Passive Aircraft Radar

Team 5 - Rushik Desai, Benjamin Du, Kyle Rogers
ECE 445 Design Document - Spring 2019
Professor: Michael Oelze, TA: Kyle Michal

1 Introduction

1.1 Objective

The major markets for passive radar technologies are military, commercial airports, and flight tracking services. Military and commercial applications are sophisticated, but expensive. Commercial applications do exist, and range from personal projects to subscription based services. Most of these applications rely on decoding ADS-B/Mode-S transponder data to identify aircraft and determine altitude. This method, while effective, is vulnerable to spoofing for air-to-ground communication [1]. Passive radar technology is also relatively new. Locating an aircraft is just one of its applications. In general, time delay of arrival (TDOA) can used to locate any transmitter.

We propose to create an affordable, accessible solution that doesn't depend on transponder data to get accurate aircraft positioning. The solution shall consist of individual receivers that together form a radar network. Instead of using ADS-B signals like other solutions [2], the network will strictly use multilateration (MLat) to determine an aircraft's position. The receivers shall be 'plug-and-play', requiring only a Power of Ethernet (POE) connection to be used in our network. Our solution will be modular so that it can be used to locate the position of any signal by modifying its front end.

1.2 Background

Radar technology has existed since the beginning of World War II. Traditional radar systems use a transmitter to send an electromagnetic (EM) wave, and read the received reflected wave in order to compute the position of an object. In recent years, research of passive radar technology has increased. A passive radar does not transmit, and only uses existing EM waves of the target in order to locate an object [3].

The military is researching passive radar solutions to detect stealth aircraft, but these solutions require a heavy amount of signal processing, and can be costly to implement [4]. There are many hobbyist solutions which use a passive receiver in order to detect aircraft, but these implementations often use external websites in order to interpret the received data, and designs which are inexpensive aren't very accurate [5].

1.3 High-Level Requirements

1. This project shall have a cost below $100 per receiver, excluding the costs of the server and POE injector.
2. This project shall have an accuracy of at least 50 m.
3. The receiver network shall sustain timing accuracy and run independently without user interactions for at least 1 week.

2 Design

The overall system design includes four receiver devices that each communicate with a central server. Each individual receiver will consist of an RF front end that receives the aircraft transponder signal, a GPS unit which captures GPS data, including the pulse per second (PPS) signal, a control unit which will verify the transponder signal, and a power unit which will power the individual components in the receiver, figure []. The receiver units will function as a network and be deployed in different parts of the community for performing airplane tracking via the travel time of the airplane's transponder, figure [] of physical digram.

