle of radius 10 meters. The target was 150 meters away from their UAVs initial location and it flew with an altitude of about 30 meters, locating it in less than 13 minutes.

[37] used a combination of RSSI and AoA to achieve a 2.7 meter localization accuracy on average. Their drone flew to the target, then noted the position once it had reached it. Their experiments were conducted on a football field.

In summary localization accuracy in the short range tests performed is good enough for sheep localization. However, only one experiment, [35] was performed at longer ranges, and they only did it with a stationary drone. Further studies are required to determine the feasibility for locating sheep although it seems like a viable option to study further.

Angle of Arrival localization using Bluetooth
Since previous research on sheep tracking has used Bluetooth, and recent off-the-shelf Bluetooth chips like the nRF52833 support AoA, how does Bluetooth AoA perform for our use?

To perform this short literature study the search term "angle of arrival localization bluetooth" was input into Google Scholar and papers were picked based on their abstract, with a focus on finding long range outdoor experiments. However the vast majority of the results were short range studies and many of those are not included here.

[38] found the direction finding error to be between 10 and 0 degrees in an outdoors scenario when outliers from their experiments were removed. They noted that "80% of the averaged estimations are affected by error below 1°" Even in an indoor environment with more multipath effects, the average estimation error is "well below 2°". Trying to find an object in a indoor 4x2.7m 2D plane, using two receivers, they had an error below 85 cm for more than 95% of the positions.

[39] developed a Convolutional Neural Network (CNN)-based indoor localization framework to tackle issues specific to indoor AoA estimation with Bluetooth in noisy environments with little LoS. The proposed CNN-based AoA framework tracks mobile agents with 87% accuracy in the presence of noise, Rayleigh fading, and elevation angle. While the accuracy of Capon and phase difference-based frameworks tested were 74% and 59%, respectively.

[40] tested using an external uniform linear array (ULA) together with Bluetooth 5.1 to estimate AoA. They observed a maximum deviation of 3° and a mean error of 1.9° in an indoor environment.

[41] simulated localization of nodes using fixed-wing UAVs using AoA. Their simulations showed a localization error between 400m and 160m depending on how many UAVs were used simultaneously (3 to 9). The results should apply to using one UAV flying the same path as the sum of several other UAVs if the targets are relatively stationary.

[42] found Bluetooth 5.1 to have an average distance error of 0,7m when RSSI was combined with AoA. The tests were conducted in a 25x15m indoor laboratory with obstructions present. The receiver using a 4x4 Uniform Rectangular Array (URA) was placed around the room to take measurements which were combined afterwards.

[43] compared indoors and outdoors AoA localization using Commercial off-the-shelf (COTS) Bluetooth 5.1 devices. They demonstrated an average angular error in an outdoor environment of just 0.28°, 73% better than indoors. They managed to obtain an average positioning accuracy outdoors of 22cm, 39.7% better than their indoor tests. Both tests were performed with the nodes at ranges less

than 10 meters from the antenna arrays.

[44] compared UWB and Bluetooth direction finding. With UWB they achieved an angular accuracy of up to 5° even under obstructed LOS and multipath, while they got an overall mean error of nearly 25° with BLE in an outdoor scenario without obstacles. However the outdoor experiment is not detailed in the paper and only mentioned in the abstract, so it cannot be verified. Experiments were performed at ranges of 2 m, 3 m and 4 m. They found that for Bluetooth using an antenna array with 3 antennas instead of 2, reduced the RSME (deg) from 45° to 5° in one of their LOS setups.

In summary Bluetooth AoA can have has sub meter localization accuracy in room-scale indoor environments. It performs better outdoors due to less multipath effects. A 22cm outdoor localization accuracy was demonstrated in [43] at a range of 10 meters. However longer range outdoor localization performance is currently unknown. Although one could imagine the localization error increasing with range as seen in Figure 2.4.

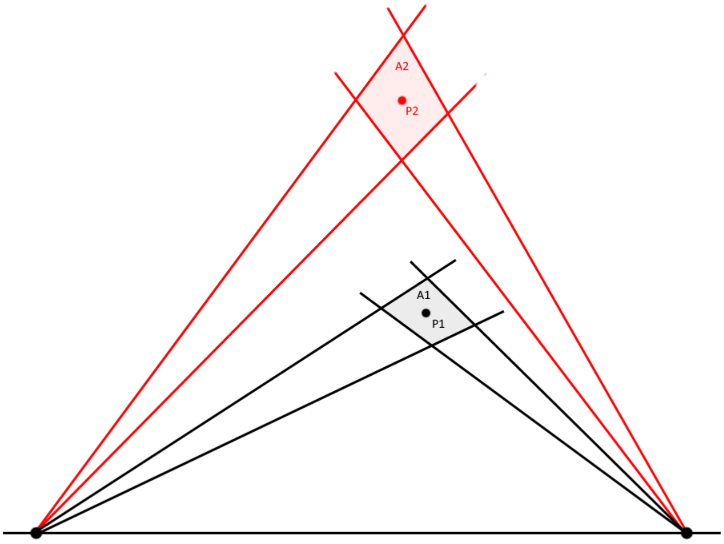


Figure 2.4: The intersection area of AoA increases with distance from the antenna(s)

As discussed in [12] Knowing which direction a signal is coming from could be beneficial for dynamic route planning, but does not necessarily lead to increased tracking precision, because of the uncertainty in Angle of Arrival measurements. If the technology was to be used, a neural network approach like the one proposed in [39] could be useful.

Other technologies

Time Difference of Arrival (TDoA) is mentioned in the literature[24]. It works in a way that several receivers receive the same signal, then compare when they received it in order to perform multilateration. We do not investigate this further as we only intend to use one drone, but for a multi-drone system or a system using a combination of drones and base stations it could be viable as it is used for indoor localization today.

2.4 Factors impacting the accuracy of RTT radio localization with UAVs

The localization accuracy of UAV based multilateration using Round Trip Time (RTT) is mostly impacted by two things, the ranging accuracy of the RTT implementation, and the accuracy of the UAVs own position estimate when performing the ranging. The most common positioning technique for UAVs is using Global Navigation Satellite Systems (GNSS), so the discussion will be limited to that in regards to the UAV factor.

2.4.1 Factors impacting ranging accuracy

The narrow bandwidth of 2.4GHz protocols like BLE make the ranging more prone to multipath effects in reflective environments compared to wider band technologies like UWB.[45, 46] In [45] they attempted to remedy this effect for Bluetooth by utilizing all the 2MHz narrowband channels available to Bluetooth.

When doing RTT measurements there is also a theoretical limit to the ranging accuracy based on the wavelength of the signal. Signals with short wavelengths like the 2.4Ghz radio waves used by BLE allow for higher resolution timing than long wavelenght signals like those in use by technologies like LoRa and Sigfox. For Bluetooth the maximum spatial resolution is 3.75 meters[45]. UWB which runs from 3.1 GHz to 10.6 GHz allows for even higher resolution time measurements.

The frequency of both the radio peripheral and the CPU are also central for ranging accuracy. Where high clock speeds/sampling rates lead to higher ranging accuracy than low ones[47]. To achieve a 30cm resolution in a single measurement, the BLE radio and timer employed for measuring the ToF should be clocked at 1 GHz[48]. Today one can expect the radio's sampling frequency to be 16 MHz[47].

When performing RTT measurements, jitter (the same operation not taking the same amount of time each time) in the hardware causes inconsistencies in the time it takes for processing the signal at both the sender and receiver side. To mitigate this, typically 3-4 packets are sent in order to perform a distance measurement. If the positions of the sender and receiver stay the same, using the average (or some other aggregate) of the measurements will help reduce the jitter error and increase the precision of the RTT measurement[49]. This comes at the cost of more communication time per distance measurement and thus higher total power consumption.

Multipath propagation is a problem that affects both RSSI and RTT ranging. In the case of the Line of Sight being blocked, the radio waves take alternate routes to the receiver. As these routes are longer than the direct LoS, the waves will travel further than the shortest distance between the two objects, leading to the object appearing further away than it is. Multipath propagation can also cause destructive interference, weakening the signal and reducing the range.

Increasing the bandwidth of the signal allows for correction of multipath effects due to more data on how the different frequencies propagate in the environment. Ultra-wideband (UWB) technologies are thus less exposed to multipath, leading to higher precision when the right algorithms are used.

One intereseting advantage of RTT over RSSI is that the error does not increase with increased transmission range[50].

2.4.2 Factors impacting GNSS precision

Global Navigation Satellite Systems (GNSS) systems typicaly have a horizontal positional accuracy of 1-3m[51]. GNSS systems like the american GPS utilize Time of Flight (ToF) just like RTT and are thus prone to some of the same errors as outlined in the previous section. Low clock precision in cheap GNSS receivers leads to worse localization accuracy.[52]. Assuming one is already using a high quality GNSS receiver, and excluding the effect of intentional jamming, the most prominent variable impact accuracy is multipath. Multipath can in the most extreme cases can lead to GNSS localization error of as much as 100m[52]. However for multipath to occur the signal has to be reflected before reaching the UAV. If the drone is flying high and utilizing an antenna cancelling out signals from below and to the side the effect of multipath should be small and similar to that of that experienced by a plane[52]. However if the drone is flying low in areas such as a valley, there is a chance that signals bouncing from the sides of the valley could interfere. The walls of the valley would also obstruct line of sight for satellites near the horizon. We were unable to find methods in the literature for quantifying the effect of these factors for an UAV.

The localization accuracy of GNSS can be improved by using Real-time kinematic positioning (RTK)[53]. Which utilizes a fixed base station at a known location to correct for errors in the GNSS measurements on the moving UAV. These systems typically have a horizontal positional error relative to the base station of just 1 cm.

2.5 Antenna considerations

In order for our tests to be as successful as possible, the right antenna type should be chosen. For small scale electronics, PCB, chip or external antennas are typically used.[54] For UAVs specifically, small size with low aerodynamic drag, as well as low weight, are important.[55]

The best performing antennas are external antennas as they are less constrained by size or shape. Their drawbacks are increased cost and size. These external antennas are typically monopoles or dipoles and have a nearly omnidirectional radiation pattern.[54] Which means that the antennas orientation is less important than for more directional antenna types. PCB and Chip antennas have the advantage of small size.

Antennas have different frequency ranges they work best at, which should be taken into consideration when choosing an antenna. Monopoles are typically 1/4 of the wavelength[26], while dipoles are 1/2 of the wavelength in total[56, 57]. For 2.4Ghz this is 3,125cm and 6,25cm respectively. When an antenna is too short for it's operating frequency, it will exhibit capacitive reactance and inductive reactance. Adding an inductor allows the antenna to be shortened.[26]

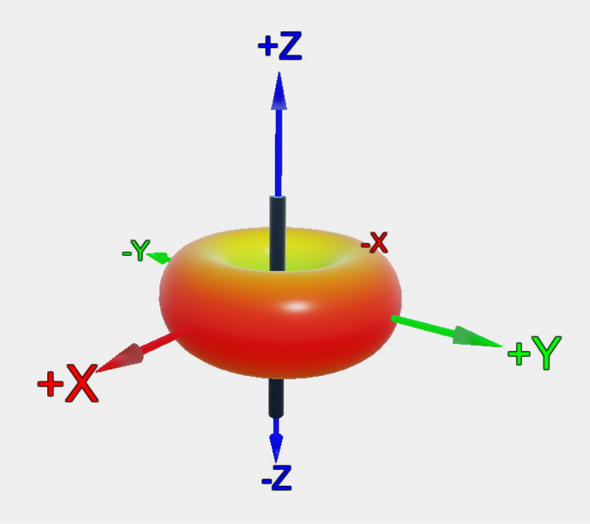


Figure 2.5: Dipole antenna radiation pattern (Visualization is based on Figure 3.7 and Figure 9.3 from [26])

Antenna orientation can also be important. For example a monopole "whip antenna should be mounted normally on the ground plane to obtain best performance"[54].

How the antennas are oriented in relation to each other is also important. With linearly polarized antennas like monopoles and dipoles, their polarization needs to match for the best reception. See "3.1.2 Polarization" in [12] for an introduction to antenna polarization. In an experiment that is available online[58], the creator starts with a linearly polarized BiQuad antenna[59] and a sleeve dipole antenna. He rotates one of the dipole antennas 45 degrees from it's ideal orientation, which results in a 3dB reduction in strength (halving of the signal strength). Rotating it 90 degrees from the ideal, results in a 21 dB decrease, which means that the signal strength is $1/2^7 = 1/128$ of what it is in the ideal orientation.

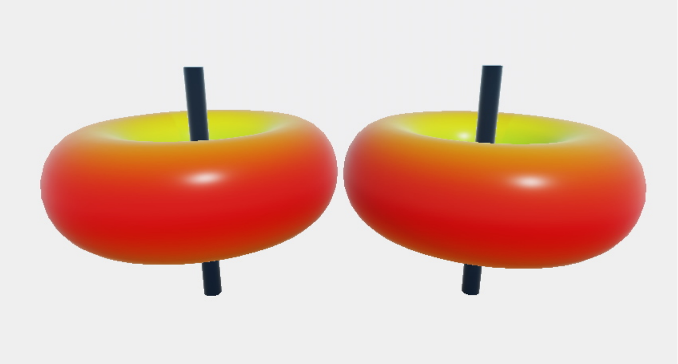


Figure 2.6: Dipole antennas oriented for optimal signal strength.

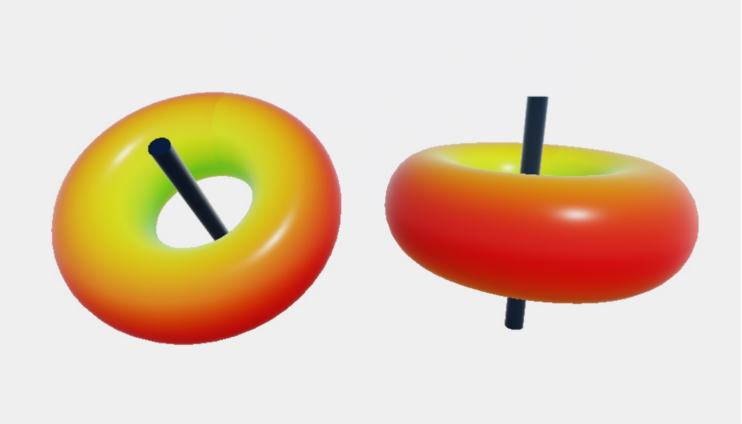


Figure 2.7: Radiation pattern of two dipole antennas, one rotated 45 degrees so that the radio signal's polarization does not match well.

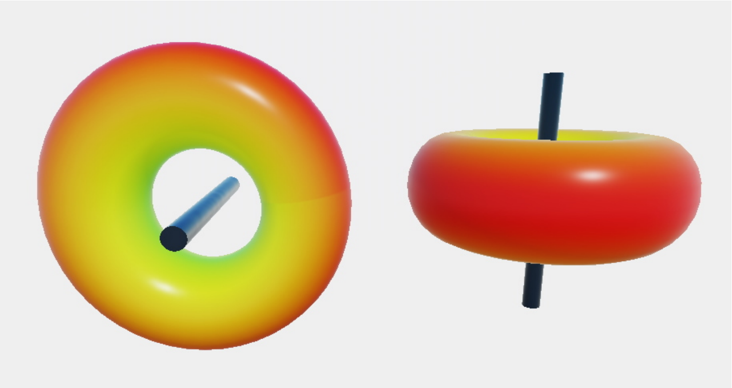


Figure 2.8: Radiation pattern of two dipole antennas, one rotated 90 degrees and thus the polarization mismatch is as bad as it can get.

In addition to polarization, their radiation fields should maximally overlap. One of the worst cases is seen in Figure 2.9, where almost no signal reaches the other antenna.

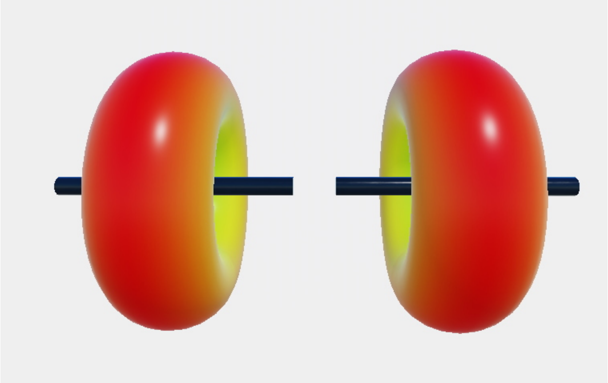


Figure 2.9: Polarization is the same, but the orientation is the worst possible in regards to signal strength.

We are unsure if the orientation in Figure 2.9 or Figure 2.8 provides the worst signal strength, and will be testing this.

In addition to linearly polarized antennas, there are also circularly polarized antennas. These are typically used by FPV drone pilots in order to increase the chance of a solid signal no matter the orientation of the drone. One such antenna is the cloverleaf antenna tested in [12]. They are heavier and bulkier than monopoles and dipoles, which is a reason for not using them in smaller drones or devices.

Since no antennas have a completely uniform three-dimensional radiation pattern, they need to be oriented in a specific way to achieve the maximum coverage possible. In [60] they write that for UAVs, "the radiation pattern of the antenna must be omnidirectional in the horizontal plane". They also write that "the low costs, vertical polarization, and omnidirectional radiation coverage of monopoles in the azimuth plane make them very attractive for UAV applications." They also aknowledge that some monopole antennas require a large ground plane. A large conductive ground plane is not at all ideal for a UAV where size and weight are important. A small monopole antenna that works well at 2.4 GHz with a proportional ground plane is proposed in [61] but we have not been able to find such an antenna commercially available.

A monopole antenna with a vertical polarization needs to be vertically mounted on the drone. A rigid antenna mounted in this way could easily snap off in the event of a crash, and thus flexible antennas are preferred for UAVs.

2.5.1 Radiation patterns of linearly polarized monopoles and dipoles

In our thesis we have only tested linearly polarized monopoles and dipoles, so the theory will be limited to these two types of antennas. In the simplest terms the difference between a dipole and monopole is visualized in Figure 2.10. The monopole requires a ground plane (Blue) to function properly, while the dipole does not. "The directivity (in linear units) of a monopole antenna is twice the directivity of a dipole antenna of twice the length. The reason for this is simply because no radiation occurs below the ground plane; hence, the antenna is effectively twice as "directive"."[62] The radiation pattern of a dipole can be seen in Figure 2.5.

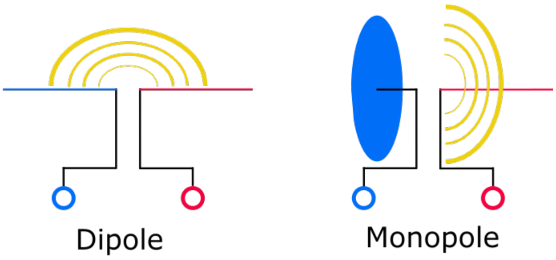


Figure 2.10: Dipole and monopole, © Glenn Robb[63] - Antenna Test Lab Co

The radiation pattern of monopoles on a finite size ground plane resembles that of a dipole, but the radiation is directed more upwards away from the ground plane, as seen in Figure 2.11

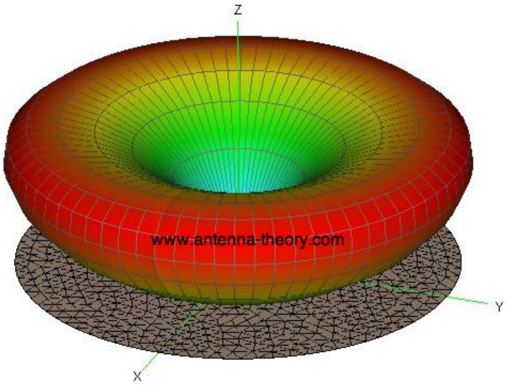


Figure 2.11: Monopole radiation pattern © Peter Bevelacqua - Antenna-Theory.com[62]

2.5.2 Antenna gain

When comparing antennas, antenna gain is a key metric. Usually it is expressed in dBi. The 'i' in dBi stands for isotropic. dBi is used when comparing an antenna to a perfect isotropic antenna that radiates equally in all directions. Such an antenna is theoretical and does not exist[26], but provides the reference for comparison. When an antenna has a gain of 2 dBi for example, it means that it it's radiation strength is 2 dB stronger at it's maximum radiation direction, than if it were an isotropic antenna.[64, 65] It is important to note that the total power radiatied by an antenna does not change at all based on it's dBi, it simply means that the radiated power is more concentrated in one or more directions. So it can be said that the higher dBi an antenna has, the more directional it is.

2.5.3 Antenna ground planes

Antenna ground planes are especially relevant when considering monopole antennas as the monopole relies on a good conducting plane for its operation.[66] "When the dimensions of the nearby conductor are large enough to materially alter the radiation pattern of the antenna at the chosen operating frequency, we call it a ground plane or, more simply, ground."[26] The radius of the ground plane should be greather than 1/2 the wavelength.[66] For 2.4 Ghz signals this means a radius of 6,25cm.

"Like any other conductor in the vicinity of a basic antenna, a ground plane functions as a parasitic element by reradiating the EM fields originating at the antenna. The resulting signal strength far from the antenna is thus a combination of signals received directly from the antenna as well as via the ground plane."[26]

2.6 UAV considerations

2.6.1 UAV technologies

For our research it is important that the UAV we are using is reliable and withing guidelines for UAV's in Norway. As such we researched different types of aerial vehicles and their benefits.

The main alternatives are lighter than air and heavier than air. Lighter than air such as balloons and airships are less common. They have has generally lower speed than alternatives due to a bigger area, creating more drag compared to its smaller counterparts, and less structural integrity making them unstable at higher speeds. On the other hand they have higher efficiency since most of the power is used for forward thrust instead of lift.

For heavier than air there exits mainly copters and wing type aerial vehicles. Copters mainly create lift with one or more horizontal rotating aerofoils providing a vertical upwards thrust. A quadcopter is a variation where the mechanical complexity of moving a single rotor design is traded for a electronically complex 4 rotor design, where the speed variation of one or more of the rotors creates movement in the wanted direction.

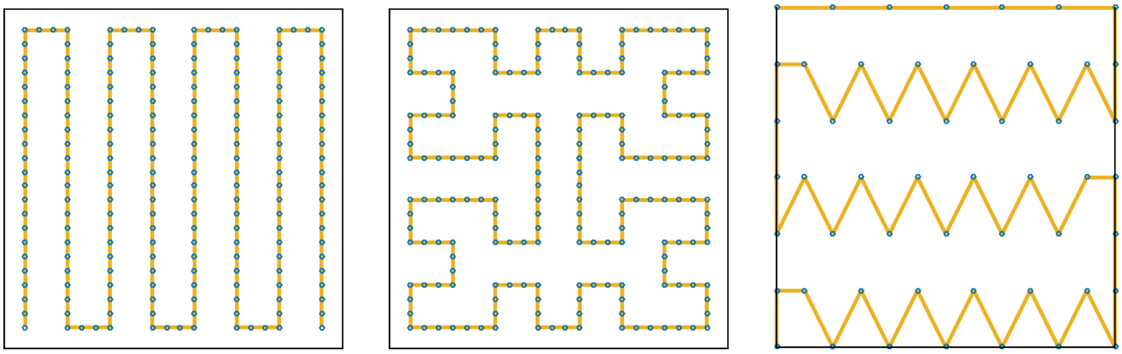
For fixed wing, lift is created by airflow through an fixed aerofoil, creating a high pressure zone under the wing creating lift. Airflow is usually created by providing thrust trough a motor rotating a propeller or propelling mass in the opposite direction (as in a rocket).

For a small electronic UAVs within the UAV restrictions in Norway, a quadcopter or a small fixed wing would be the best alternatives. The advantages of a copter are it's flexibility with take off and landing, as well as being able to hover. It would also be easier to control as the control scheme is more natural, and the small computer onboard takes care of stabilizing and making the quadcopter move in the desired direction. The fixed wing however has a higher efficiency meaning it can fly for longer, and is more robust if it crashes.

