University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018

Highly Elliptic Polar Constellation for Auroral Transport Studies (HEPCATS)

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1.0 Information

1.1 Project Customers

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Nomenclature

A/C	Alternating Current
$ADCS$	Attitude Determination and Control System
AI	Artificial Intelligence
ARM	Anisotropic MagnetoResistence Sensor
ATS	Absolutely Timed Sequence
CCD	Charge-Coupled Device
CHT	Circulat Hough Transform
$CMOS$	Complementary Metal-Oxide Semiconductor
CNN	Convolution Neural Networks
$CONOPS$	Concept of Operations
DTR	Data Transfer Rate
FBD	Functional Block Diagram
FOV	Field of View
$FPGA$	Field Programmable Gate Array
GPS	Global Positioning System
GPU	Graphics Processing Unit
HDD	Hard Disk Drive

I/O	Input/Output
IEU	Instrument Electronics Unit
IPS	Image Processing Software
IS	Image Segmentation
ISO	International Organization for Standardization
NOAA	National Oceanic and Atmospheric Administration
OS	Operating System
PDD	Project Definition Document
PTDNN	Pre-Trained Deep Neural Networks
QIS	Quantum Image Sensor
RF	Radio Frequency
RGB	’Red’ ’Green’ ’Blue’
SATA	Serial Advanced Technologies Attachment
SBC4	Single Board Computer
SDT	Spin-Dependent Tunnel Sensor
SGS	Simulated Ground Station
SIFT	Scale Invariant Feature Transform
SSD	Solid State Hard Drive
UV	Ultra-Violet

2.0 Project Description

2.1 Purpose and Overview

The Earth is continually bombarded by solar emissions known as the solar wind. A small fraction of these highly energized particles interact with the Earth's magnetic field and are guided and accelerated to high velocities around the Earth's magnetic poles. These fast, energetic particles often collide with high altitude atmospheric atoms, resulting in a captivating display of light known as auroras. However, current imaging instruments do not capture the entire polar crown to view these fascinating displays of light from space, and no satellites are dedicated to imaging the aurora. The last satellite that took images of the aurora ceased operations in 2005, with images being taken only in UV wavelengths. Auroral tourism is the most common use of NOAA's space weather website, yet only models of the auroral oval are available with no spatial detail and no temporal changes of interest to people trying to see the aurora or communications operators who must determine if there is interference from auroral particle precipitation. Moreover, radio and GPS reception are affected by this phenomena, causing inaccuracies due to interference from the geomagnetic storms. The HEPCATS system would allow near real-time imagery of the auroras to inform tourists of the most active locations and to improve scientific models of the phenomena.

To help auroral ”nowcasting” assess radio and GPS inaccuracies, drive auroral tourism, and validate current auroral models, visible light imaging of the geomagnetic storms needs to be performed from a satellite. DigitalGlobe and the CU Space Weather Center will work with an undergraduate senior design team through the Ann H.J. Smead Aerospace Engineering Department at the University of Colorado Boulder to address the need for a satellite that can capture the entire northern polar crown through visible light imaging. This project will focus on four specific components: (1) the auroral imaging system, (2) a magnetometer system that will be used to measure magnetic field strength, (3) the structure for the spacecraft to hold its payload, and (4) the software that will be used to compress, filter, process, and map the images taken.

A camera will be procured through working with the Laboratory for Atmospheric and Space Physics (LASP) which will drive the design for a Molniya orbit modeled with orbit determination software to ensure that the camera is able to capture the entire polar crown. Image processing algorithms and an instrument design interface will be designed in order to identify if an aurora is present within images and then filter and compress the desired images. Additionally, a magnetometer will be chosen to detect magnetic field magnitudes. Finally, both the camera and magnetometer will be mounted onto a manufactured spacecraft structure. The images and magnetometer data will be processed on board and transmitted to a ground station for further processing and distribution.

2.2 Objectives

Table (1) outlines the criteria for various levels of success pertaining to the project. The criteria presented in Level 1 constitutes the base level of objectives that the project must accomplish in order to be considered a success. The criteria listed in Level 3 characterize the ultimate deliverables of the project as the highest level of success. This table is a revised version of the one presented in the PDD; moreover, ”TBD”s have been replaced with specific values or phrases.

Table 1: Specific Objectives of HEPCATS Project

	Imaging System	**Magnetometer System**	**Spacecraft Bus**	**Command & Data Handling**
Level 1	Take an image Fixed FOV able to fit hemisphere of the Earth at apogee Filter out backscatter from optical system Crop image to only show earth Compress image to 70% filesize	Detect the scalar component of a constant magnetic field	Mounted within a manufactured stand-alone structure	Manually commanded payload activation & deactivation Receive, store, and send magnetometer and imaging data
Level 2	Able to image at least once every minute to capture changing aurora Fixed FOV able to image latitudes above 46° north at apogee Identify if aurora is present	Detect the vector component of a constant magnetic field		Command the payload autonomously from an on board absolutely timed sequence of commands
Level 3	Able to change rate of image capture if aurora is present Unskew images to be useful Filter out Earthshine Identify lowest latitude of aurora	Map magnitude and direction of magnetic field lines	Mounted within a manufactured mock CubeSat spacecraft bus	

2.3 Concept of Operations

Two concepts of operations are presented for the overall HEPCATS mission and the project defined in this design document. First, Fig.(1) details the overall HEPCATS mission: a constellation of CubeSats placed in a highly elliptical orbit (HEO) such that the auroral crown can be imaged and the magnetic field of interest be mapped using the onboard camera and magnetometer. Instruments are commanded ”on” for the duration of the orbit’s region of interest (ROI). A ROI denotes a segment of the orbit (a segment centered around apoapsis) in which the entire auroral crown can be imaged by the camera. During the region of interest, images taken of the aurora will be processed onboard and then, along with the magnetometer data, downlinked to a ground station. This data is then delivered to DigitalGlobe for further processing and ultimate distribution to customers.

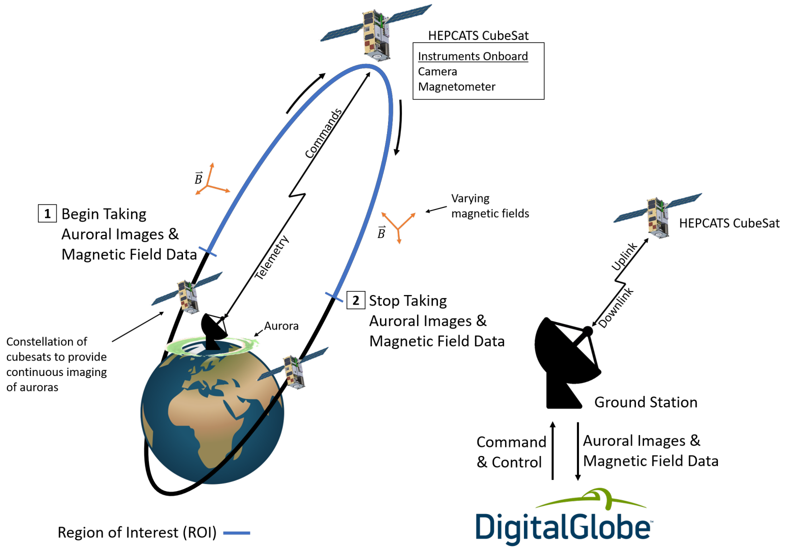


Figure 1: HEPCATS Mission ConOps

Fig.(2) presents a diagram of the project defined in this design document for reference in Fig.(4). Only the payload of a singular HEPCATS CubeSat will be designed, manufactured, integrated into a bus structure comparable to a typical 6U CubeSat, and tested in an ”Orbit in the Life” simulation, see Fig.(3). The ground station is substituted for a computer, referred to as the simulated ground station, to provide wired uplink and downlink capabilities to the CubeSat at rates comparable to what would be expected on-orbit. The ”Orbit in the Life” simulation concept of operations is depicted in Fig.(3) and begins with modeling the orbit, in orbit determination software, to determine ROI start and stop times for a given orbit to simulate. At ROI start, the commands to turn on the instruments and begin science data collection will be sent from the simulated ground station (Level 1 success) or from an onboard absolutely timed sequence (ATS) of commands (Level 2 success). The simulation will proceed with testing the camera and magnetometer using a projector and Helmholtz cage, respectively, between ROI start and stop times. The camera will capture images of a projected Earth with auroras on a projector screen and processed by the onboard computer while the magnetometer will measure a magnetic field generated by a Helmholtz cage. Data generated by the instruments and processed onboard is then sent to the simulated ground station as telemetry. The simulation is concluded with commanding the instruments ”off” at the ROI stop time either through the simulated ground station or ATS.

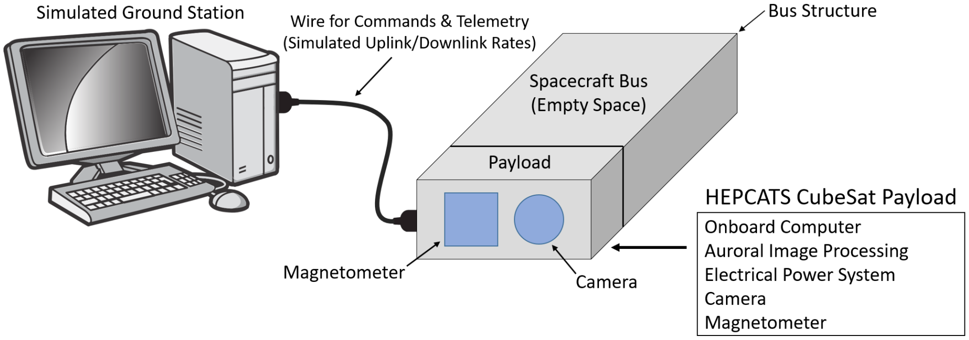
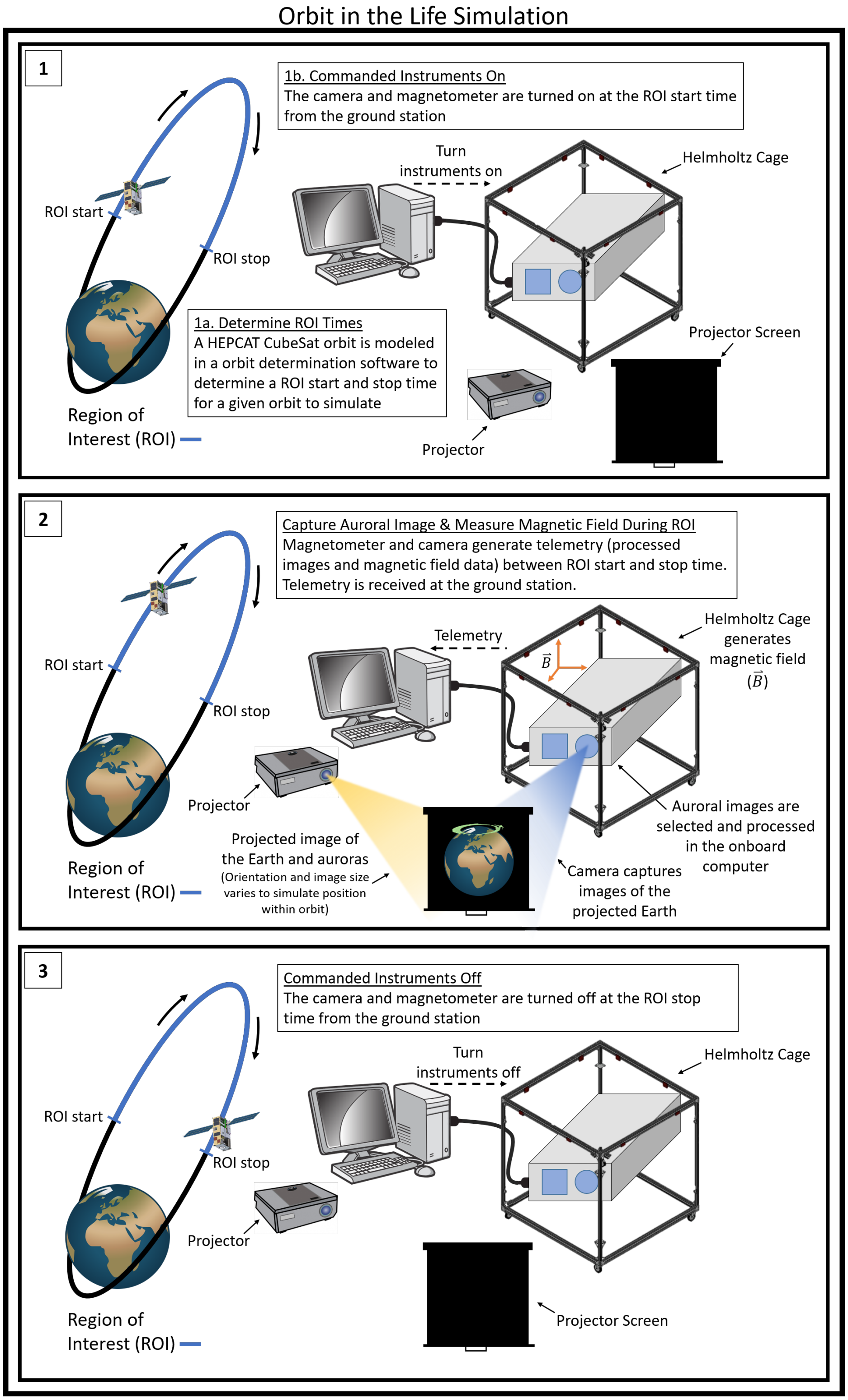


Figure 2: HEPCATS Project Diagram


Orbit in the Life Simulation

1b. Commanded Instruments On

The camera and magnetometer are turned on at the ROI start time from the ground station

1a. Determine ROI Times

A HEPCAT CubeSat orbit is modeled in a orbit determination software to determine a ROI start and stop time for a given orbit to simulate

Capture Auroral Image & Measure Magnetic Field During ROI

Magnetometer and camera generate telemetry (processed images and magnetic field data) between ROI start and stop time. Telemetry is received at the ground station.

Commanded Instruments Off

The camera and magnetometer are turned off at the ROI stop time from the ground station

Figure 3: ”Orbit in the Life” Simulation ConOps

2.4 Functional Block Diagram

The functional block diagram (FBD) to accompany the project diagram and ”Orbit in the Life” simulation ConOps is presented in Fig.(4). This is a revised version of the FDB presented in the project design document. First, command and data handling has been updated to provide more specific flow between components in the instrument electronics unit and instrument suit. Second, the electric power supply system has been moved outside the bus structure and the battery replaced with a power supply; rescoping the electric power system to an external power supply was done as the method to power the onboard components is not significant to achieving the purpose of this project.