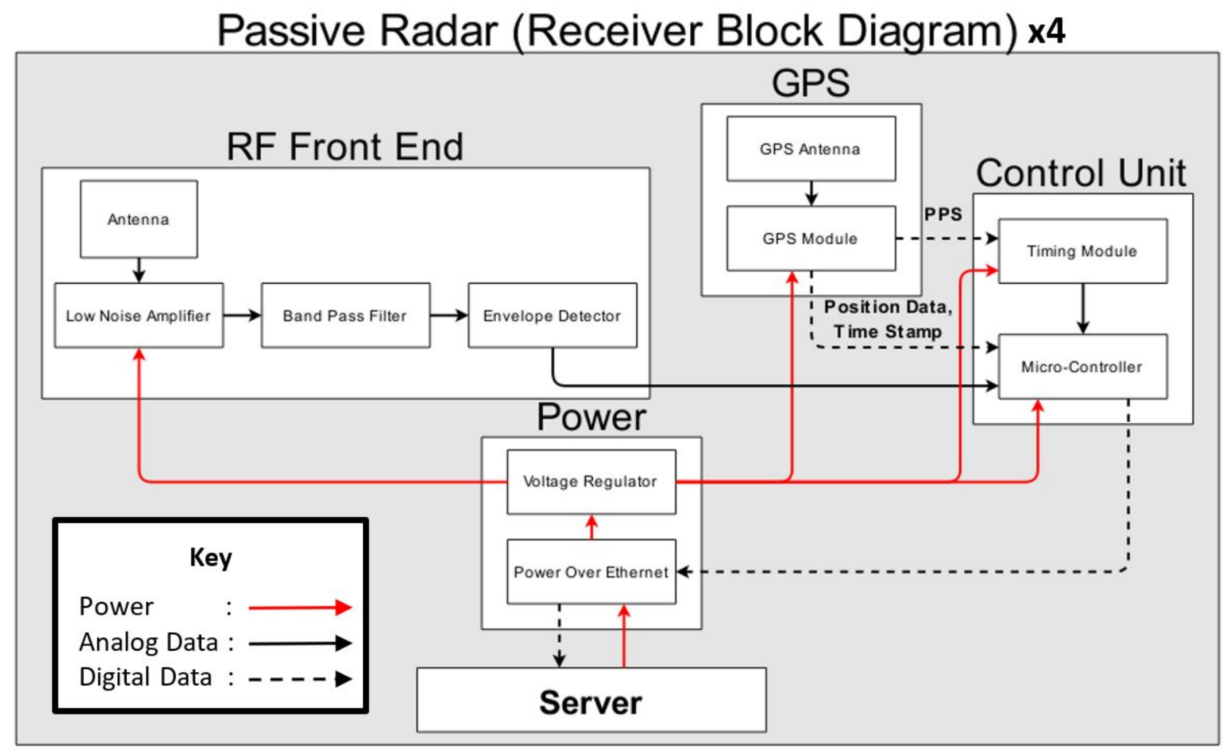

Figure [ ]: Receiver Block Diagram

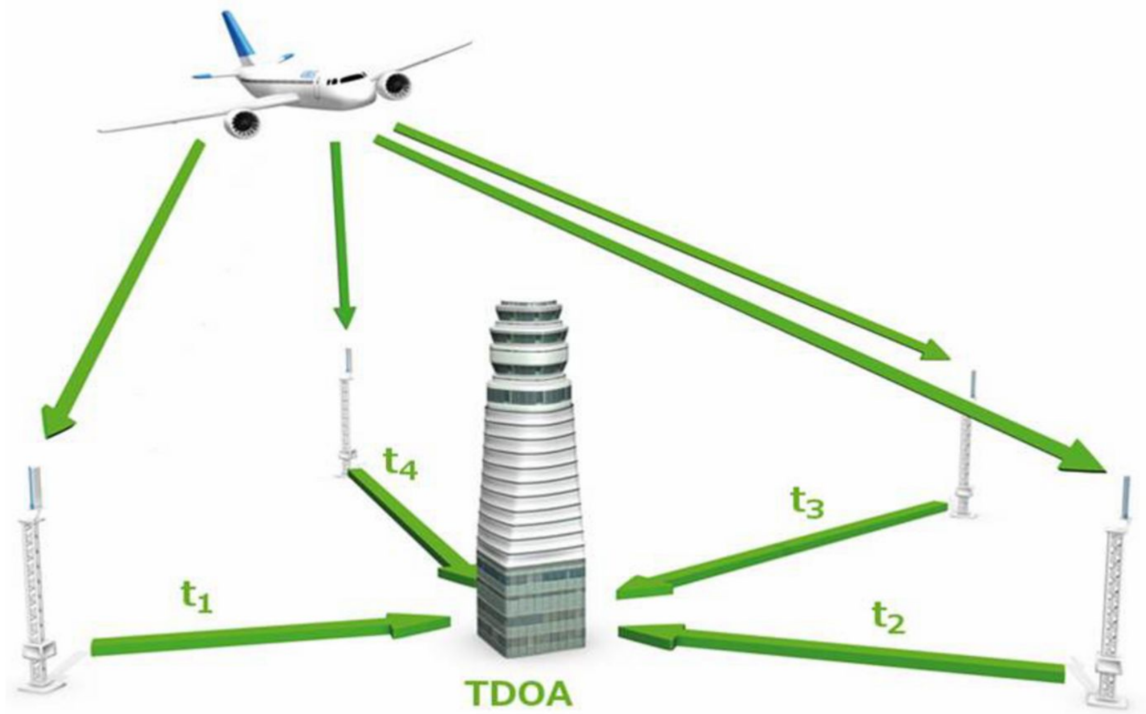

Figure [ ]: Physical Diagram

Our receiver system calculates the position of an aircraft transmitting a Mode C transponder signal (1090 MHz) using a method called “time delay of arrival” (TDOA). As seen in figure [ ] below, if and aircraft has an unknown position (x, y, z) two receivers have known positions (x_n, y_n, z_n) and the distance between the aircraft and the receivers is d_n, then the difference in distances is equal to the speed of light multiplied by the time delay of the received signal (between receivers). If a network of four receivers is created, the position of the aircraft can be calculated.