A hybrid alternative would be a Vertical Take Off and Landing (VTOL) fixed wing. It flies like a normal fixed wing aircraft, however it uses additional vertical motors to be able to land and take of vertical as a quad copter. This provides flexibility in takeoffs and efficiency in flight. The main downside is that it's usually more expensive since it needs multiple additional motors and parts to provide the functionality.

2.6.2 UAV search patterns

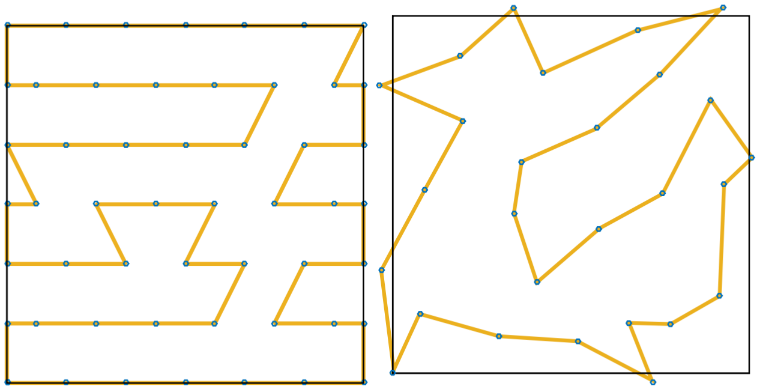
[67] gives an overview of previously proposed terrestrial and UAV search patterns for localizing terrestrial objects in a given area. See Figure 2.12. The UAV is in this context called a moving anchor. They also propose their own UAV search pattern algorithms called DIR and OMNI for directional and omnidirectional antennas respectively. They also show through simulation that their DIR algorithm leads to a shorter flight path than OMNI due to the utilization of the directional antenna.



(a) SCAN. (b) HILBERT. (c) LMAT.

Figure 2.12: Terrestrial search patterns. As illustrated in [67, Fig. 1], with permission.

In [1] Steinsvik implemented a version of the Polygon Coverage Path Planning proposed in [68]. It is similar to the "Scan" pattern in Figure 2.12, but adapted to cover any shape. [12] also proposed the use of a pattern similar to "Scan" taken from [69], and noted that the distance between the paths should be short enough for the UAV to detect the node from at least two sweep lines, to reduce positional ambiguity when performing multilateration.



(a) LocalizerBee.

(b) PreciseVerifierBee.

Figure 2.13: UAV search patterns for locating terrestrial objects. As illustrated in [67, Fig. 2], with permission.

2.7 Previous work in animal localization using drones and radios

In this section we wish to give an overview of previous scientific work into animal localization using radio and UAVs. This is in contrast to the previous section which covered radio localization in general and introduced key concepts. This section is based on research done in our thesis preparation project fall 2021.

In 2018 Louis Dressel and Mykel J. Kochenderfer[70] used an automated drone equipped with somewhat directional antennas of type Moxon to find different Sub-GHz transmitters including a wildlife collar. Their system was able to find a radio 150 meters away with a 7.3% error rate when the radio was placed in front or behind the drone. They had a 54% error rate when the radio was placed to the right or left of the drone. The UAV typically spent 37 seconds locating a radio in a 400x400 m area when the drone started in the middle.

In 2019 Nathan Hui[71] demonstrated a drone based system with 19 meters precision with a 95% confidence contour. They used transmitters with frequencies of 172 MHz and a dipole antenna. They calculated distance using Received Signal Strength Indicator (RSSI) and multilateration. They mention that other similar drone systems have demonstrated an accuracy within 20 meters, where the most precise system identified the location within a 5 m cell with a 50% certainty that it is in the cell. They also highlight the importance of time used to detect the sheep and that this should be low in order to beat out traditional radiolocalization on foot.

Hui's work demonstrated that their localization method was as fast, but not faster than traditional radiotriangulation (10 minutes). However it was much more accurate than the traditional method's precision of 20-100m.

The mean detection range for their system was 150 meters, with the lowest being 70 m. They mentioned that the drone needed to be robust as their drone kept having problems and ultimately became unusable.

Previous relevant NTNU publications

In 2020 Henrik Nyholm proposed a whole sheep localization system titled "System on Sheep"[12]. The concept consisted of a high-flying aerial vehicle for coarse localization of Bluetooth tags attached to the ears of sheep, combined with a quadcopter for more fine-grained localization that interfaced with a smartphone. Nyholm mostly experimentally investigated radio localization between the quadcopter and proposed sheep tags. The proposed sheep ear tags would consist of a BLE SoC, a PCB antenna and a simple coin cell battery.

He found that Bluetooth Coded PHY performed better than LE PHY (PHY refers to the physical layer in the OSI networking stack). He also investigated the effect of signal strength and antenna orientation on Bluetooth Package Delivery Ratio (PDR) performance over different distances. This was evaluated for the PCB antenna found on the Nordic Semiconductor nRF52840 Development Kit. Nyholm also evaluated different path loss models and found the two ray ground reflection model to be the closest match with the drone 100m above the ground. Using the Harmonic Mean on his RTT measurements, a RMS distance estimation uncertainty between 4m and 7.5m was achieved compared to 80m for the RSSI-based distance measurements. Nyholm stated that RTT ranging accuracy could be further improved by using a higher frequency clock than 16MHz for the radio peripheral.

Nyholm also proposed that a "horizontally polarized antenna oriented in a parallel direction relative to the direction of travel of the UAV is likely the best alternative" for the PCB antenna he tested. Nyholm only tested in LoS scenarios and noted that further testing would require testing with obstructions such as foliage and simulating sheep's heads in the way of the radio signal as well. Nyholm also argued that a stand-alone module for performing RTT measurements that can be attached to any drone, is a better idea than a system integrated with a drone. For future work he proposed among other things trying a RTT implementation independent of the Bluetooth software stack, combining Angle of Arrival with multilateration, and developing sheep tag prototypes and testing them on real sheep in real sheep grazing environments.

In 2021, Nerland[2], Steinsvik[1] and Swiderski[3] created a system to locate sheep using 2.4GHz bluetooth hardware, a UAV, a custom Ground Control Station, and RTT and multilateration, similar in overall idea to that of [12]. It seems to have been done rather independently as there is only one reference to [12] in total for all three papers.

Nerland built a small sub-250g automated drone to use as a test platform that interfaced directly with a drone-mounted NRF52840-MS88SF23[72] SoC over MAVLink. Their radio technology used for ranging was mostly a custom 2.4GHz protocol developed by Swiderski utilizing the same BLE hardware as [12]. Swiderski also developed and tested a RTT ranging scheme based more directly on BLE, although the custom protocol was preferred for their experiments and iterated upon. Steinsvik[1] developed a Ground Control Station for flight planning and visualizing the locations of found sheep, that also included the multilateration logic. He also evaluated a particle filter localization method using the RTT measurements but concluded that multilateration performed consistently better.

They managed to demonstrate a range of 1200 meters for Round Trip Time Line of Sight and an average localization error of 15[2]-19[1] meters. They tested using straight sweep lines to cover a Region of Interest (ROI) and were able to find the sheep tags they were looking for with sufficient accuracy. In the RTT ranging accuracy experiment presented in [1, 2] they concluded a mean distance error estimation error of 5.7m. A +-50m ranging uncertainty is mentioned for distances up to 1.2km in [1], citing [3], but the experiment is not presented in [3] for verification.

For future work Nerland[2] proposed among other things building and testing the proposed miniaturized sheep ear tags on real sheep. He also proposed improving several aspects of the UAV system, such as requesting a radio link with better stability and range for easier long range tests. Steinsvik[1] proposed several improvements to the Ground Control Station software, such as offline maps and more flexibility when creating routes. He proposed using knowledge of the drone's previous flight path to rule out locations where the sheep cannot be, and thus increase the minimum range required between sweep lines. He aknowledged that larger scale testing would require approval from the Norwegian Civil Aviation Authority. Swiderski[3] proposed testing the 1mbps transmission speed for BLE LE. This would allow for the use of Angle of Arrival (AoA) measurements in helping to locate sheep, and possibly reduce the number of RTT measurements required, increasing battery life.

2.8 The best radio technology for localization of sheep using a drone and multilateration

Considering that multilateration is a well understood and utilized localization method which has performed better than the particle method in our use case before as explained in section 2.3.2, it is the basis for further localization discussion.

When choosing a radio technology to use when locating sheep using a drone, the following criteria are important:

1. Long enough range for the drone to pick up the sheep's signal.
2. Signal can reach the drone despite obstructions in the wild environments that sheep graze in.
3. High enough localization precision to find sheep (30m uncertainty)
4. Low power consumption so that the device still has power when it is time to retrieve the sheep[2][1].
5. Low cost for the technology[2][1].

Previous work[2][1] has emphasized the the importance of low power consumption and low cost. A seemingly sufficient range has been demonstrated in open field tests.[1–3] But field tests in real sheep grazing environments are yet to be done. We are a bit worried that the previous choice of Bluetooth LE is not ideal for real sheep grazing environments due to natural obstructions such as foliage, terrain and the sheep themselves blocking the 2.4GHz signal, and have thus looked into what the alternatives are.

2.8.1 Possible radio technologies

Objects to be localized by UAVs are typically equipped with a radio transmitter or transceiver. Technologies employed for this can be grouped into 3 groups.

- Technologies operating at Sub-GHz wavelengths such as LoRa and Sigfox (863MHz to 870MHz in Europe).
- 2.4GHz technologies such as Bluetooth, Zigbee and Wi-Fi
- Ultra-wideband (UWB) technologies (typically 6-9 GHz)

In addition to the first three are less known proprietary technologies utilizing the same wavelengths.

Range and obstructions

A longer range wireless system would enable the drone to do fewer sweeps in order to find the lost sheep. This would increase localization speed and increase the area the drone could cover without needing to recharge.

UWB typically provides sub-meter precision, but the short wavelengths are not good at penetrating vegetation. It is also less efficient at transferring energy (and thus data) over longer ranges than longer wavelengths. Typical Line of Sight range is 200m.

The 2.4 GHz technologies such as Bluetooth and Zigbee are also traditionally considered short range, although Bluetooth 5 introduced a Low Energy Long Range mode that extends the range of Bluetooth. Experiments[2] have found the line of sight of Bluetooth LE to be 1200 meters. [73] used a custom radio transceiver with a claimed BLE range og 1 km at 125kbps, or maximum 7km with maximum gain (20dB)[74]. The setup was sufficient to keep their drones connected in their 500x500m test area.

Especially Coded PHY where each bit is encoded in 8 bits is promising where [12] estimated the theoretical range for an nRF52840 DK to be 2227 meters. However his Line of Sight experiments only showed a range of 600 meters with a PDR (Package Delivery Ratio) higher than 0.7 packages received for every package sent. Although a longer practical range is expected with some minor improvements outlined in the paper.

The sub-Ghz technologies like LoRa and Sigfox utilize the 868 MHz band in Europe. These radio waves can travel through buildings and foliage and their Line of Sight range is close to 20 kilometers. They require larger antennas than technologies using shorter wavelengths. Zigbee can also operate on the same lower frequency band as LoRa thus incrasing its range.

In conclusion, despite newer versions of Bluetooth having longer range, sub-GHz technologies are vastly superior in both range and foliage penetration capabilities.

Localization accuracy

Localization accuracy is a measure of how close the estimated position of an object is to it's real world position.

This paper uses multilateration as it's localization technique. Multilateration requires the range/distance between the measuring node and the object we are trying to find. The accuracy/precision of this ranging measurement is called ranging accuracy. Ranging accuracy is easier to measure as it is a simpler experiment than using multiple range measurements to derive a location in 2D or 3D space. It is a useful metric for comparison since localization accuracy directly depends on it.

In this comparison we do not look at RSSI based ranging approaches as they are not as accurate as methods such as Time of Flight (ToF)/RTT or Phase Shift.[12, 24]

The true localization position used in outdoor localization experiments is typically given by a GPS receiver, which in itself has an inaccuracy of about 1-3m[51, 75], depending on the GNSS module and number of connected satellites.

For UWB [75] demonstrated an indoor ranging accuracy of 7 cm. Their tests with a drone outdoors produced a localization precision between 8m and 1m depending on distance and angle between the object and the drone. Typically it was between 4m and 1m. In [76] the estimated position of a quadrotor drone in a room with 5 fixed anchors (measurement nodes) had an average error of 56 cm.

For Bluetooth, [12] found that when using a radio peripheral with a 16MHz clock for 2.4GHz Bluetooth packets, the resolution of the distance measurements should technically be 18.73 meters. Despite this [12] demonstrated an average ranging error of 5m when using Round Trip Time (RTT) and a drone.

[77] managed to demonstrate an accuracy of 1m indoors and 1-3 indoors doing RTT at 2.4 GHz. They used a commercially available 2.4 GHz radio and a frequency shift keying ranging scheme.

[1–3] demonstrated an average ranging error of 5.7m when using RTT. Their average localization error using RTT, multilateration and a drone was 14.4 meters.

For LoRa, tests done by [22] using an UAV were able to demonstrate a 12 meter location precision.

However, the theoretical localization precision of BLE should be better than LoRa as the shorter wavelengths of BLE allow for quicker sampling and thus better ranging precision, leading to higher localization precision. However we did not find outdoors localization papers experimentally confirming that BLE has higher precision, so we will consider them tied.

In summary, since sheep localization does not require more than 30 meters localization accuracy, all the technologies have sufficient localization precision for our use.

Power consumption

This section gives an overview of the power consumption of different radio technologies.

BLE devices can be powered by a single coin cell battery and can last up to two years[78]. When transmitting a single packet, power consumption of BLE is similar to ZigBee[79], but it is far superior to ZigBee in terms of power consumption when multiple packets are sent. The authors also compare Bluetooth to WiFi and find that Bluetooth clearly utilizes energy better.

[80] performed RSSI-based multilateration with WiFi, Zigbee, LoRaWAN and BLE. Using the same dB and transmit intervall their power consumption they found that "WiFi consumes the largest amount of power utilizing 216.71mW. LoRaWAN consumed the second largest amount of power using 19.53mW on average. Zigbee was third, which on average consumed 17.68mW of power. BLE used the least amount of power, consuming only 0.367mW."

[81] estimates the average power consumption of a BLE peripheral device to be between 2.0 µA and 3312.1 µA depending on the connection intervals (0.0075s vs. 16s). BLE connection intervals are time intervals between each time the central device asks the peripheral for data. Based on this data BLE has a power consumption of $\approx$ 10mW for the minimum connection interval according to [44].

In [44] they also looked at the results from [81] and concluded that "a BLE packet consumes approximately 75 µJ".

In [82] they looked at the results from [79] and found that Bluetooth had a power consumption of "few tens of mW".

In [44] they used UWB power consumption data from a forum spreadsheet and BLE data from a Texas Instruments BLE power estimation calculator to state that "the average power estimate for the UWB tag equals 51.9 mW. For the BLE tag it would be estimated to only 4.8 mW with the used configurations, which represents an energy consumption more than 10 times higher for UWB."

[82] looked at data from [83] and found that UWB "has a high power consumption during the ranging phase (i.e., hundreds of mW)"

According to [84] "Although UWB transmitters are simple to implement and extremely low power, UWB receivers have proven to be highly complex and consume a large amount of power when providing communication performance comparable to narrowband radios.". They also state that "UWB receivers with comparable performance (communication range and linearity) consume dramatically more power than their narrowband counterparts [14]."

A multilateration algorithm was developed in [82] that used a Wake-up radio (WUR) to keep the node's energy consumption within 31 mJ. The wake-up-radio utilizing the 868 MHz frequency only uses 3.9 µW in it's listening state[85].

In [86] they investigated the use of a Wake-up radio together with BLE for the purpose of uploading data to the BLE beacons. Using a WUR they could switch from connectable to non-connectable advertising, gaining up to 30% energy efficiency according to their simulations of a Nordic nRF52832 and TI CC2650. Their WUR was purely theoretical.

In summary, BLE and ZigBee consume the least amount of power, with BLE outperforming ZigBee when multiple packets are sent[79]. According to [80] LoRaWAN consumed more power than both of them. Still 868 MHz (the frequency LoRa uses) was chosen for the ultra-low-power Wake-up-radio presented in [85]. WiFi consumes the most power of them all according to [80] and WiFi consumed more power than BLE according to [79]. UWB also consumes more power than BLE[44], especially when receiving data[84]. It has been proposed in literature implementing UWB ranging to use Wake-up radio (WUR)s in order to increase node battery life. The use of WURs has also been proposed for BLE with potential power savings as a result.[86]

BLE seems to have the lowest power consumption, although LoRa might require less power for longer range signals.

Summary of best choice of radio technology for sheep localization

Sheep localization with multilateration and UAVs requires long range, good foliage penetration, medium localization accuracy, low power, and and low cost. A comparison of radio technologies is given in Table 2.1,

Table 2.1: Comparison of radio technologies. The best performer is labeled in bold.

	Sub-Ghz (LoRa)	BLE	ZigBee	Wi-Fi	UWB
Range (LoS)	**20km**	ca. 1km	?	?	200m
Foliage penetration	**Okay**	Bad	≈BLE	≈BLE	Very bad
Localization accuracy	**12m**	**14-19m**	≈BLE	≈BLE	1-4m
Power consumption	Low/medium	**Lowest***	Low	High	High

*When considering power consumption, one should also consider that shorter wavelengths lose power as range increases quicker than longer wavelengths. This was not taken into account here and in reality make longer wavelengths more efficient over range, possibly making Sub-Ghz and BLE consume a similar amount of power for the same distance.

Previous papers[1, 2, 12] chose Bluetooth Low Energy (BLE) due to low cost and ultra low power consumption. However LoRa has both longer range, better foliage penetration and an experimentally demonstrated better localization accuracy than BLE. Therefore we think that LoRa is better suited for sheep localization than BLE. The higher power consumption of LoRa could be offset by decreasing the gain, while possibly still maintaining better foliage penetration capabilities than BLE. A study should probably be done on LoRa in order to evalue if power consumption is low enough for the proposed ear tags using CR2032 batteries before committing entierly in that direction. Another option would be to re-design the system with a bigger battery to take advantage of the increased range that LoRa offers.

Chapter 3

Our chosen localization method

Our method under investigation uses a small 2.4GHz BLE radio attached to each sheep/lamb as proposed in [1, 2, 12]. These tags are then located using a small automated quadcopter UAV performing multilateration using it's GNSS receiver and Round Trip Time ranging data. We are also using a modified version of of Radio Sheep Ground Control Station[4] to create flight plans and retrieve data from the UAV.

3.1 Choice of radio technology

We chose 2.4Ghz Bluetooth Low Energy (BLE) hardware with a custom ranging protocol developed in [3] which is described in section 3.3.

Several years of research into sheep localization using BLE and UAVs[1–3, 12] had already established that using BLE in combination with a UAV seemed feasible for sheep tracking, and that it was ready for more realistic field trials on sheep.

The low power consumption and good enough localization accuracy was also crucial for this choice. The Minew BLE chip used on the UAV by [1, 2] was also small enough to fit in an ear tag so we already had a probable prototype. According to our supervisor Svein-Olaf Hvasshovd the technology and technique were ready for more realistic field trials and possibly commercial realization.

We also had a access to the UAV from [2] as well as nrf52833 development kits from Nordic Semiconductor which would speed up our research and help us do field trials quicker.

All of these factors made it a better choice to continue using BLE to achieve our goals in the time we had despite LoRa in theory being a better choice for the task of sheep localization using UAVs (see section 2.8.1).

3.2 Choice of radio localization method

We used the multilateration algorithm implementation in Sheep Ground Control Station from [1]. In short it draws circles with the radius of each RTT distance esimate, and places them on the map using the UAV's recorded GNSS position saved with each measurement. It then checks if the areas of the circles overlap. If they don't, each circle's radius is increased by two meters until they all share an intersection area as seen in Figure 3.1. When an intersection area is found, the mean position of the area is used to present an estimated location of the sheep to the user. This is illustrated in Figure 3.2, where the "Sheep position" is an example of the actual sheep position, and uncertainty radius refers to the additional meters added to all the RTT circles to make them intersect. For more details, we refer to the original thesis[1].

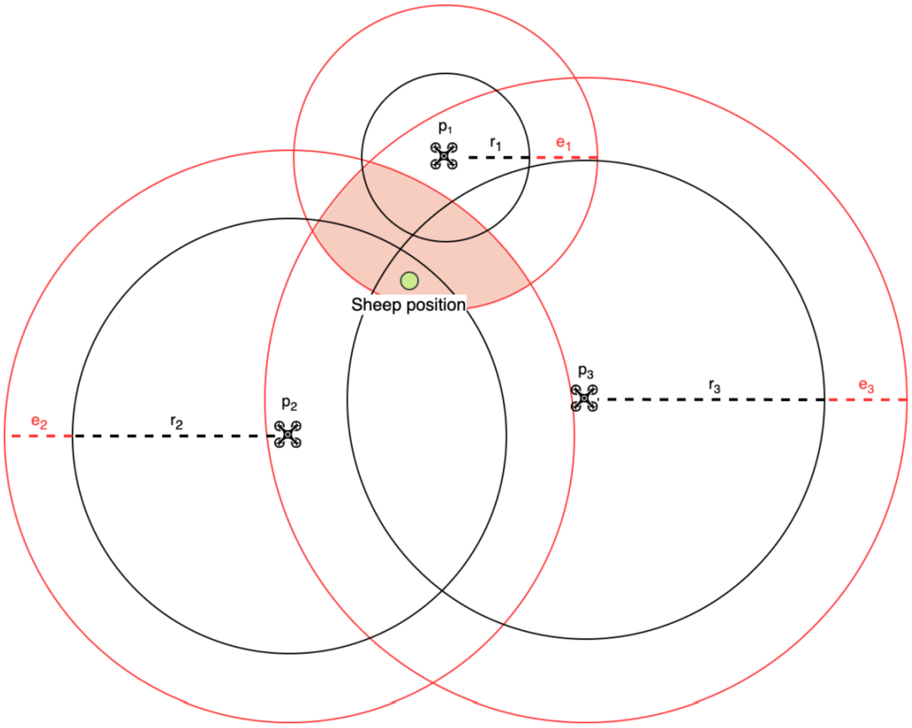


Figure 3.1: An illustration of the multilateration method we are using, originally implemented in [1]. [1, Fig. 4.14].

3.2.1 Changes to Radio Sheep GCS

We implemented six distinct changes into Radio Sheep GCS to improve localization accuracy and system stability and usability. See section A.1 for details. The updated system is publicly available on GitHub[4].

3.3 Ranging method

We chose an implementation of the Round Trip Time (RTT) ranging method, developed by Swiderski [3] together with Nerland[2] and Steinsvik[1]. The imple-

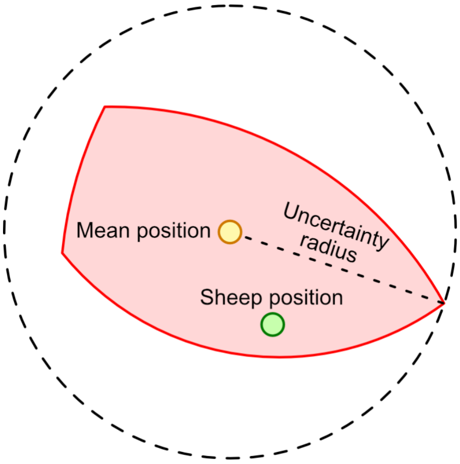


Figure 3.2: The estimated sheep position is found by taking the mean of the intersection area. Reused with permission from [1, Fig. 4.15].

mentation code or description is not publically available, but a summary of how it functions is presented below.

A high-level overview of how the RTT implementation for our thesis functions, is shown in Figure 3.3. A nRF52840 chip on the UAV labled "central" listens to advertisement packets from nRF52833 chips in the field labeled "peripheral". Once the central module picks up a peripheral's advertisement packet, it sends out an RTT ping targeted at that specific module and waits for a reply. Once a reply is received, the central module calculates the time elapsed between sending and receiving, and sends out a new RTT ping targeted at the device. When a predefined number of RTT measurements are completed for a specific tag, they are aggregated and stored to the central device's RAM before the central device starts scanning for new tags again.

