# Passive Aircraft Radar

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

# Acknowledgements

Thank you to Professor Kirill Levchenko
for sponsoring this project!

# Table of Contents

# 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 does not 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 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 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 to detect aircraft, but these implementations often use external websites to interpret the received data, and designs which are inexpensive are not 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 be able to detect an aircraft position with an accuracy of at least 100 m in 3D space.
3. Each receiver shall consume less than 15.4 W, in accordance with IEEE 802.3af standards [6].

# 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 1. The receiver units will function as a network and will be deployed in different parts of the community for performing airplane tracking via the travel time of the airplane's transponder, as shown in figure 2.

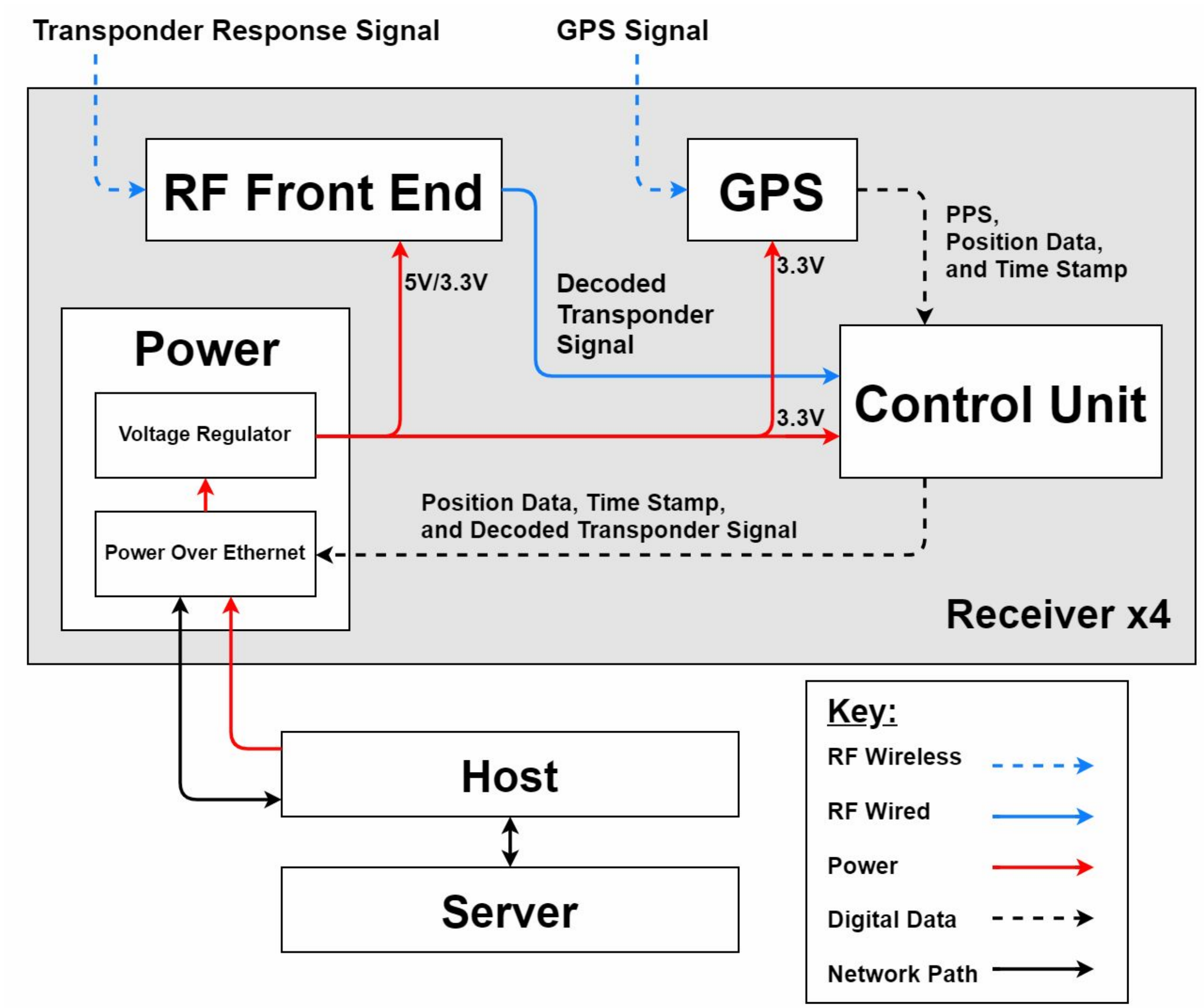



**Figure 1:** Receiver Block Diagram

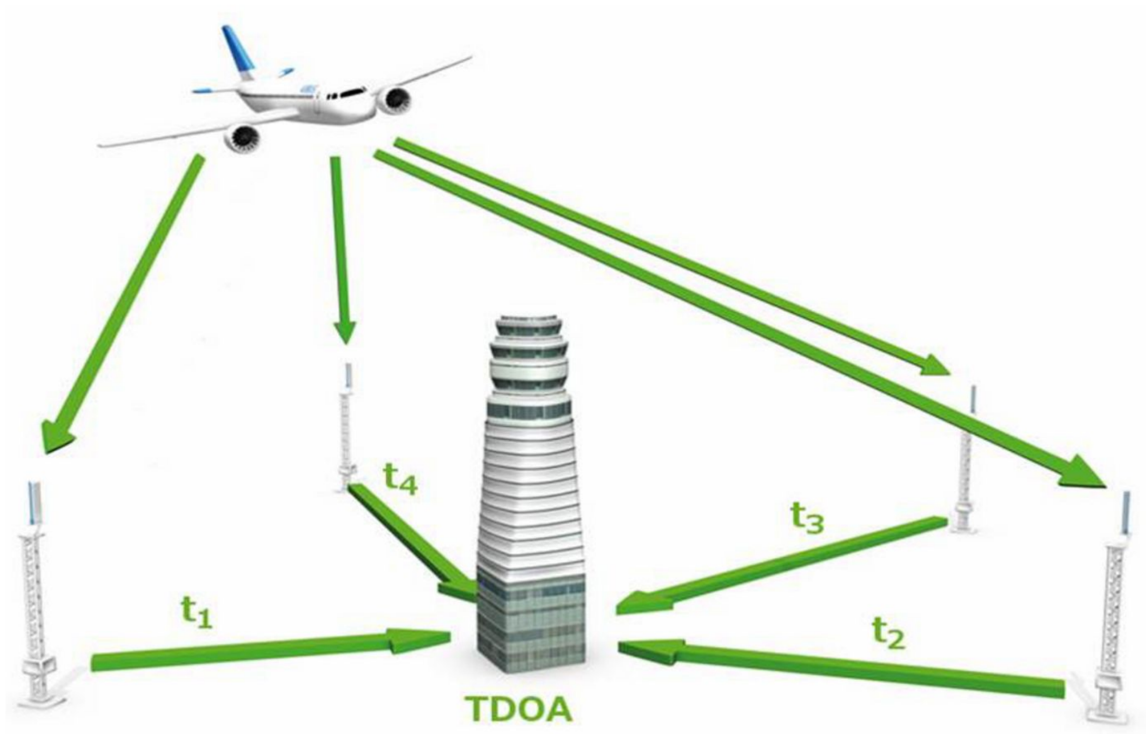



**Figure 2:** Physical Diagram

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). If an aircraft has an unknown position $(x, y, z)$ and 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.

$$d_1 = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} \quad \textbf{(Eq 1)}$$

$$d_2 = \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} \quad \textbf{(Eq 2)}$$

$$d_1 - d_2 = c\Delta t = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} - \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} \quad \textbf{(Eq 3)}$$

## 2.1 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 (the transponder signal uses on/off keying while operating in mode c [7] so we can decode it using an envelope detector). We can estimate the received signal power using the Friis transmission equation (Eq 4).

$$P_R = \frac{G_T G_R \lambda^2}{(4\pi R)^2} P_T \quad \textbf{(Eq 4)}$$

The transponder transmitter power $P_T$ can be estimated as 250 W as declared by the FAA [8], the distance between the receiver and the transponder $R$ can be estimated as 12 km, and the gains of the antenna and receiver can be set to 1 (in reality the gains are not 1, but both antennas will have relatively low gain [9] so for the purposes of this calculation we will assume that our antennas are isotropic). Since the transponder signal transmits at 1090 MHz, we can calculate the wavelength $\lambda = c/1090\ MHz = 0.275\ m$. With these parameters, we calculate the received power as $8.33 \times 10^{-7} mW = -60.8\ dBm$.

