Low-Cost Passive Aircraft Detection System & Super Resolution Imaging Device

A means to do surveillance and increase security for less!

Group 2

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Chapter 1: Executive Summary

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Chapter 2: Project Description

2.1 Motivation & Background

RF Device

Along the borders of many different countries, it is very hard for radar and air traffic controllers to detect aircraft. The reason being that it is generally far too expensive for many countries to place large high-power radar systems all over their country. These systems can cost tens of millions of dollars and require advanced infrastructure to implement. As a result, certain locations become dead zones, areas where there are no effective means of surveillance. These so-called “dead zones” make it very easy for illegal activity to happen such as illegal immigration, drug smuggling, or drone surveillance. Not only that, these aircraft may not be using a transponder of any form in order to avoid detection from air traffic control or similar systems. Naturally, this makes it an issue for governments all over the globe. Our project aims to provide a cost-effective and stealthy solution in an effort to help increase security and give governments the peace of mind they are seeking.

As aspiring engineers, senior design projects are a cornerstone of our education and provide several key benefits which include but are not limited to, hands-on application of knowledge, real world problem solving, collaboration and teamwork, and portfolio development. As a group, we must learn to problem solve underpressure, work as a collective unit toward a common goal, and design and showcase a functional product using an innovative approach. With that said, we wanted to work on a project that addressed a significant, real-world challenge.

We knew we had an incredible opportunity before us and a chance to solve a real world problem that incorporated our unique skills and expertise. This problem was introduced to us by Roy H. Wubker Jr. who, through the Department of Defense’s Southern Command (SOUTHCOM) is sponsoring this project. Based on the introduction from our sponsor we knew we had an incredible opportunity before us and a chance to solve a real world problem that incorporated our unique skills and expertise. Our sponsor's initial recommendations for solving this problem involved RF detection which led us to brainstorm more ideas, especially those that involved optics and photonics.

This problem poses many challenges but has widespread impact which is why our group decided to take on this project. From this project, we will learn about how to implement a solution to this kind of system and optimize the strengths of our solution. Our group will try to make our solution as low cost as possible and, simultaneously, as stealthy as possible. The harder it is to detect, the longer our proposed solution can relay vital information. Longevity in this case, will also help keep the replacement cost down.

Active radar is a modern radar technique that is used all over the globe to track the direction, altitude, and speed of airplanes. It works by sending out a Radio Frequency beam from an antenna to the desired target direction; The RF beam bounces off of the desired object and then makes its way back to the antenna which is listening for the reflection. Based on the time-of-flight of the signal, it can determine how far the object is, its speed, direction, and more.

Our solution, however, will be to use passive radar. This will not only lower the cost but it will also provide a more simplistic solution as compared to an active radar counterpart. Passive radar works by instead of sending out a beam of RF energy, which requires lots of power, space, and infrastructure, it uses existing RF signals in the environment, and listens for those RF signals to bounce off of the desired object. RF signals in the environment appear in the form of things like FM Radio, GPS, or even the natural resonance of an airplane's motor. By only listening to the radio signals that are reflected off of the object, the amount of power consumed will be cut down. Furthermore, the system will be much harder to find as there was no RF beam emitted from the system to be tracked by enemy countermeasures. It will essentially be completely hidden to any aircraft.

Camera Array

High-resolution imaging plays a vital role in applications such as aerial surveillance, environmental monitoring, and remote sensing. Traditional imaging systems capable of capturing fine details at long distances rely on high-performance cameras, which often cost upwards of $10,000. This high cost limits access to advanced imaging technology, particularly for smaller research teams and organizations with budget constraints. To address this issue, we propose a cost-effective alternative by utilizing an array of low-cost cameras to generate high-resolution images comparable to those of expensive imaging systems.

The key innovation of this project lies in the application of super-resolution techniques to combine multiple low-resolution images into a single, high-resolution output. This technique enhances object detection capabilities by increasing image detail and clarity, making it particularly beneficial for tracking small and distant objects such as aircraft or wildlife. Once a high-resolution image is generated, a detection algorithm will be applied to identify and analyze objects within the image. This detection performance will then be compared to results obtained using a standard, non-super-resolution image to evaluate the effectiveness of our approach.

Super-resolution is a computational imaging technique that reconstructs a high-resolution image by integrating multiple lower-resolution images. This approach is particularly advantageous in applications where imaging sensors are limited by physical constraints, such as cost, size, or atmospheric interference. By increasing image clarity, super-resolution allows for enhanced feature extraction, improving object recognition and detection accuracy.

In many real-world applications, such as aircraft detection in aerial reconnaissance, objects appear small relative to the overall image. Standard low-resolution cameras may struggle to detect these distant objects due to pixelation and loss of fine detail. Super-resolution reconstruction mitigates this issue by restoring edges, textures, and small-scale features that might otherwise be lost in individual low-resolution images. This enhanced resolution facilitates more reliable object detection, especially in scenarios where small details differentiate targets from their surroundings.

To evaluate the effectiveness of super-resolution in object detection, we will compare detection performance between super-resolution images and non-super-resolution images. A trained detection algorithm, such as a convolutional neural network (CNN) or machine learning-based object recognition system, will be applied to both image sets. Key performance metrics, including detection accuracy, false positives, and processing speed, will be analyzed to determine the impact of super-resolution on object identification. By systematically testing the system with and without super-resolution, we can quantify its benefits and assess whether it significantly improves detection capabilities in challenging imaging environments.

The effectiveness of our super-resolution system heavily depends on the arrangement of the camera array. The optimal configuration must balance coverage, alignment precision, and computational feasibility. A curved camera array offers significant advantages by ensuring that each camera is directed toward a common focal point, reducing parallax errors and simplifying image stitching. However, alternative configurations, including rectangular, circular, and elliptical layouts, will also be explored to determine the most effective design. The final configuration will be chosen based on its ability to minimize distortions and maximize image quality.

Another critical factor in our setup is camera synchronization. Since the system will capture images of moving objects, it is essential that all cameras take their images simultaneously. If there is a significant delay between exposures, objects may shift positions between frames, causing misalignment in the final composite image. This issue can lead to ghosting artifacts or detection errors, particularly in applications such as tracking aircraft or monitoring fast-moving vehicles. To prevent this, hardware and software synchronization techniques will be implemented to ensure that all cameras capture frames at the exact same moment.

Additionally, each camera in the array will be equipped with specialized lens systems tailored for specific imaging tasks. A combination of telephoto, wide-angle, zoom, and fisheye lenses will be employed to enhance coverage and resolution. Telephoto lenses will be used to capture fine details in distant objects, while wide-angle and fisheye lenses will provide broader context. This multi-lens approach ensures that the final composite image benefits from both high detail and wide coverage.

Atmospheric turbulence and environmental factors, particularly in Florida's humid climate, introduce distortions that degrade image quality. Over long distances, heat waves and varying air densities cause light to refract unpredictably, resulting in blurring and loss of detail. To mitigate these effects, the system will incorporate phase corrector plates and computational wavefront correction techniques. Phase corrector plates work by introducing an optical element that compensates for wavefront distortions before the light reaches the sensor. These plates can be custom-designed to correct for specific atmospheric aberrations encountered in our imaging environment.

The final stage of the project involves analyzing the effectiveness of super-resolution in object detection. A trained detection algorithm will be applied to both the super-resolution and non-super-resolution images, and the results will be compared across multiple test scenarios.

One key metric to evaluate will be detection accuracy, which measures how effectively objects are identified within each image type. Higher-resolution images should theoretically allow the detection algorithm to recognize smaller or partially obscured objects that might be missed in standard images. The impact of resolution enhancement on false positive rates will also be analyzed, ensuring that the system does not introduce additional noise or artifacts that could interfere with object classification.

Additionally, we will examine computational efficiency—while super-resolution processing enhances image quality, it also introduces additional processing time. It is essential to determine whether the improvements in detection accuracy justify the computational overhead, particularly in real-time applications such as surveillance or aerial monitoring. This analysis will help optimize the trade-offs between image enhancement and system performance, ensuring that the final implementation remains practical for real-world use.

By systematically comparing the performance of super-resolution and non-super-resolution images, this project will provide valuable insights into the benefits and limitations of this approach. If the results demonstrate a significant improvement in detection accuracy, it would validate the feasibility of using low-cost camera arrays as an alternative to expensive high-resolution cameras.

The development of a cost-effective super-resolution imaging system has significant implications for various fields. In aerial surveillance, such a system could enable more precise tracking of airborne objects, improving situational awareness for both civilian and military applications. In environmental monitoring, it could help researchers track wildlife populations, analyze deforestation patterns, or assess the impact of climate change. Additionally, in disaster response, high-resolution imaging from affordable drones could assist emergency teams in damage assessment and resource allocation.

Beyond immediate applications, this project lays the groundwork for future advancements in scalable imaging systems. By demonstrating that high-resolution imaging can be achieved using low-cost components, this research could pave the way for autonomous vehicle vision systems, space-based imaging, and next-generation remote sensing technologies. As computational imaging techniques continue to advance, the principles established in this study could be expanded to even more sophisticated imaging applications.

In conclusion, this project seeks to bridge the gap between affordability and performance in high-resolution imaging. By leveraging a camera array, super-resolution algorithms, and object detection analysis, we aim to demonstrate that cost-effective imaging systems can achieve results comparable to expensive commercial solutions. If successful, this project could contribute to a broader adoption of advanced imaging technologies, making high-resolution surveillance, monitoring, and research more accessible to a wide range of industries.

2.2 Existing Products & Related Works

2.2.1 Hensoldt TwInvis

The TwInvis system by Hensoldt is a passive radar that leverages signals in the environment, such as those from FM radio, digital television, or mobile communication devices. It does not emit any signals itself, making it undetectable by traditional radar-detection systems. The TwInvis system monitors reflections of the aforementioned signals off objects, including aircraft, to detect and track their movement. TwInvis passively listens to ambient RF signals emitted by sources in the area, processes how they bounce off objects in the environment, and with an array of these devices, can determine the speed and trajectory of the aircraft.

This technology is very similar to the solution we are proposing and can be applied in stealth aircraft detection, civil air traffic monitoring, and even compliments active radars when integrated with military systems. Since it does not emit its own signals, it avoids detection and interference from hostile forces and makes use of already existing infrastructure which simultaneously allows for wide regional coverage in areas dense with RF signals. However, in areas in which the density and quality of ambient RF signals is poor, this technology is not of much use. In addition, this system requires advanced algorithms to separate useful data from just noise, which increases computational demands.

A key difference between the TwInvis and our proposed solution is the integration of optical components. TwInvis can only function in areas where RF signals are dense enough and only works using RF detection. Our project incorporates an optical component in the form of an infrared camera. This approach can provide a more complete picture of the environment that is being monitored. By implementing an optical component, we can introduce a sort of 2-step verification system to reduce false positives and provide more accurate results. Not only that, capturing video of the aircraft could help the user determine the threat level and could clue the user into the intentions of the aircraft entering their airspace.

2.2.2 Thales Elvira

The Elvira system by Thales is a multisensor electronic support system designed for detection, classification, and tracking of aircraft. It integrates RF signal detection with additional tracking systems, such as optical or infrared sensors. This approach provides a holistic view of the airspace. Elvira detects emissions from communication devices, radars, or other onboard systems of aircraft. It then correlates RF data with other inputs, such as infrared tracking, to improve target identification and accuracy. In a broader sense, Elvira can use advanced algorithms to analyze emission types, origin, and even determine threat level.

This system is ideal for border surveillance as it operates covertly without filing flight plans or transponders. It can also be integrated into ground stations or shipboard systems to enhance situational awareness. By integrating multiple sensors, it is able to minimize false positives and improves tracking in challenging environments. The issue is the cost. The integration of advanced sensors and processing units makes it very expensive to both deploy and maintain. Since the main method of gathering data is the RF system, it could be susceptible to jamming or other countermeasures. In addition, the system is not simple and would require specific training to be effective.

This system, although more complex, does have many similarities to our proposed solution. Both the Elvira system and our project work based on already available RF signals in the area. Using the already existing infrastructure of radio towers, television stations, and mobile devices is a great way to maintain stealth while obtaining the information you seek. However, Elvira systems main trigger is based on RF detection with the secondary trigger being the infrared search and track system. Our project aims to use the RF detection method as the main trigger and the infrared camera system as a means to verify the detected anomaly. With this approach, we could reduce the power consumption of the device which would make for a more effective system overall.

2.2.3 Dedrone RF-300

The Dedrone RF-300 is a passive network-attached radio frequency (RF) sensor designed to detect, classify, and locate drones and their remote controls. It is capable of detecting consumer, commercial, and hobbyist drones by analyzing the RF signals they emit. While primarily focused on drone detection, its capabilities can extend to other aircraft emitting RF signals.

Some key features of this system are the ability for the RF-300 to identify communication between drones and their controllers including both Wi-Fi and non-Wi-Fi drones. It classifies drones by their manufacturer, model, and unique ID. Through internal digital signal processing, the RF-300 is also able to determine the direction of signals from drones and pilots. With multiple RF-300 units, it can triangulate and pinpoint the exact location of both the drone and its operator. Each RF-300 sensor covers a 120-degree area, requiring 3 units to achieve a full 360-degree coverage zone. The typical detection range is up to 1000 km, which can be extended to 1500 km under ideal conditions. The system is also built for extreme environments and can operate between -20 degrees to 55 degrees Celsius. Finally, to power the device, it must be connected via ethernet connection.

In addition to the key features listed, the RF-300 integrates with Drones DroneTracker software, a platform that aggregates and analyzes data from multiple sensors to provide comprehensive airspace security. The integration of this software enables real-time monitoring and alerts and when paired with a camera, offers advanced video analytics to enhance detection and tracking capabilities. The software can catalog all alerts, flight paths, and video footage of drone threats, which can be easily exported. Moreover, the software incorporates a classification engine that recognizes drones of all types. The system makes use of a sophisticated machine learning system trained on millions of data points.

This product, while much more advanced, has many similar components and restrictions as our project. One key thing to notice is that multiple units of the RF-300 are required to have a complete view of the airspace in question. Not only that, multiple units are required in order to determine crucial information like speed and direction of travel. One of the main goals of our project is to eventually be able to detect those key parameters so we have to keep in mind that we'll need multiple units to be able to do that. We also do not have the software, nor the capabilities to re-produce a similar piece of software so our project will mainly focus on detecting aircraft rather than classifying them. Eventually, a database could be implemented with software that could reference previous images and detection signals.

2.2.4 Summary

Overall, there is a lot of insight to be gained from the systems that exist already today. Given that RF technology has been around for a while, we can see many different interactions of RF detection implemented to many detection systems already due to its stealth capabilities and relative simplicity. Most of these systems also require multiple units to determine localization information. Our project will likely also need to incorporate that if we hope to get accurate location readings. In most cases, we see that RF detection, if enhanced with an optic, usually involves infrared imaging. While IR allows for a more detailed view, it is still susceptible to environmental factors such as rain. For this reason, we chose to use visible light rather than IR. This will prove to be cheaper and will allow for better imaging during the day and can be optimized for different weather conditions in the future. Most of these systems also feature some sort of pan-tilt motor setup to move the camera in the direction of the aircraft. This proves to be a difficult addition and makes things much more complex, especially since our group does not feature a mechanical engineer. For our solution, we aim to only include one mechanical system which will mainly focus on shifting the lenses in the telephoto lens system. This will keep things much simpler and will keep total cost down for the optical enhancement.

2.3.1 Goals & Objectives

RF Device Basic Goals

- Build a unit of similar ability to the ones discussed at a very low cost
- The successful detection of a metal sphere using passive detection. The reason for a metal sphere is due to its ease of detection by radar.
- Measure antenna radiation pattern and classical range measurement.

RF Device Advanced Goals

- The system should be able to detect an aircraft in flight. This will prove that our passive detection system is working as intended.
- The system should be self-sustaining. If the system were to be deployed in the field, it should be able to provide its own power. This may be done via solar, wind, or other types of power generation depending on the deployment location.
- The time it takes to deliver the information from the system to the user should be relatively quick. This will ensure that our system is actually viable and worth implementing.

RF Device Stretch Goals

- The system will be easily implemented and easily manufacturable. The main goal of this project is to provide a low-cost solution which means ease of use and construction is important to consider.

- The system should be connected with other systems to form an array. This will allow for accurate localization and will help the user determine the speed, direction, and location of any aircraft within the detection distance.
- The system should be completely autonomous. This will allow the user to “set it and forget it” and will alert them of possible incursions within their airspace.
- The system should incorporate a false alarm feature.
- Create or utilize a database that can characterize aircrafts and identify the type of plane or drone that is entering the range of the antenna. The system should have the ability to easily install and uninstall enhancements depending on the user's needs. This will be vitally important when it comes to selling the unit. Depending on the user's needs or surrounding environment, they may or may not want certain add-ons or enhancements.

Camera Array Basic Goals

- Arrange 3 low cost cameras in an array configuration.
- Capture an image at a distance of 1, 10, and 20 meters and effectively enhance the resolution of the image using image processing techniques.
- Design a simple and stable configuration for the cameras.
- Find the simplest way to connect the cameras together to the main computer so that image processing may be done.
- Use code to do image processing and to create a super resolution image.

Camera Array Advanced Goal

- Design lens systems such that a very wide view, wide view, and telephoto lens system are able to be applied to the camera array.
- Enhance our 3 cameras with lenses that will help the process of super resolution effectively.
- Capture multiple images of a drone or other object through our camera array and use image processing techniques to create a super resolution image that may be run through a detection program/software.
- Design a way to place the lenses in front of the cameras and ensure proper optical alignment.

Camera Array Stretch Goals

- Design multiple, easy to install, lens systems that can be used depending on the desired image capture distance.
- Design a sturdy, stable, and environmentally protected housing for the entire device.
- Design a connecting unit that allows the unit to be attached to a vehicle, such as an airplane, for mobile image capture.
- Design a housing for the lens system that allows for easy swapping in case the object is at a different distance.

- Incorporate a phase correction plate to account for any aberrations due to the environment.

2.3.2 Objectives

RF Device Objectives for Basic Goals

- Research, select, and buy quality and cost effective materials and components to create the device
- Ensure proper calibration of spectrum analyzer
- Test all components once they have arrived to ensure they function properly.
- Measure range of detection by using a second antenna.
- Use a second antenna to find the effective beam pattern of the antenna.

RF Device Objectives for Advanced Goals

- Create an algorithm that differentiates noise from aircraft.
- Test the prototype at Dade Collier Airport to see if we can detect passively
- Research means to power the unit autonomously and integrate it (phase 2)
- Test the amount of computer power and latency to process data.
- Increase efficiency of detection algorithms to decrease power draw.

Camera Array Objectives for Basic Goals

- Research and purchase low cost, low resolution cameras to include in the array and ensure they can easily be integrated with our devices.
- Test multiple array configurations and shapes and observe which configuration and camera spacing results in the best image after image stitching.
- Use wood, cardboard, or foam to put the camera array on so we can ensure that they are aligned properly and stable.
- Connect the cameras to a computer via a USB connection.
- Write and test code using python to do image processing techniques and create a higher resolution image out of the many that were captured.
- Use Zemax to design a lens system that will allow for quality image capture at 100 yards and account for possible aberrations that we may encounter.

Camera Array Objectives for Advanced Goals

- Purchase more of the low cost, low resolution cameras to arrange into a larger array configuration.

- Research a way to effectively connect all the cameras into a more cohesive system.
- Use the sign outside of the L3 Harris building on campus to test our camera array at a distance of 100 yards and see if we can produce a more clear image at that distance.
- Based on the separations of the cameras in the array, design a housing for multiple lens systems that can be easily attached to the array and are properly aligned.
- Research and work with CREOL professors to understand how a phase correction plate works and how to properly incorporate it into our design to produce the best possible image.

2.4 Features & Functionalities

RF Device

The unit is designed for those who purchase it to be able to detect aircraft via the passive detection of waveforms rather than via an active radar. They want it to be able to detect aircraft in radio and radar “dead zones” which have no active radars to detect aircraft, as well as no nearby infrastructure that would be able to detect aircraft in other ways. A common example of this would be an airplane that illegally passes through borders by flying into dead zones that don’t have radars to detect it, or by flying under the radars that would normally be able to actively detect it. This unit should be able to passively detect any such aircraft and with the use of multiple, be able to make an array of them that can be used to triangulate the position of any such aircraft based on the signal strength picked up by each of the devices in a way that can be shown on a phone or computer via starlink. Furthermore it has been requested that the data be livestreamed so that people can take appropriate action based on the data found.

Camera Array

The camera array device will allow the user to capture an image at a desired distance and be able to discern higher amounts of detail compared to that of a lower resolution image, that is typically only able to be done by very expensive cameras. Our device, since it will be made up of cheap cameras and affordable lens systems, will allow for clarity at a cheaper cost. The design is also meant to be scalable which will allow for even more precision and clarity depending on the user's needs. By its nature, the array will be able to capture a wide field of view while maintaining its high pixel density through image fusion. With the configuration, blind spots are also eliminated which also allows for a much clearer image. With a larger amount of cameras in the array, it may also be possible to estimate depth which is vital when it comes to surveillance scenarios. Additionally, the device uses off the shelf components which verifies that ITAR restrictions are met. Finally, due to the systems design, the device has a natural fault tolerance meaning that if a camera happens to stop working, the remaining cameras could still produce the desired outcome with a lesser quality.

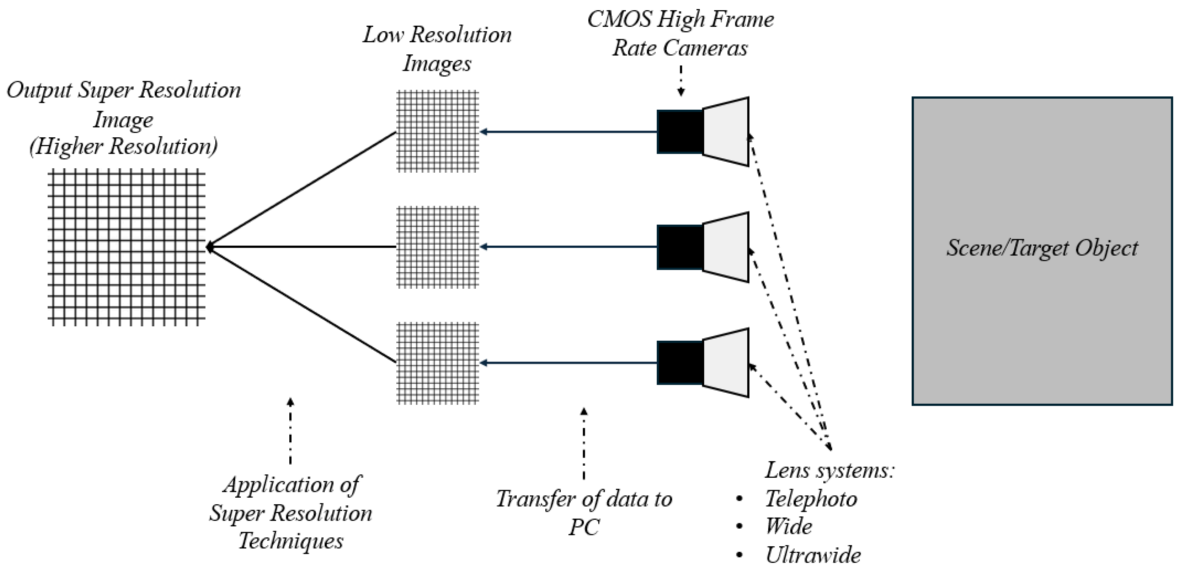

Figure XXX *Schematic diagram of camera array system*

In the figure above, the process of producing the super resolution image is shown. First the cameras, depicted by the black boxes, with their respective lens systems, capture the desired scene individually. The chosen lens systems were adopted from the iphone and other mobile phone cameras that feature 3 cameras with similar lens systems. In this case, it would most likely be a drone or aircraft that is in flight, not close to the cameras. This would be the ideal case to minimize motion blur which will help when using detection software later on. Once the images are captured, they are transferred to a pc so the image processing and fusion train can begin. In this phase, the low resolution images go through our specially designed super resolution code and then produce a single high resolution image at the output which is the super resolution image. Since this image has more detail than the low resolution images, when it is run through a detection software, it will ideally reveal the desired target object more effectively since the edges of the target are more well defined.

2.5 Engineering Specifications

Below are some specifications that were derived with the consideration of our project objectives, constraints and limitations of other similar products and projects, and quality versus cost analysis. The tables are also split into categories, namely those for the RF device and those for the camera array device.

