University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

Highly Elliptic Polar Constellation for Auroral Transport Studies (HEPCATS)

Approvals

	Name	Affiliation	Approved	Date
Customer	Neal Anderson	DigitalGlobe	Neal T. Anderson	9/17/18
Customer	Thomas Berger	CU Space Weather Center	[signature]	9/20/18
Course Coordinator	Jelliffe Jackson	CU/AES		

Project Customers

NAME: Neal Anderson Phone: (303) 589 - 0841 Email: nanderson@digitalglobe.com	NAME: Tom Berger Phone: (303) 735 - 8557 Email: thomas.berger@colorado.edu

Team Members

NAME: Alexander Baughman Phone: (720) 621 - 6811 Email: alba3651@colorado.edu	NAME: Vishranth Siva Phone: (720) 639 - 0002 Email: visi4153@colorado.edu
NAME: Hailee Baughn Phone: (720) 224 - 4033 Email: hailee.baughn@colorado.edu	NAME: Matthew Skogen Phone: (720) 288 - 3125 Email: matthew.skogen@colorado.edu
NAME: Colin Brown Phone: (303) 641 - 9860 Email: colin.brown-1@colorado.edu	NAME: Braden Solt Phone: (303) 552 - 4605 Email: braden.solt@colorado.edu
NAME: Jordan Lerner Phone: (801) 928 - 6434 Email: jole9439@colorado.edu	NAME: Benjamin Spencer Phone: (607) 377 - 4032 Email: benjamin.spencer-1@colorado.edu
NAME: Valerie Lesser Phone: (303) 728 - 4583 Email: valerie.lesser@colorado.edu	NAME: Colin Sullivan Phone: (303) 478 - 2982 Email: colin.f.sullivan@colorado.edu
NAME: Christopher Peercy Phone: (970) 215 - 7480 Email: christopher.peercy@colorado.edu	NAME: Kian Tanner Phone: (530) 204 - 7851 Email: kian.tanner@colorado.edu

1.0 Problem or Need

1.0.1 Problem Motivation

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.

1.0.2 Project Overview

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 LASP which will drive the design for a Molniya orbit modeled with an 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 DigitalGlobe for further processing and distribution.

2.0 Previous Work

A successful HEPCATS mission hopes to build off the legacy of multiple auroral imaging NASA missions, the most recent of which, the IMAGE mission, ended in 2005. Several of these missions are described below. Project HEPCATS hopes to reestablish a satellite dedicated to monitoring the aurora and prove the feasibility of a small-sat to perform such a task. Additionally, while past missions took UV imagery, a successful HEPCATS mission would focus on imaging in the visible spectrum.

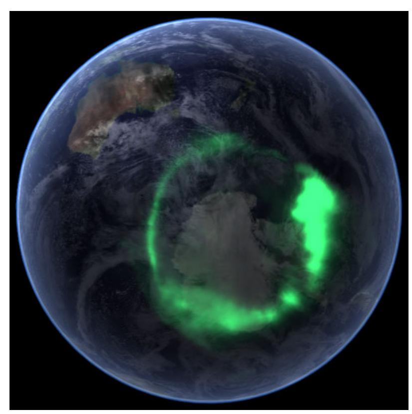

Figure 1: IMAGE's view of the Aurora Australis (Southern Lights)[4].

2.0.1 Highly Elliptical Orbit Missions

Due to the nature of the aurora, the entire objective of this mission involves observation of the Northern Hemisphere of Earth at high latitudes. Given this requirement, HEPCATS will be on the cutting edge of technology as a small satellite in a Molniya orbit to capture images of the aurora. Molniya satellites were originally launched by Russia and used to transmit military and communications data at high elevation angles to offset the high latitude of the country[6]. The United States also utilizes these orbits for the Satellite Data System, which performs reconnaissance for the military. Between these missions, the orbital elements of the Molniya orbit have been refined for long duration, highly elliptical missions.

