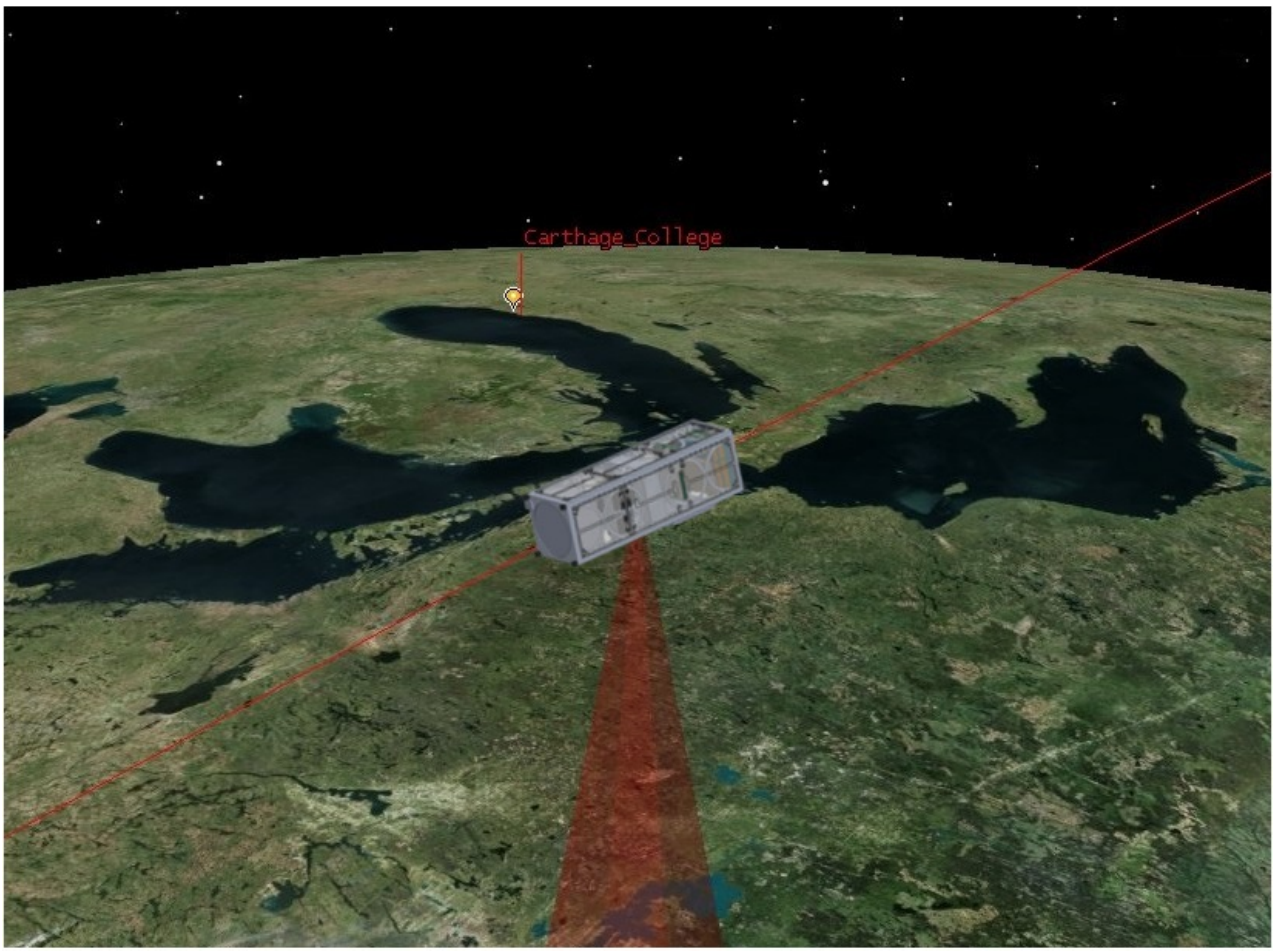
Conceptual Design Review

Canopy Near-infrared Observing Project

Carthage College Space Sciences
and the Wisconsin Space Grant Consortium
July 5, 2016



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List of Acronyms and Abbreviations

Acronym	Definition
AcM	Activation Mode
ADCS	Attitude Determination Control System
CAC	CubeSat Acceptance Checklist
CAD	Computer Aided Design
CaNOP	Canopy Near Infrared Observing Project
CDR	Critical Design Review
CDS	CubeSat Design Specification
COTS	Consumer Off The Shelf
CSLI	CubeSat Launch Initiative
DAS	Debris Assessment Software
DC	Direct Current
DSLR	Digital Single Lens Reflex
EIRP	Effective Isotropic Radiated Power
ELaNA	Educational Launch of Nanosatellites (Launch Provider)
EPS	Electronic Power System
EVI	Enhanced Vegetation Index
FAPAR	Fraction of light across PAR
FC	Flight Computer
FCC	Federal Communication Commission
FOV	Field of View
FSM	Fail Safe Mode
GIS	Geographic Information System
GPP	Gross Primary Production
GPS	Global Positioning System
GPSR	GPS Receiver
GPSRM	GPS Receiver Module
GSD	Ground Sample Distance

ICD	Interface Control Document
IFOV	Instantaneous Field of View
INC	Incorporated
IR	Infrared
ISS	International Space Station
ITU	International Telecommunication Union
IUCN	International Union for the Conservation of Nature
LAI	Leaf Area Index
Lat/Lon	Latitude/Longitude
LEO	Low Elevation Orbit
LMI	Listening Mode Idle
Ltd	Limited
LUE	Light Use Efficiency
LV	Launch Vehicle
MATLAB	Matrix Laboratory
MCU	Master Control Unit
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NEN	Near Earth Network
NIR	Near Infrared
NRCSD	NanoRacks CubeSat Deployer
NREP	NanoRacks External Platform
PAR	Photosynthetic Active Region
PDR	Practical Design Review
PIC	Point of Image Capture
PPM	Pluggable Processor Module
PRI	Photochemical Reflectance Index
px	Pixels

RF	Radio Frequency
RFB	Remove Before Flight
RTOS	Real-Time Operating System
SD Card	Secure Digital Card
STEM	Science Technology Engineering and Mathematics
STK	Systems Tool Kit
TM	Thematic Mapper
UN	United Nations
USB	Universal Serial Bus
USIP	Undergraduate Student Instrument Project
UTJ	Ultimate Triple Junction
VIS	Visible Light Spectrum
WSGC	Wisconsin Space Grant Consortium
Units	
μm	micrometer
mm	millimeter
cm	centimeter
km	kilometer
W	watt
mWh	milliwatt-hour
g	gram
kg	kilogram
K	Kelvin
ºC	degree Celsius
M	million
sec	second
msec	millisecond
MB	megabyte
MBps	megabytes per second