3.3.1 Choice of ranging implementation

In [3] Swiderski proposed primarily two methods for localization. One using Bluetooth Low Energy (BLE) labeled "Bluetooth Low Energy Stack-Based Method", and one using BLE hardware combined with a custom protocol labeled "Minimal Custom Protocol-Based Method".

The advantage of the method utilizing the BLE stack is that it could be used for any Bluetooth device, while the custom protocol can not. The custom protocol however, had superior ranging precision[2] and and lower power consumption[3]. Both methods had the same range.[2]

Since we have complete control over the hardware and envision that the same will be true for a commercial realization of our thesis, we opted for the custom protocol version with superior ranging accuracy.

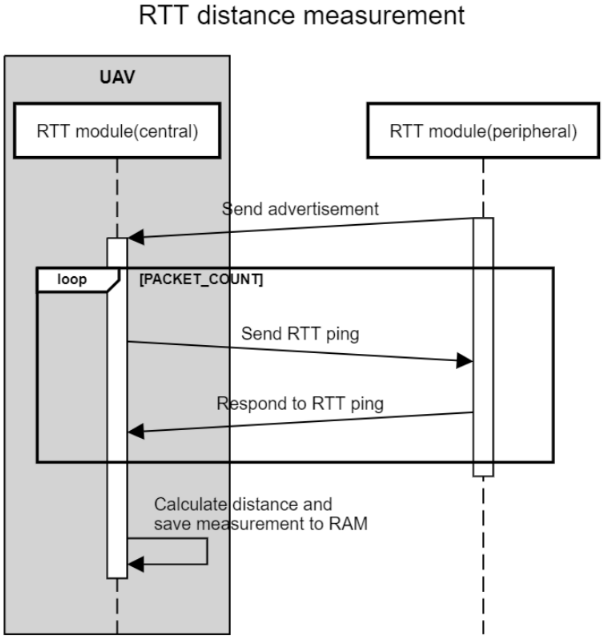


Figure 3.3: High-level overview of Round Trip Time (RTT) implementation presented in [3], as illustrated in [2, Fig. 3.5].

3.3.2 Ranging implementation details

Communication between tags

The "Minimal Custom Protocol-Based Method" presented in [3] does not use the Bluetooth Low Energy (BLE) software stack, but running on BLE hardware means that it still uses the same frequency (2.4 GHz), same bandwidth (1 MHz), same modulation technique (GFSK) and a similar packet format. It also utilizes Bluetooth Low Energy Coded PHY with S=8 coding and 125 kbps transmit speed, for maximum range. Each sheep (peripheral) ear tag is mapped to a BLE-compliant 32-bit Access Address. All the peripheral tags advertise themselves on a shared Access Address. The central tag listens on the shared Access Adress, decodes the individual sheep addresses, and starts RTT measurements. During the RTT measurement packets are exchanged every 7.5 ms. This leaves enough time to receive the previous RTT measurement before starting the next one[3]. When sending an RTT ping, the central node includes a number specifying how many packets are left before the RTT measurement is complete. When this number reaches 0, the peripheral tag switches off it's radio to conserve energy, before it starts advertising again after a set interval. The central tag goes back into scanning mode as soon as it has finished the RTT measurement.

Timing the Round Trip Time

The nRF52's radio peripheral is programmed to send an event every time a bit is received when receiving a data packet. The CPU on the central tag runs in a for loop, saving the time of receiving these events. According to experiments performed by [3], radio events for the same packet are linearly independent with respect to time, and thus can be aggregated to reduce the effect of jitter.

We configured the software to perform four RTT measurements for each stored measurement. The four RTT measurements are averaged into one before the estimated distance between the tags is calculated and stored.

3.3.3 Software configuration

Both the central and peripheral tags were set to run at the maximum nRF528xx gain of 8 dB. The central code was ran with the parameter EXPERMINENTAL_MODE=1, which fixes a small rounding error in the software. The peripheral was set to advertise once every second.

3.4 Choice of drone technology

3.4.1 Drone hardware

The quadcopter drone we started with was the drone used for the masters from the year before[2]. It was a lightweight drone using very small components and a 3s 3300mah Lithium-Ion battery. It had a fly time of 27 min [2] and was easy to control. However we managed to crash a couple of times and we couldn't find the exact same replacement parts so we had to built a new drone, while recycling some parts.

The drone we ended up with

The drone we ended up with is very diff rent from the one we started with. It uses the same battery, frame and Gps-Radio module as the last one. For the flight controller we picked the "Diatone Mamba F405 MK3" as it was suitable. We upgrade to a "TBS Crossfire Nano Tx 868mhz" radio receiver in the hopes that it would give us longer range, and more stable connection. We also omitted the WiFi module in favor of the telemetry from the TBS Crossfire We also changed the motors to "T-Motor F1204 5000KV", as the last ones had been submerged in snow and stopped working. The ESC was replaced with a "Diatone Mamba Master F45 45A 3-6S 4in1 ESC". A more robust and higher voltage ESC that hopefully could handle a crash. Because the ESC and Flight controller were 35mm instead of 25mm we also had to get new standoffs, screws and 3D print a new Gps-Compass Module stand that was suitably resized.

This is the quadcopter we used for the sheep field testing. It also crashed eventually, and the esc broke together with some motors and the GPS. However we replace the broken parts with similar ones and it continued flying.

Criteria for drone parts selection

The main reason for our choice of parts was local availability, as most parts were hard to find in Europe, and importing from outside Europe takes significant time. The second criteria was specific needs. For the flight controller the requirement was enough UART ports to connect the Minew ranging chip directly to the drone. This means 1 uart port for GPS, 1 for radio control, 1 for telemetry 1 one for the Minew. For the motors we chose the the cheapest, and lightest that could provide enough thrust for the drone. The ESC choice was the lightest one compatible with the flight controller, motors and battery.

3.5 Sheep tags

There where two version of the Sheep tags, where we used two different Minew modules based on Nordic Semiconductor SoCs. The first version, is based on the nRF52840 SoC and has an U.FL antenna connector, see Figure 3.4. The second version, is based on the nRF52833 SoC and had an integrated PCB antenna, see Figure 3.5.

Our thesis specification requested the sheep tags to be ear tags. However we got feedback from the farmers that the external monopole antenna of our original tag would get stuck and break. Thus we created 3 prototypes with an integrated PCB antenna. The old prototypes with the external antenna were instead mounted to the collars of two sheep.

Both versions were wired the same way, as seen on 3.6, connecting the ground and VDD pins on the modules to a by a CR2032 battery holder that would hold a 3v CR2032 Lithium cell battery. The nRF52833 version was mounted on the lambs ear tag with white scotch tape while the nRF52840 version was mounted on the sheep collar. A monopole antenna was installed on the nRF52840 version before it was taped to the collar with white scotch tape.

3.6 Choice of flight path

We chose to continue to use the Coverage Path Planning[68] similar to "Scan" from [67] as implemented in Radio Sheep Ground Control station[87]. Radio Sheep Ground Control station has several parameters for generating flight paths as described in [1]. Search radius and search radius overlap are used to decide the distance between the sweep lines. Our chosen values are described in the Investigation chapter where relevant, although optimal sweep line distance is not a point of study for us.

Figure 3.4: First version of our prototype tag, mounted to sheep collars. The black line shows where the antenna is, and the thicker black line where the antenna's radiating element is.

Figure 3.5: Second version of our prototype tag. It was additionally wrapped in a thin plastic bag for water protection, and taped to the ear tag.

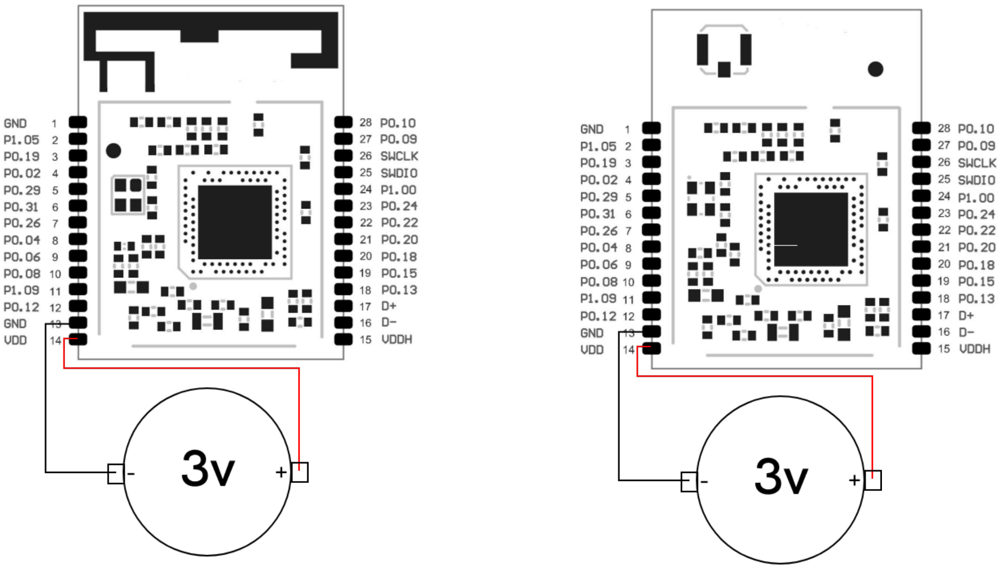


Figure 3.6: Simple wiring diagram for the sheep tag, connecting the Minew to a 3v lithium cell battery holder

Chapter 4

Investigation

This chapter contains all our experiments and literature study results chronologically with associated introductions, methods, results, discussions and conclusions.

4.1 Antenna orientation tests

4.1.1 Goal

The goal of these test was to discover the best orientation for our antennas in order to maximize the signal strength between them. Knowing the best possible orientation would give us the best performance possible for our long range test.

4.1.2 Background

As explained in section 2.5 the signal strength between two antennas depends among other things on their relative orientation in 3D space. According to the experiments presented in that section, antennas positioned either both horizontally, or both vertically, parallel to each other, should give the best signal strength. However, it was not clear to us if vertically or horizontally positioned antennas performed best, and how they compared to other orientations for our chosen antennas.

We noticed deficiencies in last year's paper's antenna orientation experiments[2] that we wanted to remedy. For their external antenna tests they attached an external antenna with a female port, to the female port of the nRF52833 Development Kit board. This means that the antenna was not in use at all for their external test, and the internal PCB antenna was used instead. The authors did not realize their mistake and their results should be considered invalid. Thus there is room to repeat the experiments with more rigour.

4.1.3 Methodology

Two small Minew nRF52840 chips with external antennas were placed at fixed distances between each other. For each distance several different orientations between the antennas were tested. The RSSI for each distance and orientation was captured by one of the Minew chips in real time and sent to a computer via a Nordic Semicondcutor nRF52833 development kit connected by USB. The RSSI values were printed to a computer screen with J-Link RTT Viwer and logged manually in a spreadsheet. The RSSI values were aggregates from four packets back and forth and provided by Swiderski's[3] Round Trip Time (RTT) embedded software.

Figure 4.1: Location for first orientation test. Høyskoleparken, NTNU

Orientation test 1

This test was performed in a flat open area in the Høyskoleparken park outside of the Hovedbygget building at NTNU in Trondheim. One of the Minew chips was mounted 155cm above the ground on a pole consisting of a metal rod, with a wooden rod taped to it. This was done to increase height of the pole while reducing the radio reflections that come from using metal. We wanted the radios mounted high to reduce the effect of multipath reflections from the ground and bring the experiment closer to the operational situation where the drone is high up. The other Minew chip was held in the hand of one of the authors. We did not opt to go for a pole here as it was quicker to change the radio's orientation when holding it. The distance between the two antennas was measured using a tape measure.

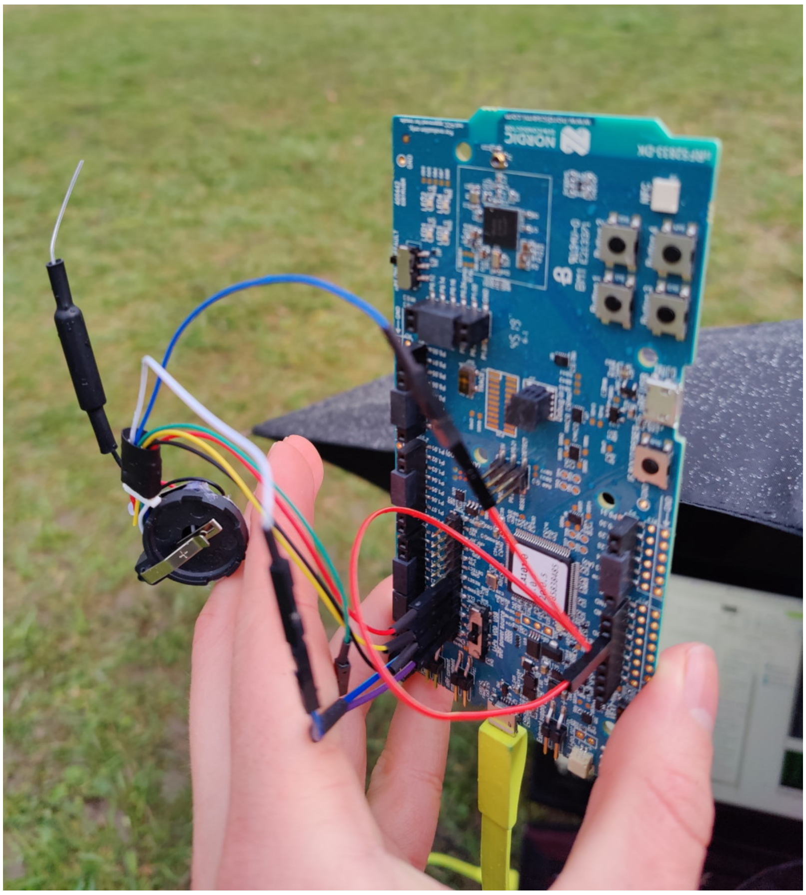


Figure 4.2: Minew nRF52840 with sleeve dipole (also called "coaxical vertical"[26]) antenna connected to nRF52833 DK. For the actual test the antenna was straightened and the development kit was positioned to the side to not be in the Line of Sight of the two radios.

The antennas used for the test are presented in Table 4.1,

Tests were performed at distances of 50cm, 5m, and 10m.

Due to some wind vibrating the antennas, and one of the antennas being held by hand introducing some vibrations and small changes in angle from the ground, the measurements were repeated at least two times.

In the middle of the 10m test, we stopped receiving RSSI data. A quick investigation found the reason to be a snapped cable connecting the Minew chip to the nRF52833 Development Kit.

As a bonus we performed the test again at 5m, but using one of the Nordic Semiconductor nRF52833 development kits instead of the Minew chip at the handheld position.

Table 4.1: Antennas used

	Handheld antenna	Pole mounted antenna[88]	PCB Antenna
Manufacturer	Unknown	No-brand	Nordic Semiconductor
Type	Sleeve dipole	Monopole	PCB
Gain	Unknown	0dBi[88]	0dBi [89]

Orientation test 2

For the 2nd orientation test we sought to reduce uncertainty in our results compared to the first test. This was done by replacing a person holding one of the antennas, with a stationary tripod as seen in Figure 4.3. This was inspired by the method used in [47]. In this way we would not get reflections from the person's hand like seen in [58] and our own observations. Also we would not have small changes in angle caused by hand movement. We also replaced the sleeve dipole antenna used in the previous test, with a monopole antenna that is identical to the one used in the previous test. This was done because we had the specifications for this antenna (and we do not for the dipole), thus it makes our experiment more reproducible. We also used a longer cable between the Minew chip with the antenna, and the Nordic Development Kit and mounted the DK further away, so it did not interfere with the antenna. The antenna setup can be seen in Figure 4.4

During the tests the tripod was moved further and further away at the distances of 50cm, 2m, 8m, 32m and 128m. At distances further than 8m, GPS on a OnePlus 9 Pro mobile phone was used to measure the distance instead of the tape measure. It claimed to have an accuracy of 3m. When moving the tripod to the 8m mark, we noticed that we got -80 dB both the antennas were oriented horizontally parallel to each other. We speculated that this was because the 8m was on a downward slope from our starting location, and reflections from the ground were causing destructive interference. This caused us to move our experiment to level ground 10m away and repeat the experiment.

Aligning of the antennas was done by eye, which could cause inconsistencies in the data due to bad alignment. We attempted to use the compass app on our smartphones to orient the antennas in the same direction, but when cross-referencing between two phones and repeating the measurements, we found the phones' compass to be inconsistent and inaccurate. Thus we did not use the compass for orienting them. There was also wind 4 m/s blowing on the antennas causing them to occasionally vibrate a bit, although we repeated the measurements if the wind gusts were strong enough to cause major oscillations.

Unlike in orientation test 1, we only tested 3 of the orientations for all the distances starting at 2m and further. This was done because we were mostly interested in comparing the vertical and horizontal orientations, and having the orientation where the antennas were pointing as each other (pointing-pointing) as a point of worst-case comparison. The results can be seen in Table 4.2.

During testing, the reported RSSI values were not stable, and could vary by

Figure 4.3: Experimental setup for the 2m distance in orientation test 2

as much as 10 dB, although typically varied by 1-2 dB. This was despite little to no movement in the antennas and the surroundings. The value we noted down was the one we perceived as the median value printed to our console, which was often also the most frequently reported value. We did the horizontal-horizontal test at 2m twice and noted the average value. The 128m test was done quicker than the others as it started to rain, so the orientation between the antennas might be slightly less optimal than in the other tests.

4.1.4 Results

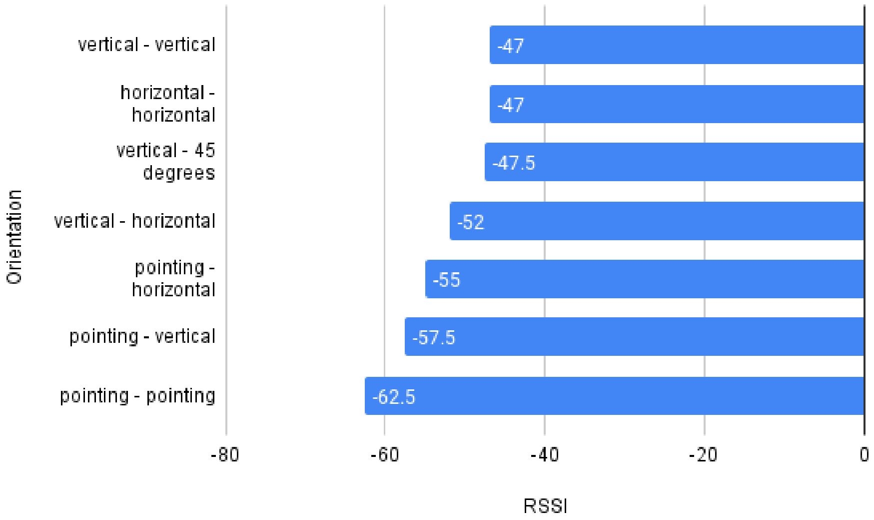
Orientation test 1

As orientation test 2 has superior methodology the main results of test 1 are not included.

Our bonus test with the nRF52833 development kit showed that using the on-board PCB antenna produced comparable results to the external antenna. In the vertical orientation the dipole-monopole pair had a dB of -49, while the PCB-monpole pair had -47 dB. In the horizontal orientation they both got -47 dB RSSI.

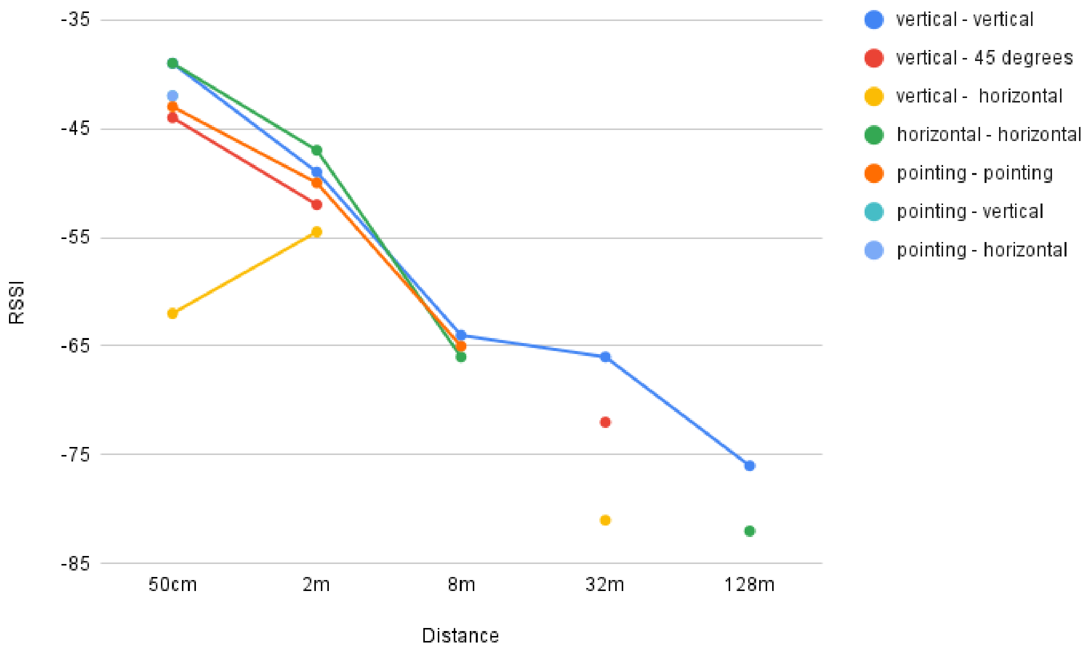
Figure 4.4: Experimental setup for orientation test 2. Two monopole antennas and the distance between them measured with a tape measured.

Figure 4.5: Bonus test. RSSI at 5m between the monopole antenna and nRF52833 Development Kit PCB antenna.



The RSSI for all orientations can be seen in Figure 4.6.

Figure 4.6: RSSI for every antenna orientation and distance.



Orientation test 2

Table 4.2: Orientation test 2 results. Best RSSI for each distance marked with bold.

Orientation	50cm	2m	8m	32m	128m
vertical - vertical	**-39**	-49	**-64**	**-66**	**-76**
vertical - 45 degrees	-44	-52		-72	
vertical - horizontal	-62	-54.5		-81	
horizontal - horizontal	**-39**	**-47**	-66		-82
pointing - pointing	-43	-50	-65		none
pointing - vertical	-42				
pointing - horizontal	-42				

As seen in Table 4.2 and Figure 4.6 the two orientations with the strongest RSSI are vertical-vertical and horizontal-horizontal.

Comparison of vertical-vertical and horizontal-horizontal

As seen in the 50cm results, vertical-vertical and horizontal-horizontal provide the best signal strength, at -39 dB.
For 2m horizontal-horizontal performs slightly better than vertical-vertical, at -47

dB and -49 dB respectively.
At 8m vertical-vertical performed slightly better than horizontal-horizontal, at -64 dB and -66 db respectively. At this range docking-docking actually performed better than horizontal-horizontal with -65 dB.
At 32m vertical-vertical performed much better than horizontal-horizontal, at -66 db and -72 dB respectively.
At 128m vertical-vertical performed much better than horizontal-horizontal, at -76 dB and -82 dB respectively. No packets were received for the docking-docking configuration, so we were not able to perform an RSSI measurement for that orientation at 128m.

It seems that at close ranges horizontal-horizontal performs as well or better than vertical-vertical, while at longer ranges, vertical-vertical is clearly better.

Change of antenna polarization, test 1 & 2

Table 4.3 shows the effect of rotating one of the antennas first 45 degrees left from the starting orientation (vertical), then 90 degrees left from the starting position, ending up oriented horizontally. The left column in Table 4.3 comes from the reference experiment mentioned in section 2.5. The two next columns show the effect that rotating one of the antennas has on RSSI.