The front end needs to be able to amplify this signal without adding noise, and needs to able to decode the message from the carrier. By accurately decoding the signal, the design will be able to meet the 2nd high level requirement, which says the receiver must be able to locate an aircraft within 100 m of 3D space. The RF front end includes an antenna which capture the signal, two low noise amplifiers (LNA) and band pass filters (BPF), an envelope detector, and a comparator. Figure 3 shows the block diagram of the RF front end, and figures 4 and 5 show the full schematic.

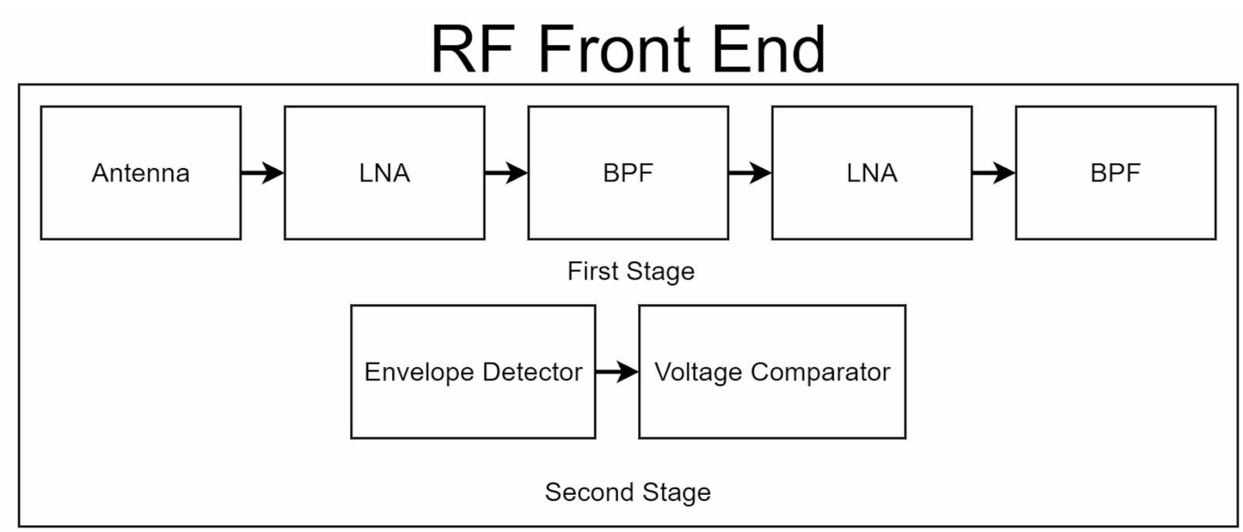



**Figure 3:** RF Front End Block Diagram

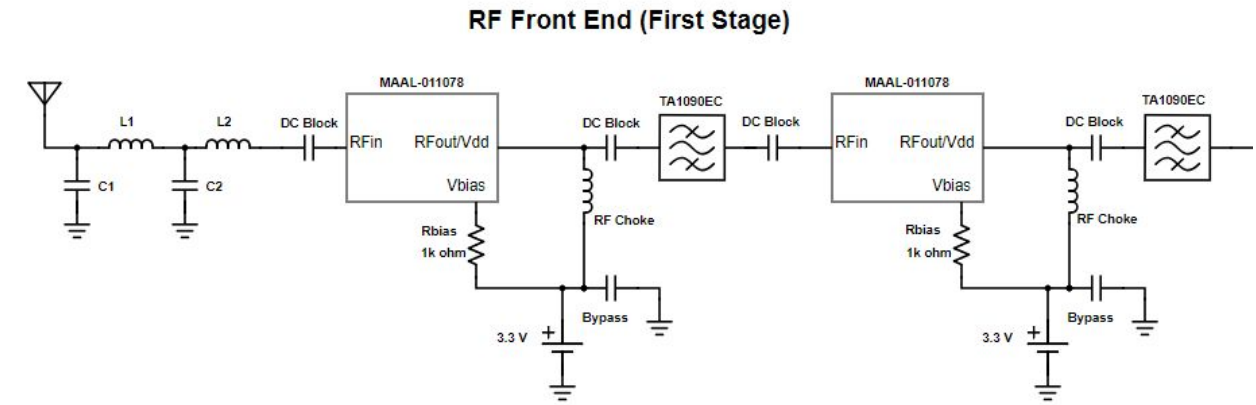



**Figure 4:** RF Front End Schematic (First Stage)

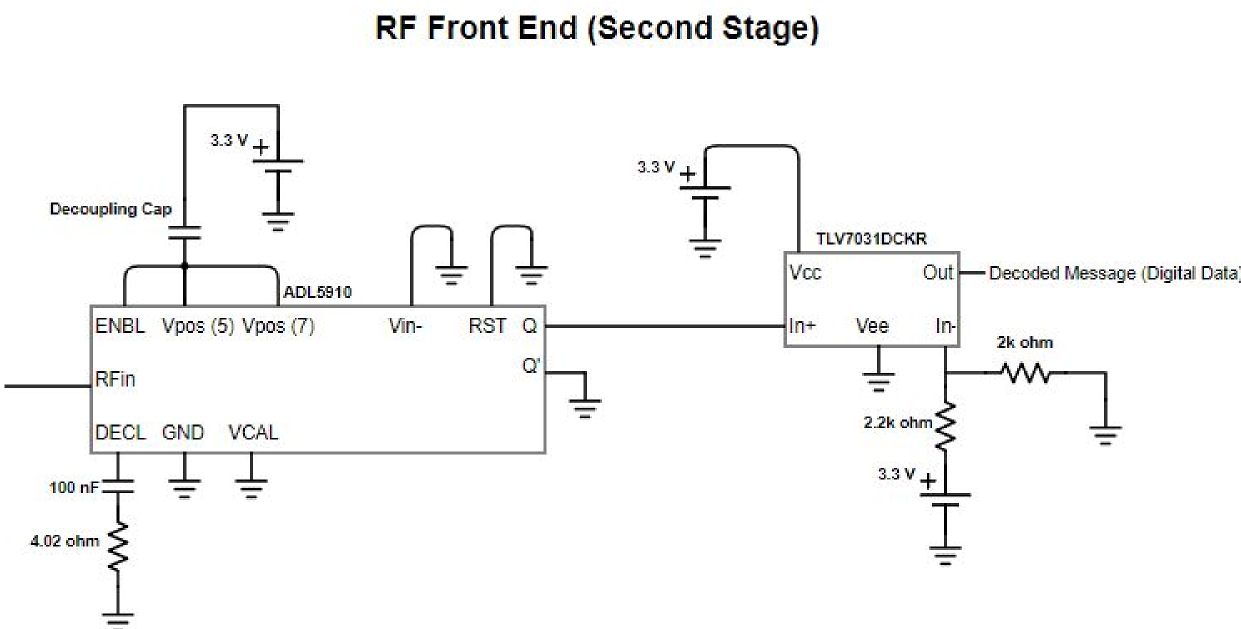



**Figure 5:** RF Front End Schematic (Second Stage)

### 2.1.1 Antenna

The antenna is what will receive the transponder signal from the aircraft. Designs for ADS-B antenna will be vertically polarized to maximize the signal power received since ADS-B is vertically polarized [9]. To maximize the chance of receiving a signal from any lateral direction, the antenna should be omnidirectional (uniform gain in the azimuth). Lateral coverage is more important than vertical coverage considering how short of a duration an aircraft will fly over our antenna. Therefore, it would be better to design a high gain antenna just above the horizontal plane (~5$^{o}$) to receive signals from planes just above the horizon. Variations of the dipole antenna share these properties, and are popular among ASD-B enthusiasts due to their simplicity and cost [10]. These antenna are typically mounted outdoors since 1090 MHz requires line-of-sight to be received, so a weatherproof radome is required for the antenna.