GHz	gigahertz
V	volt
dBi	DeciBel relative to isotropic radiator
dBW	DeciBel Watt (dB relative to 1 W)
dBm	DeciBel milliWatt (dB relative to 1 mW)

Team Members and Assignments

PI: Kevin Crosby
Project Advisors: Fred Best, Joy Mast, Isa Peterson, Michael Swedish
System Engineer: Jeremiah Munson

Jedidiah Barnes ‘19
- Science
- Structural

Brianna Faltersack ‘19
- ADCS
- Education

Daniel Gerloff ‘18
- Communications and Telemetry
- Flight Software
- Integration and Testing

Laura Hammock ‘19
- Camera
- Education
- Integration and Testing
- Social Media

Michael Hernandez ‘19
- Communications and Telemetry
- Flight Software

Michael Huff ‘19
- Camera
- Education
- Inventory and Budget
- Science

Kevin LeCaptain ‘16

- ADCS
- Structural

Ashley Marquette ‘17
- ADCS
- Structural

Jeremiah Munson ‘19
- Systems Engineer

Michael Omohundro ‘17
- GPS
- Science

Brendan Krull ‘16
- Camera
- EPS
- Thermal

Ariana Raya ‘19
- Camera
- Social Media
- Structural

Thomas Shannon ‘19
- Communications and Telemetry
- Thermal

Benjamin Tillema ‘18
- ADCS
- Integration and Testing
- Thermal

Nycole Wenner ‘19
- EPS
- Integration and Testing
- Structural

Joseph Wonsil ‘19
- EPS
- Flight Software
- Science

Mission Overview

The Canopy Near-IR Observing Project will utilize a multispectral pushbroom imager in a 3U CubeSat to carry out spectrally resolved imaging of global forest regions with spectral resolution sufficient to reproduce early LandSat and MODIS missions.

Forests currently absorb as much as 30% of annual global anthropogenic carbon dioxide emissions (Schimel, 2014). Natural carbon flux is a critical yet poorly understood component of climate change, particularly in the mitigation of its effects. Many of the scientific questions around global forest carbon-uptake are large-scale questions of landscape ecology and therefore are appropriately addressed through space-based remote sensing. The Wisconsin Space Grant Consortium (WSGC) proposes to develop a CubeSat-based platform for performing multispectral imaging of forests around the world in an effort to support and understand large-scale biomass production and carbon sequestration in both mature and young second-growth forests. CaNOP will be a CubeSat platform for performing basic multispectral imaging of forest canopies in the Landsat Thematic Mapper bands TM2, TM3, and TM4, and in select MODIS bands.

The specific scientific goals of this project are to image forests (which are categorized by biome), and collect reflectance data about the target regions. Illumination data (gathered in the visible and Near Infrared (NIR) spectra) will be used to compute the Normalized Difference Vegetation Index (NDVI), a ratio of the amount of light reflected in the NIR ranged compared to that of visible light. The comparison between young secondary and old-growth forests may help address a recent and paradoxical observation that suggests that primary forests are absorbing more carbon than their younger counterparts.

The primary technological objective of the mission is to demonstrate that the types of landform observations made possible by LandSat and MODIS class instruments can be reproduced with comparable spectral resolutions using less expensive equipment and a CubeSat based platform.

Theory and Concepts

The pigment chlorophyll in healthy vegetation absorbs sunlight preferentially in the “photosynthetic active radiation” (PAR) of the sun’s spectrum between 400-700 nm. A healthy forest canopy will absorb much of the visible sunlight incident on it and reflect comparably more of the near-infrared (NIR) light between 700-1100 nm (Jones, 2010). Stressed or unhealthy vegetation will reflect a larger portion of visible light in the PAR and will absorb more of the NIR wavelengths relative to healthy vegetation. This fundamental difference in spectral reflectance has been the basis for remote sensing of global ecosystems for decades.

The most convenient index for capturing the relative spectral reflectance of NIR and PAR light for a region of vegetation is the Normalized Difference Vegetation Index (NDVI). The NDVI is computed from spectral reflectance according to *NDVI = (NIR-VIS)/(NIR+VIS)* where NIR is the reflectance in the near-infrared and VIS represents the reflectance in the red region of PAR. The NDVI varies from -1 (non-vegetated; strong absorption in the NIR) to +1 (healthy vegetation; strong reflectance in the NIR). The NDVI is a useful first step in characterizing forest canopy coverage, biomass, chlorophyll content, and carbon dioxide capacity (Li, 1997). It is also an appropriate index for longitudinal studies encompassing drought and seasonal onset changes resulting from climate disturbances. The NDVI is insensitive to solar zenith angle and lighting conditions so it can be used reliably from on-orbit instruments regardless of the relative positions of earth, sensor, and sun.

Through photosynthesis, trees absorb CO_2 from the atmosphere and incorporate the carbon into sugars from which wood is produced. Between 40% and 60% of dry wood is carbon removed from the atmosphere (Thomas, 2012). This carbon remains locked (sequestered) in the tree for the duration of its life. When trees die and decay or burn this carbon is released back to the atmosphere as CO_2.

Almost 30% of Earth's total land area is forests, accounting for 80% of the Earth's total biomass (Pan et al.). Therefore, an accurate picture of global forest health and an understanding of the carbon exchanges between atmosphere and forest are crucial to the emerging picture of climate change. Traditional models of atmospheric carbon flux assume that old-growth forests are carbon neutral in the sense that carbon sequestration through photosynthesis is balanced by carbon losses through respiration. Recent studies have suggested that forests 200 years old and older are in fact "carbon negative," and may provide an important and misunderstood role in carbon uptake and sequestration (Luyssaert, 2012).

Moreover, recent observations also indicate that young second-growth forests, often show markedly lower carbon sequestration rates than old-growth forests and can be carbon positive, releasing CO_2 to the atmosphere (Luyssaert, 2012). This may be due to circumstances of new forest creation, which often replace existing vegetation, the decomposition of which contributes an outflow of carbon that exceeds the photosynthetic uptake of carbon in the forest.

Through quantitative comparisons of vegetation indices, such as the NDVI, and EVI in mature (200 yr+ forests) and young second-growth of the same net leaf mass, we hope to probe the connection between stress-state and forest type (young or harvested vs. old and unharvested).

The mission concept is illustrated in Fig. 1. The CaNOP team will use a COTS multispectral camera to obtain spectral reflectance data over forested regions within its field of view as dictated by the orbit provided by the launch vehicle. The payload instrument is an 8-band multispectral camera with spectral bands corresponding to the Thematic Imager (TM) bands and select MODIS bands.