Table 4.3: The effect of polarization mismatch on RSSI

	Reference experiment	Orientation test 1	Orientation test 2
dB when both vertical	0dB	-26dB	-39dB
db change rotated 45°	-3dB	-2.5dB	-5dB
db change rotated 90°	-21dB	-12dB	-28dB

On average based on our measurements, when one of the antennas is rotated 90 degrees relative to the other, the signal strength is reduced by 20dB.

4.1.5 Discussion

The results from rotating one of the antennas 45 degrees from vertical to horizontal in test 1 matched fairly well with the results obtained in [58], as seen in Table 4.3. We thus considered the experiment to function well enough to continue. However looking at the rest of the values in Table 4.3 now there are some major discrepancies from the reference experiment. Averaging the values from the two orientation tests produces a result that is much closer to the reference experiment.

The result from orientation test 1 where the PCB antenna of the nRF52833 development kit was equally good or maybe even better than the external antenna was surprising to us. It is much smaller, and we expected the larger external antenna to perform better according to the theory. However the later antenna experiment detailed in section 4.3 showed us that the monopole antenna combined with our Minew MS88SF23 ground plane did not radiate strongest straight forward. This means that if the experiment was repeated with the monopole oriented optimally, it should outperform the PCB antenna.

Horizontal-horizontal outperforming vertical-vertical at 2m in test 2 is curious. In free space a horizontal and vertical orientation should produce the same results, as seen in the 50cm measurements, where reflections are less prominent. However for the 2m measurements horizontal-horizontal outperformed vertical-vertical by 2 dB. This is most likely caused by constructive interference from signals bouncing into the ground and combining at the receiving antenna, thus increasing the RSSI.

The results from orientation test 2 show that a vertical polarization works best at range when the antennas are fairly close to the ground. A reason for this could be that destructive interference from signals bouncing off from the ground is more pronounced when the antennas are oriented horizontally, as more of the energy is directed towards the ground than in the vertical setup.

The validity of our results is somewhat reduced as the radio waves bouncing off the ground can substantially boost or decrease the RSSI, depending on if the signals are bouncing at one of the fresnel zones or not. We chose open areas for performing the tests, so signals bouncing from non-horizontal surfaces would be very low, not impacting the RSSI much. This increases the validity. However for the 128m test this was no longer the case as the receiver was placed less than 10m away from houses, trees and fences.

4.1.6 Conclusion

As expected the vertical-vertical and horizontal-horizontal orientations perform equally well in a near-free-space scenario (50cm). In the near-ground scenario that we tested in, which of them is better seems to alternate depending on where we measured, although vertical-vertical appears to provide a stronger signal at longer ranges. The effect of mismatching antenna polarization is large, leading to a decrease of 20dB on average when maximally misaligned.

4.2 Ranging accuracy compared to available technology

While this thesis was written, Nordic Semiconductor released their own Distance Measurement Library. It has an optional RTT long range mode. While the Round Trip Time (RTT) method proposed by [3] was accurate enough for sheep localization, we wanted to see how well it performed to a brand new commercially available Bluetooth distance measuring method. If it performed better, we would consider trying it in our large scale tests if time permitted it.

4.2.1 Methodology

Two nRF52833 Development Kits were attached to a pole on the side of a long road acting as Round Trip Time (RTT) reflectors. Reflectors here refers to the development kits responding to the measurement packet sent out by the transmitter/initiator nodes. The pole was a metal rod with a wooden rod taped to it to extend height and distance the nRF52833 from the metal, see Figure 4.7. We used the same straight road stretch that [2] used for their range tests. As a vertical orientation for the antennas performed better in our near-ground antenna orientation experiments at longer ranges, see section 4.1.4, vertical orientation was chosen for the integrated PCB antennas at both the transmitter and reflector side. Both of the kits on the pole were oriented in an identical way, the only difference being that one was above the other vertically. They were wrapped in plastic bags to protect them from light rain.

Figure 4.7: Pole consisting of a metal and wooden part, with two nRF52833 Development Kits attached on top.

Two more nRF52833 Development Kits were attached to a backpack as seen in Figure 4.8. An effort was made to keep the oriented the same way, although as seen in the picture the left one of them is rotated a bit away around the vertical axis. These were then connected to a computer using USB. On the computer, Swiderski's RTT implementation[3] printed RTT data to a J-Link RTT Viewer terminal, while Nordic's implementation printed via a serial connection to Nordic's terminal integrated into Visual Studio Code via the nRF Connect VS Code plugin.

To log the actual "true" distance the Android app GPS Distance meter PRO[90]

Figure 4.8: Backpack with two nRF52833 Development Kits attached to the outside.

app was used together with a OnePlus 9T smartphone, which has a self-reported accuracy of 3 meters.[91]

The experiment was performed in the following way:

1. Turned on the two development kits on the pole, and ensured they were responding to RTT messages. Wiped away any water from the rain covering the PCB antennas.
2. Walked away from the pole in a straight Line of Sight line with the backpack until the GPS app showed one of the pre-defined distances.
3. Waited for GPS accuracy on the smartphone to reach 3m. Adjusted position of self if needed to get the right distance. Took a screenshot of the app to store position and distance.
4. Made sure the backpack was facing the pole with the development kits.
5. Started logging RTT distance on both nRF52833 devices and did so for approximately 10 seconds.
6. Copy-pasted the printed distance measurements and stored them in files on the computer.
7. Repeat from step 2 until maximum possible distance was reached.

Test execution deviances

Nordic's implementation stopped providing distance measurements beyond 132 meters, so logging of those were stopped after that. After around 700 meters a

Figure 4.9: Performing the test with the nRF52833 Development Kits attached to the backpack, laptop in hand.

parking lot was reached and the backpack carrier walked to an approximately 10m elevated point on the other side of it to regain Line of Sight. During the test the development kits stopped being completely vertical, and leaned a bit outwards as seen in Figure 4.9.

Parsing of data

We had to modify the dataset as the Nordic and Swiderski datasets had an unequal amount of measurements. The least amount of data points collected at one distance was 23 for Nordic, so we used this as the standard for all distances. Meaning we used 23 data points for each distance for each of the methods.

We also discarded all measurements that measured 0 meters, as these measurements were invalid.

4.2.2 Results

Swiderski method reached a range of 823m before we ran out of physical testing space while Nordic reached 126m. This means that the range of Swiderki's method is most likely higher, although we started to experience some package loss. The Nordic method is less accurate, however it had a significant higher precision. The Swiderski method is the opposite, getting the actual distance closer but having a significantly lower precision. This can be seen in the standard deviation of both. As the average standard deviation for Swiderski is lower than Nordic, meaning a

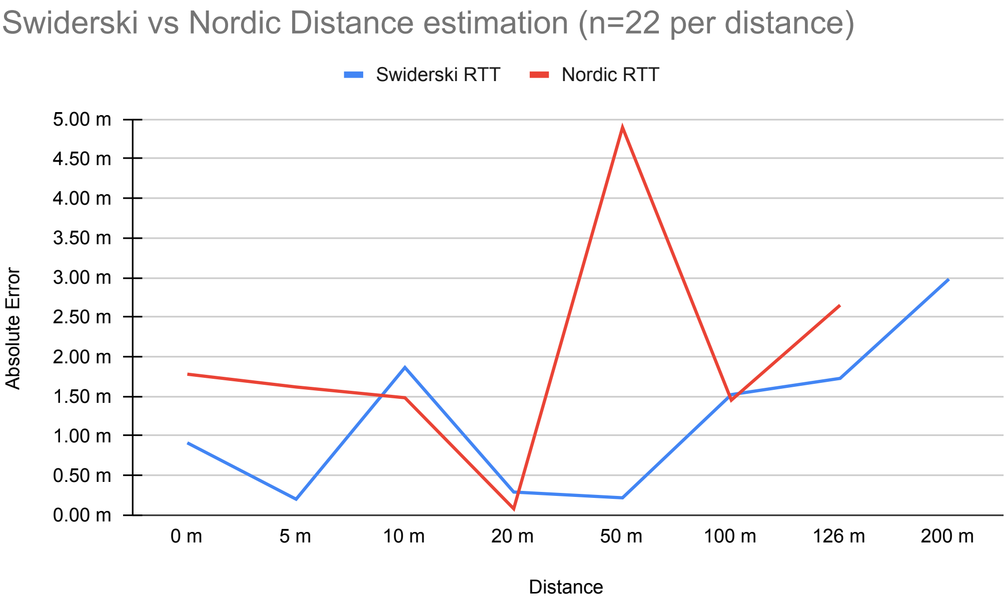


Figure 4.10: Swiderski vs Nordic Distance measurement. 22 Measurements per distance. Nordic had a max range of 126m during this test

Actual Distance	Swiderski Estimate	Nordic Estimate	Swiderski STD	Nordic STD	Swiderski Error	Nordic Error
0	0.91	1.78	0.31	0.47	0.91	1.78
5	5.20	6.62	0.87	0.33	0.20	1.62
10	8.14	8.52	1.16	0.29	-1.86	-1.48
20	20.29	20.08	1.68	0.35	0.29	0.08
50	50.22	45.10	1.65	0.29	0.22	-4.90
100	101.52	98.55	0.99	0.11	1.52	-1.45
126	124.27	128.65	0.91	0.52	-1.73	2.65
200	202.98	0	1.76	0	2.98	0
Mean Absolute	N/A	N/A	1.17	0.34	1.21	1.99

Table 4.4: Swiderski vs Nordic Distance measurement.

higher accuracy.

4.2.3 Discussion

Averaging 22 measurements when comparing the implementations might have favored Swiderki's implementation since it had a higher standard deviation than Nordic's implementation. This would have the effect of averaging out the larger individual measurement erros in Swiderki's implementation. It would have been interesting to compute the Mean absolute error in order to mitigate the effect of the averaging of the distance estimates, and thus have a clearer picture of which method is closer to the truth. Due to a lack of time we could not do this.

The difference in maximum range between Swiderski's and Nordic's RTT implementation was initially quite strange. For the test we utilized the same hardware so the range should have been somewhat similar. We asked on Nordic Semiconductor's forum and they replied that it was most likely set to 0dBm compared to Swiderski's method running at 8dBm. A 8dB increase in transmit power is 6.3 times increase in linear terms. 126m*6.3 = 793,8, bringing the Nordic range close to Swiderki's implementation. Although it is still lower as we did not reach Swiderki's maximum range. This lower output power of the Nordic RTT method could also have a possible effect on the distance estimation for that method depending on how Nordic have implemented it, for example having more packages fail and thus having less accurate results than what would be possible with a higher gain.

4.2.4 Conclusion

Swiderski's RTT implementation has a lower error than Nordic's implementation when averaged over 22 measurements for each distance. However it had lower precision as evident by the higher standard deviation.

4.3 Antenna RSSI & monopole radiation pattern test

[2] proposed combining a Minew MS88SF23 module, an antenna and a CR2032 battery to create a small tag for use on sheep. We initially chose a cheap and simple monopole whip antenna that could be ordered from china for 10 NOK a piece including shipping.[88] for this. However when studying antenna theory for this thesis, two issues were found.

1. The antenna would not have a sufficiently large ground plane to radiate efficiently (at least $\lambda/4$)[26] which would be a 3,125cm x 3.125cm plane for our 2.4Ghz signal.
2. Our antenna would not be oriented 90 degrees on the ground plane (the Minew PCB). 90 degrees on the ground plane is the typical configuration for vertical monopoles to produce an even radiation pattern in the horizontal plane[25], and deviating from this could produce unexpected results.

We thus wanted to check the radiation strength and rough maximum radiation direction of this antenna when combined with the Minew chip, and compare it to other antennas, primarily dipoles. Dipoles were chosen for comparison as they have a uniform donut radiation pattern, do not require a ground plane and are often used for UAVs.

4.3.1 Methodology

An "echo-free" room at our university, the Norwegian University of Science and Technology (NTNU) was used. See Figure 4.11

The room is 9,0 x 4,6 x 4,6 meters and has walls made out of wool spikes designed to absorb radiation above around 800 MHz. Inside the room there are

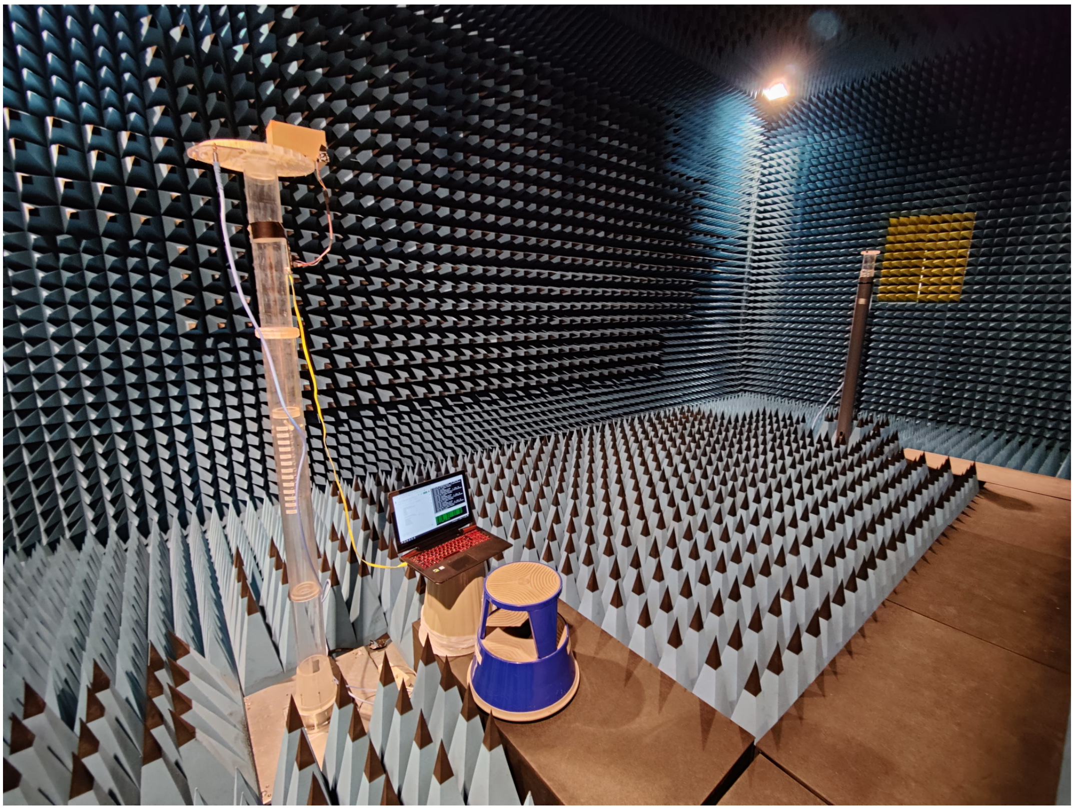


Figure 4.11: "Echo-free" antenna test chamber with our added equipment

two mounting points for antennas made out of plastic that are mostly hollow in order to reflect as little radiation as possible. Above them, 2.3m above the ground there is a 1m diamter sphere with a quiet zone refletivity of -43 dB.

For our experiments we placed a Minew MS88SF23 on each pole. On the side closest in Figure 4.11 we placed the antenna on a cardboard box to allow us to rotate it easier. On the same side we connected the Minew chip to a Nordic Semiconductor nRF52833 development kit. This kit was then connected via USB to a laptop. In an ideal scenario the laptop would be placed outside of the room to reduce reflections from it, but we considered it small and far enough away to not have a major impact on the experiment. A metal bucket for placing the laptop, and a metal stool for sitting on and adjusting the radio position was also added to the room. Ideally these would have been made of a less conductive material to reduce the reflections introduced into the room. Additionally one of the researchers was preent operating the laptop during the test, noting down RSSI values outputted by the closest Minew chip into a spreadhseet. To see if the researcher sitting there had an effect, an antenna test was done with and without the researcher present, however we did not observe a difference in RSSI. In this context the values were fairly constant when performing the same measurement, varying by maybe 1 dB from measurement to measurement. This is much less variance compared to our outdoors antenna orientation experiments.

The RSSI values outputted by Swiderski's RTT software[3] did not have any decimals. An attempt was made to change the code to increase measurement precision, but the code receives the RSSI values from Nordic Semiconductor's nrf_radio_rssi_sample_get()[92] function, which returns the RSSI as an integer. Thus a higher RSSI precision did not seem possible, although averaging of 4 measurements was done by the software and rounded to the nearest integer.

Monopole antenna radiation experiment

For this experiment the goal was to get a rough idea of the monopole antenna's radiation pattern in the horizontal plane when oriented horizontaly. To do this an angle measurement tool was used. The Minew with the antenna was mounted to a small empty cardboard box for easy repositioning. The antenna was bent a bit inwards at the mounting point, so the box had to be angled slightly to compensate for this, so that the antenna's white radiating element would point at the intended angle. The mount can be seen in Figure 4.12 and a top-down visualization of the experimental setup can be seen in Figure 4.13.

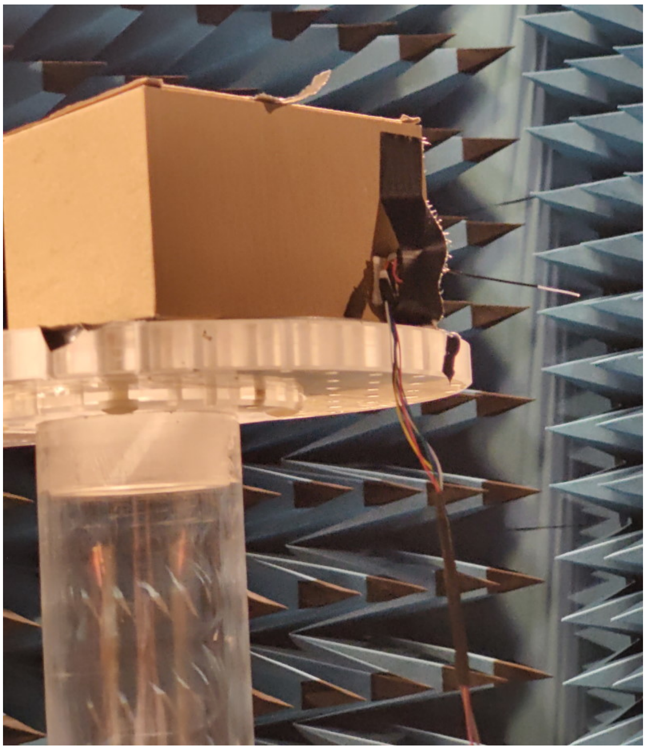


Figure 4.12: Monopole antenna attached to cardboard box for easier angle adjustment

To provide radio signals that could be measured as RSSI by the measuring antenna's Minew chip, another antenna was placed at the pole on the other side

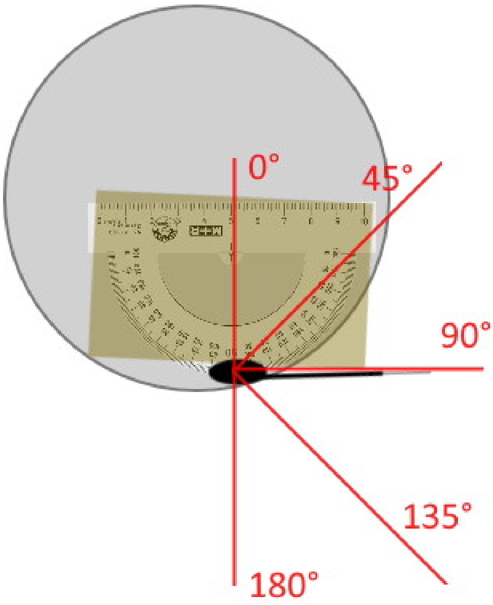


Figure 4.13: Top-down view of the horizontal monopole radiation strength test The angles show the directions the antenna was pointed in to produce RSSI values seen in the results table.

of the room. It was also oriented horizontally as seen in Figure 4.14 to have the same polarization as the monopole. This antenna was a 2.4Ghz flexible dipole. It was chosen for this experiment due to its low gain of just 1 dBi[93] and uniform radiation pattern as seen in Figure 2.5.

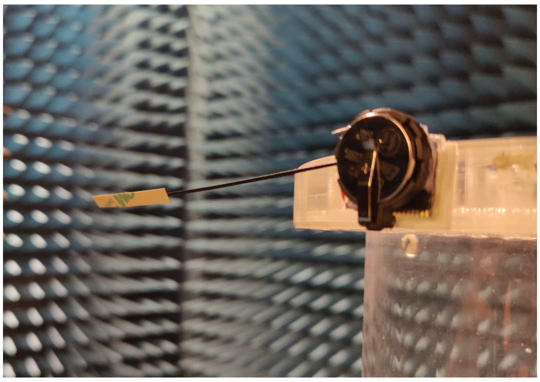


Figure 4.14: Flex dipole antenna mounted on the other side of the room

During the experiment, the monopole antenna would be placed in one of the orientations shown in Figure 4.13, then the researcher would sit still for a few seconds, then note down the RSSI value printed in J-Link RTT Viewer on the laptop into a spreadsheet. For the 45 degrees and 90 degrees orientation the experiment was repeated 3 times. For the 180 degrees orientation it was repeated twice in order to average out the measurements.

Antenna pairings experiment

The antennas were placed on each side of the room as in section 4.3.1. The antennas were oriented in such a way as to be in the orientation giving maximum gain towards the other antenna. This means parallel to the other antenna like seen in Figure 4.14, or with the two "arms" parallel to the other antenna, for the t-dipole. The exception being the monopole antenna which was oriented parallel to the other antenna, even though our experiments show that this is not the orientation giving the maximum signal strength. See Figure 4.15 for a rough radiation pattern visualization for the monopole paired with the Minew chip.

Table 4.5: Antennas used. *The "Nerland sleeve dipole" antenna is the one used in [1, 2], but the manufacturer and specifications are unknown.

Antenna name	Antenna type	Antanna gain
Team Blacksheep TBS Tracer Flex Dipole	Dipole	1dBi
Team Blacksheep TBS Tracer Sleeve Dipole	Dipole	1.5dBi
TrueRC D-Pole 2.4G U.FL	Dipole	2.5dBi
Nerland sleeve dipole*	Dipole	?
100mm 2.4G Receiver Antenna IPEX Port For FRSKY JR[88]	Monopole	0dBi

4.3.2 Results

Table 4.6: Results from pointing the monopole antenna in different horizontal directions. See Figure 4.13.

Lowest gain dipole & Monopole: Horizontal - Horizontal, 50cm	RSSI (dB)			Avg. RSSI
0 degrees	-63			-63
45 degrees	-48	-48	-47	-47.67
90 degrees	-53	-49.5	-50	-50.83
135 degrees	-55			-55
180 degrees	-62.5	-62.5		-62.5

The highest RSSI is at the 45 degree angle with an RSSI of -47.7 dB. 90 degrees is 2nd best with an RSSI of -50.8 dB. Looking at Figure 4.15 we can see that the antenna radiates the strongest in the upwards-behind it orientation (assuming it is mounted with the ground plane flat paralell to the ground).

We can see in Table 4.7 that the TBS Sleeve Dipole antenna combined with the T-dipole performed best.

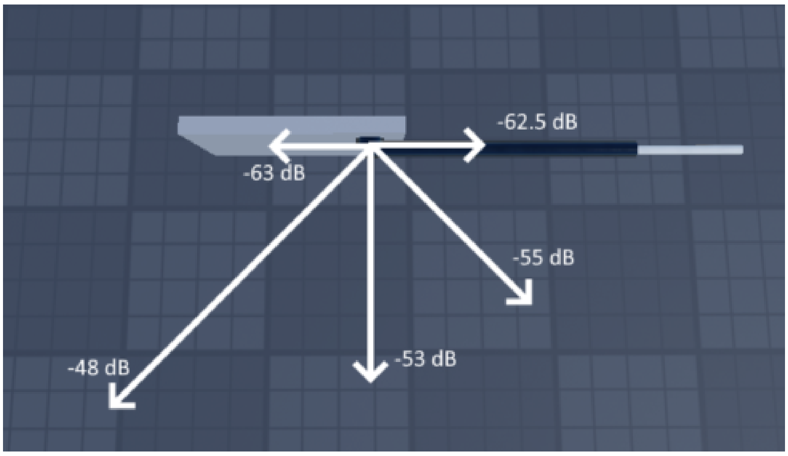


Figure 4.15: Illustration roughly showing the radiation strength in 5 measured directions in the horizontal plane.