2.0.2 NASA Missions

NASA has had multiple missions study the Earth's ionosphere and magnetosphere. NASA's Dynamics Explorer-1 launched in 1981 and studied the North and South Poles during all stages of a space weather event[2]. The Dynamics Explorer-1 carried advanced plasma wave detectors and energetic particle sensors to gather scientific data of the magnetic poles, but only captured imagery of the auroras in UV. NASA's IMAGE spacecraft launched in 2000 and was the first satellite dedicated to imaging the Earth's magnetosphere. It employed neutral atom (NA), radio plasma, and ultraviolet imaging techniques to produce stunning images of the ”invisible” region of space. The far ultraviolet imager was responsible in producing the first-ever images from space of the proton aurora[3]. After almost 6 years, the IMAGE spacecraft stopped sending signals to the ground. Although radio signals were briefly detected from the spacecraft in 2018, NASA was unable to re-establish communication and the mission is considered terminated.

3.0 Specific 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.

	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 TBD Compress image to TBD	Detect the magnitude and direction of a constant magnetic field	Mounted within a manufactured stand-alone structure	Manually commanded payload activation & deactivation Receive, store, and send magnetometer and image data at a rate of TBD
Level 2	Able to image at 16.67 mHz Fixed FOV able to image latitudes above TBD degrees north at apogee Identify if aurora is present	Detect magnetic field with magnitude between 100 to 1000 nanoteslas		Able to load and execute an absolute time sequence of commands from the ground station
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	

Table 1: Specific Objectives of HEPCATS Project

4.0 Functional Requirements

4.0.1 Concept of Operations

Two concepts of operations are presented for the overall HEPCATS mission and the project defined in this design document. First, Fig.(2) 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.

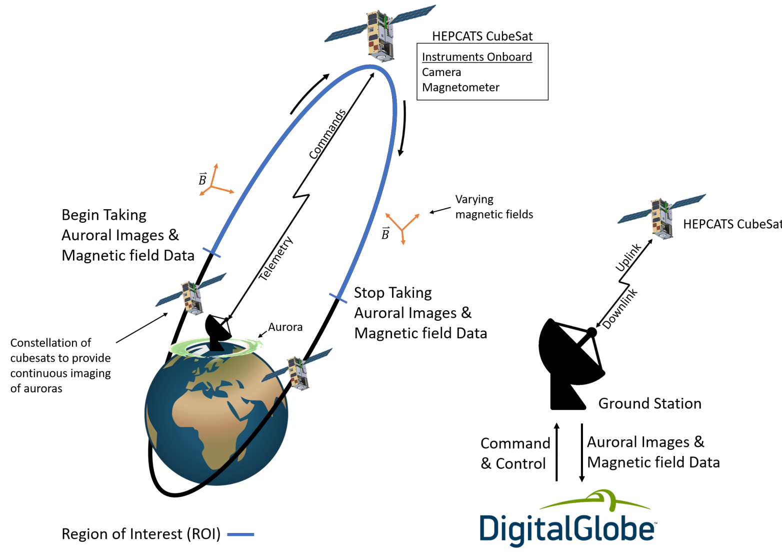

Figure 2: HEPCATS Mission CONOPS

Fig.(3) 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 a "Orbit in the Life" simulation, see Fig.(4). The ground station is substituted for a computer 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.(4) and starts with modeling the orbit, in an 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 ground (level 1 success) or from an onboard absolutely time 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 ground station as telemetry. The simulation is concluded with commanding the instruments off at the ROI stop time either through the ground station or ATS.