Table 2.5.1 Prototype Specifications ~~and Features~~

Parameter	Specification
Signal receive and detection time	**5 min or less**
Airspace coverage	10-12 miles at 12,000 feet
Wide frequency detection range	300MHz to 3GHz
Detection Range	50m to 50km
Detection Accuracy	RCS ≥ 3m^2
Size	<1m^2
Cost	<$6500

Table 2.5.2 Unit Components Specifications

Component	Parameter	Specification
Log Periodic Antenna	Antenna radiation pattern	180 degrees
Battery	Power	>600W
Spectrum Analyzer	Dynamic range	-158dbm to 10dbm
Android Phone	Power consumption	<10W
Portable solar panel	Power	>60W

Table 2.5.3 Camera Array Design Components Specifications

Component	Parameter	Specification
Camera(s)	FOV Pixel Count Frame Rate	110 degrees 3MP 15 fps
Camera Array	**Effective FOV** **Image Overlap**	**150-180 degrees** **~20-30%**
Post Fusion Image	**Pixel Density**	**At least 10 pixels/cm at 10 meter**

Lens System	Focal Length Aperture	~50-75 mm f/2.8 - f/4.0
Entire Unit	Weight Operating Temperature	Less than 5 kg 10-30 degrees Celsius

2.6 Hardware Block Diagram

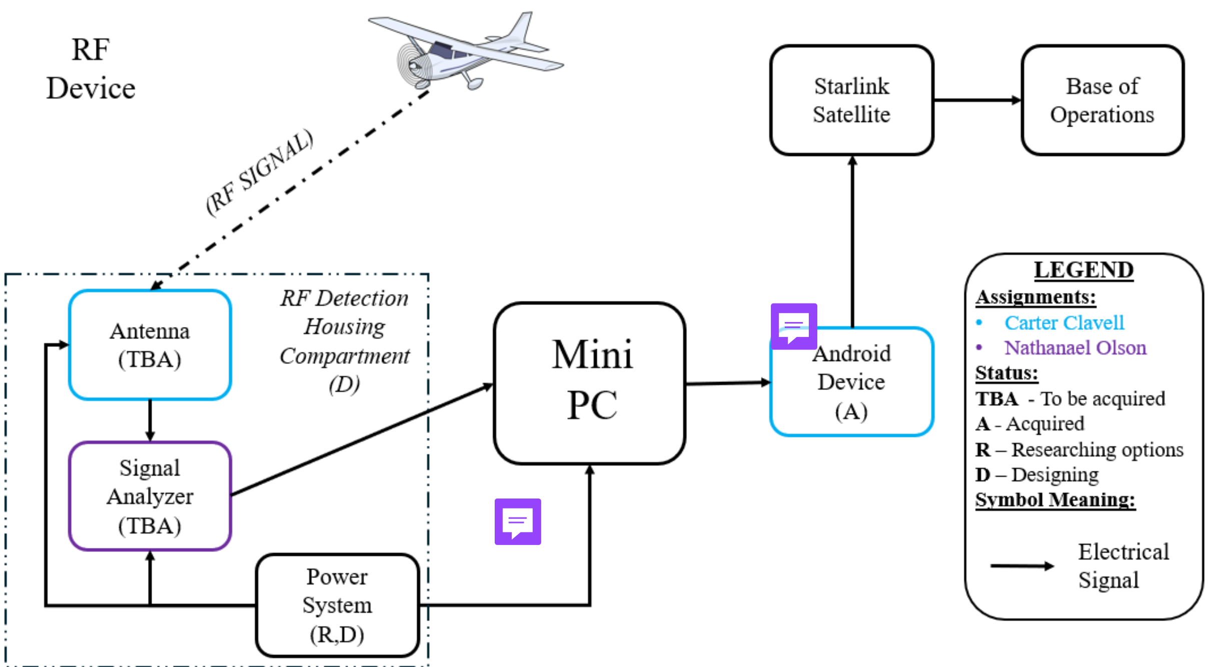

Figure XXX Hardware Block Diagram (Note: Still being worked on!)

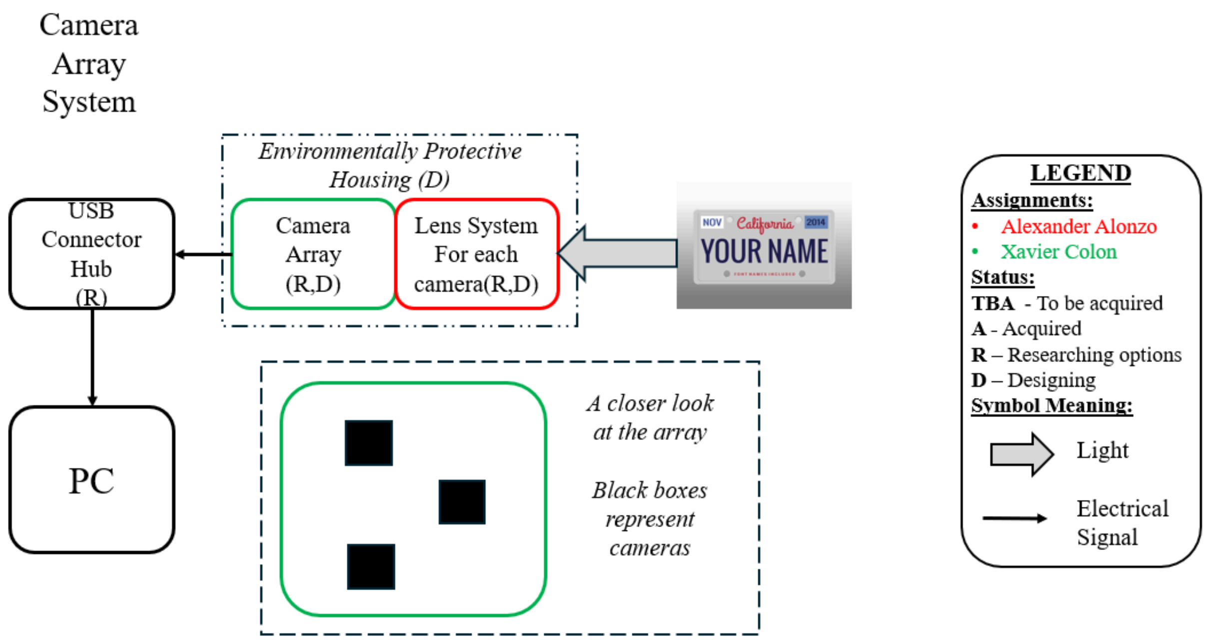

Figure XXX Optical System (Extension of Figure 6.1) (Note: Still being worked on!)

The hardware diagrams above illustrate some of the basic components that our project will implement and whose responsibilities they are. Further additions, either by our sponsor's request or by other groups on this project that are not in our senior design section may need to be accounted for. In the first diagram, a plane is depicted with its RF signal being emitted. That signal is captured by our antenna and is interpreted through our spectrum analyzer device. After that, the information from the spectrum analyzer is transferred to the mini pc where the computer science team takes over to transfer the data to the user. While the final idea is to implement this device in a low RF noise environment, for our phase of this project we will focus on detecting a signal from the target to prove our idea works. We currently do not know if other divisions, like the computer science team, will need different hardware parts or housing units yet. Moreover, the PCB requirement from senior design was voided for this project which is why it is not illustrated in the diagram.

The second diagram serves as an optical system schematic and shows how the optical systems interact. A closer look at the camera array is provided and a more detailed version will be uploaded once specific measurements and arrangements are figured out. As a small summary, the optical system will feature a number of cameras with their own lens systems and will be connected via USB to a laptop. From there, image processing and super resolution code will be used to attempt to create a super resolution image from the images captured from each individual camera. Once the super resolution image is produced, it will be run through a detection software and will act as a competitor to the RF approach to demonstrate that the problem can be solved both with electronics and optics. While our system is also rather basic and small scale, this project could act as a proof of concept to encourage more research and investment into super resolution techniques.

2.7 Software Block Diagram

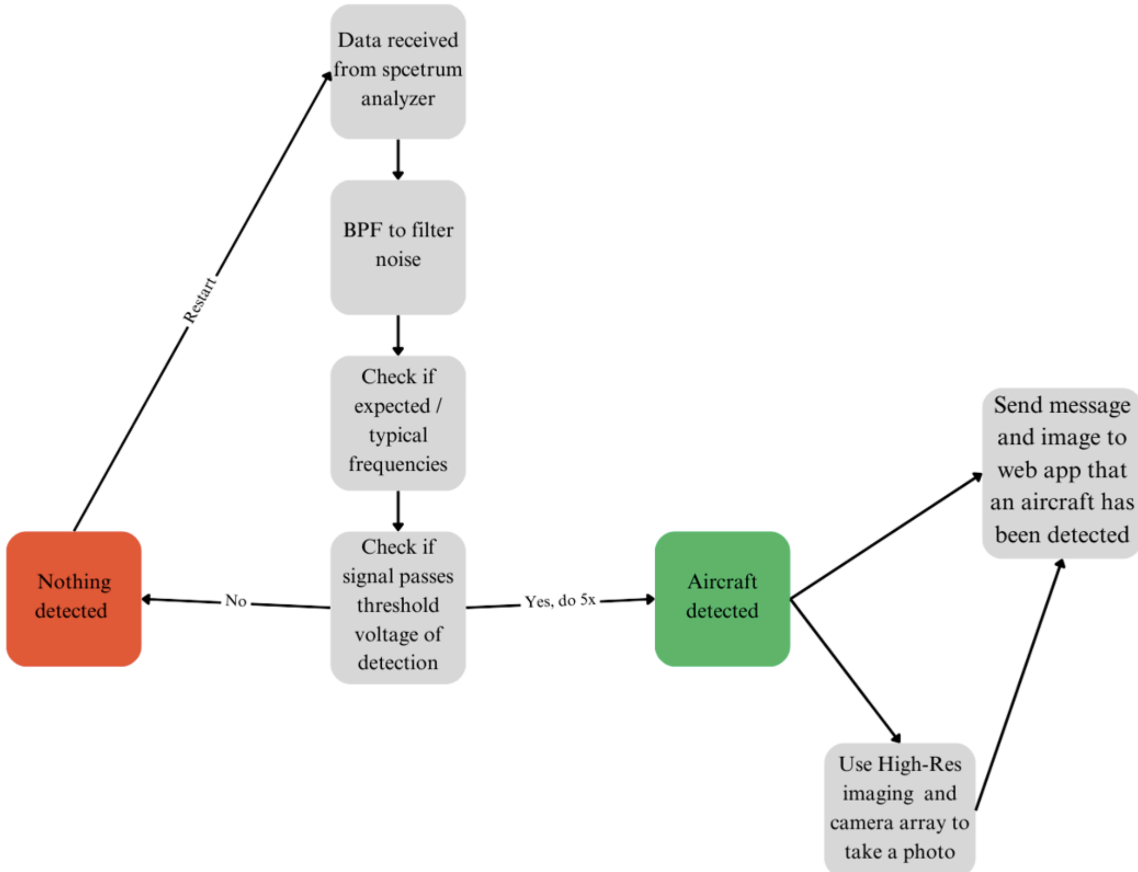

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Figure XXX Software Block Diagram (Need to adjust for new project route)

Explanation of Software Block Diagram

Shown above is a high level representation of how the software will determine the detection of aircraft. We have at first the data that is outputted from the spectrum analyzer. Which will then be sent through a filter and an algorithm to check if it is within the typical frequencies that we may see. Then we will check if the received signal is great or less than our threshold voltage of detection. If the signal voltage is higher that means there is likely something there bouncing off the radio wave into our antenna. This is a good indicator that there is likely an aircraft. If it is too low then it will continue to repeat the process. However, if an aircraft is detected it will send a packet of data and a high res image caught by the camera system to our web app. From the web app the user will be able to check and see when and where the aircraft has been detected.

2.8 House of Quality

House Of Quality

Project title:	SOUTHCOM PROJECT II
Project leader:	Xavier Colon
Date:	2/3/2025

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Desired direction of improvement (↑,0,↓)	↑	↑	↑	↑	↓
Functional Requirements (How's) → Customer Requirements - (What's) ↓	RF Detection	Metal Sphere Detection Accuracy	Aircraft Detection Accuracy	Device Connection /Starlink	Cost
Reliability ↑	++	++	++	0	--
Starlink Functionality ↑	++	0	+	++	-
Identification database ↑	+	0	+	++	-
Target Tracking ↑	++	++	++	++	--
Affordability ↑	-	-	-	0	++
Targets for Engineering Requirements	6dBi at 950MHZ	[illegible] at 950MHZ	6dBi at 950MHZ	Android Phone <10W	

Correlation:

+	0	-
Positive	No correlation	Negative

Relationships:

++	+	0	-	--
Strong	Moderate	None	Negative	Strong negative

Figure XXX Passive Radar House of Quality

Camera Array

House Of Quality

Project title:	SOUTHCOM PROJECT II
Project leader:	Xavier Colon
Date:	2/3/2025

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+ -
++
+ ++

Desired direction of improvement (↑,0,↓)	↑	↑	↑	↓
Functional Requirements (How's) → Customer Requirements - (What's) ↓	Image Capture Distance	Final Image Processing	Array Optimization	Cost
Final Image Quality ↑	+	++	+	--
Image Field of View ↑	++	+	++	-
Target Capturing ↑	++	+	+	-
Affordability ↑	-	-	++	++
Targets for Engineering Requirements	~50-75 mm focal length f/2.8 - f/4.0 aperature	3MP pixel count 15fps frame rate	150-180 degree effective FOV 20-30% Image Overlap	

Correlation:

+	0	-
Positive	No correlation	Negative

Relationships:

++	+	0	-	--
Strong	Moderate	None	Negative	Strong negative

Figure XXX Camera Array House of Quality

Chapter 3: Research

Camera Array

Research Goals

For the camera array device to be successful, a few important things need to be taken into consideration. Since we are dealing with image sensing and capturing images at a distance, the two main topics to discuss revolve around which sensors to use and which lenses to use. The goal for this section is to investigate and research the different types of technologies in the sensing and lens domain to then develop a justifiable choice for our project. Additionally, the programming language we choose to use is just as important. Different options will be investigated and evaluated to see which will best serve our needs for the project.

Overview of Camera Technologies (CMOS vs. CCD)

Selecting the appropriate image sensor technology is a critical factor in the performance of any imaging system. The type of technology that is chosen has a direct influence over the resolution, sensitivity, power consumption, and overall cost. In the context of this project, which involves spatial ray imaging where multiple low-cost cameras are utilized to achieve a high resolution image, understanding the trade-offs between CMOS (Complementary Metal-Oxide Semiconductor) and CCD (Charge-Coupled Device) sensors is vital. This section explores the fundamentals behind each of the technologies, as well as other sensor technology characteristics, and evaluates their advantages and limitations which will guide us to the best option for this project.

CMOS image sensors operate by converting light, or photons, into an electrical signal through an array of photodiodes. In this case, each photodiode represents one pixel in the sensor. When light enters the sensor, it makes contact with the photodiode and generates an electron-hole pair via the photoelectric effect. The number of electrons generated is directly proportional to the intensity of the incident light, resulting in an accumulated charge within each pixel. In CMOS sensors, each pixel typically has its own amplifier which allows for the immediate conversion of charge into voltage. With this type of design, the sensor is able to perform parallel readout, which is reading the voltages from each pixel at the same time, which then enables faster image capture and higher frame rates.

CCD cameras, on the other hand, use an array of photosensitive pixels to capture light and convert it to electrical signal. A CCD sensor consists of a grid of photodiodes which, like CMOS sensors, are made of silicon. Similarly, these sensors also function by generating electron-hole pairs through the photoelectric effect. This, again, means that the number of accumulated electrons is proportional to the intensity of the incident light during the exposure time. The main difference in CCD sensors as compared to CMOS sensors is how the charge transfer mechanism works.

Unlike CMOS sensors, where each pixel has its own amplifier, CCD's store charge and then transfer it sequentially to a central readout amplifier. This process starts with charge accumulation, where each pixel collects charge based on the light it receives. For the charge transfer, after the exposure is complete, the charges are transferred row by row (or column by column depending on the specific device) through a series of potential wells. Here, a potential well refers to an electric field-created region within a pixel where photo-generated electrons are collected and stored. To transfer the electrons from the potential wells to the amplifier, an external clocking signal is used which basically adjusts the voltages to allow for the charges to move. Finally, at the readout and amplification stage, the charge from each pixel is moved to a readout register where it is converted into a voltage by a single on-chip amplifier. The resulting signal is then digitized and used to produce a digital image. Because the charge is transferred across multiple pixels, rather than at each pixel like in the CMOS, CCD’s require precise timing mechanisms to ensure accurate charge movement. This type of sensor design results in lower fixed-pattern noise compared to CMOS sensors but also increases power consumption and readout time. (B. S. Carlson)

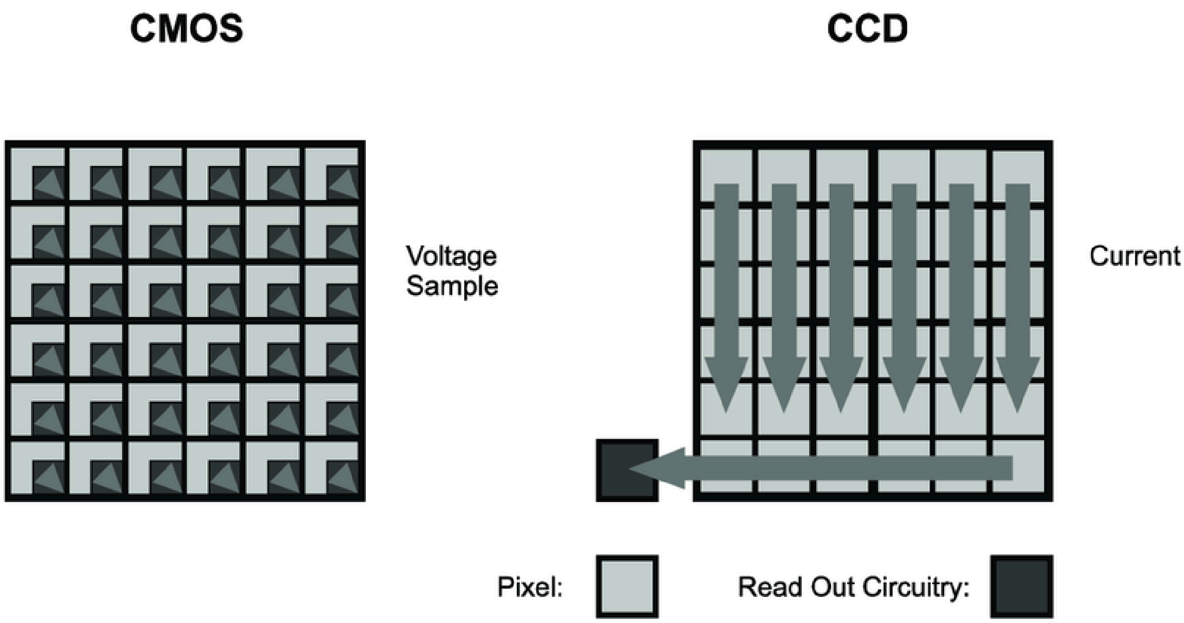

Figure XXX *CMOS and CCD sensor charge readout mechanism (ResearchGate)*

In terms of cost, CMOS sensors are significantly cheaper to manufacture than CCD’s. This is because they are produced using standard silicon fabrication processes, similar to those used for microprocessors. This allows for mass production at a much smaller cost which is why CMOS sensors are the dominant choice in consumer electronics. CCD sensors on the other hand require specialized fabrication methods. The main reason for the increased precision is because of the precise charge transfer structures and high voltage clocking circuits as previously mentioned. This process is therefore more expensive which leads to a higher cost per unit as compared to CMOS sensors.

Additionally, CMOS sensors have built-in processing capabilities, which include analog to digital (ADC) conversion, noise reduction, and signal amplification to name a few. The ability to do this with the sensor alone means that a simpler circuit design can be used which therefore lowers the system cost. CCD sensors require separate ADC’s, external timing circuitry, and higher voltage drivers which increases both the overall system cost and complexity. This can also give us insight into some other reasons that costs are higher for CCD’s. Since their circuitry is more complex and requires more components, the power consumption is higher which then leads to the incorporation of cooling requirements, another expense.

Another difference between these sensor technologies is in their shutter method. There are two types of shutter methods, rolling shutter and global shutter. The rolling shutter method, which is more widely used in CMOS technology, captures an image by scanning rows of pixels sequentially. This means different parts of the image are exposed to slightly different times. As a result, this method can cause motion blur or banding effects. This is commonly seen in consumer technology such as in smartphones, DSLRs, and mirrorless cameras, all of which usually equip a CMOS sensor. The rolling shutter method is mainly used because of its lower power consumption, simpler circuit design, and overall cost effectiveness. However, its biggest flaw comes in the form of distortion in scenes with fast moving objects or quick camera motion.

The global shutter method, which is used in CCD's and some high end CMOS technology, captures the entire image at the exact same time. This method eliminates the distortions experienced by the rolling shutter method. This, therefore, makes it much more viable for applications that require precise motion capture, machine vision, and scientific imaging. While global shutters offer a more superior accuracy when it comes to motion, they typically require more complex circuitry and higher power consumption. Global shutter is mostly found in professional and specialized cameras like those you may see at sporting events or in the film industry. Since our project will mainly focus on stationary objects, the rolling shutter method that is mainly found on CMOS technology would work best.

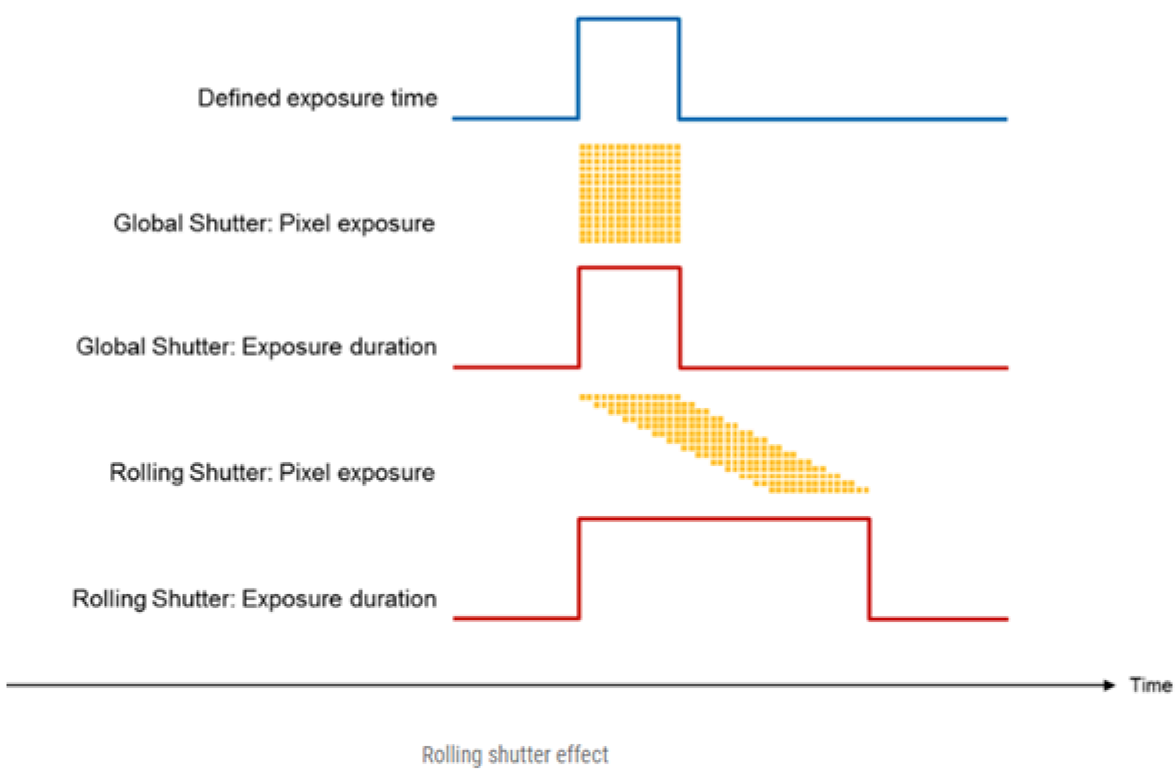

Figure XXX *Exposure time and duration for each shutter type (E-con Systems)*

The last main comparison in sensor technology we need to consider is mirrorless versus DSLR (Digital Single-Lens Reflex) cameras. DSLRs incorporate a mirror and prism system to reflect light from the lens of a camera into a photographer's eye. This method provides a real time view of the scene that the photographer is trying to capture without relying on any electronics. In contrast, mirrorless systems rely, typically, on liquid crystal display screens to display a digitally processed image. This method, while it does not provide a real time view of the scene, allows the user to see what the image would look like once the image is captured. Furthermore, because this method does not rely on a mirror, the size and weight of the system is much less compared to that of a DSLR system. Since our project will use a computer to see the scene that sensors are capturing, a mirrorless system will work best.