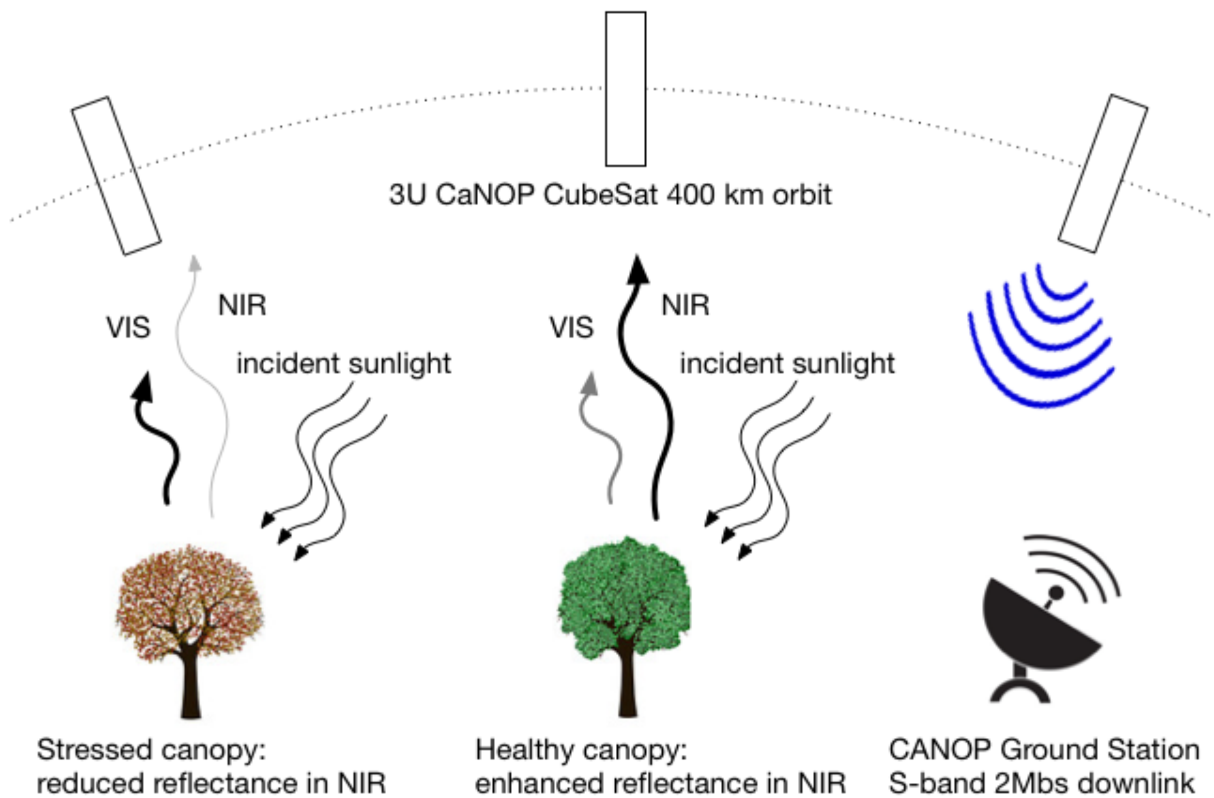

Fig.1. Mission Concept.

Given the uncertainty in orbital parameters for CubeSat missions, spectral imaging is a good choice for an educational CubeSat project because almost any orbit yields imaging opportunities of scientific and educational value. The science goals relative to obtaining spectral reflectance data from the on-orbit camera require that the CaNOP CubeSat has imaging opportunities over forested areas with a minimum linear dimension of at least ~1km. This requirement is set by the sensor and camera optics for an orbital altitude of 500km. An initial estimate the availability of such targets using ArcGIS and a simulated orbit of inclination 50° confirms that virtually every orbit will provide relevant imaging targets (ESRI, 2015).

To ensure compliance with orbital debris mitigation procedural requirements, the CaNOP team will abide by all NASA USG Orbital Debris Mitigation Standard Practices (NASA, 2012). NASA OSMA4 has accepted that battery failure is unlikely to impact the orbital debris environment, but CaNOP will only employ batteries with demonstrated space heritage. The probability of a collision with a large object (> 1cm) will be estimated using NASA Debris Assessment Software v. 2.02 (NASA DAS, 2012).

Re-entry risks will be mitigated through the exclusion of problematic materials such as tungsten, and orbital decay time will be calculated based on the orbit and geosolar environment determined at time of manifest. For the sake of specificity, given reasonable average assumptions about solar weather and geomagnetic activity, a 4-kg satellite with surface area prescribed by the 3U CubeSat specifications will have an orbital lifetime of 891 days or 2.47 years in 400 km 50° orbit before drag forces de-orbit the satellite (NASA DAS, 2012).

Based on the FCC Public Notice Guidance on Obtaining Licenses for Small Satellites, CaNOP operations fall under the experimental licensing rules of the FCC in regard to band provisioning and licensing (FCC, 2013). The CaNOP Team Lead on the COM subsystem will be responsible for compiling required information and submitting the necessary request to the ITU and FCC per the mission schedule timeline.

The CaNOP mission concept responds directly to NASA's strategic priorities concerning "advancing knowledge of earth as a system to meet the challenges of environmental change, and to improve life on our planet," and to the Strategic Objective to "optimize Agency technology investments and facilitate technology infusion." The CaNOP mission goal is to demonstrate that key functionality of early Landsat science returns can be accomplished at a much-reduced price on COTS components and delivered through an undergraduate training program. The availability of COTS sensors with high spectral resolution will have dramatic impact on climate and earth systems research, as systems are developed to provide on-demand multispectral imaging of global biomass reservoirs for real-time evaluation of carbon sequestration capacities.

The CaNOP program also serves a workforce development role in the state of Wisconsin, the nation's leading repository of climate and earth data. Assuming a project life cycle of two years, data returns of 100 images will provide adequate geographical coverage to observe and quantify both spatial differences in vegetation indices across similar forest canopies and temporal, seasonal changes in forests. Data can be benchmarked against existing Landsat data for longitudinal studies of biomass and carbon capacity.

The CaNOP mission responds directly to the Strategic imperative to “Advance the Nation’s STEM education and workforce pipeline ... to engage students, teachers, and faculty in NASA’s missions and unique assets.” Undergraduate students trained through the CaNOP program will be competitively situated to join the space industry with direct and relevant operational experiences in developing space hardware.