Additionally, it would be ideal if our antenna had a narrow bandwidth around 1090 MHz to reject spurious signals in nearby bands. A collinear antenna satisfies is an example of an antenna that satisfies this bandwidth requirement, while providing a gain of ~5.5 dBi for the mainlobe. It also has the benefits of being simple to construct and having a form factor that can fit insides a 1 inch PVC pipe, which can act as the radome for the design [11]. Other designs such as discone or sleeve dipoles, while still better than ground-plane antennas, have form factors that are not convenient for the antenna and radome construction.

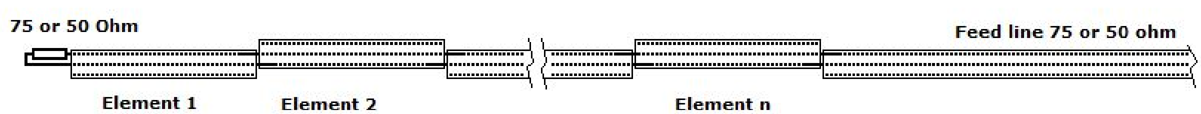



**Figure 6:** Theoretical design of an n-element collinear antenna by Dusan Balara [11]

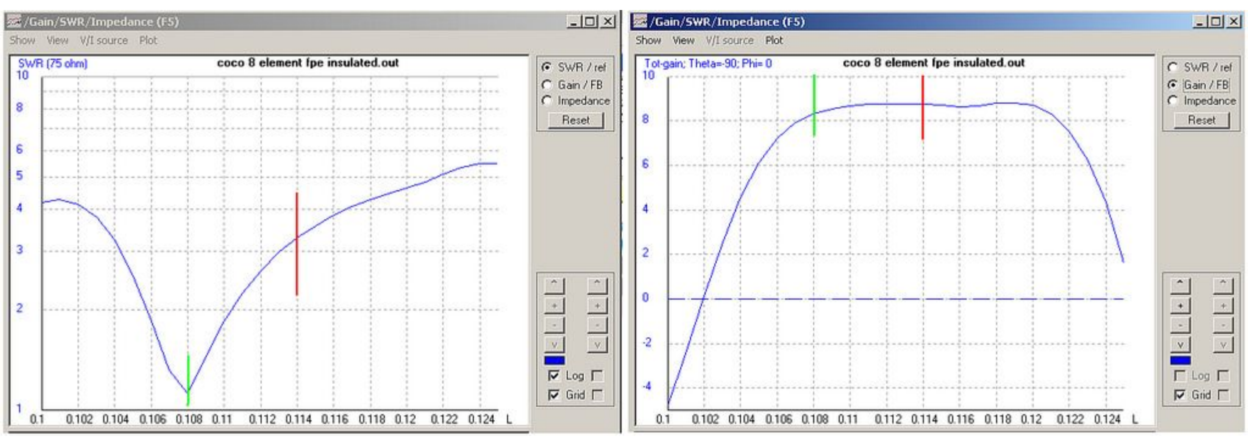



**Figure 7:** SWR and maximum gain over frequency for example simulation by @abcd567 [12]

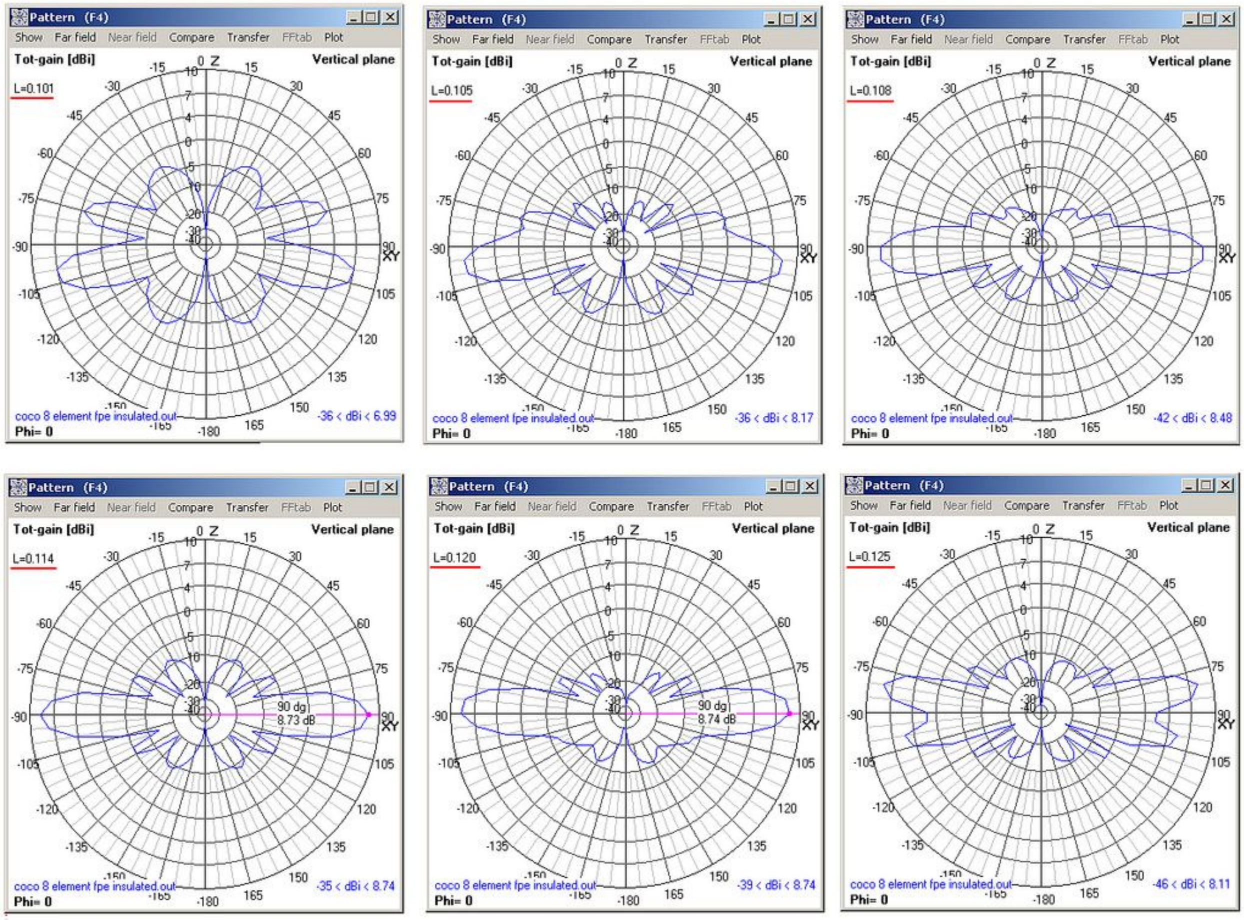



**Figure 8:** Elevation cross-section of example simulation at 1090 MHz by @abcd567 [12]

| **Requirements** | **Verification** |
|---|---|
| **1.** The antenna must have a SWR of < 2.0 for a 1 MHz band centered at 1090 MHz. SWR can be improved by tuning the antenna (either modifying the length of the antenna elements, or adding stubs to create a matching network). | **1.** Use a network analyzer to measure SWR of the antenna.<br>A. Define the parameters of the network analyzer. Set the frequency range to 1060 to 1110 MHz and the number of points to 2001.<br>B. Calibrate the network analyzer using a SOL calibration kit.<br>C. Connect ports 1 of the analyzer to the input of the antenna, using a SMA connector.<br>D. Measure and record the SWR (alternatively use S11) using markers. |

| | |
|---|---|
| **2.** The antenna must have a maximum gain of at least 3 dBi at 85° from the zenith with a radome attached. | **2.** Measure gain using a near-field chamber, and then transforming the near-fields to far-field polar plots. Alternatively, measure the far-field directly using an open range measurement setup.<br>A. Define the parameters of the gain measurement. Have the feed element (a horn antenna) transmit at 1090 MHz and vertically polarized.<br>B. Measure the antennas gain in the zenith by incrementing the antennas pitch in 2.5° increments from 0° to 180°.<br>C. For completeness, measure the gain in the azimuth by rotating the antenna in 15° degree increments from 0° to 360° with the pitch set to 0° in the zenith. |

### 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 9, and is set to work in a $50\Omega$ environment when biased using the circuit shown in figure 10.

