Project HEPCATS

Highly Elliptical Polar Constellation for Auroral Transport Studies

Preliminary Design Review

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Customer: Neal Anderson (DigitalGlobe) & Tom Berger (CU Space Weather Center)

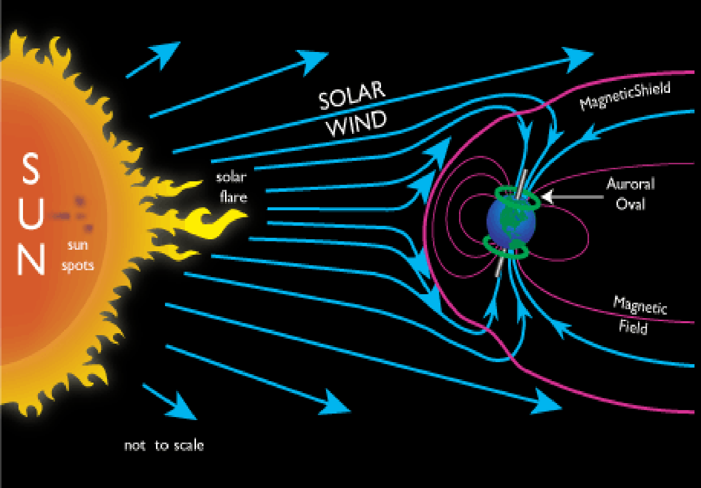
Advisor: Dr. Donna Gerren

Agenda

1. Project Overview
2. Baseline Design
3. Feasibility of Baseline Design
4. Imaging System
5. Image Processing System
6. Magnetometer System
7. Summary

Project Overview

Project Motivation



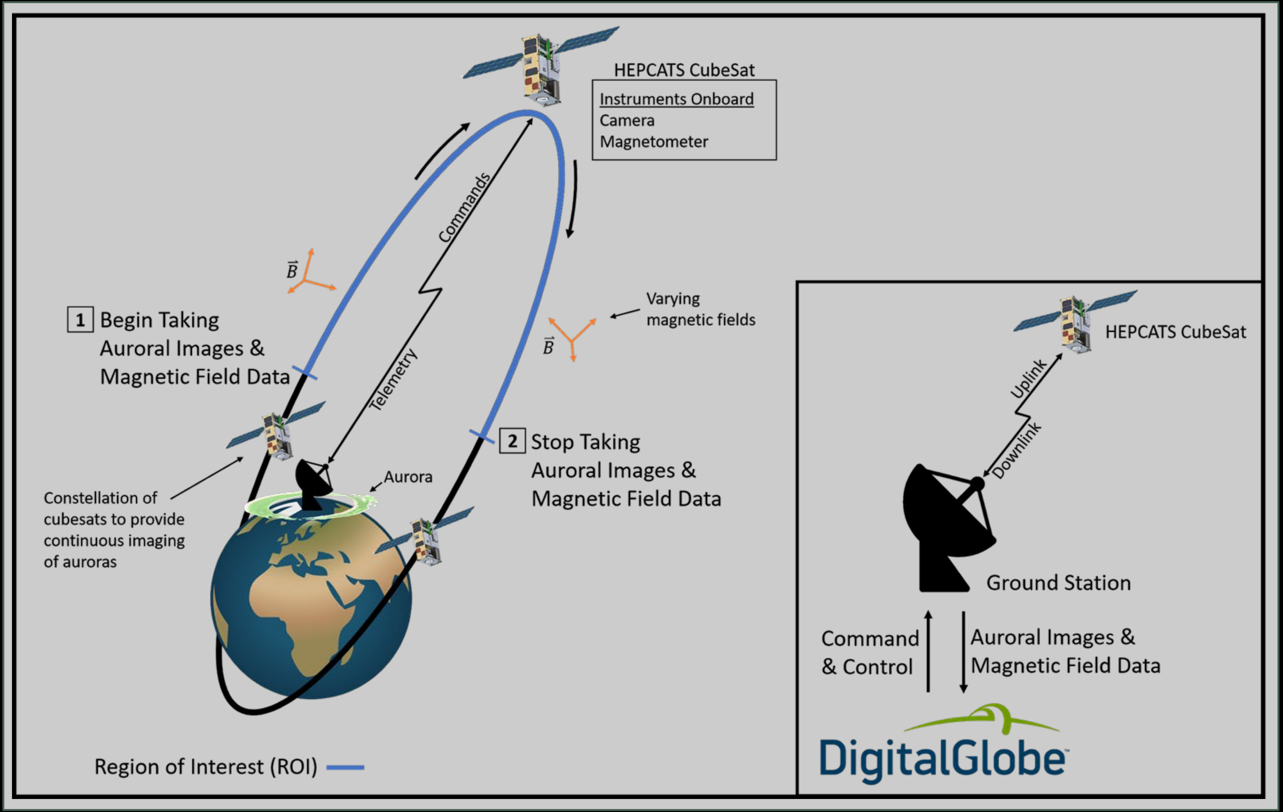
- The cause of the Aurora Borealis: originates from the solar wind and high energized particles colliding with high altitude atmospheric atoms
  - This affects radio and GPS reception
- Visible light imaging of the geomagnetic storms needs to be performed from a satellite in order
  - To assess radio and GPS inaccuracies
  - Drive auroral tourism
  - Validate current auroral models
- DigitalGlobe and CU Space Weather Center are collaborating with HEPCATS:
  - To image of entire polar crown for tourism
  - To gather science data in order to predict geomagnetic storms

Project Statement

- DigitalGlobe and the CU Space Weather Center will work with an undergraduate senior design team 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.

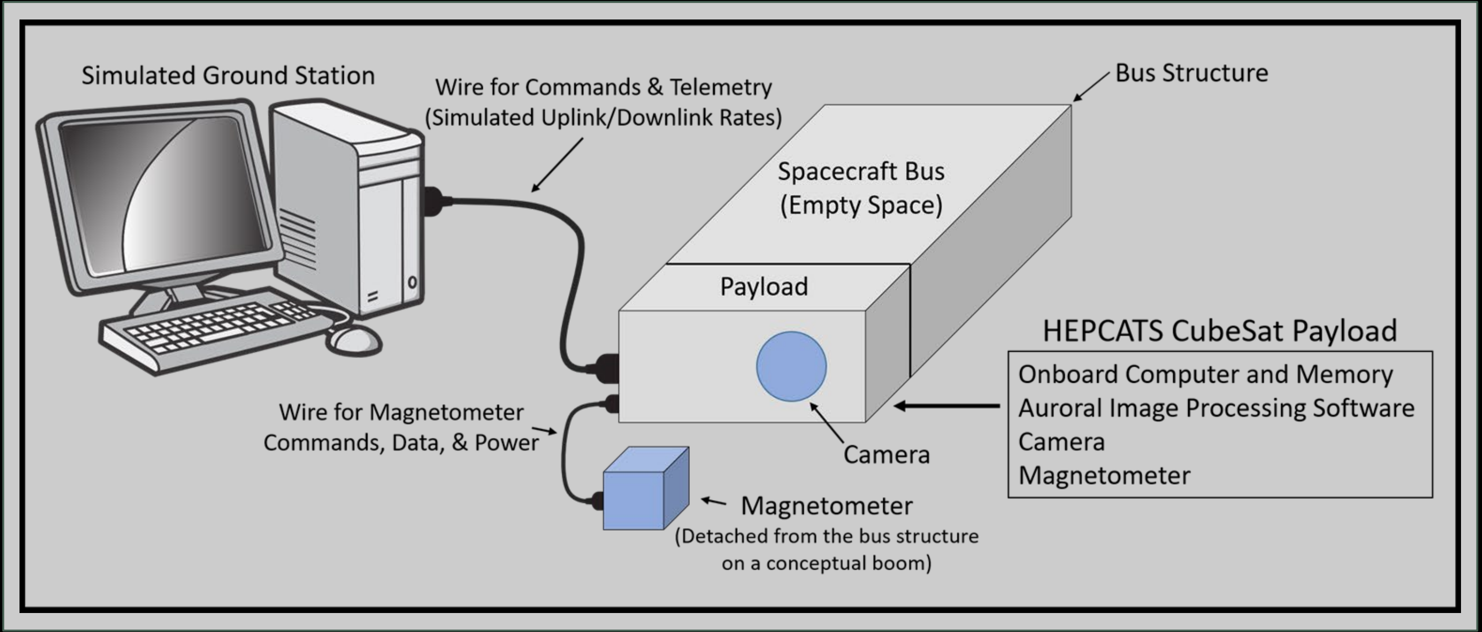
- HEPCATS project will focus on designing and implementing four specific components:
  (1) An auroral imaging system
  (2) A magnetometer system that will be used to measure magnetic field strength
  (3) The structure for the spacecraft to hold its payload
  (4) The software that will be used to compress, filter, process, and map the images taken