Table 4.7: RSSI for different antenna pairings

Antenna pairing. Both mounted horizontally.	RSSI (dB)
Monopole & Monopole (same way)	-57
Monopole & Monopole (central pointing opposite way)	-62
Monopole & Flex Dipole	-52
Monopole & Nerland sleeve dipole	-47
Monopole & T-dipole	-44.5
Monopole & TBS Tracer Sleeve Dipole	-45
Monopole in best orientation and upright T-dipole	-41
DevKit & DevKit (aligned well)	-46
TBS Tracer Sleeve Dipole & t-dipole	-39

4.3.3 Discussion

We see in Table 4.7 that the pairing of the TBS Sleeve Dipole and the TrueRC t-dipole had the best RSSI. This is to be expected as they were the two antennas with the highest gain (directivity) of 1.5 and 2.5 dBi respectively. The monopole & monopole pairing performed worst. This is to be expected as the antennas were not oriented so that their maximum radiation direction was towards the other antenna. It is not clear to us why swapping the direction one of the monopoles was pointing from right to left and still keeping them parallel had such a dramatic effect on the .

The theory for monopoles on ground planes states that it should radiate most strongly at an angle like seen in Figure 2.11. This matches our findings seen in Figure 4.15. What is interesting is that the radiation strength is not mirrored like in Figure 2.11. This probably comes from the antenna not being mounted perpendicular to the ground plane, and possibly because of the asymmetric mounting point. We should have done a complete 360 degree set of measurements to figure out what the effect of mounting the antenna upside down would be, as that would have been easier with our prototype tag due to the battery placement.

The best antenna for use with the Minew chip for our prototype ear tag is not as straight forward as choosing the antenna with the strongest RSSI towards the other antenna. Radiation strength in dBi comes from direcivity, and the drawback is that the antenna will radiate weaker in all directions that are not the strongest direction. For a horizontally mounted antenna on a sheep's ear the directivity should be low so that the drone can pick it up when it flying on the sides of the antenna, and not just when it is directly overhead. Thus our antenna pairing experiments do not help us decide what antenna to use. The monopole radiation experiment however was useful as lets us better understand in which direction the sheep ear tag's radiation would be strongest, which can then be used to decide how to mount the prototype tag so that the strongest radiation is towards the sky where the drone is.

The antenna pairing results could have been more useful if we performed a range test or RTT accuracy test with the UAV like originally planned, as we could have chosen the the highest gain antennas to maximize the range of the experiment.

4.3.4 Conclusions

The Minew tag prototype radiates strongest upwards and to the side when paired with our chosen monopole antenna. The TBS Sleeve Dipole & TrueRC t-dipole had the highest RSSI when paired. The RSSI of the monopoles should have been measured with the antennas pointing towards each other in the direction of strongest radiation, and thus the measurd RSSI cannot be directly compared to the other antenna pairings in this test.

4.4 Medium scale system test

The goal of this test was to verify that the system worked as intended over a semi-large area with several nodes. As well as to verify that our new nRF52833 Minew chips with integrated antennas worked in a real world environment. We also placed the new Minew chips in pairs with the old chips with external antennas in order to investigate if they performed differently.

4.4.1 Methodology

Three Minew nRF528xx tags were placed in an open field, while two were placed in a lightly forested area right next to the field, see Figure 4.18. Their positions can be seen in Figure 4.16. The prototypes with an integrated antenna are based on the nRF52833 chip, while the prototype with an external antenna are based on the nRF52840, although this difference has no effect on this test. The antennas were oriented horizontally to match the antenna orientation we expected the final prototypes to have as seen in Figure 4.17. The Minew chip with the external antenna was attached in such a way that the antenna was above the ground plane, for maximum radiation upward according to section 4.3. The antenna on the drone was also oriented horizontally.

Figure 4.16: Google Earth view of the test environment and tag positions.

A flight plan was created to cover the area in Radio Sheep GCS[1, 87]. The exact flight plan was not stored, but an approximation based on drone positions from stored RTT data can be seen visualized in Figure 4.19. The flight altitude was set to 42 meters above the ground.

The drone was set to automated flight, and when the flight completed the data was extracted with the Radio Sheep GCS software. However initial transmission of the data was going extremely slow. We speculated if this was because of the fact that the nRF52840 chip on the drone was still performing RTT distance measurements. Upon removing the batteries from all of the nRF52833 "sheep" nodes, the transmission speed increased significantly and we were able to receive the data. However as the number of received measurements tipped over approximately 800, the transmission speed started slowing down again. At 1370 measurements transmission speed was down to approximately one measurement a minute, and we decided to stop the loading of the RTT measurements.

4.4.2 Results

1370 RTT measurements were received (1289 when filtered for corrupted messages). However, they do not cover the whole area as seen in Figure 4.20 because we cancelled the transfer as explained above. All the RTT distance circles used for

Figure 4.17: nRF528xx chips (one with integrated PCB antenna, one with Monopole) rotated the same way, with antennas oriented horizontally.

Figure 4.18: nRF52840 MS88SF23 tag with monopole antenna (left) and nRF52833 MS88SF21 with PCB antenna (right) rotated the same way, with antennas oriented horizontally.

multilateration can be seen in Figure 4.20.

As seen in Figure 4.21 and Table 4.8 the tags in the field had a localization

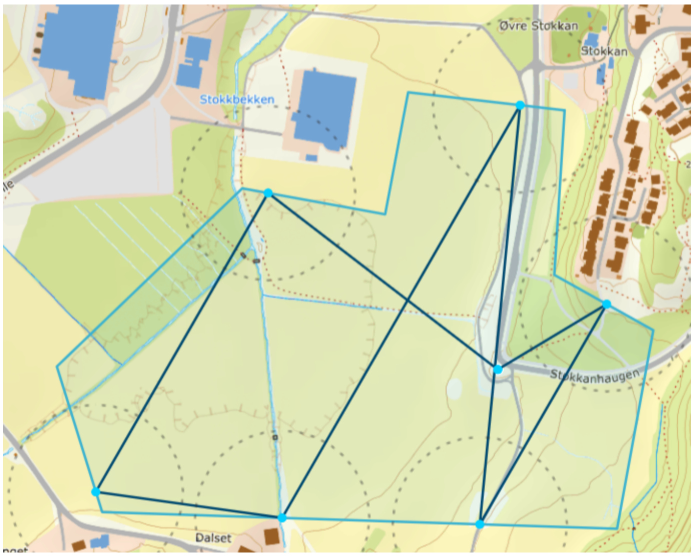


Figure 4.19: Re-created approximation of the fight path for the medium-scale system test.

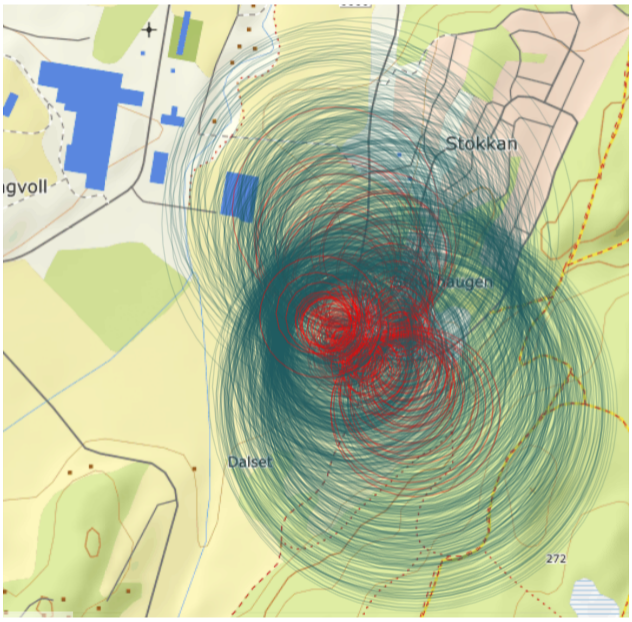


Figure 4.20: All RTT measurements visualized in Radio Sheep GCS. Red lines are for a currently selected sheep tag in the forest (ID 15097).

error of at least 142m. It can be seen in Figure 4.22 that the estimated location of tag 38938 (closest to the building) is far away from where most of the RTT distance measurement circles appear to intersect.

In Table 4.9 the localization errors for the tags in the forest using three different data sets are presented. The first dataset has 463 RTT distance estimates for

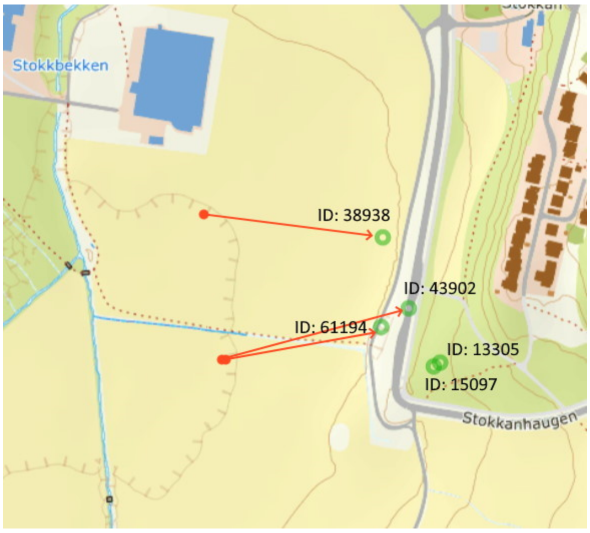


Figure 4.21: Found points for medium scale test with multilateration. The orange arrows point from the true location of the points which can be seen in more detail in Figure 4.16

Table 4.8: Medium scale test localization results

Tag ID	Antenna type	Location	Localization error (m)	Intersection area	Valid RTT measurements
15097	PCB	Forest	12.87	210.8	202
13305	Monopole	Forest	9.51	7.5	261
61194	PCB	Open field	146.67	1839.84	265
43902	Monopole	Open field	173.37	61.1	295
38938	PCB	Near building	142.5	98.0	266

the two points. In the second dataset the RTT measurements done while the UAV was taking off are removed, leaving 394. In the last dataset and only every 10th RTT measurement is kept, leaving 48 for the multilateration algoritm.

Aggregating the numbers from Table 4.8 the tags with an internal PCB antenna participated in on average 44,5 fewer (16% fewer) RTT measurements than the tags with an external monopole antenna. A quick glance at the localization errors and intersection areas in Table 4.8 indicates that there is little correlation between the numbers. The tags in the forest participated in 97 fewer RTT measurements than the tags in the open field, despite being closer to the drone.

4.4.3 Discussion

The localization error is smaller than the average reported by [1, 2] for the tags in the forest. For the tags in the open field, the localization error is very large considering the search area. The tags in the forest had a lower amount of RTT

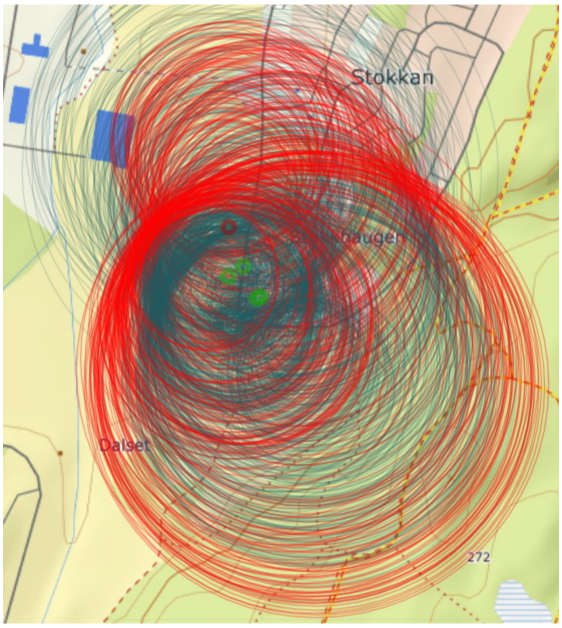


Figure 4.22: Red RTT distance circles for the tag closest to the building (ID 38938)

Table 4.9: Localization errors in meters for the tags in the lightly forested area.

Tag ID	Localization error (m)	Localization error (m) Takeoff RTTs removed	Localization error (m) every 10th RTT
15097	12.87	9.45	8.19
13305	9.51	10.28	16.24
Avg. error	11.19	9.86	12.22

measurements than the tags in the open, but it is unclear to which degree the forest foliage is responsible for this. It could also be influenced to some degree by of a worse mismatch in antenna orientation in the horiozontal plane between the drone and the tags than the tags in the field had. We do not know the antenna orientation of the drone as we do not have the flight data. Isolating the effect of the forest from the effect of the orientation could have been partly remedied by orienting the antennas of the sheep tags the same direction for all 3 locations when performing the test.

The localization accuracy for the tags in the field is as mentioned poor compared to previous field tests performed at almost the same location in [1, 2]. This is probably caused by only having data from the the first path of the UAV's flight, where it mostly flew in the north-south direction to the east of the tags, as seen in the flight plan approximation Figure 4.19 and RTT coverage seen in Figure 4.20. All the tags in the field are estimated by Radio Sheep GCS to be to the east of their true position. This is probably a weakness of the multilateration algorithm and not the RTT measurements themselves, as the majority of the distance estimate circles seen in Figure 4.22 appear to intersect near the true location. The discrepancy could be because there is no bias in the algorithm that favors the location where most of the RTT circles intersect. Rather it returns any area where all of the circles intersect.

To improve localization accuracy in cases where tags are on the outside of the drone's search coverage, the algorithm could detect when it has found such a tag and possibly adjust the multilateration algorithm. Poor localization accuracy does not appear to be a problem for the forest tags, where the drone has flown to both the north, west, south and east of the tags.

The tags shared the same location and orientation, so there was a noticeable difference in performance between the tags in favor of the external monopole antenna. However we do not have any explanation for this that is grounded in theory, so this would need to be researched further.

It can be seen in Table 4.9 that the average localization error decreased by 1.33m when the takeoff RTT measurements were removed. An explanation for this could be that at that point all the RTT measurement are taken at the same height, making any errors caused by not including height difference in the multilateration algorithm cancel each other out. However the change is small and the sample size for the experiment is too small for us to be sure of how big the effect is, if at all. More tests with tags at different ranges would need to be done to verify that removing the takeoff improves accuracy. If height difference is incorporated into the multilateration algorithm, this step might not be necessary.

When using only every 10th RTT distance estimate the average localization accuracy for the forest tags was 12.22 meters, which is better than the overall average found by [1, 2].

4.4.4 Conclusion

As long as the drone can fly on all sides of a tag, using every 10th measurement the localization error was at maximum 16m and on average 12m (+-3m because of GPS inaccuracy) when locating tags in a thin forest. For tags where the drone has only passed them on one side, the localization accuracy is poor (error of more than 142m), although this could possibly be remedied by changing the localization algorithm to favor the location where most of the circles intersect. The tags with an internal PCB antenna participated in 16% less RTT measurements than the tags with an external monopole antenna, and can thus be said to perform slightly worse.

4.5 System tests on farm with sheep and prototype tags

We performed tests of the system on 3 sheep and 2 lambs. The goal of the testing was to examine the feasibility and performance of the system in a real environment for the first time with real sheep. We wanted to investigate if the system could be used to locate real sheep and evaluate how accurate the location estimates are in a more realistic environment.

4.5.1 Test context

We reached out to Trondheim's only remaining sheep farmer, Bente Sagberg, who volunteered her sheep to participate in the tests. Bente's sheep are typically let into a approximately 83000 m^2 (20.5 acres) fenced area around the farm (see Figure 4.23), where they graze for 1-2 weeks before they are let into the surrounding nature.

In [2] and [12] it was proposed to have a Minew chip with an external whip antenna mounted on the ears of sheep and lamb. However when presenting this idea to Bente and her husband Odd, they explained to us that the antenna could easily get stuck in something, and thought that mounting the chips to the collars of the sheep would be better. Therefore we instead ordered new nRF52833 Minew chips from China with integrated PCB antennas. When we proposed mounting these to the ears of sheep and lamb the response was positive.

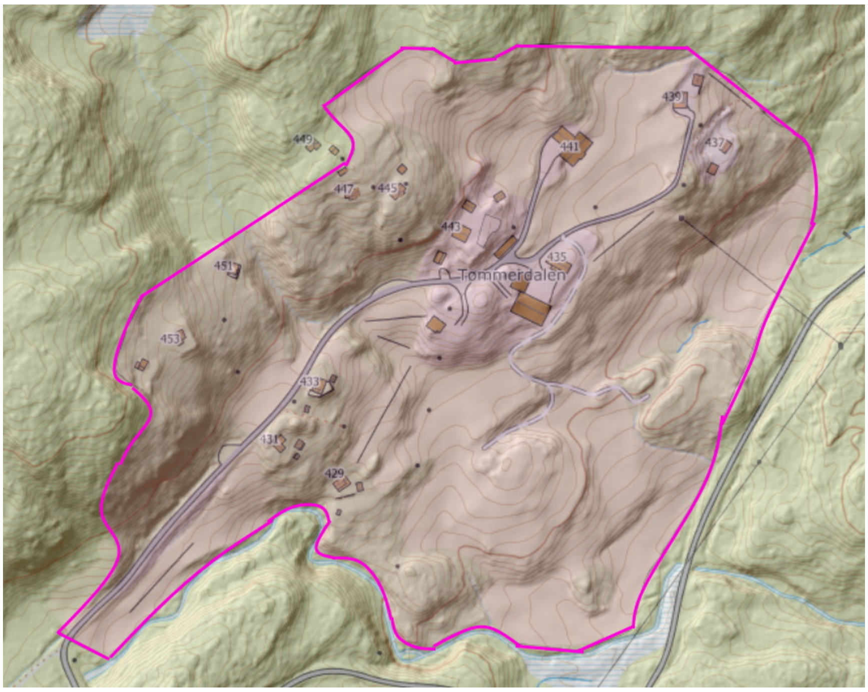


Figure 4.23: Topographical map of the initial sheep grazing area based on LIDAR scans from hoydedata.no[94], where the pink line represents the physical area fence.

4.5.2 Methodology

We used three nRF52833 Minew tags with integrated antennas, and two nRF52840 Minew tags with external monopole antennas, see section 3.5. Some days we also placed additional Nordic Semiconductor tags with horizontal PCB antennas around the farm for reference. The Development Kit tag locations for 31.05 can be seen in Figure 4.24 and the position for all of the tags are visualized in Figure 4.28.

Figure 4.24: The locations of the two nRF52833 Development Kits placed around the farm on 31.05

The two external antennas were mounted to the collars of grown sheep wearing traditional bells, while the three chips with PCB antennas were attached to the plastic ID ear-tag on two lambs and one sheep using duct tape. The lambs with tags can be seen in Figure 4.25. We checked that all the tags were sending prior to mounting them. The sheep were then released into the enclosed grazing area around the farm. The battery types and their measured voltages before starting can be seen in Table 4.10.

We used Radio Sheep GCS to create flight paths covering either parts of the farm or the whole farm. Initial flight height was 40 meters above the ground, and initial drone speed was 3m/s.

The plan was to view the estimated sheep positions in Radio Sheep GCS after a flight, and attempt to find the sheep based on these position estimates in order to verify that we were able to find sheep using the system. For some flights, one to three additional nRF52833 development kits were placed around the farm to

Table 4.10: CR2032 Battery brands and their starting voltages

TagID	Voltage start	Battery brand
38938	2.797	Varta
61194	2.918	Varta
15097	2.858	Energizer
13305	3.235	Varta
43902	3.247	Varta

Figure 4.25: The two lambs with nRF52833 tags with integrated PCB antennas, attached to their plastic ear tags.

function as "control" subjects that had a set static position. This would enable us to evaluate the localization precision of the system in this grazing environment.

For all flights the weather was clear or overcast, except for 03.06 where there was a layer of fog about 100m above the UAV's starting location, with a humidity of 99%.

The drone was always launched from an open area free from obstructions like power lines. This location is waypoint 2 in Figure 4.30 and is pictured in Figure 4.26. After each flight the drone was brought to a laptop in the middle of the farm (see Figure 4.27) and the RTT distance estimatates were extracted via USB and MavProxy into Radio Sheep GCS. We had an issue while performing the medium scale experiment in section 4.4 where we were unable to retrieve RTT measurements from the drone because the high-priority RTT measurements kept interrupting the code responsible for transmission. We modified Swiderski's software[3] to eliminate this problem, but the Minew chip on the drone required hardware modifications for it to be flashed. Thus a quicker fix was to simply wrap the antenna and UAV in aluminium foil after each flight to block the advertisement packets from the sheep tags so that the drone would stay in it's RTT measurements transmission loop.

Figure 4.26: Launch area for the UAV, with the UAV and FrSky Tarani Lite RC controller pictured. Taken 30.05.2022.

When analyzing the data we initially looked at all the RTT measurements, but when analyzing the results we modified the Radio Sheep GCS software to only use every 10th measurement for each tag. We incorporated this change into some of the results for an easier comparison with [1, 2] and more realistic evaluation of the system.

Changes to drone speed

After flight 1 on 30.05 flight speed was increased to 10m/s. This was done because during flight 1 of on the 30.05 we concluded that the drone was flying slower than the speed value set in Radio Sheep GCS. This was due to a previously set maximum waypoint flight speed parameter in mission planner of WPNAV_SPEED=300 cm/s. We changed this to 2000 cm/s. Subsequent flights were performed at 10m/s.

Figure 4.27: Station for wrapping the drone in aluminium foil and retrieving the RTT measurements. Taken 03.06.2022.

Drone crash and changes to flight height, drone tuning, drone speed and RTL height

After the crash during flight 3 on 30.05 drone speed was lowered to 8m/s, the drone's tuning parameters were halved, and RTL height was increased to 80m above start height. This was done because during flight 3 on 30.05 the drone experienced a GPS glitch and switched to Land-mode mid-flight. Once the GPS glitch cleared after a few seconds we set the drone to Return to Land (RTL), but it crashed into the top of some trees and fell to the ground. It was a severe crash that required us to replace the 3D-printed GPS mount and one motor that stopped spinning. Once the drone was repaired, it flew with rapid oscillations that made the motors hot. We tuned the drone to make it adjust it's thrust slower, which fixed the motor heat problem and made the wobbling low frequency enough for flight, although the drone was still more wobbly than before, especially during hover and landing.

Addition of external coin cell battery

Before flying on 03.06, an external coin cell battery was attached to the drone like described in section 4.10.1. This was done to attempt to remedy the problem where RTT measurements were not received after longer flights, by attempting to maintain a more constant voltage for the Minew chip.

4.5.3 Overall UAV sheep localization results

Flight success rate

The weather was good for flying the drone all of the days except for winds of around 4m/s with gusts of around 9m/s almost every flight. The wind did not impact the drone other than making landings a bit more wobbly. As seen in Table 4.11 only 40% of the flights were successful.

Table 4.11: Flight results

Date	Successful flights	No RTT data from drone	Crash or abort
27.05	0	0	1
29.05	2	0	0
30.05	0	2	1
31.05	3	1	0
03.06	1	2	1
Total	6	6	3

Overall localization error

The average localization error for all Development Kits and tags was 15m as seen in Table 4.12.

We do not have the true positions for the sheep, so data for the static development kits placed around the farm on 31.05 and 03.06 is used instead to evaluate the localization precision. The results from Flight 4 on 03.06 are not included as the flight was aborted mid-flight. The localization estimates and subsequent errors presented in Table 4.12 are based on every 10th RTT measurement like in [1, 2].

