S-Band Radar Altimeter

Project Proposal

ECE 445: Senior Design

Spring 2024

Team 18:
Elliot Rubin
Bobby Sommers
Rayan Nehme

TA:
Koushik Udayachandran

1. Introduction

1.1. Problem

Consumer drones often rely on GPS or IR sensing for navigation and terrain avoidance. GPS, while reliable outdoors, requires line of sight to the sky and will not function properly in highly urban environments or indoor spaces. IR sensing reliably works indoors or in confined spaces, but its performance quickly degrades with increased distance, surface reflectivity, and drastic light changes [5], among other conditions commonly faced by pilots. Alternative sensor technologies such as lidar or mmWave radar improve on these issues to some degree, but are prohibitively expensive for consumers and suffer from low maximum range.

1.2. Solution

Our solution implements a radar altimeter operating in the S-band (2.25 GHz - 2.5 GHz), which can be mounted on large consumer drones. The radar will use an internal microcontroller and frequency modulator to generate FMCW (frequency-modulated continuous-wave) pulses of variable bandwidth for different distances. On the receiver side, the radar will use a LNA, a mixer, and op-amps for the IF filter. For transmission and reception, the radar will rely on two small Yagi antennas. All parts are off-the-shelf discrete amplifiers, passives, logic components, etc.

Inside the radar, a mixer multiplies the transmitted and received signals to produce a difference signal, giving us information about the distance to the target (terrain). The distance is calculated using standard formulae for FMCW radars and is stored to an onboard SD card. To assess the precision and accuracy of the radar, an onboard barometric sensor will also be used and its data will be written to the SD card as well for post processing.

1.3. Visual Aid

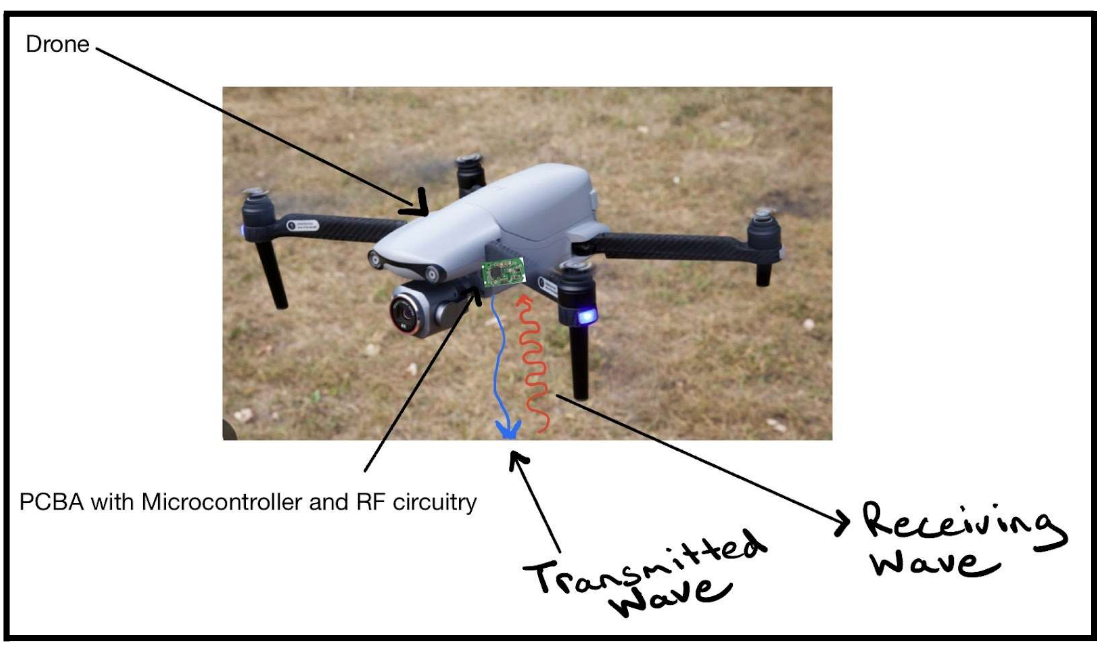

Figure 1: visual aid.

1.4. High-Level Requirements

- The radar must have a maximum range greater than 20 m. This means that the lower bound on our maximum measurement range is 20 m, not including range resolution.
- The receiver noise figure must be less than 10dB. This will more easily allow us to detect faint radar returns which undergo reflection and attenuation. As a result, the received signal quality degrades less and makes signal processing more straightforward.
- The radar must have a range resolution of 1.5m or better. As 1.5m is 7.5% of the 20m range spec, this will provide us with acceptable accuracy.