Table XXX Comparison of CMOS and CCD technology

Feature	CMOS Camera/Sensor	CCD Camera/Sensor
Manufacturing Cost	Lower - Uses standard silicon fabrication, allowing for mass production with lower cost.	Higher - Requires specialized fabrication, increasing cost of production.
System Cost	Lower - On-chip integration of analog to digital converter, amplifiers, and signal processing reduces need for additional external components.	Higher - Requires separate analog to digital converters, timing circuits, and high voltage drivers, increasing cost and complexity.
Power Consumption	Lower - Each pixel has its own amplifier, requiring less power.	Higher - Charge must be transferred across the sensor, consuming more power and generating heat.
Image Quality	Good - Modern CMOS sensors rival CCDs in many applications.	Great - Lower noise, preferred for scientific imaging.
Motion Capture	Rolling shutter in some CMOS sensors can cause distortion. High-end CMOS sensors use global shutter.	Uses global shutter, making it ideal for capturing fast moving objects.
Applications	Smartphones, webcams, security cameras, etc.	Scientific imaging, astronomy, medical imaging, etc.

Overall, each type of sensor has its strengths and weaknesses. CMOS sensors are the most effective for capturing images of slow moving objects because of how frequently they are paired with rolling shutters. They are also usually much cheaper compared to CCD sensors because their circuitry is much simpler and requires less power to operate. CCD sensor strength lies in its ability to capture a better image when an object is moving. While they are more expensive than

CMOS sensors, they typically also feature better resolutions, frame rates, and motion capture which allows them to do what CMOS sensors can and more. For our project, if we decide to go with a CMOS sensor, we would be limiting our ability to capture images of moving objects. However, if we were to use CCD sensors instead, we could compete with the RF detection device and see which system would be better when it comes to aircraft detection. Since they are more expensive, our array size would definitely have to be reduced compared to if we were using CMOS sensors, but our application range would be much larger.

Based on the table though, CCD sensors clearly outperform CMOS sensors. What is not represented effectively here is higher level CMOS sensors. Some CMOS sensors are able to compete with CCDs to a good degree with certain characteristics such as a high frame rate. For our purposes, and with our budget, a high performance CMOS camera with a higher fps should do the trick. The goal is for us to produce a super resolution image and we would be able to show that effectively with high level CMOS cameras which would keep our cost lower and still fit our needs. If we test this idea with a drone for example, these types of cameras should work very well.

Evaluation for Selection

In order to have an effective demonstration of our project, some evaluation of criteria have to be made. Firstly, we have to consider the resolution of the sensors that we will purchase. In our design, we want to compile an array of lower resolution cameras to then produce an enhanced super resolution image using image processing tools. This would then lead to the belief that we should purchase the lowest resolution sensors possible, but this would be a mistake. Since one of our goals is to capture an image at a distance, we would need sensors that have at least a decent resolution to make this work the way we intend. The sensors that we choose should be greater than 1 megapixel, with higher values providing better clarity but coming at a greater cost. When they are organized in an array, this will produce the necessary quality to be able to discern certain details while simultaneously maintaining the affordability.

The next parameter to consider is the frame rate. Since our goal is to capture an image at 100 meters, choosing an appropriate frame rate, commonly known as frames per second (FPS), depends on different factors. Among these factors are motion blur, exposure time, lighting conditions, and the purpose of the system. Since our system intends to capture a stationary object, we'll have to evaluate which frame rate would serve best for that situation. Typically, when imaging stationary or slow-moving objects, a low frame rate is usually sufficient. This is because there is minimal movement which means aberrations and distortions are also minimized. Typically, for fast moving objects like aircraft, vehicles, or athletes in game, a higher frame rate is necessary to minimize blur and improve tracking. For the latter, it is customary to have at least 30 or more frames per second, with the large values making the risk of motion blur even less. For our system, 30 frames per second is not necessary, however, a frame rate that is too low may prove detrimental. For this reason, we will evaluate options between 10-30 frames per second. This will allow for some minimal movement, which is expected especially if the user is taking the picture while holding the system or if there is slight movement in the object's area.

The consideration is crucial to the success of our project and it is the synchronization of capture. In order for the camera array to really show its strengths, synchronized capture is important. If the images from the cameras are captured at the same time, we would then be able to fuse the images together to get finer details. If the images are not captured at the same time, we run the risk of getting extremely distorted or unclear images. The latter technique is not impossible to do and is actually sometimes used by artists who capture two completely different scenes and merge them together. For our purposes though, we are trying to get more detail from one scene. In a surveillance setting, you cannot guarantee that the object you are trying to capture will not move at least a little bit, so being able to synchronize the capture is incredibly important.

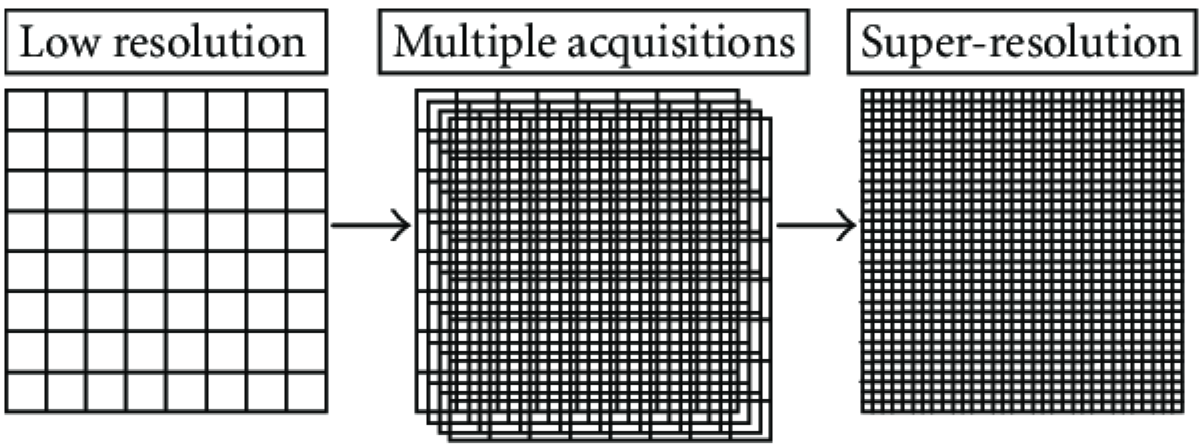

Figure XXX How Super-resolution functions (ResearchGate)

The image above demonstrates how the process of creating a super resolution image works. It can be easily visualized as multiple captures being superimposed on each other to increase the pixel density and thereby the resolution of the final image. If the multiple captures do not capture the same scene at the same time, there will be distortion and blur that will be hard to correct. The best example to show this is with any smartphone's panoramic camera setting. The goal of that setting is to be able to capture a wide scene but it depends on minimal movement both by the scene and the user, otherwise distortion will take place (Samsung). Sometimes, this can lead to some funny and slightly disturbing images.

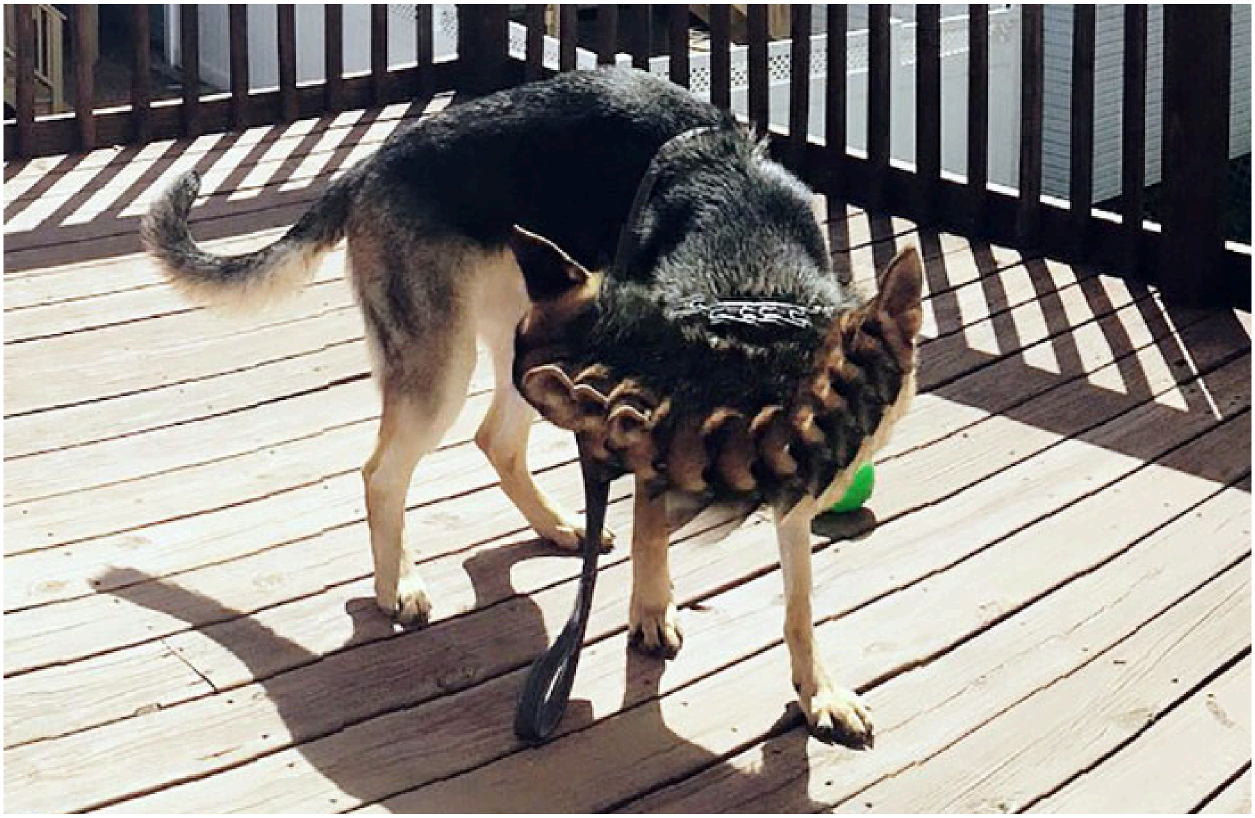

Figure XXX Distortion of dogs face due to movement during image capture (Bored Panda)

The image above shows the importance of synchronized image capture. While in the depicted instance, it is done with the panoramic photo setting, the same ideas and considerations need to be taken into account for our design. To address this factor, we will need to look into cameras and sensors that have the capabilities to do synchronized capture, and if they cannot, they will need to be compatible with our computers so that we can code them to capture and image simultaneously. The code may need to involve some sort of computer vision as well to ensure that a viable image is able to be produced. This would add another safety net to our design which will allow for an easier user experience.

In terms of power consumption, we are aiming to keep that to a minimum. For our device to be effective and viable, power consumption cannot be too high. If there is a large power requirement, it may require the user to carry around a battery or power bank which reduces the appeal of our idea. Since our demonstration will likely involve the computer vision approach mentioned earlier, a power source that is easily accessible, such as a USB connection, may be the direction we want to take. This will allow for easy installation and allows us to both power the cameras and use them as intended with the code that we will write.

Another characteristic to consider is the bandwidth. During our PSE midterm demo, we encountered an issue we did not expect. Our setup, which consisted of 3 cameras, was connected via a USB hub to our computer. To our surprise, only 2 of the cameras were functioning, and after looking into what caused the issue to occur, we learned about bandwidth, specifically video bandwidth. Our approach used a code that, when run, opened separate windows to show you what each camera was seeing. With just 2 cameras operating, it was clear that the cameras were operating sub-par to their regular individual performance. This was a result of the bandwidth limitations of our USB hub. To address this, we will need to look into effective means of reducing bandwidth and some devices that handle video well, especially if there are more than 3 cameras running at a time.

The last evaluation is the cost. The main idea of this SOUTHCOM sponsored project is to provide a more affordable solution to the problem while still maintaining the appeal of what makes the more expensive options attractive. Our goals for the camera array can be easily achieved by some products on the market, like high resolution cameras, most of which come with large lenses, but they have a steep cost. For this reason, our research will focus on cameras and sensors that can achieve all the previously discussed characteristics that we need but are also affordable. This means, for each camera, the goal is to find an option that is $50 or less. If we are able to find options in this range, our device's appeal stays high and when completed, will still be more affordable than professional grade setups.

Product Research (Specific Models)

The first product that we considered was the **Arducam OV9281** camera. The Arducam OV9821 is a 1 megapixel camera which uses a global shutter camera and is mainly designed for high-speed imaging applications where motion clarity is critical. The reason this camera is being considered is because of the goals of the RF side of the project. Since the RF side of the project is attempting to detect an aircraft, or other object, that emits an RF signal, the incorporation of this camera can rival and compete with the RF device to attempt to locate that same aircraft or object. Therefore, a global shutter may be necessary to incorporate since rolling shutter cameras introduce motion blur and make it difficult to discern detail with moving objects. Additionally, the use of a global shutter ensures that all pixels capture the image simultaneously as described earlier which actually benefits our project in terms of synchronized capture. Though it would require the use of a USB hub that can handle multiple streams at once, it would serve as a good option for motion and synchronized capture.

While the resolution of this camera is lower, listed at 1280 x 800 pixels, its high frame rate, which can reach up to 120 frames per second, would help capture finer details of a moving object. This camera also features a monochrome sensor, meaning it only captures the intensity of the light, which translates to a grayscale image. While this may seem like a disadvantage, a monochrome sensor would help capture more detail than a color sensor. Since the sensor does not have to process color information, the grayscale image would possess more detail in the picture. A monochrome sensor would also be more advantageous in lower light conditions since it is only capturing light intensity. This camera connects via a USB 2.0 which makes it easy to integrate with Python and OpenCV, a computer vision library. However, since its resolution is on the lower end, it may not be as useful to us if we are trying to get a very high resolution image at the end. Finally, the size and price of this camera are very attractive. Since the camera is only 28 x 38 mm in size, it makes it ideal for an array arrangement approach. This specific one is listed on Amazon for around $50 which would make the final array more affordable than other options (Arducam).

The next product we looked at was the **IMX219 8 megapixel** camera module. This camera module is a compact and low cost imaging unit that is commonly used in embedded vision projects. It is typically paired with a Raspberry Pi and NVIDIA platform. It features the Sony IMX219 sensor which is an 8 megapixel, or 3280 x 2464 pixels and uses a rolling shutter CMOS sensor. This provides a good balance between resolution and power efficiency since CMOS sensors use less power than CCD sensors. The module is widely available and is easy to integrate which makes it an appealing option for our array setup. Its frame rate can go up to 30 frames per second which is suitable for capturing an image of a moving object, as long as it is not moving too fast.

The cost effectiveness of this option, being that it is one of the more affordable options that offers a higher resolution sensor, makes it very feasible for a multi camera array on a budget. Since it is not powered through a USB connection, we would have to use a battery to power the camera, though its power consumption is not very high which won't make that too much of a burden. (Seedstudio)

The next consideration was the **See3CAM_CU135**, a 13 megapixel camera. This camera was designed for computer vision applications, which is part of our approach with the camera array. The camera provides sharp images with an excellent dynamic range, meaning there is a lot more clarity in the image. It allows the user to manually control the exposure levels, gain adjustments, and white balance giving fine control over image conditions. It uses a USB 3.0 interface which allows for faster data transfer than its USB 2.0 counterparts, and makes it more ideal for multi-camera setups. It also features interchangeable lenses which will help us when integrating the lens system that we will design. The more glaring disadvantage of this camera is its price. While it is still relatively cheap when compared to the types of cameras on the market, for our applications, it will prove difficult to use. (See3CAM)

Another camera we researched was the **Raspberry Pi Camera Module 3**. This camera is very similar to the previously mentioned OV9281 camera. It features a 11.9 megapixel resolution, and a Sony IMX708 CMOS sensor. It has a frame rate of 100 frames per second when operating at 720p resolution just like the OV9281. However, this camera module uses a rolling shutter as opposed to a global shutter making moving objects much harder to capture. Additionally, the interface for the camera is not usb, instead, it is MIPI CSI. This would mean we would need an additional Raspberry Pi module to be able to use the camera. The main issue with the MIPI CSI is the number of allowed connections, which in our case, would not be helpful as our project consists of multiple cameras in use at the same time. Bandwidth limitations would also be an issue since the CSI bus shares bandwidth across all the connected cameras, whereas USB cameras can be spread across multiple ports for better performance. It is slightly cheaper than the OB9281 camera, but its lack of flexibility does not make it the best option for our project. (RaspberryPi)

Feature	Arducam OV9281	IMX219 8MP	See3CAM_ CU135	Rasp. Pi CM3
Resolution	1280x720	3280x2464	4208x3120	4608x2592
Shutter Type	Global	Rolling	Rolling	Rolling
Max Frame Rate	100 fps (720p)	30 fps (1080p)	60 fps (1080p)	100 fps (720p)
Pixel Size	3 um	1.12 um	1.1 um	1.4 um
Connection Type	USB 2.0	MIPI CSI	USB 3.0	MIPI CSI
Price	~$50	~$35	~$100	~$40
Best for Motion Detection	Yes, global shutter prevents motion blur	No, rolling shutter leads to motion blur	No, rolling shutter leads to motion blur	No, rolling shutter leads to motion blur
Super Resolution Feasibility	Good, multiple cameras with high frame rates	Possible, limited by rolling shutter	Possible, limited by rolling shutter	Possible, limited by rolling shutter

The table above compares the four camera modules that were previously discussed. While they each have their advantages and limitations, we believe the Arducam OV9281 will be the best option for our project. The global shutter, paired with a USB connection, and high frame rate make it the best option for super resolution applications. Additionally, the price makes it an affordable option and would allow us to purchase more modules. Although its resolution is lower than the other camera modules, our project will address that limitation by using multiple cameras at once. This will help increase the overall resolution of the final image since cameras capturing an image of the same object from slightly different perspectives provides more detail to the full picture.

As of this research, we also believe that 3 cameras should provide the necessary amount of information. This is based on how smartphone cameras such as the iphone work and use their cameras. The iphone 16 pro max, for example, utilizes 3 cameras, one with a ultra wide fov, one with a wide fov, and one with a telephoto lens. Using these 3 cameras, they are able to achieve high resolution imaging through image fusion. The use of 3 different fields of views also helps with depth control and focus which will help our super resolution process. Though their cameras are built with much more expensive technology that features much higher resolutions than our proposed solution, the 3 cameras should be enough to showcase what we want (Apple).

Lens System

Research Goals

The primary research goal for the lens design of each camera in the array is to optimize the trade-offs between magnification, field of view, and aberration control to ensure the best final image. Each camera will have a unique focal length and aperture size, selected to maximize resolution while maintaining sufficient overlap between adjacent fields of view. Additionally, due to the hot and humid atmospheric conditions of the region, wavefront distortions will degrade the image quality over long distances. To mitigate this, the system will incorporate a phase corrector plate, designed to counteract these phase shifts caused by differing refractive indices in the air. This corrector plate will function similarly to adaptive optics but in a passive manner, compensating for distortions before computational super-resolution algorithms process the final image. The effectiveness of the phase correction will be analyzed to ensure optical clarity and resolution in the constructed image.

In designing a multi-camera system for super-resolution imaging, careful consideration must be given to the selection of optical components and image processing techniques. Each camera in the array plays a unique role in capturing different magnifications, fields of view (FOV), and perspectives, all of which contribute to the final high-resolution composite image. To achieve optimal clarity, a combination of telephoto, wide-angle, zoom, fisheye, and aspheric lenses will be utilized. These lenses allow for diverse data collection, capturing fine details from distant objects while also providing broad contextual information. However, challenges such as parallax, distortion, and atmospheric turbulence—especially in Florida's hot and humid environment—necessitate advanced stitching and correction techniques. These include feature-based stitching, optical flow alignment, multi-resolution pyramid blending, deep-learning-based super-resolution, and wavefront correction. Together, these methodologies will ensure a seamless and high-quality final image, overcoming the limitations of individual camera units.

Lens System Types for Multi-Camera Imaging

A well-designed optical system requires multiple types of lenses to capture both fine details and broader scene information. Each lens type brings unique benefits that contribute to the multi-camera array's ability to construct a super-resolution image.

Telephoto Lenses for High-Resolution Detail

Telephoto lenses, which typically have focal lengths between 100mm and 600mm, are indispensable for capturing distant objects with high precision. These lenses provide a narrow FOV, which enables the system to isolate fine details that would otherwise be lost in wider lenses (Firoozfam, 2004). A key advantage of telephoto lenses is their ability to minimize perspective distortion, ensuring that objects retain their natural proportions even at long distances. However, their small FOV necessitates precise alignment within the array to prevent gaps between images (Brady et al., 2020).

Another challenge with telephoto lenses is their susceptibility to atmospheric distortions. Over long distances, heat waves and humidity variations in the air create wavefront distortions that degrade image sharpness. To mitigate this, phase corrector plates can be integrated into the optical system. These plates function similarly to adaptive optics in astronomical imaging, counteracting phase shifts induced by the atmosphere before the image reaches the sensor (Harfouche et al., 2023). Computational post-processing, such as wavefront reconstruction algorithms, can further correct distortions, enhancing the final image quality.

Wide-Angle Lenses for Contextual and Peripheral Imaging

Wide-angle lenses, with focal lengths ranging from 10mm to 35mm, play a critical role in capturing a broader FOV. While they lack the magnification of telephoto lenses, their ability to cover large portions of a scene ensures that contextual and peripheral information is preserved (Al-Harasis & Sababha, 2019). This is particularly important when multiple telephoto cameras are capturing different portions of a distant object; wide-angle images can provide alignment references to help with image stitching.

One drawback of wide-angle lenses is barrel distortion, where straight lines appear curved, particularly near the edges of the frame. This effect can be corrected using optical elements within the lens itself or through computational de-warping techniques. Additionally, while wide-angle lenses excel in providing scene context, their lower resolution at long distances makes them less suitable for capturing fine details. As a result, they are best used in conjunction with higher-magnification optics within the array.

Zoom Lenses for Adjustable Focal Ranges

Zoom lenses, with adjustable focal lengths such as 24-70mm or 70-200mm, provide versatility by allowing dynamic adjustments based on the imaging scenario (Chu et al., 2020). This adaptability is particularly useful when tracking moving objects or when the scene composition changes. Unlike fixed focal length lenses, zoom lenses enable a single camera to serve multiple purposes, making them valuable in a system where space and weight constraints must be considered.

However, zoom lenses introduce additional optical complexities. As focal length changes, focus shifting and chromatic aberrations can occur, requiring precise calibration (Lin et al., 2015). Additionally, mechanical zoom mechanisms may introduce minor vibrations or misalignments over time. Computational corrections, such as autofocus optimization and digital sharpening, can help maintain image integrity when using zoom optics.

Fisheye Lenses for Panoramic Coverage

Fisheye lenses, which typically provide a FOV of 180° or greater, are useful for capturing hemispherical images that can later be stitched together into a panoramic composite. These lenses are particularly valuable for surveillance and environmental monitoring applications (Zheng, 2010). By positioning fisheye cameras at key points in the array, the system can ensure complete coverage of a scene, reducing the likelihood of missing important visual information.

The primary drawback of fisheye lenses is their extreme distortion, which results in a curved representation of straight lines. Advanced de-warping techniques, such as cylindrical or spherical projection mapping, must be employed to correct these distortions before integrating the images into the final composite (Brady et al., 2020).

Aspheric and Custom Lens Designs for Aberration Control

To minimize optical aberrations such as spherical and chromatic aberrations, aspheric lenses can be incorporated into the system (Yuan et al., 2017). These lenses provide sharper images by reducing the need for additional corrective elements, which can introduce light loss or distortions. Custom lens designs, tailored for specific wavelength ranges or optimized for low-light performance, can further enhance image quality (Fang et al., 2025).

Table XXX Comparison of Lens System Types

Lens Type	Focal Length Range	Positive Features	Negative Features
Telephoto Lenses for High-Resolution Detail	100mm-600mm	Minimizes perspective distortion and high precision with long distances	Narrow field of view
Wide-Angle Lenses for Contextual and Peripheral Imaging	10mm-35mm	Wide field of view to give peripheral information	Barrel distortions and low magnification
Zoom Lenses for Adjustable Focal Ranges	24mm-200mm	Best used for moving objects	Focal length changes causing image blur and chromatic aberrations
Fisheye Lenses for Panoramic Coverage	Wide Ranging	Field of view 180 degrees or more	High distortions
Aspheric and Custom Lens Designs for Aberration Control	Wide Ranging	Minimizes spherical and chromatic aberrations	Can be expensive

Image Stitching Methods for Super-Resolution Reconstruction

Once images are captured, they must be seamlessly combined to produce a high-resolution composite. Several advanced stitching techniques are employed to achieve this.

Feature-Based Image Stitching

Feature-based stitching aligns images by detecting and matching distinct key points within overlapping frames. Algorithms such as Scale-Invariant Feature Transform (SIFT) and Speeded-Up Robust Features (SURF) allow for accurate image registration even when minor shifts occur (Harfouche et al., 2023). This method is particularly useful for integrating images from cameras with different focal lengths, ensuring a seamless transition between high-magnification and wide-angle captures.

Optical Flow-Based Stitching for Dynamic Adjustments

Optical flow techniques estimate pixel displacement between frames, allowing for real-time image alignment (Lin et al., 2015). This approach is beneficial in dynamic conditions where objects may shift slightly due to atmospheric turbulence. By continuously adjusting pixel positions, optical flow methods ensure that images remain aligned, even in challenging environments.

