Animal Movement Research Using Phase-based Trilateration

A Design Project Report

Presented to the School of Electrical and Computer Engineering

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering, Electrical and Computer Engineering

Submitted by: peidong qi

NetID: pq32

MEng Field Advisor: Joe Skovira

MEng Outside Advisor: Julian Kapoor

Degree Date: May 2018

Abstract

Master of Electrical Engineering Program

Cornell University

Design Project Report

Project Title: Animal Movement Research Using Phase-based Trilateration
Author: Peidong Qi
Abstract:
AMRUPT is a technology being designed for the localization of small animals in the field of ecology. This is used for the study of flight patterns, social interactions, or other biological attributes to most species. The system utilizes Phase Interferometry for use in estimating the Angle of Arrival (AOA) of radio signals. These systems are substantially more accurate than other common methods, although performance scales strongly with the spatial scale of the receiver network. Because many researchers are interested in small-scale movements of animals within populations, such a system may be extremely useful. To accomplish this, a low weight radio tag is being developed to transmit signals to radio base stations. These tags will transmit sub 1-GHz UHF frequencies.
RF signals phase information is calculated on the RTL SDR. This requires multiple receive antennas connected to an RF switch which is attached to the RTL SDR which communicates the I & Q values of the received to a Raspberry Pi for angle of arrival calculation. A three antenna system is used for angle of arrival. An angle of arrival will be computed between Antenna 1 and Antenna 2 that is ambiguous between Quadrants 1&2 and Quadrants 3&4. An angle of arrival will be computed between Antenna 1 and Antenna 3 that is ambiguous between Quadrants 2&3 and Quadrants 1&4. The angle of arrival will be determined to be in the quadrant that contains both AOAs.

Executive Summary

AMRUPT is a technology being designed for the localization of small animals in the field of ecology. This is used for the study of flight patterns, social interactions, or other biological attributes to most species. The system utilizes Phase Interferometry for use in estimating the Angle of Arrival (AOA) of radio signals. These systems are substantially more accurate than other common methods, although performance scales strongly with the spatial scale of the receiver network. Because many researchers are interested in small-scale movements of animals within populations, such a system may be extremely useful. To accomplish this, a low weight radio tag is being developed to transmit signals to radio base stations. These tags will transmit sub 1-GHz UHF frequencies.

RF signals phase information is calculated on the RTL SDR. This requires multiple receive antennas connected to an RF switch which is attached to the RTL SDR which communicates the I & Q values of the received to a Raspberry Pi for angle of arrival calculation. A three antenna system is used for angle of arrival. An angle of arrival will be computed between Antenna 1 and Antenna 2 that is ambiguous between Quadrants 1&2 and Quadrants 3&4. An angle of arrival will be computed between Antenna 1 and Antenna 3 that is ambiguous between Quadrants 2&3 and Quadrants 1&4. The angle of arrival will be determined to be in the quadrant that contains both AOAs.

Literature Review

Transmitted signals at antenna array elements can be quantized at receivers to provide signal strength, phase difference, or time arrival information to be used in a Watson-Watt, Phase Interferometry, or Time Difference of Arrival (TDOA) systems respectively ([1] , [2], [16], and [22]). Phase based measurements can be skewed by multipath effects in the environment by constructive and destructive interference for line of sight signals [2]. TDOA systems are not as susceptible to multipath effects; however, obtaining precise positioning from close proximity transmitters in TDOA is difficult because nanosecond synchronization is required to compare lightspeed propagated signals. This flaw in time difference of arrival can be mitigated by subsample interpolation at signal correlation peaks [22].

Although lightspeed propagation substantially helps with obtaining real time results, it adversely affects the collection of synchronized data at antenna array elements in the radio frequency direction finding systems mentioned. More intensive hardware synchronization can be avoided by using a time-modulated array to switch between antennas in a direction finding system [21], shown in Figure 1 [21]. In coherent receivers running on a single clock signal, synchronization errors from clock drift and other delays can be corrected by incorporating a signal generator input to each channel [20]. In addition, clock drifts and bulk delays can be mitigated by implementing cross correlation with virtual sources on a software level [23].