2. Design

2.1. Block Diagram

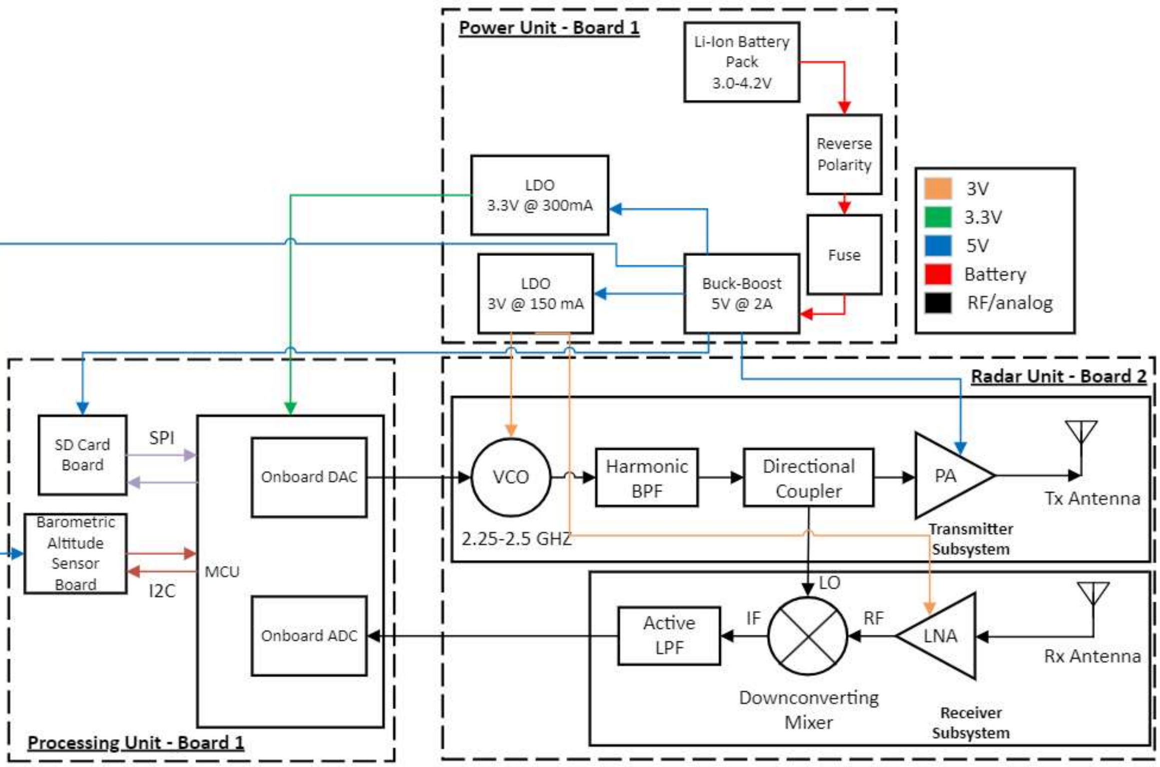

Figure 2: high level block diagram.

2.2. Subsystem Overview

Radar Unit	**Transmitter Subsystem:** This subsystem is responsible for generating and transmitting FMCW waveforms used in the radar. A VCO (voltage controlled oscillator), driven by a triangle wave from the microcontroller, creates an FM signal over a specified bandwidth from 100 MHZ - 250 MHz. This waveform is split off by a directional coupler to be used as the LO (local oscillator) in the receiver subsystem. Finally, a PA (power amplifier) amplifies the signal to be transmitted by the antenna. **Receiver Subsystem:** This subsystem is responsible for receiving and demodulating the reflected FMCW signal from the target. It consists of a LNA (low noise amplifier), a mixer, and an active IF (intermediate frequency) filter. The mixer LO port is driven by the transmitted signal to produce small sum and difference frequencies used in range calculation. The IF filter cleans the demodulated signal so it can be sampled by the microcontroller ADC without aliasing. Both of these subsystems are contained on a single radar board (board 1) separate from the other units.
Power Unit	The power unit subsystem will be responsible for distributing necessary power to the radar and processing unit. A lithium ion battery will be used to supply power to the entire system. A Buck Boost converter will take the lithium ion battery as an input and up-convert to 5v. We will take advantage of two LDOs (Low Dropout Regulator) to then deliver 3V at 150mA and 3.3v at 300mA to the radar unit and processing unit respectively. There will also be under voltage protection and fuse to provide protection to the circuit from the lithium ion battery.
Processing Unit	This subsystem is responsible for receiving a signal from a low pass filter and going to a microcontroller. The microcontroller contains an analog-to-digital converter within the chip. After the signal becomes digital, it will be used to calculate the height from the ground using the time shift. This information will then be transferred to an SD card using the SPI communication protocol. Included is also a barometric altitude sensor which gives the true height of the drone. This information will be transferred to the microcontroller using the I2C communication protocol.