Mission Requirements and Minimum Success Criteria

The minimum success criteria for the CaNOP program are the following:

- Successful deployment of the CaNOP CubeSat into low-eccentricity LEO
- Downlink of satellite status indicators
- Confirmed detumble and satellite pointing data
- Acquisition of 10 location-tagged multispectral data cubes

Table 1 summarizes the broad mission requirements for the CaNOP CubeSat. These will be refined during subsequent design phases. Note that not all properties are independent of one another. The latitude of the proposed ground station at Wallops Flight Facility dictates the orbital inclination requirement of at least 37.9°. A larger inclination would provide imaging opportunities over more geographically diverse sites and so we suggest a nominal inclination of ~51° for the CaNOP mission.

Table 1. Mission requirements for resolving forest canopy differentiation on a 200 m scale.

Orbit Properties	Data Communications	Image Properties	Mission Duration	ADCS Performance
Altitude < 500km	> 0.115 Mbs S-band downlink	GSD < 100 m; Image scale < 200 km	>12 months	1º pointing accuracy
Inclination > 38º Circular orbit	~ 1 data cube downlink/nominal pass	Spectral bandwidth ~ 10 nm	De-orbit in < 5 years	

Concept of Operations

This section outlines the concept of operations for the science phase of the CaNOP mission. Detail for the launch, detumble, and check-out phases will be provided in subsequent design specifications.

The primary mission of CaNOP is to return spectrally resolved images of diverse forest landscapes from a variety of ecological and climatological niches. In order to do so, CaNOP will be launched into a high-inclination orbit. For the purposes of this design reference, we assume a circular orbit of 51º and altitude 400 km as would be provided by deployment from the International Space Station.

Launch to ISS will be provided by NASA/ELaNA and will be in a NanoRacks CubeSat launch container. Until deployment from ISS, CaNOP will remain in the power-down state per CubeSat requirements. Power-on will occur upon deployment from ISS/NanoRacks secondary deployer. Per CubeSat specifications, CaNOP will not execute maneuvers until 30 minutes after deployment, though solar panel voltages will be logged and sensor data will be recorded during this period. At deployment+30 minutes, the flight computer will initiate system checks to ascertain stored energy and thermal environment parameters. If within bounds, the flight computer will initiate de-tumble operations. De-tumble will last for approximately one orbit and will result in the S-band antenna and camera unit in the nadir orientation.

Subsequent to de-tumble, CaNOP will enter a quiescent mode in which only minimal station-keeping operations are active to log temperature and subsystem data, to charge batteries, and to maintain a nadir orientation for the camera and S-band antenna. During this period, based on data from the onboard GPS receiver, the flight computer will calculate the timing for the next pass over a NASA Near Earth Network (NEN) ground station. When in range of a NEN asset, the FC will power on the S-Band Comm system and begin transmission of station-keeping (thermal, power, orientation, subsystem status) and dynamical (orbital position, velocity) data.

Given a successful downlink of initial station-keeping data and an internal “PASS” on subsystem checks, the CaNOP CubeSat will begin its science mission. During the science phase, the CaNOP CubeSat will continue to monitor power and subsystem status, maintain pointing orientation, and monitor proximity to NEN assets. In addition, the FC will compare GPS coordinates with a list of stored image targets (lat/lon coordinates of forests and other features) for image acquisition. When an image target is in daylight and on the orbital track and when power and subsystem status is conducive to camera operations, the CaNOP camera will be brought into standby mode and high-rate GPS data will be logged until the predetermined image acquisition coordinates when the camera will be activated. The camera will acquire data until the predetermined image track coordinates are reached and the camera is returned to standby mode as the image data is processed for storage on the FC's SD card. After image transfer to the FC SD, the camera will be powered down.

As the CaNOP CubeSat returns to a low-power state, the FC will calculate, based on continuous data from the GPS receiver, the next daylight pass over a NEN station and prepare for data downlink. At the next daylight pass over a NEN station, the FC will move the comm system to active, will power down GPS (to save energy), and will downlink the camera data as detailed in subsequent sections.

Illustration for the concept of operations can be found in the form of Figure 2.

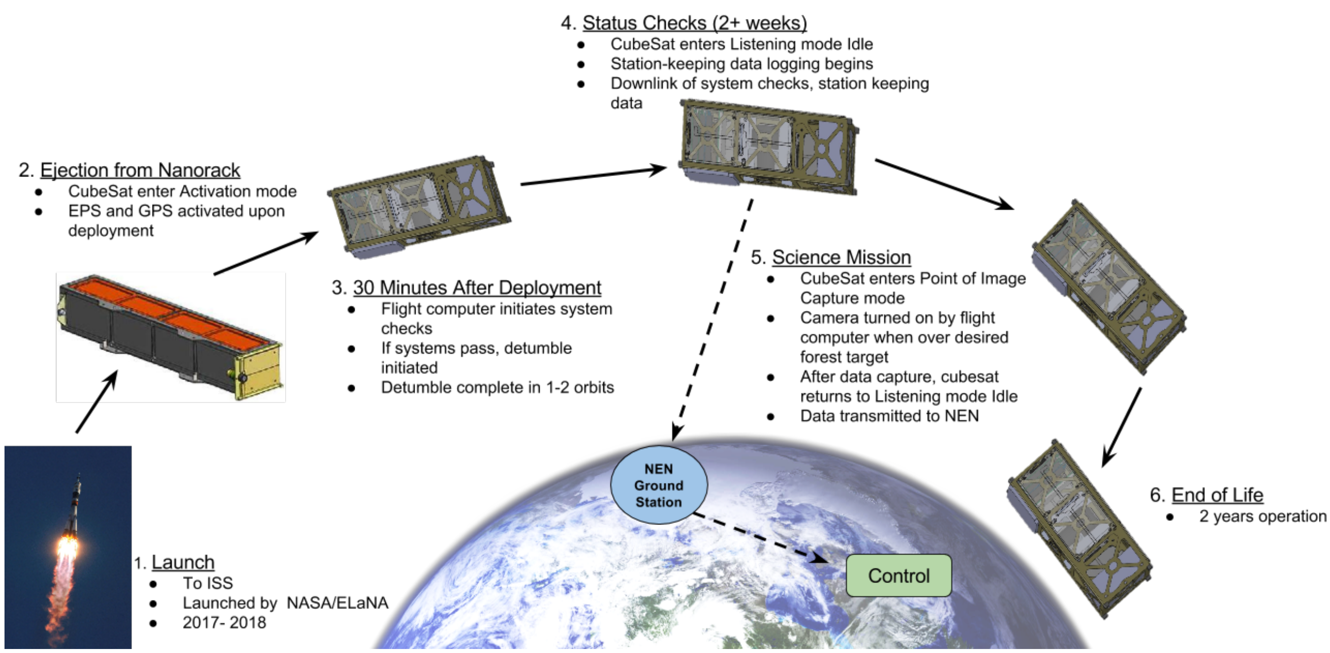

Fig. 2. CaNOP Concept of Operation.