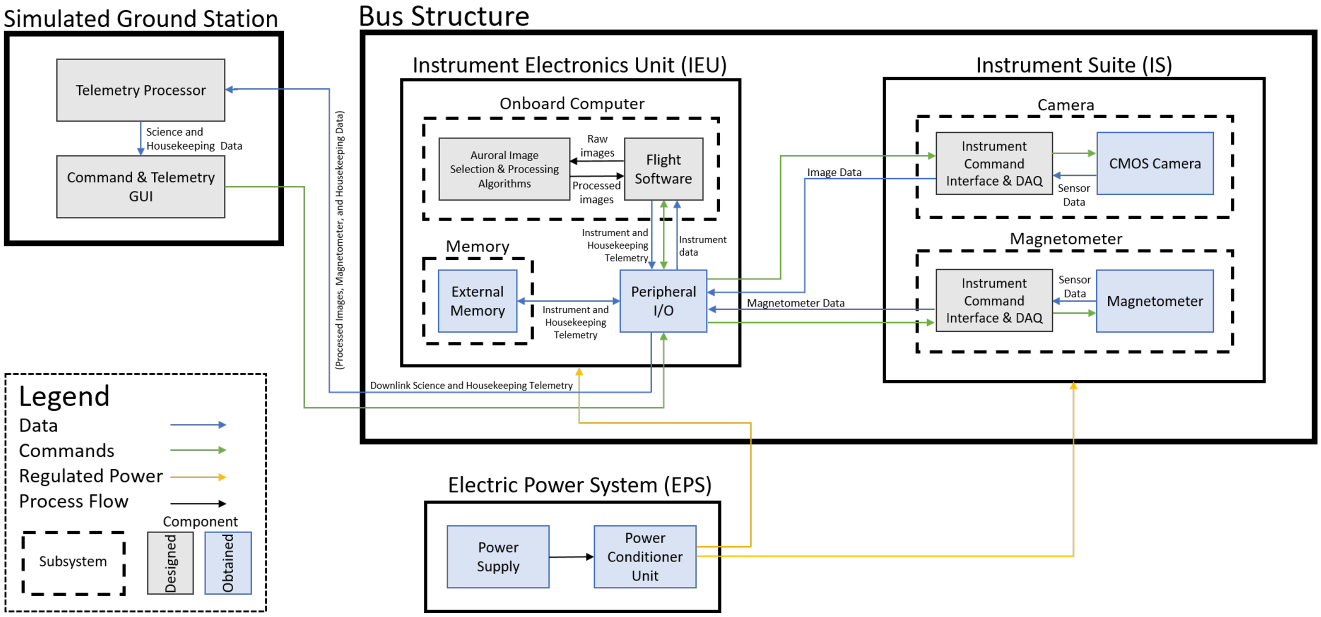


Figure 4: HEPCATS Project Functional Block Diagram

2.5 Functional Requirements

1. The imaging subsystem shall be capable of taking images of a simulated Aurora Borealis.
2. The on-board image processing subsystem (IPS) shall convert raw imagery to useful imagery for downlink.
3. The magnetometer system shall be capable of measuring a magnetic field.
4. The manufactured spacecraft bus shall be the infrastructure of the spacecraft that is capable of housing the Instrument Electronics Unit, the Instrument Suite, and the Electric Power System.
5. The electric power system which will consist of 120 volts AC from an outlet that will provide regulated power to the instrument electronic unit and instrument suite for the duration of the “Orbit in the Life” simulation.
6. The simulated ground station shall be able to command and receive telemetry from the instrument electronics unit.
7. The instrument electronics unit shall be capable of storing all instrument telemetry, housekeeping telemetry, and command sequence data.
8. The instrument electronics shall be capable of sending telemetry to the simulated ground station.
9. The instrument electronics unit shall be capable of executing commands from the simulated ground station or on board absolutely timed command sequences.

3.0 Design Requirements

Imaging System

1. The imaging subsystem shall be capable of taking images of a simulated Aurora Borealis.
   Motivation: The primary goal of the imaging system is to act as proof of concept for the image processing and recognition algorithms to recognize the Aurora Borealis. The main purpose of the optical system shall be to provide imagery in an orbital simulation to be used by the image processing software.
   V & V: Test using "Orbit in the Life" simulation.
   - 1.1. The primary imaging system shall be capable of taking images of a G1 magnetic storm during a minimum of a third of the orbital period. This shall be defined as mission imaging time.
     Motivation: A future proposed constellation of HEPCATs spacecraft will contain a minimum of three spacecraft. Having a singular HEPCATs spacecraft image at 33% of the orbital period will allow for continuous imagery of the geographic area of G1 storms.
     V & V: Testing using orbit determination software.
     - 1.1.1. The imaging subsystem shall have a field of view (FOV) of less than 24 degrees.
       Motivation: Based on the requirement for 33% imaging time this FOV is calculated such that the geographic region of interest for G1 magnetic storms is imaged effectively at the lowest and highest imaging altitude. Based on simulation, FOVs higher than 24 degrees do not increase imaging time and would only lead to degradation in image quality.
       V & V: Testing with Camera Calibration. FOV can be calculated using simple optical relations and imaging objects of known sizes at known distances.
     - 1.1.2. The imaging subsystem primary imaging system shall have an FOV of no less than 7 degrees.
       Motivation: A smaller FOV than 7 degrees will not allow for Requirement 1.1 to be fulfilled as through simulation, FOVs greater than this cannot achieve a useful imaging time of more than 33%.
       V & V: Testing with Camera Calibration. FOV can be calculated using simple optical relations and imaging objects of known sizes at known distances.
     - 1.1.3. The imaging subsystem shall be capable of taking images at a rate of 0.2 Hz over the entirety of mission imaging time.
       Motivation: Derived from customer interactions and rough estimates of approximate 5 second timescales on which space weather changes. This allows for useful imaging while also keeping in mind time needed to process and downlink imagery taken on the spacecraft.
       V & V: Hardware Test.
   - 1.2. The imaging subsystem shall maintain a minimum spatial resolution of 48 arcseconds/pixel.
     Motivation: The greater the resolution, the better the quality of the images. This is based on maximum FOV along with the assumption that any primary science camera will have a pixel array size greater than 1800x1800.
     V & V: Simulation & Analysis.
   - 1.3. The imaging subsystem shall have a signal to noise (S/N) ratio of no less than 20dB
     Motivation: In order to achieve a useful image of the aurora this signal to noise ratio is necessary to achieve useful and clear images of the aurora. A 20dB S/N ratio is rated by ISO as an 'acceptable image' and thus offers guidance on acceptable thresholds for noise in imaging.
     V & V: Analysis of images from "Orbit in the Life Simulation."
     - 1.3.1. The imaging subsystem shall have a dynamic range of no less than 8 bits.
       Motivation: A high dynamic range will improve the overall image quality by increasing the luminosity levels. 8-bit images offer a good tradeoff between image quality and image size.
       V & V: Inspection of optical sensor output files.

2. The on-board image processing software (IPS) shall convert raw imagery into image data that shall be transmitted to the simulated ground station.
   Motivation: Due to the design of a highly elliptical orbit, the downlink rate from a small satellite such as this one will be severely limited. Compression, cropping and omission of irrelevant data will assist in minimizing downlink rate.
   V & V:

2.1. The IPS shall implement machine learning techniques to design a program capable of identifying auroras with an F1 score of 95%.
Motivation: The capability for the IPS to identify aurorae in images will allow resources to be saved by emitting the downlink of images which do not contain visible aurorae. The F1 score of an identification algorithm combines the metrics of accuracy and recall to account for both true positive rate and false positive rate. The true positive rate of 96% was recently achieved using ground-based aurora photography [3].
V & V: A portion of the selected training data set will be used for verification of the algorithm (typically 30% [3]).

  2.1.1. The identification program shall be adjustable such that retraining with a different data set is possible.
  Motivation: It is likely that the training data set used will be different enough from operational data to affect the performance of the identification software. Being able to retrain the software based on operational data would allow the identification software to be optimized during operation.
  V & V: Training of the algorithm shall be done twice with different data to ensure it is retrainable.

  2.1.2. Calibration data can be sent from the ground to satellite.
  Motivation: In order to accommodate the above requirement, calibration of the software should be able to be changed via uplink. It shall be easier to do the retraining of the software on the ground, so uplinking of this new calibration.
  V & V: A recalibration of the IPS shall up uploaded from the simulated ground station to verify this capability.

2.2. The IPS shall be capable of mapping image data longitude, latitude values based on orbit ephemeral.
Motivation: Verification of aurora models require the data to be mapped to Earth.
V & V: The orbit simulation will generate imagery which will be used to test this capability.

  2.2.1. Mapping of image data shall be accurate to within 5–15 km
  Motivation: Accurate mapping is required to verify models and for auroral tourism.
  V & V: Calculation of these uncertainties will be computed and verified with the orbit simulation.

  2.2.2. Mapping algorithm shall be capable of accounting for orbital position as well as spacecraft attitude.
  Motivation: Without accounting for orbital position, mapping will not be accurate.
  V & V: System will be tested with disturbances in attitude and position added to test the mapping accuracy.

2.3. The IPS shall be capable of performing cropping, rotation, and other simple tasks on data.
Motivation: Simple transforms will be required to create consistent images for AI processing.
V & V: These operations will be demonstrated through software tests using the available imagery.

  2.3.1. Cropping shall be performed such that the output image only shows the Earth's polar caps and not the background of space.
  Motivation: Simplification of the background will create more consistent images for AI processing.
  V & V: Sample images will be cropped by the IPS.

  2.3.2. Rotation shall be performed such that the north pole is always aligned with the top of the images if necessary.
  Motivation: Consistent orientation will create more consistent images for AI processing.
  V & V: Sample images will be rotated by the IPS.

  2.3.3. Unskewing shall be performed such that images are square (perpendicular lines on image are perpendicular on Earth).
  Motivation: Consistent axes/scaling will create more consistent images for AI processing.
  V & V: Sample images will be unskewed by the IPS.

2.4. The IPS shall implement loss-less compression algorithms to minimize downlink rates. Compressed data shall be at least 35% smaller than raw data.
Motivation: Compression of image data will allow us to further minimize downlink rates per image.
V & V: Inspection of file sizes and quality of images compressed by the IPS will verify that the compression is working as expected.

Magnetometer System

3. The magnetometer system shall be capable of measuring a magnetic field.
Motivation: Magnetic field data of the Earth is very useful from as many satellites as possible for agencies like NOAA.

Thus, the magnetometer shall be capable of measuring a magnetic field.
V & V:

- 3.1. The magnetometer shall be capable of measuring the magnitude of a magnetic field.
  Motivation: Measuring the magnitude of the magnetic field will give insight into how strong its influence may be on the aurora, as well as how strongly it is disrupted from solar flares.
  V & V: Test. Observe whether the magnetometer can detect the magnitude of a magnetic field in a Helmholtz Cage.
  - 3.1.1. The magnetometer shall measure the magnitude of a magnetic field within a range of 100 nT to 40000 nT.
    Motivation: The Earth's magnetic field will vary from a strength of 100 nT (for maximum altitude of 39905 km at apoapsis) to 40000 nT (for minimum altitude of 537 km at periapsis) in determined Molniya orbit. This was determined by assuming an average magnetic field strength of 50 μT at the surface and using the relationship that B α $\frac{1}{d^3}$ where B is the magnetic field strength and d is distance from the source. Using this proportionality yields these magnetic field strength at apoapsis and periapsis.
    V & V: Test. Observe whether the magnetometer can detect magnetic fields at these strengths in a Helmholtz cage.
    - 3.1.1.1. The magnetometer shall be capable of measuring the magnitude of a magnetic field with a resolution less than or equal to 100 nT.
      Motivation: Since the minimum magnetic field strength will be 100 nT, its accuracy resolution must at least be this precise in order to detect the presence of a magnetic field at apogee.
      V & V: Test. Observe whether 100 nT change in magnetic field strength from Helmholtz cage is accurately measured by magnetometer.
- 3.2. The magnetometer shall be capable of measuring the vector quantity of a magnetic field.
  Motivation: The vector components of a magnetic field provide additional information than its magnitude; it indicates the direction of the field. This is also useful for agencies like NOAA.
  V & V: The magnetometer will be rotated on an axis. If the magnetometer reading is able to give the rotational change for a constant field, the magnetometer will be capable of measuring the direction of the magnetic field.
- 3.3. The magnetometer shall measure the magnetic field for the duration of each orbit.
  Motivation: Regardless of whether the CubeSat is at an altitude of 500 km at apoapsis, or an altitude of 40000 km at periapsis, magnetic field data will still be useful for agencies like NOAA, whether it be the scalar or vector quantities.
  V & V: Test. Ensure that the magnetometer is able to take data for the entirety of the simulated orbit.

Spacecraft Bus

4. The manufactured spacecraft bus shall be the infrastructure of the spacecraft that is capable of housing the Instrument Electronics Unit, the Instrument Suite, and the Electric Power System.
   Motivation: The spacecraft bus will need to be able to house all of the system's hardware in a way that it will remain stationary and completely mounted to the bus. Also, it must protect the hardware and onboard software from collisions and keep the system together.
   V & V: The stability of the spacecraft bus will be verified by inspection and series of movement tests to see if components remain stationary.
   - 4.1. The spacecraft bus shall be capable of housing the Instrument Electronics Unit (IEU) which includes the onboard computer and memory storage.
     Motivation: The Instrument Electronics Unit will need to be housed in the bus so the images that are taken can be processed and stored on board the spacecraft.
     V & V: The stability of the IEU will be verified by inspection and series of movement tests to see if components remain stationary.
     - 4.1.1. The onboard computer shall be able to fit within the IEU contained within the bus structure.
       Motivation: The onboard computer will process and store the images that are taken and needs to be located on the spacecraft bus so that the payload will be together. The onboard computer will need to fit within the

IEU contained on the spacecraft bus.
V & V: The spacecraft bus will be able to hold the payload which contains the IEU which has the onboard computer. This can be verified through inspection.

- 4.1.2. The memory storage shall be able to fit within the IEU contained within the bus structure.
  Motivation: The memory storage is a necessary component that will need to be stored on the spacecraft bus so that the images that are taken will be saved.
  V & V: The IEU will hold the memory storage which should fit in the spacecraft bus. This can be verified through inspection.

4.2. The spacecraft bus shall be capable of housing the imaging system.
Motivation: The spacecraft bus must house a fixed imaging system so that the images of the aurora can be taken.
V & V: The stability of the imaging system will be verified by inspection and series of movement tests to see if components remain stationary.

- 4.2.1. The spacecraft bus shall be capable of housing the imaging system in a way that it remains stationary.
  Motivation: The imaging system needs to be contained within the instrument suite and the spacecraft bus. This is to keep it protected from outside interference.
  V & V: This can be verified through inspection and manipulating the bus to verify the stability and ability of the imaging system to remain stationary.

4.3. The magnetometer system shall be mounted in a way that it will not interfere with the magnetometer readings by a tolerable amount of nT.
Motivation: The spacecraft bus should not disturb the measurements that the magnetometer takes so that the magnitude and direction can be measured accurately.
V & V: The magnetometer system will be tested within a Helmholtz cage. If the magnetometer still gives the same readings within a tolerable amount of a few nT inside the spacecraft bus then the spacecraft bus is not interfering with the magnetometer system.

5. The electric power system which will consist of 120 volts AC from an outlet that will provide regulated power to the instrument electronic unit and instrument suite for the duration of the “Orbit in the Life” simulation.
Motivation: Each of the systems contained within the spacecraft need to have regulated powered that will be supplied from on outlet that will connect with the spacecraft bus. Powering the instruments on the spacecraft is crucial to the operation of the mission so each subsystem can perform its task The “Orbit in the Life” simulation is quantified as one-third of the Molniya orbit.
V & V: In order to verify the regulated power being sent to each system is correct, a series of multimeter measurements will be made to ensure the power allocation to each instrument and system is optimal.

5.1. An outlet will provide power to the electric power system.
Motivation: An outlet will provide unlimited power for the electric power system. The mission will not be flight ready so a battery that is necessary for space will not be required for this mission. Using power from an outlet will be more practical to prove that the subsystems are working and show proof of concept.
V & V: Each system will need to have a determined power rating and the 120 volt AC that comes through the system will need to be distributed and adjusted for each system accordingly. This can be tested using a multimeter to make sure the requirements are met.

5.2. A power conditioner shall be used to regulate the power which will be delivered to each of the systems contained within the spacecraft bus.
Motivation: A power conditioner will ensure the proper allocation of electricity to each system. It will also aid in the prevention of “cross-talk” between components as well as provide voltage regulation.
V & V: Test that all systems are properly powered through the regulation of the power conditioner. This testing can be done with a multimeter to measure the voltage and current being sent to each instrument.

5.3. The wiring for all instruments shall be contained within the bus structure so that it does not interfere with the functionality of any systems.
Motivation: Proper wiring throughout the spacecraft bus is important to ensure that each of the systems can properly function.
V & V: This can be verified through proper inspection of the spacecraft bus and the wiring.