2.3. Subsystem Requirements

Radar Unit	• The radar unit must consume fewer than 2W when in operating mode. This means that, altogether, both the receiver and the transmitter must not consume over 2W of power. We can verify this by using a power analyzer or a simple DC supply. • The VCO second harmonic must not exceed -20 dBc. This prevents a spur from being mixed into the received signal, interfering with range measurement. We will verify this using a signal analyzer in the lab. • The PA and LNA must be stable across the whole 2.25 GHz - 2.5 GHz operating band. This prevents oscillation and destruction of parts. We will verify this with a VNA in the lab.
Power Unit	• The power unit must include reverse polarity protection to prevent damage to power supplies, batteries, and other subsystems. • The power unit must contain a fuse which will open if over 2.5 A of current is flowing from the battery. • The power unit must contain undervoltage protection set at 3 V to prevent damage to the battery, which should nominally operate between 3 V and 4.2 V. • The DC-DC converter must be able to supply 5V with < 0.1 Vpp ripple at 2 A maximum current, so as not to damage dependent parts. • Both the 3.3V LDO and the 3V LDO must also be able to supply their respective voltages with < 0.1 Vpp ripple for sensitive analog parts. All of the above can be verified in the lab or with SPICE simulation.
Processing Unit	• The processing unit must have an error rate of less than 10% to be considered successful. An error will occur when the radar measurement is not within 5% of the barometric sensor reading. We will use the SD card to read radar measurements and barometric measurements for post processing.

2.4. Tolerance Analysis

Radar Noise and Range

The performance of the radar itself is limited by noise, antenna parameters, system losses, and radar cross sections, among other factors [4]. For this analysis, we will use the well-known radar equation [3], as well as system parameters, to construct a link budget for the radar.

$$P_r = P_t \frac{\lambda^2 G_t^2}{(4\pi)^3 r^4} \sigma_{RCS}$$

P_t : transmitted power
λ : wavelength
G_t : transmitting antenna gain (same as the receiving antenna gain)
r : range to target (same for transmit and receive)
σ_{RCS} : target radar cross section
We will rearrange this equation as follows [2], where P_r becomes P_{min} – the minimum detectable signal at the receiver. The antenna gains and operating wavelengths are assumed to be equal.

$$R_{\max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{P_{\min} (4\pi)^3}}$$

To find P_{min} , we consider the receiver noise floor, principally consisting of thermal noise. This can be expressed as kTBF, where k is the Boltzmann constant, B is the noise bandwidth (of one FFT bin), T is receiver noise temperature, and F is the total noise figure. Using the Friis cascaded noise figure equation $F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + ... + \frac{F_n - 1}{G_1 G_2 ... G_{n-1}}$ [7], we can calculate the total noise figure.

Component	
PSA-5453+ (LNA) [11]	Gain: 19.6 dB Noise figure: 0.7 dB
HMC213B (mixer) [10]	Conversion gain: -10 dB Noise figure: 10 dB
IF Amplifier/Filter [7]	Noise figure: 10 dB (conservative estimate based on thermal noise from input resistors)

Table 1: receiver component specifications.

For an IF amplifier/filter noise figure of 10 dB, the total noise figure comes out to be ~3.76 dB using the Friis equation. An even more conservative estimate of 15 dB would yield a noise figure of ~6.76 dB, which still meets the spec. In this case, it would be beneficial to place another LNA in the receiver to minimize the impact of the op-amp [2], [8]. In total, the noise floor (from kBTF) evaluates to -147.2 dBm using the most conservative op-amp noise figure of 15 dB.

The maximum detectable range is then calculated with an antenna gain of 6 dBi (conservative for Yagi or horn) and a wavelength of 12.5 cm for 2.4 GHz. A table from [6] shows the RCS distribution in dB for linearly polarized radiation incident on soil and rock, which can be used to calculate the minimum range.