HEPCATS Mission ConOps

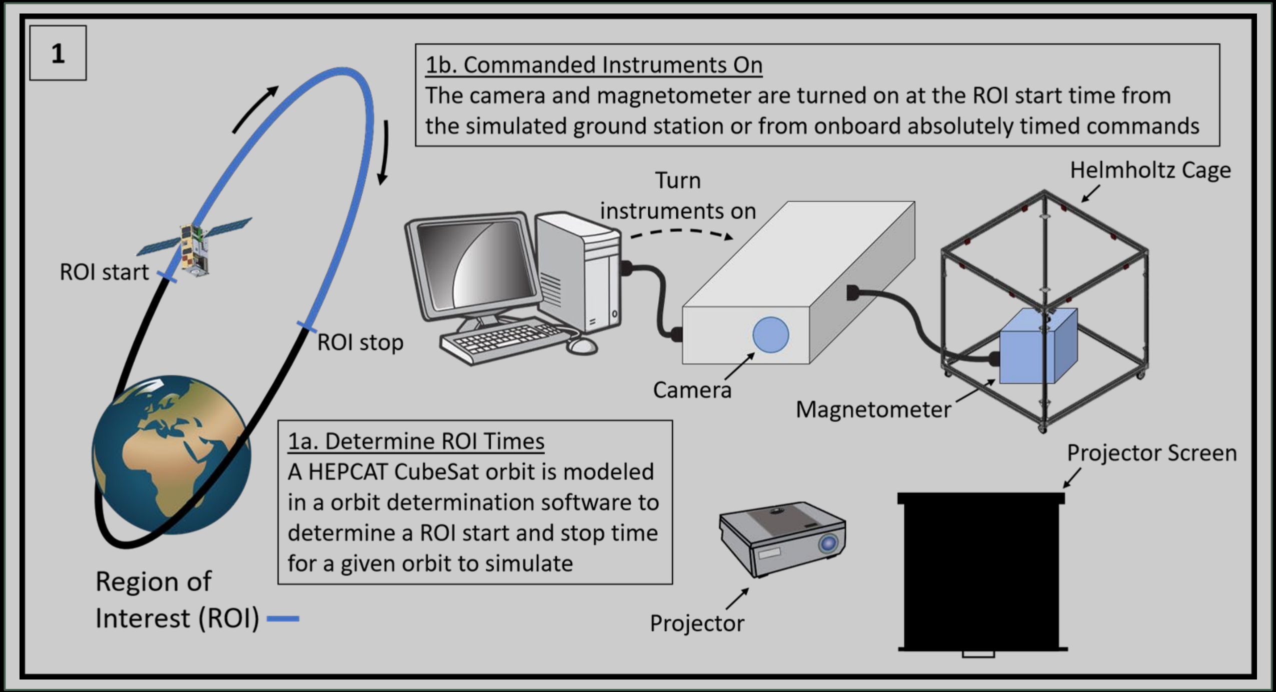


Baseline Design

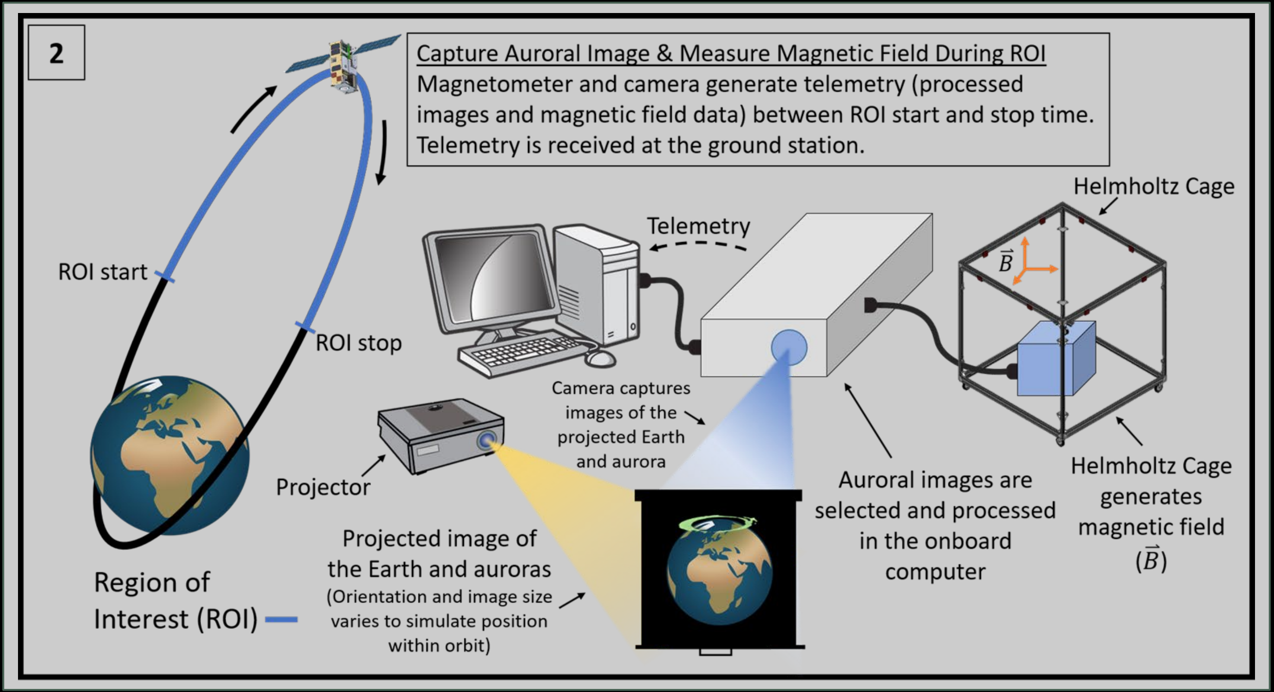
HEPCATS Project



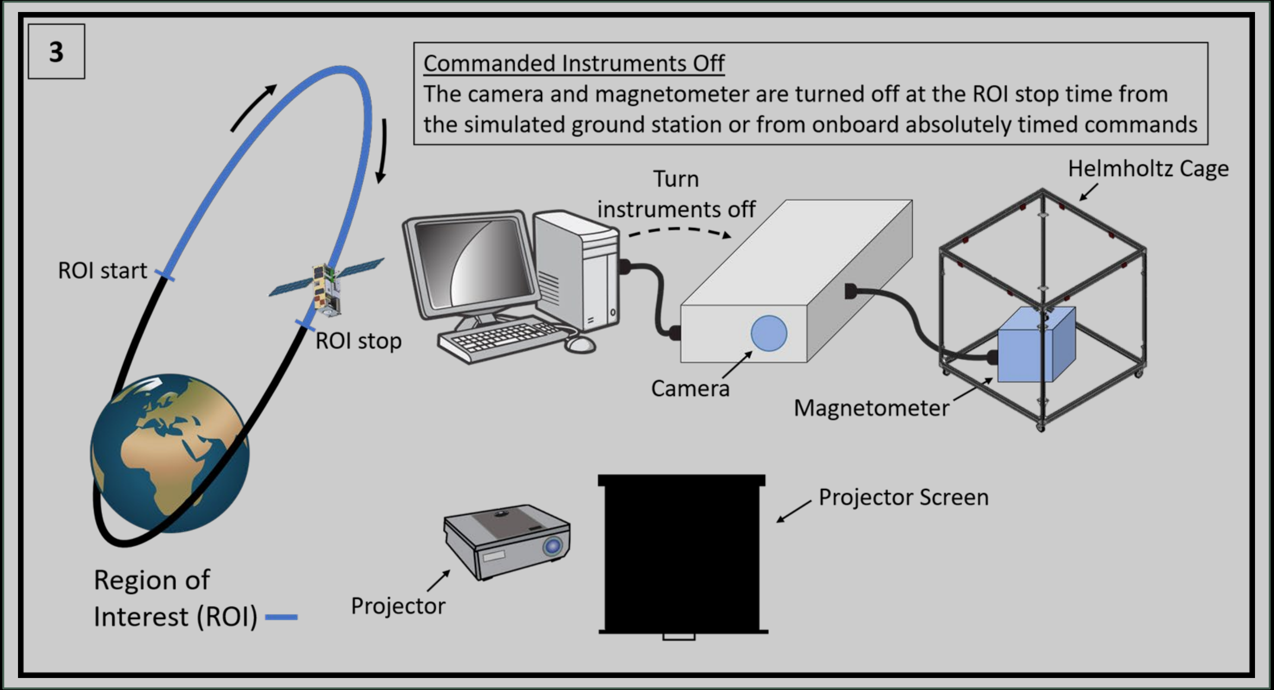
"Orbit in the Life" Simulation Part 1



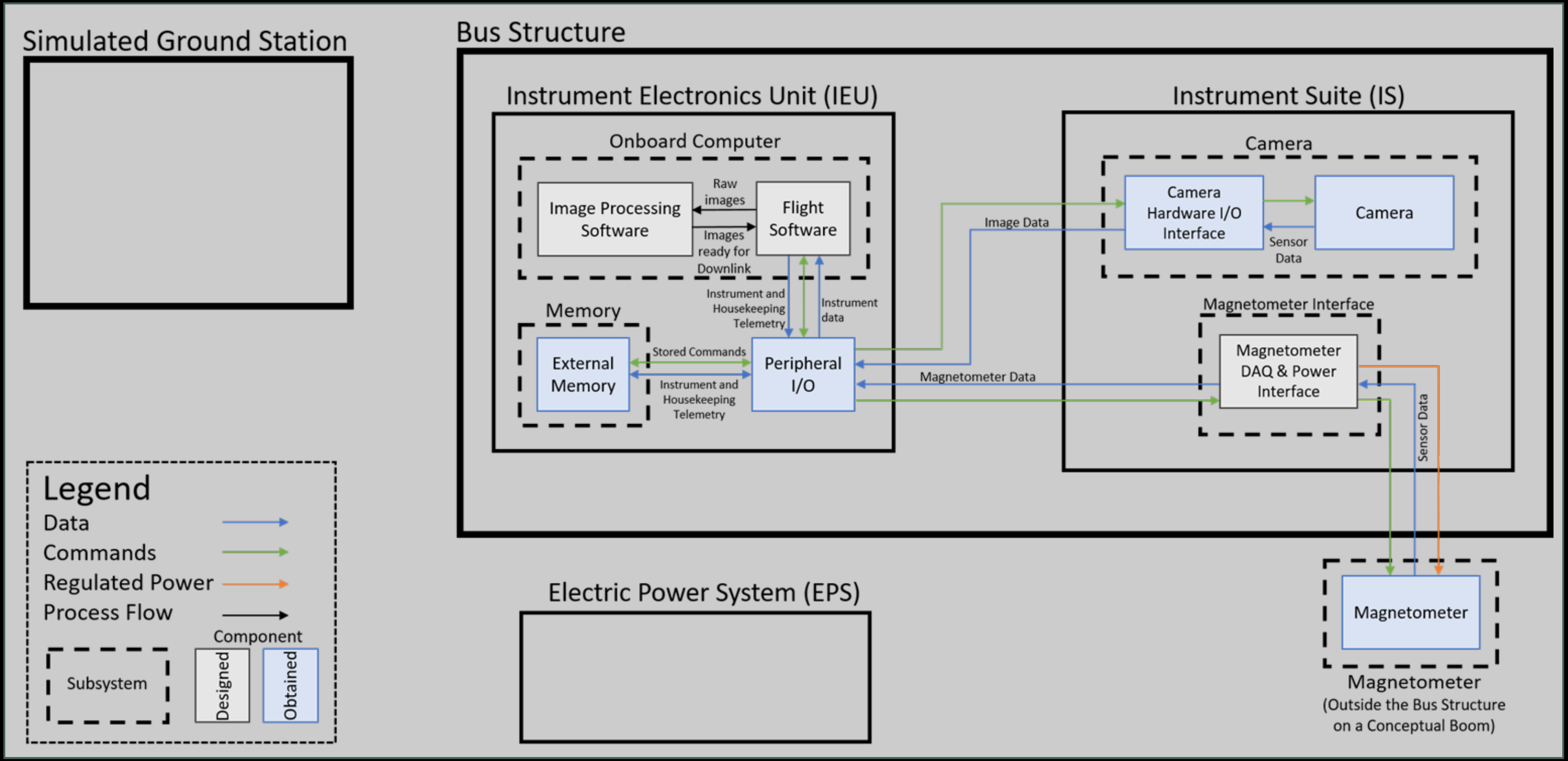
"Orbit in the Life" Simulation Part 2



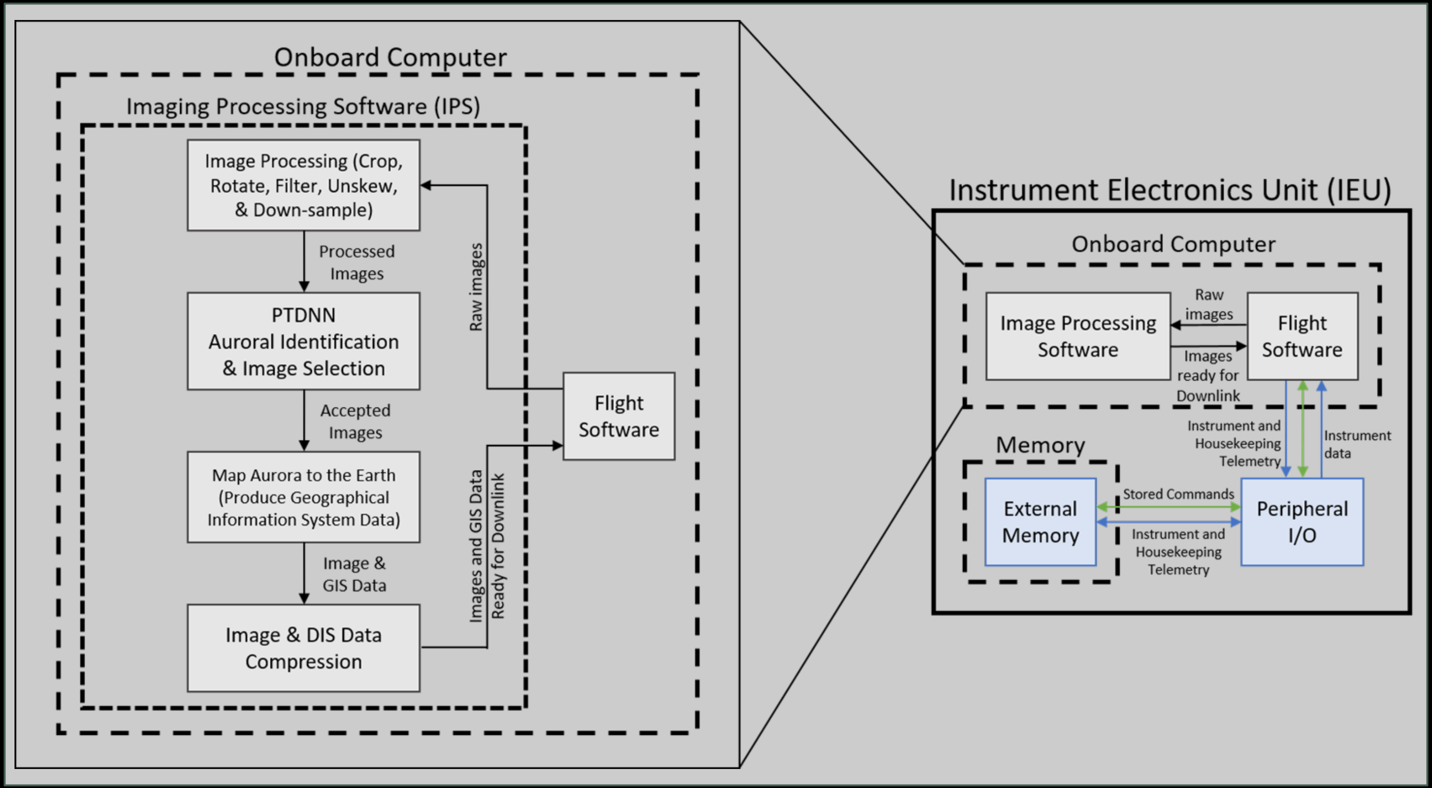
"Orbit in the Life" Simulation Part 3



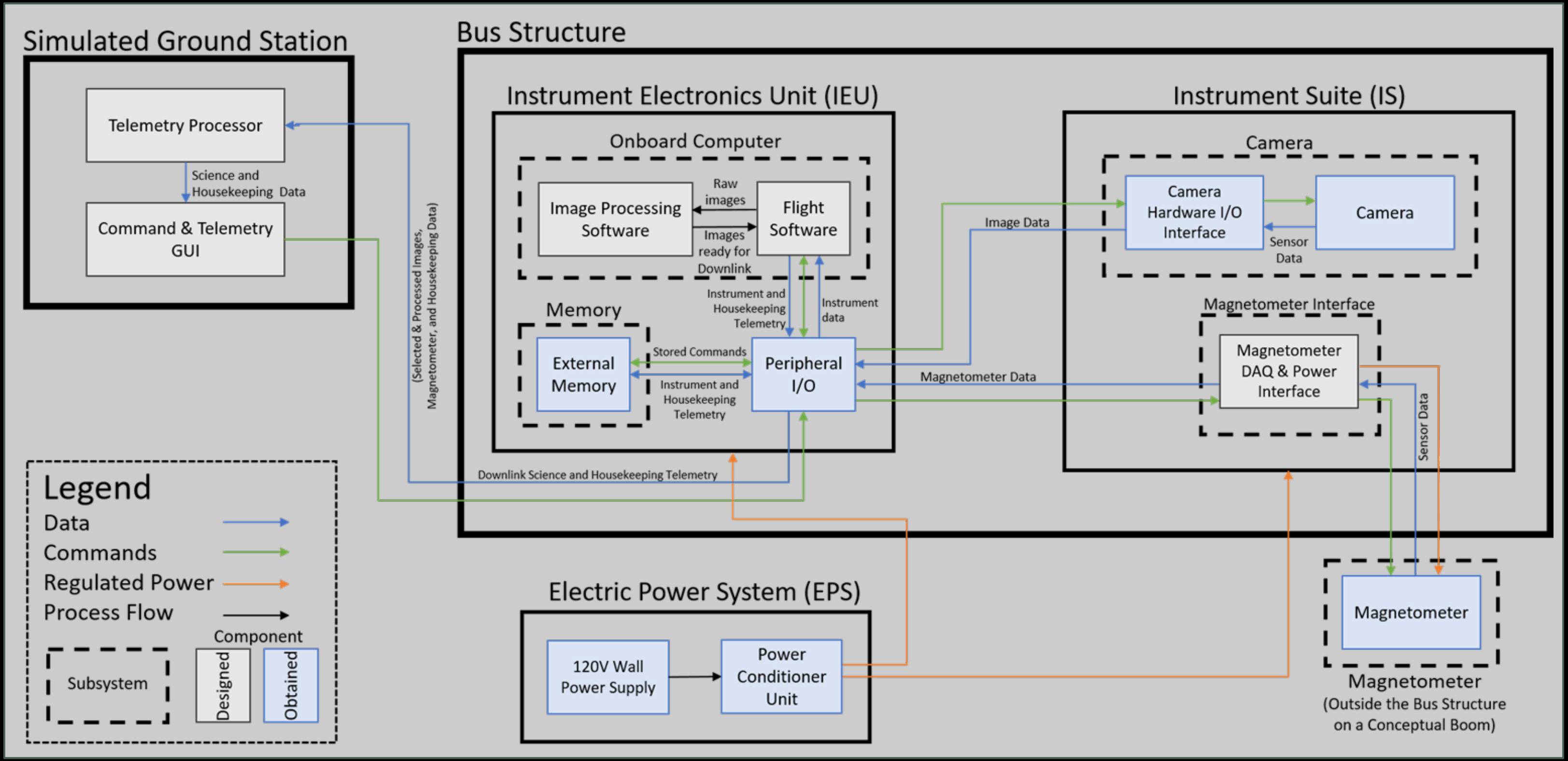
Functional Block Diagram



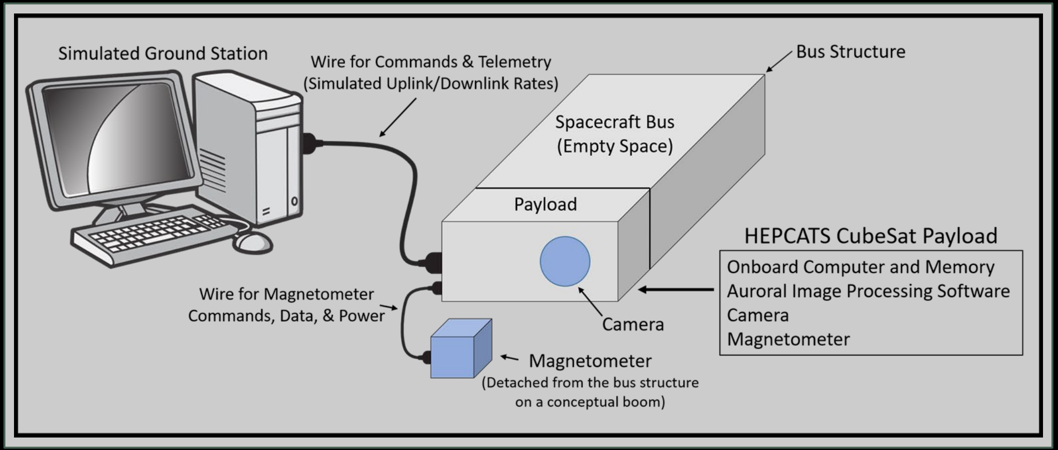
Functional Block Diagram: IPS



Functional Block Diagram



HEPCATS Baseline Design Overview



<u>Baseline Design</u>

- Onboard Computer
  - Single Board Processor
- Memory
  - Solid State Drive
- Camera
  - RGB CMOS Sensor
- Magnetometer
  - Vector Fluxgate Magnetometer
- Auroral Image Processing Software
  - Pre-Trained Deep Neural Network (PTDNN)
- Bus structure
  - 6U cubesat structure