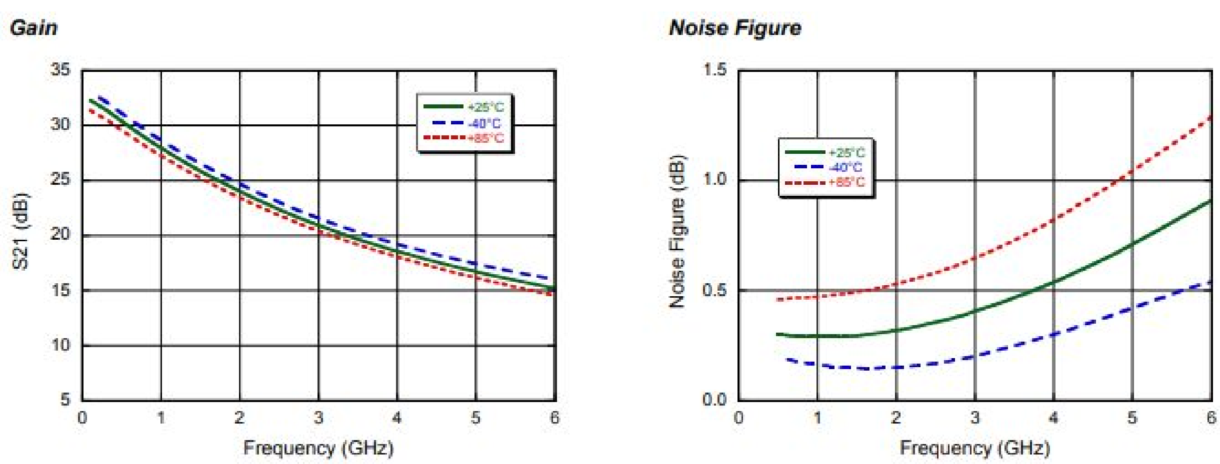



**Figure 9:** Gain and Noise Figure plots for the MAAL-011078 LNA [13]

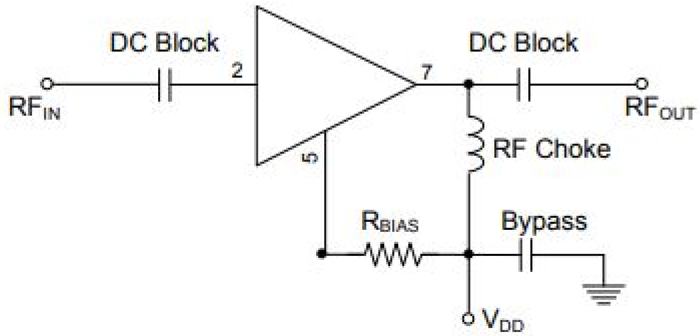



**Figure 10:** Circuit diagram for MAAL-011078 LNA to be used in a 50Ω system [13]

| **Requirements** | **Verification** |
|---|---|
| **1.** The LNA must have a supply voltage of 5 V +/- 50 mV, and must draw a load current of 70 +/- 10 mA | **1.** The bias resistance can be set to 1 kΩ so that the LNA will draw 71 +/- 10 mA [13] |
| **2.** The LNA must have a gain (S21) of 27 +/- 2 dB at 1.09 GHz | **2.** Use a network analyzer to measure the S-Parameters (particularly S21) of the LNA in order to verify its performance.<br>A. 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!)<br>B. Calibrate the network analyzer using a TRL or SOLT calibration kit.<br>C. Connect ports 1 and 2 of the analyzer to the input and output of the LNA, respectively, using pigtails.<br>D. Measure the gain of the LNA (S21) using markers.<br>E. Perform a power sweep of the LNA in order to measure its input/output p1dB. |
| **3.** The LNA must have a noise figure < 1 dB at 1.09 GHz | **3.** Measure the noise figure using a noise figure analyzer (NFA)<br>A. Set the frequency range from 1.08 to 1.10 GHz, the number of points to 21, and enter any cable losses into the analyzer.<br>B. Calibrate the NFA using a noise diode.<br>C. Measure the noise figure of the LNA by attaching the noise source to the input and measuring the output. |

### 2.1.3 Band Pass Filter (BPF)

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

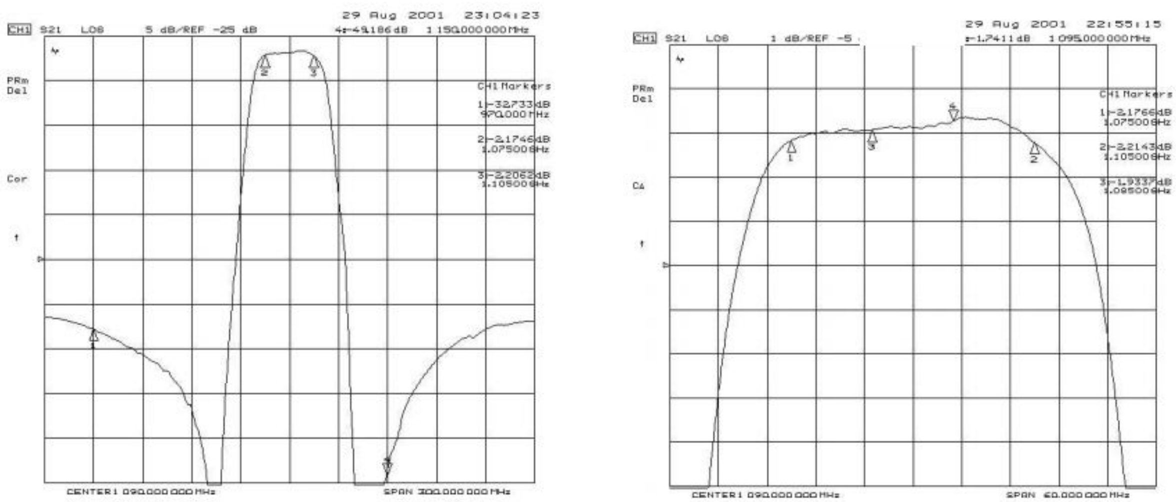



**Figure 11:** S21 Measurements for TA1090EC BPF (200 and 50 MHz span) [14]

| Requirements | Verification |
| --- | --- |
| **1.** The BPF must have an insertion loss (S21) less than 2.5 dB<br><br>**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.<br>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.<br>B. Calibrate the network analyzer using a TRL or SOLT calibration kit.<br>C. Connect ports 1 and 2 of the analyzer to the input and output of the BPF, respectively, using pigtails.<br>D. 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 LNA/BPF Cascade Analysis

The noise figure of the LNA/BPF cascade can be calculated as follows:

$$F_{LNA} = 0.35\ dB, G_{LNA} = 27\ dB,\ L_{BPF} = 2.2\ dB$$

$$F = F_{LNA} + \frac{L_{BPF}-1}{G_{LNA}} + \frac{L_{BPF}(F_{LNA}-1)}{G_{LNA}} + \frac{L_{BPF}(L_{BPF}-1)}{G^2_{LNA}} = 1.0855 = 0.356\ dB$$

We can also calculate the p1dB of the cascade. The p1dB of the LNA is 20 dBm [13], which means that the p1dB of the cascade is also 20 dBm (at the output), and the OIP3 is about 29.6 dBm. The input p1dB is -29.6 dBm.