Multi-Resolution Pyramid Blending

To minimize visible seams between stitched images, multi-resolution pyramid blending is used. This technique constructs a multi-scale representation of each image and selectively blends details across different resolution levels (Zhuang & Tran, 2020). This approach ensures smooth transitions between adjacent images, eliminating hard edges that might otherwise appear in the composite.

Deep Learning-Based Super-Resolution Fusion

Deep learning techniques, particularly convolutional neural networks (CNNs), have revolutionized image stitching and super-resolution reconstruction. These networks are trained on vast datasets to intelligently fuse multiple images, enhance resolution, and correct distortions (Fang et al., 2025). By leveraging machine learning, the system can generate high-resolution images that surpass the native resolution of individual cameras.

Wavefront Correction for Atmospheric Distortions

Phase corrector plates are optical elements designed to pre-compensate for predictable phase distortions introduced by atmospheric turbulence. They work by introducing an inverse distortion pattern that cancels out the wavefront perturbations caused by air turbulence. These plates can be particularly useful in a static imaging setup where the distortions follow a predictable pattern, such as near heat-generating surfaces or over large bodies of water. By correcting for known aberrations before the light reaches the camera sensor, phase corrector plates help mitigate some of the long-range imaging issues that typically degrade resolution.

There are two primary types of phase corrector plates: static phase plates and deformable phase plates. Static phase plates have a fixed correction pattern etched into them, making them ideal for long-term deployments where the turbulence profile remains relatively constant. They are often designed for specific wavelengths, ensuring maximum correction efficiency. In contrast, deformable phase plates are made from liquid crystal or piezoelectric materials, allowing for tunable wavefront modulation. These plates can adjust dynamically to changing atmospheric conditions, providing a more versatile solution for varying turbulence levels.

Several manufacturers offer high-quality phase plates that can be integrated into optical systems. Thorlabs, for instance, produces a range of phase plates designed for atmospheric correction, while Meadowlark Optics specializes in liquid crystal-based phase correctors that allow real-time adjustments. Boston Micromachines provides MEMS-based deformable mirrors that serve a similar function by dynamically altering the wavefront to counteract turbulence. Depending on budget constraints, a custom-etched static phase plate may be a cost-effective solution, while a liquid crystal-based corrector could offer real-time adaptability at a higher cost.

Adaptive Optics for Real-Time Correction

Adaptive optics (AO) is a more advanced approach that actively measures and corrects for wavefront distortions in real time. Unlike static phase corrector plates, which address pre-determined distortion patterns, adaptive optics systems continuously analyze incoming wavefronts and apply corrections dynamically. This capability makes AO particularly effective for applications that require real-time adjustments, such as astronomy, military surveillance, and biomedical imaging.

A typical adaptive optics system consists of three primary components: a wavefront sensor, a deformable mirror (DM) or spatial light modulator (SLM), and a real-time control system. The wavefront sensor measures incoming wavefront distortions using techniques such as Shack-Hartmann sensing or curvature sensing. Based on this data, the real-time control system calculates the necessary adjustments and transmits them to the deformable mirror, which then alters its surface to compensate for the distortions. This process happens within milliseconds, allowing for continuous correction even in rapidly changing atmospheric conditions.

Several commercially available adaptive optics solutions could be integrated into the multi-camera system. Thorlabs offers adaptive optics kits that include wavefront sensors and deformable mirrors, making them suitable for laboratory testing and field applications. Boston Micromachines provides MEMS-based deformable mirrors that can achieve high-speed correction, making them ideal for dynamic turbulence effects. Imagine Optic produces HASO wavefront sensors that, when paired with adaptive optics hardware, can significantly improve long-range imaging performance. While adaptive optics offers the highest level of correction, it comes at a higher cost and increased complexity, making it less feasible for budget-constrained applications. However, a simplified AO system using liquid crystal spatial light modulators (SLMs) may provide a balance between performance and affordability.

Table XXX Comparison of Resolution Strategies and Corrective Optics

Stitching Method	Method	Advantages	Applications	Limitations	Cost
Feature Based Stitching	Detects and matches key points	Can be effective for multiple focal lengths	Aerial imaging and panoramas	Cannot do dynamic Scenes	Moderate
Optical Flow - Based Stitching	Estimates pixel displacement in frames	Real time alignment	Remote sensing	Cannot do significant motion	Moderate
Multi - Resolution Pyramid Blending	Blends images at different resolution levels	Minimizes seams	Medical imaging	Long computation time	High
Deep Learning - Based Super - Resolution	Uses CNNs to enhance resolution	Extremely high resolution	Surveillance and medical imaging	Requires training data	High
Wavefront Correction	Uses phase corrector plate to pre - compensate for distortions	Reduces predictable distortions	Long range imaging and astronomy	Needs predictable distortion patterns	Moderate to high
Adaptive Optics	Uses wavefront sensors and mirrors to adjust light	Real time alignment	Astronomy and military surveillance	Very complex and high cost	High

By integrating multiple lens types and advanced stitching techniques, the multi-camera array can produce a high-resolution, super-resolved image capable of capturing distant objects with exceptional clarity. Each lens system serves a unique function, while computational algorithms ensure seamless integration of captured data. This combination of optical and computational strategies will allow the system to overcome environmental challenges and achieve superior imaging performance.

Evaluation for Selection

Focal length is a critical parameter in lens design as it directly affects both magnification and field of view (FOV). Longer focal lengths provide greater magnification, capturing fine details of distant objects, while shorter focal lengths offer a wider FOV, which is essential for capturing broader scene context. In a multi-camera array, employing a range of focal lengths—from telephoto lenses (100mm–600mm) for detail to wide-angle lenses (10mm–35mm) for context—ensures comprehensive scene coverage. Zoom lenses (24mm–200mm) add versatility by allowing dynamic focal adjustments based on the imaging scenario. However, managing the trade-offs between focal length and FOV is challenging, as telephoto lenses may introduce perspective distortions, while wide-angle lenses can suffer from barrel distortions. Selecting the appropriate combination of lenses helps optimize both detail and context in the final composite image.

Field of view (FOV) determines the extent of the scene captured by each camera. Adequate FOV overlap between adjacent cameras is crucial for seamless image stitching, as insufficient overlap can lead to artifacts while excessive overlap increases redundancy and processing time. Typically, an overlap of 20–30% is recommended for reliable feature matching during the stitching process. Wide-angle and fisheye lenses are beneficial for capturing broad scenes, with fisheye lenses offering a FOV of 180° or more for panoramic coverage. Correcting distortions from these lenses, such as barrel and edge distortions, is essential to maintain the accuracy of the stitched images. Balancing FOV across different lenses in the array is necessary to simplify stitching and ensure that all critical information is captured.

Aberration control is essential for maintaining image sharpness and clarity. Chromatic aberration, caused by different wavelengths focusing at varying points, and spherical aberration, resulting from peripheral rays focusing differently than central rays, are the primary concerns. Using aspheric lenses helps minimize spherical aberrations by optimizing light paths, while low-dispersion glass and achromatic doublets can reduce chromatic aberrations. Custom lens designs tailored to specific wavelength ranges or optimized for low-light performance further enhance image quality. However, these solutions can significantly increase costs and complexity. Efficient aberration control not only improves the clarity of individual frames but also simplifies the super-resolution and stitching processes by providing cleaner, high-contrast images.

Cost considerations for lens design are a significant factor when selecting components for a multi-camera array. The type of lens—be it telephoto, wide-angle, zoom, or custom aspheric—directly influences costs due to differences in material quality, coatings, and manufacturing precision. Aspheric lenses, for instance, offer superior aberration control but are more expensive due to complex manufacturing processes. Selecting a mix of cost-effective lenses without compromising on essential parameters like focal length and aberration control can help balance performance and budget. Prioritizing lenses with high-quality coatings for key positions in the array while using standard lenses for less critical roles can optimize both performance and cost.

Resolution is a fundamental parameter for achieving high-quality super-resolution imaging. Higher resolution captures more detail, which is essential for both feature-based and optical flow-based stitching techniques. Ensuring consistent resolution across different lenses simplifies the stitching process and reduces interpolation artifacts. Deep learning-based super-resolution methods can enhance resolution beyond the native capabilities of individual cameras by intelligently merging information from multiple images. However, achieving higher resolution also demands increased storage, processing power, and training datasets, making it necessary to balance resolution requirements with computational resources and costs.

Computational complexity is a critical parameter that impacts both the feasibility and cost of implementing advanced stitching and correction techniques. Feature-based methods, such as Scale-Invariant Feature Transform (SIFT) and Speeded-Up Robust Features (SURF), offer moderate complexity suitable for static scenes, while optical flow methods, which estimate pixel displacement, require significant computational resources for real-time applications. Deep learning-based methods, though capable of producing the highest resolution and accuracy, are the most computationally intensive, often necessitating specialized hardware like GPUs. Efficiently managing computational complexity involves selecting the right combination of algorithms based on the specific requirements of the scene—whether it is static or dynamic—and the available processing capabilities.

Computation time is a practical concern for applications that demand real-time or near-real-time imaging, such as surveillance and navigation. Longer computation times can introduce delays, making the imaging system less responsive to rapidly changing scenes. Optimizing computation time involves leveraging hardware acceleration, such as GPUs, for deep learning and optical flow algorithms, as well as implementing multi-threading techniques to parallelize tasks. Selecting algorithms that balance accuracy with speed, like optical flow for dynamic scenes and feature-based methods for static scenes, can help manage computation time effectively without compromising on image quality.

Price and cost efficiency of stitching strategies and corrective optics are significant factors in the overall system design. High-end solutions, such as deep learning-based super-resolution and adaptive optics, offer superior performance but at a steep cost due to the need for specialized hardware and extensive computational resources. Open-source software solutions like OpenCV and TensorFlow can help reduce software costs, while cloud-based processing can offload the need for high-performance local hardware. Cost efficiency can also be improved by modularizing the system—using high-cost, high-performance components only where they provide the most significant benefits and standard components elsewhere.

Distortion and aberration correction using corrective optics is essential for long-range imaging, especially in hot and humid environments where atmospheric turbulence is a concern. Techniques such as wavefront correction and adaptive optics significantly improve clarity by compensating for distortions before the image reaches the sensor. Wavefront correction, using phase corrector plates, is cost-effective for predictable distortion patterns, while adaptive optics, involving real-time adjustments with deformable mirrors and wavefront sensors, is necessary for dynamic conditions. Selecting between these techniques depends on the predictability of distortions and budget constraints, with adaptive optics offering superior performance at higher costs and complexity.

Cost of corrective optics is influenced by the type of technology employed. Static phase plates offer a lower-cost solution for correcting predictable distortions, while deformable mirrors and real-time control systems used in adaptive optics significantly increase costs. Integration complexity also adds to costs, as precise alignment and synchronization between corrective optics and camera sensors are required. To manage these costs, a hybrid approach that combines static phase plates for predictable distortions and simplified adaptive optics using liquid crystal spatial light modulators (SLMs) for dynamic scenarios can provide a balanced solution.

Complexity of integration is a crucial parameter affecting the reliability and maintenance of the imaging system. Complex corrective optics and stitching algorithms require precise alignment and calibration to function effectively, which can increase failure rates and maintenance costs. Modular designs that allow individual components—such as lenses, phase corrector plates, and adaptive optics modules—to be replaced or upgraded independently can simplify integration. Standardizing communication protocols between components and using software-based calibration tools can also reduce integration complexity and enhance the overall robustness of the system.

Balancing these parameters—focal length, FOV, aberration control, resolution, computational complexity, and cost—is essential for optimizing the design of a multi-camera system. A strategic combination of diverse lens types, efficient stitching algorithms, and cost-effective corrective optics can enhance the clarity, resolution, and reliability of the final composite image. Careful selection based on these parameters ensures that the system meets both performance and budgetary requirements, making it feasible for deployment in challenging environments such as those characterized by atmospheric turbulence and long-range imaging demands.

Product Research (Specific Models)

Justification of Selection

- Which and why?
- Tie back to project goals and why the model chosen meets our requirements
- **Challenges and Trade-offs**

Conclusion of Lens System Research

- Key takeaways
- Highlight how chosen camera aligns with our needs

RF Device Research Goals

The RF device will require a few different things in order for us to be successful in our testing. One of the main things is our antenna technology. We will have to be very careful with what kind of antenna we choose as that is how all of our information is received. If we do not get an antenna that is wideband enough or sensitive enough then the rest of the equipment will not work. The next part is our spectrum analyzer which has to be accurate and sensitive enough for our use case. Next is our power source which will prove the viability of the overall functionality. Having a lower maintenance power source is a good idea as it allows us to place these in remote locations. Finally, we hope to find what kind of communication protocols will happen between all of the different devices. It is important for our computer to be able to decode the information that the spectrum analyzer may produce. With all of these in mind we will be able to successfully create a working prototype.

Overview of Antenna Technologies

Antennas are a technology that allows us to send Radio Frequency electromagnetic waves across space. There are many different types of antennas and uses for them depending on the parameters that may be found useful for a specific use case. For example, your ear acts as an antenna for sound waves as opposed to electromagnetic waves. They redirect the sound waves flying around space and send them to your eardrum. Your ear drum then vibrates and translates it to language. Antenna work in two different distinct modes, transmitting and receiving. Transmitting is the use case in which we will send an electromagnetic wave. Receiving is where we will “listen” to the transmitted wave and convert it into electrical signals.

Furthermore, they are incredibly useful as it allows for wireless communication between devices. Before antennas, long lines of wire would have been needed to communicate between long distances. Such as when the telegram or early telephone were used, they needed to run a physical wire between the two places which is very costly and can be challenging in rough environments. With antennas, we can forgo a lot of that cost by simply sending it across space.

As previously mentioned, there are many different types of antennas which we will explore for the use of our system. First, we need to define the parameters of antennas and how they will be useful for this system. There are also many different frequencies at which the antennas operate which will have to be narrowed down for our use case.

First, we need to define some basic parameters so we can research the specific antenna we may use. The first one being frequency; Which simply put is how quickly the electromagnetic wave will repeat in a given time. Naturally, we will need to define the wavelength which is the distance between the peaks of each wave. Finally is radiation intensity. Which is the “power per unit solid angle.” (tutorialpoint)

Next, we need some antenna specific parameters which will help us in choosing the best antenna possible for our system. Before that, in antenna theory, we like to compare anything we do to a “isotropic antenna.” Which is an antenna that radiates equally among all directions. Shown in *Figure 3.1*. We use this as a reference for all other antennas to measure their specific parameters. Isotropic antennas are impossible, but are used because they are easy to make calculations with and act as an ideal case. Simply put, they are a reference at which we like to compare.

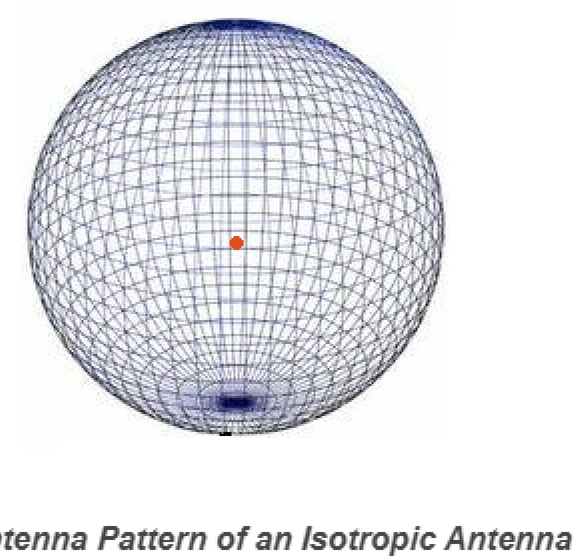

Figure 3.1 *Isotropic antenna radiation pattern (everythingRF, 2021)*

The first parameter discussed will be directivity. Which is the comparison of the maximum radiation intensity of the antenna in comparison to the radiation intensity of the isotropic antenna. Formula. Next is the Aperture Efficiency. Which is the ratio of the “effective radiating area to the physical area of the aperture.” (tutorialpoint) Meaning, how much of the area of the antenna will actually be able to radiate. Formula. Next will be the antenna efficiency which is the ratio of the radiated power to the input power. Finally, is the antenna gain which describes how much power is transmitted in dB.

Furthermore, there are many different types of antennas that will need to be researched for the sake of finding the best type for our use case.

The first type that we will explore will be Dipole antennas. Also known as transmission line or wire antennas. They work by leaving one end of a wire open to space. The energy tries to escape and radiates the energy into the atmosphere. For this to work most effectively, the end of the transmission line must be impedance matched to free space.

There are a few different types of dipole antennas.

First we will start with the half wave dipole. This name simply comes from the fact that length of wire is half a wavelength. The half wave dipole is one of the most widely used antennas. It is typically used in radio receivers or television receivers. It can operate anywhere from 3KHz to 300GHz. This provides a very wide band of frequencies that we could choose from. However, the draw back of this is that you will need to design the antenna for specific frequencies. The bandwidth of this type of antenna is small and not good for our specific use case.

Dipole antennas are also omni-directional in the horizontal plane. Making this seem very desirable for our application as we want to cover as much air space as possible with as little antennas possible. Not only that, but this type of antenna is very cheap to manufacture. Making this a great option for us as we are trying to keep costs as low as possible. It also has great directivity of about 2.15dbi on average. The efficiency of this kind of system is quite good as it allows less loss. As previously mentioned, this has major drawbacks such as the limited bandwidth. It can also be quite large as the size of the transmission line relies on the frequency. It also needs to be at least a quarter wavelength off the ground in order to work. It is also easily affected by other nearby objects and can degrade the performance. This all sums up for a bad implementation into our system.

The next technology that we will explore is the Half-wave folded dipole. This works a lot like the previous half wave antenna however it is folded closed together in a cylindrical shape. On both sides of the antenna the wire length is quarter wavelength as opposed to the half wavelength of the previous antenna. An image of this antenna can be found in *Figure 3.3*. The radiation pattern of the half-wave folded dipole is very similar to that of the previous antenna as well as the frequency range.

The main benefit and difference in comparison to the regular half wave antenna is that it has a higher input impedance of 300Ω in comparison to the half waves 70Ω input impedance. It’s important to note that we can achieve an even higher input impedance by adding more wire elements. This is important for use in systems that may have a higher input impedance or where optimal power transfer is necessary. Such as its use in Yagi-Uda antennas where this acts as a feed for the system. Not only that it has better bandwidth characteristics which could be useful for our use case. However, it is still too small for what we need. It also has better signal to noise ratio performance which in turn allows higher resolution and signal quality. This type of antenna faces the same drawbacks as the previously mentioned half wave antenna.

Next, we will discuss the microstrip or patch antenna. The microstrip antenna is a very thin metal strip placed on a dielectric. The patch is usually half wavelength and when power is added it will radiate from the edge of the strip. The microstrip has a very large radiation pattern. However, its radiation power is very small and has a very thin bandwidth. One of the great things about this type of antenna is it is very low cost and lightweight. They typically have these inside of cell phones or other high speed and precision computing.

Furthermore, the types of antennas discussed so far have not been the most useful for our use case. They have primarily been the basic antennas that are used in very particular uses or for antenna arrays. As mentioned, the Half-wave folded dipole is typically used as a feed for Yagi-Uda antenna arrays which we will explore. Antenna Arrays is simply combining the strengths of a single antenna and multiplying it by adding many similar antennas. The antennas will be placed so close together that they lie in each other's induction field. Which is important as it allows “the radiation pattern to be the vector sum of the individual ones.” (tutorialspoint)

This is extremely important as it allows us to have high gain, high directivity, and overall better performance for every part of the antenna while having very little drawbacks. Some more strengths include a higher signal to noise ratio, which is extremely important for our use case as the amount of power received from the aircraft will be very small. Having a higher signal to noise ratio allows us to reduce the probability of a false alarm. The amount of power used is much lower.

Some of the major drawbacks of antenna arrays include: Large antenna dimensions, which leads to harder implementation and mounting. The resistive losses between elements are increased. They are typically used in satellite communications and wireless communications. One of the major use cases is also military radar. Which is a good indicator that they will be one of our best options. Antenna arrays aren't absolutely perfect, but seem to be the best trade in performance. We will take a look into a few different types and their advantages which will then lead to the selection of the antenna used in our project.

Collinear arrays are antenna arrays that are made of half wave dipoles placed end to end. They are called collinear because they are typically placed on a parallel line or axis. (tutorialspoint) This is a great benefit because as we explored, half wave antennas are very cheap to produce. They also have great forward gain and directivity. The frequency range can be from 30Mhz to 3Ghz. (tutorialspoint) This is the kind of frequency range that we really want to work with as a lot of aircraft and telecommunications lay on this frequency range. Those are the types of things that we are particularly interested in picking up. One of the other interesting things about the collinear antenna is that it's gain is dependent on the amount of elements. The more elements the higher gain. Anywhere from 1.9dB to 4.3dB which is a very high gain. (electronics-notes) Of course the radiation pattern will have some side lobes, However, this makes the radiation pattern uni-directional. An image of the beam pattern can be found in Figure 3.5. Some of the drawbacks are the size and deployment of this type of antenna. They are typically very large and reserved for outdoors which may pose an issue to the deployment of the system. An image can be found in Figure 3.6.

Next, we will discuss the Yagi-Uda antenna. It is made up of parasitic elements and dipole antennas. (tutorialspoint) Parasitic elements are elements that do not have their own feed. (tutorials point) As previously mentioned, the half wave folded dipole is the feed for this antenna type. An image can be found in Figure 3.7. This antenna has a very small bandwidth and a very high directive beam pattern. It also has an extremely high gain of 10dB or more. The frequency range can be from 3 Mhz to 3Ghz depending on the use. They are used everywhere in the world and can be found on rooftops everywhere. However, the main drawback of this antenna for our use case is the fact that the bandwidth is very small. Typically a few percent of the desired center frequency. (antenna theory) This could be an incredibly powerful antenna for our use case if we were to choose a frequency to detect planes. However, since we are going for a completely passive radar approach, it would likely be better to have a large bandwidth. The Yagi-Uda is a very strong contender for our use case.

The last antenna type we will explore is the log-periodic antenna.The log-periodic very similar to the Yagi-Uda antenna. It has a frequency range from 30 Mhz to 3Ghz. Making it a very wide band antenna. However, one of the major advantages over the Yagi-Uda is that it has "constant characteristics over a desired frequency range of operation." (tutorialspoint) Meaning that it has a very wide bandwidth and we can work with a very wide range of frequencies. It also has relatively strong and constant gain and radiation patterns across the operating frequency range. A chart of a log periodic dipole can be found in Figure 3.8 which plots the VSWR of the antenna across the frequency range. Low VSWR means that the antenna works well. The radiation pattern is unidirectional or bidirectional depending on how you orient it. We would like the unidirectional pattern as it works very well for our application. A figure of the radiation pattern can be found in figure 3.9. It also has very good gain ranging from 6 - 12 dB depending on how many elements the antenna has. This wide range of gain will allow us to optimize our system for the absolute most amount of frequency coverage while providing good accuracy for detection. The major drawbacks of log periodic antennas is of course the size. Just like the Yagi, it is a little bit on the larger side. It also costs more than simple antenna systems, but that will ring true for any kind of antenna array. This is by far the strongest contender as it has a wide bandwidth and frequency range. While also providing a great gain. We will explore some specific commercial options for these types of antennas and the benefits. After that, we will evaluate the best antenna for our use. Below the VSWR or Voltage Standing Wave Ratio of a log periodic antenna can be found. The lower the VSWR the less noise and better, more accurate data will be present. It is important to see that the VSWR is extremely low for a large range of frequencies. Much larger than that of the other antennas. Not only that, but an image of the radiation pattern can be found and we can see how wide it is. Working for a large range of angles will increase our chances of detection. Making this an extremely strong contender.

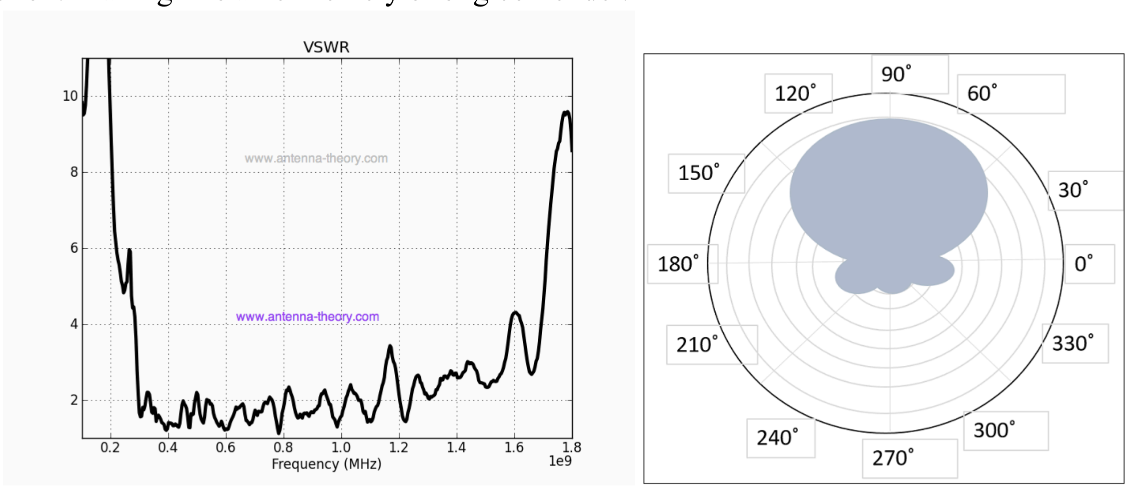

Figure X and X *VSWR of LPDA and Radiation pattern, (antennatheory, 2009) (tutorialspoint, 2025)*

Finally, we have compared a lot of different antenna technologies. However, we will be diving deeper into the antenna array technologies as they are an extremely good fit for our use case.