Feasibility of Baseline Design

Functional Requirements

Level	Functional Requirement
1.0	The imaging subsystem shall be capable of taking images of a simulated Aurora Borealis.
2.0	The on-board image processing software (IPS) shall convert raw imagery into image data that is capable of being sent to the Simulated Ground Station.
3.0	The magnetometer system shall be capable of measuring a magnetic field.
4.0	The manufactured spacecraft bus shall be the infrastructure of the spacecraft capable of housing the Instrument Electronics Unit and the Instrument Suite.
5.0	The electric power system shall 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.
6.0	The Simulated Ground Station shall be able to command and receive telemetry from the Instrument Electronics Unit.
7.0	The instrument electronics unit shall be capable of storing all instrument telemetry, housekeeping telemetry, and command sequence data.
8.0	The instrument electronics shall be capable of sending telemetry to the Simulated Ground Station.
9.0	The Instrument Electronics Unit shall be capable of executing commands from the Simulated Ground Station or on board absolutely timed command sequences.

Feasibility Concerns of Select CPEs

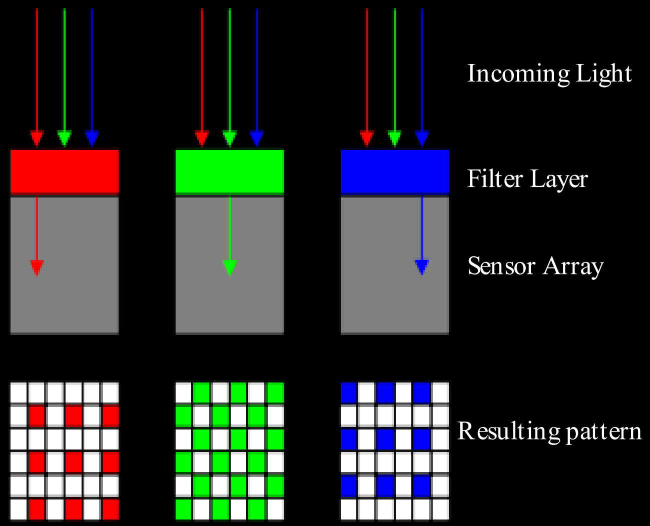
	Critical Project Element	Description
I1	Proper Camera & Lens System	Need to select proper FOV in order to have continuous coverage of polar crown and ensure a spatial resolution that produces useful images
P1	Image Processing & Aurora Detection	Image processing should be able to identify if an aurora is present in each image
M1	Magnetometer System Bias	The magnetometer sensor needs to be placed a distance away from the payload so that system bias from the payload does not saturate the sensor

Imaging System

Imaging System Baseline Design

1 High-Resolution RGB CMOS Sensor

- CMOS Sensor converts photons to electrons for digital processing
- Digital-to Analog converter translates cells into pixels
- RGB filter uses Bayer Filter which is a color filtering array that arranges RGB filters on each pixel.
- Camera then combines all three colors to create full spectrum
- “High-resolution” defined as minimum of 2 megapixel resolution (1920 x 1080 pixels)



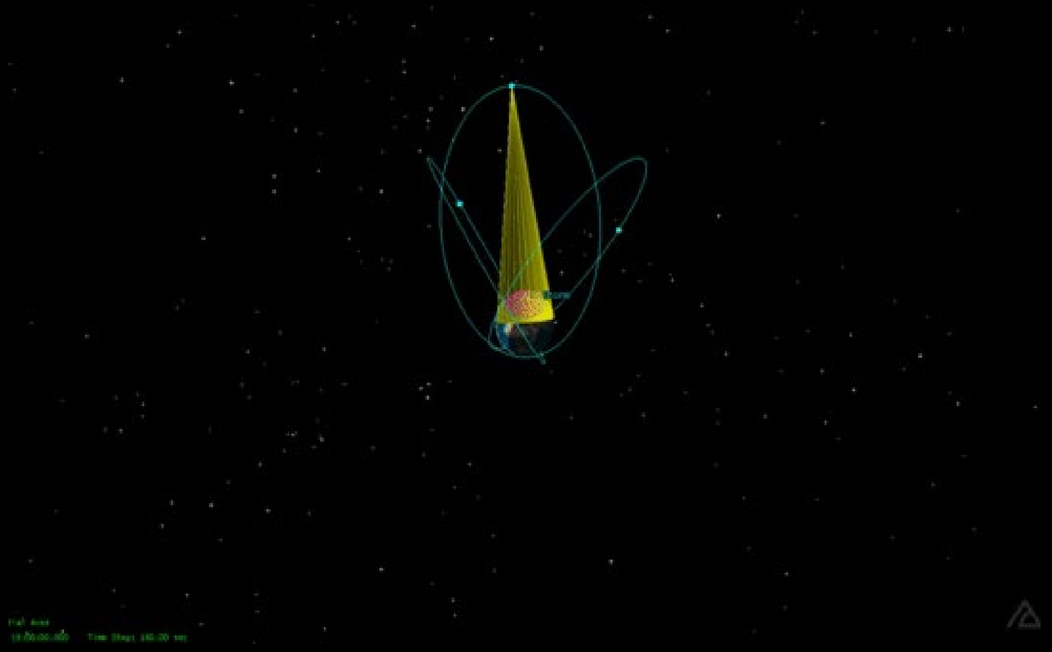
Bayer Filter - RGB Built in Filter

Imaging System Feasibility

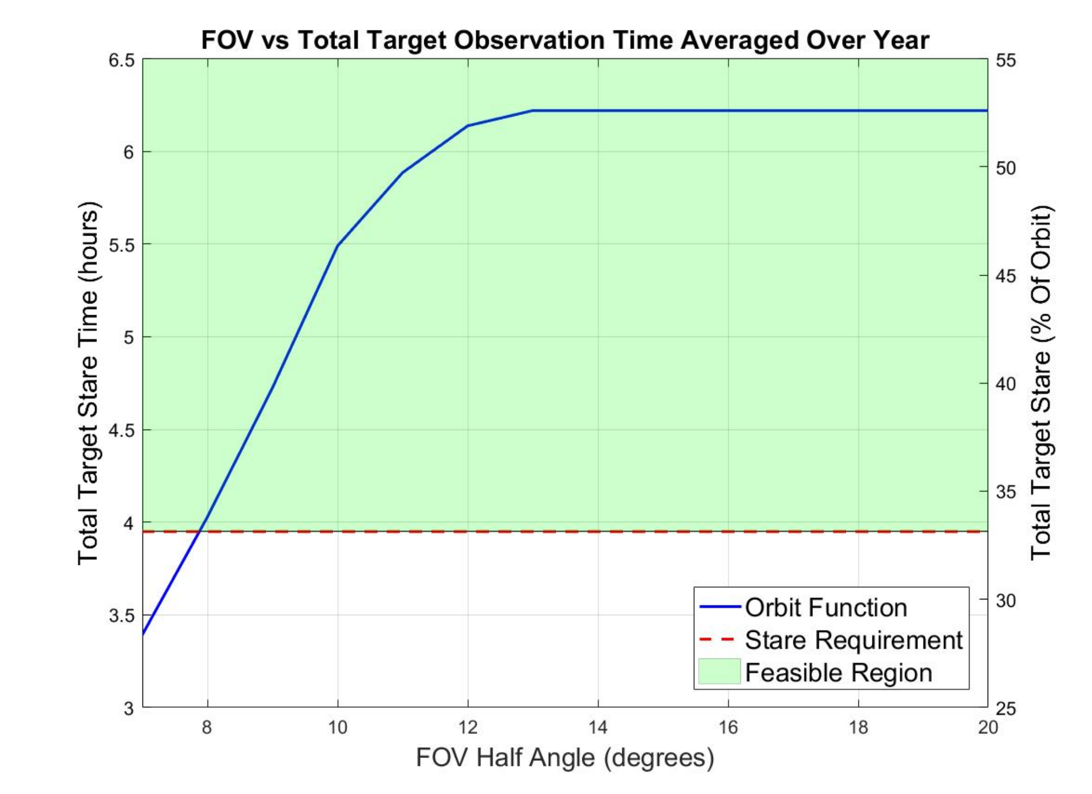
- FOV must be selected to optimize spatial resolution and observation time

- Requirement 1.1 - Need 33% on-orbit imaging
  - Doesn't necessarily mean continuous imaging

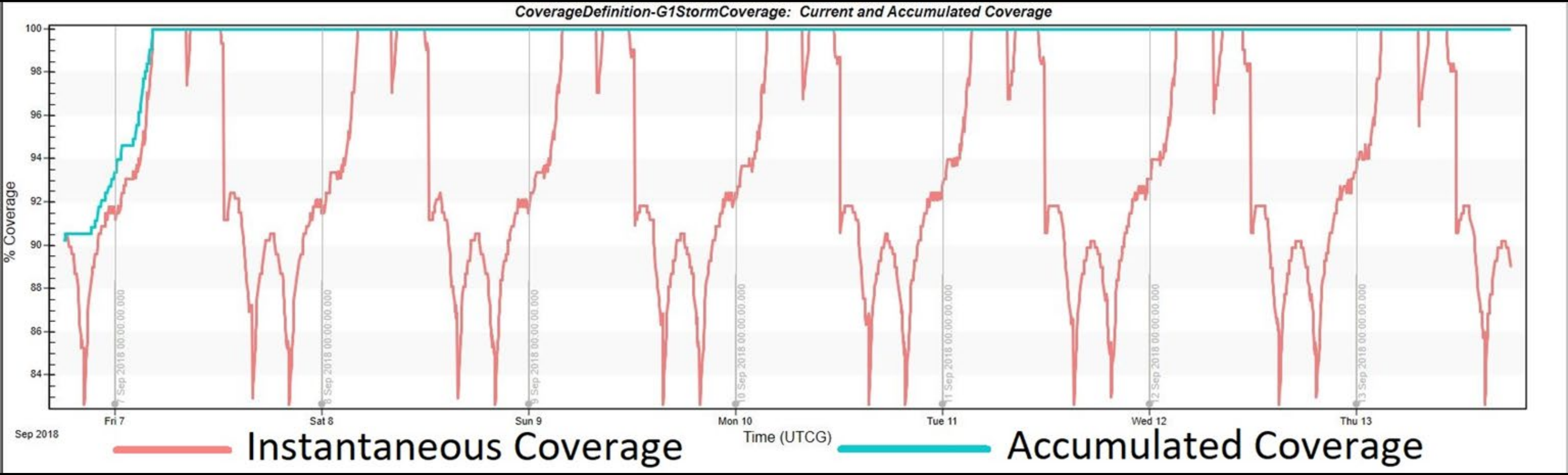
- Observation time exponentially approaches asymptote of 6.2 hours as FOV increases