Statistical Distribution Table for **Soil and Rock Surfaces**

S Band, **HH** Polarization

Angle	N	σ^o_{max}	σ^o_5	σ^o_{25}	Median	σ^o_{75}	σ^o_{95}	σ^o_{min}	Mean	Std. Dev.
0°	264	20.1	16.7	7.2	1.7	-3.0	-8.1	-11.3	2.6	7.5
5°	186	12.4	7.5	4.0	0.3	-4.9	-10.1	-14.7	-0.4	5.7
10°	442	6.0	3.3	-0.5	-3.6	-7.2	-12.5	-16.0	-3.9	4.7
15°	361	5.3	-0.1	-2.6	-5.4	-9.5	-14.1	-19.4	-6.2	4.5
20°	442	0.9	-2.0	-5.8	-8.8	-12.0	-16.2	-21.5	-9.0	4.5
30°	264	0.8	-2.9	-8.8	-12.7	-15.4	-20.6	-25.5	-12.2	5.1
40°	82	-5.3	-9.0	-11.6	-14.3	-20.2	-26.0	-29.2	-15.8	5.7
50°	16	-15.0	-16.4	-18.0	-18.9	-21.3	-22.1	-22.4	-19.2	2.2

S Band, **HV** Polarization

Angle	N	σ^o_{max}	σ^o_5	σ^o_{25}	Median	σ^o_{75}	σ^o_{95}	σ^o_{min}	Mean	Std. Dev.
0°	258	-1.7	-5.2	-10.6	-14.8	-18.8	-22.9	-25.5	-14.5	5.5
5°	181	-6.7	-11.9	-14.0	-16.9	-22.1	-25.3	-28.8	-17.8	4.6
10°	311	-8.7	-14.1	-17.1	-19.8	-23.8	-27.3	-31.1	-20.3	4.2
15°	275	-14.5	-16.0	-19.2	-22.6	-25.5	-30.2	-36.0	-22.6	4.3
20°	393	-8.9	-15.6	-20.0	-23.2	-26.2	-30.2	-36.4	-23.1	4.6
30°	264	-8.7	-16.0	-19.7	-25.4	-28.6	-34.0	-38.6	-24.7	5.7
40°	80	-9.9	-15.6	-19.9	-23.8	-29.8	-36.1	-40.3	-24.9	6.7
50°	14	-25.9						-35.3	-31.7	2.7

S Band, **VV** Polarization

Angle	N	σ^o_{max}	σ^o_5	σ^o_{25}	Median	σ^o_{75}	σ^o_{95}	σ^o_{min}	Mean	Std. Dev.
0°	264	19.7	16.2	7.2	1.0	-3.1	-8.1	-11.7	2.4	7.5
5°	186	11.7	7.4	3.2	0.0	-5.6	-10.0	-14.2	-0.9	5.7
10°	441	6.2	3.1	-0.4	-3.8	-7.3	-12.5	-16.9	-4.0	4.7
15°	362	4.9	-0.1	-2.7	-5.4	-9.8	-14.3	-20.1	-6.4	4.7
20°	442	1.5	-1.9	-5.7	-8.6	-12.2	-16.6	-23.3	-9.0	4.6
30°	263	0.8	-3.1	-8.8	-13.5	-16.3	-20.3	-24.1	-12.6	5.2
40°	82	-3.4	-8.0	-10.4	-14.3	-17.6	-23.4	-26.0	-14.2	4.9
50°	16	-10.0	-13.5	-16.9	-18.5	-19.7	-20.8	-21.8	-17.8	3.0

Table 2: RCS [dB] model for S-band linearly polarized radiation incident on soil or rock.

We will use an output power of 20 dBm (100 mW) which accounts for cable and PCB loss and can evaluate the minimum and maximum ranges for linear polarization (HH/VV) in Python.

```
max range hh:  166.2553229669458
min range hh:  25.87598040821954
max range vv:  162.47088978532884
min range vv:  25.28697118363547
system nf:  6.768685611440928
```

Figure 3: Python script output showing worst-case system NF and maximum ranges.

The evaluated result shows that, for the worst RCS at 0° incidence and the worst op-amp noise figure of 15 dB, the minimum ranges for horizontal and vertical polarizations are 25.88m and 25.29m, respectively.

Radar Range Resolution

Our design specification stipulates that the range resolution of the radar must be 1.5m or better. Since our VCO can sweep from 2.25 GHz to 2.5 GHz, we can say that the best range resolution can be achieved with the maximum bandwidth of B = 250 MHz. We can use the FMCW range resolution equation $S_r = \frac{c}{2B}$ to verify this [1], [9]. With the maximum bandwidth, our range resolution is 0.6m. If we restrict the bandwidth to 100 MHz, the range resolution degrades to 1.5m – the worst allowable. We will operate the radar at ≥ 100 MHz bandwidth as a result.