First we will start with the collinear array antenna. The antenna found was the Laird / Antenex BB8965C. It is a 14 in long antenna that has a good gain of 5dB. It works from 896 Mhz to 970 Mhz. As previously mentioned, it has a small frequency band. The reason that this band was specifically chosen was because it includes some aeronautic mobile communications and land / mobile communications as well. If we are trying to increase our chances of detection this would be a good range to go with. However, it was difficult to find antennas that worked specifically in the aeronautical radionavigation bands. Which typically range from 960 to 1164 Mhz. This one is good because there is a fair chance that a signal could bounce off a transponder on the ground. It also touches a bit into the aeronautical radio navigation band. Another benefit of this antenna is that it is very small and cheap. This could possibly be a good option. However, the bandwidth is a little small for what we may need. In the image shown below you can also find the radiation pattern of a collinear antenna. It makes it a strong contender as it is very broad and allows us to be less picky about what direction the antenna is pointed. It will also increase our chances of detecting an aircraft as we are picking up a larger area of signals.

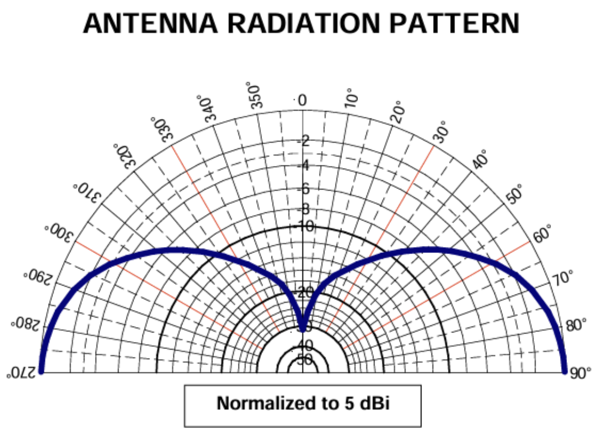

Figure X *Collinear Radiation Pattern*

Next, we will focus on the Yagi antenna. The Kathrein TY900 is a great option for our use case. As previously mentioned, it works in the same frequency range as the last. This one has a peak gain of 12.2dB and is also weather proofed. It is a larger antenna measuring at 24 x 6.6 in. However, given the fact that it is weather proofed, it should be a great option if we would like to mount it in a tree. The high gain means it would be extremely accurate as well. The price is a little bit higher, but the trade off is well worth it as we lower our probability of a false alarm dramatically with higher gain. However as with the last the bandwidth may be a bit too small for our application. Below an image can be found of the radiation pattern of a yagi antenna. We can see that it is highly directional which may be a large problem for our use case.

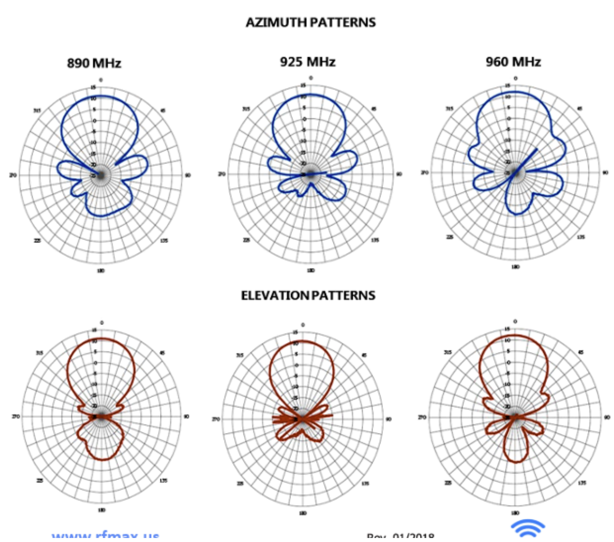

Figure X *and Radiation Pattern (RFMax, 2018)*

Lastly, we will look at the log periodic dipole antenna. The Aventas AX-37A log periodic dipole antenna. This antenna has a frequency range from 300 to 3000 Mhz. By far the widest frequency range we have had yet. This would be incredible for our uses as it allows us to capture almost any communications or reflections that may happen. It also has a forward gain of 6dB. The antenna also has a built in low noise amplifier. This would help our spectrum analyzer and overall accuracy. The radiation pattern is also omni directional which will work well with our system. It is also dimensionally very small as there is a version that is meant to act as a portable antenna. The major drawbacks of this solution is the cost. This is by far the highest cost solution, but will provide the most benefits in the most amount of fields. Jack of all trades and the price comes with it.

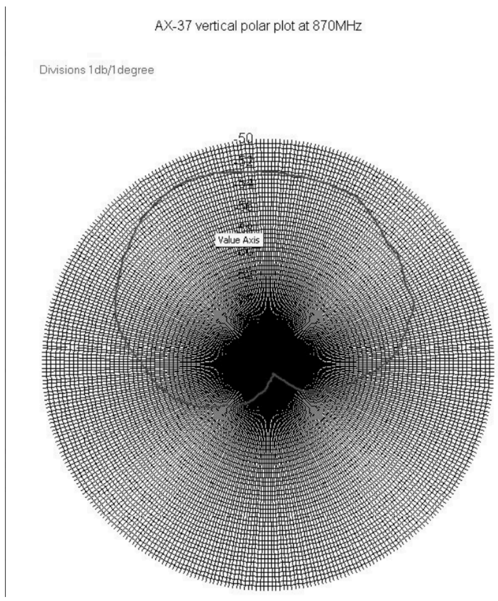

Figure X *Aventas AX-37A and Radiation Pattern (Aventas, 2025)*

Note for this table, the link for a specific product has been embedded in the antenna type

Antenna Type	Frequency Range	Beam Pattern	Gain (dbi)	Cost
Half Wave	3K to 300G	Omni	2.15	$80.00 - $200.00
Half Wave Folded	3K to 300G	Omni	4	$509.00
Microstrip	915-930 Mhz	Broad	2	$14.00
Collinear	896 - 970 Mhz	Omni	5	$85.15
Yagi-Uda	880 - 960 Mhz	Omni	12.2	$247.00
Log Periodic	300 - 3000 Mhz	Omni	6	$0.00

Comparison of Antenna Technologies

Evaluation for Selection

For our solution, we need an antenna that has a very wide bandwidth as we are not sure what kind of frequencies may reflect off of an aircraft. Not only that it needs a high gain in order for us to be able to accurately detect the aircraft. The antenna that works best is by far the Aventas AX-37A as it has good forward gain, and the largest by far band width. It is also dimensionally small and will work extremely well for our use. It is the most expensive but works best. For our use case our sponsor bought the log periodic antenna for us as we both agreed it would be the best technology. As a result the price is reflected in the table.

Overview of Spectrum Analyzer Technologies

Spectrum analyzers are an Electrical Engineering essential. They allow us to capture an electrical signal and display it in graphs that make it easy for us to understand. With this we are able to detect whether there was an aircraft detected based on the amount of power that we will receive with the antenna. Subsequently if we see a spike that means that we were able to detect an aircraft or something else like a radio transmitter. We will be doing analysis in the frequency domain meaning our spectrum analyzer has to be real time. The signals will be received in real time. This allows for wideband analysis, greater degree of accuracy. This allows us to get the best understanding and analysis of the electrical signals we are receiving.

Spectrum Analyzers have a few very important parameters that we will need to look out for. One of them being the Real Time Bandwidth or the RTBW. RTBW is how much of the frequency range can be analyzed without any gaps in the electrical signal. Subsequently, we will need a good frequency range. The more range that the spectrum analyzer and the antenna have the better chance we have at detection. Next is the dynamic range and sensitivity. Dynamic range is the ability for the spectrum analyzer to detect a low power signal in the presence of other stronger signals. Sensitivity or sometimes called Displayed Average Noise Level is how well it can react to weaker signals. Resolution Bandwidth is also very important as it determines how well it can distinguish two very close together signals. Another important parameter is size. The spectrum analyzer needs to be small enough to be carried to remote locations. Finally, likely the most important parameter is the cost.

The first spectrum analyzer is the Tektronix RSA306B USB Spectrum Analyzer. It has a frequency range from 9 Khz to 6.2 Ghz. This will provide more than enough range for our use case. It has a RTBW of 40 Mhz. The dynamic range is -160dBm to 20 dBm. This is overall a great option as it is also USB powered making it compact and easy. The spectrum analyzer also comes with analysis software. Some of the performance may not be necessary as 6.2 GHz may be too high. Subsequently this could possibly be a place to save some money.

Next is the Siglent SSA3032X-R. This seems to be a great offering as it has the perfect frequency range of 9 Khz to 3.2 Ghz. This will likely be our most effective frequency range and should be optimized cost wise. This has an even greater difference between DANL than the last at -165dBm/Hz. It also has an RTBW of 40 Mhz. However, it is not necessarily compact and is more like a regular spectrum analyzer in terms of size. This will subsequently need a 120V wall outlet and will be a big trouble for our use case. Not only that but it has only 100 hours for free trials of the software. There is also an additional software based accessory you have to pay for which is the SSA3000XR-RT40.

Furthermore we have an offering from Signal Hound, the BB60D. This is a very compact spectrum analyzer that is powered by USB. It uses only 6 watts which is an incredibly low power figure. Not only that it has a very wide frequency range from 9 Khz to 6 Ghz. It has a dynamic range from -158dBm to 10dBm. The major drawback is that it has only a 27 MHz RTBW. However, it is the cheapest of the bunch so far and also has free software that you don't have to subscribe to. It has incredible system specs while also being compact and small. They may not be the best performing specs, but it is the cheapest smallest and does most of what may be necessary.

Finally, we will talk about the Keysight N9023B PXA. It has the widest frequency range from 2 Hz to 55 Ghz. The RTBW is a staggering 2 Ghz and has a DANL of -167dBm. It has a dynamic range of -170 dBm to 30 dBm. This is by far the best performing spectrum analyzer with top of the line specifications. The drawbacks of this system are the size and power consumption. Not to mention this costs $207292.56.

Evaluation for Selection

Finally, we chose the Signal Hound BB60D. This is because it is simply the lowest cost. One of the design constraints of the system is that it has to be low cost. It has specifications that get extremely close to the rest of the spectrum analyzers. Excluding the Keysight. The main drawback of this is the smallest RTBW. However, once we test and find the most probable frequencies it shouldn't be that much of a problem as 27 Mhz is still quite a wide range of frequencies. Not only that but it has an incredibly dynamic range and DANL. Which should prove extremely useful for our purpose as the power received from the aircraft will be extremely small. The team and the sponsor also agreed that this would be the best option for our project. It has the most benefits for the least cost. As such, the price is reflected in the table as we didn't pay for the device.

Note for this table, the link for a specific product has been embedded in the antenna type

Spectrum Analyzer	Frequency Range	DANL dBm/Hz	RTBW	Dynamic Range	Cost
Tektronix RSA306B	9 Khz to 6.2 Ghz	-160	40 MHz	-160 dBm to 20 dBm	$6490
Siglent SSA3032X-R	9 Khz to 3.2 Ghz	-165	40 MHz	60 dB	$6545
Signal Hound BB60D	9 Khz to 6 Ghz	-158	27 Mhz	-150 dBm to 10 dBm	$0.00
Keysight N9023B PXA	2 Hz to 55 Ghz	-167dBm	2 Ghz	-170 dBm to 30 dBm	$207292.56

Comparison of Spectrum Analyzers

Overview of Communication Protocols

Naturally, since we have chosen a spectrum analyzer we will need that data to be transferred and processed locally so that we can transmit the data anywhere in the world. First, we will talk about the local communication protocols i.e. between the spectrum analyzer and our mini PC. Then we will do some discovery into how that data will be extracted for the sake of triangulation.

The communication protocol that we will explore is I2C. I2C works on a Master-Slave architecture. Meaning that our MCU will provide the clock and control the communication. The slave devices will simply respond to what is required of the master. It is a two wire communication system where there is a serial data line (SDA) and a serial clock line (SCL). It also operates at speeds from 100Khz to 3.4Mhz. I2C is a more low level technology that may be inside of the spectrum analyzer. It is typically used for things like interfacing with high resolution analog to digital converters. They can also be used for controlling a display which may be how our spectrum analyzer display is controlled. However, this is not the correct technology for our use case as it is a serial protocol. Meaning that it can only transmit one bit at a time and is severely limited by its clock speed. Even at the top of its frequency range it may only be able to transfer up to 400KB/s. This could be used if we had another low speed peripheral that is in the system. However, because we have extremely high resolution FFT data, I2C will not be sufficient for this specific use case.

The next technology we will explore is Universal Asynchronous Receiver-Transmitter or UART for short. It is a serial communication protocol that works asynchronously. Meaning that two devices can send and receive data without sharing a clock. It is a two wire protocol that has a transmit and receive data wire. UART is great because it is widely standardized and supported. Meaning that it is great for use with microcontrollers and embedded systems. However, this is also greatly limited by its speed, around 10 Mbp/s. This could be great for small peripherals or more simple low bandwidth things like I2C is. However, seeing as our spectrum analyzer is already assembled and has these small things already figured out it may not be the best for our use case. As previously mentioned, we need a much higher bandwidth in order to process our extremely complicated data.

Finally, we will talk about Universal Serial Bus. USB is without a doubt the best option for our use case. It is extremely versatile and robust. It is used in many different applications. It has the ability to not only send data between computers but also to charge or power things like our spectrum analyzer. It is a four pin system and has a power pin, a data in and out pin (Or data plus and minus), and finally a ground pin. In the early days of USB it had a data rate greater than I2C and UART at 12 Mbp/s. In more modern USB 3.0, it can transfer from 5 - 10 Gbp/s. Which absolutely trounces the previously mentioned protocols. As previously mentioned it can also provide power, with almost 5W of power which is more than enough for our spectrum analyzer. It is important to note that our spectrum analyzer connects to the computer through USB 3.0. This is great as we don't have to have a separate power source for the spectrum analyzer and antenna. Not only that, but it has extremely high data transfer rates which will be completely sufficient for our computer to process. We are likely going to be more compute power limited than we will be data rate limited. Our spectrum analyzer is an incredibly high precision tool and as a result needs only the best of the best data communication protocols which could only be USB.

Next, we have to learn about how we will transfer our data. These devices and prototypes will be placed remotely. As a result, it would be impractical to run hundreds of miles of wire around the world in order for these to all work properly. We will of course need wireless communications as they allow us to send the data across vast distances with extreme levels of accuracy.

The obvious solution would be to use cell service, 4G LTE, as it is mobile and is used all around the world. These transmitters also have extreme levels of power efficiency. Consuming from 1 - 2 watts on a phone. This is incredible for our system as we would have better fulfilled our power constraint. They also typically work from 700 Mhz to at most 2.6 Ghz. This lower frequency is great because it allows long ranges with the trade off of data rates. The maximum data rate that is typically seen is from 100 - 300 Mbp/s which is more than enough speed and bandwidth for us to send a detection signal.They also have low latency so the data transmitted will be very accurate. These seem like the easy and best solution; However, one of the major issues is the location of these units. They are intentionally placed in extremely rural areas where there might not be a cell tower for hundreds of miles. This of course will be a huge problem for this communication protocol as the possibility of that data travelling will be none. This automatically eliminates this from our prototype as one of the constraints is the ability to work anywhere in the world.

Next, is Starlink which is a new service being offered. It works by using the large network of low orbit satellites to transmit and receive data. This is extremely useful for our use case as it allows us to communicate anywhere in the world. Which already has a leg up over the last solution. It operates in many different frequency ranges such as Ku-band (12 - 18 Ghz), Ka-band (26.5 - 40 Ghz), and V-band (40 - 75 Ghz). This is great as the more bands that we operate at, the more satellites we will be able to transfer data with. This is an extreme advantage as it has similar data rate speeds and bandwidth as 4G LTE. It also retains the low latency of 4G LTE which helps with the accuracy of the data. However, one of the major drawbacks of this technology is that it is power intensive. Typically anywhere from 10 - 100 Watts depending on the load. Also because of its high operating frequency it makes it more susceptible to interference from the rain which may lead to a large problem as the climate this will operate in is likely going to be South America. Starlink is really unbeatable when it comes to this use case and the power constraint will have to be worked around.

However, the FCC has recently started the approval of Starlink use in mobile phones. This would be a major driving point of our product as we can retain the low power consumption of 4G LTE while also having the ability to communicate anywhere in the world. This essentially turns any mobile phone into a satellite phone. This would also allow us to simplify our prototype by having all of the data processing done on a modern smartphone. Which has incredible computing power and power efficiency. Starlink is naturally the best communication protocol for our use case as we can use it anywhere in the world.

Evaluation for Selection

When it comes to how we are going to communicate between the processor and the spectrum analyzer, it seems as though USB is the best choice. It has the highest bandwidth and data rate which will be great for the accuracy and reliability of our system. As for how the data will be transferred from our local site to around the world, Starlink is by far the best option. It has extremely high data rates and works absolutely anywhere in the world which is a major driving aspect our sponsor wants.

Overview of Mini PC

The Intel NUC 13 NUC13ANHi7 Arena Canyon Mini PC is an excellent option to process data from a spectrum analyzer with an excellent mix of performance, portability, and power efficiency. Equipped with an Intel Core i7-1360P processor, 16GB RAM, and a 512GB SSD, the mini PC is able to process the signals in real time, acquire and analyze data for applications such as RF spectrum monitoring and passive radar systems that are computationally demanding in nature. Since it has a small form factor, it can be conveniently deployed in the field or in small spaces, making it appropriate for mobile and fixed signal processing applications.

A prominent advantage of the Intel NUC 13 Arena Canyon is its multi-core performance. The Intel Core i7-1360P processor features 12 cores (4 performance cores and 8 efficiency cores) and 16 threads, which makes it highly capable of handling the high-speed data streams from spectrum analyzers like the Signal Hound BB60D. The combination of efficient cores and high clock speeds ensures that the real-time processing of data is not interrupted and happens seamlessly, even with large spectral data. Additionally, the 16GB RAM provides more than sufficient memory to run advanced signal processing software such as MATLAB, GNU Radio, or SDR# without the risk of delays or bottlenecks.

A second key feature of the NUC 13 Arena Canyon is that it is equipped with high-speed storage and connectivity. The 512GB NVMe SSD offers high-speed data logging, which is crucial in wideband RF signal capture and analysis. Spectrum analyzers have a tendency to generate large files of data that should be stored and accessed at high speeds, and the high read/write speeds of NVMe SSDs enable data processing in real time with as minimal latency as possible. On top of that, the multiple USB ports, Thunderbolt 4, and Ethernet connectivity allow simple integration with numerous RF equipment, external storage, and networked processing systems, making it an excellent hub for data acquisition and analysis.

Besides its performance attributes, the NUC 13 Arena Canyon is a power-saving computing solution as well. It has a maximum power usage of approximately 90W and therefore consumes much less power than full-sized desktop workstations, making it ideal for remote or off-grid deployments. Paired with a solar panel and portable power station, it can be run for weeks in the field without access to a constant power supply. This makes it highly suitable for mobile spectrum monitoring tasks, e.g., passive radar detection, interference monitoring, or environmental RF scans.

In conclusion, the Intel NUC 13 NUC13ANHi7 Arena Canyon Mini PC is a powerful, compact, and low-power computing solution for processing data from a spectrum analyzer. Its powerful processor, large amount of memory, fast storage, and decent connectivity features all work together to make it a great platform for real-time signal processing use cases, while low power consumption and small form factor make it a great candidate for deployment in various environments, from lab setups to field-deployed RF monitoring stations.

Overview of Phone

Power requirements:

Passive aircraft radar systems exploit available signals, such as commercial broadcast transmissions or cell networks, to detect and track aircraft without emitting their own radar pulses. This method significantly reduces power consumption compared to active radar systems, rendering them applicable for covert surveillance and cost-effective air traffic monitoring.

While passive radar systems have lower energy demands, they nonetheless require a highly optimized power supply for continuous signal processing, real-time analysis of data, and communication with other systems. Some of the key power demands are stable power supplies for high-performance computing, low-latency signal processing, and continuous data transmission. Power efficiency is also desirable for mobile or remote installations, where battery life, integration of renewable energy sources, and system optimization are of paramount concern.

The power needs of an Aventas AX-37A log-periodic dipole antenna and a Signal Hound BB60D spectrum analyzer must be considered thoroughly to be able to continue running uninterruptedly and efficiently within a passive aircraft radar system. The Aventas AX-37A log-periodic dipole antenna is a passively operated receive antenna and does not contain an external power source for minimal use. But since it has an LNA that acts to enhance reception of the signal, it will require additional power, typically between 5V to 12V DC, depending on the type of amplifier model. The power consumption of an LNA is typically low, typically between 0.1W to 1W, but will have to be added to the overall system power consumption.

The Signal Hound BB60D spectrum analyzer, which itself processes and analyzes the incoming signals through the antenna, has more particular power requirements. It is powered through USB 3.0 and requires a stable 5V DC power source, at around 4.5W (or roughly 0.9A of current). Though this power is relatively low compared to much larger spectrum analyzers, it still requires a stable and consistent power supply so as not to disrupt the signal processing. Because the BB60D is powered via USB, it can be supplied from a connected laptop, but for extended field operation—especially under off-grid situations—an external power station or battery bank with USB 3.0 output is recommended.

For a complete power solution, a portable power station with USB and DC outputs is ideal for use in the field. A minimum capacity power supply of 300Wh can support several hours of operation before being recharged. For continuous usage over extended time, solar panel hardware to provide a minimum of 100W can support continuous operation. With a guarantee of stable, noise-free power supply, BB60D and AX-37A antenna would support effective operation and thus are efficient for passive radar aircraft use.

Additionally, the power requirements of the mini PC must be taken into account. The Intel NUC 13 NUC13ANHi7 Arena Canyon Mini PC is a tiny yet efficient mini PC intended for performance-intensive activities like data processing, media streaming, and even passive radar signal analysis. Its power requirements are supported by its Intel Core i7-1360P processor, 16GB of RAM, and 512GB SSD, all of which are factors in its power usage.

This model supports a 19V DC power supply, rated to deliver up to approximately 90W in full load configurations. In typical usage, e.g., web surfing or light calculations, power consumption will typically fall between 10W and 30W. Under extreme computational processing—e.g., signal processing for a passive radar system—it can draw around 50W to 75W depending on CPU loading and peripheral loading.

For off-grid or mobile applications, such as field deployment with a passive radar system, a portable power station with a 19V DC output or its equivalent AC inverter will be required. A 300Wh to 500Wh battery power station would provide several hours of operation time. For round-the-clock power supply, especially in remote areas, it is best to couple the power station with a 100W or larger solar panel. Also, enabling power-saving options on Windows 11 Pro and BIOS—such as reducing screen brightness, disabling unwanted background tasks, and making use of Intel's power-saving modes—can help extend battery life and improve power efficiency.

~~This section will discuss passive aircraft radar system essential power requirements, exploring trends in power consumption, power management strategies, and the trade-offs between performance, portability, and efficiency, as well as power supply options.~~

The most power-consuming component of a passive radar system is the signal processing unit. Passive systems employ high-performance computing to process reflections, cancel out noise, and track aircraft movement in real-time. According to Griffiths & Baker (2005), passive radar processing requires significant computational power to support the correlation algorithms and the Doppler shift analysis that may consume from 50W to several hundred watts, depending on the complexity of the system and the number of receiving channels.

Passive radar systems make use of multiple receiver antennas to receive signals from different sources. The receivers' power consumption is a function of sensitivity and bandwidth. SDR receivers, which are now commonly used in passive radar, feature typical power consumption of between 5W and 50W per receiver module (Willis, 2011). While low-power consumption receivers improve energy efficiency, high signal-to-noise ratio (SNR) is necessary for making accurate detections.

Passive radar systems generate large amounts of data, which require large storage and communications bandwidth. In networked radar systems, transmission of processed data to centralized control points via satellite or wireless channels can be a large power consumer. Cherniakov (2008) reports that data transmission on long-range wireless channels can be 20W to 100W depending on the bandwidth and encryption requirements. Efficient data compression and low-power communication protocols are required to attain optimum power consumption.