Command & Data Handling

6. The simulated ground station shall be able to command and receive telemetry from the instrument electronics unit.
   Motivation: To complete the ”Orbit in the Life” simulation, the simulated ground station will need to be capable of commanding the spacecraft and receive telemetry.
   V & V: Demonstration that the simulated ground station can send commands and receive telemetry from the instrument electronics unit.

   6.1. The simulated ground station shall simulate an interface with the instrument electronics unit by wired serial communication.
   Motivation: Interfacing with the instrument electronics unit by wired serial connection is sufficient for sending commands and receiving telemetry per design options and trade study.
   V & V: Demonstration of wired serial communication.

      6.1.1. The simulated ground station shall be capable of varying the uplink rate to the instrument electronics unit.
      Motivation: Varying the uplink rate to the IEU will simulate rates comparable to what will be expected on-orbit determined through a link budget.
      V & V: Demonstration of variable uplink rates.

   6.2. The simulated ground station shall have a command and telemetry (C&T) GUI that will allow the user to send commands to the spacecraft bus and display housekeeping data.
   Motivation: A GUI to send commands and display housekeeping data (e.g. instrument status and command counts) is effective and operator friendly in operating the CubeSat.
   V & V: Demonstration of a command and telemetry GUI.

      6.2.1. The GUI shall be capable of interpreting a human readable command into a command bit pattern.
      Motivation: Forming/typing human readable commands in the command and telemetry GUI, rather than a bit pattern, is operator friendly.
      V & V: Demonstration of a human readable command to bit pattern conversion in the command & telemetry GUI.

   6.3. The simulated ground station shall be a personal computer.
   Motivation: For the scope of this project, simulating the ground station with a personal computer is sufficient.
   V & V: Demonstration of the ground station as a personal computer.

   6.4. The simulated ground station shall receive telemetry in a downlink compatible telemetry format (adhering to a standard file delivery protocol) from the instrument electronics unit.
   Motivation: Telemetry is generated by the instrument electronics unit in a downlink compatible telemetry format and sent to the simulated ground station.
   V & V: Demonstration of the simulated ground station receiving telemetry from the instrument electronics unit.

      6.4.1. The simulated ground station shall process telemetry into raw data.
      Motivation: Telemetry sent to simulated ground station will be have to be converted from its downlink compatible format to raw data for display in the command and telemetry GUI and later review of science (camera & magnetometer) data.
      V & V: Demonstration of telemetry to raw data conversion.

   6.5. The simulated ground station shall be capable of loading an absolutely timed sequence of commands to the instrument electronics unit.
   Motivation: Level 2 success. Loading absolutely times sequences allows the spacecraft to be commanded autonomously on board and simulates on-orbit operations.
   V & V: Demonstration of loading an absolutely timed sequence of commands.

7. The instrument electronics unit shall be capable of storing all instrument telemetry, housekeeping telemetry, and command sequence data.
   Motivation: Storing telemetry and command sequence on board simulates on-orbit operations.
   V & V: Demonstration of storing telemetry and command sequence data.

   7.1. The instrument electronics unit shall format science and housekeeping data into a downlink compatible telemetry format adhering to an industry standard file delivery protocol.
   Motivation: Adhering to an industry standard file delivery protocol is necessary for on-board data handling and generating telemetry.
   V & V: Demonstration of adhering to an industry standard file delivery protocol.

   7.2. The instrument electronics unit shall be capable of storing science telemetry, housekeeping telemetry, and command sequences on external memory.
   Motivation: Storing telemetry and command sequences on the external memory will simulate on-orbit operations: storing telemetry until it can be downlinked to the ground station and autonomously commanding the spacecraft through on-board absolutely timed command sequences.
   V & V: Demonstration of storing science telemetry, housekeeping telemetry, and command sequences on the external memory.

      7.2.1. External memory shall be capable of storing science telemetry, housekeeping telemetry, and command sequence data for the duration of at least entire orbit.
      Motivation: Storing at least one entire orbits worth of telemetry and command sequence data will allow the "Orbit in the Life" simulation to be performed.
      V & V: Demonstration of storing at least one orbits worth of telemetry and command sequences.

8. The instrument electronics unit shall be capable of sending telemetry to the simulated ground station.
Motivation: Telemetry generated on board needs to be sent to the simulated ground station.
V & V: The IEU will transmit science data and spacecraft housekeeping data to the simulated ground station.

   8.1. The instrument electronics unit shall simulate interface with the simulated ground station by wired serial communication.
   Motivation: Interfacing with the simulated ground station by wired serial connection is sufficient for sending commands and receiving telemetry per design options and trade study.
   V & V: Demonstration of wired serial communication.

      8.1.1. The instrument electronics unit shall be capable of adjusting downlink rate via a command to the instrument electronics unit.
      Motivation: Varying the downlink rate to the simulated ground station will simulate rates comparable to what will be expected on-orbit (determined through a link budget analysis).
      V & V: Demonstration of commanding downlink rates.

   8.2. The instrument electronics unit shall be capable of sending science and housekeeping telemetry generated realtime and from the external memory to the simulated ground station.
   Motivation: Sending telemetry real time or that stored in the external memory to the simulated ground station will simulate on-orbit operations.
   V & V: Demonstration of sending telemetry generated realtime and stored on the external memory.

9. The instrument electronics unit shall be capable of executing commands from the simulated ground station or on board absolutely timed command sequences.
Motivation: The spacecraft will be operated from a ground station, and when not in contact with the ground station, will need an on-board absolutely timed sequence of commands for autonomous commanding.
V & V: Demonstration of the spacecraft executing a command sent from the simulated ground station.

   9.1. The instrument electronics unit shall receive a bit pattern from the simulated ground station and interpret it into a recognizable command.
   Motivation: The command and telemetry GUI sends a command as a bit pattern to the instrument electronics unit. This bit pattern is then interpreted into a recognizable command to be executed.
   V & V: Demonstration of bit pattern to recognizable command interpretation.

   9.2. Upon receiving and executing a valid (recognized) command, the instrument electronics unit shall generate one "acknowledged" and one "executed" command count.
   Motivation: Generating command counts for received and executed commands allows for command success

verification.
<u>V & V:</u> Demonstration of command count generation.

9.2.1. Command counts shall be included in housekeeping telemetry.
Motivation: Housekeeping telemetry is sent to the simulated ground station and displayed by the command and telemetry GUI. The operator will be able to easily verify that a command was sent to the spacecraft and executed successfully.
<u>V & V:</u> Demonstration of displaying command counts in the command and telemetry GUI.

9.3. There shall be an onboard clock.
Motivation: An onboard clock is required for absolutely timed commands to execute autonomously on board.
<u>V & V:</u> Demonstration of an onboard clock.

9.3.1. The onboard clock shall be capable of synchronizing with the simulated ground station time via a command from the simulated ground station.
Motivation: Synchronizing the clock with the simulated ground station time allows absolutely timed commands to execute at the correct (or expected) time.
<u>V & V:</u> Demonstration of an onboard clock synchronizing time with the simulated ground station.

4.0 Key Design Options Considered

4.1 Imaging System

As specified by the requirements, the primary goal of the imaging system is to capture images of a simulated Aurora Borealis which shall be utilized by the image processing software (IPS). This is primarily to act as a proof of concept for the image processing software and as such, the imaging system must thoughtfully simulate flight images. Care must go into the design of the imaging system such that images taken will mimic those in-orbit for characteristics including but not limited to FOV, S/N ratio, imaging rate, and spatial resolution.

Accomplishing this goal requires careful examination of possible design options and examining of their feasibility. The primary design decisions of the HEPCATS imaging system consists of three different design options. The first design option is the type of image sensor used. The primary decision here is between CCD and CMOS image sensors. Each offer their pros and cons and these are more fully explored below. The second major design decision physical configuration of imagers on the spacecraft as well as the type of imagers. The options presented here are as follows: a single high-resolution grayscale imager, a single RGB camera, a set of three grayscale imagers filtered at different wavelengths, and a combination of a high-resolution grayscale imager and a high-resolution RGB camera. The third major design option is the choice of algorithm that the image processing system will use to automatically detect the presence of the Aurora. Again these design options are explored more fully below.

4.1.1 Sensor Type

Over the years, photography has evolved from vidicon tubes used in early television sets to the small CMOS cameras seen in today's smartphones. Image quality is vital for mission success, thus different image sensors were considered. CMOS cameras are continually decreasing in size and their image quality is beginning to rival its CCD counterparts. In the past, if image quality was preferred, CCDs were the option, whereas CMOS were used mainly for small weight and power applications. With today's developments in semiconductor technology, the choice between CCD and CMOS sensors has become increasingly difficult. Additionally, other sensors like an oversampled binary image sensor and a quantum image sensor were investigated. Quantum film technology was revealed in 2010 and has the potential to revolutionize image sensing capabilities. Even though this technology is still under development, it is worth noting for future design options.

1. *Charge-Coupled Device (CCD)*

   At its core, a charge coupled device (CCD) in imaging is a piece of electronics designed to convert energy from photons into electrons. This is done utilizing specialized capacitors placed in a two dimensional array. Each capacitor will gain an electric charge proportional to the total intensity of light that falls upon it. In essence this allows this two-dimensional array to record a snapshot image projected onto the focal plane of the sensor by the optical system. After each capacitor is charged a circuit will pass its charge to its neighbor until it reaches the edge of the array where the charge for each individual capacitor is read-out as a voltage. This voltage is then put into an ADC where a count value is assigned to it and essentially an image is produced.

   CCDs are widely used in all types of imaging and for a long time were considered to have the highest image quality. CCDs are also known to have extremely high quantum efficiency allowing for high signal to noise ratios with relatively low exposures. As such, CCD chips are currently the standard in astronomy and space based observation of the Earth.

   Some issues that stem from CCD chips are their artifacts including blooming which occurs when a single capacitor reaches its threshold charge and it starts to spill over into adjacent pixels. This could be an issue as when imaging the aurora a primary concern is the earth-shine on the sunlit side of the earth. This side of the Earth would likely saturate in an image and resulting blooming could cause issues in overall image quality. A summary of the pros and cons of a CCD sensor can be seen in Table (2).

Table 2: Pros and Cons of CCD Sensor

Pros	Cons
High quantum efficiency	Blooming artifacts
Large amount of heritage in space-based observation	Higher cost
Good in low-light conditions	

2. *Complementary Metal–Oxide–Semiconductor (CMOS)*

Again at its core a Complementary Metal-Oxide-Semiconductor (CMOS) is a simple piece of electronics that converts photon energy into electrons. It fulfills the same role as a CCD sensor however has slightly different performance characteristics. A CMOS is a type of active pixel array where each individual photosensor has its own active amplifier such that each individual pixel is read out individually instead of being transferred to neighboring sensors in order to read out at the edge of an array. A visual depiction of CMOS v. CCD imaging sensors is shown in Fig. (5). CMOS arrays have become increasingly popular primarily due to their use in almost all mobile phone cameras. This use has allowed the rapid advance to where many would consider that CMOS and CCD chips now offer similar image quality.

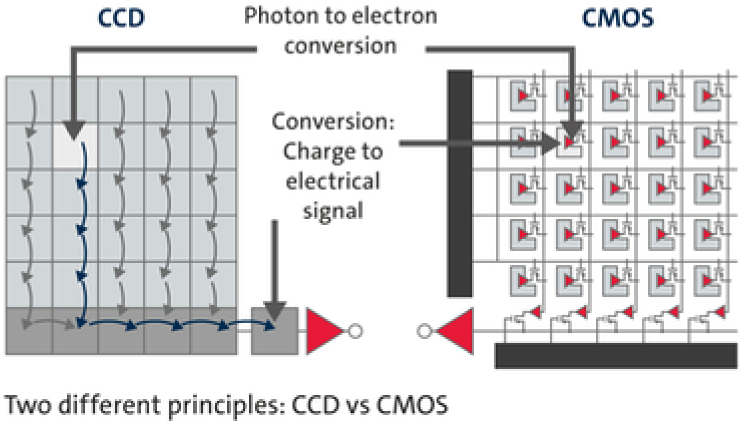


Figure 5: Visual Depiction of CMOS v. CCD Sensors [13]

Primary advantages in CMOS sensors lie in primarily in its low cost which was a primary driver in its use in mobile phones. This could also be a key factor in the the HEPCATS mission with its very limited factor. Additionally CMOS sensors typically have better performance with pixel blooming which is also highly advantageous in auroral imaging where earth shine can easily create blooming effects with the use of a CCD sensor.

Primary disadvantages in CMOS sensors primarily lie in its low quantum efficiency when compared to a CCD sensor. This could create issues with velocity aberration and jitters effects that result from longer exposure times. Furthermore use of a CMOS sensor in an on-orbit situation would require use of a global shutter as opposed to a typical rolling CMOS shutter. This is due to the non-still nature of images to be captured by the HEPCATS mission and this will likely result in a slight bump in price. A summary of the pros and cons of a CMOS sensor is shown in Table (3)

Table 3: Pros and Cons of CMOS Sensor

Pros	Cons
Less expensive	Relatively low quantum efficiency
Less blooming effects and artifacts	Less historic applications for space-based observation
Rapid development and cost reduction in past decade	

3. *Oversampled Binary Imager*

An oversampled binary imager is an image sensor that produces a non-linear response like that of the photographic film. Every pixel in the sensor has a binary response, giving a one-bit quantized measurement of the light intensity. The way the image sensor works is that at the start of exposure period, all the pixels are set to 0 [**Revolvy**]. If the number of photons reaching a pixel is equal to a given threshold, then the pixel is set to 1. A depiction of the imaging model is shown in Table (6).

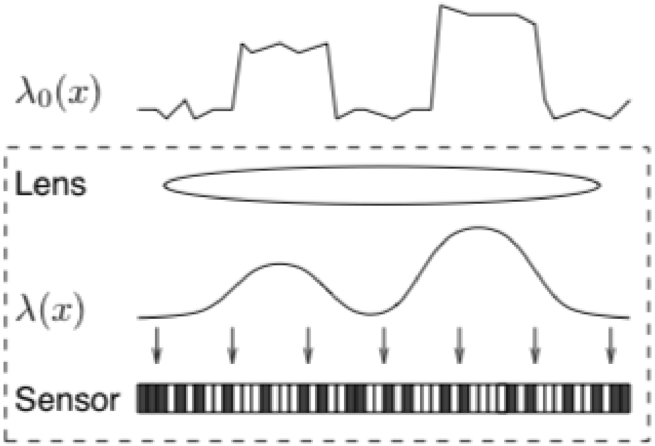


Figure 6: Imaging model of Oversampled Binary Sensor [1]

Essentially an incident light field denoted by λ_0(x) passes through the optical lens, that acts as a linear system. This results in a smooth light field λ(x) that is captured by the imaging sensor.

This type of sensor is good for high dynamic range imaging because the dynamic range isn't just defined for one pixel, but for a bunch of pixels. In addition, the high dynamic range will improve the luminosity of the images.

The primary downside to this sensor is that because there are only two possible values for the pixel, the images will be in 'black and white'. The Aurora does emit in the visible light spectrum which makes this sensor not very useful for the purposes of this project. Another major issue with the binary sensor is the reconstruction of the light intensity from the binary measurement. It would involve a sophisticated algorithm that may not be feasible in this project. A summary of the pros and cons of the oversampled binary imager is shown in Table (4) below.

Table 4: Pros and Cons of Oversampled Binary Imager

Pros	Cons
High dynamic range	Does not image in 'color' so may be difficult to detect aurora
High luminosity	May not satisfy goal for auroral tourism imagery.
Not very expensive	Involves complicated algorithms to process images.

4. *Quantum Image Sensor (QIS)*

The quantum image sensor (QIS) is a technology that is currently under development even though prototypes have recently been tested in limited trials.[2] This type of image sensor has the potential to revolutionize the photographic industry just like the CCDs and CMOS did with vidicon tubes.[6] Much like CCDs and CMOS, the QIS is an array of specialized photon-counting pixels called jots. A jot is a nano-scale active pixel with a binary output and this sensor array works like the oversampled binary imager in a way. By creating binary bit planes that record photon location at a particular instant of time, a complex algorithm then stitches the image back together. This is demonstrated in Figure (7) below.