Imaging System Feasibility

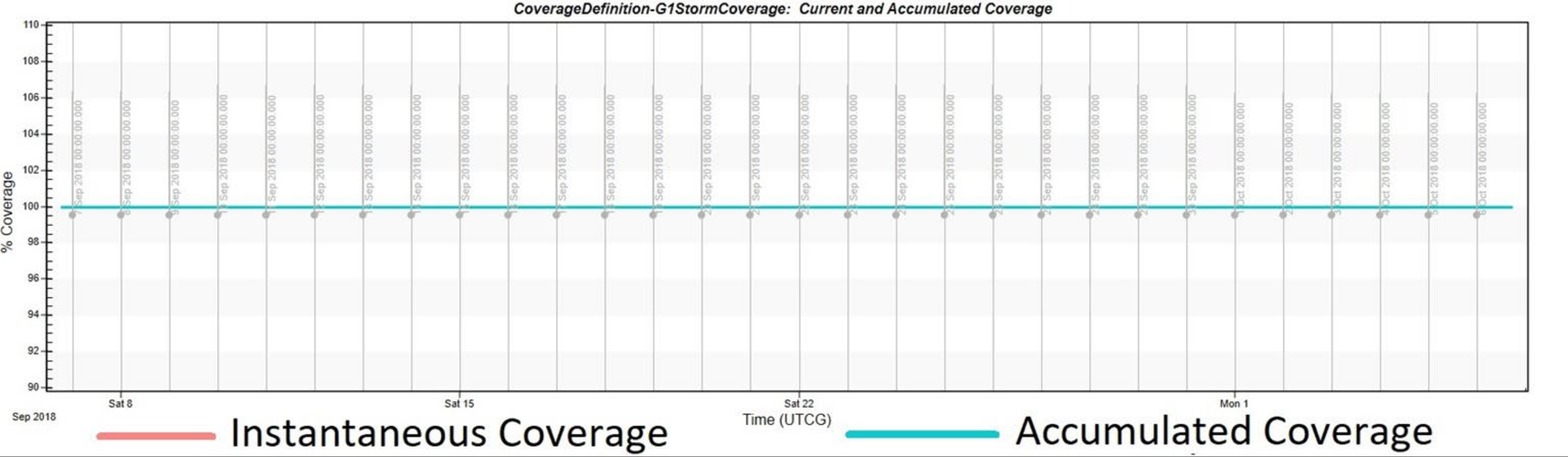


Imaging System Feasibility



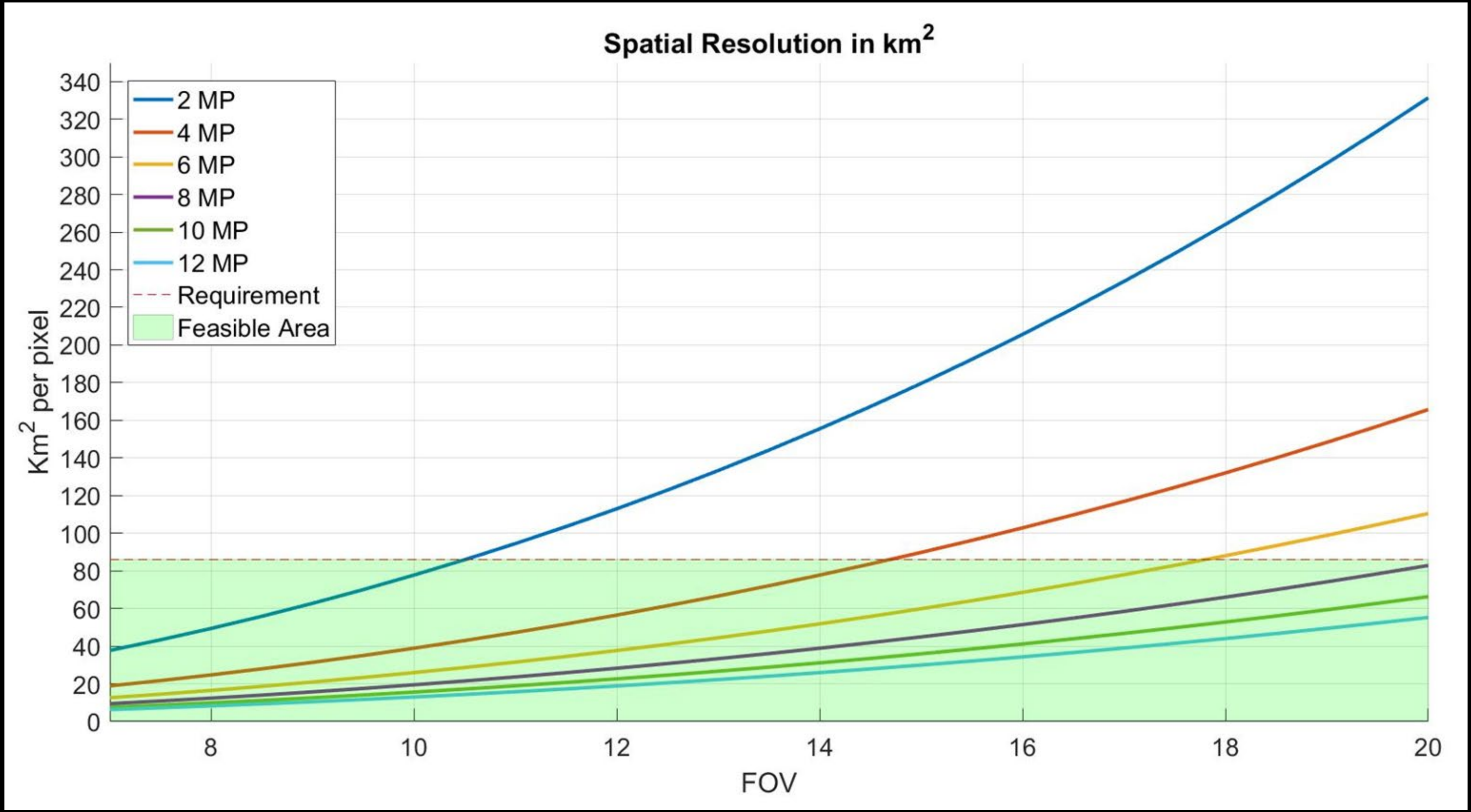
Sensor coverage of Latitudes above 46°N over one week with 7 deg half angle FOV

Imaging System Feasibility



Sensor coverage of Latitudes above 46N over one month with 9 deg half angle FOV

Imaging System Feasibility



Feasibility Summary

	Critical Project Element	Solution	Feasibility
I1	Proper Camera & Lens System	There is a wide selection of FOV which can offset sensor cost and be offset by higher resolution sensors	Feasible
P1	Image Processing & Aurora Detection		
M1	Magnetometer System Bias		

Image Processing System

Image Processing: Why Detect Auroras?

- Downlink rates for HEPCATS will be limited
- Images are only downlinked when Auroras are detected
- This functionality was requested by the customer

Image Processing: What it Does

Auroral Detection Algorithm will distinguish between:

Images which contain Auroras →

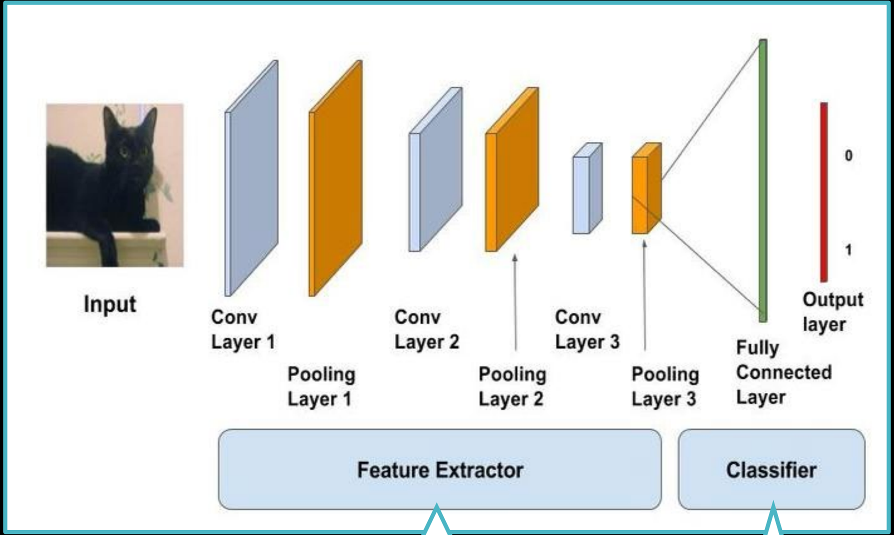
And...

← Images which do not

Image Processing: Baseline Design

Pre-Trained Deep Neural Network

- Using a highly capable, deep neural network to recognize features
- Quick and robust with less training time and data needed than a custom network
- Training done on ground and calibrations for classifier will be updated via uplink



Pre-Trained Deep Neural Network

Custom Classifier trained via Transfer Learning

Image Processing: How it Works

- We all know that in traditional programming, a set of rules are created which transform data into answers

- Machine learning flips the process, instead providing the program with the data and the answers, and letting the training process determine the set of rules

Image Processing: How it Works

- By providing the neural network we are using with labeled training data, it will learn the features which make an Aurora

Shape

- Shape can be learned through the detection of individual edges which combine to form shapes

Color

- Color can be learned through differences learned between the three color channels of the image (RGB)

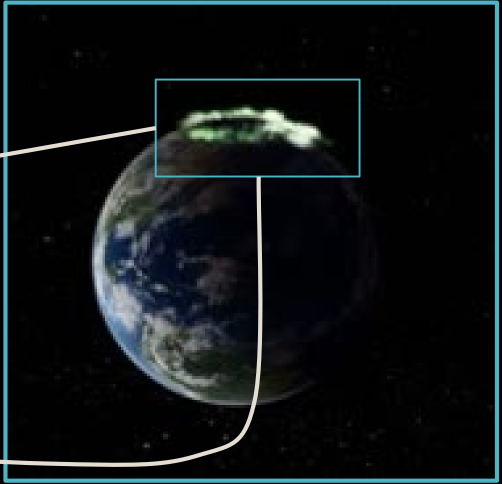


Image Processing: Feasibility Example

Training Example: Satellites vs. Airplanes

- The problem chosen is to differentiate between images showing satellites and images showing airplanes

- Images used are widely varied in composition
- Features of satellites are more complex than auroras

- Code was written using Google’s TensorFlow framework
- 900 Total images were used from training and validation

1

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Image Processing: Feasibility Example

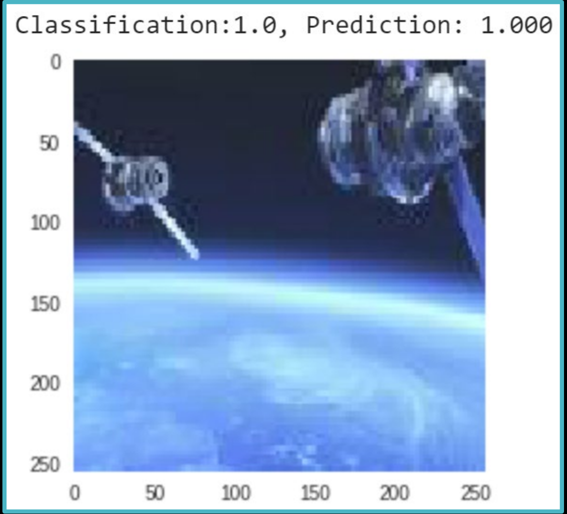
- Functional Requirement 2.1 specifies that the Auroral detection algorithm should achieve an accuracy of 95%

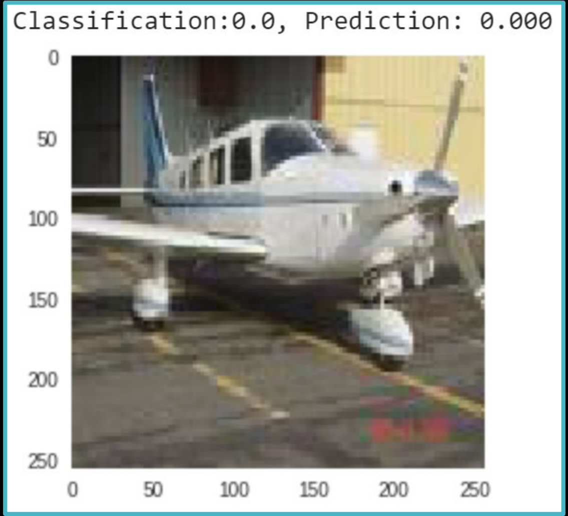
- The Satellite vs. Airplane example network quickly achieved an accuracy of >97%

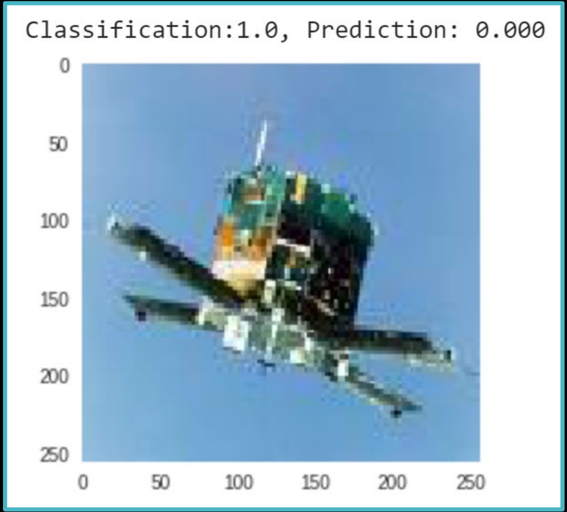
Image Processing: Example Images

Proper Classification Examples (97% in this category)

Mis-classification Example







Feasibility Summary

Critical Project Element		Solution	Feasibility
I1	Proper Camera & Lens System	There is a wide selection of FOV which can offset sensor cost and be offset by higher resolution sensors	Feasible
P1	Image Processing & Aurora Detection	A PTDNN works for recognizing satellites in this example data and can be implemented to identify auroras	Feasible
M1	Magnetometer System Bias		

Magnetometer System

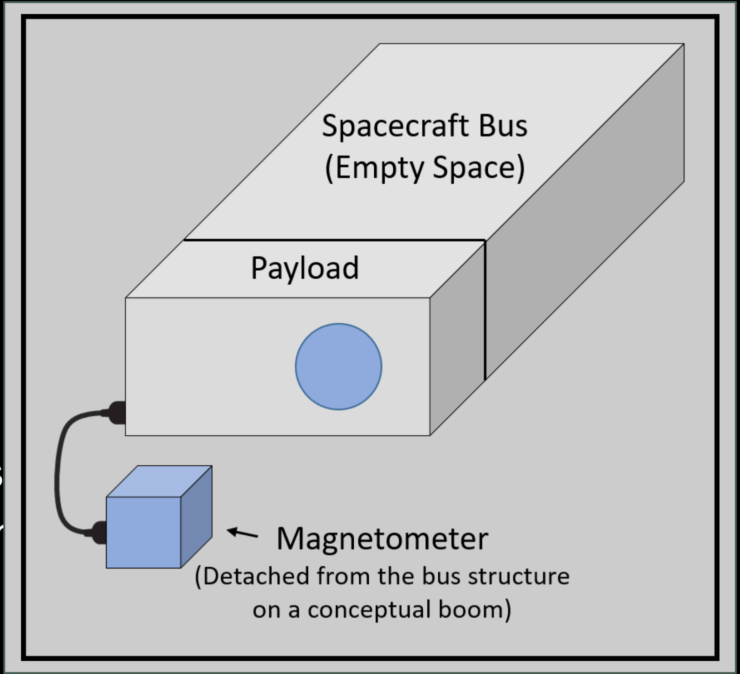
Magnetometer System Baseline Design

Vector Fluxgate Magnetometer

- Has high COTS availability
- Easy integration with system
- High resolution: <.1 nT
  - +/-70uT Range

Implementation: Mounted on a Boom

- Magnetometer mounted to a boom will decreas electromagnetic interference (EMI) caused from the spacecraft
- Background fields will appear unchanged



Magnetometer Feasibility: System Bias

1. What is bias for a magnetometer sensor?

- Additional induced magnetic field from onboard electronics
- Can be subtracted out from reading once bias is determined

2. What does bias have to do with feasibility?

- System bias could cause magnetic field strength to exceed magnetometer range (satur
- Bias decreases with distance from system
- Must ensure that threshold to prevent saturation occurs at a feasible boom length