$$d_1 = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2} \; ; \; d_2 = \sqrt{(x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2}$$

$$d_1 - d_2 = c\Delta t = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2} - \sqrt{(x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2}$$

Figure [ ]: TDOA Calculation

2.1 RF Front End

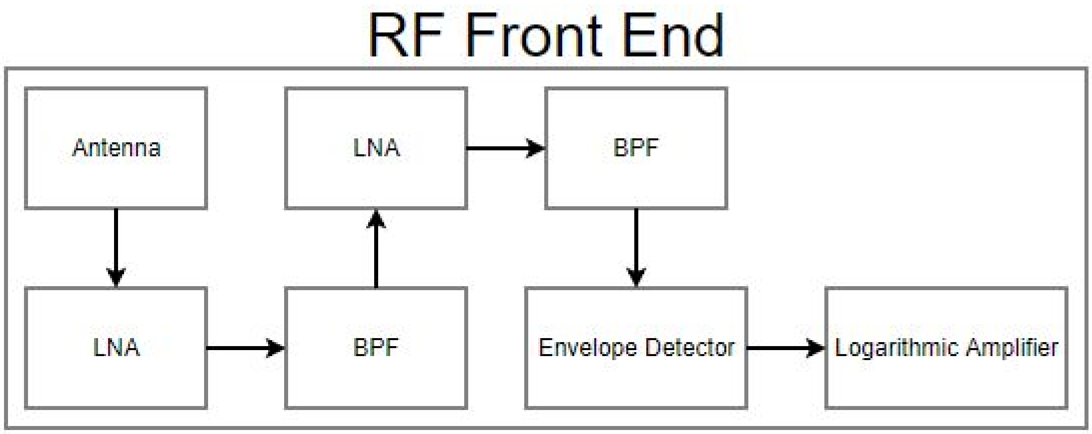

Figure [ ]: Block Diagram of the RF Front End

The RF front end is responsible for capturing an aircraft's transponder signal (transmitted at 1090 MHz) and decoding it using an envelope detector. It includes an antenna which capture the signal, two low noise amplifiers (LNA) and band pass filters (BPF), an envelope detector, and a logarithmic amplifier.

2.1.1 Antenna

Requirements	Verification

2.1.2 Low Noise Amplifier (LNA)

The LNA amplifies the signal without adding a significant amount of noise. The MAAL-011078 has a very low noise figure (< 0.5 dB at 1 GHz) and a high gain (~27 dB at 1 GHz) as seen in figure [ ]. It requires a supply voltage of 5V and consumes 70mA of current.