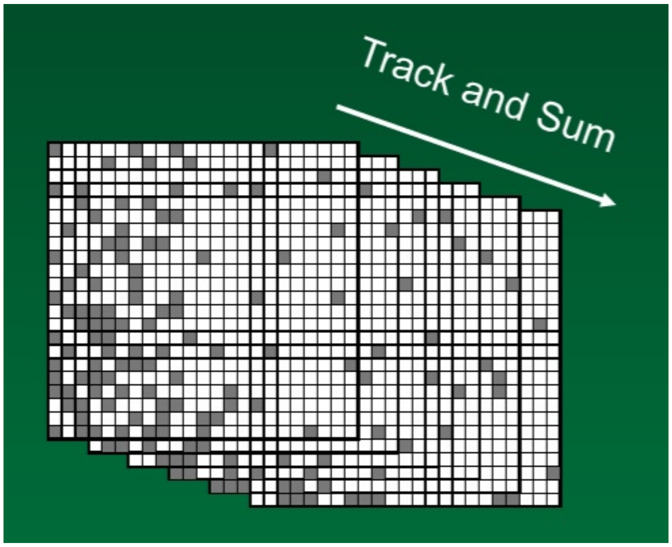


Figure 7: Analytical Model of Quantum Image Sensor

The jot is a major breakthrough as it collects nearly 100% of incident light that passes through the pixel array versus roughly 25% that silicon absorbs. This allows for a higher dynamic range and overall image quality. Additionally, the QIS has global shutter capabilities versus rolling shutter which allows it to capture moving objects without significant image distortion.

Table 5: Pros and Cons of Quantum Image Sensor

Pros	Cons
High dynamic range	Still under development
Fast light absorption	Lacking heritage
Global shutter	Very expensive
Small size/power	

4.1.2 Imaging Configuration

1. *One High-Resolution Grayscale Camera*

   One imaging configuration type considered is a singular high resolution grayscale camera. This configuration will essentially image in 'black and white' and achieve a high spatial resolution while only recording relative intensity data of all incoming wavelengths.

   Any given image sensor has a characteristic known as spectral sensitivity and indicates the sensor's relative sensitivity to light at a given wavelength. These sensors can then be classified as either wide band or narrow band indicating whether they are sensitive to a large range of electromagnetic signals (such as that of the sun or some other known source) or are sensitive to only a narrow and specific band (such as a specific wavelength that must be captured).

   In the case of a grayscale camera there is typically a wide spectral sensitivity. An example of this is seen in Fig. (8) which shows the spectral sensitivity of a Sony IMX287LLR-C grayscale CMOS sensor. It can be seen that the the spectral sensitivity of this specific example roughly matches that of the Sun which allows for effective visual imaging and this is a key characteristic of grayscale cameras.

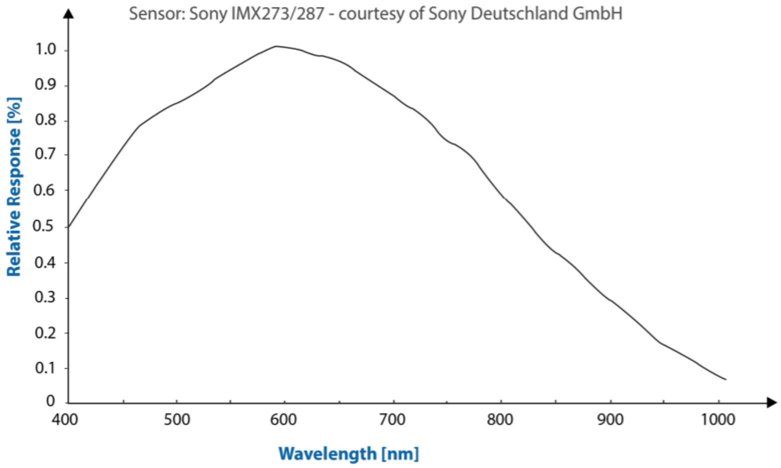


Figure 8: Spectral Sensitivity of a Sony IMX287LLR-C grayscale CMOS sensor [4]

The key issue that arises with this imaging configuration is that it does not record individual ‘colors’. Because of this much more light will fall on the sensor and a much higher signal can be achieved with a relatively low exposure time. This allows for high performance in low light conditions and will reduce optical issues that come with longer exposures. This includes limiting issues in velocity abberation, ADCS slough and system jitter.

The main drawbacks with only a grayscale camera is in the fact that data about individual wavelengths are not recorded. This has multiple issues. The first issue is that while the Aurora Borealis does emit in the broad visible spectrum the the highest intensities are in red at 630nm and green at 557nm. This means that while the Aurora Borealis is generally captured the most important data is being lumped together in a single relative intensity value. Thus the aurora is not being imaged to its full extent. Additionally this creates challenges in image processing software as it is quite difficult to train an algorithm to pick the aurora out of a wide band grayscale image. There is little differentiation between for example the clouds and the aurora. Instead if there were data about individual wavelengths it is easier to pick out aurora from the images. A summary of the pros and cons of a single grayscale camera is shown in Table (6).

Table 6: Single Grayscale Imager Pros and Cons

Pros	Cons
High overall spatial resolution	No spectral data on aurora
Simple design	Difficult to detect aurora
Relatively low amount of data produced by camera	May not satisfy mission goal for auroral tourism imagery
High signal in with relatively low exposures	

2. *One High-Resolution RGB Camera*

The alternate to a single grayscale camera is the use of a single standard RBG camera that takes images in ‘color’. This has the clear advantage of capturing spectral information about the aurora however it is at the cost of the actual resolution of images.

Each individual pixel in an RGB sensor has different type of light that is is sensitive to. Normally these sensors will have arrays of mixed ’R’ pixels that will record red light, ’G’ sensors that will record green light and ’B’ sensors that will record blue light. A common way of achieving this is through the use of a Bayer filter as shown in Fig. (9). Using interpolation algorithms it is possible to look at other pixels in the neighborhood of the a sensor and interpolate the color. Another thing to note in a Bayer filter is that there are more ’G’ pixels than ’R’ or ’B’ pixels. This is due to the fact that since the Sun primarily emits in the green visible wavelength and subsequently the human eye is most sensitive to such wavelengths it is necessary to contain more information about ’G’ pixels so that it is interpreted as true color by the human eye. This will also lead to an unnatural bias in RGB sensors in green.

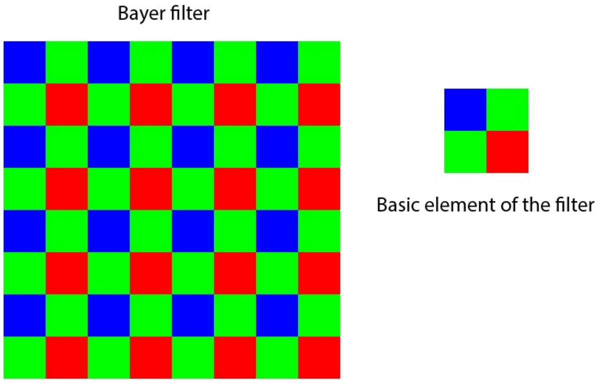


Figure 9: Visual Depiction of an RGB Bayer Filter [7]

The issue with this process is that it down-samples the image from the actual data being recorded. Instead of having a direct measurement of intensity at every individual pixel, only every second or third pixel shows the desired information for a given color. This has the effect of essentially cutting down the resolution of an image. When imaging from orbit at very far distances this has the resulting effect of losing information about whatever is being imaged. Instead of having a spatial resolution of 1km with a grayscale camera you may only have a 2km or 3km spatial resolution with an RGB sensor. While it is possible to use software or interpolation algorithms to improve this, in the end data is still lost when compared to a grayscale camera. Additionally these sensors can portray somewhat of a ‘false’ color and are typically not used for scientific observations.

Having said that, for the purposes of the HEPCATS mission and imaging the region of the Aurora Borealis, an RGB camera is definitely better than a grayscale camera. Having information of specific colors of the images taken offers insight onto specific aurora spectra and make the job of recognizing the aurora in images far easier. Instead of trying to pick out aurora from similar intensity features in the Earth’s atmosphere, having spectral information makes this much easier. For example if it needs to be determined if a certain image contains green oxygen spectral emissions then a image processing algorithm can simply look primarily at the data from the ’G’ pixels. Furthermore, as a primary goal of the HEPCATS mission is to create auroral tourism imagery, ‘true color’ images are the most desirable. Tourists will want to look at HEPCATS imagery and see a direct correlation between what is being taken and predicted and what they can expect to see on the ground. This is not possible with a grayscale camera alone. In addition to this, RGB cameras are often less expensive than the grayscale cameras and are relatively simple to process. A summary of the pros and cons of a single RGB camera as a imaging configuration is shown in Table. (7).

Table 7: Single RGB Sensor Pros and Cons

Pros	Cons
Can image the aurora in color	Lower spatial resolution than grayscale
Relatively simple to process	Colors not fully representative of actual image
Less expensive than monochrome imagers	
Easier to recognize aurora in imagers	

3. *Three High-Resolution Grayscale Cameras*

A third design option to be considered is the use of three different high-resolution grayscale cameras each filtered to receive a specific wavelength of light. This is essentially a way of getting very high resolution ’true color’ images however has obvious drawbacks in complexity and cost. A sample diagram of such a setup is shown in Fig. (10).

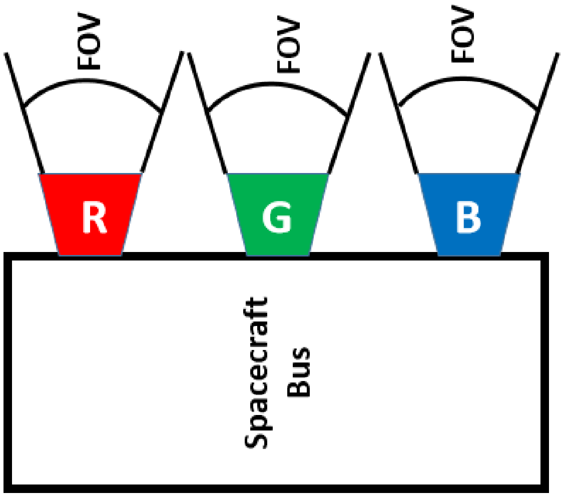


Figure 10: Configuration of Three Grayscale Cameras

By using three different grayscale cameras it is possible to essentially image in color. This is done by filtering incoming light down to a narrow and specific wavelength such that each individual camera captures only information about that wavelength. This would most likely be done in a configuration where one camera measures a red visible wavelength, one camera a blue visible wavelength and one camera a green visible wavelength. This allows for a complete image to be reconstructed from the information of each of the three sensors without the sampling loss of a Bayer filter. There is a large complexity with a configuration like this as it would prove to be quite difficult to align the three cameras such that their FOVs are roughly the same at a given distance. Additionally there is a lot of complexity in creating a single image from three different cameras three different physical locations in space. While it is certainly possible this may greatly exceed the scope of this project. Additionally this method creates three times as much data as a single grayscale camera which is something that is important to consider with a tight link budget.

Additionally, the most obvious drawback of this configuration method is the fact that it is more than three times as expensive as using a single grayscale camera. Additionally filters for each sensor must be purchased and depending on the fidelity of these filters this can be quite expensive. This method does, on the other hand, have the effect of having the highest spatial resolution while also receiving data about individual colors and is likely why past NASA missions including POLAR have utilized this approach. A summary of the pros and cons of this method can be seen in Table (8).

Table 8: Pros and Cons of Three Grayscale Camera Imaging Configuration

Pros	Cons
High resolution	Very expensive
Easy to recognize aurora in images	Very complex
Captures specific colors of aurora at high resolution	Highest amount of data produced

4. *One High-Resolution Grayscale Camera and One RGB Camera*

   The final design option to be considered is the combination of a single high-resolution grayscale camera and a single high-resolution RGB camera. This serves as a compromise between a single grayscale camera and a set of three grayscale cameras set to image a certain wavelength. High-resolution imagery is captured and additionally color is captured at a slightly lower resolution. A diagram of this configuration is shown in Fig. (4.2.1).

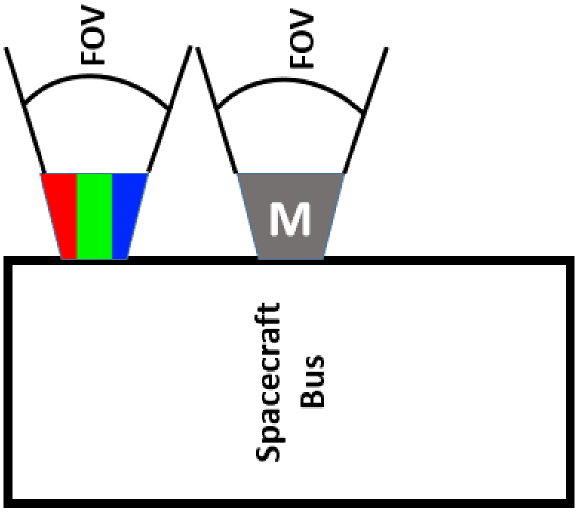


Figure 11: Configuration of One Grayscale Camera and One RGB Camera

This configuration allows for high resolution imagery in its grayscale camera however it is also capable of receiving information about the colors of the aurora from a secondary, lower resolution camera. With proper alignment and interpolation techniques it would also be possible to interpolate colors in the grayscale images using the secondary RGB camera. This could be done through the use of geometric transformations as well as algorithms that interpret colors of individual pixels based on those around it. The primary benefits of this configuration lie in the fact that a high spatial resolution is achieved in grayscale that is supplemented with data from the RGB camera.

A few possible issues with this configuration primarily stem from complexity and cost. This configuration relies on both physical and software calibration such that color pixels could be interpolated from those around it and additionally there is a an added physical complexity with the alignment of the two cameras. Failure to align to two cameras effectively will create issues when trying to combine images from the grayscale and RGB camera. Even misalignment of a few degrees could make this process very difficult. Additionally, while not as expensive as three grayscale cameras, an RGB camera with a grayscale camera will likely take up a large portion of the HEPCATS budget and this is something that needs to be considered. A summary of the pros and cons for this configuration is shown in Table. (9).

Table 9: Pros and Cons of One Grayscale One RGB Configuration

Pros	Cons
High spatial resolution	Fairly expensive
Relatively easy to recognize aurora	Fairly complex
Captures specific colors of aurora	Fairly high amount of data created

4.1.3 IPS Detection Algorithm

The ability for the IPS to automatically detect the presence of the Aurora is the most computationally difficult operation that must be performed. The relevant requirement for this operation is **2.1**. This kind of computation belongs to the field of computer vision. In the past, techniques were hand-crafted and highly customized to fit a specific purpose. Today, the cutting edge of computer vision techniques revolves around deep neural networks.

Neural networks are complex systems of functions which contain many variables. Neural networks are used for a variety of machine learning tasks, including many in computer vision. They contain multiple layers of simulated ”neurons,” each which computes an activation value based on its input values, weights, activation function, and bias. The activations of the neurons in each layer serve as inputs for the following layer. For the purposes of this project, a neural network would take imagery from the telescope as an input for the first layer, and output a binary classification of whether or not the image contains auroras.

In order to configure neural networks to serve a particular purpose, they must be trained on a large amount of data. A large database of images which are correctly classified. The network is trained by comparing the predicted results of the network's current state to the ground-truth data already known. Using this method, the enumerable weights and biases, which are initially random, can be adjusted to more correctly classify the training data. The method for decreasing error in this way is called *Stochastic Gradient Descent*, and the gradient is determined via an algorithm called the *Backpropogation*[9].