Imaging Targets

This section provides details on the initial image targets selected by the CaNOP team for study.

The following variables were considered when selecting the forests that the CaNOP satellite will target:

- Regional climate
- Weather patterns
- Latitude
- Terrain (mountainous or flat)
- Available history regarding logging/harvesting

Currently, CaNOP has selected three old-growth target forests, as seen in Figure 3 and Table 2, and more will be added to the list from all three forest biomes. The first of these biomes is tropical. Tropical rainforests are located very close to the equator in South America, Africa, and Asia. The next type of biome is temperate, and temperate forests are located in the midlatitudes. The final type of forest CaNOP will look at is boreal forests. Boreal forests are most commonly found in the upper midlatitudes to subarctic.

Table 2. Specifications of the three initial forest targets.

Target Name	**Countries**	**Location (Latitude and Longitude)**	**Total Area**	**Biome**	**Type of Growth**
Los Katíos National Park	Colombia, South America	7°50’30.6”N 77°15’07.6”W	720 km^2	Tropical	Primary
El Caura	Venezuela, South America	6°06'22.4"N 64°42'57.2"W	51,340 km^2	Tropical	Primary
Sangha Tri-National Forest	Central African Republic, Cameroon and Congo-Brazzaville	2°36’34”N 16°33’15”E	7,463 km^2	Tropical	Primary

Los Katíos National Park is located in Colombia, South America and is an equatorial tropical rainforest having an average temperature of 24°C with high temperatures reaching 29°C. This national park has an annual rainfall that averages between 250-450 cm, resulting in a humid climate. The ecology of the area is varied; there are numerous species of both plant and animal life in the forest (Protected Planet, 2015).

Fig. 3. Map of initially selected forests.

El Caura in Venezuela, South America is an equatorial tropical rainforest with a wet season between April to December, and an average rainfall of 81 cm per year. This area has a consistent average annual temperature range of 26°C to 28°C (Protected Planet, 2015).

Sangha Tri-National Forest is an equatorial tropical rainforest situated between the nations of Central African Republic, Cameroon and Congo-Brazzaville. The forest is situated right on the equator, so it has a relatively high average annual temperature range of 24°C to 29°C. The rainy season for the Sangha Tri-National Forest occurs during the months of October to November and May to June. The Sangha experiences a large amount of rain every year totaling 150 cm. The forest is quite dense, so the soil present is incredibly nutrient rich and the surrounding area is abundant with species. (Protected Planet, 2015).

Each of these rainforests are on the United Nations list of protected forests, meaning they have signs of human impact. These forests are under strict conservation policies. Each forest that is on the UN protected forest list is organized into 7 different categories by the International Union for the Conservation of Nature (IUCN). These categories are as follows:

- Category Ia – Strict Nature Reserve,

- Category Ib – Wilderness Area,
- Category II – National Park,
- Category III – Natural Monument or Feature,
- Category IV- Habitat/Species Management Area,
- Category V – Protected Landscape/Seascape,
- Category VI – Protected Area with sustainable use of natural resources.

Los Katíos National Park is listed as a Category II, El Caura is listed as Category VI, and the Sangha Tri-National Forest in the Central African Republic is listed as Category VI and Category II in Cameroon and Congo-Brazzaville.

Science Requirements

In order to meet the science goals of the CaNOP mission, the following top-level requirements are stipulated.

The CaNOP mission must provide spectrally resolved data sufficient to compute three primary vegetation indices as defined below.

Normalized Difference Vegetation Index (NDVI)
The NDVI is computed from spectral reflectance according to *NDVI = (NIR-VIS)/(NIR+VIS).* NIR should be obtained from spectral reflectance data corresponding to the LandSat Thematic Mapper (TM) band TM4 (760-900 nm). VIS should be obtained from spectral reflectance data corresponding to TM bands TM2 (520-600 nm) and TM3 (630-690 nm).

Enhanced Vegetation Index (EVI)
The EVI is an optimized vegetation index that is more sensitive than NDVI to forest canopy structure and Leaf Area Index (LAI). Topographical features do have an effect on EVI (Matsushita *et.al,* 2007). The EVI complements the NDVI and can help differentiate chlorophyll content from environmental influences. The EVI formula is given in Table 3. The MODIS RED band spans 620-670 nm, and the MODIS BLUE band spans 459-479 nm. The NIR band is equivalent to the TM4 band. For the CaNOP mission, we will adopt the MODIS-EVI constants: L=1, C1=6, C2=7.5, and G=2.5.

Photochemical Reflectance Index (PRI)

The PRI measures the response to stress of a plant, tree, or forest, through photo-synesthetic light use efficiency. The PRI is obtained from the spectral ratio of narrow-band reflectances at 531 nm and 571 nm according to $PRI = \frac{(p531 - p570)}{(p531 + p570)}$.

The primary indices discussed above will be used to generate *derived* indices, and to estimate relative carbon content across forests as described below.

Derived Index: LAI
The Leaf Area Index is a normalizing parameter that the CaNOP team will use to establish structural equivalence across different forest canopies. The LAI is defined in terms of the EVI according to $LAI = (3.618 * EVI - 0.118)$.

Derived Index: FAPAR
The spectral band from 400-700 nm is considered to be "photosynthetically active radiation" (PAR) and corresponds to the range of visible wavelengths. The integrated fraction of light across the PAR that is absorbed by vegetation is denoted as FAPAR and is difficult to measure directly but is pertinent to the question of carbon sequestration in forests. We will use existing models of radiative transfer defined in the MODIS operations handbook (REF) to estimate FAPAR from our spectral data.

Gross Primary Production
The GPP is the primary measure of sequestered carbon in a forest. Traditional means of computing GPP rely on both FAPAR and a model-based parameter, known as Light Use Efficiency (LUE). Both the FAPAR and LUE depend on empirical models of the radiative transfer of energy through the canopy of a forest and are quite sensitive to the details of the particular model in use. However, recent research suggests that the correlation between seasonally adjusted EVI and GPP is strong and EVI may be a valid proxy for GPP. The correlation is particularly strong in deciduous forests (Sims, 2006). For this reason, the CaNOP team will rely on EVI as an indicator of GPP.

A summary of the primary and derived indices is provided in Table 3.

Table 3. Definitions of primary and derived indices.