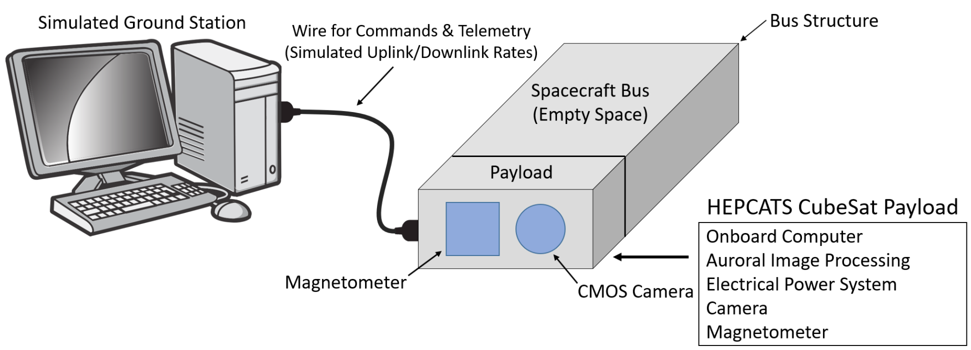

Figure 3: HEPCATS CubeSat Project Diagram

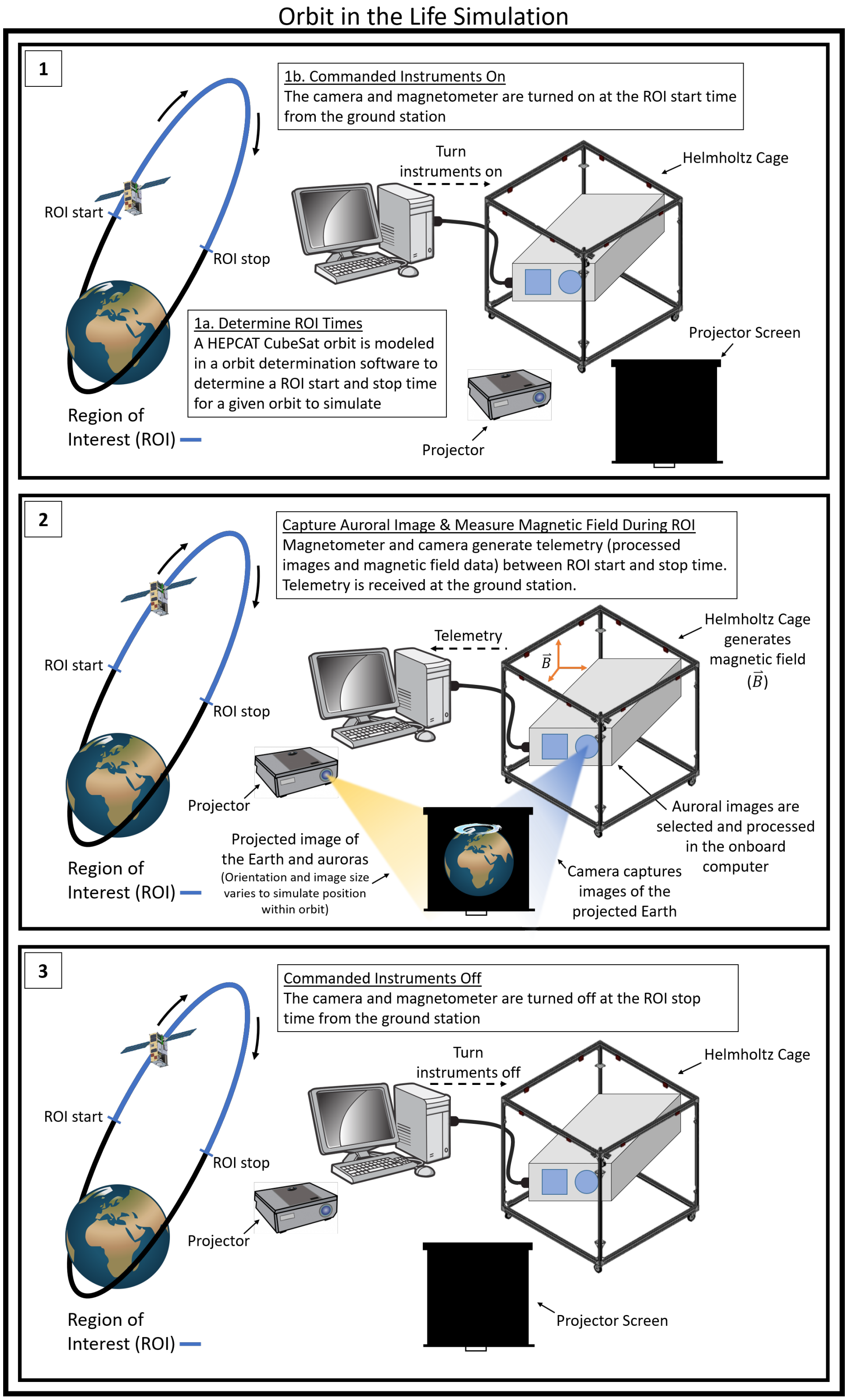

Figure 4: "Orbit in the Life" Simulation ConOps

4.0.2 Functional Block Diagram

The functional block diagram (FBD) to accompany the project diagram and "Orbit in the Life" simulation ConOps is presented below. A gray box indicates that the component will be designed by the team whereas a blue box means that the components will be obtained.