1. *Convolutional Neural Networks (CNN)*

   The most relevant and prevalent types of neural networks used in computer vision are called convolutional neural networks. Using every pixel from an input image as raw inputs to the network, or a "fully-connected network," has two major downsides. Firstly, using even a low resolution image such as 128x128px, the input layer would consist of 16,384 neurons, and each neuron in the next layer would need 16,384 weights. These large number of variable can make the problem computationally unworkable. The second problem with using fully-connected networks for image processing tasks is that they become translation-variant, meaning that changing the location of scale of an image's constant would change the output of the network. Both these problems are addressed by using operations called convolutions.

   Generally speaking, convolutions perform operations on an image to output values for each pixel based on their surrounding pixels. This type of operation is extremely useful in image processing application because it breaks down images into smaller, more manageable chunks. It greatly simplifies the problem of looking at the whole image at once, while also maintaining spatial relationships. In larger networks, repeated convolutions can break down pixels into patterns, patterns into features, and features into objects. The other major operation used in these kind is called pooling, which further reduces the number of operations used by basically down-sampling the images after convolutions.

   The Advantages of using a convolutional neural network are that, once trained the program can very quickly and efficiently classify images. The algorithm of a fully trained convolutional neural network is equivalent to a series of finely-tuned convolutions of vectors and such operations can be highly optimized by software packages such as `MATLAB` or `NumPy`. Re-calibration of the network based on different training data is definitely possible and could be done remotely to determine a new set of weights and biases. Implementing the new weights and biases could be as simple as uploading the values from the ground station.

   The disadvantages of this method are mostly involved in the initialization and training of the network. Before training can even happen, the structure of the network must be determined. There are many relevant factors here, including the number and size of the network's layers. Networks with more layers are generally able to learn and perform more complex tasks. Similarly, networks with more neurons within their layers are capable of performing better. With both of these parameters, using too few neurons will make an incompetent or incapable network, while using too many neurons can be unnecessary and slow down training and operations.

   Two other important factors to consider are choice of *activation function* and *learning rate*. The activaiton function is the operation performed by each neuron to transform the weighted sum of the previous layer's activations to that neuron's activation. The main purposes of the activation function are to bound the possible activation value and to introduce non-linearity into the system. The learning rate is a parameter involved in the stochastic gradient descent performed during training. This value basically determines how quickly the algorithm attempts to approach the local minimum of the loss function. Research in the field is ongoing on how different activation functions and learning rates affect performance.

Table 10: Pros and Cons of Convolutional Neural Networks

Pros	Cons
Quick Classification	Training Data Required
Robust Capabilities	Lengthy Training Computation
Re-calibration is feasible	Need to determine structure

2. *Pre-Trained Deep Neural Networks (PTDNN)*

One popular variation of developing convolutional neural networks from scratch is to take advantage of existing image classification networks. The term ”deep” is used in artificial neural networks to loosely refer to the number of layers used in a network, where deeper networks are composed of more layers in general. One image classification neural network is the Inception architecture [14] which has been shown to achieve very good performance at relatively low computational cost. General purpose networks such as inception are trained on very large datasets. One such database, which is used to train networks for the ”ImageNet Large Scale Visual Recognition Challenge” (ILSVRC) contains over 1.2 million images belonging to 1000 classes. Any deep learning network capable of processing this many images will be highly skilled in general purpose pattern and feature recognition.

Using a deep learning neural network such as `inception-v4` would allow much of the work of image recognition to be determined well, and produce a feature vector. Instead of using the features to classify images into the labels used to train the network such as triceratops and scuba-diver, a the final layer can be retrained to classify images into any custom classification are fit for an application. This process is called *transfer learning*. For the purposes of this system, the classifications should be at least ”aurora present” or ”no aurora present”.

Once the pre-trained network is configured to compute the specific relevant classification, the weights of the network's hidden layers can be tweaked to further improve performance. This technique is appropriately called *fine-tuning*.

Table 11: Pros and Cons of Pre-Trained Deep Neural Networks

Pros	**Cons**
Improved capabilities	Transfer Learning Required
Reduced Training Computation	Slightly Increased Complexity

3. *Scale Invariant Feature Transform (SIFT)*

SIFT or Scale Invariant Feature Transformation is a feature detection algorithm used to describe local features in images. It is particularly useful because it processes images that are scale, rotation, translation, shift, and partial illumination invariant. That is the images produced will maintain a consistent scale with practically no image shift or translation. It was first developed for the use of single channel images (greyscale), however, it is now capable of processing images across three channels. It is able to use images across RGB (Red, Green, & Blue) or HSV (Hue, Saturation, & Value) systems.

The SIFT algorithm follows a four stage process. First, it develops a scale space using a Gaussian Kernel. Second, it processes the image with contrast and edge response elimination to reduce the number of noticeable key points on the image. Third, it assigns a consistent orientation to the key points based on local image proprieties. Finally, it develops a set of histograms over a window centered on the key points. For efficient real-time processing, parallel implementation of SIFT has been applied using Graphical Processor Units (GPU's) and Field Programmable Gate Array's (FPGA's).

Table 12: Pros and Cons of SIFT

Pros	**Cons**
Large breadth of Varients	Patented
Multi-view matching	Mathematically Complicated
Very accurate	Not effective for low powered devices

4. *Image Segmentation Combined with Circular Hough Transform (IS & CHT)*

Image segmentation is the process of dividing an image into several sections of similar pixels. This process is used to simplify images before using other image processing algorithms on them. K-means clustering or a variant of k-means clustering would be used to partition the images. The k-means method is an iterative process. Given the k means, assign each pixel to the mean that has the least squared Euclidean distance. The centroids of the clusters are then set to be the new means. The process is then repeated until it converges. Each cluster of pixels then is a segment of the image.

The Hough transform is a method of feature extraction used in image processing and computer vision to extract arbitrary shapes from images. The Hough transform algorithm uses a voting procedure to find imperfect shapes. The circular

Hough transform first requires a binary image with just the edges. For every pixel in the edge detected image a circle is generated in the parameter space, and every point on the edge of the circle represents a vote. Then, the pointss with the most votes represent the centers of the circles present in the original image. The circular Hough transform only works for circles with a known radius, but it is possible to iterate through a range of radii to find a circle with an unknown radius.

Table 13: Pros and Cons of Image Segmentation Combined with Circular Hough Transform

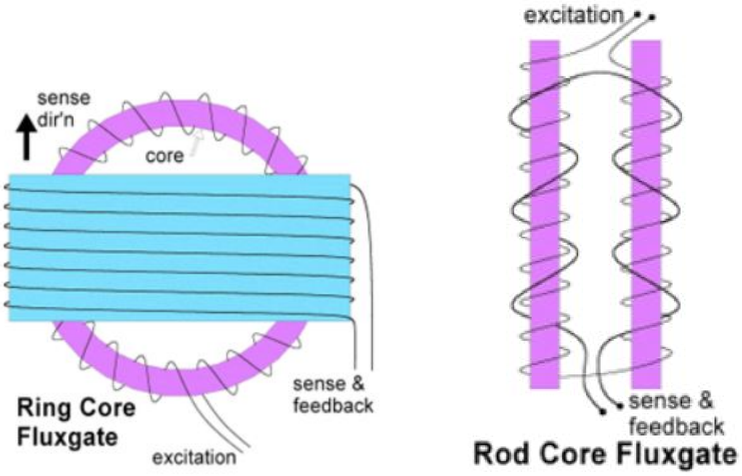
Pros	Cons
Parameters can be changed	Algorithm requires tuning
Robust capabilities	Memory hungry
	Vulnerable to noise in images

4.2 Magnetometer System

4.2.1 Magnetometer Sensor

There are three different types of magnetometer sensors that will be appropriate for detecting the vector components associated with a magnetic field as well as mapping the magnitude and direction of the magnetic field. The four different types of sensors that will be studied are Fluxgate Sensors, Anisotropic MagnetoResistance Sensors or AMR, and Spin-Dependent Tunnel Sensors or SDT. These were selected by determining sensors that would meet Requirement 3.1.1. and measure the magnetic fields within the desired range.

Fluxgate sensors are able to detect a vector magnetic field. A Fluxgate sensor works by having the core gate flux in and out of the sense coil. The two main types of Fluxgate sensors are rod core and ring cone sensors. The two diagrams below show the differences between the rod core and ring cone. A ring core like a rod core is permeable in letting flux in. A ring core sensor will be magnetically saturated in the core. It will then cycle the flux. A Rod Core Fluxgate Sensor will have its core be magnetically saturated and let the flux flow in alternating directions. There are many different versions of Fluxgate sensors but these have been studied the most and would be within budget. Neither the rod core or ring cone would be too difficult to construct. A Fluxgate Sensor has electronic simplicity and is relatively easy to construct. Another benefit of using a Fluxgate sensor is that they are manufactured by many companies. [5]



(b)

Figure 12: A Rod Core Fluxgate is shown above. The core is magnetically saturated in different directions on an axis. A Ring Core Fluxgate Sensor is shown on the left. It will be magnetically saturated in one cycle and then release on another cycle. It will sense direction by being magnetically saturated in a different direction the next cycle.

Table 14: Pros and Cons of Fluxgate Sensor

Pros	Cons
Electronic simplicity	Many styles but only two options that are viable: rod core and ring core
High Resolution	Large power consumption
High availability COTS	Expensive

An Anisotropic MagnetoResistance or AMR Sensor is able to sense the direction of the magnetic field based on the angle and direction of the electric current and magnetization running through the sensor. AMR Sensors are popular and are manufactured by many companies. The price of AMR Sensors range based on their sensitivity. A disadvantage of most AMR Sensors is that they can be disturbed by different types of magnetic metals. This means that most Anisotropic Sensors that have higher sensitivity must be placed on a boom. [10] [12]

Table 15: Pros and Cons of Anisotropic MagnetoResistance, AMR

Pros	Cons
Many producers such as Honeywell, GmbH, NXP Semiconductor	Low Resolution
Low power consumption	Can be disturbed by magnetic metals
Inexpensive	Field size can affect the trip point

A Spin-Dependent Tunnel Sensor or SDT uses nanotechnology to produce a large change in resistance through insulated layers. The spin is then detected through these layers. An advantage of using SDT is that these types of sensors can be some of the most sensitive on the market. SDT sensors use low power and are also compact. These types of sensors are used in the military for their small size. A disadvantage of using SDT sensors is that they have lower maturity than Fluxgate or AMR sensors. [12] [15]

Table 16: Pros and Cons of Spin-Dependent Tunnel, SDT

Pros	Cons
High resolution	Mostly used for military applications
Low power consumption	Few COTS Models
Compact nanotechnology, smallest sensor size	Lower maturity than Fluxgate and AMR Sensors

4.2.2 Magnetometer Location

Magnetometers have been used since Sputnik 3 and have been placed in many different locations. The magnetometer location will affect the overall performance of how well the magnetometer is able to map the magnetic field location and direction. The three options that will be studied in this report are integrated inside of the spacecraft bus, surface mounted on the spacecraft bus, and mounted on a boom that is attached to the spacecraft bus. A main factor that affects the performance of the magnetometer is electromagnetic interference (EMI). EMI is generated by communications which will be used on the spacecraft. A boom can be used to create distance between the magnetometer and the system, reducing EMI. However, using a boom will add more complexity and increased cost to any system. Many past missions have used magnetometers and this will also be used as a reference to decide where the magnetometer should be placed so that it will be able to map the location and direction of a magnetic field.

Magnetometers can be integrated inside a spacecraft bus. However, these magnetometers are usually the simplest type. These types of magnetometers are sufficient to sense the attitude but are usually only used in Low Earth Orbit. Magnetometers that are implemented in a spacecraft bus are close to the communication system and will be affected more by EMI. Another disadvantage of having magnetometers inside the spacecraft bus is that there are not many missions that have tried this approach. A lot of the research will be required during the design phase in order to have accurate science data, but will be harder to come by. An advantage of having a magnetometer inside the spacecraft is that the design will be less complicated.

Table 17: Pros and Cons of Magnetometer Integrated inside of Spacecraft Bus

Pros	**Cons**
The simplest magnetometers are surface mounted within the spacecraft	Near potential interference such as ferrous metals and vehicle currents
Sufficient for attitude sensing	Only used in LEO
Design is less complicated than using boom	Not a lot of heritage

Magnetometers that are mounted to the spacecraft bus usually consist of simple forms of magnetometers. These types of magnetometers have to deal with interference with metals from the spacecraft bus as well electromagnetic interference. However, there is less interference by surface mounting a magnetometer to the spacecraft instead of inside the bus. Magnetometers that are attached to a spacecraft are becoming more miniaturized in order to create a better trade-off between magnetic performance and spatial resolution.

Pros	**Cons**
Simple magnetometers are mounted on spacecraft	Must use sensors that are miniaturized
Sufficient for attitude sensing	Close to potential interference
Less complicated than using a boom	Not a lot of heritage

Magnetometers that are attached to a boom are the most sensitive magnetometers and need to be attached to a long, rigid boom. This configuration allows for the magnetometer data to pick up a significantly reduced amount of EMI produced by the spacecraft. Another benefit of attaching a magnetometer to a boom is that the background fields will appear unchanged as well as many past missions that have used a magnetometer have used a boom. A disadvantage of using a boom is that the design will could be more complicated.

Table 18: Pros and Cons of Having Magnetometer Attached to a Boom

Pros	**Cons**
Most sensitive magnetometers put on boom	Magnetometer boom must be long and rigid
Contaminant fields decrease with distance	Complicated design
On boom background fields appear unchanged	

4.3 Simulated Ground Station and Instrument Electronics Unit Communication

There are two methods in which communication between the simulated ground station (SGS) and the instrument electronics unit (IEU) can be accomplished: wired or radio frequency (RF) communication. The latter of these two methods requires an onboard and ground RF system to be designed whereas the primary leverages IEU I/O to network with the SGS (a personal computer).

An example of the RF system that would be designed to achieve communication between the SGS and the IEU would require a similar design as presented in Fig. (13).

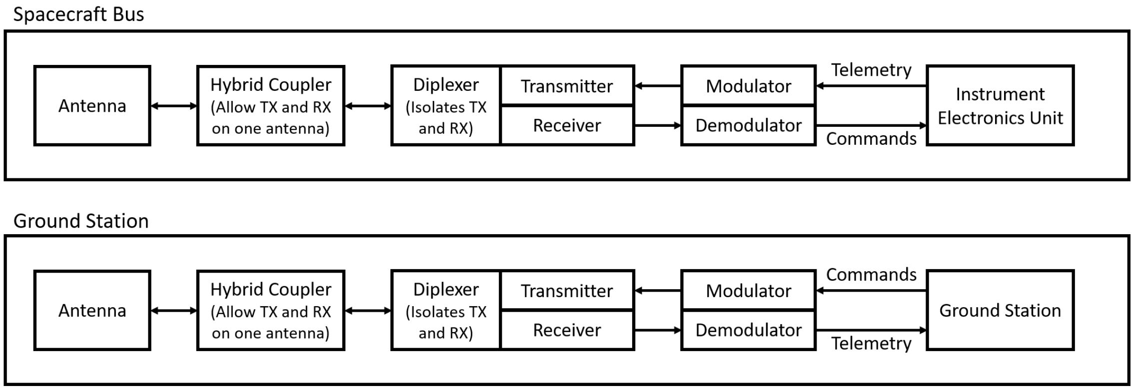


Figure 13: Spacecraft and Ground Station RF System Function Block Diagram

The added complexity in designing an RF system for both the IEU and SGS would require significant time to be spent on only this aspect of command and data handling. It is true that Fig.(13) can be substituted for off-the-shelf modules, such as XBee or XBee-Pro RF Modules, that would remove the complexity from this design choice; however, it must be noted that both uplink and downlink rates are required to be capable of being varied (see requirements 6.1.1 & 8.1.1) such that their rates are comparable to what will be expected on orbit (as determined through a link budget analysis). Using XBee or XBee-Pro as an example, its data sheet [**xbee**] reports that the RF data rate is set to 250kbps and cannot be changed.