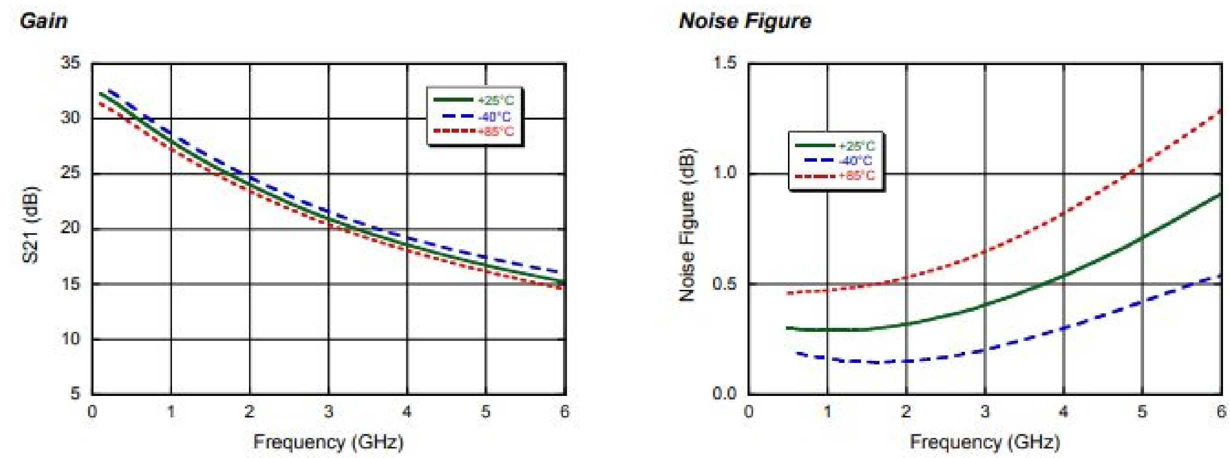

Figure [ ]: Gain and Noise Figure plots for the MAAL-011078 LNA

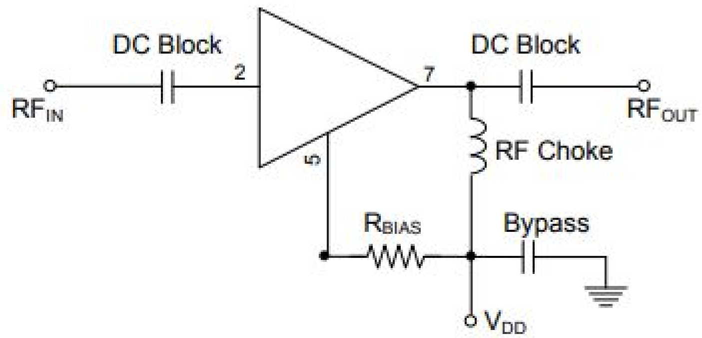

Figure [ ]: Circuit Diagram for MAAL-011078 LNA

Requirements	**Verification**
Driven at 5V with a bias current of ~70 mA, **1.** The LNA must have a gain (S21) of 27 ± 2 dB at 1.09 GHz **2.** The LNA must have a noise figure < 0.5 dB at 1.09 GHz	**1.** We will use a network analyzer to measure the S-Parameters (particularly S21) of the LNA in order to verify its performance. A. First, define the parameters of the network analyzer. Set the frequency range to 1060 to 1110 MHz and the number of points to 2001. Set the attenuation to 20 dB (very important!) B. Calibrate the network analyzer using a TRL or SOLT calibration kit. C. Connect ports 1 and 2 of the analyzer to the input and output of the LNA, respectively, using pigtails. D. Measure the gain of the LNA (S21) using markers.

	E. Perform a power sweep of the LNA in order to measure its input/output p1dB.

2.1.3 Band Pass Filter (BPF)

The BPF isolates the modulated transponder signal and filters out unwanted frequencies.