Index:	Formula:
NDVI	$NDVI = \frac{(NIR\ -\ VIS)}{(NIR\ +\ VIS)}$
EVI	$EVI = G\frac{(NIR - Red)}{(NIR\ +\ C1\ *\ Red\ -\ C2\ *\ Blue\ +\ L)}$
PRI	$PRI = \frac{(p531\ -\ p570)}{(p531\ +\ p570)}$
GPP	$GPP = LUE * fAPAR\ * PAR$
LAI	$LAI = (3.618 * EVI - 0.118)$

Spectral Band Requirement

To generate the spectral reflectance indices defined above, the CaNOP multispectral camera should be capable of capturing spectrally resolved images of spatial scale 100 km with spectral bands centered on 450, 530, 570, 680, 750, 830, 900, 970 nm.

Ground Sample Distance Requirement

To ensure sufficient differentiation of land features, the camera should operate such that the GSD is less than 100m at the nominal orbit of 400 km.

Multispectral Imaging

In the following, the design specifications of a nominal pushbroom sensor are used to estimate image properties. The nominal sensor has ~ 2Mpx arranged in a 1000px x 2000px grid. The 2000px side is divided into 8 spectral bands of 250px per band, as shown in figure 4. The sensor must therefore be oriented so that the 8 bands are perpendicular to the velocity vector of the satellite. The cross-track direction is along the 1000px side. Each pixel has characteristic length $d_p = 5.5\mu m$. To minimize the cross-track image scale, a 35mm objective lens will be used in the analysis below.

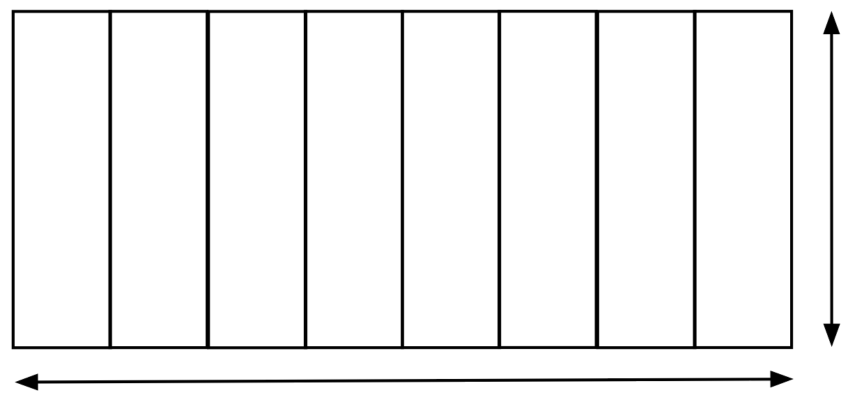

Fig. 4. Pushbroom sensor showing the arrangement of 2 Mpx into 8 spectral bands.

The image properties obtained from a pushbroom sensor moving along a scan track are characterized by the following quantities. The geometry of pushbroom imaging is illustrated in Fig. 5.

Field of View: The FOV(º) is a function of the sensor dimensions and the focal length of the objective lens. Our sensor has dimensions of h_x = 5.93 mm in the cross-track direction and h_y =11.86 mm (11.86/8 = 1.48 mm per band) in the along-track direction. The FOV in each direction is therefore

$$Cross-track\ FOV\ \beta_1 = 2tan^{-1}\ (h_x/2f) = 9.68º$$
$$Along-track\ FOV\ \beta_2 = 2tan^{-1}\ (h_y/2f) = 2.43º/band$$

Swath Width: The swath width *L* is the cross-track image scale on the ground. It represents the width of each strip of image data acquired in a pass over the target terrain. The imaging height is assumed to be the orbital altitude *H = 400 km.*

$L = 2Htan(FOV/2) = 67\ km.$

Ground Sample Distance: The GSD is the ground projected pixel size:

$GSD = d_p \times H/f = (5.5x10^{-6}m)\times(400\times10^3 m)\ /\ (35\times10^{-3}m) = 63\ m.$

Instantaneous Field of View: The IFOV measures the angular image cone of a single pixel and is given by

$$IFOV = GSD/H = 157\ \mu Radians\,.$$

Dwell Time: The dwell time is a measure of the time each pixel is exposed to a terrain feature and is related directly to the signal-to-noise ratio for the imaging process. For a pushbroom sensor, the dwell time is related to the GSD and the orbital velocity V. At 400 km, the orbital velocity V= 7.67 km/sec.

$$t_d = GSD/V = 63\ m/(7.67{\times}10^3 m/s) = 8.2\ msec.$$

A dwell time of 8.2 msec suggests a shutter time of 8.2 msec, which is within the capabilities of the camera unit under consideration for the CaNOP mission.

To estimate the image size in bytes of a strip of imaging data obtained under the conditions derived here, we consider a frame rate of 1 exposure per band - that is one exposure in the time it takes the sensor to move a distance of 250 x GSD = 15.75 km. The along-track FOV is 19.2º, which provides a total exposure track of 136 km. The actual ground pixel coverage is 126 km (for a GSD of 63 m). The cross-track image width is *L* = 67 km for an area of 9112 km^2. Let us assume 8 exposures across the 2 Mpx sensor in the 16.4 seconds required for each band to pass along 126 km of the track. At 10 bits/pixel, the data acquired along the imaging track is (8 exposures) x (10bits/px) x ($2{\times}10^6$px) = $1.6{\times}10^8$ bits = 20 MB.

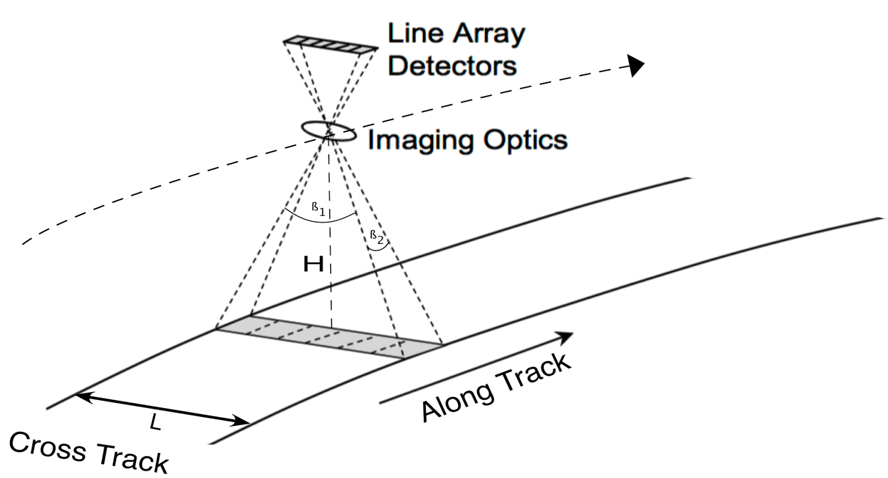

Fig. 5. Pushbroom imaging geometry.

The corresponding image area for a target near Los Katios National Park in Antioquia, Colombia is illustrated in Fig. 6.