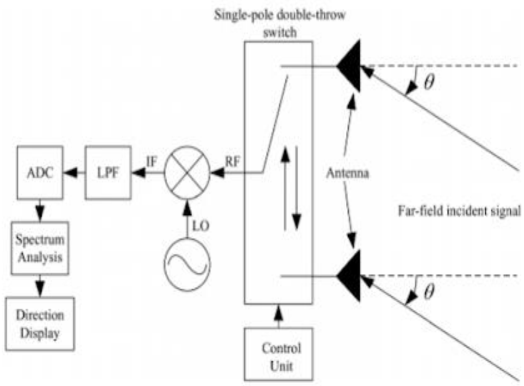

Figure 1: Time Modulated Array Setup

A phase interferometry system with real time operation on multiple receivers without an apparent phase offset correction/controlled noise source system was able to identify an angle of arrival within 2.5degrees for all emitter distances from 1 km to 100 km [1]. The error threshold from this system is less than the 5degree angle of arrival threshold error determined in the time-modulated approach [21].

The phase interferometry system in [1] was primarily developed to handle UHF frequencies for airborne sources. Because the frequency of this system was relatively high for phase interferometry, antennas were spaced at distances larger than half the wavelength of transmitted signals. Thus, the system was optimized to handle phase ambiguity, which is explored more in the technical section of this proposal. Testing protocols and optimization were handled in Matlab and C, modeling the effects of antenna spacings on AOA accuracy under worst-case conditions. In the hardware setup, three antennas were used to resolve phase ambiguities and determine the azimuthal AOA in a synchronized three channel system with RF mixers driven by a common local oscillator. The design of this system provides a basis for a three antenna architecture as discussed in the technical section of this proposal. The block diagram of this system is shown in Figure 2.

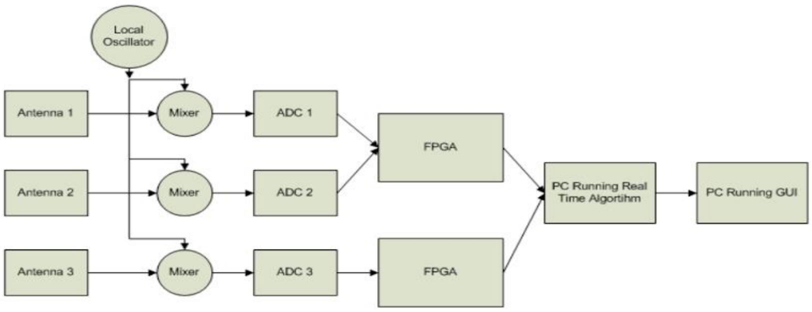

Figure 2: Block diagram for Phase Interferometry in Guerin, Jackson, and Kelly [1]

Ma, Hui and Kan [2] proposes a 3D indoor passive tag localization method with an accuracy of a few centimeters in a multi-frequency identification system. The paper leverages nonlinear backscatter which exploits nonlinear elements in passive devices to generate second or higher-order harmonics for an uplink response. This paper introduces a novel approach in mitigating multipath interference, defined as the occurrence when radio waves reach a receiver via two or more paths. This causes a constructive and destructive interference of the signal, as well as phase induced error (Figure 3). In order to combat multipath interference, a phase error threshold is used within a hueristic multi-frequency continuous wave (HMFCW) ranging algorithm to find an optimal frequency combination that generates an undistorted line of sight path. HMFCW ranging correctly pinns down a phase cycle integer by transmitting a sequence of frequencies determined by a genetic algorithm to maximize an error tolerance equal to the percent bandwidth of the signal. The larger the bandwidth of the multi-frequency transmission, the more robust the system will be to multi-path induced phase error. The forward compatibility of this system to ours is discussed in the design objectives section of this proposal.

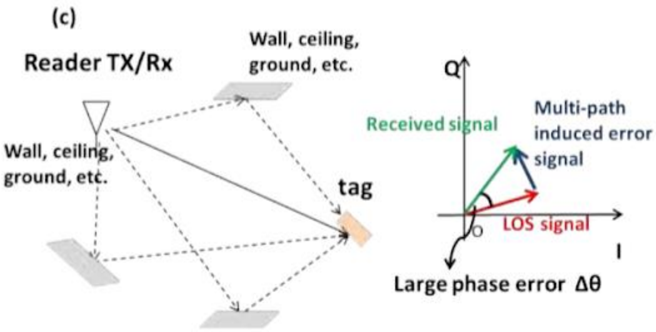

Figure 3: Dense indoor multi-path induced phase error [2].