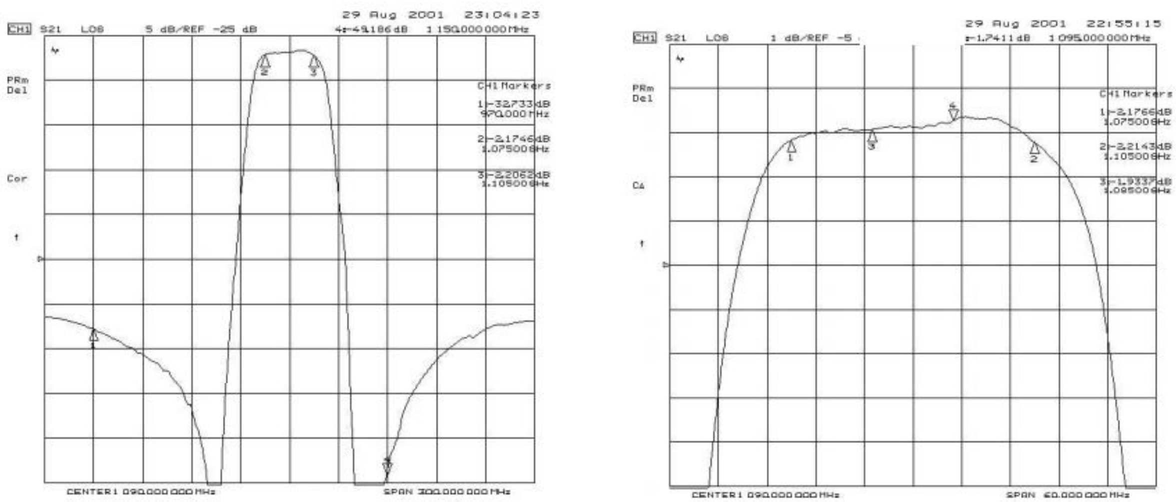

Figure [ ]: S21 Measurements for TA1090EC BPF (200 and 50 MHz span)

Requirements	Verification
1. The BPF must not have a insertion loss greater than 2.5 dB **2.** The BPF must have a 0.5 dB bandwidth of less than 50 MHz	**1 & 2.** We will use a network analyzer to measure the S-Parameters (particularly S21) of the BPF in order to verify its performance. F. First, define the parameters of the network analyzer. Set the frequency range to 1060 to 1110 MHz and the number of points to 2001. G. Calibrate the network analyzer using a TRL or SOLT calibration kit. H. Connect ports 1 and 2 of the analyzer to the input and output of the BPF, respectively, using pigtails. I. Use markers in order to measure the insertion loss (S21) of the filter at various points around 1090 MHz. These markers will also be used to verify the 0.5 dB bandwidth.

2.1.4 Envelope Detector

The envelope detector demodulates the transponder signal. As seen in figure [ ] below, the transponder signal uses an on/off encoding scheme. This message is sent using a 1090 MHz carrier, and can be decoded using an envelope detector. Our design uses TDOA in order to locate an aircraft. In order to achieve an accuracy of 30m, the envelope detector needs to be able to detect the transponder signal's envelope with an accuracy of 100ns ($c \times 100ns = 30m$). Figure [ ] below shows the large step response for the MAX4003 detector, which meets this accuracy.

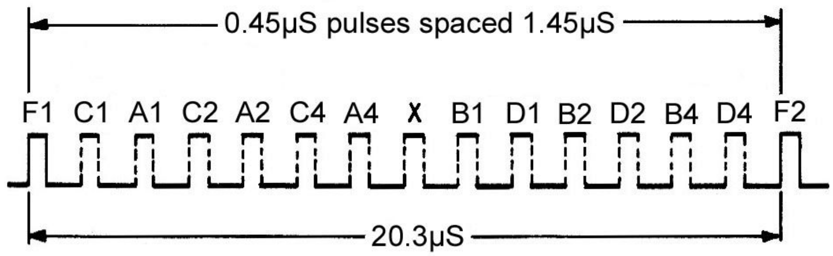

Figure [ ]: Mode A/C Transponder Response Signal

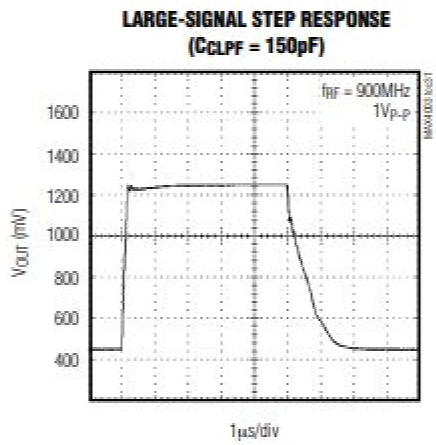

Figure [ ]: Large Signal Step Response for MAX4003 Envelope Detector

2.1.5 Logarithmic Amplifier

2.2 GPS

The GPS unit will be used for gathering the location of the receivers, as well as time stamping the received signals of each receiver.

2.2.1 GPS Antenna

The GPS Antenna will receive the GPS signal.

2.2.2 GPS Module

The GPS Module will decode the GPS signal for position and time syncing. This serial data will go to the Control Unit. The timing module requires the PPS output from this module.

2.3 Control Unit

The control unit supports the overall functionality of the receiver's ability to react to the detection of a transponder signal from the RF Front End and deliver the time data to the server for processing the location. Minimal latency and reliability of detecting the signals are the key concerns for maintaining accuracy. Furthermore, the unit needs to handle configuration settings of the ethernet communication, updating the server with its location, and provide reasonable user functionality to reset and test the system.