Recorded Global Navigation Satellite Systems (GNSS) location of Development Kits and their estimated locations are visualized in Figure 4.28. Their error compared to the GNSS location is presented in Table 4.12.

Table 4.12: Overall localization error for development kits in meters, using every 10th measurement.

TagID	Flight date	1st flight error	2nd flight error	Avg. error
945	03.06	17.67	N/A	17.67
13959	31.05	9.97	3.88	6.93
35207	31.05	26.26	15.70	20.98
Total avg.				15.19

Figure 4.28: All position estimates for Development Kits placed around the farm, visualized in Google Earth. The points with X-marks are estimated locations.

Success rate locating sheep using the system

We were unable to use the system to physically locate sheep due to technical difficulties with the UAV and Radio Sheep GCS as described in the more detailed results. However the location estimates for the sheep given by the system on 29.05, 31.05 and 03.06 match with locations where we have seen sheep while we were at the farm, and are reasonable, with the exception of flight 4 on 03.06 where there were very few measurements.

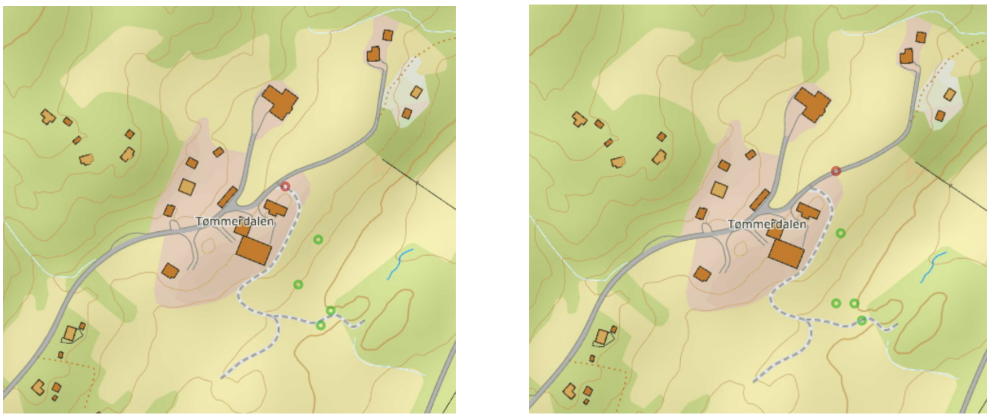
4.5.4 Sheep localization results grouped by day

27.05 (Test day 1)

The drone was not able to get a GPS fix. Thus we could not perform an automated flight. We found it was because the solder point between the GPS power cable and drone was loose, causing a bad connection.

29.05 (Test day 2)

After doing a few intial test flights, two proper flights were performed. For both flights, all 5 sheep tags were given estimated positions by the software, although we did not visually confirm the locations of the sheep against the estimates given by the system. The 1st flight was small in scale and produced 361 valid RTT measurements, while the second one produced 1296 valid RTT measurements. The estimated positions of the sheep are visualized in Figure 4.29. Figure b) and d) use every 10th distance estimate like done by [1, 2]. The proposed sheep locations appear to be quite similar even with just 1/10 of the data. The figure shows that according to the system, the sheep with tags have moved between the two flights.



(a) Flight 1 all RTT distance measurements

(b) Flight 1 every 10th RTT distance measurement

(c) Flight 2 all RTT distance measurements

(d) Flight 2 every 10th RTT distance measurement

Figure 4.29: Estimated sheep locations flight 1 and 2, 29.05. For the figures to the right, only every 10th RTT distance estimate is used. The locations are marked with red or green circles, where the red circle is tag 61194.

This day we observed that the collar of the sheep wearing tag 43902 had rotated 90 degrees, putting the antenna the side of the sheep's neck. The sheep wearing tag 13305 still had the antenna flat on top of it's neck like intended.

Table 4.13: Number of RTT distance estimates for each tag 29.05

TagID	Tag type	Sheep or lamb	Dist. estim. flight 1	Dist. estim. flight 2
13305	Monopole antenna	Sheep	25	75
15097	PCB antenna	Lamb	110	341
38938	PCB antenna	Sheep	103	392
61194	PCB antenna	Lamb	64	203
43902	Monopole antenna	Sheep	59	285

30.05 (Test day 3)

Three flights were performed but we were unable to retrieve RTT distance estimates any of the times. The drone flew around the whole farm two times and did not return any RTT data either time. The flight plan and flight position log can be seen visualized in Figure 4.30. We attempted to do a few takeoffs and landings to verify that the system was working and that we could retrieve RTT measurements, before trying again. On the third flight the drone experienced an EKF fail due to a GPS glitch and went into Land mode. As it was above some trees we set it into RTL instead, however it hit a tree on the way back and crashed into the ground as RTL was set to maintain it's current altitude, and it had lost some altitude during it's initial Land maneuver.

Figure 4.30: Flight plan for all 3 flights on 30.05. Flight 2 is visualized here.

In the end no RTT data was retrieved this day.

31.05 (Test day 4)

Four flights were performed, gradually increasing the flight duration. RTT distance estimates were extracted for the first three flights. When the drone landed it did not send data for the fourth and longest flight. The flight plans can be seen in Figure 4.31.

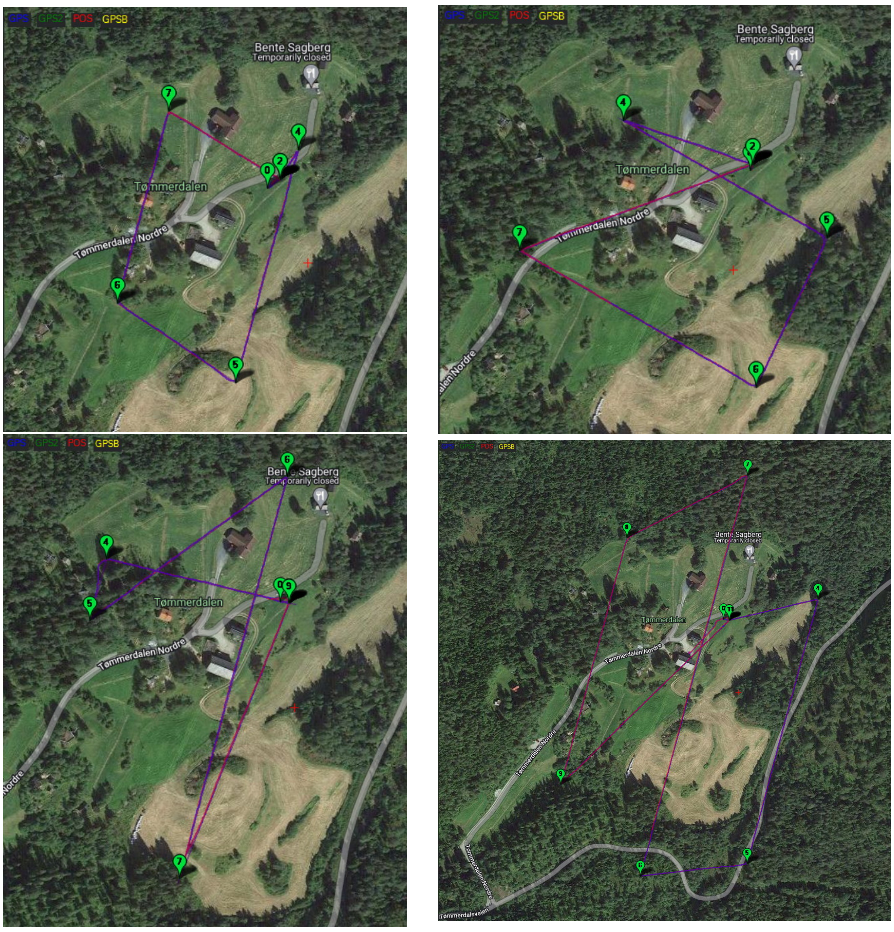


Figure 4.31: Flight plans 1 to 4 on 31.05, starting from top left.

When attempting to perform multilateration on the data in the field, Radio Sheep GCS threw an error as detailed in subsection A.1.4. Thus we were unable to use the system to visually confirm the locations of the sheep this day. Further analysis was performed once that issue was resolved.

Table 4.14 gives an overview of which tags were found. Additionally the two development kits placed around the farm, and a development kit we forgot to turn off inside the car, were also found. After fixing the error described in subsection A.1.4, when attempting to perform multilateration with Radio Sheep GCS, tag 61194, 13959 and 945 would show up in as being in the country of Algerie. This bug was fixed later as explained in subsection A.1.5. The DevKit in the car

(ID 945) is not included in further analysis.

Table 4.14: Sheep tags found on 31.05. The columns "Dist. estim. flight x" contain the amount of valid distance estimates for each tag.

TagID	Tag type	Sheep or lamb	Dist. estim. flight 1	Dist. estim. flight 2	Dist. estim. flight 3
13305	Monopole antenna	Sheep	98	99	100
15097	PCB antenna	Lamb	48	97	103
38938	PCB antenna	Sheep	67	60	85
61194	PCB antenna	Lamb	126	143	124
43902	Monopole antenna	Sheep	0	0	0
13959	PCB antenna	DevKit	N/A	152	163
35207	PCB antenna	DevKit	N/A	143	144

In Table 4.14 it can be seen that tag 43902 was not discovered at all, last being detected on 29.05.

Table 4.15: Localization error in meters for the Development Kits with know locations 31.05. Both using all RTT distance estimates and every 10th RTT distance estimate for each tag.

	Error flight 2 (meters)		Error flight 3 (meters)	
TagID	All RTT	1/10 RTT	All RTT	1/10 RTT
13959	15.23	9.97	2.92	3.88
35207	15.36	26.26	8.39	15.70

03.06 (Test day 5)

Four flights were performed, of which 2 were successful. Flight 1 went well producing 413 valid distance estimates and detecting two sheep, while flight 2 and 3 did not produce any RTT data. The possible reasons for no data being returned are detailed in section 4.10.1 but were in essence related to the on-board Minew nRF52840 chip responsible for distance estimations not working due to low voltage. Flight 4 was performed 1 hour and 7 minutes after flight 1 and had to be aborted and set to RTL due to a low battery warning on the drone. Despite this, 89 RTT distance estimates were retrieved, and two sheep were detected during this flight. We were unable to confirm the positions of the sheep visually this day as we were focused on attempting to get the system working reliably. The flight plan for all the flights can be seen in Figure 4.32.

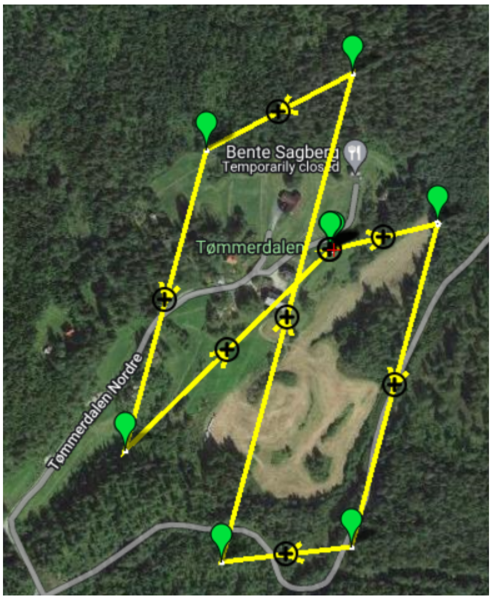


Figure 4.32: Flight plan for all of the flights on 03.06

Looking closer at the number of RTT distance estimates for each tag, seen in Table 4.16, it can be seen that tag 15097 was detected during the first successful flight (see Figure 4.33) but not the second, and that tag 13305 was detected during the second successful flight, but not the first. Tag 61194 was not detected at all even though it was detected in the previous test on 31.05, and tag 43902 is still missing.

The sheep wearing tag 13305 was observed, still with the antenna in the correct position flat on top of it's neck, as seen in Figure 4.27.

Table 4.16: Number of RTT distance estimates for each tag 03.06

TagID	Tag type	Sheep or lamb	Dist. estim. flight 1	Dist. estim. flight 4
13305	Monopole antenna	Sheep	0	7
15097	PCB antenna	Lamb	43	0
38938	PCB antenna	Sheep	167	2
61194	PCB antenna	Lamb	0	0
43902	Monopole antenna	Sheep	0	0
945	PCB antenna	DevKit	203	80

Table 4.17: Localization error in meters for Development Kit 934 on 03.06. Shown for all RTT distance estimates and every 10th RTT distance estimate.

	Localization error (meters)	
Flight nr.	All RTT	Every 10th RTT
1	17.94	17.67
2	No data	No data
3	No data	No data
4	25.42	50.99

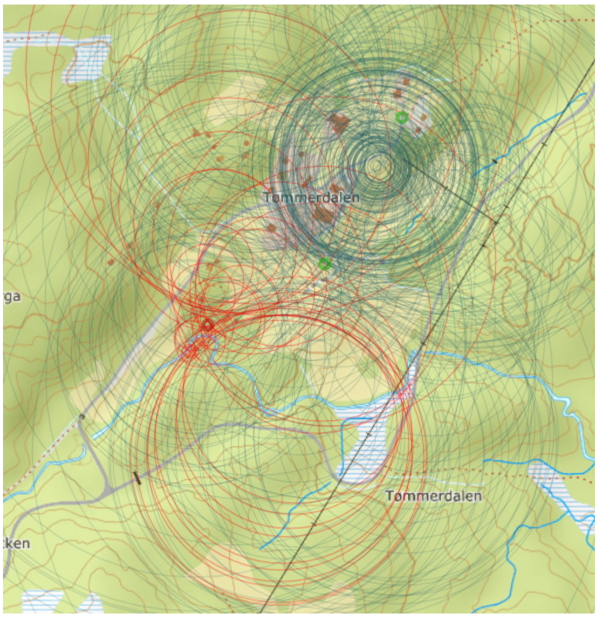


Figure 4.33: RTT distance estimate lines (in red) for tag 15097 during flight 1 on 03.06.

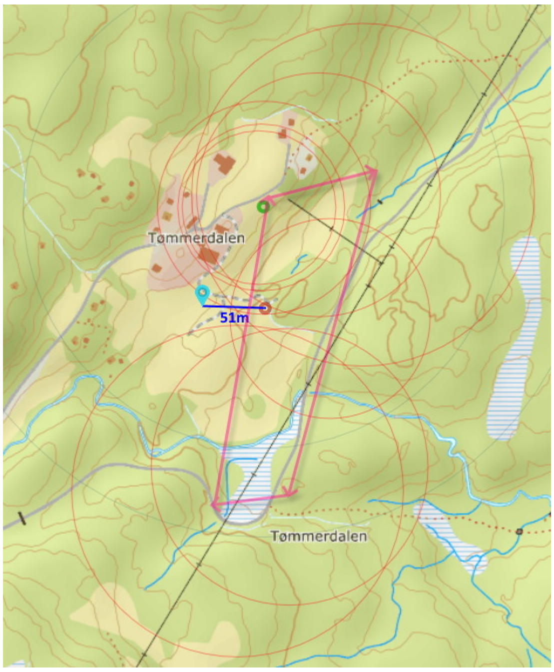


Figure 4.34: For 03.06, true location of Development Kit (Cyan marker) vs. estimated location (red circle) with RTT distance estimates and the flight path of flight 4 plotted in.

Prototype tag mounting results

Bente and Odd thought that the collar of the sheep would not rotate, thus keeping the antenna on top of the sheep. However we observed on 29.05 seen in Figure 4.35a that for tag 43902 the sheep's collar had rotated, putting the radiating element of the monopole antenna vertically on the side of the sheep's neck, in stead of horizontally on top. On 03.06 we observed that the lamb with prototype tag 13305 had lost it's ear tag, as seen in Figure 4.35b. The previous day we were there we had seen that the duct tape of one of the lamb tags had already started to loosen. It thus appears the duct tape had gotten loose and the tag had fallen off.

(a) Rotated collar on 29.05. The radiating element of the antenna is marked with a black line.

(b) Lamb with the tag having fallen off on 03.06

Figure 4.35: Problems with the mounting of the prototype tags

4.5.5 Discussion

The system's ability to locate sheep

Through our experiments we found the average localization error of the nRF52833 development kits to be 15 meters. The plan was originally to use Radio Sheep GCS and the UAV to locate the sheep, but this was not possible for us due to technical difficulties with the UAV and Radio Sheep GCS. The question then remains if the system is able to locate sheep?

We have previously verified in section 4.4 that the system can locate our prototype tags with an average error of 12m when they are stationary in a lightly forested area next to a field. In our farm experiments we were able to repeat that success in a more realistic environment with uneven terrain and obstructions (in this case buildings). We are thus fairly certain that the system can locate a tag with an average localization error of 15m. This probably means that it can locate sheep wearing the tag with the same or similar precision.

One issue that could cause worse accuracy on real sheep is that the sheep's head could obstruct the signal. We did not investigate the effect of this. The ear tags however, are mounted quite high on the sheep and thus the head would only block signals traveling close to the ground. For the collar mounted tag the head blocking the signal could be a bigger issue, as we saw in section 4.5.4 that the position of the antenna fell to the side of the neck. It did however not stop the system from giving a position estimate for the tag, as seen in Figure 4.29. In fact the antenna had a similar amount of RTT measurements compared to the other tags on 29.05. The differences in amount of RTT measurements could be because of the direction each sheep is facing, causing mismatch with the drone's antenna for some.

Another possible issue is that the sheep can move while the UAV is flying, causing the error to increase. We did observe the sheep moving around the farm, although they were mostly still and resting or moving slowly while grazing.

Localization accuracy

Comparing our localization accuracy of 15m +-3m with that of [1, 2] confirms that the localization accuracy of their system holds up in a more challenging environment. It is not a completely fair comparison as we performed more accurate multilateration, which could explain our slightly better results than their 19m average presented in [1].

The stationary tags do not cover all possible locations for sheep. We do not have data for tags at the edge of the farm, or tags under foliage. We attempted to place tags in more challenging locations such as under vegetation on 30.05, but were unable to retrieve the RTT data from the UAV for these tests. There were however buildings, elevation differences, and some foliage close to the tags we do have data for, making for a more challenging environment than previous open field tests.

We did have a case where the system produced a localization error of 51m seen in Figure 4.34. This result is similar to the poor results we got for some of the tags in the medium scale system test (section 4.4) and we consider the problem to be lack of flight coverage from more than one side, as both the outbound and return flight were east of the tag's real location. Thus that specific result is not included in analysis of average localization accuracy.

Tag 43902 gone missing on 31.05

The last time we saw the sheep wearing tag 43902 was on 29.05, pictured in Figure 4.35a. We were able to locate it that day using Radio Sheep GCS, but the tag was never detected again. Maybe the bell seen rubbing against the tag damaged it somehow when the sheep was moving around. The prototype tags are only protected by duct tape and held together by weak solders and hot glue, so this is quite likely. It could also have been water damaged.

Few RTT distance estimates and missing tags on 03.06

On 03.06 sheep monopole tag 13305 produced 0 RTT distance estimates on the first flight, despite producing 7 on the 4th flight. This is a puzzling result as the first flight covered more ground than the fourth flight. It could be because the sheep was under very dense tree cover. However we still should have been able to detect it based on the results of our forest range experiment detailed in section 4.7. We also greeted and took pictures of that specific sheep close to us both a few minutes prior to and a few minutes after flight 1, like in Figure 4.27. Thus we have no hypothesis for why we were unable to detect it during flight 1.

Another puzzling result is the drop from 167 distance estimates to 2 for tag 38938 between flight 1 and and flight 4 on 03.06. We speculated that it could be because the battery on the tag had ran out, as the two measurements were taken while the drone was at maximum altitude during takeoff and then never again. However looking at the RTT distance estimates plotted by Radio Sheep GCS in Figure A.1 shows that the UAV was performing successful RTT distance estimates even at the end of the flight (when the UAV was north of the takoff location). Thus a more likely reason is that the sheep had moved to a position where the UAV did not have Line of Sight due to flight 4’s short flight. This quite likely to be the reason for not finding tag 15097 during flight 4 as well.

Tag 61194 was not detected at all. Since it was a lamb tag, it can be speculated that it was the tag that fell off the lamb pictured in Figure 4.35b. When it fell off it could have ended up in bad orientation relative to the drone’s antenna, in a sub-optimal location like a ditch, or been disabled by water damage, leading to no RTT measurements being produced. If it was not the tag that fell of, we do not have an explanation for why we were unable to find it. The batteries should have lasted for at least 48 weeks according to [3]. Although this was probably reduced somewhat by the RTT measurements performed during our flights.

Using fence information to improve localization accuracy

Looking more closely at the RTT distance estimates for tag 13305 as visualized by Radio Sheep GCS in Figure 4.36, we can estimate the position by comparing the distance estimates with the known locations of the fence seen in Figure 4.23. With this information we can draw in an estimated area the sheep could be in as seen in Figure 4.36. If the knowledge of fences or impassable geographical obstructions could be plotted into Radio Sheep GCS, this could be used to improve the localization performance in situations with few RTT distance estimates. Implementing it into the point estimation logic of Radio Sheep GCS should actually not be that hard, as it only requires adding another polygonal area that the multilateration algorithm needs to intersect with.

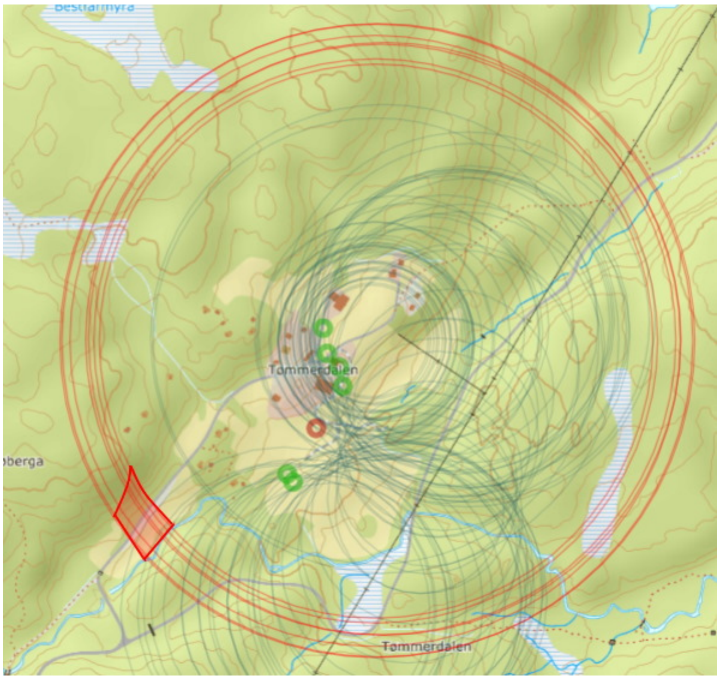


Figure 4.36: Possible location of tag 13305 on 03.06 marked with the red polygon, based on RTT distance estimates and knowledge of the fenced farm perimiter.

Prototype tag design

We did not observe the sheep or lambs responding to the presence of neither the ear tags nor the collar mounted tag. Thus we conclude that they were not bothered by them to any greater extent than having the the plastic collars and ear identification tags there in the first place. This should be taken with the caveat that we are not experts on sheep behaviour and are unable to observe subtle changes in behaviour that could be caused by the installation of our Minew prototype tags.

We do not consider the duct tape mounting method that we used to attach the Minew tags to the ear tags to the sheep to be a good mounting method. The intention was for the tags to stay on for at least two weeks, but we presented in section 4.5.4 that one had fallen off within 7 days.

Future work

We did not perform any flights where we subsequently attempted to locate the sheep on foot as we were unsuccessful in making the Minew chip on the UAV more reliable, and were running out of time for the thesis. This is regrettable as it means we were also not able to perform experiments after the sheep were released into the wider nature. Doing this, possibly in combination with a more high-flying UAV as proposed by [12] could be a next step in evaluating the system in an even more realistic environment.

Not knowing the exact locations of the sheep we were trying to find has definitely been a hindrance during the analysis of the results, and we propose that future experiments have the sheep wearing GPS trackers providing reference location data.