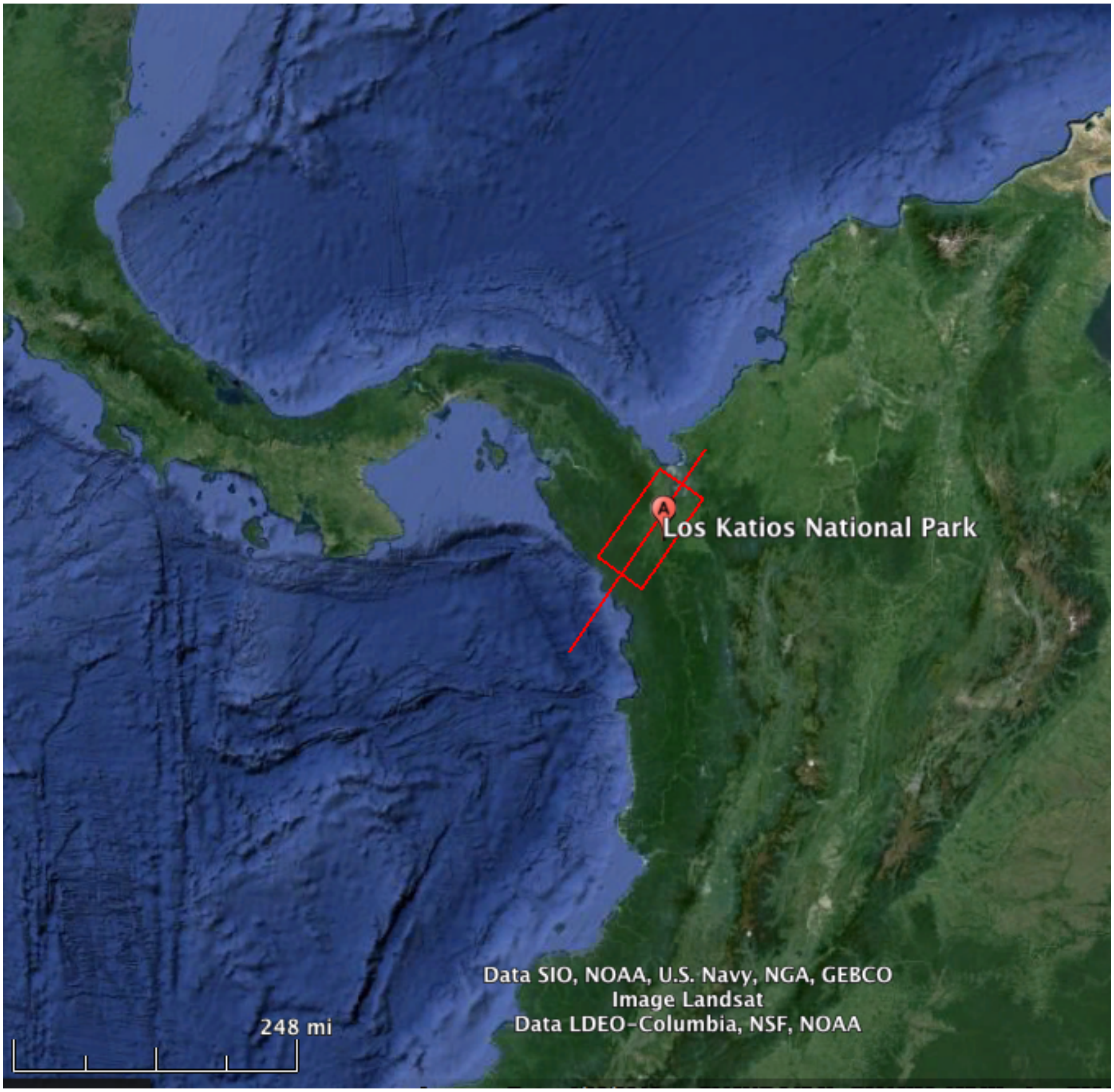

Fig. 6. Image swath of width 67 km and length 136 km along an orbital pass over Los Katios National Park, Columbia.

Hardware Conceptual Design

Design Overview

The CaNOP hardware will be a 3U CubeSat with a nadir-facing multispectral pushbroom imager and a nadir-facing S-Band patch antenna. De-tumbling and active attitude determination and control will be via an onboard ADCS using both momentum flywheels and magnetorquers. Spacecraft orientation information will come from onboard earth horizon sensors.

The CaNOP CubeSat will be powered by a Clyde Space distributed Electrical Power System (EPS) that will provide two regulated DC bus voltages at 5V and 12V. The choice of EPS is dictated by NanoRacks deployer requirements. The EPS will provide 40Wh of backup battery support for eclipse operations and will be fed by side-mounted solar panels with seven Spectrolab UTJ solar cells in the 7S1P configuration per 3U face. A Functional Block Diagram for the CaNOP hardware concept is shown in Fig. 7.