Magnetometer Feasibility: System Bias

Dipole vs Induced Magnetic Field

1. Dipole:

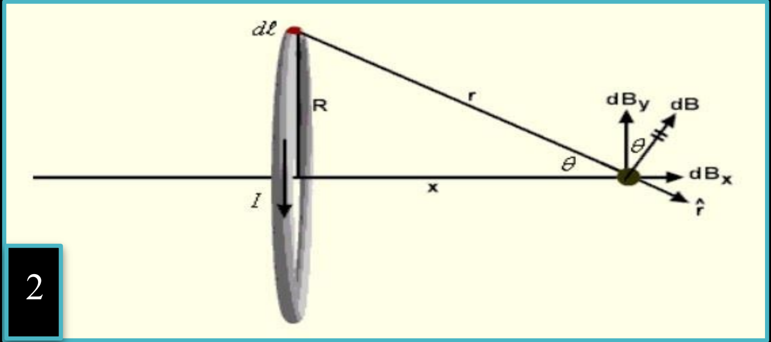
$$B\alpha\frac{1}{d^3}$$


1

2. Induced Magnetic Field:

Biot-Savart Law:

$$\vec{B} = \frac{\mu_0}{4\pi}\int_{wire}\frac{I\vec{dl}\times\hat{r}}{r^2}$$



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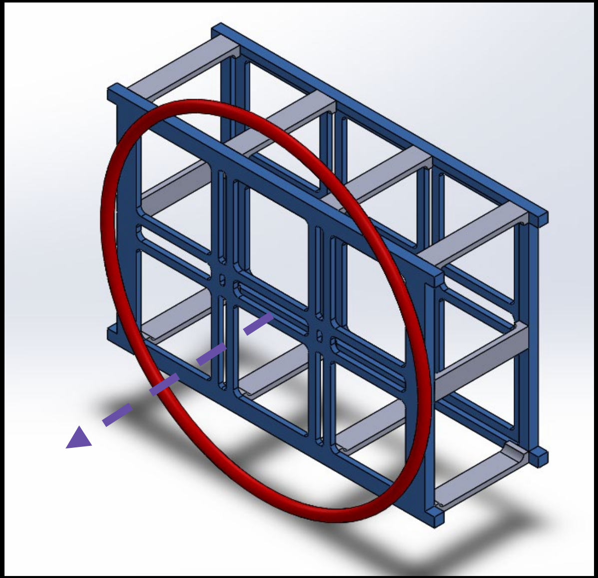
Magnetometer Feasibility: System Bias

Treating the System as a Circular Loop:

$$B_x = \frac{\mu_0 I R^2}{2\sqrt{x^2 + R^2}^3}$$



Equivalent wire loop approximation

Boom distance from center of circle

Where:

- x = distance from center of circle
- R = radius of circle
- Bx = magnetic field strength in x-direction

Magnetometer Feasibility: System Bias

Treating the System as a Circular Loop:

$$B_x = \frac{\mu_0 I R^2}{2\sqrt{x^2 + R^2}^3}$$

Where:

- x = distance from center of circle
- R = radius of circle
- Bx = magnetic field strength in x-direction

<u>Range of Current:</u>

- From 1.25 A - 5.83 A
  - System voltage is 120 V by FR 5.0
  - Industry standard 12 V to magnetometer
  - I = P/V
  - 6U CubeSats have a typical power range between 15 - 70W

Magnetometer Feasibility: System Bias

Treating the System as a Circular Loop:

$$B_x = \frac{\mu_0 I R^2}{2\sqrt{x^2 + R^2}^3}$$

Where:

- x = distance from center of circle
- R = radius of circle
- Bx = magnetic field strength in x-direction

Maximum Distance

- Maximum distance of 2.5 m
  - Maximum length of a magnetometer boom flown (FedSat mission)

Magnetometer Feasibility: System Bias

Treating the System as a Circular Loop:

$$B_x = \frac{\mu_0 I R^2}{2\sqrt{x^2 + R^2}^3}$$

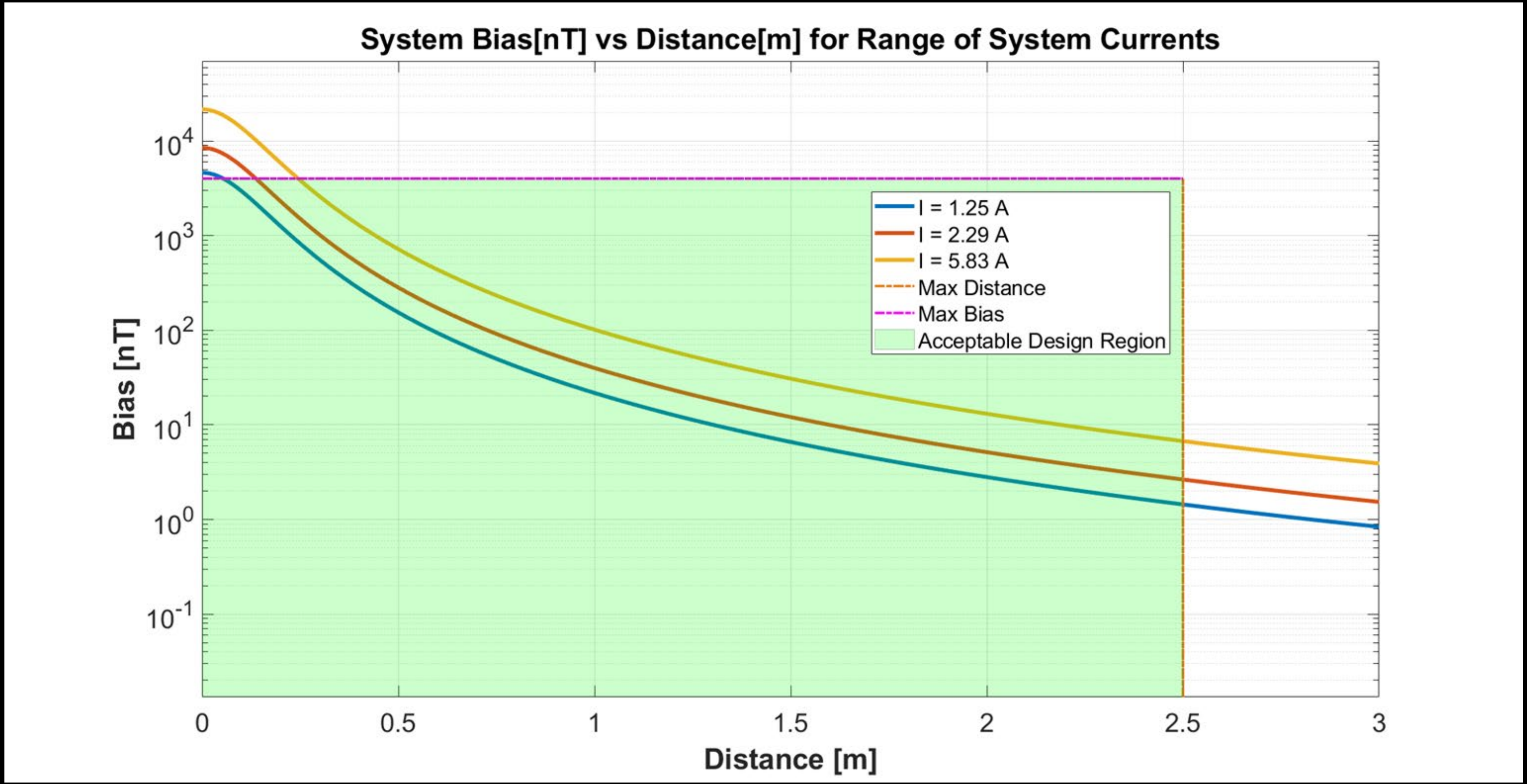
Where:

- x = distance from center of circle
- R = radius of circle
- Bx = magnetic field strength in x-direction

<u>Maximum Bias:</u>

- Max bias of 4000 nT
  - Magnetometer range of 70000 nT
  - Highest Earth magnetic field strength of 66000 nT
  - Saturation if total magnetic field strength exceeds 70000 nT

Magnetometer Feasibility: System Bias



Feasibility Summary

	Critical Project Element	Solution	Feasibility
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P1	Image Processing & Aurora Detection	A PTDNN works for recognizing satellites in this example data and can be implemented to identify auroras	Feasible
M1	Magnetometer System Bias	Placement of the magnetometer sensor at a distance in the range of 0.25 m - 2.5 m prevents sensor saturation and is a feasible boom length	Feasible

Summary

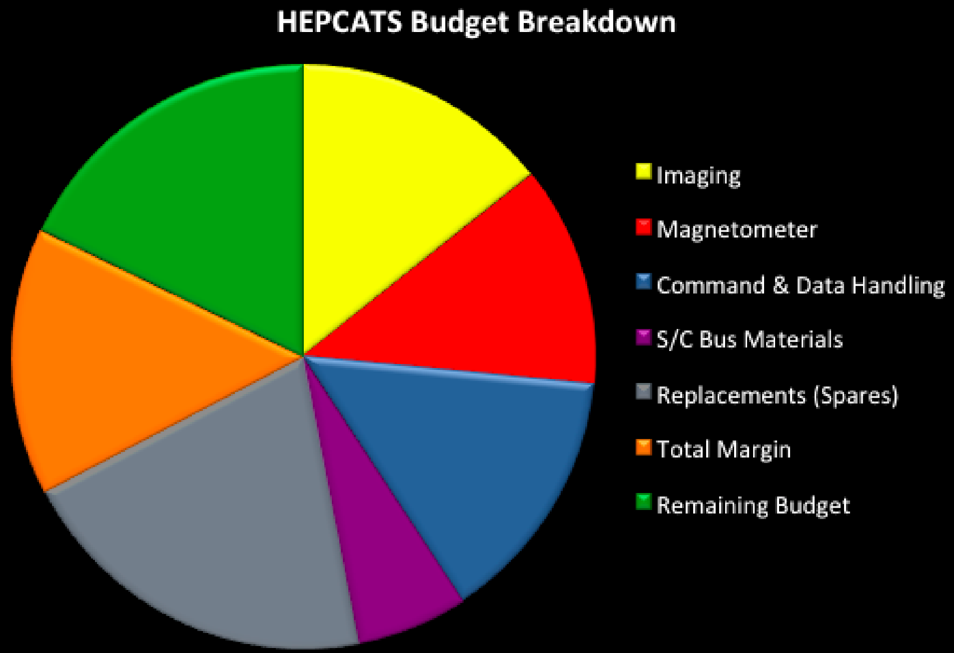
Feasibility Summary

	Critical Project Element	Solution	Feasibility
I1	Proper Camera & Lens System	Any field of view greater than 9 degrees will provide continuous coverage of target area	Feasible
P1	Image Processing & Aurora Detection	A PTDNN works for recognizing satellites in this example data and can be implemented to identify auroras	Feasible
M1	Magnetometer System Bias	Placement of the magnetometer sensor at a distance in the range of 0.25 m - 2.5 m prevents sensor saturation and is a feasible boom length	Feasible

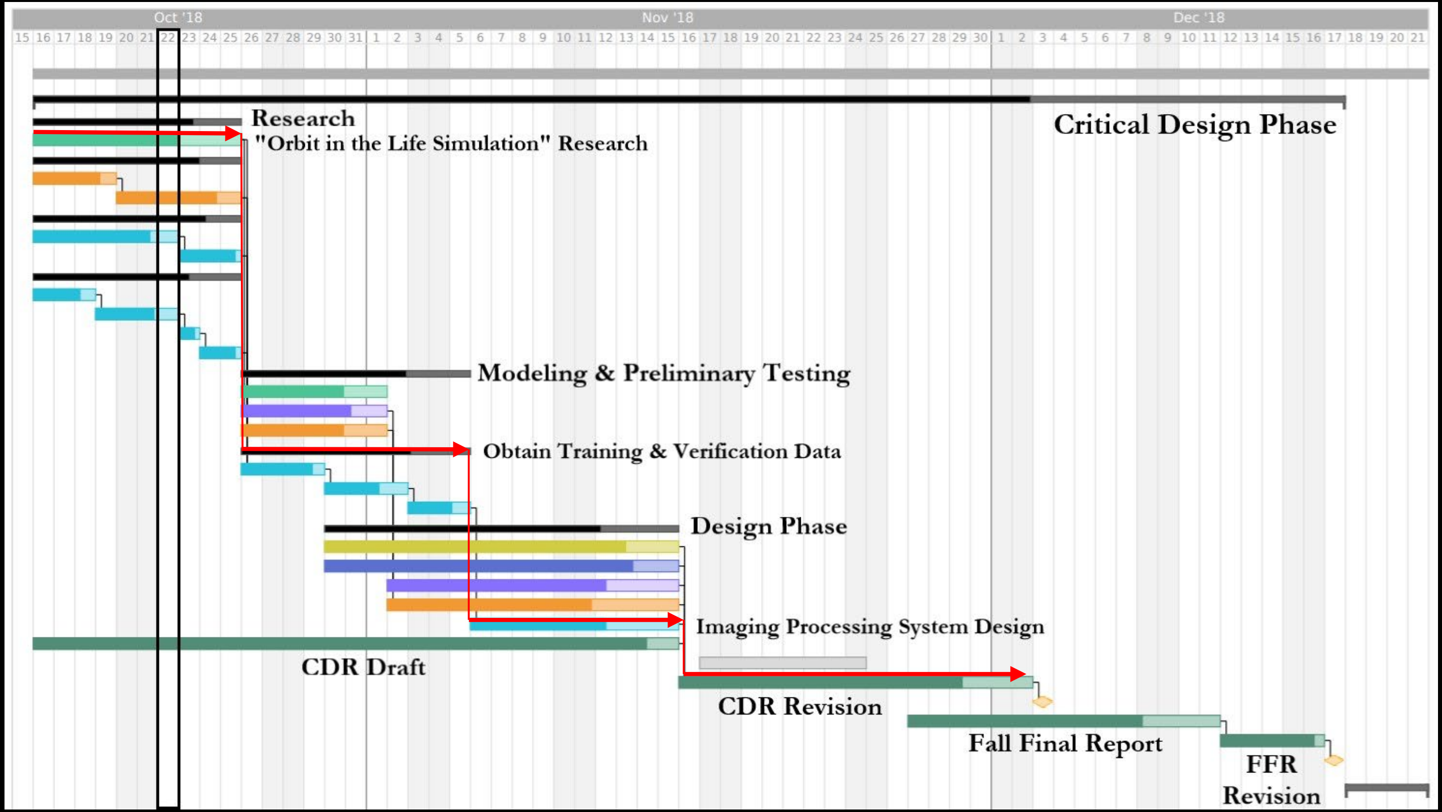
Budget

Financial Summary		
System	**Cost ($)**	**Margin($)**
Imaging	700	200
Magnetometer	600	300
Command & Data Handling	800	100
S/C Bus Materials	300	125
Replacements (Spares)	1000	N/A
Total	**3400**	**725**
Total w/ Margin	**$4125**	