4.5.6 Conclusion

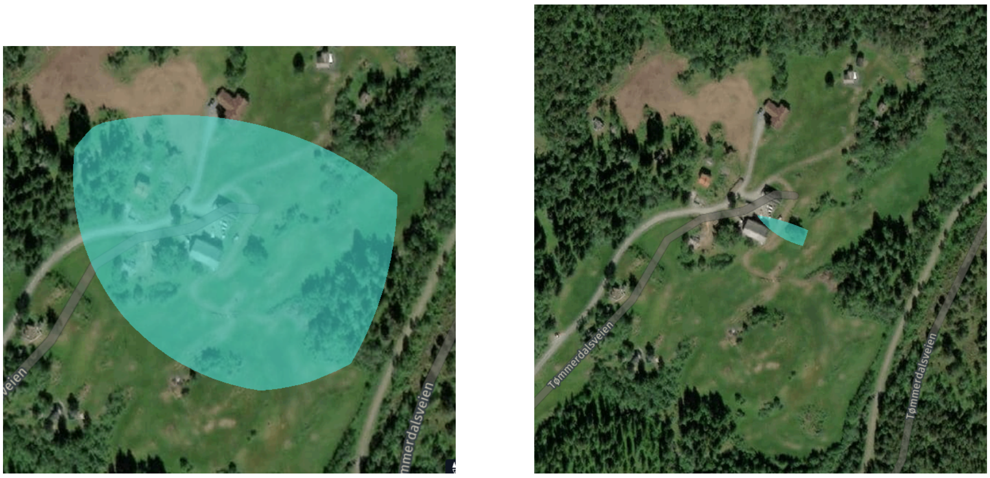
We demonstrated that the system has a localization accuracy of 15m for stationary tags in a grazing area around a farm. We have argued that this localization accuracy could be extended to apply to sheep as well. The system was able to give reasonable position estimates for all five sheep tags on 29.05. On 31.05 reasonable estimates were given for 4 of the tags, and one tag was not detected. On 03.06 another tag was not detected, and only 2 had reasonable location estimates due to few data points. The loss of tag 61194 and 43902 was likely due to the prototype tags not working due to having fallen off or been damaged somehow. The few RTT estimates for tag 13305 on 03.06 could be due to the sheep being somewhere where it was hard to detect, such as under dense foliage. However we are not certain as we do not have reference location data for the sheep. In the future sheep localization experiments should be conducted with GPS collars for reference.

4.6 Effect of changing error radius in Radio Sheep GCS

As a side effect of attempting to perform multilateration when some of the distance estimates are "corrupted" (showing 0 as the RSSI and distance), Radio Sheep GCS would print an error radius up to 128m. This can lead to very large intersection areas, such as the one seen in Figure 4.37a. Reducing the growth of the error radius for the multilateration algorithm like described in subsection A.1.3 produced similar results to the example seen in Figure 4.37 where the position estimates seen in Figure 4.37a moved to the locations seen in Figure 4.37b.

What is interesting is that the mean point of (which is the location Radio Sheep GCS returns for it's estimate) is often very similar before and after the change. This can be seen in Figure 4.38. The exception being tag 13959 which ended up on top of the roof of a building in Figure 4.38a while ending up much closer to it's actual location (shown in Figure 4.24) when using the new error radius algorithm, as seen in Figure 4.38b.

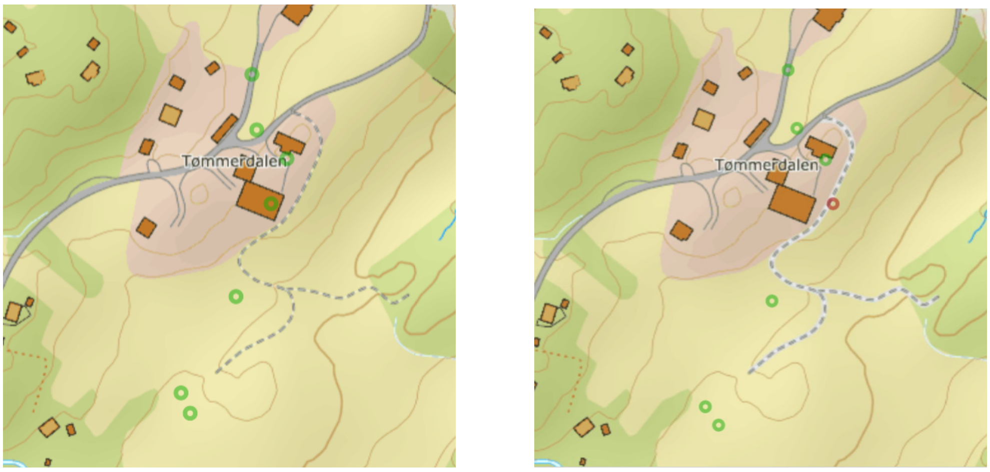
Changing the growth in the error radius increased the time it took to perform multilateration of five tags from approximately five seconds to close to 30 seconds. The time to a solution could most likely be improved by using an algorithm similar to binary search that converges towards a successful error radius number by attempting to both over and under-estimate, instead of simply doing +2 until an intersection is found.



(a) Intersection area with an error radius of 128m

(b) Intersection area with an error radius of 60m

Figure 4.37: Intersection areas outputed by Radio Sheep GCS visualized in geojson.tools[95]



(a) Before changing the growth in error radius

(b) After changing the growth in error radius

Figure 4.38: Tag 13959 marked in red in Figure 4.38b

For our research purposes the additional calculation time was worth it to obtain more accurate localization results, although it could be annoying for end users to have to wait longer for the more accurate multilateration results.

4.7 Forest range test

The purpose of this test is to evaluate the system's range when surveying a thickly forested area. This can be used to optimize path planning over forested areas.

4.7.1 Methodology

We chose a stretch of fairly uniformly thick forest with a maximum ground elevation difference of 15m over the whole flight path (see Figure 4.40 and Figure 4.39). We used publicly available LIDAR scans of the area from [94] to obtain the ground elevation. The area was also chosen because of an adjacent path that could be used to traverse the forest if needed.

Figure 4.39: LIDAR elavation data generated for the flight path from https://hoydedata.no/LaserInnsyn2/. Approximate height of "sheep" tag is drawn in.

We used the same Minew nRF52840-MS88SF23 tag with an external monopole antenna used in previous experiments. It was mounted battery down on top of the pole, with the antenna pointing horizontally in approximately the same compass direction as the UAV's antenna would have during the flight. This was done to maximize the match in antenna polarization and orientation to maximize the signal strength of the system.

A straight flight plan was created in Mission Planner with an altitude of 80m, and a length of 484m each way. The plan can be seen in Figure 4.40. The UAV was launched on an automated flight from a small open area. As we did not want the battery voltage to go below the minimum level required for the on-board Minew nRF52840-MS88SF23 chip to operate, the flight speed was set to 5m/s.

After the forest flights, the experiment was repeated in an open field to gather reference data. This experiment failed, most likely due to low voltage, and is thus not detailed further here.

Nyholm[12] proposed using Package Delivery Ratio (PDR) to evaluate the system performance. This would be ideal for us, but our experimental setup only allows for measuring the amount of RTT distance estimations, not the amount of packages sent and received. For this, logging of each individual RTT measurement

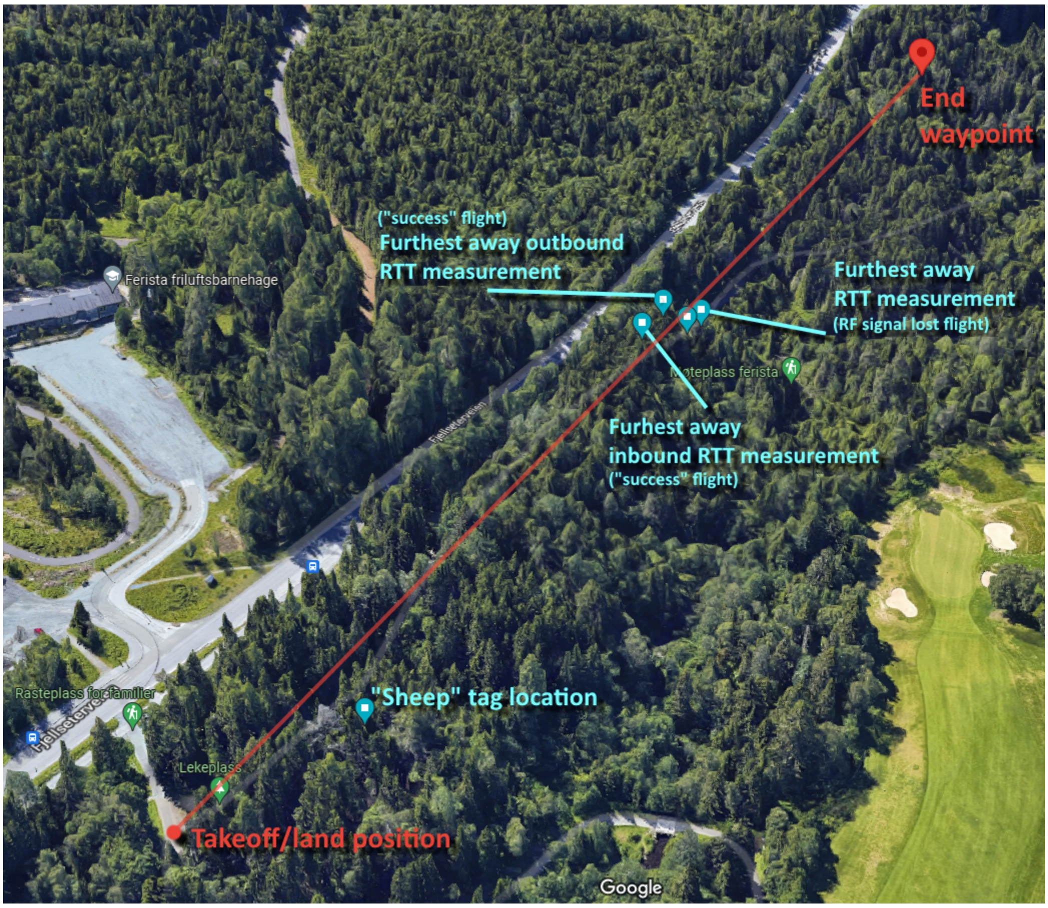


Figure 4.40: Forest flight plan and key positions

must be performed. This means that every distance estimation we record could represent anywhere from 1 to 4 RTT measurements, and thus cannot be used for PDR calculations.

4.7.2 Results

Flight 1 (RF signal fail)

The UAV flew approximately 55% the way to the end waypoint before entering a radio failsafe and switching to Smart RTL. Analysis of the DataFlash logs (a type of detailed flight log) from the drone indicates the radio failsafe was due to deteriorating signal strength between the UAV and remote control.

Upon landing the drone, 182 valid distance estimates were retrieved through Radio Sheep GCS. The measurement furthest away was 216.17 meters in aerial distance from the "sheep" tag, and 234.41 meters away when accounting for the altitude difference of 90,67m.

Flight 2 (Success flight)

This time one of the authors followed the UAV along the path next to the UAV's flight path. This mitigated the radio failsafe issue from the previous flight. However, the UAV did not return. After 90 seconds of the drone hovering in place, the mode was switched to Return to Land (RTL) and the drone returned at 7m/s. Post-flight analysis of the DataFlash logs show that this was because there was no waypoint set in the mission plan to make the drone fly home. The flight with the takeoff, landing, and unexpected mid-flight hover time removed, totaled 168 seconds.

Upon landing the drone, 213 valid distance estimates were retrieved through Radio Sheep GCS. The measurement furthest away was 200.49 meters in aerial distance from the "sheep" tag, and 218.45 meters away when accounting for the altitude difference of 86,74m.

Removing the RTT measurements from the drone taking off and landing, leaves a total of 71 measurements. Of these 40 were made on the outbound flight to the waypoint, and 31 on the way back.

Localization accuracy
This is not a test of localization accuracy as the drone only flew in a straight path right above the tag and back again. However the localization error for flight 1 was 23.68m and for flight 2 it was 35.51m. The average was 29,595m.

Ratio of successful distance estimates
According to our model presented in section 4.8 a flight lasting 168 seconds should have a maximum of $168 - 0.0075 * 4 * 168 = 162,96 = 163$ distance estimations. This means that for the whole flight where the UAV was traveling laterally 71/163 = 0,435 = **43,5% of the distance estimates were completed.**

By analyzing the timestamps of the received RTT distance measurements, the total time the drone was flying laterally (after takeoff, before landing) and still receiving RTT measurements is 76.35 s. Using the same formula as above we calculate that the maximum possible amount of distance estimates in this time was 74. Of the 74 distance estimations that theoretically could be done while flying within maximum range $71/74 = 0,96 =$ **96% were completed.**

Open field experiment

The drone returned from the experiment and did not send any RTT data to Radio Sheep GCS. We hypothesise that this is due to the voltage of the battery being too low for the on-board nRF52840 chip to function properly and persist measurements in RAM.

Average maximum range

The maximum range for the system in a forest from tag to drone, with our configuration, taken from the average of the maximum range from both flights is $\frac{234.42m+218.45m}{2}$ = 226,435m = **226m**.

4.7.3 Discussion

The first observation is that it is possible to detect and perform several RTT measurement on a sheep tag in a thick forest with a drone, as this was achieved in both tests. The second observation is that when flying within maximum range over a forest, 96% of distance estimates are completed successfully. We do not however know how many of these distance estimates were derived from less than the ideal four RTT measurements. Based on our experiments in section 4.2 we know that distance estimates are performed by the software even when less than four RTT packets are received, although due to the lack of averaging, these will be less accurate.[3]

Our results indicate that 22,5% fewer RTT distance estimates were performed on the drone's return flight. However the UAV was flying 40% faster on the way back due to the drone being in RTL mode. This results in a 28,5% reduction in travel time, which accounts for the entire decrease in distance estimates.

Our experiment was ran with the maximum 8dB of transmit power and 1 advertisement per second from the peripheral tag. According to [1, 2] a more realistic advertisement interval due to power consumption is once every 10 seconds. However since our ratio of successful distance estimates within the maximum range is almost 100%, 10% of 71 measurements would still be 7 measurements, which is enough to perform multilateration, although with lower localization accuracy.

8dB transmit power is required to replicate our results. An 8dB increase in transmit power is a 6.31 times increase in power consumption compared to 0 dB. If reducing the transmit power to 0 dB, the distance would be reduced by 6.31, ending at 226m/6.31 = 35,88m. This is lower than what we consider the safest flight altitude over a forest, so surveying a forest would require that the peripheral tag advertising at the maximum gain of 8dB or close to that gain.

4.7.4 Conclusion

It is possible to estimate the distance of a sheep tag that is 226m away when operating the system with our chosen configuration. When operating within this distance, the ratio of successful to unsuccessul distance estimates is 96%. However for the 2.4GHz signals to reach the UAV, a high transmit power of close to 8dB is required.

4.8 How many distance estimations per minute?

In order to evaluate the performance of the system in a forest (see section 4.7) we needed to know how many distance measurements are done per minute in a scenario with 0 packet loss, between the central tag and one peripheral tag.

4.8.1 Expected outcome

The peripheral board is set to advertise once per second. Thus the amount of distance estimates should be equal to the amount of seconds elapsed. However in [3] it is noted that the central tag spends 0.0075 seconds performing each RTT measurement. Since there are four RTT measurements for each distance estimation it means that $0.0075 seconds * 4$ are spent on the measurement itself, and thus needs to be taken into account. The formula for estimating number of RTT distance estimates performed for a given time in seconds is then given by.

$$numOfDistEstimates = timeElapsed(s) - 0.0075 * 4 * timeElapsed(s) \quad (4.1)$$

There could be some additional hardware waiting such as waiting for MAVLink messages from the drone, or time spent storing the measurements in RAM that is not taken into account here.

4.8.2 Methodology

Two nRF52833 Development Kits were placed on a table 50cm from each other, oriented to be roughly pointing at each other. One was flashed with the "central" software, and one with "peripheral". The "central" board was connected to the computer via J-Link RTT Viewer[96], and terminal logging was enabled. A two minute countdown was started as the same time as the power-switch on the peripheral board was flipped to on. As the timer flipped to 0, the peripheral board switch was switched to off.

4.8.3 Results

Calculated outcome

Using Equation 4.1 with timeElapsed set to 120 gives 116,4 as the estimated number of distance estimates.

Measured outcome

The experiment produced 116 distance estimates.

4.8.4 Discussion

The expected and measured outcome is identical when rounded to the nearest complete measurement. However the experiment was performed without a drone attached to the Development Kit, so overhead from communicating with the drone over MAVLink as well as storing dato to RAM was not taken into account. MAVLink communication is implemented asynchronously, and storing to RAM is typically so fast that it can be ignored here. Thus we consider the measured outcome to be accurate enough, confirming the model.

4.8.5 Conclusion

In two minutes both the estimated and measured number of distance measurements was 116. This means that the model for estimating the amount of distance estimates is valid for our configuration. For our configuration the central tag performs 58 distance estimations per minute when communicating with one tag.

4.9 Battery voltage drop investigation

As discussed in section 4.5 we were unable to detect any RTT packets from tag 61194 and 43902 on 03.06 after just 7 days of use. It could be that the battery lifetime estimate of 46 to 67 weeks provided in [2, 3] was wrong. To investigate this we regularly measured the voltage of a prototype tag setup as a peripheral (sheep) advertising once every second.

4.9.1 Method

The peripheral Minew 52840 was constantly sending messages to a central devkit sitting close by. A timer was set and the voltage of the battery was measured when the battery was still in the Minew. At the start the voltage was measured every half hour, then after 11 hours we measured every hour. During nights the battery was taken out to stop the draining, and the test was continued in the morning. This was done over the span of 3 days. This was done inside with normal room temperature around 24 degrees.

4.9.2 Results

Since we measured voltage while the Minew was on we noticed that the voltage would vary. It would periodically drop around 0.030 voltage every second or so, we tough this was caused by the Minew sending Bluetooth data or Bluetooth advertising as it also is supposed to happen every second. One can also see in the figure 4.41 that after pausing the experiment until the next morning, the battery would recover somewhat and have a higher voltage the day after. However the voltage would decline rapidly and slow down once it reached the prior days voltage. The voltage drop per hour is quite low, 0.1V after 27 hours, so for a week that would be a voltage drop of 0.62v for a battery voltage of 2.4v.

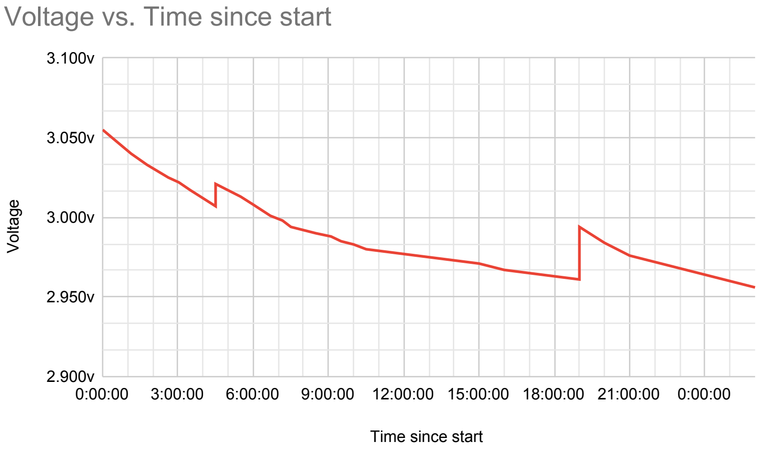


Figure 4.41: Graph of the voltage measurements over the course of the test

4.9.3 discussion

The minimum voltage that the system can take according to the spreed sheet of nrf52833 is 1.4V, meaning it would still be running in this controlled environment. This is also the worst case solution for the Minew, constantly transmitting and receiving data. In the field this would only happen a couple of minutes every other day, when the drone was searching. This would result in less power usage than demonstrate in this test.

4.9.4 Conclusion

The test measured a voltage drop of 0.1V after 27 hours, where the Minew is constantly transmitting and receiving data, which is too low to be out of power after a week. And the field test wasn't in transmitting mode constantly, so it is unlikely that the problem was the system's power usage. Rather it is highly likely there is some other factors that affected the battery life.

However the voltage estimates isn't entirely correct, it's hard to measure power usage by measuring voltage, since the voltage dropping isn't linear. So a proper test with wattage testing tools would be needed to draw a stronger conclusion.

4.10 Experience using a custom UAV for research, and usability compared to other solutions

Noticeable things about our experience with the UAVs. Things that we fixed, that went wrong etc. Especially in regards to using drones for research.

4.10.1 UAV construction

UAV construction was difficult as the parts were small and delicate. We managed to short out two flight controllers due to bad soldering or plugging in the wrong cable. About a dozen parts broke during our flights, needing replacement, and cables got lose and got cut multiple times.

Experience using ArduPilot
Ardupilot has a lot of flexibility and is open source, at the same time the flexibility made it difficult to configure right and it took a lot of trial and error to make it fly properly. After we ruined the first flight controller, changing to another one, it felt like starting from scratch and it took us several days of tests and tuning to get the new UAV working again.

We recommend that researchers doing similar work buy a robust drone that supports custom flight plans, and have the RTT ranging module as a separate module attached to it.

Unable to extract RTT data from some flights

For many of our flights, such as those detailed in section 4.5.3 and section 4.7 we were unable to extract RTT distance measurements from the drone through Radio Sheep GCS upon landing. Investigating the Radio Sheep GCS code for RTT transfer revealed that it was simple and stateless, thus probably not being the cause of the problem.

Since other MAVLink messages were coming through fine from the drone into Radio Sheep GCS, we hypothesised that the problem was probably caused by an issue with the Minew MS88SF23 chip on the drone responsible for performing and storing the RTT distance measurements.

Trough review of data-flash logs we noticed that the drone was consuming alot of power, causing a voltage drop of 1,6 voltage while flying over 10 m/s before recovering when slowing down. We theorised that the voltage measurement came after the current voltage drop of the motors. As such we theorized that the voltage drop from the motors resultated in an unstable central Minew.

To counteract this issue we tried connecting the Minew to a separate power source. We soldered a CR2032 battery holder with a brand new battery measuring 3.3V and fastened it on the drone as seen in Figure 4.42. This would provide 3.0V nominal to the Minew, avoiding the reduced voltage issue entirely. At first we didn't get signal from the Minew. However after connecting the ground pins on the flight controller and the Minew module together it seemed to work as normal. This is because the ground pin is required for the data connection between them.

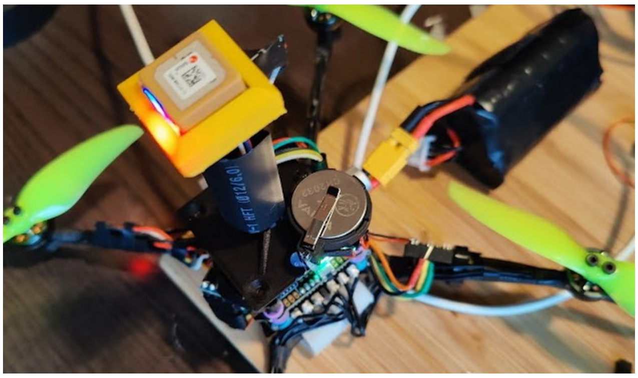


Figure 4.42: Drone modified with CR2032 coin cell battery

Our first flight after the modification on 03.06 (see section 4.5.4 worked as expected and we were able to extract RTT distance measurements from a longer flight than ever before.

However when attempting to repeat the flight with the same setup (flight 2), no RTT measurements were received. After landing the battery measured 2.9V. Putting in another brand new CR2032 battery and repeating the flight produced no RTT distance estimates to be extracted. The battery was measured to 2.7V after the flight.