The majority of passive radar installations are either remote or mobile and require ruggedized and power-efficient power supplies. Deployments on UAVs or on ground-based sensor stations often utilize battery power, fuel cells, or other forms of alternative energy sources like solar panels. It has been researched and proven that solar-powered passive radar systems with energy storage can operate with a total power consumption as low as 200W (Griffiths & Long, 2013). Nonetheless, energy storage solutions need to be optimized for round-the-clock operation, with redundancy and resilience to withstand power fluctuations.

All portable power stations have special advantages and disadvantages, which make them suitable for different applications. For the purposes of this prototype, four possible power supplies have been selected to consider. The Westinghouse 100-Watt Solar Powered Portable

Power Station, EF ECOFLOW RIVER 2 Pro, EF ECOFLOW DELTA Max 2000, and Jackery Explorer 300.

The Westinghouse 100-Watt Solar Powered Portable Power Station is highly portable with a weight of just 3.75 lbs, one of the lightest available in the market. It is an affordable and eco-friendly solution for charging small devices such as smartphones, tablets, and LED lights. It also comes with additional versatility with multiple output ports such as USB-A, USB-C, and AC. However, its low battery pack capacity of 155Wh and tiny power output of 150W make it unable to supply power to larger electronics or high-wattage appliances. Moreover, its six-hour charging duration from a wall outlet is inconvenient.

EF ECOFLOW RIVER 2 Pro stands out with its high-speed charging ability, charging up to full capacity in just 70 minutes, one of the fastest for a portable power station. Its 768Wh LiFePO4 battery offers extended lifespan and superior safety level, making it suitable for off-grid uses. At 800W of output and 1600W of X-Boost capability, it can power small kitchen devices and tools, and its multiple AC, USB, and DC outlets support dual device charging. Though, at 17.2 lbs, it's far too heavy for smaller power stations and not very portable. Also, its mid-size capacity may not be sufficient for backup power for extended periods, and it is more expensive than some of its competitors in its class.

For high-capacity, the EF ECOFLOW DELTA Max 2000 is an ideal choice with its massive 2016Wh expandable battery, perfect for powering high-wattage devices. It boasts a stunning 2400W output capacity with 5000W surge and can hence support heavy use appliances such as fridges and power tools. The 1.8-hour fast charging maintains a minimal downtime period, whereas diverse charging provisions are an additional convenience under mixed situations. However, powerful as they are, they are heavy, weighing at 48 lbs, it is the easiest to maneuver on-the-go. In addition, it is one of the most expensive power stations, and its enormous capacity can be redundant for low power devices.

The Jackery Explorer 300 strikes the perfect balance between portability and mid-power. With a weight of just 7.1 lbs, it is extremely easy to transport and ideal for camping, traveling, and outdoor recreation. Its 2.5-hour fast charging using AC and USB-C is efficient for its size, and its 293Wh battery bank carries more energy than the Westinghouse model but in a smaller package. The variety of output ports, such as USB-C, USB-A, AC, and DC, provides compatibility with multiple devices. It is not ideal for charging large electronics, however, with its modest 300W (500W surge) power output. Also, its 100W solar input capacity supports slow solar charging and, while smaller capacity, is more expensive than some of the other competitors in the same category.

Much of the reason for the differences between the power supplies is the type of battery that they utilize, with the Westinghouse 100W and the Jackery Explorer 300 both using lithium ion batteries, while the EF ECOFLOW RIVER 2 Pro and the EF ECOFLOW DELTA Max 2000 use LiFePO4 batteries. In selecting a source of energy for a passive airborne radar system, the criteria are energy efficiency, lifespan, weight, safety, and suitability to the environment. Out of the two battery options, Lithium-Ion (Li-Ion) and Lithium Iron Phosphate (LiFePO4), there exist respective advantages and disadvantages in terms of utilization depending on the radar system's application demand.

Lithium-ion batteries possess greater energy density, typically 150-250 Wh/kg, and can facilitate a light and slim design. They are therefore suitable for applications in mobile or UAV-based radar systems, where weight saving is essential (Whittingham, 2004). They also provide quicker charging than LiFePO4 batteries, which makes them suitable where rapid replenishment of energy is essential. Additionally, lithium-ion batteries are readily available and used in numerous applications, thus easier to implement. However, these benefits come with some drawbacks. Lithium-ion batteries have a short lifespan, typically lasting 500-1,000 charge cycles, meaning they degrade quicker with extensive use (Chaykina et al., 2019). They also come with thermal instability risks, being more prone to overheating and thermal runaway, which can be a safety hazard in extreme conditions. Furthermore, lithium-ion batteries feature a shallow depth of discharge, i.e., they require advanced battery management systems (BMS) to prevent deep wear and degradation.

Compared to them, LiFePO4 batteries offer much increased life, i.e., 2,000–5,000 charge cycles, and can be used in constant or prolonged passive radar use (Kumar & Jain, 2022). They provide enhanced thermal stability and safety and are resistant to overheating, hence are capable of working reliably even at high temperatures or under harsh environments. Stable discharge voltage is yet another key advantage, and this ensures the supply of a constant power source to radar processing apparatus and receivers and minimizes downtime in performance. LiFePO4 batteries do have their flaws, however. They have a reduced energy density of 90-160 Wh/kg and weigh and are heavier and bulkier than lithium-ion equivalents, being possibly a setback to UAV-based or highly mobile radar systems (Wang et al., 2021). Also, LiFePO4 batteries charge longer, which would limit their usage in situations calling for rapid refilling of energy. Their higher initial cost can also be a budget constraint for cash-starved organizations, though their long lifespan offsets long-term expenditure.

The choice between lithium-ion and LiFePO4 batteries is finally determined by the specific needs of the passive radar system. For permanent or fixed installations, LiFePO4 batteries are the better choice since they offer a longer life, consistent performance, and better safety. However, lithium-ion batteries are preferable for mobile, UAV-based, or portable radar systems due to their light weight and higher energy density, which allows for higher mobility. If reliability and lifespan are the most important concerns, LiFePO4 is the preferred choice, but if weight and size constraints are the most important factors, lithium-ion batteries are still a good choice.

For our purposes, going with a model that has a lithium-ion battery makes more sense because the prototype we make needs to be more mobile, and how long it lasts on its own battery-wise isn't as important. Though an official release of the product would likely benefit more from a LiFePO4 type battery due to its long lasting nature and the product's stationary nature.

The Westinghouse 100-Watt model is compact, eco-friendly solar charging but has limited solar input capacity of around 30-40W. This means solar panel charging can be sluggish, especially in low sunlight conditions. While third-party solar panel compatible, it may be adapter-limited, which could decrease convenience. With its small 155Wh battery, solar charging can remain a viable alternative for low-power consumers.

The RIVER 2 Pro has premium solar charging technology, with an input of up to 220W solar. This allows for a full charge in as little as 4 hours of optimal sunlight exposure, making it an excellent choice for off-grid applications. Not only is it compatible with EcoFlow solar panels, but it's also compatible with third-party solar panels, hence offering users freedom. The LiFePO4 battery also features a flat charge-discharge profile, making the efficiency of long-term solar charging better. Its MPPT (Maximum Power Point Tracking) controller ensures maximum efficiency in solar energy conversion under changing sunlight conditions.

The DELTA Max 2000 has the highest capacity of solar input among the compared power stations with the ability to handle a maximum of 800W solar input. It supports high-speed solar charging, and charging its 2016Wh battery to full capacity is feasible in 2.5–3 hours using multiple high-efficiency solar panels. This renders it one of the best options for home backup and off-grid power solutions that can power high-energy appliances without relying on the grid. Like the RIVER 2 Pro, it features an MPPT controller, which optimizes solar efficiency. However, to utilize it at its best, several high-wattage solar panels will be required, which is costly and takes up a lot of setup space.

Jackery Explorer 300 is moderately powered solar, with a maximum input of 100W. It will charge fully in about 5 hours using Jackery's SolarSaga 100W panel under perfect sun conditions. Not as powerful as the EcoFlow models, it supports efficient off-grid charging for low to medium-powered devices such as laptops, devices, and cameras. But its solar input limit guarantees that charging can take much longer if sunlight conditions are not ideal.

Solar power capabilities are very important for this prototype because the final project will be reliant on the ability to be self-sufficient when it comes to power. They are designed to stay in one place for incredibly long periods of time without needing to be actively maintained, meaning that they need to have batteries that don't run out, and more specifically, the ability to recharge themselves without anybody needing to manually recharge it. Though the low-power nature of the device means that the solar capabilities don't need to be very powerful, rather the device should be able to sustain itself off of a low-speed charge via the sun, so sacrificing solar power speed for cost will be worth it.

One of the largest determining factors between the power supplies is of course the cost. Since the main goal of this prototype and eventual full product is to introduce a very low-cost passive radar into the market of similar quality, the ultimate goal is to hit that low cost, high affordability threshold. Low costs are produced by choosing components and necessary pieces of the product that are similar quality to others on the market while maintaining a low price, this means that the lowest cost option that still meets all of the requirements is the ideal product.

Table XXX Comparison of Power Supply Technologies

Feature	Westinghouse 100W	EF ECOFLOW RIVER 2 Pro	EF ECOFLOW DELTA Max 2000	Jackery Explorer 300

Battery Type	Lithium-Ion	LiFePO4	LiFePO4	Lithium-Ion
Battery Capacity	155Wh	768Wh	2016Wh (Expandable)	293Wh
Power Output (Rated/Surge)	150W / Not specified	800W (1600W X-Boost)	2400W / 5000W	300W / 500W
Solar Input	Yes	220W max	800W max	100W max
Weight	3.75 lbs (Lightest)	17.2 lbs	48 lbs (Heaviest)	7.1 lbs
Price	$0(cheapest)	$379	$1299(most expensive)	$259
Dimensions (inches)	7.4 x 6.6 x 3.7	10.6 x 10.2 x 8.9	19.6 x 9.5 x 12	9.1 x 5.2 x 7.8
Best Use Case	Small devices, ultra-light travel	Mid-range power needs, tools, RVs	Home backup, high-power appliances	Camping, small device backup

Lastly, choosing the most appropriate power station is a personal need issue. The Westinghouse model is appropriate for light travel and low power demands, the RIVER 2 Pro offers power and portability, the DELTA Max 2000 is appropriate for heavy use, and the Jackery Explorer 300 is an excellent middle-of-the-road option.

Westinghouse 100-Watt Solar Powered Portable Power Station is the most suitable power supply for a passive aircraft radar system due to its portability, lower cost, and sufficient power output for low-power radar functionality. Passive radars, unlike active radars utilizing active transmissions, require low to moderate power consumption to drive the signal processing, data analysis, and communications hardware. With its 155Wh lithium-ion battery and pure sine wave output, the Westinghouse power station provides stable and clean power, ensuring solid performance for radar equipment without introducing electrical noise or instability.

One of the finest features of this power station is that it is portable, with a weight of only 3.75 lbs, which is ideal for mobile or field-deployed passive radar installations. Since passive radar systems are typically used for covert surveillance or mobile reconnaissance, a lightweight and easily transportable power supply is an excellent advantage. Its several output ports also allow for powering laptops, signal processors, and communications equipment at the same time, which are essentials for running radar.

The Westinghouse 100-Watt's solar readiness also enhances its suitability for passive radar use. With its ability to charge through solar panels, it can be topped off continuously even in the middle of nowhere, with a guarantee of long-term performance without the requirement for traditional power sources. While its 150W peak power delivery may not be sufficient to support power-intensive radar setups, it is more than adequate for low-power passive radar implementations where efficiency is given more priority than raw power.

While the Westinghouse 100-Watt represents the most pragmatic choice for a passive aircraft radar, the other power supplies all possess drawbacks which make them less ideal for this specific application. Passive radar systems tend to require low to moderate power consumption, with an emphasis on portability, efficiency, and affordability being more important than redundant energy reserves. The other power stations all have different advantages, but also have drawbacks that make them less suitable for passive radar applications.

The EF ECOFLOW RIVER 2 Pro, for instance, has a significantly larger battery capacity (768Wh) and faster charging rates compared to the Westinghouse 100-Watt. With the ability to charge from 0-100% in just 70 minutes, it is a high-power option for customers who need a reliable, high-capacity power station. In addition, its LiFePO4 battery lasts much longer than traditional lithium-ion batteries, making it a long-term option for long-term use. These advantages come with trade-offs that make it less ideal for passive radar systems. Its larger and heavier form makes it less portable than the Westinghouse lightweight model, an important factor for radar installations requiring mobility. Aside from this, the RIVER 2 Pro is also much more expensive, routinely retailing at nearly three to four times the price of the Westinghouse offering. Because a passive radar will not require such capacity, it is superfluous to spend more money on a higher capacity, larger power station.

Similarly, the EF ECOFLOW DELTA Max 2000 is even more overkill for the needs of passive radar, boasting a 2016Wh battery capacity and expandable power. While this makes it an excellent choice for home backup power or heavy off-grid applications, it is too heavy and expensive for a passive radar system, where efficiency and portability are more important than raw power. The DELTA Max is one of the heaviest and largest units in this comparison, so it's not suitable for field deployments where mobility is required. Additionally, its large power output is overkill for passive radar use, where power consumption is dominated by low-power signal processing and computing rather than powering high-wattage equipment. The DELTA Max's fast recharge time (1.8 hours full charge) is a nice feature to have but is not required here, as passive radars do not drain power as quickly as power-hungry systems. The DELTA Max's price is also exorbitantly high, making it a poor investment when the same operational needs can be met with a much smaller power station.

The Jackery Explorer 300, while a cheaper mid-range option, still doesn't give the same cost-to-performance ratio as the Westinghouse 100-Watt. It also has a higher battery capacity (293Wh), which might initially seem to be advantageous for extended radar use, but also means longer charge times and additional weight compared to the Westinghouse unit. Because a passive radar system does not require continuous high-wattage draw, the additional battery life is not a significant advantage. Moreover, the solar input limitations of the Jackery (100W max) mean that it doesn't charge as well as newer units, such as the EF ECOFLOW RIVER 2 Pro, and is also more expensive than the Westinghouse. The Explorer 300 also weighs more, making it less portable for use in the field where smaller, lighter power sources are preferable.

Ultimately, all three alternative power stations provide more power than necessary for a passive aircraft radar at the cost of portability and price. The EF ECOFLOW RIVER 2 Pro and DELTA Max 2000 are significantly larger, heavier, and more expensive than necessary for a low-power portable radar system. While the Jackery Explorer 300 attempts to achieve a greater balance, it still fails to be as compact or affordable as the Westinghouse 100-Watt. As passive radar installations prefer light, portable, and low-cost solutions, the Westinghouse 100-Watt remains the better choice, offering just enough power in a compact, affordable, and solar-friendly form factor.

Furthermore, the affordability of the Westinghouse 100-Watt makes it a financially feasible choice compared to big power stations like the EcoFlow DELTA Max 2000 or Jackery Explorer 300, which feature much more power than is needed for passive radar demands. This makes it an ideal choice for economically limited deployments with a high degree of assured and stable power for important radar components. Lastly, the combination of portability, solar functionality, constant power output, and affordability makes the Westinghouse 100-Watt the perfect choice to supply power to a passive aircraft radar system in various operating conditions.

Communication Protocol (Camera Array) - USB Hubs

The main hurdle to deal with when using USB connections and cameras is bandwidth. To really make use of the OV9821's high frame rate, we'll need to avoid what is known as bottlenecking. This refers to the limitation of a communication method, like a USB connection, to handle data. Since each camera can have a max frame rate of 100 frames per second, connecting them all through a usb hub won't be enough. This was a problem we ran into during our midterm demo testing with cameras that only had 15 frames per second. With that said, the next section of research will be looking at different USB hubs that have the capability to handle the bandwidth of multiple camera connections.

The first USB hub we researched was the **Anker 10 port** USB 3.0 data hub. The total bandwidth of this device is 5 Gbps which is shared across all of its ports. It also features a 60 watt external power supply adapter which makes it a good choice for connections that require stable power distribution. Each USB 3.0 port can handle around 480 Mbps if all ports are used simultaneously. If we were to connect 3-4 cameras to the USB hub, each camera could get around 1.2 Gbps which would be suitable for our needs. The price of the USB hub is around $50 which makes it a little expensive for a connection hub, especially considering that when all connections are used, the full 5Gbps speed would not support all ports.

The second USB hub we researched was the **StarTech 4-Port** USB 3.0. This USB hub would be ideal for preliminary testing since it features only 4 ports and is less than other USB hubs out there that do the same thing. Like the Anker model, this hub has a total bandwidth of 5 Gbps which, when four cameras are in use, would likely cover the amount of bandwidth needed to run each camera. The main downside to this hub is the power. Since it doesn't have an external power adapter it runs the risk of not having sufficient power for each of the cameras. While the cameras may not consume a lot of power, this may be a risk we want to avoid.

The third USB hub we researched was also a StarTech brand hub, this time with 7 ports. The **StarTech 7-port** USB 3.0 hub is in all ways an upgrade from its 4-port counterpart. Like the 4-port, it also features a shared bandwidth of 5 Gbps but is better suited for multi camera use. Since, with this model, all ports would not be used at the same time with 5 cameras, the hub would be able to provide good bandwidth for each camera. It also features an external power adapter, listed at 36 watts, which should be plenty sufficient for our camera array setup. While the price is higher than the 4-port version, the additional features that this model provides reduces certain risks that we otherwise would've encountered.

The last USB hub we researched was the **Plugable 7-port** USB 3.0 hub. This USB hub also has 7 ports like the StarTech and features a total bandwidth of 5 Gbps. The external power adapter for this model however is listed at 60 watts which is more than sufficient for our case. This model would be the choice in the ideal case since it is more robust and industry level grade, however, it is not as readily accessible as the other models. Some of their other models are available on Amazon which would make the process of obtaining them much easier, whereas this model is ordered directly through the makers website, leaving uncertainty in the arrival time. Additionally, this model is more expensive but is definitely the best option.

USB Hub	# of Ports	Bandwidth	External Power	Bandwidth for each port	Best for multi-camera use	Price
Plugable 7-Port	7 - USB 3.0	5 Gbps	60 W	Highest stability for each port	Best for multiple camera setup	~$50
StarTech 7-Port	7 - USB 3.0	5 Gbps	36 W	Higher stability for each port	Best if all ports are not used, 4-5 cameras	~$60
Anker 10-Port	10 - USB 3.0	5 Gbps	60 W	Lower bandwidth per port	Lots of ports, but when all are in used, performance issues	~$40
StarTech	4 - USB	5 Gbps	None	Lower		~$35

USB Hub	# of Ports	Bandwidth	External Power	Bandwidth for each port	Best for multi-camera use	Price
4-Port	3.0			bandwidth and possible power issue risk		

Overall, the best choice for this project would be the Plugable 7-port USB hub. Its higher external power availability would ensure that power would not be an issue. Additionally, if we were to use around 5 cameras, each camera would have sufficient bandwidth and would have good stability. The alternative option, the StarTech 7-port, has the necessary bandwidth with slightly less power but would still work well for 4-5 cameras. The pricing is slightly higher, but we would be able to ensure a delivery time that is conducive to our success for senior design. The other options have either too many ports, in the case of the Anker, which reduces the bandwidth availability per port, or have a risk of not providing the necessary power for our cameras, in the case of the Startech 4-port. For this reason, the Plugable 7-port will most likely be our choice of USB hub. On Amazon, it is currently listed for $24 which makes it more affordable than the other choices and with more features.

Programming Languages (Camera Array)

Another consideration we will have to make is which programming language or packages would help us to do super resolution. Since super resolution involves digital image processing, some basic machine learning, and algorithms that involve convolution, we'll have to find the programming language and any packages that would be best suited for that need. Since our part of the project, as PSE students, is only focused on creating a super resolution image, we won't have to worry as much about detection algorithms.

The clear frontrunner for our project was Python. Python features extensive libraries with image processing tools, and has lots of tools that can assist with deep learning, which is used in computer vision. Additionally, it is easy to integrate with OpenCV, a computer vision package, which is something we ended up using during our midterm demo. Python is also generally listed as one of the best languages for super resolution, both for AI based or classical interpolation based super resolution. As mentioned, one of the packages we would need would be OpenCV which is for general image processing. We would also need Numpy, this would allow us to do our mathematics more efficiently, especially when dealing with array and matrix operations. Overall, Python worked well for our midterm demo and may be the best option for our future iterations.

The next programming language we researched was C++. This programming language emerged as a possible option because of its real-time applications and its general speed compared to

Python. This language, like Python, also works well with OpenCV and has similar libraries to Python that allow for fast matrix operations and good image processing. While this is a strong option, our experience with C++ is very minimal and using it would require a lot more time to get right. For this reason, C++ would not be great for our project.

The last programming language we looked at is one that PSE students are very familiar with, MATLAB. MATLAB features strong built-in image processing and interpolation tools which are vital to our project. Its main drawback is in its use case. Unlike Python or C++, MATLAB is better suited for algorithm development rather than real-time development. However, MATLABs strength in image processing could be good as a supplemental tool if we were to use Python. Since Python would be in charge of running the cameras, to lessen the load or make computations slightly faster, we could use MATLAB to do the image processing while Python focuses on capturing usable images. With this system, our project's overall efficiency would be much faster, and we'd be using two programming languages we are very comfortable with. For these reasons, we will opt to use Python and MATLAB in tandem to produce the best results possible as quickly as possible.

Super Resolution Techniques

Now that our programming language is established, we'll need to look into different ways to actually apply super resolution techniques. First, we have to understand what super resolution actually means. Super resolution refers to any technique that works to enhance the resolution of an image beyond the native capabilities of the imaging system. It mainly works by using one or multiple low resolution images and attempts to reconstruct a high resolution counterpart from the information of the low resolution images. The best example of how this would work in an ideal world actually appears in hollywood. In some crime shows, it is very common for there to be a low resolution image that is then zoomed in and enhanced to reveal extraordinary detail about whatever scene is being shown. While that level of super resolution is certainly not realistic, it shows how powerful this type of technology could be and its potential applications.

So, how is it done? Super resolution leverages the idea that any low resolution that lacks detail can be reconstructed with multiple images or AI based methods. With that said, we can explain super resolution as a process of reconstructing a high resolution image, typically denoted as I_HR, from low resolution images, I_LR. This process involves signal reconstruction, image alignment, and learning based enhancements. Mathematically, we can model the process as the following:

$$I_{LR} = D(B(I_{HR})) + N$$

In this equation, we model the degradation process, or the process of getting a low resolution image from its high resolution counterpart, as a blurring function B, due to optics, sensors, or motion, and a downsampling function D, representing the loss of spatial resolution, onto the high resolution image I_HR. After those processes are applied to the high resolution image, there is also a compensation for noise N, due to the sensor noise or compression artifacts for example. Now that this process of degradation has been established, our goal when we do super resolution is to reverse this degradation and estimate the high resolution image from its low resolution counterpart.

While mathematically it appears very simple, there are many different approaches and methods that all have varying degrees of accuracy. Since it is generally impossible to get a perfect high resolution counterpart, often called the ground truth high resolution image, defining what success is when it comes to our context is important. For our purposes, we will define accuracy in 2 ways. The first way is just through general appearance to the naked eye, essentially answering the question of whether or not the image looks more clear or crisp. The other way we will define our accuracy will be through edge detection programs. While making the image look better is important, the edge detection protocol is how we prove that our concept and method of application is actually useful. Typically, when you want to detect if an aircraft or drone is in the sky above you from a picture, the image usually does not possess the clarity or resolution to effectively define edges, such as the wing of a plane, that a detection software can see. By defining our success as seeing if an edge detection software can detect more edges in the high resolution image compared to the low resolution counterpart, we will be able to claim that our approach is actually viable for the proposed application. The naked eye test is present as well to make sure that the images are actually representative of what the scene is showing. One method used to measure the quality of a super resolution image known as mean squared error shows why including the naked eye test is important. In the image below, all the super resolution counterparts have equal mean squared error values but the image at the top is clearly the best and most convincing high resolution image out of the group.