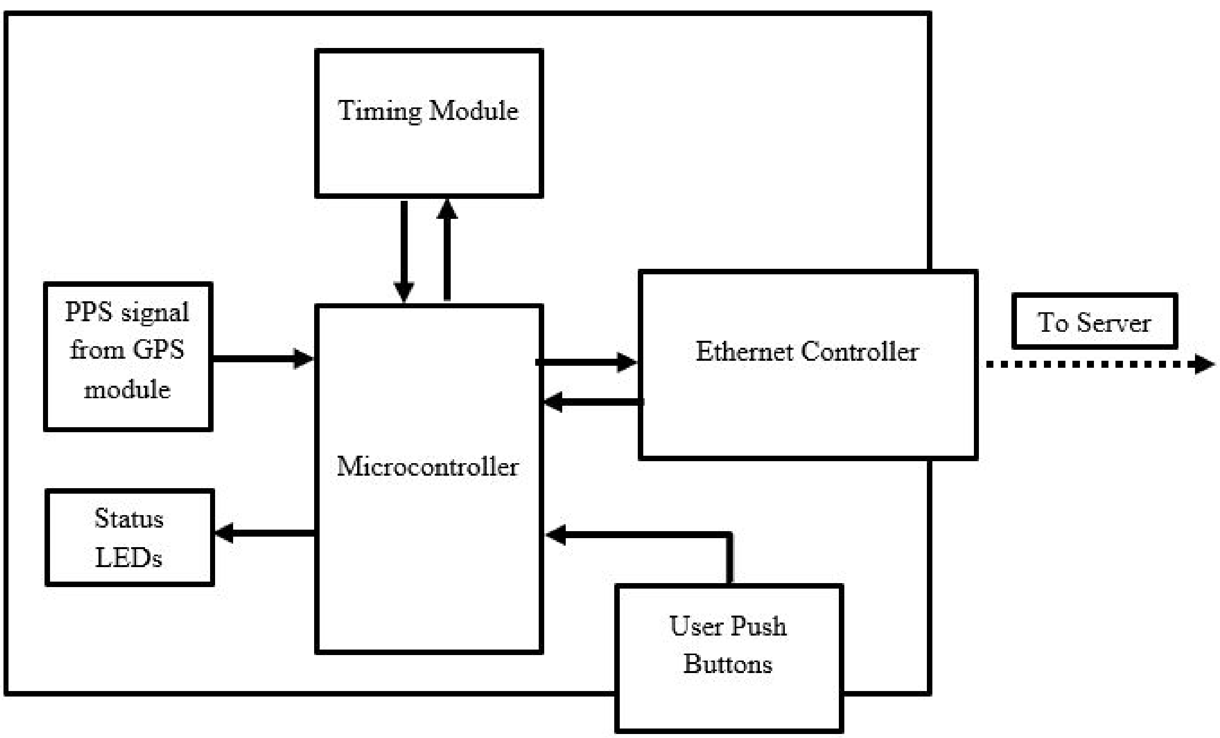

Figure [ ]: Block Diagram of Control Unit

2.3.1 Timing Module

External counter and flash memory storage provides stable timing resolution and synchronizes with the GPS' PPS signal. A microcontroller shall control the data movement between the components. The project specific application of this module is the generation of an accurate timestamp upon aircraft transponder signal detection. The frequency of the counter and the succinct ability to synchronize the resets between each receiver directly correlates to the potential accuracy of the system. 40 MHz approximately represents ~7.5 meters of light travel per clock cycle.

Requirements	Verification
1. Unit shall operate at a frequency of at least 40 MHz. **2.** Supports continues counting for at least 2 seconds (data representation of 27+ bits). **3.** Control logic to collect timestamps and supports GPS synchronization.	**1. & 2.** An oscilloscope, wave generator, and voltage supply will be used to monitor the data pins of the external counter and check the maximum value reached. **2.** Data representation is device specific, so correctly sourcing the parts is required **3.** The microcontroller program development will provide access to the data using the I/O pins. A development board (such as an Arduino) provides a platform to support reading the I/O data.