The additional complexity of an RF system and restricted downlink/uplink rates if using off-the-shelf modules would not be considered a good design choice. The SGS and IEU communication aspect of this project is not significant relative to the project goals to warrant implementing an RF system; moreover, variable rates is a requirement that would not be met if choosing this design option. Wired communication would resolve both of these issues seen with RF: complexity and variable uplink rates. It would implemented by leveraging the I/O of the onboard electronics in the IEU to network with the SGS through a standard communication protocol (such as internet protocol); moreover, the complexity of the design is simplified. Rate variability with downlink to the SGS and uplink to the IEU is managed through data transfer rate (DTR) of the network.

Wired communication is chosen for communication between the SGS and IEU without a trade study as the method of communication is not significant for this project. The added complexity of designing and implementing an RF system would not be worth while and using off-the-shelf modules to simplify said design complexity may not allow requirements (6.1.1 & 8.1.1) to be met.

4.4 Instrument Electronics Unit

To interface with the spacecraft's instruments and ground station three different processing options are reasonable, each with characteristics which would benefit the design and detract from it. The IEU must be capable of not only processing and executing commands from the ground station, but must also be capable of short term storage of instrument data, as well as long term storage of mission critical command sequences and associated data. To this end, three separate design choices are considered below.

1. *Single Board Computer (SBC)* A single board computer would be the most versatile option, accommodating a wide range of design choices including software language selection, preconfigured software packages, native I/O support, and diverse OS support. Single board computers ship with a standardized PC/104 form factor of 96mm by 115mm.

PC/104 form factors all have standard mounting configurations, and can be stacked with other PC/104 boards. Each SBC includes a microprocessor, integrated system RAM, as well as onboard I/O ports which generally include USB, RS-232, RJ-45, and a SATA controller.

Table 19: Single Board Computer Pros and Cons

Pros	**Cons**
Built in peripheral integration	Moderate Unit Cost
Diverse software capability	Some hardware may be unused
Shared functionality between systems	Higher power consumption
High team familiarity	

2. *Microcontroller* A microcontroller is a feasible design option as well. Microcontrollers are most famously used on Arduino prototyping boards and feature a reasonable amount of processing capability, but are best suited to performing very specific tasks with well defined input and output parameters. Microcontrollers can be thought of as a ”computer on a chip”, in the sense that they have a processor, memory and I/O capability on a single chip. Microcontrollers are physically very small, often only 2 cm by 2 cm across. Due to their small size however, their processing capabilities are very limited.

Table 20: Microcontroller Pros and Cons

Pros	**Cons**
Very small size	Low clock speed
Fast reset on power loss	Limited onboard resources
Low unit cost	No shared functionality capability

3. *Field-Programmable Gate Array (FPGA)*

   An FPGA or Field-Programmable Gate Array is another viable design option. FPGA’s are useful when performing complex digital calculations. There is a large spread of FPGA’s which are capable of doing many things. Some FPGA’s are capable of performing both analog and digital processing. Also, they are capable of performing data conversions between digital and analog and visa versa. They typically have large resources of logic gates and RAM blocks. FPGA’s are known for being quite fast due to the parallel processing capabilities, having quick I/O rates, and containing bidirectional data buses. FPGA’s stand out among other units because there are re-programmable in the field making bug fixes quicker and easier. This typically allows for shorter time to market as well as non-recurring engineering costs.

Table 21: FPGA Pros and Cons

Pros	**Cons**
Very Fast	Steep Learning Curve
Very Resilient	Very Expensive
Easy to Modify	Poor Documentation

4.5 External Memory

There are multiple design options for reading and writing the data received during the mission. The magnetometer data will be in the form of vectors and thus will not require large read and write speeds or storage space. The images however will have high resolution requirements and will thus require much more storage space, thus being a large driver on the design options. Along with storage space, the mission requirements state that images are to be captured at least once per minute. This requires the read and write speed to be sufficiently high enough to succeed in recording the images and down linking them to the ground station, thus making it the most significant driving requirement.

1. *USB 3.1* The first design option considered is a USB 3.1 flash drive. This design was considered mostly due to its low cost and low complexity.

Table 22: USB 3.1 Pros and Cons

Pros	**Cons**
Low complexity	Limited storage
Low cost	Slow read/write speed
Minor power Draw	

2. *Solid State Hard drive (SSD)* The next design option considered is a solid state hard drive. The biggest advantages to this design are higher storage capacity and very fast read and write speeds.

Table 23: SSD Pros and Cons

Pros	**Cons**
High storage capacity	High cost
Fast read/write speeds	Large physical size
Low power draw	Integration with onboard computer

3. *Micro SD* The next design option considered was a micro SD card. This design is very small in size and is easily integrated with the other on board electrical components.

Table 24: Micro SD Pros and Cons

Pros	**Cons**
Small size and lightweight	Slow read/write speed
Low cost	Small storage space
Low complexity	

4. *Hard Disk Drive (HDD)* Finally, a hard disk drive was considered as a design option. This design was chosen on the same basis as the SSD, with high read and write speeds and high storage capacity.

Table 25: HDD Pros and Cons

Pros	**Cons**
Fast read/write speeds	Less reliable performance
High storage space	High Cost
	Large physical size
	High power draw

5.0 Trade Study Process and Results

5.1 Imaging System

5.1.1 Sensor Type

Table (26) shows the trade study parameters for the selection of the image sensor with the applied weights, driving requirements and rationale for using each parameter.

Table 26: Image Sensor Criteria and Weighting

Metric	Weight	Driving Requirements	Description & Rationale
Cost	0.3	N/A	Team HEPCATS has a limited budget and specialized sensors can deplete a majority of the team's resources. It is vital that the image sensor expenses don't consume >50% of the allocated budget.
Power	0.1	5.2	CubeSats are small vehicles and contain limited power supplies so it is desirable to have minimal power consumption for the imaging system. A weighting of 0.1 was applied because, in general, image sensors do not consume a lot of power.
Heritage	0.1	N/A	Team HEPCATS is inexperienced with image sensing technologies and reliable solutions with proven success is desirable. A weighting of 0.1 was applied due to the fact that the image sensor will be tested by the manufacturer and assumed to operate at its stated performance levels.
Quantum Efficiency	0.25	1.2, 2.2	In order to satisfy 2.2 and map the aurora's extent in low-light conditions, a high quantum efficiency is preferred.
Color Reproduction	0.25	1, 2.1	An accurate representation of the aurora in the visible spectrum is required to produce useful images for the image processing system, driven by 1 and 2.1.

Table (27) shows how each parameter was scored in the trade study. There are many variations and applications for image sensors so the following ratings were based off preliminary research into camera selection and general comparisons from industry reports. [**Revolvy**]

Table 27: Image sensor Scoring Parameters

Metric	1	2	3	4	5
Cost	Exceeds allocated budget	Will put budgetary constraints on other subsystems	Fits within the budget allocated for imaging system	Affordable and may allow for additional expenses	Least expensive
Power	Requires additional power that EPS cannot provide	Requires significant allocation of power from EPS (>50%)	Power consumption from image sensors need to be considered	Insignificant power consumption in relation to other subsystems	Least power consumption
Heritage	Still under development	Few examples of sensor in use	Reliable, resources available if malfunction occurs	Well-documented applications of use	Well-documented and history of proven success
Quantum Efficiency	Does not meet requirements	Marginally meets requirements	Meets requirements	Exceeds requirements	Most desirable
Color Reproduction	Does not meet requirements	Marginally meets requirements	Meets requirements	Exceeds requirements	Most desirable

Table (28) shows the scores each design option was given for the selected parameters, and the overall score of each option. The results are discussed below in the Appendix.

Table 28: Image Sensor Trade Study Results

Metric	**Weight**	**CCD**	**CMOS**	**Oversampled Binary**	**QIS**
Cost	30%	4	5	4	1
Power	10%	4	5	4	5
Heritage	10%	5	5	2	1
Quantum Efficiency	25%	4	3	4	5
Color Reproduction	25%	3	3	1	5
Total	100%	3.85	**4.00**	3.05	3.40

From the table, a close decision still remains between CCD and CMOS image sensors with a difference in overall score of 3.75%. The ”Orbit in the Life” simulation doesn’t require a flight-ready imaging system and for the purpose of providing acceptable imagery to the image processing system, a CMOS camera will be selected due to their relatively low costs. A greater importance was placed on minimizing costs within the imaging system due to the fact that the camera during the ”Orbit in the Lift” simulation may not be the final design option.

5.1.2 Imaging Configuration

The imaging configuration trade studies look at different methods to achieve the requirements pertaining to the project. All four design options provided various pros and cons and the metrics with which each solution is measured are discussed in the table below. Each metric is weighted based on its importance and value to the project.

Table 29: Image Configuration Trade Study Metrics & Weighting

Metric	**Weight**	**Driving Requirements**	**Description & Rationale**
Cost	0.3	N/A	Keeping in mind that the HEPCATS team has a budget of \$5000, cost plays the biggest factor in deciding the imaging configuration and a weighting of 30% has been given to it. Some design options involve multiple imaging sensors so the team has to make sure that the final baseline design is budget feasible.
Spatial Resolution	0.2	1.2	The number of pixels per meter is key in this project. In order to capture clear images of the Aurora without any, a high spatial resolution is needed. As mentioned in the requirements, the imaging system shall have a minimum spatial resolution of 48 arcseconds/pixel The spatial resolution is given a weight of 0.2.
Image Processing	0.2	1.3, 2	Image processing is also given a weight of 0.2. It is important to be able to process the photo. This could be geometric manipulations of multiple images to form one image or just the processing needed to get usable information from one image. In general, the less processing required for the image, the better.
Data Size	0.15	2.1	The size of the data is not as important as the other metrics for the purposes of this project, but still plays a role. To be able to store as many high quality images in the on-board computer, the size of data should not be too big. Additionally this is an important consideration in link budget of the project. Data size has been given a weight of 0.15.
Data Usability	0.15	1, 1.1.1	Data Usability refers to three different things in the image than can be generally summed up as how useful the data collected by the imaging software is. The first is how easy it is to recognize the aurora in imagery. This is a function of the spectra in which the aurora is imaged and the resolution at which it is imaged. The second is the usefulness of this data in both auroral tourism and as validation for auroral models. This is based on whether or not this data could be used by space weather forecasting agencies as well as use by these agencies for auroral tourism uses.

Each metric is then given a score and categorized from 1-5 based on the design requirements. This is shown in the table below.

Table 30: Image Configuration Metric Score Categorization

Metric	**1**	**2**	**3**	**4**	**5**
Cost (\$)	>2000	∼ 1500	∼ 1000	∼ 500	<500
Spatial Resolution (arcseconds/pixel)	Very low	Low	Medium	High	Very high
Image Processing	Impossible to process	Very difficult	Difficult	Not so difficult	Easy
Data Size	N/A	Configuration that produces largest size	Second largest	Third largest	Smallest data size
Data Usability	Can’t recognize Aurora	Somewhat useful data.	Useful data.	Very useful data.	Data is extremely useful.

The scores for each image configuration are explored in the trade study below.

Table 31: Image Configuration Trade Study Results

Metric	**Weight**	**1 High-Res Grayscale**	**1 High-Res RGB**	**High-Res 1R + 1G + 1B**	**1 High-Res Grayscale + 1 High-Res RGB**
Cost	30%	3	5	2	3
Spatial Resolution	20%	5	3	5	5
Image Processing	20%	4	4	1	2
Data Size	15%	4	5	2	3
Data Usability	15%	2	3	5	4
Total	100%	3.6	**4.1**	2.85	3.35

5.1.3 IPS Detection Algorithm

The image processing software detection algorithm investigates the four different detection algorithms for object determination. This will be used as the main algorithm used for determining if an aurora is present. The trade study, metrics, and rationales are described in Tables (32), (33), and (34) below.

Table 32: IPS Detection Algorithm Trade Study Metrics & Weighting

Metric	**Weight**	**Driving Requirements**	**Description and Rationale**
Accuracy	0.4	2.1	Accuracy is the most crucial measure of the detection algorithm's performance. Strictly speaking, accuracy measures the ratio of true classification to false classifications and is a good general measure. For our purposes, the metric of F1-Score will be used instead as described below.
Speed	0.2	2.1	Speed is important for the success of the mission. The algorithm needs to exhibit quick and efficient processing speed. The reason that speed is weighted as 20% is because this is the second most important metric when considering the algorithms. In order to produce near real-time images, it is important that processing of the images be as quick as possible. It does not have a higher weighting because it was determined that accuracy was more important than the speed otherwise the mission would be obsolete.
Feasibility	0.2	2.1	Feasibility is a key aspect of the image processing system. Several algorithms have significant feasibility issues, such as cost or training time. Weighting was set at 20% as feasibility is crucial, but not the only key aspect of the image processing system.
Adaptability	0.2	2.1.1, 2.1.2	Due to the nature of the data this algorithm is designed on, it will be difficult to obtain a large amount of appropriate training data. The algorithm would ideally be able to be reconfigured based on operational data. This metric is also weighted at 20% because this capability is crucial for the scope of our project, but would be needed on a flight-ready version.

It should be noted that the metric of ”Accuracy” will not be measured by the statistical measure of accuracy, but rather the so called F1-Score. The F1-Score is basically a more comprehensive measure of a classifier's overall performance. This score is the harmonic mean of the classification's precision, which describes the ratio of true positives to cases classified as true, and the recall, which describes the ratio of true positives to total positives. For our purposes, the cost of false negative is greater than that of false positives, namely the loss of data. For this reason the metric of recall is more important, because it gauges how many positive cases are correctly classified. [8]

Table 33: IPS Detection Algorithm Metric Score Categorization

Metric	**1**	**2**	**3**	**4**	**5**
Accuracy (F1-Score)	75%	80%	85%	90%	%95
Speed	Slower	Slow	Moderate	Fast	Faster
Feasibility	Likely Unfeasible	Challenging	Reasonable	Relatively Simple	Trivial
Adaptability	Rigid	Fairly Rigid	Adaptable from the Ground	Adaptable from S/C Hardware	Adapts in Real-Time

Table 34: IPS Detection Algorithm Trade Study [3][11][9][16]

Metric	**Weight**	**CNN**	**PTDNN**	**SIFT**	**IS & CHT**
Accuracy	40%	4	5	4	4
Speed	20%	4	4	3	2
Feasibility	20%	2	3	1	4
Adaptability	20%	3	3	3	3
Total	100%	3.4	**4.0**	3.0	3.4

5.2 Magnetometer System

5.2.1 Magnetometer Sensor

The magnetometer sensor trade study investigates the various design options for the sensor used to measure magnetic field strength. Table (35) below outlines the metrics used along with the associated weight and rationale.

Table 35: Magnetometer Sensor Trade Study Metrics & Weighting

Metric	**Weight**	**Driving Requirements**	**Description and Rationale**
Resolution	0.35	3.1.1.1.	The accuracy of the sensor is a major component of the magnetometer system. It will be crucial in determining changes in the magnetic field at small magnitudes and to differentiate the magnetic field strength from system noise. Thus, it was given a weight of 35%. It should be noted, however, that this is not to be confused with the bit resolution, or the quantization error.
Sensor Noise	0.15	N/A	The noise of the sensor will play a role in the total noise observed by the magnetometer. However, it will likely be smaller than the noise from the rest of the cubesat, depending on the magnetometer's sample rate and distance from the system, and is therefore given a weight of 15%.
Power Consumption	0.2	5	The power consumed by the magnetometer is a crucial component of the system. The cubesat's available power will be limited and must be split between all its subsystems. Thus, power is a limiting factor that must be taken highly into consideration, and was given a weight of 20%.
Cost	0.1	N/A	Cost will be a relatively important factor when choosing a magnetometer, as this project has a budget of $5000. Magnetometers can be several hundreds of dollars, and will not be cheap if they need to be replaced. That being said, they are a fairly large component of the subsystem and will not be nearly as expensive as the camera. Thus, a weight of 10% was given to cost.
Availability	0.15	N/A	The availability is also a relatively important factor, as some magnetometers are not as widely available and may be much more difficult to obtain. If the magnetometer breaks, it is important to ensure that it can be easily replaced to ensure the project is not set behind. Therefore, availability was given a weight of 15%.
Mass	0.05	N/A	The mass of the magnetometer is not a defining component, as most do not exceed ∼100 grams, which is very small compared to the overall mass of the cubesat. However, it will be important to counter-balance the cubesat to ensure that its weight is distributed evenly. Therefore, mass was given a weight of 5%.