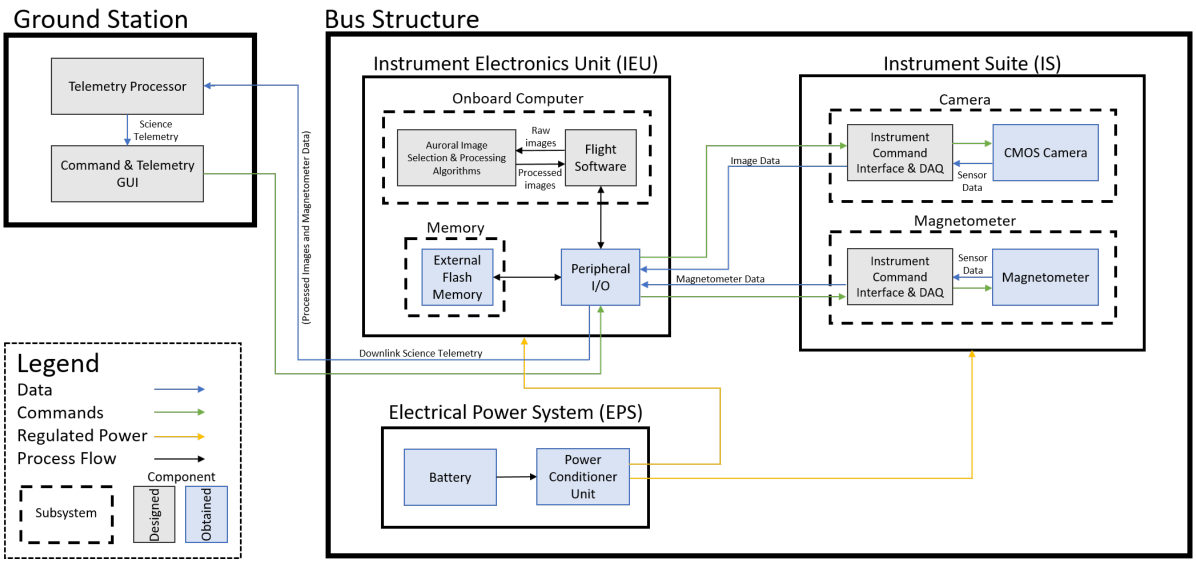

Figure 5: Functional Block Diagram of the HEPCATS CubeSat Project

5.0 Critical Project Elements

The critical project elements (CPEs) are summarized in Table 2. The most critical element which will drive the entirety of the rest of the design will be the imaging sensor selection and system design (T1). This will drive the optics and C&DH requirements. The second most critical element is the design and operation of on-board image processing (T2). The ability for the satellite to detect the presence of an aurora will allow image downlink to occur only when necessary. The magnetometer system (T3) presents less of a technical challenge, but will still be difficult to properly calibrate and operate. Due to the design of the mission, the storage of data and proper downlink transmissions will be difficult to maintain (T4). It will be critical to store, compress, and transmit data accordingly. Proper allocation of budget due to camera expense (F1) will influence the extent of the prototyping and design for the bus structure (T5). It is also important to secure reliable, effective, and accurate testing environments to ensure the success of the mission (L1 & L2).