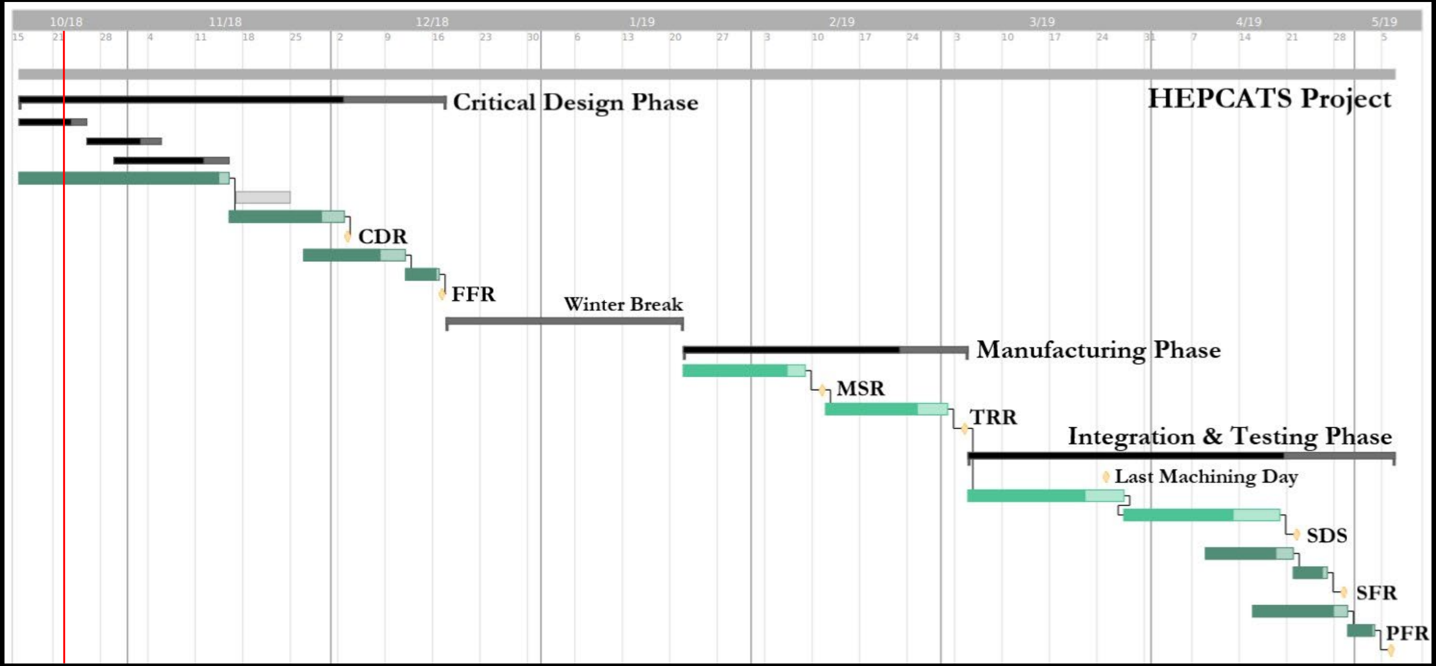
Total Budget: $5000



Schedule for PDR to CDR



Schedule Overview for PDR to PFR



Acknowledgements

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- Dr. Gerren
- Matt Rhode
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- Dr. Marshall
- Dr. Jackson
- Professor Jason Glenn
- Ian Cooke
- Christine Reilly
- GHOST Team

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Thank You!

Questions?

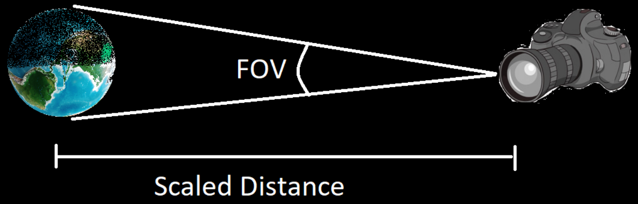
Appendix

Appendix Slides Index

Alternative Camera Testing Methods

Scale darkroom model

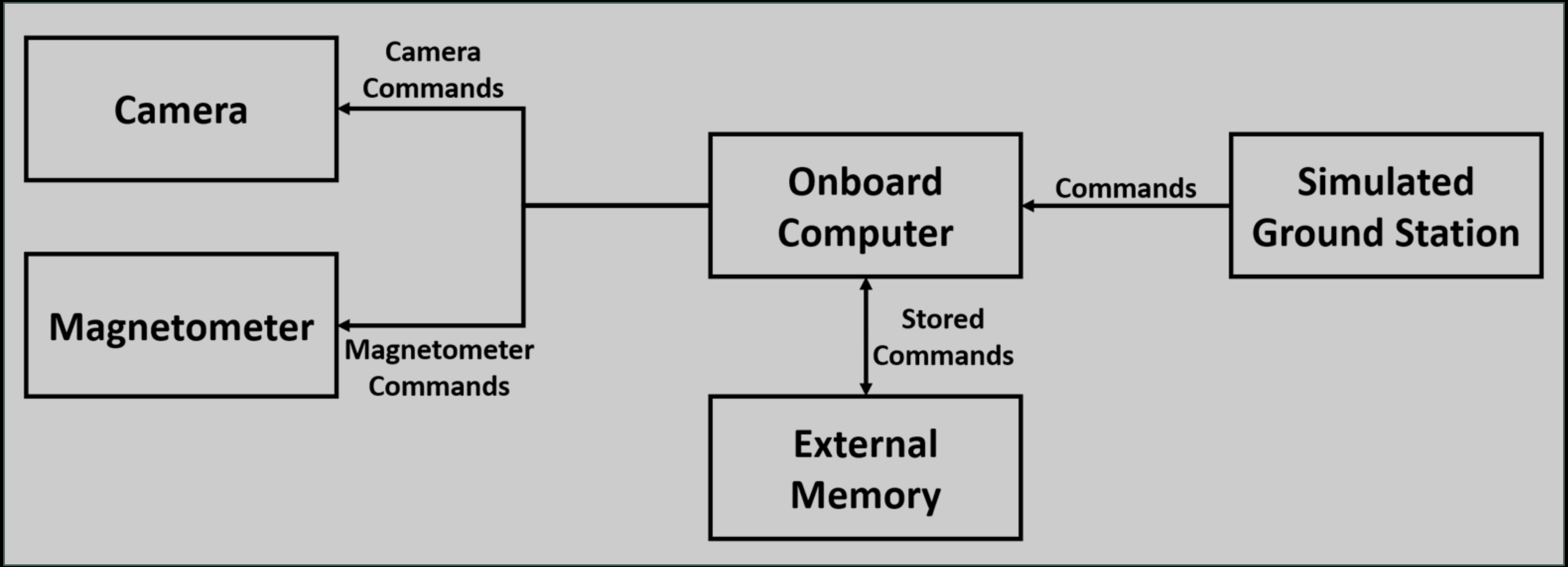
- Provides lighting environment closer to actual system application
- More difficult to simulate orbit in the life



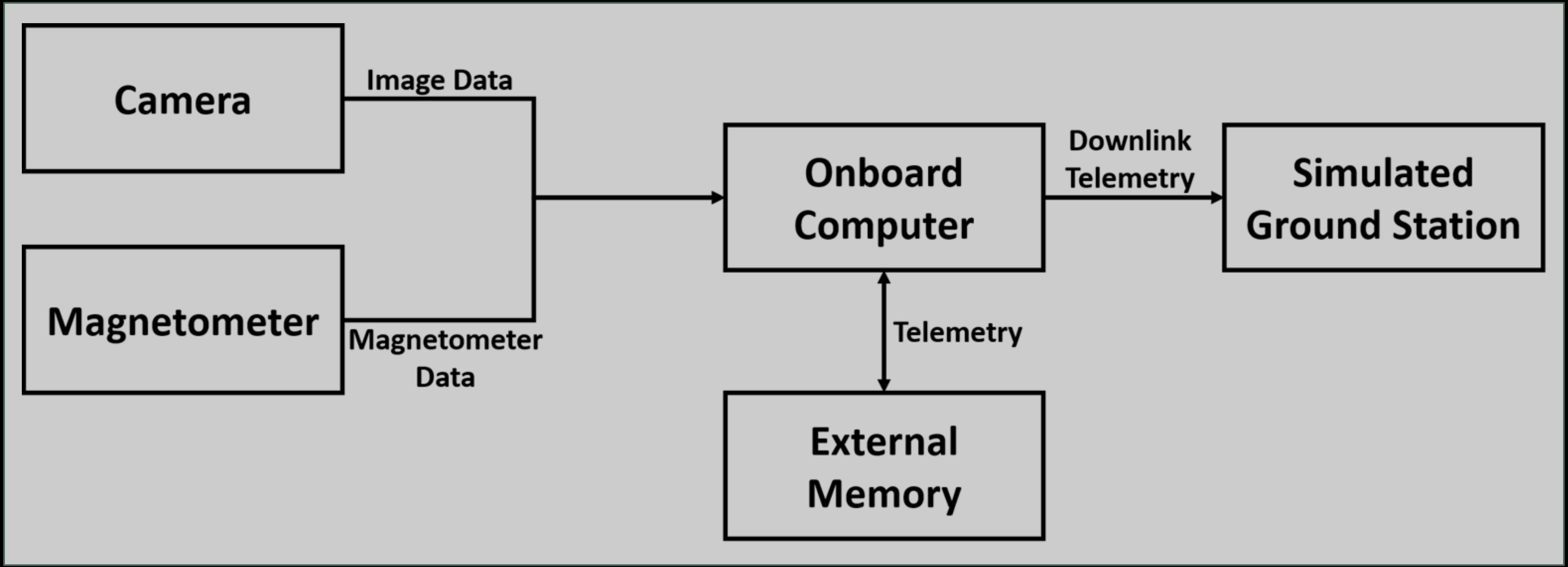
Functional Requirement Feasibility

Level	Functional Requirement	Feasibility
4.0	The manufactured spacecraft bus, the structure of the spacecraft, shall be capable of housing the Instrument Electronics Unit and the Instrument Suite	Design and fabrication of a 6U bus structure is accomplished by referencing pre-existing designs and aerospace faculty expertise.
5.0	The Electric Power System shall 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.	Design of an electric power system is accomplished by team experience and aerospace faculty expertise.
6.0	The Simulated Ground Station shall be able to command and receive telemetry from the Instrument Electronics Unit.	Communication interface is provided by physical wired connection and leverages a standard protocol to networking IEU and SGS.
7.0	The Instrument Electronics Unit shall be capable of storing all instrument telemetry, housekeeping telemetry, and command sequence data.	Data storage on an external solid state drive is within team experience.
8.0	The Instrument Electronics Unit shall be capable of sending telemetry to the Simulated Ground Station.	Communication interface is provided by physical wired connection and leverages a standard protocol to networking IEU and SGS.
9.0	The Instrument Electronics Unit shall be capable of executing commands from the Simulated Ground Station or on board absolutely timed command sequences.	Command execution (real time and absolutely timed) is a functionality of the onboard operating system. This functionality is heavily documented in any operating system that would be choosed.

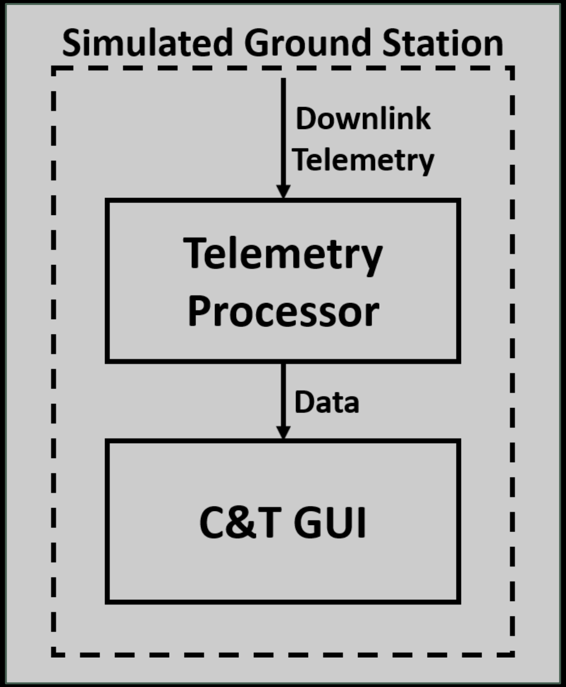
Command Distribution



Telemetry Flow



Simulated Ground Station



Imaging System

Baseline Design: 1 High-Resolution RGB CMOS Sensor

- CMOS Sensor
  - Cheap, competitive image quality
  - Low power consumption, small size

- High-Resolution RGB Filter
  - Cheap, small data size
  - Produces acceptable images for Image Processing System
  - Information on specific colors makes it easier to recognize Aurora

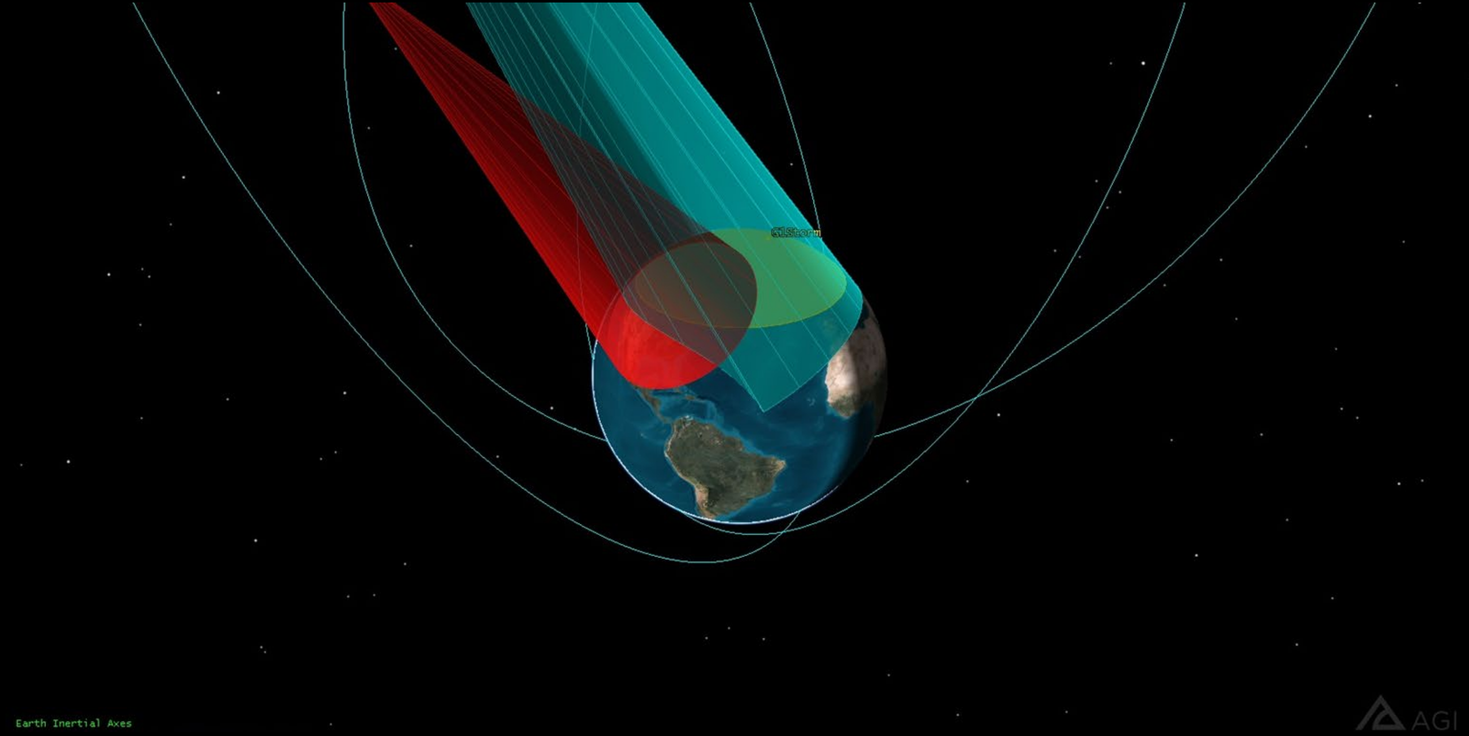
Capturing Images from Projector Screen

- Adjustable camera with variable shutter speeds, ISO and white balance
- Stabilized camera aligned center with the screen
- Post-processing to brighten darker areas, enhance contrast and smooth potential grainy photos
- All possible with today's cameras and post-editing software