The metrics were then given scales to assign scores between 1 and 5, with 1 being the worst and 5 being the best. This was based off of performance of various magnetometer sensors. This can be seen below in Table (36).

Table 36: Magnetometer Sensor Metric Score Categorization

Metric	**1**	**2**	**3**	**4**	**5**
Resolution(nT)	> 50	10-50	5-10	1-5	< 1
Sensor Noise Density ($\frac{nT}{\sqrt{Hz}}$)	> 10	5-10	1-5	0.1-1	$< .1$
Power Consumption (mW)	> 1000	500-1000	250-500	100-250	< 100
Cost ($)	> 500	350-500	200-350	50-200	<50
Availability	Difficult to Obtain. Custom Order	Special Order. Place Order to Manufacture.	Few COTS Sensors available	Many COTS Sensors Available	Easily Obtainable. COTS Abundant.
Mass (g)	>200	100-200	50-100	1-50	<1

The trade study was then performed based on these weightings and scales to determine which sensor would be most ideal for this project. The weights were multiplied by each sensor's corresponding score and summed to get a total between 1 and 5. These results can be seen below in Table (37).

Table 37: Magnetometer Sensor Trade Study

Metric	Weight	Fluxgate Sensor	SDT Sensor	AMR Sensor
Resolution	35%	5	4	2
Sensor Noise Density	15%	5	4	3
Power Consumption	20%	2	4	5
Cost	10%	3	4	5
Availability	15%	5	2	5
Mass	5%	2	5	5
Total	100%	**4.05**	3.75	3.65

The trade study reveals that the fluxgate magnetometer is the best design option for this project. Having the best resolution and sensor noise density, it is clear that it is the most precise sensor. This precision comes at the cost of power consumption, cost, and mass, however. For the purposes of this project, this is outweighed by its benefits, as it is has a score roughly 7.5% higher than the SDT sensor, and 10% higher than the AMR sensor. Additionally, due to its availability, it will be much easier to obtain than the SDT sensor.

5.2.2 Magnetometer Location

The magnetometer location trade study investigates the various design options for the placement of the magnetometer. Table (38) below outlines the metrics used along with the associated weight and rationale.

Table 38: Magnetometer Location Trade Study Metrics & Weighting

Metric	Weight	Driving Requirements	Description & Rationale
EMI	0.4	3.1,2	Electromagnetic interference is a major contributing factor when determining the location of the magnetometer. EMI is cause by the electronics in the system and depending on the strength can lead to inaccurate data recorded by the magnetometer. This major affect leads to a weighting of 40% for this metric as relevant and significant scientific data is an important aspect of the project. This metric is specifically driven by requirements 3.1 and 3.2, which require the magnetometer system to be capable of measuring the magnitude and vector quantity of a magnetic field. Therefore without low EMI from the system, these requirements will not be met.
Complexity	0.25	N/A	The complexity of the design option is considered to be the ease of implementation. This metric is given a weight of 25% as even though it is an important contributing factor to the final decision it does not affect the overall project goal to the same degree as other metrics.
Heritage	0.25	N/A	Heritage of the design option is considered to be how long the methodology has been employed and tested. Thus the score categorization ranges from research based to commercial off teh shelf. This checks that the design option being considered will work for the application and is a low risk. This metric was given a weight of 25% because although it has a low impact on the scientific data recorded it does have a significant affect on the ease of design of the system.
Cost	0.1	N/A	Cost of the design option implemented takes into account the overall approximate cost given the amount of material required to implement the design option. Specifically, the amount of mag free material that would need to be acquired to effectively implement the design option is considered. Given the large variation in price of potential mag free housing options, this metric is defined qualitatively relating to the amount of required material. This metric is given a weight of 10% as its affect on the system is small and mainly affects the budget of the project.

In table (39), each metric is defined on a scale of one to five to be used to score each design option accordingly.

Table 39: Magnetometer Location Metric Score Categorization

Metric	1	2	3	4	5
EMI	Extremely High	High	Moderate	Low	Negligible
Complexity	Overscoped	Involved	Moderate	Simple	Trivial
Heritage	Research Based	Under Development	Made and Tested	Used in Real World Scenarios	Commercial Off the Shelf
Cost	Out of Budget	Expensive	Moderate Price	Inexpensive	Negligible

The trade study below in Table (40) scores each design choice for magnetometer location based on the metrics outlined above.

Table 40: Magnetometer Location Trade Study [3][11][9][16]

Metric	**Weight**	**Inside S/C**	**Surface Mounted on S/C**	**Mounted to Boom**
EMI	40%	3	3	5
Complexity	25%	2	3	2
Heritage	25%	2	3	4
Cost	10%	2	3	4
Total	100%	2.4	3	**3.9**

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5.3 Command & Data Handling

5.3.1 Instrument Electronics Unit

The IEU trade study quantifies each design option's effect on the overall design by using quantifiable metrics. The metrics, weights and descriptions are presented in Table (41).

Table 41: Instrument Electronics Unit Trade Study Metrics & Weighting

Metric	**Weight**	**Driving Requirement**	**Description & Rationale**
Processing Speed	0.2	7.1, 8.2, 9,	The IEU is responsible for processing, compressing, storing, and receiving instrument data, as well as executing ATS commands, receiving and processing ground station commands, and packaging telemetry, spacecraft health and housekeeping data for downlink. As such, the capability to process data from a robust set of I/O streams is imparitive to mission success.
Power Consumption	0.2	5.2, 5.3	Keeping power consumption low will allow other systems more power and reduce bus electrical design complexity. Additionally, in order to prove feasibility of design, power consumption must be kept as low as possible. Using a solution drawing the power equivalent to a desktop computer does not show design feasibility.
Difficulty	0.15	N/A	Difficulty encompasses the difficulty and likely design time to implement the design option. Included in the difficulty metric is team familiarity with design options, as well as consideration for necessary design time.
OS/Software Compatibility	0.15	6.3, 7.1	The availability of COTS and open source operating systems and software packages will directly effect software design time and complexity. A design for which all hardware I/O device drivers must be written individually will be much more complex and have a longer necessary design time than a design where software packages for hardware components already exist.
Built in I/O Hardware	0.15	7.2.1, 8.1	The IEU will need to interface with multiple devices, including the instruments, on-board storage devices and the ground station. Selecting a design option with little to no built in I/O capability will increase design complexity by introducing device compatibility issues. A good design choice should interface have native I/O hardware in order to avoid hardware compatibility problems.
Thermal	0.1	N/A	While thermal design is not being considered for the system as a whole, thermal design for the C&DH system is a factor which must be considered. Any processing solution will need some form of cooling with some cooling solutions complexity being based on the amount of heat needing to be rejected. Additionally, some design options are thermally constrained, which will add to design complexity.
Cost	0.05	N/A	The total cost for the entire project must be less than 5,000 dollars. However, due to the importance of the C&DH system to both spacecraft health and science processing, cost is less of a constraint.

Table 42: Instrument Electronics Unit Metric Score Categorization

Metric	1	2	3	4	5
Processing Speed	Slowest	Middle	Fastest	N/A	N/A
Power Consumption	Highest	Middle	Lowest	N/A	N/A
Thermal	High Output	Medium Output	Low Output	N/A	N/A
Cost	Most Expensive	Midrange	Least Expensive	N/A	N/A
Difficulty	Hardest	Medium	Easiest	N/A	N/A
OS/Software Compatibility	Low Compatibility	Medium Compatibility	High Compatibility	N/A	N/A
Built in I/O Hardware	Least Built In	Middle Built In	Most Built In	N/A	N/A

Table 43: Instrument Electronics Unit Trade Study Scoring

Metric	Weight	SBC	FPGA	Microcontroller
Processing Speed	20%	2	3	1
Power Consumption	20%	1	3	2
Difficulty	15%	3	1	2
OS/Software Compatibility	15%	3	1	2
Built in I/O Hardware	15%	3	2	2
Thermal	10%	1	2	3
Cost	5%	2	1	3
Total	100%	**2.15**	1.9	1.95

Each design option was given a score based on it's contribution and detriments to the overall design, based on the evaluated metrics. This score was then multiplied by the weight for that metric and then totalled. The score for each option is justified below in the Appendix.

5.3.2 External Memory

The following trade study explores the four design options chosen for external memory. Seven metrics were chosen to compare the designs, with justification shown in Table (44). Quantifiable scores were applied to each to narrow down the design options to a baseline design.

Table 44: External Memory Criteria

Metric	**Weight**	**Driving Requirements**	**Description and Rationale**
Read/Write Speed	0.3	1.1, 1.2, 2.3, 3.3, 7.1, 8.2	This metric is simply how quickly the external memory device can read and store the data that is being captured during the mission. This is the most heavily weighted metric as it is critical to the success of the mission. To meet the requirement of capturing an image at a rate of at least one per minute, this speed must be sufficiently high enough and is thus a major driving metric.
Performance/Reliability	0.2	7.2	This metric is important to insure the external memory storage functions for the duration of the mission, in the harsh space environment. This is not a major concern with most of the design options, however the mechanical nature of the HDD required this metric to be included. It is weighted as it is because a failure of the external memory storage would result in failure of the entire mission.
Storage Space	0.2	1.2, 2.3, 1.1, 7.1, 7.2	Storage space is also a major driving metric of the mission. The magnetometer data will be very small in size and thus not an issue, however the captured images are expected to be very large in size. In order to store at least an orbit's worth of data, this storage size needs to be sufficiently large, making it another major driving requirement of the mission.
Power Draw	0.1	5.1	Power draw is important for the mission, as this value needs to be realistic for the actual mission to succeed. Each of the design options have significant differences in power requirements, thus this was an important metric to consider. This metric is weighted slightly less however, due to the ”Orbit in the life” simulation being performed using power from an outlet.
Cost	0.1	N/A	Cost is considered as a metric due to the limited budget of the mission. Although not a firm requirement, this metric needs to be considered to assure that the budgetary constraints are met. All of the design requirements are however relatively low cost, thus this metric was considered with less weight than the metrics mentioned above.
Size/Weight	0.05	4.1	Size and weight are considered as a metric as well to assure the external memory device can fit into the spacecraft bus in conjunction with the other hardware. Due to the spacecraft bus not being a fixed size, along with each design option being relatively small in size, this metric was weighted less. The metric is still considered however, as it is important to have the external memory a realistic size to assure the requirement is met.
Complexity	0.05	N/A	Complexity is considered as a metric to assure that the external memory can be easily integrated with the rest of the components on board the spacecraft bus. Due to the likely high complexity of the on board computer, it is important that this metric exists to avoid complications in in the data storage process. This metric is weighted as low as it is due to each design option having a relatively low complexity.

Table 45: External Memory Metric Score Categorization

Metric	**1**	**2**	**3**	**4**	**5**
Read/Write Speed (MB/s)	<100	100-200	200-300	300-400	>400
Performance and Reliability	Unreliable	Significant Concerns	Moderate Concerns	Minor Concerns	No Concerns
Storage Space (GB)	<64	128	256	400	>400
Power Draw (W)	< 5	4-5	3-4	2-3	<2
Cost ($)	>350	250-350	150-350	50-150	<50
Size/Weight	Prohibitive	Large	Moderate	Small	Neglibigle
Complexity	Impossible	Difficult	Medium	Simple	Trivial

Table 46: External Memory Metric Score Categorization

Metric	**Weight**	**USB**	**SSD**	**MicroSD**	**HDD**
Read/Write Speed	30%	2	5	1	3
Performance/Reliability	20%	5	5	5	2
Storage Space	20%	3	5	4	5
Power Draw	10%	4	4	5	1
Cost	10%	5	2	4	4
Size/Weight	5%	4	3	5	3
Complexity	5%	5	4	5	3
Total	100%	3.55	**4.45**	3.5	3.1

6.0 Selection of Baseline Design

6.1 Imaging System

6.1.1 Sensor Type

The design choice of the imaging sensor was determined to be a CMOS imager based on the trade study results outlined in Table (28). The decision was close with the other option being a CCD camera, but ultimately cost was the deciding factor between the two. As stated in the motivation for Functional Requirement 1, the imaging system is to act as a proof of concept for the image processing system by providing expected imagery from an ”Orbit in the Life” simulation. The final design option for an image sensor needs to be tested with reliable auroral imagery, in which case a further study between CCD and CMOs is required. However, to minimize costs and ensure the image processing requirements are met, a reliable and affordable CMOS camera will be selected.

6.1.2 Imaging Configuration

After completion of the various trade studies, the design choice for the image configuration was determined to be the ’1 High-Resolution RGB sensor’. Although the spatial resolution of this configuration is inferior relative to others, it is the most feasible for the purpose of this project. The sensor is not expensive and it is fairly easy to process images without too much of a hassle. The grayscale imager was closest to it but because the Aurora emits in the visible light region, that camera would not be useful for this project. The configuration that involed 1 high-res grayscale imager along with an RGB imager would’ve been useful but it did not meet the project’s cost and image processing requirements. Lastly, the design option with 3 grayscale imagers with R+G+B filters recieved the lowest score. This configuration is too expensive for this project and also involves a lot of complicated geometry and algorithms to process the images.

6.1.3 IPS Detection Algorithm

The design choice of the IPS detection algorithm was determined to be the use of pre-trained deep neural networks. The algorithm was chosen through the trade study shown in Table (34). The pre-trained networks were specifically determined to be more accurate than any other considered algorithm, just as fast, and only slightly harder to implement than the option of image segmentation techniques. In general, the use of pre-trained deep learning networks allows for the benefits of highly capable and adaptable convolutional neural nets, without having to amass large amounts of training data or undertake computationally heavy training of large networks.

6.2 Magnetometer System

6.2.1 Magnetometer Sensor

The design choice of the magnetometer sensor was confirmed through the conduction of a trade study based on performance metrics, as shown in Table (37). The best option for this project was determined to be a fluxgate magnetometer due to its high resolution, low sensor noise density, and high availability. Its high resolution will allow for precise measurement of the magnetic field at small magnitudes and to be able to more easily filter out noise. Even though the SDT and AMR sensors received comparable scores to within 10%, the fluxgate sensor’s benefits make it the best design alternative for this project.

6.2.2 Magnetometer Location

The design choice of the magnetometer location was determined to be attached to a boom. This option is a clear winner given that it has a margin of 25% with the next design option. This option scored higher in every category, except for complexity. Complexity of this design was rated lower along with the complexity of an integrated magnetometer as a rudimentary boom would need to be constructed for data and power purposes. This is a similar complexity to constructing a mag free housing that would be integrated into the spacecraft bus. The boom design also had the lowest cost and EMI along with a well defined heritage, making it the optimal choice for the magnetometer location.

6.3 Command & Data Handling

6.3.1 Simulated Ground Station and Instrument Electronics Unit Communications

The design choice to communicate between the SGS and IEU through wired communication was confirmed without a trade study due to considerations with design complexity and project requirements. The method of communication between each component is not a significant in the scope of this project; moreover, the added design complexity of a radio frequency communication system would make the time spent designing and implementing said system not a worth while investment. Substituting a RF system with off-the-shelf components would simplify the design complexity but may not allow uplink and downlink rate variability requirements (6.1.1 & 8.1.1) to be met. Wired communication on the other hand leverages I/O of the onboard electronics in the IEU to network with the SGS through a standard communication protocol; data rates is then managed through data transfer rate of the network. As a result, wired communication is chosen between the simulated ground station and instrument electronics unit.

