Project HEPCATS
Highly Elliptical Polar Constellation for Auroral Transport Studies

Preliminary Design Review

Presenters: Hailee Baughn, Jordan Lerner, Valerie Lesser, Christopher Peercy, Vishranth Siva, Braden Solt & Benjamin Spencer

Team: Alexander Baughman, Colin Brown, Matthew Skogen, Colin Sullivan & Kian Tanner

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

1. Begin Taking Auroral Images & Magnetic Field Data
   - Constellation of cubesats to provide continuous imaging of auroras

2. Stop Taking Auroral Images & Magnetic Field Data
   - Varying magnetic fields

Region of Interest (ROI)

HEPCATS CubeSat
- Instruments Onboard
  - Camera
  - Magnetometer

Ground Station
- Command & Control
- Auroral Images & Magnetic Field Data

DigitalGlobe
Baseline Design
HEPCATS Project

Simulated Ground Station

Wire for Commands & Telemetry (Simulated Uplink/Downlink Rates)

Bus Structure

Spacecraft Bus (Empty Space)

Payload

HEPCATS CubeSat Payload

Onboard Computer and Memory Auroral Image Processing Software Camera Magnetometer

Camera

Magnetometer

(Detached from the bus structure on a conceptual boom)

Project Overview Baseline Design Feasibility of Baseline Design Imaging System Image Processing System Magnetometer System Summary
“Orbit in the Life” Simulation Part 1

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

1b. **Commanded Instruments On**
   The camera and magnetometer are turned on at the ROI start time from the simulated ground station or from onboard absolutely timed commands.

- **Region of Interest (ROI)**
- **Helmholtz Cage**
- **Camera**
- **Magnetometer**
- **Projector Screen**
- **Projector**
“Orbit in the Life” Simulation Part 2

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.

Projected image of the Earth and auroras (Orientation and image size varies to simulate position within orbit)

Auroral images are selected and processed in the onboard computer

Helmholtz Cage generates magnetic field ($\mathbf{B}$)
“Orbit in the Life” Simulation Part 3

Commanded Instruments Off
The camera and magnetometer are turned off at the ROI stop time from the simulated ground station or from onboard absolutely timed commands.

Region of Interest (ROI)

Helmholtz Cage

Projector Screen
Functional Block Diagram: IPS

Onboard Computer

- Imaging Processing Software (IPS)
  - Image Processing (Crop, Rotate, Filter, Unskew, & Down-sample)
  - Processed Images
  - Raw images

- PTDNN
  - Auroral Identification & Image Selection
  - Accepted Images

- Map Aurora to the Earth (Produce Geographical Information System Data)
  - Image & GIS Data

- Image & DIS Data Compression

Flight Software

Instrument Electronics Unit (IEU)

- Raw images
  - Flight Software

- Image Processing Software
  - Images ready for Downlink

- External Memory
  - Stored Commands
  - Instrument and Housekeeping Telemetry

Onboard Computer

- Flight Software
  - Instrument and Housekeeping Telemetry

Peripheral I/O
HEPCATS Baseline Design Overview

Baseline Design

- 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

<table>
<thead>
<tr>
<th>Level</th>
<th>Functional Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>The imaging subsystem shall be capable of taking images of a simulated Aurora Borealis.</td>
</tr>
<tr>
<td>2.0</td>
<td>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.</td>
</tr>
<tr>
<td>3.0</td>
<td>The magnetometer system shall be capable of measuring a magnetic field.</td>
</tr>
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<td>4.0</td>
<td>The manufactured spacecraft bus shall be the infrastructure of the spacecraft capable of housing the Instrument Electronics Unit and the Instrument Suite.</td>
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<td>5.0</td>
<td>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.</td>
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<td>The Simulated Ground Station shall be able to command and receive telemetry from the Instrument Electronics Unit.</td>
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</table>
## Feasibility Concerns of Select CPEs

<table>
<thead>
<tr>
<th>Critical Project Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1 Proper Camera &amp; Lens System</td>
<td>Need to select proper FOV in order to have continuous coverage of polar crown and ensure a spatial resolution that produces useful images</td>
</tr>
<tr>
<td>P1 Image Processing &amp; Aurora Detection</td>
<td>Image processing should be able to identify if an aurora is present in each image</td>
</tr>
<tr>
<td>M1 Magnetometer System Bias</td>
<td>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</td>
</tr>
</tbody>
</table>
Imaging System
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)
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

![Graph showing FOV vs Total Target Observation Time Averaged Over Year]

- Total Target Stare Time (hours)
- FOV Half Angle (degrees)
- Orbit Function
- Stare Requirement
- Feasible Region

- Project Overview
- Baseline Design
- Feasibility of Baseline Design
- Imaging System
- Image Processing System
- Magnetometer System
- Summary
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
## Feasibility Summary