In order to improve the cost effectiveness of direction finding, [22] and [23] have used low-cost RTL SDRs to extract in-phase and quadrature samples from incoming radio signals for TDOA and AoA calculations respectively. Direction Finding Implementations using RTL SDRs are promising alternatives to more expensive options by achieving up to 3.5m accuracy in TDOA [22] and by having an extensive hobbyist base with multiple Github repositories such as this one [24], demoed here. The advantages of having this repository available to us is that it will provide us with a point of reference when implementing our code and hardware. This specific repository was a precursor to the RTL SDR system developed by Sam Whiting in [23].

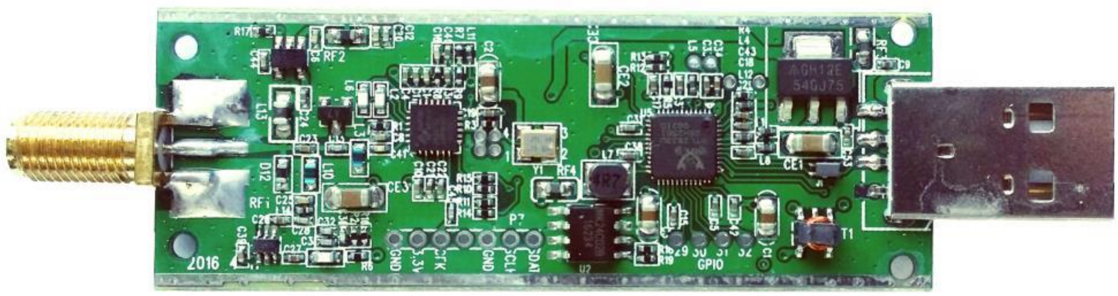

Figure 4: RTL-SDR (RTL2832U). Image Credit: rtl-sdr.com

Design Requirements

In order to accomplish the goals listed in the problem statement, we have proposed the following objectives in the design:

1. The receiver system is low-power and can track up to 50 lightweight and low-power radio tags
2. System architecture is resilient in cluttered environment (unsusceptible to multipath interference, electromagnetic interference, and other environmental conditions)

3. System is able to achieve two dimensional high spatial accuracy (error for triangulation results is limited within 5 meters) with a 100-300m distance between receivers
4. Forward compatibility: Must be compatible with and adaptable to a multi-frequency-phase-integer-disambiguation approach for future versions.
5. System is cost-efficient (almost all components are commercially off-the-shelf)

The first objective is to successfully track the locations of 50 individuals in the testing environment. We need to design the tags as lightweight as possible since the individuals are small in size and heavy tags may affect the individuals' biological activities. To allow for the least possible human intervention during the tracking process, both the receivers and tags need to operate with minimal power consumption to increase automatic tracking period. In addition, both the transceivers (ground nodes) and tags (mobile nodes) follow a communication protocol in which the mobile nodes will go to sleep when they are not communicating with the ground nodes to reduce power consumption.

The communication protocol is an intended route for development, but has not yet been designed. It specifies that mobile nodes wake up every 5 minutes to prepare for data transmission to the ground nodes. The mobile node will receive a 5-second countdown signal once it wakes up. As soon as the mobile node is verified to be within the receiver's range and has good link, it will be synchronized to global time before it is given a scheduled transmission time by the receiver or sent back to sleep again. If the mobile node is not within range of any receiver, it will go to sleep and wake up every 5 minutes to check whether it's within range again. The complexity of the ground to node communication protocol will be governed by how accurate our receivers are when taking angle of arrival measurements. If angle of arrivals from a couple of base stations intersect to a triangulation area of no more than 5 meter error (discussed further) over the specified tracking area, then tags will not have to be linked to different receivers depending on location. The communication protocol will also be used for a multi-frequency system, which is a possibility in the future of this project.