3. Ethics and Safety

When developing an S-band radar altimeter for drone height detection, several ethical and safety considerations must be addressed. These considerations encompass both the development process and the potential misuse of the technology.

A significant concern relates to measurement accuracy, and the implications of the radar's measurements. Inaccurate height measurements could lead to dangerous decisions based on erroneous data. In extreme cases, inaccurate altitude data could cause injuries and destruction of both the radar and the drone. This is a potential conflict with section 1.2 in ACM's Code of Ethics [13], which mandates engineers to avoid harm wherever possible. To mitigate this, we will validate and calibrate the radar altimeter to ensure accurate height measurements. We will ensure that users understand that the altimeter may produce inaccuracies, and to use proper judgment when flying.

Similarly, our use of a Lithium-based battery comes with safety implications. If users are harmed by a fault in the battery system, we would be in violation of section I-1 of the IEEE Code of Ethics [12], which mandates engineers to disclose hazards and protect the health of the public. Our design includes battery undervoltage and overcurrent monitoring so as not to cause dangerous damage to the battery or the radar itself.

Finally, in the development of prototypes or experimental hardware such as our radar, it is critical that our team is open to extensive review of our design. This is directly pursuant to section I-5 of the IEEE Code of Ethics, which mandates that we accept constructive feedback and make informed design choices based on all available data [12]. In order to stay in accordance with I-5, we will seek out design feedback from instructors, students, and professional connections. To make justifiable design decisions based on data, we will use simulation tools and academic resources to validate our design process.

References

[1]“Radar Basics,” Radartutorial.eu, 2019. https://www.radartutorial.eu/02.basics/Frequency%20Modulated%20Continuous%20Wave%20Radar.en.html

[2]H. Forstén, “Third version of homemade 6 GHz FMCW radar,” Henrik’s Blog, Sep. 28, 2017. https://hforsten.com/third-version-of-homemade-6-ghz-fmcw-radar.html (accessed Feb. 08, 2024).

[3]E. Kudeki, “ECE 350 Lecture Notes,” https://courses.engr.illinois.edu/ece350/ece350lecture_notes_ver2024.pdf, 2023. https://courses.engr.illinois.edu/ece350/ (accessed Feb. 08, 2024).

[4]S. Frick, “RADAR ALTIMETERS OVERVIEW OF OPERATION, DESIGN, AND PERFORMANCE,” 2021. Accessed: Feb. 08, 2024. [Online]. Available: https://avsi.aero/wp-content/uploads/2021/12/Radar-Altimeter-Overview-of-Design-and-Performance.pdf

[5]“User Manual,” DJI. Available: https://dl.djicdn.com/downloads/DJI_Mini_2/20210630/DJI_Mini_2_User_Manual-EN.pdf

[6]F. Ulaby, M. C. Dobson, and J. L. Álvarez-Pérez, Handbook of Radar Scattering Statistics for Terrain. Artech 2019, 2019.

[7]S. Franke, “ECE 453 Wireless Communication Systems,” https://courses.engr.illinois.edu/ece453/fa2023/secure/supplementary_notes/ECE453Notes_SP19.pdf, (accessed Feb 08, 2024).

[8]J. Karki, “Calculating Noise Figure in Op Amps,” 2003. Accessed: Feb. 08, 2024. [Online]. Available: https://www.ti.com/lit/an/slyt094/slyt094.pdf

[9]I. Rosu and F. Rosu, “S-Band 2.4GHz FMCW Radar.” Accessed: Feb. 09, 2024. [Online]. Available: https://www.qsl.net/va3iul/Radar/S-Band_2.4GHz_FMCW_Radar/S-Band_2.4GHz_FMCW_Radar.pdf

[10]“HMC213B Datasheet,” Analog Devices, Feb. 2018. Accessed: Feb. 09, 2024. [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/hmc213b.pdf

[11]“Monolithic Amplifier PSA-5453+,” Mini-Circuits. Accessed: Feb. 09, 2024. [Online]. Available: https://www.minicircuits.com/pdfs/PSA-5453+.pdf

[12]IEEE, “IEEE Code of Ethics,” ieee.org, Jun. 2020.
https://www.ieee.org/about/corporate/governance/p7-8.html

[13]ACM, “ACM Code of Ethics and Professional Conduct,” Association for Computing Machinery, Jun. 22, 2018. https://www.acm.org/code-of-ethics