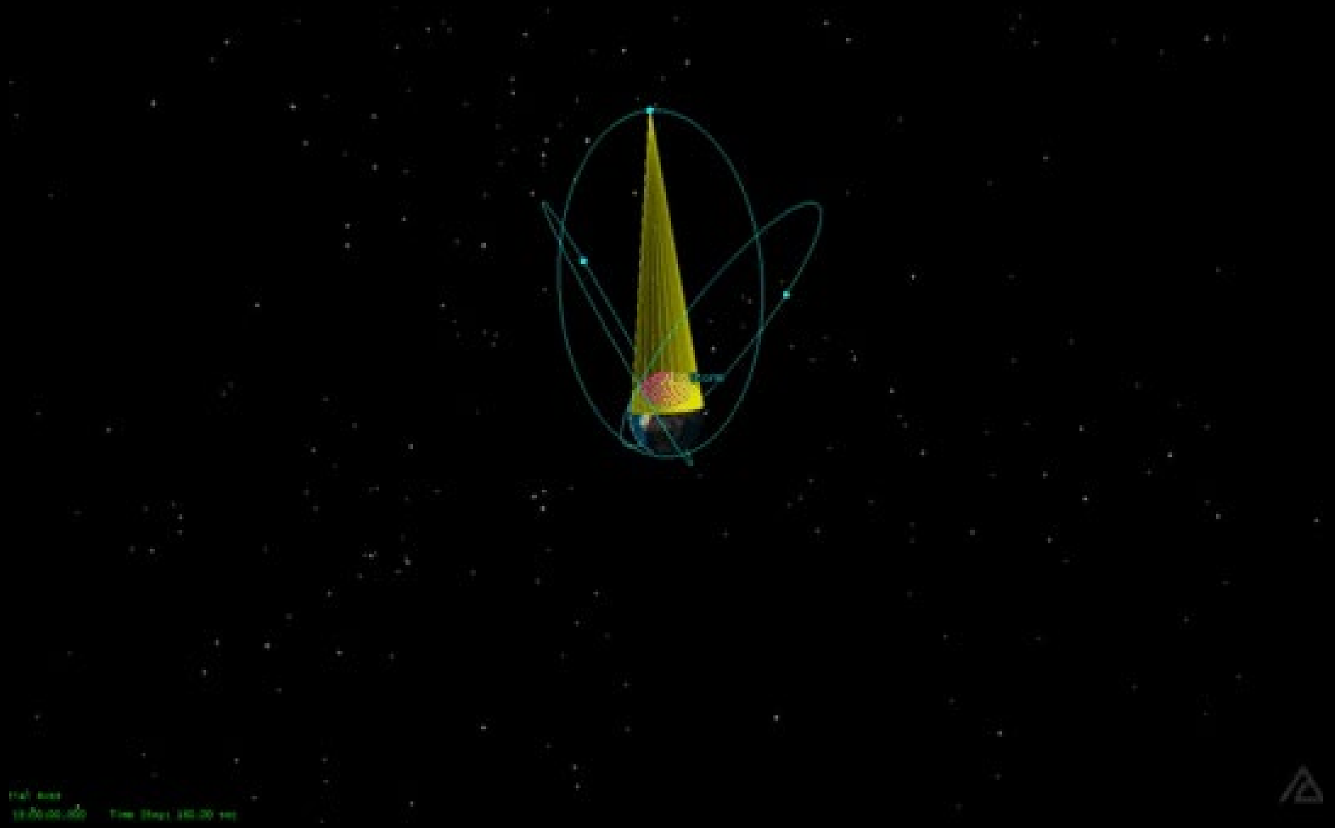
Methods to minimize Earth shine

- Long exposure time, high dynamic range, CMOS is less susceptible to "blooming" due to overexposure effects
- http://www.globalbedo.org/ (albedo map of Earth, 1 km resolution)
  - Can be used to calculate reflected intensity of light from Sun at various points in orbit
- Day-night VIIRS imaging suite apart of the Joint Polar Satellite System
  - Provided "nighttime" map of Earth
- Images from astronauts on -board ISS shows timelapse of both night side and day side taken from same camera (Kodak Pro DCS 760)

Constellation Sensor Coverage of G1 Storms

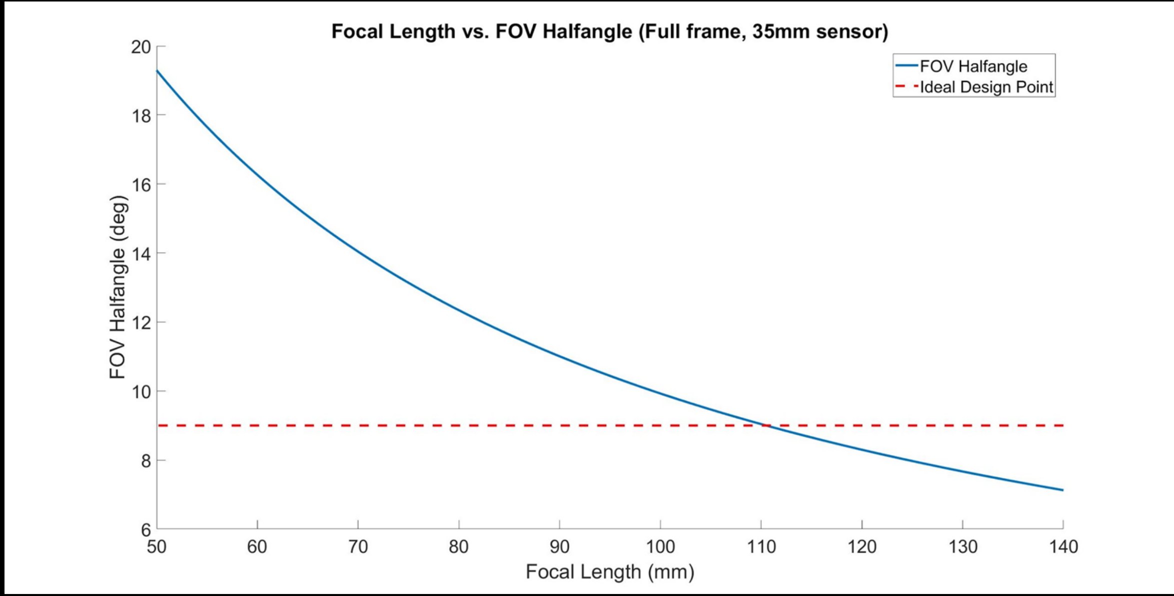


Constellation Sensor Coverage of G1 Storms



Focal length and Field of View

- Field of view is inversely proportional to focal length



$$HFOV = 2Dtan(FOV)$$

$$L_f = \frac{W_s D}{HFOV}$$

Where:
W_S is sensor width (35mm)
D is distance from lens to target
L_F is focal length
FOV is angular field of view
HFOV is horizontal field of view in meters

“Orbit in the Life” Simulation: Earth Projection

“Orbit in the Life” Simulation will project the Earth with an aurora for the camera to image

- This projection of the Earth will change with the position of the satellite as it travels along its orbit
    - Size and orientation of the Earth will vary just as it would on-orbit
- This can be accomplished using orbit simulation software or even an interactive space flight simulation program called Kerbal Space Program
    - Kerbal Space Program is pictured here with the Earth with an aurora

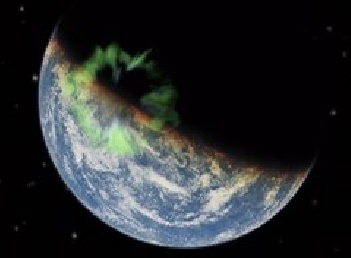


Image Processing Training Image Examples

- Unfortunately, no imagery available is completely analogous to HEPCATS data, so UV Imagery from the POLAR or IMAGE missions will have to be used

POLAR VIS
(UV Earth Camera)

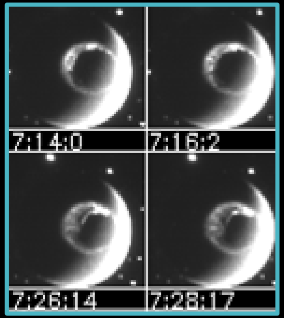
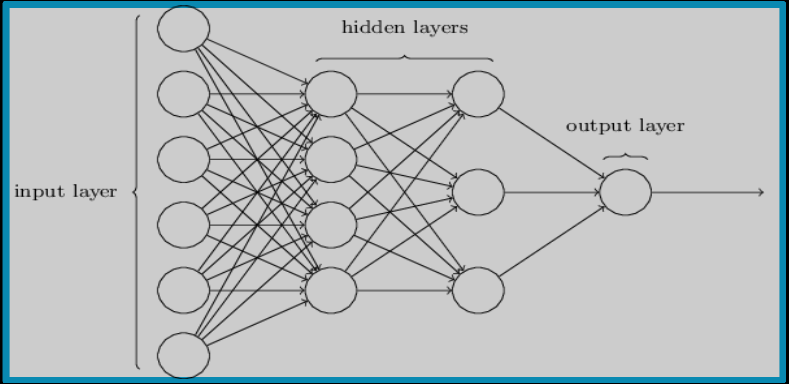


IMAGE
(Neutral Atom Imager)

Image Processing: Neural Networks (NNs)

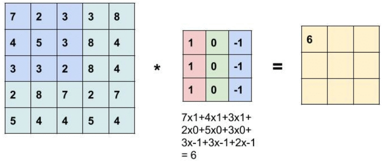
- Inputs are connected to the output by a series of *hidden layers*
- Each connection has a *weight* which defines the strength of the connection
- Each node, or *neuron*, computes a non-linear activation function on the weighted sum of its inputs and a given *bias*



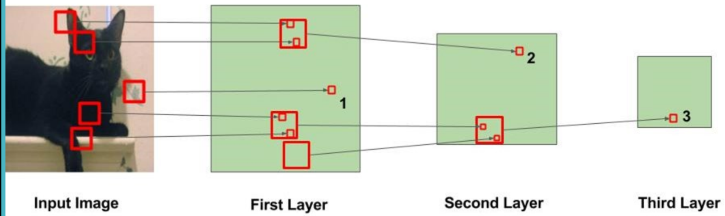
- A *loss function* is defined to quantify the error of the network compared to training values
- Weights are adjusted through the *gradient descent* of the *loss function* in a process called *backpropagation*

Image Processing: Convolutional NNs

In the field of image processing, many operations operate on pixels based on a grid of surrounding pixels. These types of operations are called *Convolutions* and these are the type of operations used by *Convolutional Neural Networks (CNNs)*

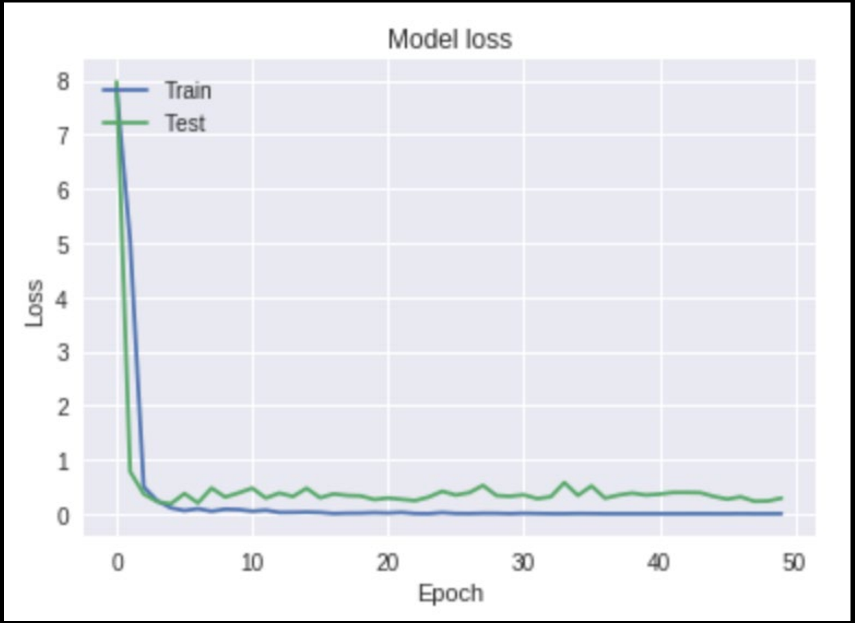


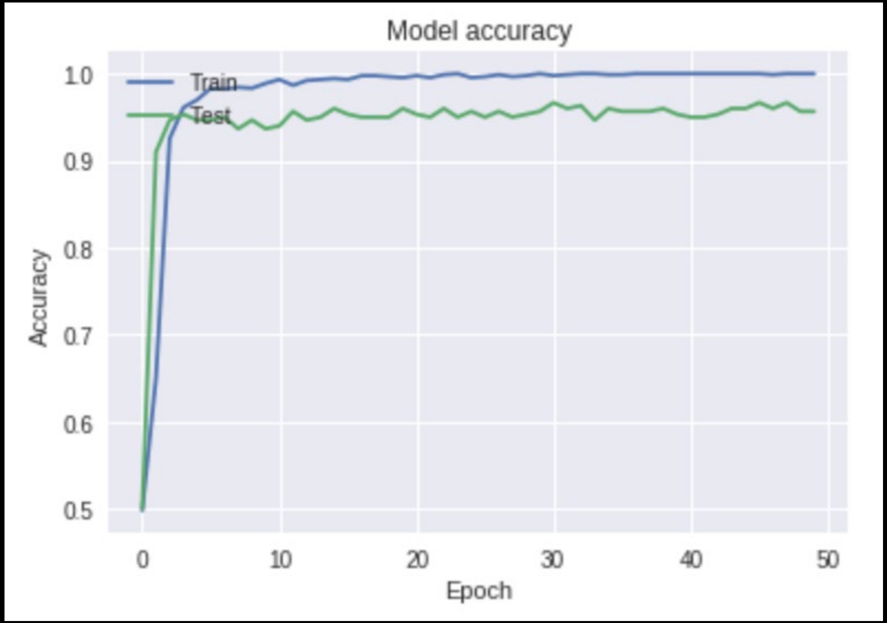
Example of a convolution on an image of size 5x5