Furthermore, the system must be able to obtain accurate results in a cluttered environment. We agreed that a real environment would have substantial multiple interference as there will be trees and rocks that can reflect a wireless signal. Multipath interference could result a false transmit signal which would give us wrong information about the location of the tags. The effects of multipath are more amply discussed in the literature review section.

We agreed to set the tracking accuracy of our system to 5 meters because this is a minimum requirement to monitor the social interactions and movements of small mammal species and is already much more accurate than existing systems mentioned in the literature section. We propose a triangulation algorithm for Phase 1 of the project in order to acquire this accuracy: Phase 1 will be the development of the necessary base station algorithms and hardware setup to achieve an accurate angle of arrival measurement. In a future semester, we plan to modify our system to better overcome the effects of multipath interference by frequency hopping to obtain minimum variation results (Phase 2). If necessary, we plan to implement a multi-frequency phase integer disambiguation system that trilaterates positions of mobile nodes if a 5-meter accuracy level has not been achieved by previous efforts (Phase 3).

The diagram below is used to better understand error minimization with relation to AOA calculations.

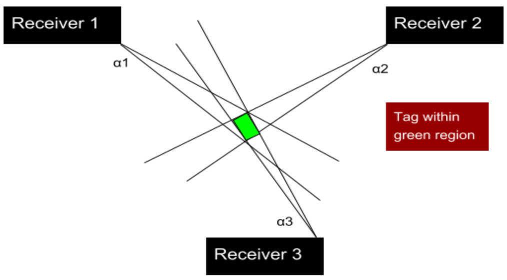

Figure 5: Error in triangulated area

In order to accomplish at least a 5 meter accuracy, a line of more than five meters cannot be drawn within the triangulated area of error . This area of error will be determined by α1, α2, and α3 (Figure 5) which resemble the angle of arrival error from receiver 1, 2, and 3 respectively.   α1, α2, and α3 will be determined by phase difference errors from a transmitting RF signal to multiple antennas. Sources of AOA error are further discussed in the technical section of this proposal, and simulations have been planned to find algorithms that can make additional steps in minimizing this error.

To address forward compatibility, several design decisions are considered. One such design parameter is distinguishing tags. The CDMA scheme is a very popular method for doing this due to the coding infrastructure. However it is unclear if CDMA is compatible with making phase-based AOA measurements. Gold codes are mutually orthogonal to each other, so it is possible to distinguish multiple bit streams from multiple tags at the same time. However, gold codes may not be able to differentiate phases.

Last, but not least we have devised a system that is composed of cost-effective, off-the-shelf components. This is done to make this setup more reproducible in future works and more accessible to ecological hobbyists/researchers.

Design Implementation

A protocol has been developed in [23] to synchronize multiple channels in a coherent radio receiver platform using SDRs. The flowchart below defines a sequence of DSP functions that need to be implemented to correct time and frequency offsets from RTL SDR measurements. This protocol can be adapted to a platform with four different SDR receivers, but has been truncated to 2 input SDR blocks for the means of simplicity.