We hypothesised in the field that maybe the power was somehow leaking out through the ground wire going to the drone, and thus also connected the red power wire from the drone to the Minew. The exact same flight path was repeated, but while flying, the drone dipped to around 10V and we got a Warning for a Low Battery Failsafe. We set the drone to RTL and it returned to us. After the flight the measured battery voltage was 3.0V. We were able to extract 89 successful RTT distance estimates. The voltage of the battery had increased by 0.3V since the last flight, and we speculate that plugging in the red wire caused the CR2032 battery to be charged by the drone's battery, leading the drone to warn us about low voltage.

Flying without the CR2032 battery again during section 4.7 functioned fine for two flights, before no longer being able to extract RTT measurements for the third flight. The lowest voltage recorded by the drone during the last successful flight was 10.565V.

Conclusion

Our attempts to use an external battery did not resolve the issue. Using an external CR2032 battery appeared to fix the issue initially, but we were not able to repeat the success with a new battery. Plugging in the red wire as well caused the drone's voltage to dip to 10V during the flight, prompting us to abort the flight, although it did allow us to retrieve RTT measurements when the drone landed. Our tests show that the drone is able to perform RTT measurements as long as the voltage does not dip below 10.565V at any point during the flight. The RTT module needs to be made more resilient to low voltages, or completely independent from the drone's power source, for longer flights to be possible.

Fixed wing UAV

After the first generation drone (see subsection 3.4.1) stopped working we decided on making a fixed wing drone to supplement the quadcopter to enable us to perform longer flights, and act as a backup. We ended up building it.

We used the same Radio Receiver and GPS as the quadcopter due to local availability and our own familiarity. The flight controller was a "Mateksys - F765-WSE", it had enought UART ports for automated flight and extra for the Minew. Most parts were available locally and compatible with similar firmware as the quadcopter, but for planes (ArduPlane). The control motors, ESC, thrust motor and plane body came in a kit called "Nano Talon EVO". This one was not locally available so we had to wait a long time for it. However it was cheap and the total build weight would be less than 250 grams. This plane crashed 3 times at takeoff and was never able to fly. Mainly because it seems it couldn't provide enough trust.

4.10.2 Usability of drone based system compared to other systems

This section is based on the work in our thesis preparation project.

Advantages of solutions based on GPS and NB-IoT (Radiobjella, Smartbjella, NoFence, Anicare) are higher precision (4 meters for GPS vs. 15 for drone), and more frequent updates to the farmer about the positions of the sheep. Disadvantages are lacking NB-IoT coverage in certain areas and higher cost. Using satellite instead of NB-IoT also incurs an even higher cost as evident by the price of FindMy Model 2. But from a usability standpoint it is probably the best solution as it provides accurate positional data and data connectivity everywhere. For the sheep it could be less comfortable as it is heavier, although it is unclear how important this is.

Nerland, Swiderski and Steinsvik's solution does not provide real-time updates while drone is surveying the area, with the exception of the drone being within WiFi range. Rather the updates are delivered when the drone lands. Real-time updates could be added by adding a cellular or satellite connection on the drone. The drone's higher elevation and general lack of surrounding obstructions should let it receive cellular connectivity in areas where a ground based device could not. The value farmers get from real-time updates is somewhat uncertain, but farmers have expressed in an interview with one of the current vendors that they enjoy the nearly real-time updates.

We and Nyholm[12] do not consider the lower accuracy of a drone based system to be disadvantageous, as sheep are quite large and can be located visually or with bells within the 19 meters error margin demonstrated. But more research could be done into how this lower location accuracy impacts monitoring and retrieving the sheep.

Most of the commercially available systems have a longer lifetime than a year, before the battery needs to be removed. Replacing the battery on 300 sheep is a time consuming task so having a system that requires less maintenance is preferred. It should be possible to increase the battery time, probably ten or twenty-fold by simply increasing the battery size correspondingly. This would however remove the option of having the entire unit as an ear tag. A question is then if sheep farmers prefer having an ear tag or longer battery life, and how the position of the device on the sheep affects Bluetooth range.

It is unclear how valuable the small form factor sheep tag proposed by the previous NTNU papers is, when compared to the tradeoff of longer battery life of a collar-mounted device. The implementation tested in 2021 had an estimated battery life of 46-67 weeks[2]. Henrik Nyholm's paper[12] had a battery time of 1.6 to 9.8 years depending on how often the sheep tags advertised their presence. 2021's solution has a worse battery life than every other solution on the market except for NoFence's worst-case scenario and arugably FindMy Model 2. However it is not clear in [2] or [3] how this battery life has been calculated. Sheep live 10-12 years so a battery life longer than that is not necessary.

Chapter 5

Discussion of research questions

5.1 RQ1: How well does a UAV-based sheep localization system function in a real world environment?

We demonstrated in section 4.5 that the system can perform multilateration on tags attached to sheep in a real farm environment. However as we were unable to confirm the true position of the sheep, the accuracy is unknown. However using fixed tags mounted on poles in the same area the average localization error was found to be 15.19m. The localization accuracy in a thin forest was demonstrated to be 12.22m in section 4.4. However the test was only performed once, with the drone flying quite close to the tags. For tags that only got covered by the flight path on one side the localization accuracy was very poor, at least 142m. These finding can probably be generalized for the sheep as well, assuming they do not move. The effect that the sheep moving have on localization accuracy is unknown, but the multilateration algorithm should be able to handle it already by increasing the radius of the intersection circles until they all interact. The localization accuracy will then be lower.

We found the system's range to be at least 823m in a near-ground Line of Sight scenario with an optimal antenna orientation (see section 4.2). In a thick forest consisting of mostly pine trees the maximum range was found to be 226m from the drone to the tag, including the height difference. Within the maximum range, 96% of the expected RTT measurements were performed successfully (see section 4.7).

Despite LoRa potentially being a better choice due to better range and foliage penetration, the RTT ranging method based on Bluetooth Low Energy (BLE) used in our thesis seems to have sufficient range and accuracy for sheep localization. Last year's thesises[1, 2] demonstrated that the localization technology works in open fields, and we demonstrated that the system can locate tags within a light forest and in a valley. A proper localization experiment in a thick forest was not performed, although our straight line test flight had an average localization error of 29,595m. If performing a similar flight path to the other tests, we expect the localization error in a forest to be similar to our other results. Although it will probably be somewhat worse due to less Line of Sight.

Both the ear mounted and collar mounted tags worked well for performing RTT measurements with the UAV. However a commercial sheep tag needs to be tested thoroughly to discover any potential sources of tag malfunction, as we lost contact with 2/5 prototypes.

5.2 RQ2: What kind of antenna and orientation is best for sheep localization?

5.2.1 Antenna polarization

The antenna on a UAV should be oriented so that it radiates omndirectionally in the horizontal plane according to [60]. This means that for monopoles and dipoles the antenna must be mounted so that it is vertical. Ideally then, the antenna on the sheep should point upwards and be vertical as well. A maximum polarization mismatch, for example with a vertical antenna on the drone and a horizontal one on the sheep, could lead to a 21 dB decrease in signal strength as shown in [58].

Our antenna polarization experiments (section 4.1.4) confirmed this effect, having an average reduction in signal strength of 20dB when the antennas were oriented 90 degrees on each other.

However for our sheep ear tag prototype tags, mounting the antenna vertically was not achievable for us. Our simple method of taping the antenna to the sheep's existing ear tag did not allow for secure vertical mounting. Thus the tags were mounted with the antenna horizontal. We mounted the sheep collar tags' antenna horizontally too so that their polarization would match the ear tags for easier comparative evaluation of the two mounting methods.

Since our sheep tags had horizontal antennas we decided to mount the antenna on the drone horizontally as well so that their polarization would match.

During our farm trials we observed that collar tag 43902 had rotated on 29.05, changing the antenna from being horizontal to being vertical as seen in Figure 4.35a. However this did not seem to affect the amount of measurements much, as the amount of measurement was similar to that of the other tags as seen in Table 4.13. Thus it seems that the previously observed decrease in signal strength when the antennas are mis-polarized does not translate into significantly worse performance in a real world system test. We do not have a theoretical explanation for why the performance did not suffer more. One possible idea is that the reflective environment of the valley could have allowed the signals to bounce in favorable ways not experienced in the previous experiments, somewhat mitigating the mis-polarization.

When choosing an antenna, one should test it's radiation pattern with it's ground plane to ensure that it radiates strongest towards the sky when mounted on the sheep like done in section 4.3.

5.2.2 PCB antenna vs. monopole antenna

In Table 4.8 we can see that the PCB and monopole tags mounted in the forest had 202 and 261 vaid RTT measurements respectively, the PCB then having 16% fewer measurements. They were mounted next to each other facing the same way. It seems from this test that the monopole antenna performed slightly better, although some of this could be explained by different foliage in the way of the signal, as they were mounted 1m away from each other. However the foliage coverage was very similar so the effect of this factor should be small.

We do not consider the data from the sheep farm tests to be viable for comparing the antenna types, as there are too many variables such as where the sheep are, which way they are heading, and if they are upright or eating with their head down. For a more conclusive result, further trials are needed.

We can see in Table 4.7 that the paring of two PCB antennas has a a lower RSSI than that of two directional dipoles. But the 0dBi of the PCB antennas might still allow for equally many or more RTT measurements to be done as the signal does not only travel mostly straight upwards.

The farmers preferred the prototype tags with internal PCB antennas over the external monopole antennas, so this should also be kept in mind when chosing the antenna type.

5.3 RQ3: What is the best radio technology for localization of sheep using UAVs?

In section 2.8 we concluded that according to radio theory and previous literature, the best radio technology would be something utilizing the 868 MHz (EU) band like LoRa. However our experiments show that for a low-flying UAV a 2.4GHz technology like Bluetooth Low Energy (BLE) is also viable for locating sheep. For areas with a low vegetation our UAV utilizing BLE hardware was initially able to provide location estimates for all 5 of our sheep and lambs, which decreased gradually in subsequent tests, most likely due to problems with the prototype tag construction and mounting, and not BLE. We demonstrated that the system can also perform range measurements in densely forested areas, but the range is severly reduced from approximately 1200m to 226m. To create a system that will perform reliably in all vegetation types, LoRa or similar is probably still the better choice. The question still stands however, if these LoRa tags have a low enough power consumption to be used as ear tags with small coin cell batteries, or if another form factor is needed. It could also be interesting to add a Wake-up radio (WUR) to the sheep tag to further reduce power consumption by eliminating the tag's periodic advertising. This would howeve increase the cost of each tag and the drone somewhat.

Chapter 6

Future work

6.1 Dynamic route planning

We saw in section 4.4 that the localization error was at least 142m when flying on just one side of the tag. A future system should include the option for UAV to change the flight path when a sheep is found on the edge of the search area, and perform another sweep to make sure the sheep are covered adequately. This would however require either onboard computing, or having the drone connected to a more powerful computer, for example through a cellular connection, in order to perform the required multilateration on the fly.

6.2 Fence/natural boundry information in GCS

Radio Sheep Ground Control station could easily be improved by letting the user of the system draw in fences or natural obstructions so that sheep on the edge of the coverage area can be located with fewer distance measurements. The program already supports constraining the multilateration intersection area with arbitrary polygons. An example of how this change could have helped localizing one of our sheep can be seen in section 4.5.5. "Inverse" areas where the sheep cannot be such as lakes could also be added.

6.3 Accuracy locating moving sheep

As explained in section 4.5.5 we do not know the localization accuracy when sheep are moving. Future studies should consider mounting a GNSS receiver to the sheep to provide reference positional data that can be compared to the position estimated by Radio Sheep GCS.

6.4 LoRA as an alternative to Blueooth LE

In section 2.8.1 we found LoRa or similar 856MHz radio technologies to be superior in terms of range and foliage penetration compared to Bluetooth, and even slightly better in terms of localization accuracy. Utilizing LoRa should allow for a higher flying drone that can cover more ground and thus make the search even more efficient. The unknown factor for LoRa is power consumption for our system, and this needs to be investigated as well as testing it in foliage dense environments.

6.5 Wake-up Radio

In section 2.8.1 we presented literature proposing the use of Wake-up radios to further reduce power consumption. Logically it makes a lot of sense that the tags on the sheep should only transmit when a UAV is near, and this can be achived by the use of WURs. There is currently very little research available into the use of WUR's and Bluetooth, so there is definitely room for more studies.

6.6 Localization accuracy in forests

We only performed a range experiment in section 4.7. It is unclear what the localization accuracy is when the drone is flying in a reasonable path covering a forest. We expect the localizaion error to be larger due to a lack of direct Line of Sight (LoS), but exactly how much larger is unknown.

6.7 Changes to multilateration algorithm

In our medium scale test where the drone only flew on one side of the tags, (see subsection 4.4.3), we observed that the estimated position for the tags in the field was not where the distance estimate circles intersected, but rather much closer to the drone. We speculated that this was because the multilateration algorithm did not favor at all the point where most of the multilateration circles intersect, rather simply finding where there was an intersection between all circles. It would be interesting for future work to bias the location where most of the circles intersect, and see if it improves localization accuracy both in edge cases like the tags in the field and cases where the flight path is more ideal.

6.8 Large scale tests with fixed-wing UAV

Due to technical difficulties and UAV regulations in Norway we were unable to perform any larger scale tests. To really know if the system can locate sheep in a large area with difficult terrain and vegetation, such a test should be performed.

A fixed-wing UAV was actually built for this thesis but we did not have time to tune it to fly. This UAV is now available for future use.

6.9 Reasons for prototype failure

During our week of field testing on real sheep the tags lasted shorter than expected. After the battery test we concluded that the batteries should have lasted a lot longer, even tough the software wasn't configured optimally. A further test and literature search would be required to see what effects environmental impact like movement, rain and temperature could have on the tags to find the true reason they started failing so early.

6.10 Optimal prototype tag design

The question still stands as to how exactly the final sheep tags should be constructed. Our thesis description stated that the form factor should be ear tags, but we also performed tests with two collar tags, and they functioned seemingly fine, even when the collar was rotated from it's ideal position 90 degrees. We have some data in section 4.4 concerning if the external monopole or internal PCB antenna functions best, but the dataset is too small to be conclusive. Thus more tests should be performed, and more farmers should be interviewed as to which form factor and mounting method they prefer.

Chapter 7

Conclusion

We have shown that a custom RTT protocol running on on inexpensive off-the-shelf Bluetooth Low Energy hardware is a viable technology choice for sheep localization when combined with an UAV. Our BLE sheep tags can be located using an automated UAV with an average localization error of 15m in a small valley farm grazing environment when stationary. We have shown that the system based on Radio Sheep Ground Control Station can provide reasonable sheep position estimates of sheep wearing the tags in the same farm environment using multilateration. The system can also localize tags in thin forests, and perform ranging with an error of approximately 30m in thick forests with a maximum range of 226m. This is a 81.2% decrease from the 1200m BLE range found in [2]. Combining our results with the work of [1, 2] shows that sheep tags based on BLE hardware can be localized with an average error of 15-19 meters using a drone and multilateration in a uneven valley farm grazing environment, light forest, and open fields.

In our initial antenna experiments we have studied the effects of polarization mismatch and antenna orientation in a flat near-ground environment. These results allowed us to verify that the radio components worked as expected by comparing our results to a previous experiment. Our tests in an "echo-free" room showed that the radiation pattern of our prototype tag is not symmetrical, and that tests should be done on future prototype tags to discover which orientation gives the strongest signal between the sheep tag and the drone.

In our sheep tag field study we accidentally discovered that the orientation of the antenna on the sheep collar does not have a dramatic effect on the amount of RTT measurements completed, despite our earlier near-ground tests showing a 20dB signal decrease when one antenna is oriented 90 degrees off the axis of the other antenna. We recommend that this experiment is repeated again with a simulated sheep and flying UAV in both a very reflective, and not so reflective environment to verify this finding.

In our literature study we concluded that LoRa or other 868 MHz technologies are probably better suited for sheep localization than BLE, although a more thorough investigation needs to be made into the power consumption of such a sheep tag and the possible inclusion of a Wake-up radio (WUR) to reduce power consumption.

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Appendix A

Additional Material

A.1 Changes to Radio Sheep GCS

We requested and performed several changes to Radio Sheep Ground Control Station throughout the project. They are explained below.

A.1.1 Fixed error when distance estimates are 0

Initially the system would throw an error if it was given an RTT distance with range 0. The software author Gard Steinsvik provided us with a fix for this which we implemented on May 2nd.

A.1.2 Only render RTT circles when swapping selected sheep

Previously when transfering sheep RTT measurements from the drone to Radio Sheep GCS, the map would re-render between each RTT message loaded into the software. With more than 800 measurements the software would become unbearably slow during RTT message transition. Thus the software was changed to only update the map once the user selects a different sheep to view the RTT measurements for. The change was implemented on May 27th.

A.1.3 Changed growth of error radius

On June 2nd we reduced the growth of the error radius in use by the multilateration algorithm. Previously it would double for every time an intersection was not found between at least one of the circles and the rest. Instead it was changed to be +2 meters every time an intersection was not found.

A.1.4 Changes to circle polygon detail

To perform multilateration, Radio Sheep GCS uses turf.js under the hood. Sometimes during the multilateration step turf.intersect() would throw an error saying "found non-noded intersection between LINESTRING ...". This prevented us from using the system to locate the sheep on 31.05. Decreasing the number of steps (edges) each circle consists of from 360 to between 320 and 300 by changing the NUMBER_OF_PARTICLE constant in the software in SheepPointsEstimation.tsx solved the issue. This was continually tweaked whenever the problem occured.

A.1.5 Automatic removal of RTT measurements with faulty coordinates

Added automatic filtering of RTT measurements with the coordinates [0,0]. It fixed a bug where found sheep show up Algerie. The fix was implemented on June 6th.

A.1.6 Added an option within the software to only use every 10th RTT measurement in the dataset.

Added option to only use only every 10th RTT distance estimation. Instead of simply taking every 10th measurement from the whole dataset, it splits the measurements by sheep tag, and uses every 10th measurement for each tag. This change was implemented on June 17th.

A.2 Additional figures

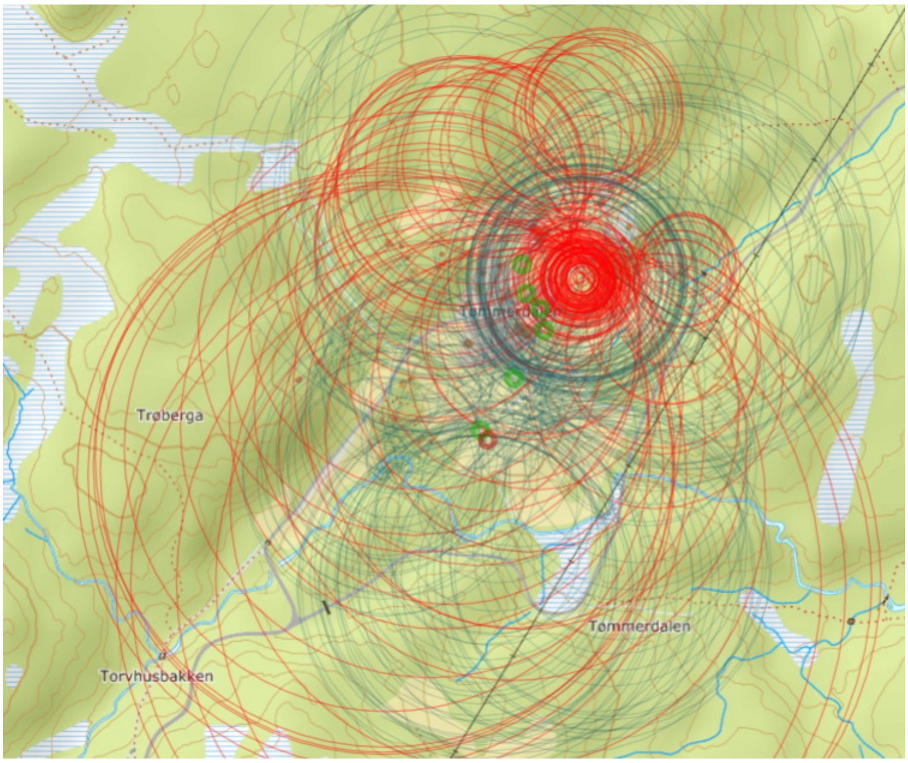

Figure A.1: RTT distance estimates for tag 38938 for flight 1 on 03.06.

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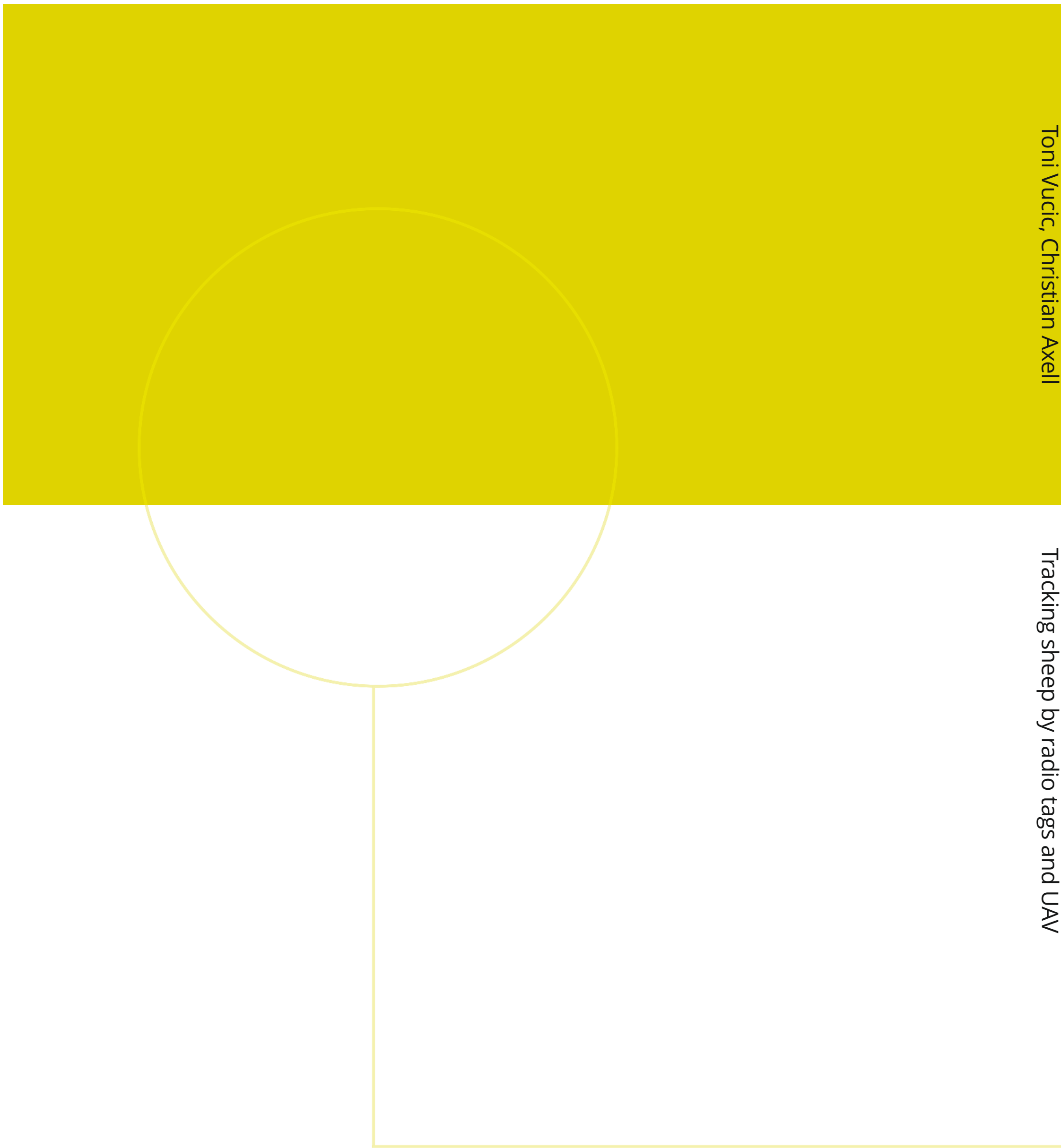

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