2.3.2 Main Microcontroller

The microcontroller is responsible for reading timestamp data from the timing module, interpreting the transponder signals, posting data to server/website, and general management (acquire IP, find server, reset/test control).

Requirements	Verification
1. Sufficient operating rate: at least 40 MHz. **2.** Capable of communication with ethernet module, timing unit, and user inputs.	**1.** Confirm operational conditions via datasheet, includes reviewing IVdd and Frequency curves. **2.** Communication testing requires test benching the particular interactions. A small program is loaded to trigger a read from the timing unit, another test to confirm user's push button signals are received, and finally a test for the microcontroller to publish data to the central server.

2.3.3 Status LEDs

The status LEDs provide basic operational visuals for the receiver. The main states for a user-friendly module include normal functionality, connection issues to server, and device failure. Embedded LEDs also allow for debugging and given status updates during design iterations.

Requirements	**Verification**
1. Visible to user (visually inspected)	**1.** Perform benchmark test using breadboard and a basic program loaded on the microcontroller to set a I/O port to high in order to illuminate the LED.

2.3.4 Control Buttons

One button will provide the ability to manually reset the receiver to force a reconnection to the server. Another button will be implemented to trigger a false received transponder signal to verify server functionality and connectivity.

Requirements	**Verification**
1. Push button only trigger an active pulse once per user press. **2.** Microcontroller shall receive the signals via polling input pins and react accordingly to the interrupts	**1.** Verify by placing component on a breadboard and using an oscilloscope to measure the number of peaks corresponding to each press. **2.** After programming the microcontroller with the appropriate code, the push buttons will cause the LEDs to change based on function and a test data point will be sent to the server.

2.4 Power

2.4.1 Power Over Ethernet (POE)

One distinct difference between our design and commercial designs is it will be powered by power over ethernet. In order to transmit the receiver's data to our central server, we will not require data speeds greater than 100 Mbps. As seen in figure [ ] below, operating on mode B (DC on spares) will allow us to use a T568 ethernet cable in order to transmit data and receive DC power on separate wires(other modes transmit data and power on the same wire).

Pins at switch	T568A color	T568B color	10/100 mode B, DC on spares	
Pin 1	White/green stripe	White/orange stripe	Rx +	
Pin 2	Green solid	Orange solid	Rx −	
Pin 3	White/orange stripe	White/green stripe	Tx +	
Pin 4	Blue solid	Blue solid		DC +
Pin 5	White/blue stripe	White/blue stripe		DC +
Pin 6	Orange solid	Green solid	Tx −	
Pin 7	White/brown stripe	White/brown stripe		DC −
Pin 8	Brown solid	Brown solid		DC −

Figure [ ]: 802.3af Standards A and B from the Power Sourcing Equipment Perspective

Requirements	Verification
1. Our POE cable must be able to provide 12V and up to 1A to our circuit. **2.** The POE cable must allow communication between the central server and ethernet microcontrollers.	**1.**

2.4.2 Voltage Regulators

All of the components in our design require a voltage of either 5V or 3.3V. Voltage regulators will be used in order to ensure that the components receive constant voltage. The MC7805 will be used for the 5V regulator, as it's line and load regulation are less than 25 mV given an input voltage of 11V, and an output current of 1A. Under variable load currents and input voltages, this regulator will provide a constant output voltage.

Requirements	Verification
1.	

2.5 Server

The central server will receive the time stamps of the received transponder signals, and will use multilateration in order to compute the position of the aircraft based on the time delay between receivers [6].