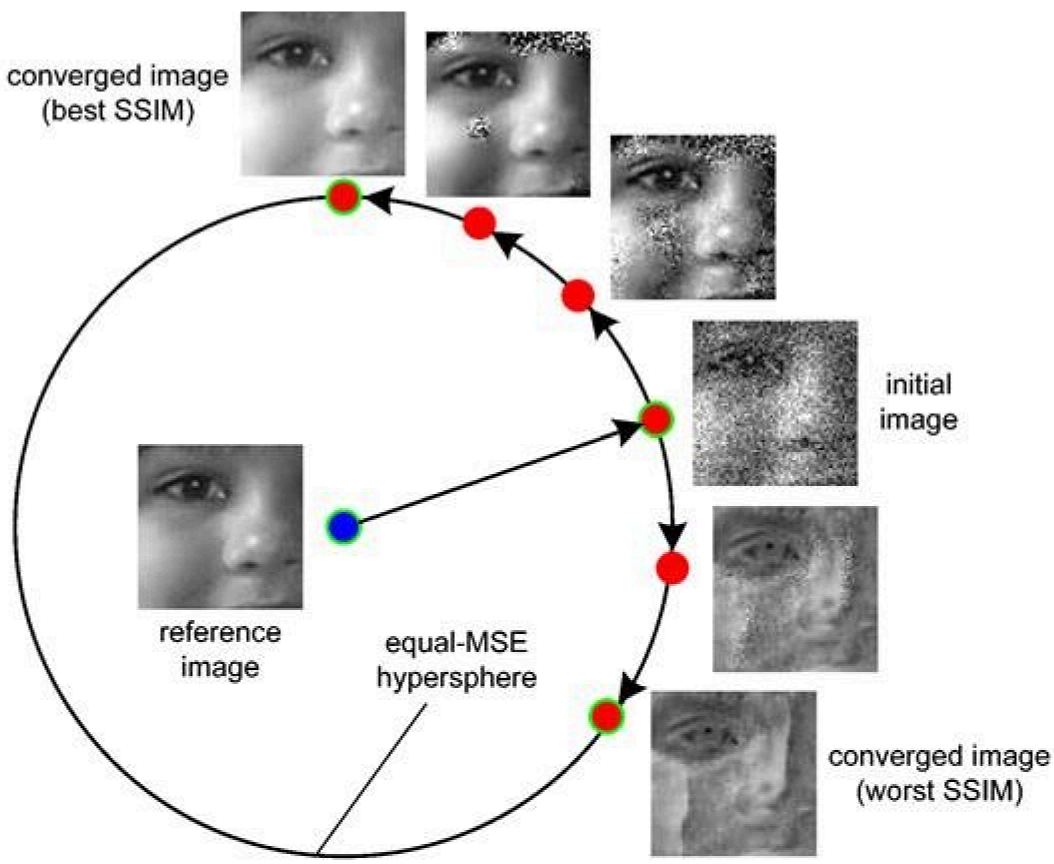

Figure XXX *Mean squared error reliability example (ResearchGate)*

Now that our success condition is established, let's look at the different methods of doing super resolution. One of the approaches to this problem is the interpolation based strategy. This approach tends to be one of the simplest super resolution methods and it works by estimating missing pixel values. While these methods are computationally efficient, they are unable to add any new information than what is already present in the image. Under this umbrella, there are three main types of interpolations: nearest-neighbor, bilinear, and bicubic. The nearest neighbor interpolation method uses the nearest pixel value and copies it to the pixel it is attempting to estimate. This usually results in blocky or pixelated images. Bilinear interpolation uses a weighted average of the four closest pixels to the pixel it is attempting to estimate. While similar to the nearest neighbor, this method produces a smoother image but generally lacks detail. The last method, bicubic interpolation, works similarly to bilinear but uses a weighted average of the nearest 16 pixels. This results in the smoothes images of the three methods but is still limited when it comes to restoring high frequency details.

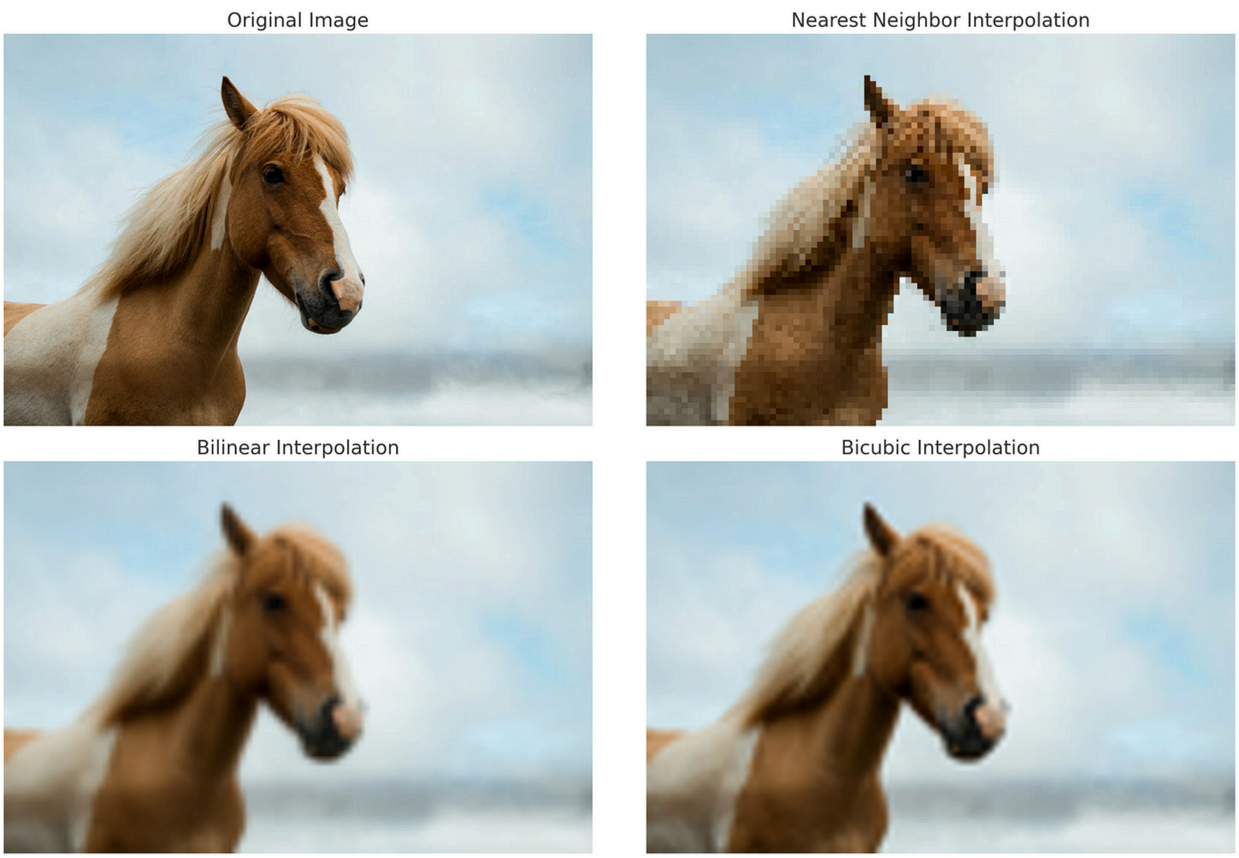

Figure XXX *Nearest neighbor vs. Bilinear vs. Bicubic interpolation (Medium)*

Above is an image that shows how these three methods compare when looking at the same scene. From the image above, it is clear to see that the more computational power that is being used, the better the result is. While these methods are not perfect, they are able to act on a single image to produce a higher resolution counterpart. The main limitations are of course the clarity of the image and the inability to capture finer details.

The next approach we'll look at is the multi-image super resolution approach or MISR. MISR reconstructs a high resolution image from multiple low resolution images captured from slightly different viewpoints or at different times. Before this can be done though, the images must be properly aligned. This involves estimating the transformation T that would map one image onto another. In this context, the transformation T can represent a translation, rotation, scaling, shearing, or homography which is perspective correction. This transformation can be done through feature based techniques, which looks for similar features in the images and attempts to align them, or through optical flow techniques, which estimates pixel displacements. Both techniques work best when the imaging devices are close to each other or are capturing a far scene. If those conditions are not met, there is a high risk of distortion appearing in the final image, an issue we dealt with during our midterm demo.

Once the images are aligned, the reconstruction process can commence. The two main techniques to do this are back projection and Bayesian estimation. Back projection is a common imaging technique that is often seen in tomography. It involves sending a signal from different perspectives to image something more clearly. In the case of MISR, back projection is an iterative algorithm that refines a high resolution image estimate by comparing it to the original low resolution image and correcting errors. The key to this technique is that if you downscale the estimated high resolution image, it should match the observed low resolution images. This method, therefore, ensures that the high resolution image is consistent with the input low resolution images and it corrects errors rather than blindly sharpening or upscaling parts of the scene. This technique works well for multi frame super resolution since different images are able to provide different perspectives of the scene but is limited when the image is large or is severely degraded. The algorithm is best depicted through a visual representation which can be seen below in a more advanced way, as proposed in a paper titled Deep Back-Projection Networks for Super Resolution.

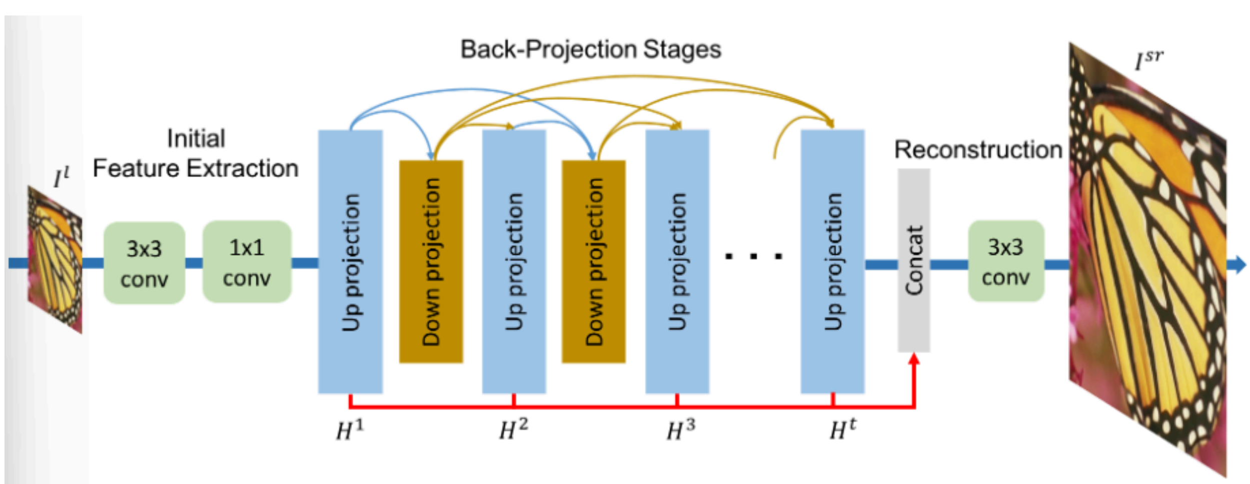

***Figure XXX** Back projection algorithm visualization (Haris, Shakhnarovich, Ukita)*

The other technique, Bayesian super resolution, uses probabilistic models to infer the high resolution image by maximizing the posterior probability. In more simple terms, it maximizes the probability of the high resolution image it produces being the best image given the observed low resolution inputs.

$$P(I_{HR}|I_{LR}) \propto P(I_{LR}|I_{HR})P(I_{HR})$$

The equation above is known as Bayes' theorem and we want to find P(I_HR|I_LR), which is the posterior probability. Here, P(I_LR|I_HR) is how likely the low resolution images are given the high resolution image, and P(I_HR) is the prior which is what we assume about natural images such as the smoothness. While the math is a little complex, the main idea is that Bayesian super resolution is a technique that incorporates prior knowledge which makes it more robust to noise and missing details. It works well in low-light or noisy environments but is computationally expensive and intensive. However, it does yield more stable results than back projection alone.

The last group of super resolution approaches are defined by their learning based approach. This approach is the way modern super resolution techniques are done. It involves deep learning, particularly convolutional neural networks or CNNs, and transformers to learn complex image mappings. One technique using this approach is known as SRCNN or super resolution CNN. The model takes an interpolated low resolution image and learns to predict the high resolution details. This process involves feature extraction which is done by applying convolution to extract edge and texture features, non-linear mapping, which transforms features into a high frequency detail representation, and reconstruction to generate the final high resolution image. Mathematically it can be represented as the following equation where W is the CNN parameters and F is the process done on the low resolution image to obtain the high resolution image.

$$I_{HR} = F(I_{LR}; W)$$

ESRGAN

Comparison of super resolution methods and justification for choice

Chapter 4: Standards & Design Constraints

Optical Standards

As engineers, understanding standards and constraints is one of the most important parts of our profession. Standards, which are established guidelines or requirements that define how something should be done, help make sure that safety and regulatory laws are followed. Constraints, on the other hand, help you to define what is actually possible or realistic in the context of the problem you are trying to solve. In senior design, understanding these two things is crucial to our success and help us to create feasible projects.

While there are many standards that relate to our project, some of the most important to consider and understand are ISO 12233 which defines the method for measuring spatial resolution of an imaging system, USB3 Vision which defines how cameras transmit video over USB 3.0 connections, and IEEE 754 which defines floating point arithmetic which is used in image processing algorithms for precision in super resolution calculations. These three industry standards all relate to the camera array and address different parts of the super resolution process, being the definition of resolution, communication using USB 3.0, and image processing with floating point arithmetic. For optics purposes, we will explore two of these standards, ISO 12233 and IEEE 754, and see how each one really contributes to our project and help us through our senior design process.

First is ISO 12233. This is a standard that defines test methods for measuring the resolution of digital cameras and imaging systems. It is relevant to our project since we are attempting to use super resolution techniques and this standard provides a quantitative way to evaluate and improve image resolution. Super resolution techniques aim to reconstruct details from multiple low resolution images and this standard has standardized charts and methods to quantify the spatial resolution of a system before and after super resolution processing. This helps us to validate if our system is actually enhancing detail. Additionally, this standard can help evaluate lens performance by inspecting different types of characteristics such as distortion, sharpness, and contrast loss which helps guide our optical design process. While we are comparing different approaches or arrangements of our camera array, this standard will help provide a benchmark to go off of and will ultimately help us determine the best configuration and most effective setup. So, while this standard does not seem like it's being used often, everytime we consult the resolution of an image or the effectiveness of a certain setup or technique, we are actually making use of this standard. Without this standard, measuring resolution would be much more difficult and would likely require the naked eye, which may not be able to pick up slight improvements in resolution depending on the image that is being used. Overall, this standard is not just important to our project but to any imaging system.

The second standard that affects our optical design is IEEE 754. This standard is the floating point arithmetic standard which is primarily used for representing and computing numbers in digital systems. While it is not directly related to image resolution like the previous standard, it plays an important role in numerical accuracy for our super resolution application. Super resolution is an inherently mathematically intensive process and when things like image alignment, filtering and convolution, and interpolation and reconstruction are done, high precision is required. Floating point arithmetic helps make sure that these processes are done accurately and more efficiently. Without this standard you would run the risk of introducing rounding errors which are present in other algorithms, precision loss, and overflow or underflow when dealing with large or small pixel values. IEEE 754 helps mitigate these risks by defining standardized floating point arithmetic formats, such as single precision and double precision, ensuring predictable results during our image processing process. Additionally, based on which level of precision we are looking for, we can use this standard to help balance speed and accuracy throughout the super resolution process.

To summarize, there are many different standards that relate to the context of our problem. The main ones we have considered help us define key parts of our project such as resolution and parts of the image processing train. Without these standards, finding a consistent way to evaluate the performance of our system or the effectiveness of our image processing techniques would be nearly impossible. For that reason, it is important to understand how these and other standards affect our design process.

Optical Design Constraints

One of the main constraints of this project is the budget. While there is no set budget, our project is attempting to find a low cost solution to the aircraft detection problem. For optics, this can result in many challenges. When trying to deal with low cost optical components, it can be hit or miss. ***Continue***

- Budget → cameras → pixels/resolution
- ITAR restrictions
- Time constraint limits how much we are able to accomplish → phase correction plate for example

Hardware Standards

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Software Standards

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Chapter 5: Comparison of ChatGPT With Other Similar Platforms

AI has quickly become one the most popular and revolutionary technologies of our generation. With platforms, like ChatGPT, making interacting with AI easier than ever, it is important to understand its strengths as well as its limitations. As engineers, we need to be able to understand how to use AI as a tool since it is a technology that will be part of our future. To showcase how helpful or harmful the use of AI can be when dealing specifically with senior design, each of us conducted a case study specific to our area of study.

Case Study 1: (**Make more technical**)

The first example relates to optics and was conducted using Chatgpt. In this project, Chatgpt was really helpful when we were first starting and figuring out what we wanted to do. Originally, our project was based around a single RF detection device and our goal was to figure out a way to enhance that device with optics. Since I personally didn't have much experience with RF technology prior, Chatgpt was able to provide much needed context around it and how it is used for detection. After I understood how RF technology worked, I wanted to understand how optics could be involved, since it wasn't clear to me how optics would merge with an RF based device. This is where I really began to understand how optically enhanced detection devices worked, and Chatgpt provided multiple examples that I was able to read into and learn more about. These examples were what I based my similar products research on. In this case, when learning about something, Chatgpt excelled at providing lots of information and context with relevant examples. The main issue here was that some of its information was slightly inaccurate or outdated which can be attributed to its database. However, rather than spending hours upon hours trying to get a baseline of what I was dealing with, Chatgpt helped me establish that baseline much faster.

Next, I really wanted to see how good Chatgpt was when it came to optics and engineering. To test this out, I presented Chatgpt with our project's main problem. I asked Chatgpt to come up with a solution to detect an aircraft using optics. The result it provided was actually not too bad but left a lot to be desired. Chatgpt provided its answer in the form of a list with different methods to solve my proposed problem. In total, Chatgpt provided five different methods that involved optics, one of which included our proposed solution involving super resolution. Each method was paired with a small list of justifications and explanations that informed you which was best for what situations. Additionally, it provided some alternative enhancements to help each of the methods possibly perform better, including the use of polarization filters. Overall, not bad, but pretty basic.

To further test this, I wanted to see how it would go about doing its proposed super resolution solution, so I asked it to dive deeper into that one. To my surprise, Chatgpt provided a lot of quality information. It was able to explain, at surface level, different ways to do super resolution, different computational imaging techniques, some of which are even beyond my understanding, and provided different applications where this method is used and what possible challenges may be encountered. This insight, when starting out, is incredibly helpful and gives you a good basic understanding of what goes into doing super resolution. One thing I dont like about this is how simple its responses are though, it makes things look too easy. Realistically, executing an idea like this would take lots of knowledge of mathematics, physics, optics, and image processing and the way Chatgpt presents it makes it look like anyone can do it, and here is where the danger lies.

The real danger of using LLM like Chatgpt is actually in its presentation of information. If you were not as educated on optics, or mathematics, or image processing, you would look at this information and be set. To the trained eye, however, it is very easy to see where Chatgpt makes mistakes or does not evaluate the entirety of the situation. If you were to go into senior design and only rely on Chatgpt, you would learn absolutely nothing. While it is helpful to learn about things you may not have understood well before, the fact that it presents information so simply and quickly to you is a real risk. Without doing your own proper research, even if it's just to verify what Chatgpt is saying, you leave yourself vulnerable to mistakes. Chatgpt operates on a database, one which may contain outdated information, meaning it is vital to make sure what Chatgpt tells you is actually accurate. Additionally, if Chatgpt can basically tell you how to do an entire project, what use are you as an engineer? To be a successful engineer in our age, you need to find a way to be valuable, and that means being able to add to AI. Simply relying on AI and its outputs will not be conducive to any kind of success, especially as an engineer, but using it to your advantage and as a tool to make you more efficient is how you become a valuable asset in the AI age.

Case Study 2:

One of the problems for the electrical engineers when looking for the Displayed Average Noise Level (DANL) of the spectrum analyzers. For a lot of the sources that we used it was not very apparent where to find that information. Seeing as it is a fairly common and important specification of spectrum analyzers. Which prompted a question for chatGPT being, “What’s the best way to advertise DANL.” This was prompted as there may be lingo or jargon involved in this field that isn’t apparent to someone that doesn’t particularly know much about it. ChatGPT took the question from a marketing perspective. It mentions using a standardized format, dBm/Hz or specifying key conditions such as Preamp, RBW or Frequency range. It also mentions using graphical representations may help drive our point. Or that we need to highlight the real world benefits and even compare against competitors. This was not quite the engineering approach that was specifically wanted from ChatGPT. It tried its best, but ultimately may have misled someone that may have not known what they were looking for. In our case, this was immediately seen as it took the wrong way and promptly led to a google search to see if there were any other ways to find this important specification.

Case Study 3:
One of the examples relates to the power requirements of the passive radar for detecting aircraft. I have very little experience with RF devices in general and there is a lot of variance between different products based on how complex they are, how accurate they are, whether they are active or passive, etc. Chatgpt was an excellent resource in finding not only the kind of information I was looking for, but also where to find that information by having it provide me the sources that it was getting the information from, allowing me to check and read them for myself so I could better grasp how much power a device like this would require. This led directly into searching for power sources for the passive radar.

Chatgpt was also very helpful when it came to comparing the data that I had found. Once I had found multiple power sources that met the requirements for the passive radar I needed to compare and contrast them, normally this would require a lot of in-depth searching and take a lot of time to create a table that easily compares every metric that I was looking at for making the decision between them, but by prompting Chatgpt to compare the power sources and their usefulness when it comes to powering a passive radar, it put all of the data I could need and then some into a table that directly compares each of the power banks based on output, battery capacity, battery type, price, solar input capability, weight, and size dimensions. These were the factors that were taken into account when choosing which of the 4 options I had to pick from for powering the passive radar.

Furthermore, Chatgpt also helped with the writing process for comparing each of the power banks. After prompting it to compare and contrast them for use in powering a passive radar for aircraft detection, it gave me the table, and also listed out pros and cons for each of the devices in bullet point format, giving me ideas and making the writing process for actually explaining my decision a bit easier, since I had all of the important points that I needed to hit listed out in separate sections for each of the power banks and a small summary of what situations they would be better or worse than the other options for this specific device.

Although this paints its strengths very well, I also wanted to test its weaknesses. To do that I began by adding some bias into prompts essentially asking the same things as before. One at a time I prompted Chatgpt to compare and contrast each device and explain which one is the best for use in powering a passive radar for aircraft detection, but for each of these prompts I specified that it needed to explain why a different option was the best option for our purposes-for example: “explain why the Westinghouse 100W is the best option for powering a passive radar”- and doing that style of prompt for each of the four options. Chatgpt did a great job arguing and explaining exactly what it was asked, but this is a weakness of the AI because it means that the information it gives is biased to what you ask it, so regardless of what the best option for a passive radar actually is, it will just tell you what it is asked at the time.

This is a major problem with AI because it means that regardless of how helpful it is, it is important to be very careful with the prompts that you ask it, because the slightest amount of bias in a question will result in a biased answer, further compounded by the fact that previous answers in a conversation with it will influence later answers, so if you ask it biased questions in the beginning, and later ask it an unbiased one in the same topic, it is likely to give you an answer based on the previous bias given.

Ultimately the important takeaway from this study is that it’s important to use Chatgpt for what it is, a tool. It is an amazing tool for summarizing and explaining information, it’s a great tool for getting ideas for what to research on your own and where, and it’s really good at helping in the writing process when you get stuck and need to move forward with your thoughts. But reliance on it to do the research and work for you will result in biased information and decisions that should be made through critical thinking, instead being made based on what has been done before, rather than what the best option truly is.

Case Study 4:
One of the major challenges in developing our multi-camera super-resolution imaging system was understanding the concept of super-resolution itself and determining the best lens configurations for our setup. Initially, I had a limited grasp of how super-resolution worked and why it was necessary for our project. I turned to ChatGPT with a simple question: "How does super-resolution work?" The AI provided a detailed explanation, describing how multiple low-resolution images can be combined computationally to reconstruct a high-resolution image. It introduced me to different methods such as multi-frame super-resolution, deep-learning-based enhancement, and interpolation-based upscaling. While the explanation was helpful, I needed more specific guidance on why we should use multiple cameras with different lenses instead of identical ones.

After prompting ChatGPT with "What are the advantages of using different lens types in a multi-camera system?", it provided a thorough breakdown of why a diverse lens configuration would yield better results than a uniform one. I learned that using a mix of several lens systems, such as: telephoto, wide-angle, zoom, and fisheye lenses would allow us to capture both fine details and a broader field of view. Telephoto lenses would provide high magnification for distant objects, ensuring that small targets like aircraft remain visible and detailed. However, their narrow field of view meant that they alone would not be sufficient for large-scale scene capture. Wide-angle lenses, on the other hand, could provide a much broader field of view, making them ideal for capturing large portions of the scene and ensuring that all relevant objects appear in the final composite image. Zoom lenses would offer flexibility, allowing us to adjust focal lengths depending on imaging conditions, while fisheye lenses would enable panoramic coverage, reducing blind spots.

Before using ChatGPT, I had assumed that using identical lenses across all cameras would simplify the system and reduce calibration complexity. However, its explanation helped me realize that diversity in lens selection would significantly improve the quality, accuracy, and usefulness of our final image. This led me to rethink how the cameras should be arranged within the array and how different lens types could be combined to create an optimized imaging system.

Once I understood the importance of using multiple lens configurations, I needed to compare specific lens models and specifications. ChatGPT proved to be an incredibly useful tool for this step, as it was able to process large amounts of data and organize it into structured tables for easy comparison. Instead of manually sorting through specifications across different manufacturer websites, I provided ChatGPT with a list of lens systems and their key characteristics. It then generated a structured table summarizing focal length, aperture size, field of view, distortion characteristics, and cost. This streamlined the decision-making process and allowed me to compare lenses side by side without spending excessive time gathering and organizing the data manually.