### 2.1.5 Envelope Detector

The envelope detector demodulates the transponder signal. 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 30 m, the envelope detector needs to be able to detect the transponder signal's envelope with an accuracy of 100 ns ($c \times 100\ ns = 30m$). This means the rise time for the envelope detector's output needs to be less than 100 ns. The AD5910 detector meets these requirements [15].

| **Requirements** | **Verification** |
|---|---|
| **1.** Given a 1090 MHz carrier (with a power greater than -10 dBm) modulated with rectangular pulses with a width of 0.45 µs and spacing of 1 µs, the AD5904 envelope detector must be able to demodulate the carrier, and output the pulses with a rise time no longer than 100 ns and amplitude greater than 700 mV. | **1.** The modulated carrier can be generated using an SDR (available in 5080). Using an oscilloscope, the response at the Q output of the AD5904 envelope detector can be measured, and the rise time and output voltage can be measured. |

### 2.1.6 Comparator

The comparator will take the pulse given by the envelope detector and convert it to a digital signal. The envelope detector outputs a digital signal, however the voltage maximum of the output is not great enough to be used by the microcontroller (which requires that a "high" be represented by a voltage greater than 2 V"). To account for this, our design uses a comparator, which compares the input to a reference voltage, and then outputs a "high" as Vcc, and a "low" as a very low voltage (<100 mV). In our design, we will be using the TLV7031DCKR, as it has a low propagation time, and is inexpensive.

| **Requirements** | **Verification** |
|---|---|
| **1.** When given a square pulse with an amplitude greater than 700 mV, the comparator must be able to propagate the pulse with a propagation time no longer than 5 µs. The resulting pulse's maximum amplitude should be Vcc (which in our case is 3.3 +/- 25 mV). | **1.**<br>A. Use a signal generator/pulse generator in order to generate a square wave with a period of 2 µs, and an amplitude of 1.5V<br>B. Use a pigtail in order to connect the input of the comparator to the signal generator, and connect the output of the comparator to an oscilloscope.<br>C. Connect the signal generator to a separate channel on the oscilloscope<br>D. Use the oscilloscope in order to verify that the square wave has a propagation time through the comparator of less than 5 µs and has an amplitude of 3.3 +/- 25 mV |

## 2.2 GPS

The GPS unit will be used for providing the receivers' position and to provide an accurate time reference for the received-signal time-stamp. Interestingly enough, the GPS unit uses time difference of arrival to determine an accurate position and time [23]. This position and time is updated with a 1 Hz PPS signal. This means that GPS receivers can provide accurate timekeeping every second, which is not sufficient for our application. There exist modules that generate a higher frequency clock that references the PPS known as GPSDO. The higher clock will be synchronized and coherent with the PPS signal, meaning it can be reliably used as an accurate clock [16]. Unfortunately, these systems are very complex and expensive, which is why the design uses its own timing module instead. The GPS modules our project will be using is a full receiver including the antenna and module in one package.

| **Requirements** | **Verification** |
|---|---|
| **1.** The GPS module must be able to generate a 1 Hz PPS signal. | **1.** The module will be powered with a voltage supply and measured using a oscilloscope. The frequency and rise/fall time can be recorded over time to measure PPS time stability (preferably in a ppm format). |

| | |
|---|---|
| **2.** The GPS module must be able to provide time and position data that can be interpreted by a microcontroller. | **2.** For convenience, another microcontroller such as a Arduino can be used to receive the GPS data and unpack the data. Ideally, the microcontroller can support I2C or UART data transfer (which an Arduino can). |

## 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 time data to the server for processing the airplane location using TDOA. Minimal latency and high reliability of detecting the transponder signals are key concerns for maintaining accuracy. Furthermore, the unit needs to handle configuration settings for ethernet communication, update the server with its location, and provide reasonable user functionality to reset and test the system.

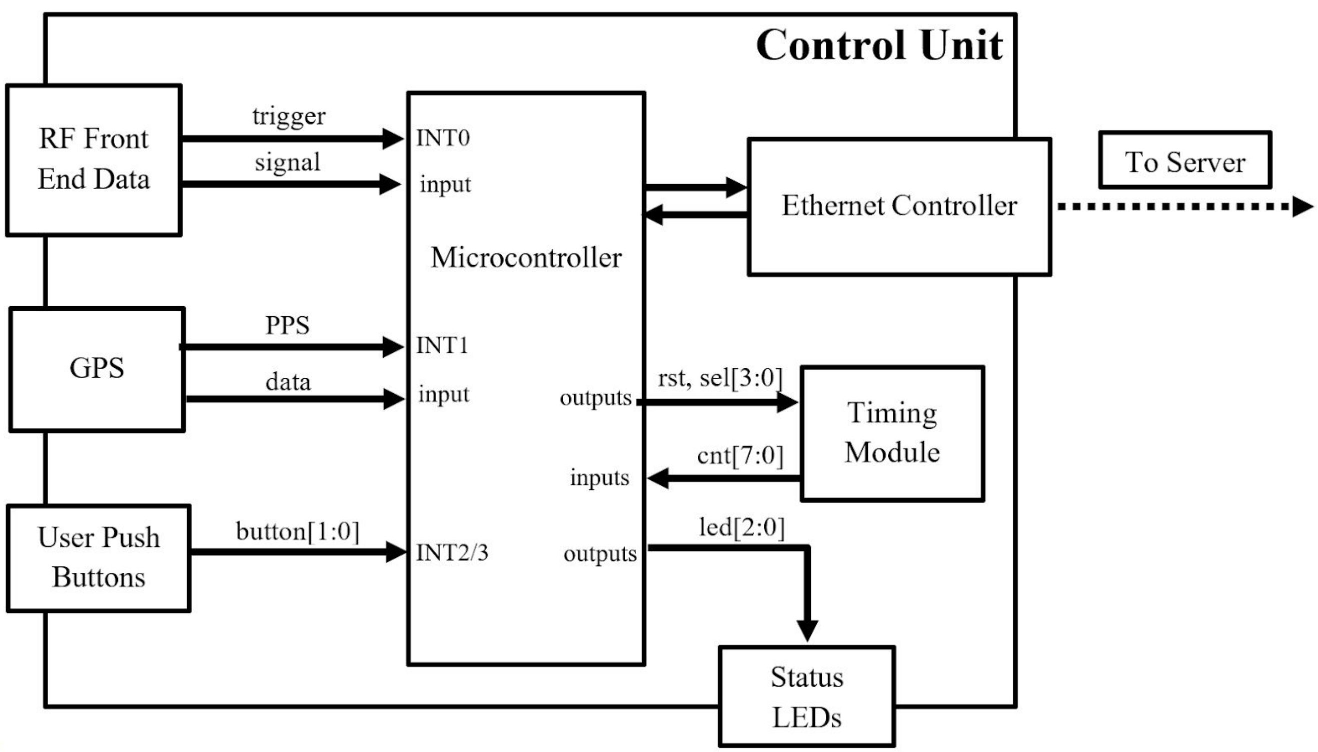



**Figure 12:** Block Diagram of Control Unit

### 2.3.1 Timing Module

An external counter provides stable timing resolution and synchronizes with the GPS' PPS signal. This device shall be enslaved to the microcontroller, which is responsible for accessing counter data and controlling the reset and select pins of the counter IC. A 3-8 bit decoder IC reduces the control logic for the counter to 3 bits to access each byte of the counter data and perform a counter reset, see figure 13. 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. Counter resolution and accuracy are limited by both input counter frequency and data access latency. For instance, a clock rate of 40 MHz approximately represents 7.5 meters of light travel per clock period and implies the quantized representation of time limits accuracy to the nearest 7.5 meter increment
$(1/40\ MHz\ =\ 25\ ns,\ 25\ ns\ \times\ c\ =\ 7.5\ m)$