6.3.2 Instrument Electronics Unit

Based on the results of the trade study shown in Table (43) the best design choice is a single board computer. While the SBC is not the fastest processing choice, its built in hardware capabilities as well as overall software compatibility make it the best choice for the IEU. Other design choices such as the FPGA and microcontroller did not feature the same amount of built in hardware or software compatibility, which increased their overall difficulty and helped eliminate them from the trade study.

6.3.3 External Memory

Analyzing the results of the trade study shown in Table (46), a solid state hard drive is identified as the best external memory option for this mission. This option is more expensive than the other design options considered and is slightly larger in size. For the sake of this particular mission however, read and write speed, along with storage space were very high priorities for this component. Solid state hard drives boast the highest performance in each of these areas, for all the design options considered. The hard disk drive was strongly considered, however due to its outdated technology and slower speeds, the decision was made to use a solid state drive. This decision is also backed up via heritage, where this design is almost exclusively used on all other similar missions.

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Appendix

0.1 Metric Score Justification

0.1.1 Image Configuration

1. Cost

   1 High Resolution Grayscale Imager- (3/5) The Monochrome sensors can be very expensive and prices reach up to $ 10 000. However, there is a fair amount of cameras in the $1000 range and hence a score of 3 is given.

   1 High Resolution RGB Camera- (5/5) A standard high resolution RGB camera is cheap and can be purchased for less than $500.

   1 High Resolution "R" Imager + 1 High Resolution "G" Imager + 1 High Resolution "B" Imager - (2/5) Three separate sensors for each color will cost three times the price of just one hence a score of 2.

   1 High Resolution Grayscale + 1 Low Resolution RGB Imager - (3/5) With a grayscale and an RGB imager, the price is around the $1000 range. Hence the score of 3.

2. Spatial Resolution

   1 High Resolution Grayscale Imager- (5/5) As mentioned in the design options, the spatial resolution for a grayscale camera is very high. It is able to detect a broader light spectrum, increasing its overall performance especially in low light conditions.

   1 High Resolution RGB Camera - (3/5)) Although the High Res RGB camera will provide 'colorful' Aurora images, it does not have a high spatial resolution as discussed in the design options. A score of 3 is given to this design option.

   1 High Resolution "R" Imager + 1 High Resolution "G" Imager + 1 High Resolution "B" Imager - (5/5) Having three different sensors of each color will definitely increase the resolution. There wouldn't be any biasing of colors like with the single RGB sensor. A score of 5 is given for this solution.

   1 High Resolution Grayscale + 1 Low Resolution RGB Imager - (5/5) Combining a high res monochrome imager with a low res RGB imager will provide a high spatial resolution. The grayscale sensor will provide highly pixalated images while the RBG sensor will provide 'colorful' images which will make it easier to recognize the Aurora.

3. Image Processing

   1 High Resolution Grayscale Imager - (4/5) Overall a singular grayscale camera will be fairly easy to process and will require little manipulation before being given to the IPS for further analysis. As such, a score of 4 has been given for this option.

   1 High Resolution RGB Camera - (4/5)) While processing the photo would still require some work, it would be a lot easier to process a colored image as opposed to a grayscale one. Stacking sub-frames is often the prefered method to reduce noise over increasing exposure time and a colored photo would only require about 30 to 40 subframes as compared to a high res grayscale camera (90-120). A score of 4 is given for this.

   1 High Resolution "R" Imager + 1 High Resolution "G" Imager + 1 High Resolution "B" Imager - (1/5) This design option would be extremely difficult to process as merging three different images and colors requires complicated geometry that may not be feasible.

   1 High Resolution Grayscale + 1 Low Resolution RGB Imager - (2/5) Once again it will require a lot of work to process two different images. This is, however slightly easier than three cameras and as such recieves a 2

4. Data Size

   To estimate the data size that each configuration will provide, the following assumptions can be made:

   - Every image (from all configurations) has 'd' bits
   - Every sensor is a square
   - High resolution imagers have nxn size

- Medium resolution imagers have (nxn)/4 size
- Low resolution imagers have (nxn)/9 size.

The raw image size size can be calculated by the following equation:

$$RawDataSize = ResolutionSize * Bits \tag{1}$$

The high-res grayscale Imager configuration has nxn pixels and will have a size of:

$$DataSize = d(n^2) \tag{2}$$

The second configuration (1 RGB imager) can be broken into 3 medium resolution sensors. Therefore for this configuration:

$$DataSize = d(\frac{3n^2}{4}) \tag{3}$$

The third image configuration involves 3 separate high resolutions sensors (R+G+B) and hence the data size is the same as the single grayscale imager multiplied by 3.

$$DataSize = d(3n^2) \tag{4}$$

Finally, 1 high-res grayscale imager + 1 low res RGB will have a size of:

$$DataSize = d(n^2) + d3(\frac{n^2}{9}) = d(\frac{4n^2}{3}) \tag{5}$$

Referring to table 5, we can now score each image configuration based on their size.

1 High Resolution Grayscale Imager - (4/5) - Second smallest data size

1 High Resolution RGB Camera - (5/5)) Smallest data size

1 High Resolution "R" Imager + 1 High Resolution "G" Imager + 1 High Resolution "B" Imager - (2/5) Largest data size

1 High Resolution Grayscale + 1 Low Resolution RGB Imager - (3/5) Third smallest data size

5. Data Usability

1 High Resolution Grayscale - (2/5) Having a grayscale image doesn't really satisfy customer requirements for auroral tourism. In addition, the auroras distinct color makes this option unreasonable for auroral tourism imagery and will make image recognition software nearly impossible.

1 High Resolution RGB Camera - (3/5) - This method introduces color to images making auroral recognition easier however it does not have as high of a resolution as other options and could still make this task somewhat difficult. Therefore this configuration recieves a score of a 3.

1 High Resolution "R" Imager + 1 High Resolution "G" Imager + 1 High Resolution "B" Imager - (5/5) This is perhaps the best option as this would create very high resolution color images in which it would be extremely easy to recognize the aurora and would satisfy the high-level mission goal of auroral tourism imagery. Thus it recieves the highest score of 5.

1 High Resolution Grayscale + 1 Low Resolution RGB Imager - (4/5) This is somewhat of a middle ground option between a singular lower-resolution RGB camera and three filtered grayscale cameras for each color. This would offer high spatial resolution along with color making auroral recognition extremely easy and would also make images good for auroral tourism. Thus it recieves a score of 5.

0.1.2 External Memory

1. **USB 3.1**
   Read/Write Speed (2/5): This score was given due to the slow read and write speeds of USB flash drives. Due to the nature of these devices, they are not capable of the speeds required for this mission ***Performance/Reliability (5/5):*** USB drives have no moving parts and have little to no concerns on the basis of reliability. The environment of space was considered for this metric and was not determined to be an issue. ***Storage Space (3/5):*** Although USB drives can be purchased in varying sizes, there is still a significant limit on storage space, even in the largest sizes. For the purpose of this mission, the storage space ability is mid tier for this design option. ***Power Draw (4/5):*** USB flash drives have a very small power draw, however still must be considered for the success of the mission. This design option scored relatively high in this criteria but was beat out by the lower power draw of the other options. ***Cost (5/5):*** This design option is very low cost comparatively, even in its larger sizes, thus it scored the highest possible for this criteria. ***Size/Weight (4/5):*** USB flash drives are very small in space thus this option scored well in this metric. It was however beat out by another option in size, thus it did not receive a perfect score. ***Complexity (5/5):*** USB flash drives are very compatible with other devices and are very simple in nature, thus it scored very high in this area.

2. **SSD**
   Read/Write Speed (5/5): Solid state drives have the fastest read and write speeds of all the design options considered. Due to no other options being able to top this performance, this design scored the highest possible score. ***Performance/Reliability (5/5):*** This option has no moving parts and is most resilient to the types of stresses this mission will present, such as high-g loading and the magnetic fields in space. Thus, this option was given the highest possible score in this area as well. ***Storage Space (5/5):*** Of all the design options considered, the SSD allows for the largest storage space. Given the realistic requirements of the mission, there isn't really any limit to this storage space thus the SSD was again given the best possible score in this area. ***Power Draw (4/5):*** This design option has a relatively low power draw, compared to the others considered, thus it was assigned a very high score. Other options however provided slightly lower power draw, thus it did not receive a perfect score. ***Cost (2/5):*** This design option has the highest cost of all the options, thus it scored very low in this metric. ***Size/Weight (3/5):*** Solid state drives are larger in size and weight than most of the other design options, thus it scored lower in this area. The size is however still relatively low and not overly constraining on the mission, justifying the mid tier score. ***Complexity (4/5):*** This option is slightly more complex than the USB and micro SD options, thus it scored slightly lower in this area. That being said, it still boasts a relatively low complexity for the requirements of this mission so it still scored well in this area.

3. **Micro SD**
   Read/Write Speed (1/5): Micro SD cards have the lowest read and write speeds of all the design options considered for this mission. These slow speeds would be detrimental to the mission and thus the score of this option was the lowest possible. ***Performance/Reliability (5/5):*** There are no concerns for the performance and reliability of this design option, as micro SDs are very simple with no moving parts, thus it scored the highest possible score in this area. ***Storage Space (4/5):*** Like the USB drives, micro SDs vary greatly in storage capacity. The options explored actually provided storage sizes that would be mostly adequate for this mission, so this option scored well in this metric. ***Power Draw (5/5):*** Of all the options considered, micro SDs boasted the lowest power draw. For this reason, this design option scored the highest possible in the power draw metric. ***Cost (4/5):*** Although lower in cost than some of the other options, to meet the storage requirements of the mission, the higher storage micro SDs are slightly more expensive, thus justifying this score. ***Size/Weight (5/5):*** Predictably, the micro SD is the smallest of all the considered design options. For this reason, it was given the highest possible score in this area. ***Complexity (5/5):*** Micro SDs are very simple and require very little integration with the rest of the hardware on the mission, thus it scored perfectly in this area.

4. **HDD**
   Read/Write Speed (3/5): Hard disk drives are faster than the likes of USBs and micro SDs, however still have mid tier speeds for reading and writing data. The speeds could be adequate for the mission, but are definitely a big consideration, thus this score was given. ***Performance/Reliability (2/5):*** There are major concerns for the performance and reliability of this design option. Due to the mechanical nature of HDDs, the magnetic fields in space could have a detrimental effect on the device and thus this score was greatly affected. ***Storage Space (5/5):*** This design option has very high storage space. Much like the SSD, with the given mission requirements, the storage space is more than adequate for a successful mission, thus the HDD scored perfect in this metric. ***Power Draw (1/5):*** Hard disk drives have fairly high

power requirements and draw more power than any of the other design options considered. For this reason, it scored the lowest possible score for this metric. ***Cost (4/5):*** HDDs are relatively outdated compared to the other options and the price reflects this. Hence, the price of this option is very low and only beat out by the USB option, thus it scored well in this area. ***Size/Weight (3/5):*** Similar in size to the solid state drive, this design option is fairly large in size, but still not overly constraining to the mission. This justified its mid range score. ***Complexity (3/5):*** Although still relatively simple in complexity, given the requirements of the mission, hard disk drives scored lower in this area than the other options. This was mostly due to the moving parts of the option, along with its outdated technology.

0.1.3 Instrument Electronics Unit (IEU)

1. **Single Board Computer**
   Processing Speed (2/3): This score was assigned due to the single board computer being at the mid-tier of processing capability. While some SBCs can outperform a FPGA in processing speed, most reasonable design options will be slower than an FPGA, but faster than a microcontroller. A single board computer is also able to handle less inputs which may not be precisely defined.
   Power Consumption (1/3): Single board computers are the most power hungry of all design options due to faster processors and more system resources. A SBC can easily require more than 8 W when running.
   Difficulty (3/3): All team members have the highest familiarity working with computers, rather than microcontrollers and FPGAs. Additionally, the integrated peripherals will decrease design complexity and streamline the software development process by reducing the need to write hardware drivers from the ground up.
   OS/Software Compatibility (3/3): Single board computers are able to run a variety of operating systems, including Windows, Linux, FreeBSD, RTLinux, and VXWorks. The wide range of OS compatibility also allows software to be written in languages familiar to team, including MATLAB, C, C++, and Python.
   Built in I/O Hardware (3/3): *Most SBCs include common I/O slots, including SATA, RS-232, RJ-45, and USB. Single board computers tend to have the most built in hardware of all the design options.*
   Thermal (1/3): *Due to higher speed microprocessors and higher power consumption, the thermal output of SBCs is higher than other design options. While most boards ship with some form of heatsink or passive thermal system, cooling a SBC will be harder than microcontrollers or FPGAs.*
   Cost (2/3): *Single board computers can cost anywhere from 35 dollars (Raspberry Pi) to 2000 dollars depending on desired configuration. Most design options considered for this trade study averaged around 600 dollars.*

2. **Microcontroller**
   Processing Speed (1/3): While microcontrollers excel at processing tasks with well defined inputs and outputs (such as a motor controller), they are slowest at processing tasks which require a more diverse set of inputs and outputs, and generally are clocked slower than mircroprocessors.
   Power Consumption (2/3): Due to less onboard processing capability, microcontrollers generally require very little power, sometimes even less than a watt. This is less than SBC's, but can be more than an FPGA depending on the application.
   Difficulty (2/3): While the team has some familiarity with microcontrollers, they will be more difficult than a SBC to implement due to the lack of onboard I/O hardware. Thus drivers for any I/O device will need to be programmed from scratch, or adapted from open source solutions.
   OS/Software Compatibility (2/3): Microcontrollers do not run any operating system, but are generally capable of being programmed in C or C++. The lack of an operating system will increase the difficulty of interfacing with mass storage devices, as well as require most applications to be built from the ground up.
   Built in I/O Hardware (2/3): The middle tier score was assigned to microcontrollers because while their I/O capability is limited, most ship as part of a board with I/O pins defined, and some standard connectors such as USB or RJ-45.
   Thermal (3/3): Microcontrollers emit less heat than every other design option, due to their low power requirement, and low processing speed, making them the best for applications where thermal heat rejection may be problematic.
   Cost (3/3): Microcontrollers Most microcontrollers cost in the range of 35-50 dollars due to their low hardware integration.

3. **FPGA**
   Processing Speed (3/3): This score was assigned to the FPGA due to the parallel processing capability with the FPGA. FPGA's are known for their processing speed. Of the three design options the FPGA was definitely the quickest in terms of processing speed.
   Power Consumption (3/3): This score was assigned to the FPGA because they consume considerably less power compared to the microprocessor and single board computer. This is because the FPGA contains less software compared to the microprocessor and single board computer because it focuses on only the functionally needed.
   Difficulty (1/3): Of the three options, the FPGA is certainly the most complex and least user friendly of the three options. Learning how to properly code and debug with FPGA's. They would be quite difficult to learn and manage.
   OS/Software Compatibility (1/3): FPGA's are the least compatible of the three options when it comes to OS/Software capability. For the most part, whatever software the FPGA's come with is what you can use. It is not compatible with any OS's and has very limited software available.
   Built in I/O Hardware (2/3): Provided that there is enough logic behind the FPGA's hardware and software FPGA's are capable of having a large range of I/O features. This is a particularly useful feature of the FPGA which is similar to the microcontroller, but not quite as extensive as the single board computer.
   Thermal (2/3): While the FPGA has the lowest power consumption, it doesn't have the least amount of thermal output. In fact it's thermal output is higher than the single board computer, due to the faster speed and more extensive hardware components. However, it does have a lower thermal output than the microcontroller. This is due to the extensive hardware and software capabilities of the microcontroller.
   Cost (1/3): Of all three design options, the FPGA is definitely the most expensive. It has unique hardware and improved in-field re-programming capabilities which makes it very expensive. It is also the fastest of the three options which plays a role in the cost of the FPGA.