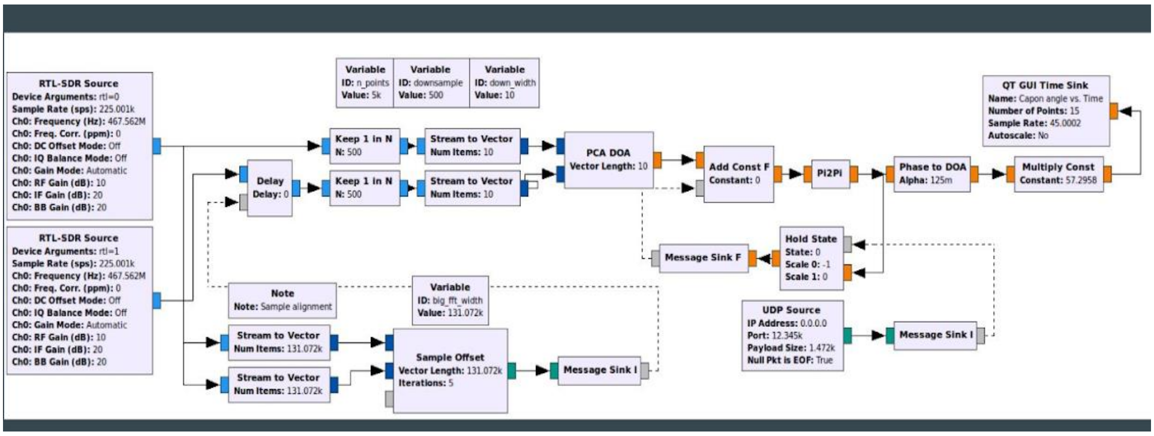

Figure 11: GNU Radio Digital Signal Processing Flowchart

The two RTL-SDR sources output signals harvested from antennas connected to the RTL-SDR cards. Even though SDRs in our system will share a common clock, signal sampling of these receivers is not expected to start at the same time, causing large bulk delays [23]. To compensate for bulk delay, each of our SDRs will be coupled with an RF Switch connected to a common noise source. The noise source will be used in cross correlating samples between signal channels in the Sample Offset Block of the above flowchart.

The Sample Offset Block computes the delay of one signal over another by taking a Fast Fourier transform of both signals, convoluting both signals in the frequency domain, and then taking the inverse Fast Fourier transform of the convolution to find the maximum argument (time value) of the output signal’s amplitude in the time domain. The reason for the performing the final step is that the peak of the convolution will correspond to the delay between the two signals.

The Sample Offset block will determine the median phase difference of the signals after 5 iterations of sampling, and output this value into a message connected to the Delay Block in the top left of the figure. When the receiver channels are connected to the noise source, the phase offset in the Delay Block will be continuously updated every 5 iterations of sampling. When the receiver channels are connected to the SDR antennas, the delay block will not update the phase difference value, and will add this phase difference value to the second SDR signal; therefore, synchronizing both receiver channels.

After synchronizing both receiver channels from the cross correlation described above, the two input signals will be downsampled for more cost efficient AOA calculations. The subsampling of the synchronized signals did not reduce the integrity of the system described in [23]. The PCA DOA block computes the phase difference from the downsampled signals.

The phase difference calculation in the PCA DOA block is described below:

The incoming signals received by two different antennas is x1(t) and x2(t) respectively. Those are the initial signals received by the antennas at time t. Then we set x1(t) to be our reference and x2(t) has the time delay

x1(t)=a(t)cos(wt)

x2(t)=a(t-T)cos(w(t-T))

In the two equations above [23], a(t) represents the baseband signal. T is the time delay. We will use the narrow-band assumption to assume that the phase difference is a phase shift e-jfrom a(t) as shown below [23].

$$\tilde{x}_1(t) = a(t)$$
$$\tilde{x}_2(t) = a(t)e^{-j\phi}$$

We will put those two signals into a vector to calculate a phase difference of maximum reliability to be outputted from the PCA DOA block.

This output phase difference will be subtracted by the calibration offset and then sent to a pi2pi block. The pi2pi block will wrap the modified phase difference into a range from -pi to pi to prevent phase ambiguity in the next calculation. Finally, a phase to DOA block contains the AOA calculation as shown in the code: `//DOA = arccos(phase/(2*pi*alpha)) - pi/2` from the project's github (Sam Whiting) in [30]. In this system, antennas were placed at a half wavelength distance from each other. Alpha is ½ to represent this characteristic in the AOA calculation. This formula corresponds to the geometric relation described in section IV. vi. of this proposal.

Test Results

For this project, we have tried to run ettus's project.   We have tried serval different platform to run GRC. So far, we have tried Raspbian, Ubuntu MATE, Ubuntu Core, Windows. Unfortunately, we have run different problems with those operating systems. For Raspbian, we have problem about the miss library which the Ubuntu have. After we checked Ettus's configuration, we found out the Ettus run their project on Ubuntu operating system. Then we switched to ubuntu system. At beginning, we installed UbuntuMATE on Raspberry Pi3. Then we installed everything we needed to run Ettus's project. However, we have another problem that we can't import error for the Ubuntu operating system. So we decided to switched to Ubuntu Core. After we installed everything, we found out that Ubuntu Core didn't support GUI interface. And the GRC need GUI interface to run. We have tried a lot of solutions to install GUI interface on Ubuntu Core. However, none of those solutions works. Then we installed Ubuntu on the PC, the import error has fixed. But the PC didn't recognize the SDR cards since itis the virtual system. Then we use VM to be our final chose. we has successfully run the GRC on VM. The VM has problem with continue data input. We can measure the AOA for one times.