<table>
<thead>
<tr>
<th>Critical Project Element</th>
<th>Solution</th>
<th>Feasibility</th>
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<tr>
<td>I1 Proper Camera &amp; Lens System</td>
<td>There is a wide selection of FOV which can offset sensor cost and be offset by higher resolution sensors</td>
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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
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
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)

- Classification: 1.0, Prediction: 1.000
- Classification: 0.0, Prediction: 0.000

Mis-classification Example

- Classification: 1.0, Prediction: 0.000
# Feasibility Summary

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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 decrease 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 (saturate)
   • 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:

\[ B \propto \frac{1}{d^3} \]

2. Induced Magnetic Field:

**Biot-Savart Law:**

\[
\vec{B} = \frac{\mu(0)}{4\pi} \int_{wire} \frac{I\,d\vec{l} \times \hat{r}}{r^2}
\]
Treating the System as a Circular Loop:

\[ B_x = \frac{\mu_0 I R^2}{2\sqrt{x^2 + R^2}} \]

Where:

- \( x \) = distance from center of circle
- \( R \) = radius of circle
- \( B_x \) = 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
- \( B_x \) = magnetic field strength in \( x \)-direction

Range of Current:
- From 1.25 A - 5.83 A
  - System voltage is 120 V by FR 5.0
  - Industry standard 12 V to magnetometer
  - \( I = \frac{P}{V} \)
  - 6U CubeSats have a typical power range between 15 - 70W
Magnetometer Feasibility: System Bias

Treating the System as a Circular Loop:

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

Where:
- \( x \) = distance from center of circle
- \( R \) = radius of circle
- \( B_x \) = 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:

\[ B_x = \frac{\mu_0 I R^2}{2\sqrt{x^2 + R^2}} \]

Where:
- \( x \) = distance from center of circle
- \( R \) = radius of circle
- \( B_x \) = magnetic field strength in \( x \)-direction

Maximum Bias:
- 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

![Graph showing system bias vs distance for different system currents.](image)
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Summary
# Feasibility Summary

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<td>Any field of view greater than 9 degrees will provide continuous coverage of target area</td>
<td>Feasible</td>
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<td>A PTDNN works for recognizing satellites in this example data and can be implemented to identify auroras</td>
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Budget

Total Budget: $5000

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<tr>
<th>System</th>
<th>Cost ($)</th>
<th>Margin($)</th>
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<tbody>
<tr>
<td>Imaging</td>
<td>700</td>
<td>200</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>S/C Bus Materials</td>
<td>300</td>
<td>125</td>
</tr>
<tr>
<td>Replacements (Spares)</td>
<td>1000</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3400</strong></td>
<td><strong>725</strong></td>
</tr>
<tr>
<td><strong>Total w/ Margin</strong></td>
<td><strong>$4125</strong></td>
<td></td>
</tr>
</tbody>
</table>

HEPCATS Budget Breakdown

- Imaging
- Magnetometer
- Command & Data Handling
- S/C Bus Materials
- Replacements (Spares)
- Total Margin
- Remaining Budget
Schedule for PDR to CDR

Project Overview Baseline Design Feasibility of Baseline Design Imaging System Image Processing System Magnetometer System Summary
Schedule Overview for PDR to PFR
Acknowledgements

Special thanks to:

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

• “dslr cmos camera” https://www.amazon.com/s/ref=nb_sb_noss?url=search-alias=electronics&field-keywords=dslr cmos camera&rh=n:172282,k:
References cont.

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Thank You!

Questions?
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Constellation Sensor Coverage of G1 Storms Video
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Trade Study - IPS Detection Algorithm
Trade Study - Magnetometer Sensor
Trade Study - Magnetometer Location
Trade Study - IEU
Trade Study - External Memory
S/C Materials Budget
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

<table>
<thead>
<tr>
<th>Level</th>
<th>Functional Requirement</th>
<th>Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>The manufactured spacecraft bus, the structure of the spacecraft, shall be capable of housing the Instrument Electronics Unit and the Instrument Suite</td>
<td>Design and fabrication of a 6U bus structure is accomplished by referencing pre-existing designs and aerospace faculty expertise.</td>
</tr>
<tr>
<td>5.0</td>
<td>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.</td>
<td>Design of an electric power system is accomplished by team experience and aerospace faculty expertise.</td>
</tr>
<tr>
<td>6.0</td>
<td>The Simulated Ground Station shall be able to command and receive telemetry from the Instrument Electronics Unit.</td>
<td>Communication interface is provided by physical wired connection and leverages a standard protocol to networking IEU and SGS.</td>
</tr>
<tr>
<td>7.0</td>
<td>The Instrument Electronics Unit shall be capable of storing all instrument telemetry, housekeeping telemetry, and command sequence data.</td>
<td>Data storage on an external solid state drive is within team experience.</td>
</tr>
<tr>
<td>8.0</td>
<td>The Instrument Electronics Unit shall be capable of sending telemetry to the Simulated Ground Station.</td>
<td>Communication interface is provided by physical wired connection and leverages a standard protocol to networking IEU and SGS.</td>
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<tr>
<td>9.0</td>
<td>The Instrument Electronics Unit shall be capable of executing commands from the Simulated Ground Station or on board absolutely timed command sequences.</td>
<td>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 chosen.</td>
</tr>
</tbody>
</table>
Command Distribution