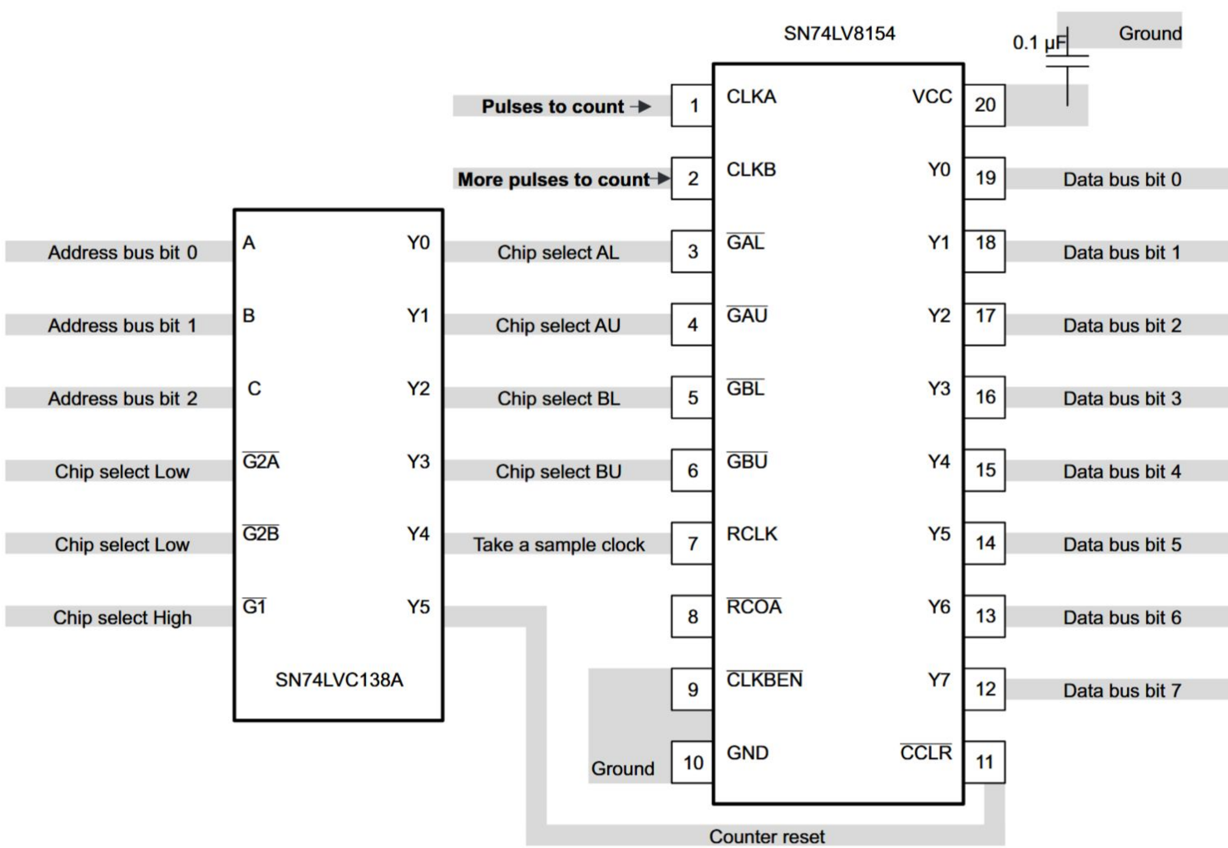



**Figure 13:** Dual Counter With Address Mapping [17]

| Requirements | Verification |
|---|---|
| **1.** Unit shall operate at a frequency of at least 40 MHz. | **1.** Testing the frequency of the unit requires providing a known input frequency and monitoring the output for correctness of data and the switching delay on the output pins.<br>A. Place the counter unit on a breadboard with 0.1uF +/-5 % capacitors between Vcc pin and voltage supply of 3.3V +/- 9%, drive pins 4, 5, & 6 to 3.3V +/- 9%, ground pins 3 & 10, connect pins 8 & 9 together.<br>B. Configure the wave generator to output a 40 MHz square wave to pins 1, 2, & 7.<br>C. Probe the LSB of counter A (pin 19) and input wave signal for reference using an oscilloscope with reference to the common ground.<br>D. Evaluate characteristics of the output signal for stability and identify the frequency of the output.<br>E. Repeat for each output pin on counter to ensure expected output waveforms for data bus without control glitches when overflowing. |
| **2.** Supports continues counting for at least 2 seconds (data representation of 27+ bits). | **2.** Data representation is device specific. Device's datasheet correctly demonstrates ability to hold the required amount of bits. |
| **3.** Control logic to access timestamps and supports GPS synchronization using the PPS signal. | **3.**<br>A. Following pin connections in component's datasheet and figure 13, connect device to a microcontroller to provide the control signals and intake the counter data.<br>B. Activate a clear by sending logic LOW to pin 11 and begin reading the counter's data with debug statements to show the incrementation of values.<br>C. Address the four bytes of data to receive the full content from the counter and verify results via datasheet time diagram [17]. |

### 2.3.2 Microcontroller

The microcontroller is responsible for reading timestamp data from the timing module, interpreting the transponder signals, posting data to the server/website, and general management (acquire network protocols, find server, reset/test control). Latency from processing interrupts from PPS, user input, and the RF front end's decoded signal will delay the ability to accurately generate a synchronized timestamp in relation to each receiver and reduce the estimation accuracy achieved using TDOA calculations on the server.

| **Requirements** | **Verification** |
|---|---|
| **1.** Sufficient operating frequency: at least 40 MHz.<br><br>**2.** Controller requires at least 4 interrupt pins (two buttons, RF Front End output data, and PPS signal from GPS module).<br><br>**3.** Capable of communication with ethernet module, timing unit, user inputs, and GPS. | **1.** Confirm operational conditions via datasheet, includes reviewing I/Vdd and Frequency curves.<br><br>**2.** Pins are based on packaging and hardware support of the interrupt pins, consult datasheet specifications for sourced component.<br><br>**3.** Communication testing requires test benching particular component interactions.<br>A. Using SPI, connect device to the ethernet controller. Run test program to verify upload and download capability.<br>B. Connect microcontroller's digital I/O pins to the timing unit. Then program microcontroller with test bench code to clear, increment, and read data from timing unit.<br>C. Verify push buttons trigger interrupts that are handled by the microcontroller by connecting the buttons to an input voltage and ground. The output goes to the interrupt pins. The interrupt code simply needs to be a debug statement or LED illumination to confirm connection.<br>D. Finally, connect GPS module to microcontroller and configure input data. Use supported libraries to read from the module and decode the positional data.<br>E. Combine benchmarks to send timestamp and GPS data to the server using the ethernet interface. |

| | |
|---|---|
| **4.** Processed timestamp shall be communicated to the server within 500 ms of first receiving the interrupt signal. | **4.**<br>A. Following benchmark verification in step 3, create a combined data packet of a fake timestamp, transponder signal, and GPS position with the addition of the local time.<br>B. Send the data packet to the server through the ethernet controller and have the server document the time received.<br>C. Decode packet and calculate time difference and average over multiple test to determine the expected average network delay. |

### 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 give status updates during design iterations.

| **Requirements** | **Verification** |
|---|---|
| **1.** Visible to user under direct sunlight (visually inspected). | **1.**<br>A. Place LED in series with 1k ohm resistor using a breadboard as a base.<br>B. Ground the cathode side of the component and place a variable voltage supply as the input voltage.<br>C. Sweep voltage from 0V up to 3.6V.<br>D. Characterize the visibility of the LED component when it turns on and the voltage supply's output when the LED is clearly visible to the human eye. |

### 2.3.4 Control Buttons

Users will have two push buttons available to provide overrides to the receiver unit. 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 fake transponder detection to verify server functionality and connectivity.

| Requirements | Verification |
| --- | --- |
| **1.** Push button only trigger an active pulse once per user press. | **1.**<br>A. Attack component to breadboard with input voltage of 3.3V +/- 9%, ground the gnd terminal and have the push button's output connected to an oscilloscope with reference to common ground.<br>B. View the output waveform for proper rise and fall features for single, slow press and release conditions.<br>C. Repeat characterization when pressing and releasing the button every 0.5 seconds to ensure stable resolution. |
| **2.** Microcontroller shall receive the signals via polling input pins and react accordingly to the interrupts | **2.**<br>A. Connect component output to microcontroller interrupt pin and apply input voltage and ground the gnd terminal.<br>B. Pre-program microcontroller to handle interrupt by triggering a debug statement upon pressing the button.<br>C. Press the button slowly to test response as well as at a faster 0.5 second intervals to confirm receival. |