For our final project, we still want to use Raspberry pi to run direction finding program. We make sure all the code is working. Then we need to fix the path issue with Raspberry Pi. Then we can test our system by measuring the AOA.

The test strategy will be test the prototype from ideal and small environment to complicate and large environment. In order to start testing the prototype, We will set the tag 20 meters away from the base station. The first test performed will be set in an small open area with no large natural vegetation to eliminate the multipath interference effect. The verification experiments will be performed in such a way that when we move the tag, the prototype we have developed will calculate the updated AOAs along the way. As a comparison, we also will measure the expected angle by protractor. The appropriate errors and standard deviations for these data trials will be computed. The next experiment will be to test the multipath interference. Some large blocking items such as large desks or chairs will be put in the same testing environment to see how our system handles the multipath interference. Again, many trials of measured and expected AOAs will be tested and compared in the block-free and with-block environments. After those two test suites are finished, we are going to improve the detection range from 20 meter to 50 meter so the tags are now more far apart. We will start with the block-free environment, collecting data for both the measured and expected AOAs, and then move to the with-block environment. In addition, we plan to test 100 meter, 200 meter, 300 meter, 500 meter, 1000 meter separation to check the limit of our prototype. In addition, these changes in distance also partially simulate the movement of an animal although the animal may move really fast in the environment while our test manually set the distance between the tag and base station at a much slower rate. Therefore, our test cases are taken under really good SNR conditions. For each test case, we will measure the angle several times to make sure we test our prototype properly. For the phase one, we are not able to solve the multi-path issue due to our direction finding algorithm.

Conclusions

In order to accomplish the localization of small animals, we plan to develop a cost effective and automated system to track animal movements within the range of five meters while taking into account expected causes of error. Our proposed system consists of a receiver architecture that is built specifically for phase interferometry direction finding to facilitate accurate measurements from radio tags on tracked individuals. In order to accomplish this, a low weight radio tag is being developed to transmit signals to radio base stations. These tags will transmit sub 1-GHz UHF frequencies.

References

[1] D. Guerin, S. Jackson, and J. Kelly, "Passive Direction Finding: A Phase Interferometry Direction Finding System for an Airborne Platform," Oct. 10, 2012. https://web.wpi.edu/Pubs/E-project/Available/E-project-101012-211424/unrestricted/DirectionFindingPaper.pdf.

[2] Y. Ma, X. Hui, and E. Kan, "3D Real-time Indoor Localization via Broadband Nonlinear Backscatter in Passive Devices with Centimeter Precision," Oct. 3, 2016. https://dl.acm.org/citation.cfm?id=2973754.

[3] "Sub-1 GHz and 2.4 GHz Antenna Kit for LaunchPad and SensorTag," May 3, 2016. http://www.ti.com/tool/CC-ANTENNA-DK2.

[4]: "CC1310 LaunchPad Default Antenna," Nov. 14, 2016. https://e2e.ti.com/support/wireless_connectivity/proprietary_sub_1_ghz_simpliciti/f/156/t/554880.

[5] "CC1310 LaunchPad Design," Jul. 28, 2016. https://e2e.ti.com/support/wireless_connectivity/proprietary_sub_1_ghz_simpliciti/f/156/p/532331/1938371.

[6] "CC1310 SimpleLink Ultra-Low-Power Sub-1 GHz Wireless MCU," http://www.ti.com/lit/ds/symlink/cc1310.pdf.

[7] "CC1310 IQ Samples," http://www.ti.com/lit/an/swra571/swra571.pdf.

[8] "CC13XX Antenna Diversity," http://www.ti.com/lit/an/swra523b/swra523b.pdf.

[9] "Crystal Oscillator and Crystal Selection for the CC26XX and CC13XX Family of Wireless MCUs," http://www.ti.com/lit/an/swra495f/swra495f.pdf.

[10] "The Raspberry Pi UARTS," https://www.raspberrypi.org/documentation/configuration/uart.md.

[11] "UART vs SPI vs I2C," http://www.rfwireless-world.com/Terminology/UART-vs-SPI-vs-I2C.html.