CNNs learn hierarchical features by learning convolutions of convolutions

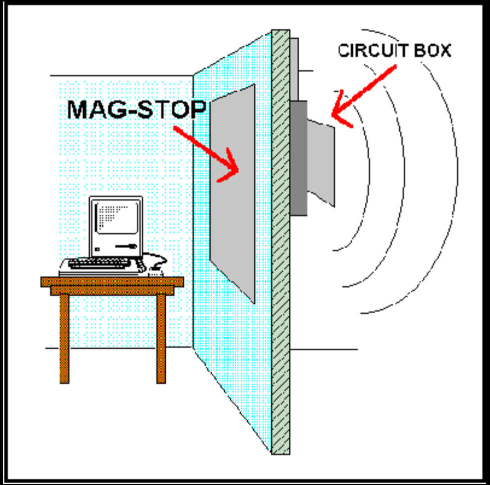
Custom Classifier Training Process 1





Mu Metal Shielding for Magnetometer

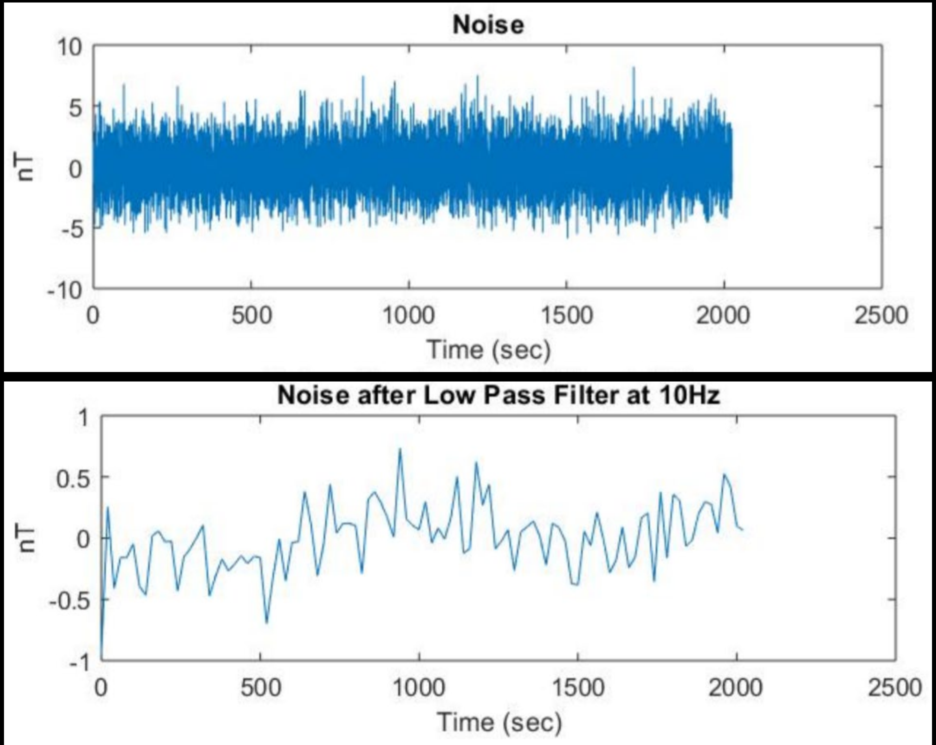
- What is it?
  - High permeability metal material that blocks against low frequency and static magnetic fields
    - Permeability ~ 80,000-100,000 H/m
  - Most effective for slowly varying magnetic fields
  - Very ductile and workable material
- Design:
  - Use sheet of Mu Metal to shield back side of magnetometer
    - Only the side of the magnetometer facing the EMI source will be shielded
    - Prevents blocking the actual desired magnetic fields
  - Line interior of spacecraft bus with Mu Metal material
- Decision to not use:
  - An estimate of EMI magnitude was made based upon predicted electronics
  - Dipole magnetic field relations showed that this EMI would not be significant enough to warrant the use of Mu Metal



Magnetometer Noise

- COSMO
  - Sampling Rate: 2000 Hz
  - Bandwidth: 2 Hz
  - Max Noise < 10 nT

- HEPCATS
  - Sampling Rate: 80 Hz
  - Bandwidth: 2 Hz
  - Desired Max Noise < 10 nT



COSMO Magnetometer Noise

Command and Data Handling

Solid-State Hard Drive (External Memory)

- Flash memory storage device without any moving parts
- Offers ample read and write speeds and storage space for mission
- Hardware will remain unaffected by magnetic interference

Single-board Computer

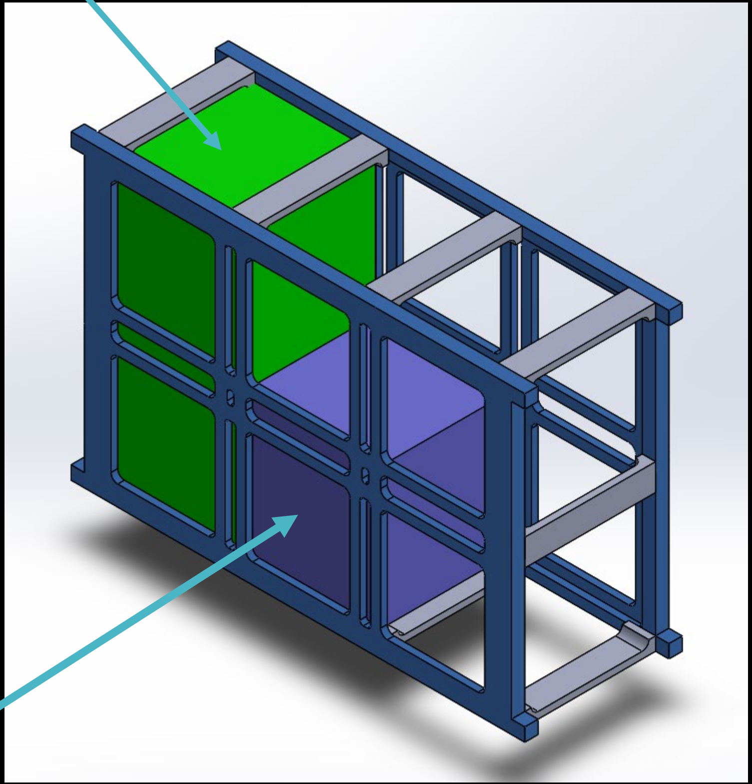
- Functional computer completely built on one circuit board
- Allows for integration with all other electrical components
- Single-board design will be adequate for running image processing software

Simulated Ground Station

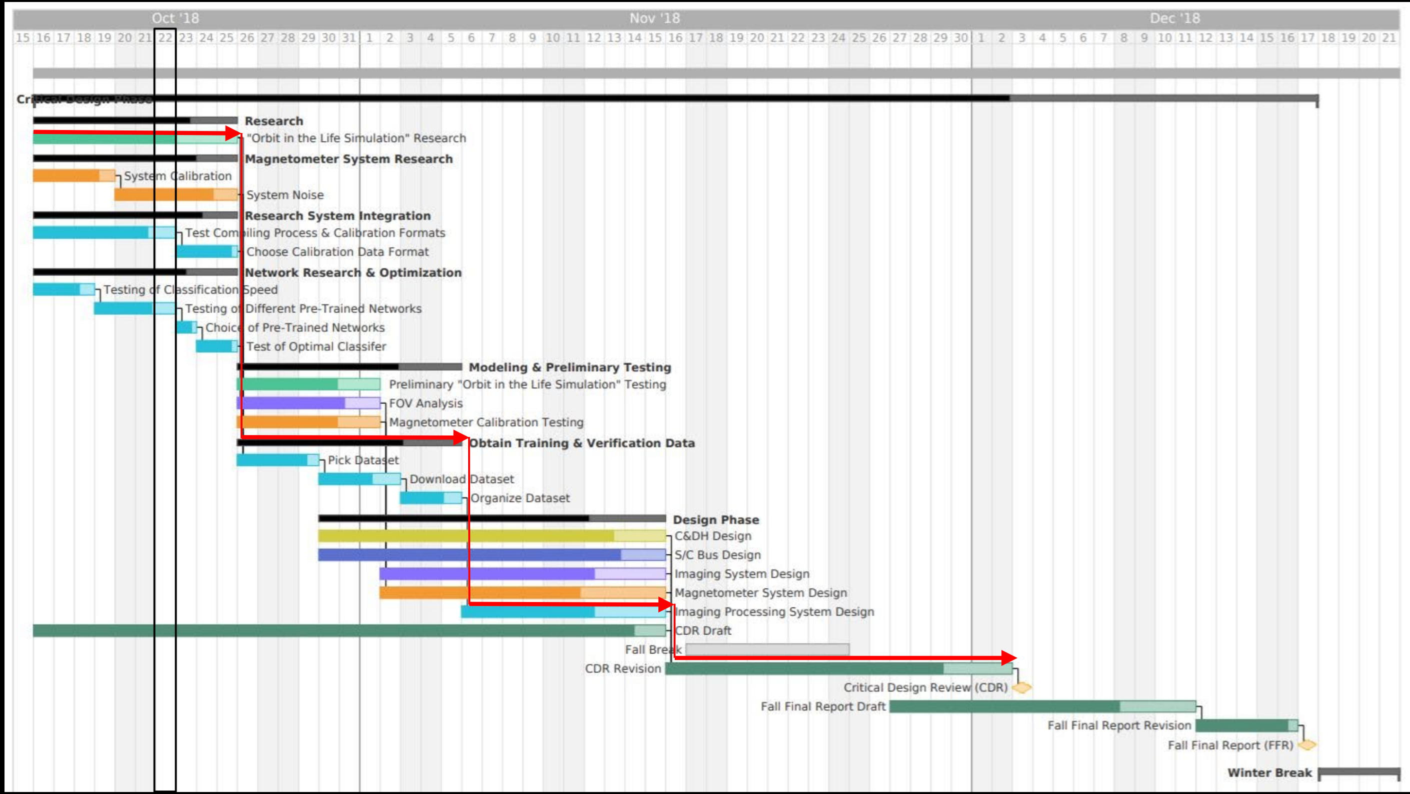
- Wired communication b/w simulated ground station and IEU
- Avoids the complexity of designing and implementing RF system
- Sufficient to meet proof of concept mission design

Spacecraft Bus

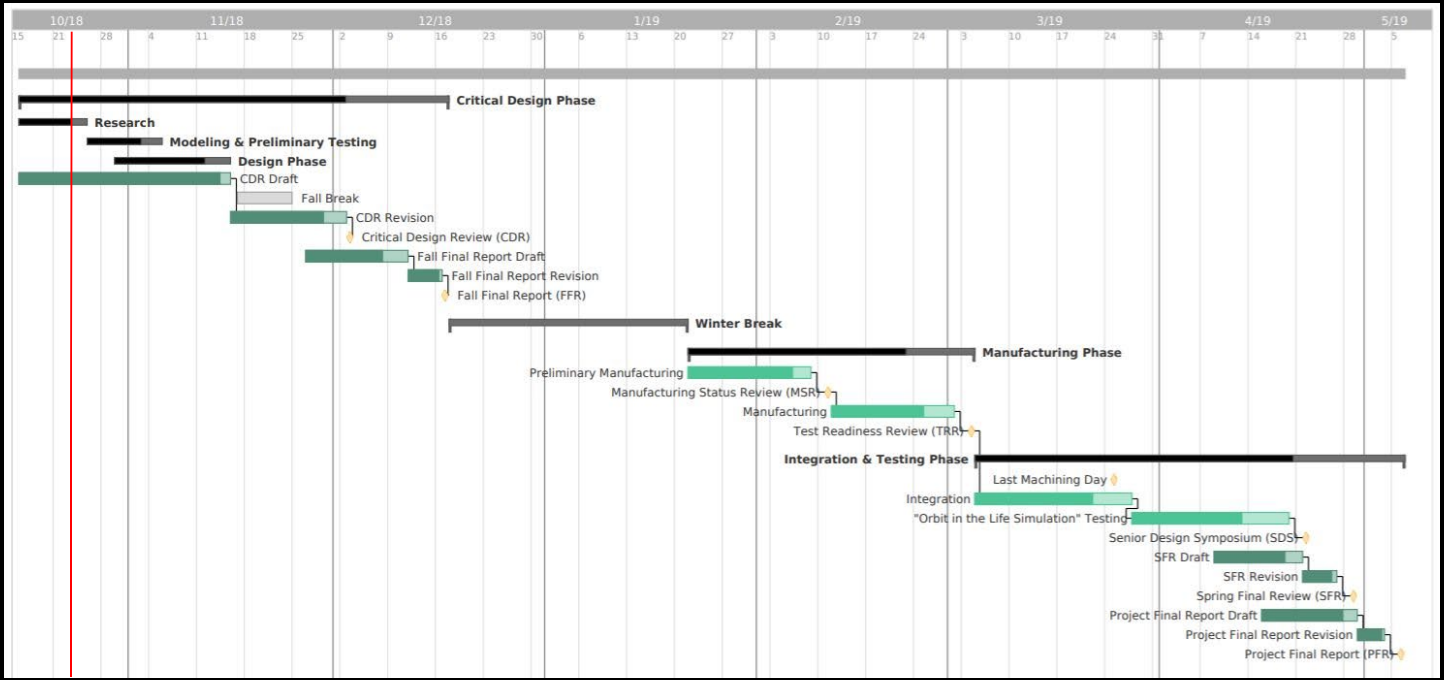
- Purpose
  - House all the payload systems
  - Magnetometer excluded
- 6U CubeSat
- Materials
  - 3D - Printing Plastic (PLA, ABS)
  - Machined Parts (Aluminum, Titanium, Steel)



Schedule for PDR to CDR



Schedule Overview for PDR to PFR



Trade Study - Image Sensor

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

Trade Study - Image Configuration

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

Trade Study - IPS Detection Algorithm

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

Trade Study - Magnetometer Sensor

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

Trade Study - Magnetometer Location

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**

Trade Study - Instrument Electronics Unit

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

Trade Study - External Memory

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

S/C Materials Budget

MATERIAL	MASS (kg)	SolidWorks Mat	COST/KG ($/kg)	COST($)	(x2) MOUNTING($)	(x2) EXTRA (MISTAKES)
ABS	0.5	ABS	21	10.5	21	42
PLA	0.61	PEI	21	12.81	25.62	51.24
Aluminum	1.37	2219-T62	5	6.85	13.7	27.4
Titanium	2.33	Ti-3Al-8V-6Cr-4Mo-4Zr (SS)	30	69.9	139.8	279.6
Steel	3.86	AISI 304	3	11.58	23.16	46.32