## 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 (POE). 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 14 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). In order to meet our third high level requirement, the power module must supply sufficient power to each component without exceeding the power limit of 15.4W.

| 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 14:** 802.3af Standards A and B from the Power Sourcing Equipment Perspective [18]

| **Requirements** | **Verification** |
|---|---|
| **1.** The POE cable must be able to provide up to 12V and up to 1A to our circuit. | **1.** An electronic load can be used to measure the voltage from the POE cable. The current draw can be set to 1A, and the voltage can be measured using a digital multimeter. |
| **2.** The POE cable must allow communication between the host and ethernet microcontrollers. | **2.** The ethernet controller will ping the host using the ethernet port, and the host must recognize it. |

### 2.4.2 Voltage Regulators

All of the components in our design require a voltage of either 5 V or 3.3 V. Voltage regulators will be used in order to ensure that the components receive constant voltage. The MC7805 will be used for the 5V regulator, and the LD1117A will be used as the 3.3 V

| **Requirements** | **Verification** |
|---|---|
| **1.** Given an input voltage of 12V, the MC7805 must able to supply a constant voltage of 5 +/- 50 mV, and the LD1117A | **1.** An electronic load can be used to draw 1A of current, and a digital multimeter can be used to measure the voltage across the |

| | |
|---|---|
| must be able to supply a constant voltage of 3.3 +/- 50 mV for a period of 20 minutes while drawing 1A of current. | terminals of the voltage regulators. |

## 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 [19].

## 2.6 Tolerance Analysis

In order to accurately track the position of an aircraft in 3D space, we need to ensure that our design has timing consistency and accuracy. The position of the aircraft will be determined using time delay of arrival, as mentioned in the introduction. Since the difference in distances from the transponder to each receiver is proportional to the speed of light, i.e. $\Delta d = c\Delta t$, a small inaccuracy in timing can result in a large error in the calculated aircraft position. For perspective, a timing error of 10 ns results in a distance error of 3 m. Some parts of our design have consistent time latencies, which means that they can be accounted for. Other parts of our design are not consistent, as described in 2.6.2 below. Minimizing this error is essential to our design. This inconsistent timing is what will determine if we meet our second high level requirement. In this case, for 100 m we need a timing error of less than 333.33 ns.

### 2.6.1 Consistent Latency

Figures 15 and 16 below show the propagation delay through the ADL5910 envelope detector and the TLV7031 comparator, respectively. While the datasheets for these parts give estimates on the propagation delay, we will have to measure the actual propagation delay when we construct our receiver. The purpose of these figures is to show that the propagation delay through the parts can be measured, and that it can be accounted for when calculating the position of the aircraft. We will be measuring the propagation delay through the entire RF front end using an oscilloscope, and will change our calculations based on the delay.

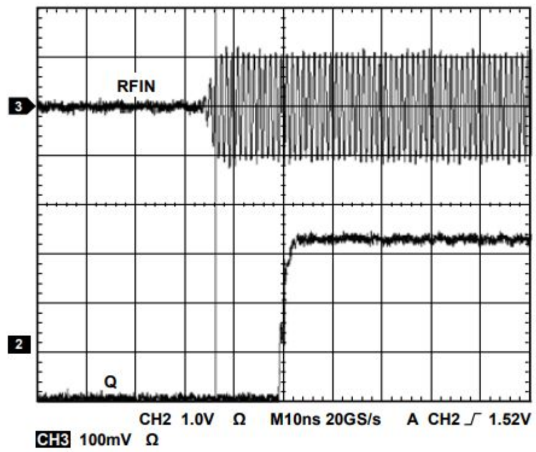
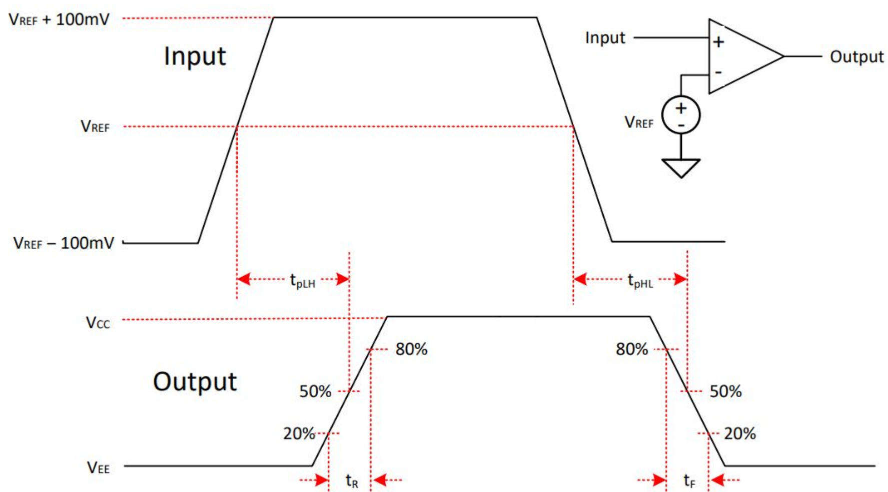



**Figure 15:** Q Output Response for RFin = 900 MHz, Pin = off to -9 dBm [15]




Typical values are at $T_A$ = 25°C, $V_{CC}$ = 5 V, $V_{CM}$ = 2.5 V; $C_L$ = 15 pF, input overdrive = 100 mV (unless otherwise noted).

| PARAMETER | | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|---|
| $t_{PHL}$ | Propagation delay time, high-to-low ($R_P$ = 2.5 kΩ TLV7041 only) | Midpoint of input transition to midpoint of output, $V_{OD}$ = 100 mV | | 3 | | μs |
| $t_{PLH}$ | Propagation delay time, low-to-high ($R_P$ = 2.5 kΩ TLV7041 only) | Midpoint of input transition to midpoint of output, $V_{OD}$ = 100 mV | | 3 | | μs |
| $t_R$ | Rise time (for TLV7031 only) | 20% to 80% | | 4.5 | | ns |
| $t_F$ | Fall time | 80% to 20% | | 4.5 | | ns |
| $t_{ON}$ | Power-up time | During power on, $V_{CC}$ must exceed 1.6 V for 200 μs before the output is in a correct state | | 200 | | μs |

**Figure 16:** Propagation Delay Timing Diagram for the TLV7031 Comparator [20]

### 2.6.2 Inconsistent Latency

As discussed in 2.2, we decided to not use a GPSDO in our design due to cost. The tradeoff is that our 40 MHz counter isn't coherent with our 1 Hz PPS signals. This means that the 40 MHz clock can be desynced from the PPS signal even if they were initially synced (which they won't be since the counter is synced to the microcontroller, independent of the GPS receiver). This can result in a desync of a upto $40\,MHz^{-1} = 25\,ns$ with the PPS rising edge. A desync of 25 ns is an error of 7.5 m.