[12] Řeřucha, Š., Bartonička, T., Jedlička, P., Čížek, M., Hlouša, O., Lučan, R. and Horáček, I. (2015). The BAARA (Biological Automated Radiotracking) System: A New Approach in Ecological Field Studies. PLOS ONE, 10(2), p.e0116785.

[13] Weiser, A. W., Orchan, Y., Nathan, R., Charter, M., Weiss, A. J., & Toledo, S. (2016). Characterizing the Accuracy of a Self-Synchronized Reverse-GPS Wildlife Localization System. 2016 15th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN). doi:10.1109/ipsn.2016.7460662

[14] B. Porat and B. Friedlander, "Fractionally-Spaced Signal Reconstruction Based on the Maximum Likelihood", Proc. IEEE Workshop on Higher-Order Statistics, July 1997.

[15] A. Smith, H. Balakrishnan, M. Goraczko, and N. Priyantha. Tracking moving devices with the Cricket location system. In Proceedings of MobiSys, pages 190–202, 2004.

[16] D. Zhang, J. Ma, Q. Chen and L. M. Ni, "An RF-Based System for Tracking Transceiver-Free Objects," *Fifth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom'07),* White Plains, NY, 2007, pp. 135-144.

[17] Wescott, Tim. "Sampling: What Nyquist Didn't Say, and What to Do About It." 20 June 2016, www.wescottdesign.com/articles/Sampling/sampling.pdf.

[18] Wolff, Christian. "Radar Basics." *Radar Basics - In-Phase & Quadrature Procedure*, www.radartutorial.eu/10.processing/sp06.en.html.

[19] National Instruments. "What Is I/Q Data?" *What Is I/Q Data?*, 30 Mar. 2016, www.ni.com/tutorial/4805/en/.

[20] Bartolucci, Marco, et al. "Synchronisation of Low-Cost Open Source SDRs for Navigation Applications." *2016 8th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC)*, 2016.

[21] He, Chong, et al. "Direction Finding by Time-Modulated Array With Harmonic Characteristic Analysis." *IEEE Antennas and Wireless Propagation Letters*, vol. 14, 2015.

[22] Krüger, S W. "An Inexpensive Hyperbolic Positioning System for Tracking Wildlife Using off-the-Shelf Hardware." May 2017.

[23] Whiting, Sam, et al. "Time and Frequency Corrections in a Distributed Network Using GNURadio." 2017.

[24] "Tejeez/rtl_coherent." *GitHub*, 6 July 2016, github.com/tejeez/rtl_coherent.

[25] "RTL-SDR Blog silver dongle first impressions, compared to NooElec blue dongle"https://medium.com/@rxseger/rtl-sdr-blog-silver-dongle-first-impressions-compared-to-nooelec-blue-dongle-4053729ab8c7

[26] "VIDEO TUTORIAL: INSTALLING GQRX AND RTL-SDR ON A RASPBERRY PI"https://www.rtl-sdr.com/video-tutorial-installing-gqrx-and-rtl-sdr-on-a-raspberry-pi/

[27]https://github.com/jakapoor/AMRUPT/blob/master/Course%20materials%20and%20assignments/Weekly%20meetings/2018_Spring/Week_7_(03-16-18)/DF_week_7_03_16_18.pdf

[28] https://www.rtl-sdr.com/about-rtl-sdr/

[29] https://osmocom.org/projects/sdr/wiki/rtl-sdr

[30] https://github.com/samwhiting/gnuradio-doa/blob/master/gr-doa/lib/phase2doa_ff_impl.cc

Appendix A: Relevant Links and Tutorials

External antenna module for the CC1310:

http://www.ti.com/tool/CC-ANTENNA-DK2

In Phase and Quadrature Helpful Tutorial:

http://whiteboard.ping.se/SDR/IQ

Analog to Digital Conversion (Plan B):

MCP3008: https://www.adafruit.com/product/856

ADC Connection to Raspberry Pi 3: https://learn.adafruit.com/reading-a-analog-in-and-controlling-audio-volume-with-the-raspberry-pi/overview

MCP3008(external ADC) datasheet:

https://cdn-shop.adafruit.com/datasheets/MCP3008.pdf