ChatGPT also played a key role in helping me write and structure explanations for our research findings. After reviewing the comparison table, I asked it to summarize the pros and cons of different lenses for our use case. It provided a clear, structured analysis of each lens type, outlining situations where a given lens would be most effective and where it might introduce challenges. This helped me articulate why certain lenses were better suited for specific roles within our camera array. By having these pros and cons clearly laid out, I was able to more effectively justify our design decisions in technical discussions and documentation.

Beyond research and writing, I also tested ChatGPT's limitations and potential biases. To see how it responded to leading questions, I deliberately asked it biased prompts, such as "Explain why telephoto lenses are the best option for super-resolution imaging", and noticed that it was able to construct a compelling argument for that viewpoint—regardless of whether it was truly the best option. I then repeated the experiment with other lens types, and in each case, ChatGPT provided strong arguments supporting whatever I had asked it to justify. This demonstrated an important limitation: ChatGPT does not independently determine the best option—it tailors responses to the framing of the question. If I had relied solely on its initial answers without critically analyzing the information, I could have been misled into making suboptimal design choices.

Another way I tested ChatGPT's capabilities was by asking it to compare and contrast different camera configurations and justify which was best. When I phrased the prompt neutrally, it provided a balanced analysis of each configuration, listing advantages and drawbacks. However, when I asked it to argue why a curved array was the best option, it presented a detailed case in favor of that configuration, despite the fact that there were still trade-offs to consider. This reinforced the need to approach ChatGPT's outputs with critical thinking and independent verification, ensuring that decisions were based on objective analysis rather than AI-generated justifications tailored to specific prompts.

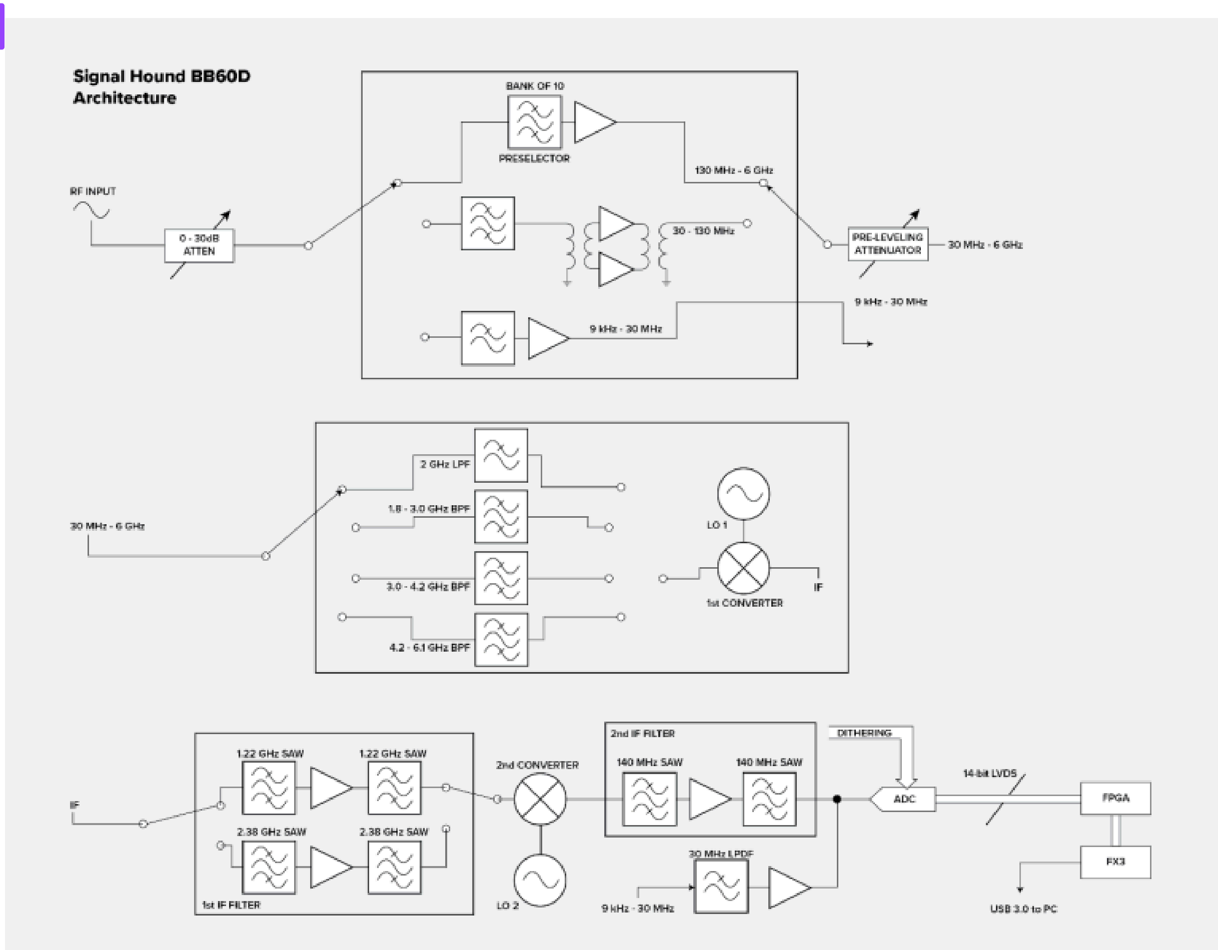
Ultimately, ChatGPT has been an invaluable tool in helping me understand complex imaging concepts, compare technical specifications, and structure research findings efficiently. It provided clear explanations of super-resolution imaging, lens configurations, and image processing techniques, which allowed me to make well-informed decisions throughout the project. However, this experience also reinforced the importance of using ChatGPT as a research aid rather than a final authority. While it was incredibly useful for summarizing information, organizing data, and generating comparative analyses, its responses were limited by how questions were framed and needed to be verified with external research.

In the end, ChatGPT significantly improved the efficiency of my research and decision-making, but it also highlighted the importance of critical thinking and independent validation. By leveraging AI as a supplementary research tool rather than a definitive source of truth, I was able to enhance my understanding, refine our imaging system design, and ensure that our final decisions were based on objective, well-researched information.

Chapter 6. System Design

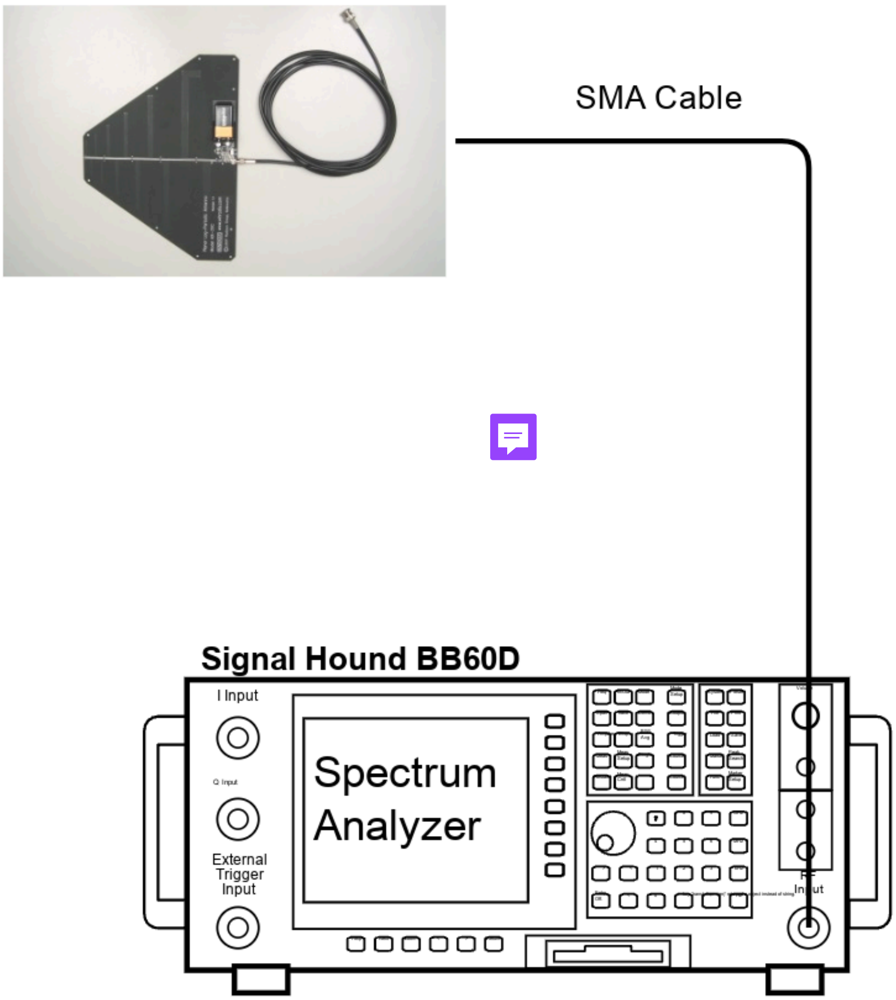
Hardware Diagrams:

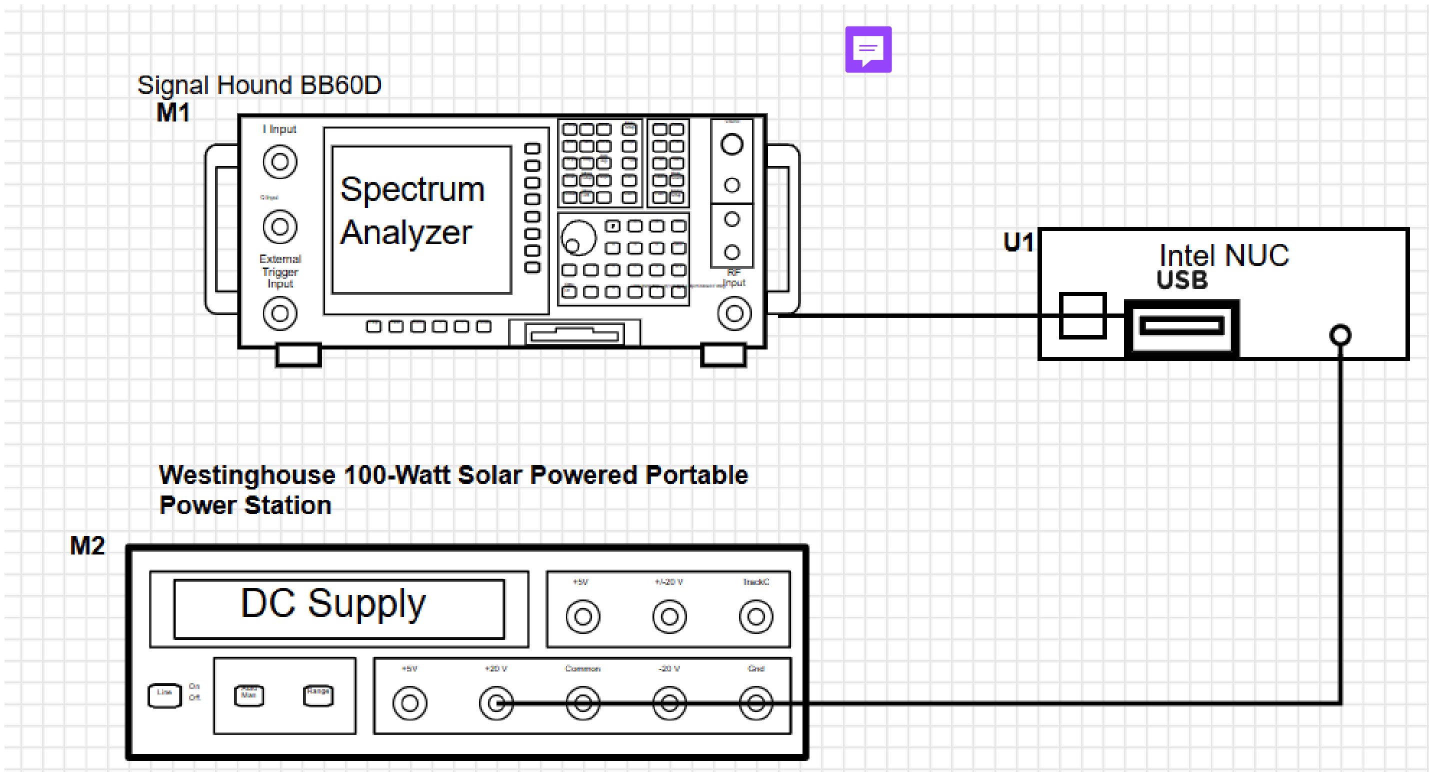
Spectrum Analyzer hardware diagram



Signal Hound BB60D Architecture
BANK OF 10
PRESELECTOR
130 MHz - 6 GHz
RF INPUT
0 - 30dB ATTEN
30 - 130 MHz
PRE-LEVELING ATTENUATOR
30 MHz - 6 GHz
9 kHz - 30 MHz
9 kHz - 30 MHz
2 GHz LPF
1.8 - 3.0 GHz BPF
3.0 - 4.2 GHz BPF
4.2 - 6.1 GHz BPF
30 MHz - 6 GHz
LO 1
1st CONVERTER
IF
1.22 GHz SAW
1.22 GHz SAW
2.38 GHz SAW
2.38 GHz SAW
1st IF FILTER
IF
2nd CONVERTER
LO 2
2nd IF FILTER
140 MHz SAW
140 MHz SAW
30 MHz LPDF
9 kHz - 30 MHz
DITHERING
ADC
14-bit LVDS
FPGA
FX3
USB 3.0 to PC

Aventas AX-37A log periodic dipole antenna with built in amplifier powered by 9V battery.





Software Diagrams:

Chapter 7: System Testing & Evaluation

Camera Array

As part of the PSE requirements for senior design 1, there is a midterm demo around 2 months or 8 weeks into the semester. The goal of this midterm demo is to demonstrate a subset of your optical design to a group of faculty members in order to receive feedback. In this case, Dr. Hagan, Dr. Likamwa, and Dr. Kar reviewed our midterm demos.

For our group's midterm demo, we displayed a simple 3 camera super resolution setup. The goal of this demo was to simply show that multiple images could be fused together to get more detail. To do this, we researched and purchased 3 cheap, low resolution USB cameras from Amazon, each at $15. Additionally, we purchased a simple USB hub to connect all cameras to a laptop. We then played around with code, occasionally seeking guidance from Chatgpt since we were not as familiar with many of the OpenCV capabilities. The first problem we ran into was the bandwidth problem. When the 3 cameras we purchased were connected via the USB hub, only one of them would actually operate properly. To work around this, we had to plug each camera directly into one of our laptops, which limited our demo to only 2 cameras. Although this problem was not expected and definitely a little confusing, we figured out that we were still able to demonstrate what we wanted with 2 cameras.

After testing many different configurations of code, we ended up getting an iteration we thought was good. The code, when run with 2 cameras, would first detect the operating cameras and then assign them an integer index. This helped to define which image came from which camera for the fusion, although with 2 cameras, it does not make much of a difference. After assigning each camera an indice, a small window would appear to show you the feed from each camera, this feature was why our 3 camera setup and USB hub connection was not working. Once each window popped up, we made sure that the cameras were capturing as much of the same scene as possible from different perspectives, as is necessary for super resolution. Once that was confirmed, we pressed the ‘s’ button on our laptop to capture an image and the code was allowed to run. The code we used, which was created with help from Chatgpt, attempted to locate similar features from each image to try to produce the best super resolution image possible. Because of this feature, our success rate was actually only around 70%. This was due to some misalignment issues and image overlap inconsistencies. Sometimes, if either of the previously mentioned conditions were a factor, a super resolution image would be produced that would look heavily distorted, except for one common feature from the scene. This led us to think of our demo case and what conditions would be best for our demonstration.

After testing different scenes around the CREOL building, we realized the best way to demo our 2 camera setup was to use an object about 1-5 meters away. We also noticed that the background behind the object would sometimes heavily confuse the code and lead to images that looked heavily distorted. For this reason, we decided that our best demo case was a QR code against a solid background. The use of a QR code would help us show that super resolution was in fact taking place, and by comparing the super resolution image to the image of a single camera, we could effectively show that some corners of the QR code were more well defined in the super resolution image. The white background was used as a means to increase our success rate and limit the production of distorted images. Overall, the demo taught us about bandwidth issues with USB cameras, the density of code that goes into super resolution, and the best ways to be able to demonstrate it. Dr. Hagan was also able to get us thinking about what types of cameras or scenes each imaging device should be capturing, since multiple low resolution cameras capturing the same thing doesn't provide as much detail as you’d hope. He mentioned the iPhone and led us to start thinking about how its camera systems operate and how our project could benefit from learning about that.

Chapter 8: Administrative Content

8.1 Finances

Table 8.1 Preliminary Budget Table for RF Device

Item	Approximate Price
Antenna(x2)	$450 each

Motors(x2)	$10 each ($20 total)
Signal Analyzer	$4000
Solar / Power System	$420
Android Phone	$600
PC/laptop	$200
Total:	$8,000

Table 8.2 Preliminary Budget Table for Camera Array

Item	**Approximate Price**
Cameras (x3)	$15 each
Lens System (x3)	$25 each
USB Connector	$20
Material for Housing	$30
PC/laptop	$400
Total:	$570

The budget for this project is set by our sponsor, Roy H. Wubker. The goal of this project is to create a cost-effective solution. Components that require a higher standard of quality were allocated a larger portion of the total funds. As it currently stands, many of the components could be subject to change based on quality versus cost assessments or customer standards. In addition, the solar power system may not end up being part of the final product, but we have funds allocated for it in the case that it does become a part of the system.

While this project is sponsored, the optical components may or may not be covered depending on the sponsors willingness to provide the equipment. As was mentioned earlier, the sponsor's main focus is an RF detection device. However, since the optical project would pique the interest of the same customers as the RF device, it may be possible to justify the sponsorship of the optical contributions of this project.

The cost per unit comes out to around $7000. This price, which is flexible based on optimization and inclusion or exclusion of the optical enhancement portion, is a much more appealing price especially since the user would need multiple to localize effectively. Compare this to radar systems from big companies that do contract work with the government. Our device is much more affordable while still providing essential information. While we do not want our device to cost the user anywhere near the price of a radar system, there are a lot of potential enhancements that can be made to elevate the quality of the unit.

8.2 Project Timeline

Below we have created both a table and Gantt chart to help organize our group and get a clearer view of the approaching deadlines. We have currently set up our schedule in even increments of about 3 weeks per step. This may turn out to be unrealistic as certain milestones may take more or less time to achieve. The main idea, however, is to give us insight into the quick turnaround we will need to have, especially going into the summer session of senior design 2.

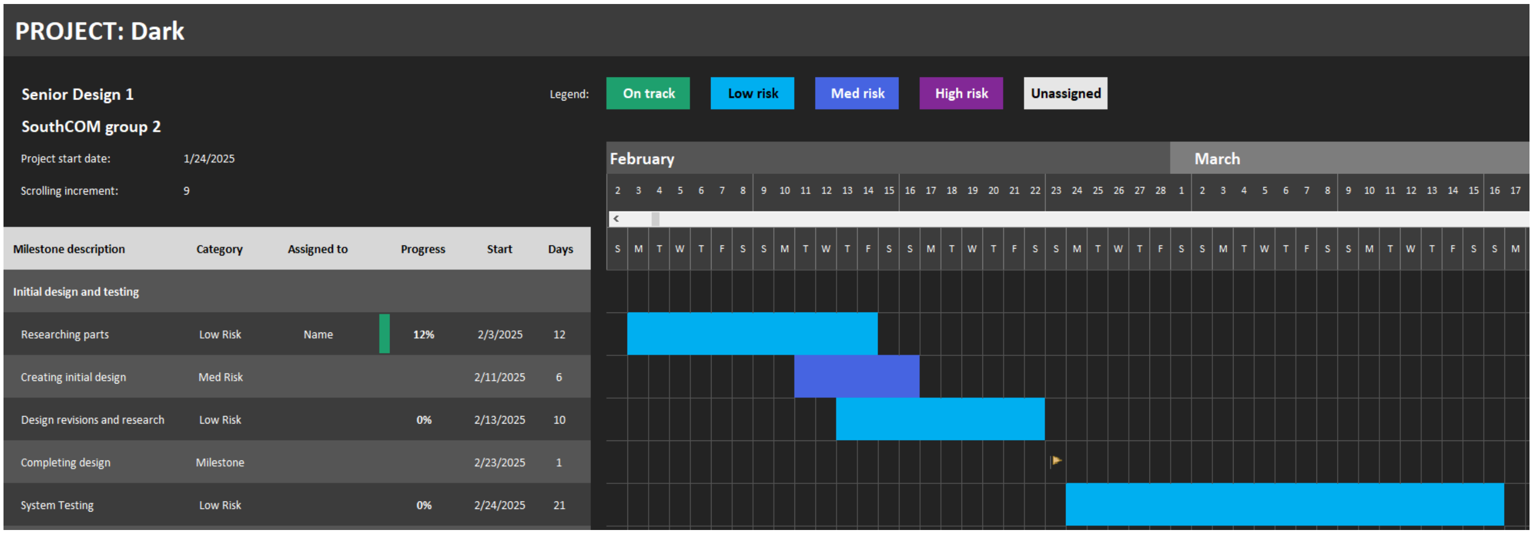
Table 8.2 Senior Design I Milestones

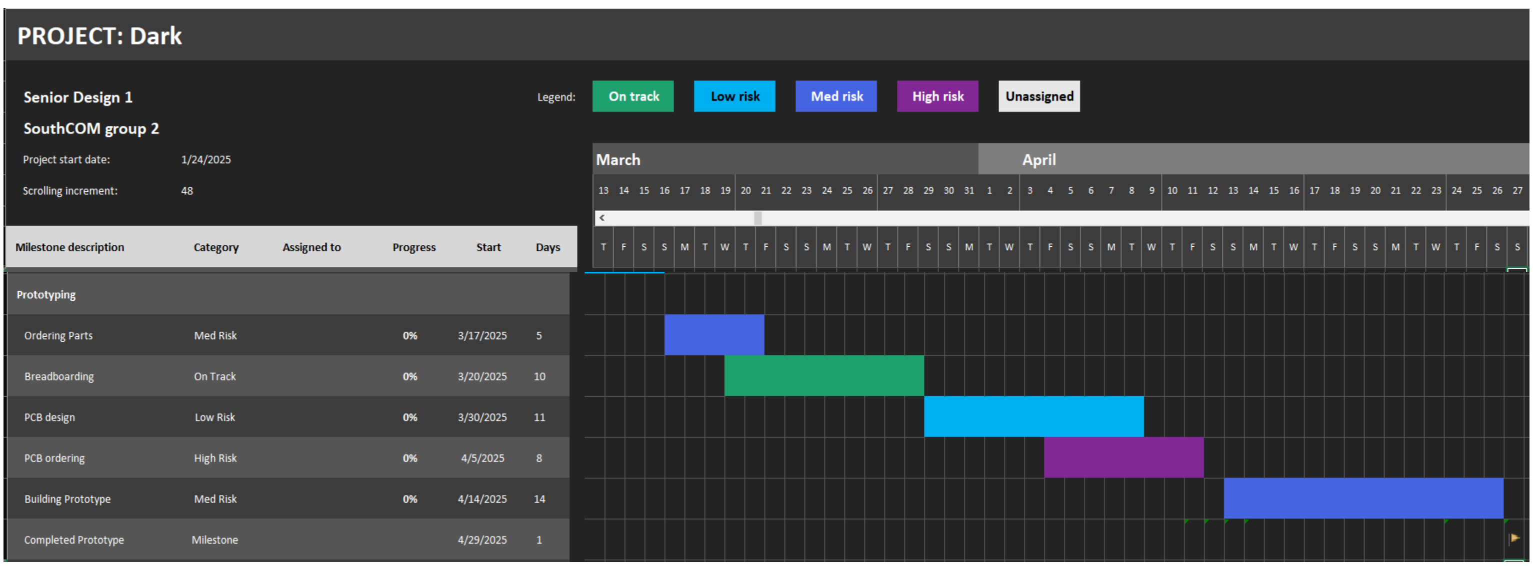
Milestone	Expected Start	Expected End	Duration
System Design	02/03/2025	02/23/2025	3 weeks
System Testing	02/24/2025	03/16/2025	3 weeks
Breadboard Prototyping	03/17/2025	03/30/2025	2 weeks
Finished Prototype	03/31/2025	04/29/2025	4 weeks

Table 8.3 Senior Design II Milestones

Milestone	Expected Start	Expected End	Duration
Multiple prototypes made	05/19/2025	06/16/2025	4 weeks
Designing Array setup	06/02/2025	06/22/2025	3 weeks
Testing Array	06/23/2025	07/20/2025	4 weeks
Final Product Completed	07/21/2025	08/23/2025	2 weeks

Gantt Chart for Schedule:





Chapter 9: Conclusion

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Appendix:

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