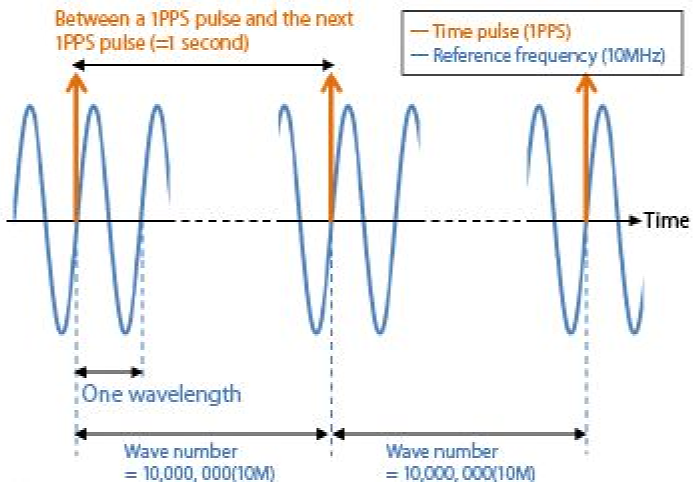



**Figure 17:** Example of a coherent clock signal synced to PPS in a GPSDO [16]

# 3 Cost and Schedule

## 3.1 Cost Analysis

### 3.1.1 Labor

The average starting salary for electrical engineer B.S. graduates is $71,000/yr according to engineering career services (2016). If we consider that an average engineer gets 3 weeks of paid vacation time, and works 40 hours per week, the hourly cost is as follows:

$$\$71,000\frac{1}{yr} \times \frac{1yr}{49\ weeks} \times \frac{1\ week}{40\ hours} = \$36.22/hr$$

We will be spending 10 hours per week per person, so our overall labor cost comes to the following: $10\ \frac{hours}{person \times week} \times 3\ people \times 11\ weeks\ \times \$36.22\frac{1}{hr} = \$11,952.60$

### 3.1.2 Parts

| Part Description | Manufacturer | Part Number | Vendor | Quantity | Unit Cost |
|---|---|---|---|---|---|
| LNA | MAAL-011078 | MACOM | Digikey | 2 | $ 5.88 |
| BPF | TA1090EC | | Ali Express/ Ebay | 2 | ~ $ 3.00 |
| 5V Regulator | M7805 | Texas Instruments | ECE Supply Shop | 1 | $ 0.57 |
| 3.3V Regulator | LD1117A | STMicroelectronics | Digikey | 2 | $ 0.55 |
| Envelope Detector | AD5910 | Analog Devices | Digikey | 1 | $ 5.62 |
| Comparator | TLV7031DCKR | Texas Instruments | Digikey | 1 | $ 0.60 |
| GPS Module | NEO-M8N | U-blox | U-blox | 1 | $ 15.05 |
| 32 Bit PIC Microcontroller | PIC32MX795F512HT-80I/PT | Microchip Technology | Digikey | 1 | $ 9.06 |
| Dual 16-bit Counter | SN74LV8154N | Texas Instruments | Digikey | 1 | $ 1.09 |

| | | | | | |
|---|---|---|---|---|---|
| 3-to-8 Bit Decoder | SN74LVC138A QPWRQ1 | Texas Instruments | Digikey | 1 | $ 0.61 |
| Ethernet Controller | ENC28J60 LAN Network Module | HanRun | Ali Express | 1 | $ 2.88 |
| Red LED | HLMP3301 | Broadcom Limited | ECE Supply Shop | 1 | $ 0.16 |
| Yellow LED | HLMP3401 | Broadcom Limited | ECE Supply Shop | 1 | $ 0.21 |
| Green LED | HLMP3507 | Broadcom Limited | ECE Supply Shop | 1 | $ 0.18 |
| SMT Push Button | MPB-43 | | ECE Supply Shop | 2 | $ 0.43 |
| Resistors, Capacitors, Inductors | | | ECE Services Shop or Digikey/ Mouser | | ~ $ 5.00 |
| Clock Oscillators | | | Digikey/ Mouser | | ~ $ 6.00 |

Total Cost Per Receiver = **$66.75**

### 3.1.3 Grand Total

Grand Total = Cost Per Receiver (4 Receivers) + Labor Cost = **$12,219.60**

## 3.2 Schedule

| Week | Ben | Rushik | Kyle |
|---|---|---|---|
| 2/25/19 | Finalize antenna design, order parts, simulate antenna design (FEKO) | Determine impedance matching for antenna, order parts | Order parts, understand microcontroller programming, ethernet interface |
| 3/4/19 | Schematic/Layout Design | | |
| | Creation of simulated transponder signal on SDR | Simulation of Antenna test/verify 5V regulator | Continue microcontroller programming and schematic |
| 3/11/19 (PCBway) | Construct and test antenna | Construct and test antenna, begin testing components | Begin software programming, server side communication |
| 3/18/19 (Break) | Begin Testing Parts, Modular Assembly (Spring Break) | | |
| 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. Begin integrating digital components. |
| 4/1/19 | Integrate all modules & perform unit configuration to improve module performance | | |
| | Collect full chamber measurements for report | Begin data collection on full RF front end | Debug program and optimize for minimum algorithm latency |
| 4/8/19 | Finish debugging and data collection for report | | |
| | Compile antenna and gps data onto report | Compile RF front end and power data on report | Compile control unit data onto report |
| 4/15/19 | Prepare for demo/presentation | | |
| | Lab-based demo using USRP and single | Prepare demo showing the output of the | Preparation to demo software connectivity and |

| | | | |
|---|---|---|---|
| | receiver | comparator (using the oscilloscope) | latency calibration for microcontroller, gps, and counter modules |
| 4/22/19 | Continue work on final paper/presentation | | |
| | Describe antenna and GPS module on final paper and presentation | Describe RF front end on final paper and presentation | Describe control unit on final paper and presentation |
| 4/29/19 | Present project, finalize and submit final paper | | |
| | Check all figure descriptions, ensure data is referenced properly | Final readthrough of final paper, check for grammatical issues, ensure all thoughts are complete | Confirm the accuracy of citations for our used resources and page organization/layout |

# 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. [21]". This is similar to the #1 IEEE Code of Ethics [22]. 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.

# 5 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]** "What is Power Over Ethernet (PoE) and what is it used for?" *versatek.com* [Online]. Available: https://www.versatek.com/what-is-power-over-ethernet/ [Accessed: 19-Feb-2019]

**[7]** "Radar Basics", Radartutorial.eu. [Online]. Available: http://www.radartutorial.eu/13.ssr/sr07.en.html. [Accessed: 20-Feb-2019].

**[8]** Mott, "Estimation of aircraft distances using transponder signal strength information", *Taylor & Francis*, 2018. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/23311916.2018.1466619 [Accessed: 20-Feb-2019].

**[9]** Sensor Systems Inc, "ADS-B/UAT S65-5366-895L", S65-5366-895L Datasheet [Accessed 21-Feb-2019].

**[10]** Eham.net. *3 Easy 1090MHz ADS-B DIY Antennas for Beginners*. [online] Available at: https://www.eham.net/ehamforum/smf/index.php/topic,112703.0.html [Accessed 21-Feb-2019].

**[11]** Balarad.net. (n.d.). *Coaxial Collinear Antenna for ADS-B*. [online] Available at: https://www.balarad.net/ [Accessed 21-Feb-2019].

**[12]** FlightAware Discussions. (2015). *Coaxial Collinear (CoCo) Antenna - Hyps & Facts.*. [online] Available at: https://discussions.flightaware.com/t/coaxial-collinear-coco-antenna-hyps-facts/17274 [Accessed 22-Feb-2019].

**[13]** MACOM, "Low Noise Amplifier, 700 MHz - 6 GHz," MAAL-011078 Datasheet [Accessed: 19-Feb-2019]

**[14]** TAI-SAW Technology, "Saw Filter 1090 MHz," TA1090EC Datasheet, [Accessed: 20-Feb-2019

**[15]** Analog Devices, "DC to 6 GHz, 45 dB Envelope Threshold Detector/Trigger," ADL5910 Datasheet [Accessed: 20-Feb-2019]

**[16]** "Technology FURUNO GPS/Multi-GNSS Disciplined Oscillator (GPSDO/GNSSDO)," *Dead Reckoning (DR) | Technology | GPS Receiver Chips & Modules | FURUNO*. [Online]. Available: https://www.furuno.com/en/gnss/technical/gnssdo. [Accessed: 22-Feb-2019].

**[17]** Texas Instruments, "Dual 16-Bit Binary Counters With 3-State Output Registers," SN74LV8154 Datasheet, Aug. 2004 [Revised Oct. 2015].

**[18]** "How to wire Ethernet Cables", Ertyu.org. [Online]. Available: https://www.ertyu.org/steven_nikkel/ethernetcables.html. [Accessed: 21-Feb-2019].

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

**[20]** Texas Instruments, "TLV7031 and TLV7041 Small Size, nanoPower, Low-Voltage Comparators," TLV7031 Datasheet, [Accessed: 20-Feb-2019]

**[21]** "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].

**[22]** "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].