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

3.1.2 Parts

Part Description	Manufacturer	Vendor	Cost (Quantity)
MAAL-011078 (LNA)	MAACOM	Digikey	$ 5.88 (2)
TA1090EC (BPF)		Ali Express	$ (2)
M7805 (5V Regulator)	Texas Instruments	ECE Supply Shop	$ 0.57 (1)
LD1117A (3.3V Regulator)	STMicroelectronics	Digikey	$ 0.55 (1)
MAX4003 (Envelope Detector)	Maxim Integrated	Digikey	$ 1.27 (1)
LTW-420D7	Lumex Opto/ Components Inc.	Digikey	$ 0.54 (3)
AT25SF041-SSHD-T	Adesto Technologies	Digikey	$ 0.36 (1)
PIC32MX130F064B-I/ SS-ND	Microchip Technology	Digikey	$ 2.56 (2)
mini-ENC28J60 Module		Ali Express	$ 2.20 (1)

3.1.3 Grand Total

3.2 Schedule

Week	Ben	Rushik	Kyle
2/25/19	Finalize antenna design, order parts, simulate antenna design (FEKO)	Determine impedance matching, order parts	Order parts, Figure out microcontroller programming, ethernet interface
3/4/19	Schematic/Layout Design		
	Creation of simulated transponder signal on SDR		
3/11/19 (PCBway)	Construct Antenna	Construct Antenna	Begin software programming, server side communication
3/18/19 (Break)	Begin Testing Parts, Modular Assembly		
3/25/19	Finalize PCB redesign (if necessary)		
	GPS timing and testing	Verify Performance of LNA, BPF, RF Front End, determine new impedance match values if necessary	Verify timing of counter and microcontroller blocks
4/1/19	Integrate all modules		
4/8/19	Finish debugging and data collection for report		
4/15/19	Prepare for demo/presentation		
4/22/19	Continue work on final paper/presentation		
4/29/19	Present project, submit final paper		

4 Ethics & Safety

The proposed project incurs several possible ethical and safety concerns that require attention when proceeding in the design, implementation, and deployment phases. These ethical concerns will reference both IEEE and Association of Computing Machinery (ACM) Code of Ethics.

From the Association of Computing Machinery's Code of Ethics, "An essential aim of computing professionals is to minimize negative consequences of computing, including threats to health, safety, personal security, and privacy. [7]". This is similar to the #1 IEEE Code of Ethics [8]. A particular concern arises as the data acquired by the proposed receiver solutions includes GPS positional data and this information is needed on the server, sent over the ethernet. In order to protect the locational privacy of our users, we shall encrypt both the data before sending and the database of collected timestamps and locations on the server back-end.

Although the transponder signals are be collected by each receiver unit, these devices are inherently designed to be passive and shall not interfere with any FCC regulations.

References

[1] M. Thurber, "ADS-B Is Insecure and Easily Spoofed, Say Hackers," *Aviation International News*, 03-Sep-2012. [Online]. Available: https://www.ainonline.com/aviation-news/aviation-international-news/2012-09-03/ads-b-insecure-and-easily-spoofed-say-hackers. [Accessed: 08-Feb-2019].

[2] "How It Works," *Flight Radar 24*. [Online]. Available: https://www.flightradar24.com/how-it-works. [Accessed: 07-Feb-2019].

[3] "PASSIVE RADAR ACTIVISTS," *Thales Group*, 19-Nov-2014. [Online]. Available: https://www.thalesgroup.com/en/worldwide/aerospace/case-study/passive-radar-activists. [Accessed: 07-Feb-2019].

[4] J. R. Wilson, "New frontiers in passive radar and sonar," *Military & Aerospace Electronics - Military technology, weapons, equipment & systems for the military industrial complex.*, 08-Feb-2016. [Online]. Available: https://www.militaryaerospace.com/articles/print/volume-27/issue-2/special-report/new-frontiers-in-passive-radar-and-sonar.html. [Accessed: 07-Feb-2019].

[5] J. Vierinen, "Building your own SDR-based Passive Radar on a Shoestring," *Hackaday*, 01-Jul-2015. [Online]. Available: https://hackaday.com/2015/06/05/building-your-own-sdr-based-passive-radar-on-a-shoestring/. [Accessed: 07-Feb-2019].

[6] U. Feichter, "Elaboration of Methods and Algorithms for Passive Aircraft and Vehicle Detection over Time of Signal Arrival Differences," thesis, 2010.

[7] "ACM Code of Ethics and Professional Conduct," *Association for Computing Machinery*, 2018. [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed: 08-Feb-2019].

[8] "IEEE Code of Ethics," *IEEE - Advancing Technology for Humanity*. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 08-Feb-2019].