	Technical	
T1	Imaging System	Need to select proper camera and lens system to ensure usable photos are taken
T2	Image Processing	Image processing should be able to identify if auroras are present
T3	Magnetometer	Magnetometer must be properly calibrated and operated
T4	Data Handling	Developing proper buffer size, simulating uplink and downlink, and collecting data
T5	Bus Structure	Designing and manufacturing a structure to mount payload in an effective and viable manner
	Logistical	
L1	Helmholtz Cage Availability	Helmholtz cage may not be available for testing
L2	Imaging System Testing	Procurement of acceptable imagery and development of sufficient testing procedures
	Financial	
F1	Expense of Camera	Cost-benefit of camera selection as camera expense may be a large percentage of the budget

Table 2: Critical Project Elements

6.0 Team Skills and Interests

Team Members	Associated Skills/Interests	Critical Project Elements
Alexander Baughman	Programming, research and design, and manufacturing	T1, T3, T5, L1, L2
Hailee Baughn	Programming, project management, testing, STK	T1, T3, T4, L1, F1
Colin Brown	Programming, orbital mechanics/design and flight software, 3D modeling, budget allocation, manufacturing	T1, T3, T5, L1, F1
Jordan Lerner	Systems engineering, software development, research and design, 3D modeling software, optics design	T1, T3, T5, L1
Valerie Lesser	3D Modeling, prototyping, 3D printing, economics	T1, T5, L1, F1
Christopher Peercy	Orbital mechanics, basic photography, systems engineering, image stacking, research, STK	T1, T3, T5, L2
Vishranth Siva	Budget allocation, marketing, economics, 3D modeling, research & design and optics	T1, T5, L2, F1
Matthew Skogen	Programming, 3D modeling, economics, software development and testing, research and design	T1, T2, T5, L2, F1
Braden Solt	Programming, systems engineering, and image recognition and processing	T2, T3, T4, L2
Benjamin Spencer	Systems engineering, flight software, STK, command & data handling, integration, and testing	T1, T4, T5, L2, F1
Colin Sullivan	Optics calibration, image recognition and processing software, manufacturing and optical system design	T1, T2, T5, L2
Kian Tanner	Programming, electronics design, image recognition, flight software and command & data handling	T2, T3, T4, L2

Table 3: Team Members, Associated Skills, and Critical Project Elements

7.0 Resources

Critical Project Elements (CPEs)	Resources	Subject Matter Expert (SMEs)
T1	(1) LASP (2) APS Department (3) Sommers Bausch Observatory	(1) Tom Berger (2) Jason Glenn (3) Fabio Mezzalira
T2	(1) DigitalGlobe (2) SWPC (3) CS Department	(1) TBD (2) Tom Berger (3) TBD
T3	(1) SWPC (2) AES Department	(1) Tom Berger (2) Marcus Holzinger, Robert Marshall, Scott Palo
T4	(1) AES Department	(1) Robert Marshall, Dennis Akos, Trudy Schwartz, Bobby Hodgkinson
T5	(1) AES Machine Shop (2) iFusion (3) AES Department	(1) Matt Rhode (2) Michael Mann (3) Scott Palo
L1	(1) AES Department (2) APS Department	(1) Scott Palo, Marcus Holzinger (2) Jason Glenn
L2	(1) DigitalGlobe (2) CS Department	(1) TBD (2) Dan Larremore
F1	(1) LASP	(1) Tom Berger

Table 4: Critical Project Elements and Associated Resources and Subject Matter Experts

8.0 References

[1] Baranoski, G.v.g., et al. Simulating the Aurora Borealis. Proceedings the Eighth Pacific Conference on Computer Graphics and Applications, 2000, doi:10.1109/pccga.2000.883852.
[2] Dynamics Explorer 1. NASA, NASA, eospso.nasa.gov/missions/dynamics-explorer-1.
[3] Hamilton, C. J. (n.d.). IMAGE Spacecraft. Retrieved from http://solarviews.com/eng/image.html
[4] IMAGE Spacecraft Pictures Aurora. (n.d.). Retrieved from https://earthobservatory.nasa.gov/images/6226/image-spacecraft-pictures-aurora
[5] Jackson, Jelliffe. "PDD Assignment", University of Colorado-Boulder, Retrieved September 13, 2018, from https://canvas.colorado.edu/co
[6] Pike, John. Space. Global Security, www.globalsecurity.org/space/world/russia/molniya.htm.