- **Camera**
  - Camera Commands
- **Magnetometer**
  - Magnetometer Commands
- **Onboard Computer**
  - Commands
  - Stored Commands
  - External Memory
- **Simulated Ground Station**
  - Commands
Telemetry Flow

- Camera
  - Image Data

- Magnetometer
  - Magnetometer Data

- Onboard Computer
  - Downlink Telemetry
  - Telemetry
  - External Memory

- Simulated Ground Station
Simulated Ground Station

Simulated Ground Station

Downlink Telemetry

Telemetry Processor

Data

C&T GUI
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/](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

\[ HFOV = 2D \tan(FOV) \]

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)
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* a process called *backpropagation*.
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

![Model loss](image1)

![Model accuracy](image2)
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](image)
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

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>CCD</th>
<th>CMOS</th>
<th>Oversampled Binary</th>
<th>QIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>30%</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Power</td>
<td>10%</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Heritage</td>
<td>10%</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>25%</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Color Reproduction</td>
<td>25%</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td>3.85</td>
<td>4.00</td>
<td>3.05</td>
<td>3.40</td>
</tr>
</tbody>
</table>
**Trade Study - Image Configuration**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>1 High-Res Grayscale</th>
<th>1 High-Res RGB</th>
<th>High-Res 1R + 1G + 1B</th>
<th>1 High-Res Grayscale + 1 High-Res RGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>30%</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>20%</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Image Processing</td>
<td>20%</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Data Size</td>
<td>15%</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Data Usability</td>
<td>15%</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td><strong>3.6</strong></td>
<td><strong>4.1</strong></td>
<td><strong>2.85</strong></td>
<td><strong>3.35</strong></td>
</tr>
</tbody>
</table>
## Trade Study - IPS Detection Algorithm

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>CNN</th>
<th>PTDNN</th>
<th>SIFT</th>
<th>IS &amp; CHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>40%</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Speed</td>
<td>20%</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Feasibility</td>
<td>20%</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Adaptability</td>
<td>20%</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td>3.4</td>
<td><strong>4.0</strong></td>
<td>3.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>
# Trade Study - Magnetometer Sensor

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>Fluxgate Sensor</th>
<th>SDT Sensor</th>
<th>AMR Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>35%</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Sensor Noise Density</td>
<td>15%</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>20%</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Cost</td>
<td>10%</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Availability</td>
<td>15%</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Mass</td>
<td>5%</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td><strong>4.05</strong></td>
<td>3.75</td>
<td>3.65</td>
</tr>
</tbody>
</table>
# Trade Study - Magnetometer Location

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>Inside S/C</th>
<th>Surface Mounted on S/C</th>
<th>Mounted to Boom</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMI</td>
<td>40%</td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Complexity</td>
<td>25%</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Heritage</td>
<td>25%</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Cost</td>
<td>10%</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td>2.4</td>
<td>3</td>
<td><strong>3.9</strong></td>
</tr>
</tbody>
</table>
### Table 43: Instrument Electronics Unit Trade Study Scoring

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>SBC</th>
<th>FPGA</th>
<th>Microcontroller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing Speed</td>
<td>20%</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>20%</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Difficulty</td>
<td>15%</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>OS/Software Compatibility</td>
<td>15%</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Built in I/O Hardware</td>
<td>15%</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Thermal</td>
<td>10%</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>5%</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td><strong>2.15</strong></td>
<td>1.9</td>
<td>1.95</td>
</tr>
</tbody>
</table>
# Trade Study - External Memory

## Table 46: External Memory Metric Score Categorization

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>USB</th>
<th>SSD</th>
<th>MicroSD</th>
<th>HDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read/Write Speed</td>
<td>30%</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Performance/Reliability</td>
<td>20%</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Storage Space</td>
<td>20%</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Power Draw</td>
<td>10%</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Cost</td>
<td>10%</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Size/Weight</td>
<td>5%</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Complexity</td>
<td>5%</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
<td><strong>3.55</strong></td>
<td><strong>4.45</strong></td>
<td><strong>3.5</strong></td>
<td><strong>3.1</strong></td>
</tr>
</tbody>
</table>
# S/C Materials Budget

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