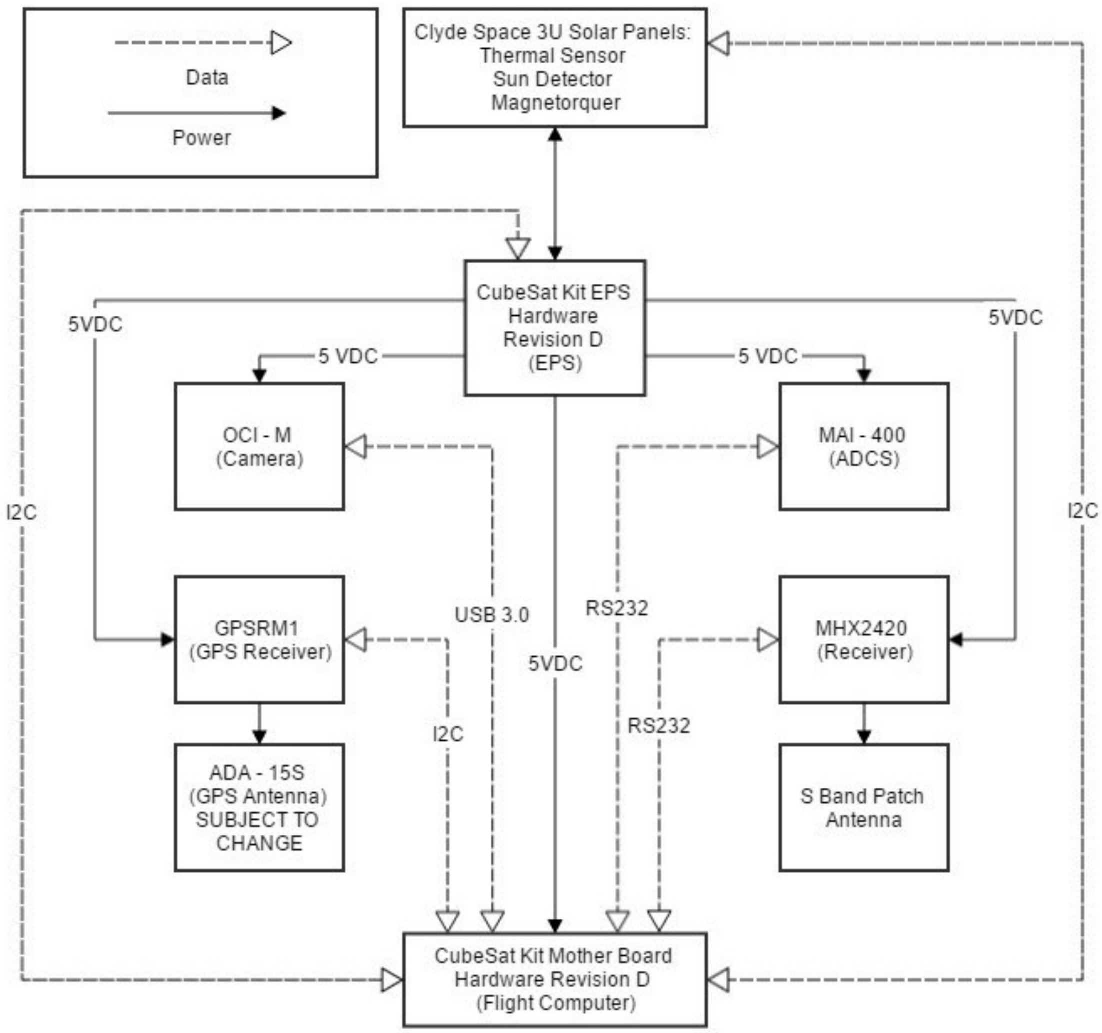

Fig. 7. Functional Block Diagram for the CaNOP CubeSat concept.

Subsystems

Structures

Structural Requirements:

- The structural envelope of the CubeSat shall conform to the 3U specifications described in the CubeSat Design Specifications document.
- The center of mass of the CubeSat shall be within 2 cm of the geometric center.
- The total mass of the CubeSat shall be less than 4 kg.

- The structural envelope of the CubeSat shall conform to the NanoRacks Deployer specifications.
- The CubeSat shall have no deployable elements.
- The CubeSat structural elements shall be constructed from space-grade materials.

The structural envelope of the CubeSat conforms to the 3U specifications as described in the CubeSat Design Specifications Document. The outer dimensions for the payload structure will be 10 cm x 10 cm x 34.05 cm. All measurements are within +/- 0.1 mm. Hardware will not protrude from the structure more than 6.5 mm from any side. The skeleton selected to structure and house satellite components is the Clyde Space 3U design. This is constructed from Aluminum 6082-T6, while the rods within the skeleton are constructed from Titanium Ti-6Al-4V. An exploded view of all the components is illustrated in Fig. 8.

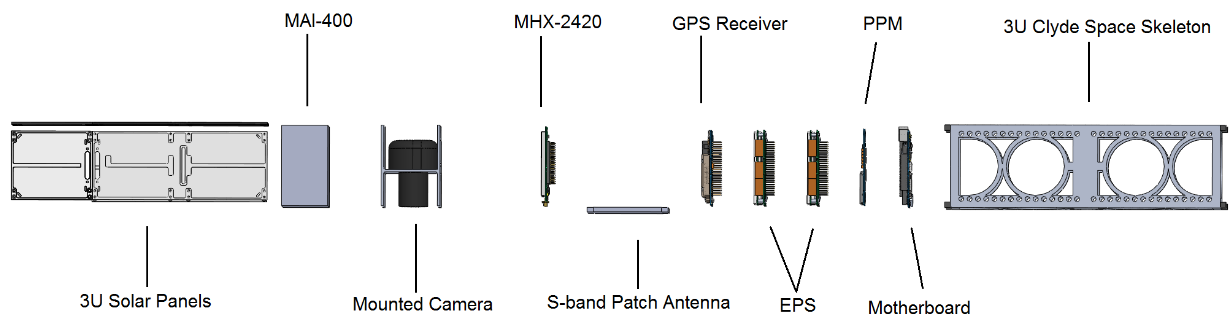

Fig. 8. Exploded view of components

The EnduroSat S-Band Patch Antenna Type I will be mounted to the nadir-facing side of the CubeSat. The antenna utilizes a nearly squared slanted form of the patch. The GPS patch antenna we will be utilizing is the Adactus ADA-15S. The GPS receiver we have selected is the Pumpkin GPSRM 1. The processor we will be utilizing is the PIC24FJ256GA110. The modem we will be utilizing is the Microhard Systems Inc. MHX-2420. The flight computer we have selected is the Pumpkin Single Board Computer Motherboard (MCU). The weight of each component in the structure is shown in table 4.

The BaySpec OCI™-M Hyperspectral Camera and its mount will take up 1U of space in the center of the CubeSat, with the aperture facing nadir (-y face). There will be a 3U solar panel mounted to the +x face and +y face. A 2U panel will be mounted to the -x face. The electrical power system we will be utilizing is the Pumpkin Linear EPS. The MCU, PPM, EPSs, GPSRM, and MHX-2420 will all be housed on the +z end of the CubeSat. The ADCS we will be utilizing is the Maryland Aerospace MAI-400. It will be housed at the -z end of the structure. This will take up ½U of space. This includes a magnetometer, which must not be within 12.7 cm of the ADCS unit. Two horizon sensors will be on the -z and -x faces. The pointing accuracy of the ADCS is .2 degrees.

The complete hardware concept is illustrated in Fig. 9.

Table 4. Component Masses.

Component	Mass (g)	Number of components required	Dimensions (mm)
3U skeleton	394.38	1	100 x 100 x 340.5
MAI-400	694	1	97 x 97 x 55.9
GPS Receiver	106	1	96 x 90 x 1.6
GPS Antenna	4 +/- 0.5	1	15 x 15 x 6
EPS	80	2	96 x 90 x 1.6
MHX-2420	55	1	89 x 53.4 x 17.8
MCU, PPM, & MHX connector	103	1	MCU: 96 x 90 x 1.6 PPM: 54.6 x 89.5 x 1.6
Camera	180	1	80 x 60 x 60
S-Band Antenna	64	1	98 x 98 x 5.59
3U solar panel	150	2	98 x 298 x 5
2U solar panel	100	1	98 x 198 x 5
Camera Mount	218.28	1	70 x 97.46 x 97.46
Total mass	**2236.0**		

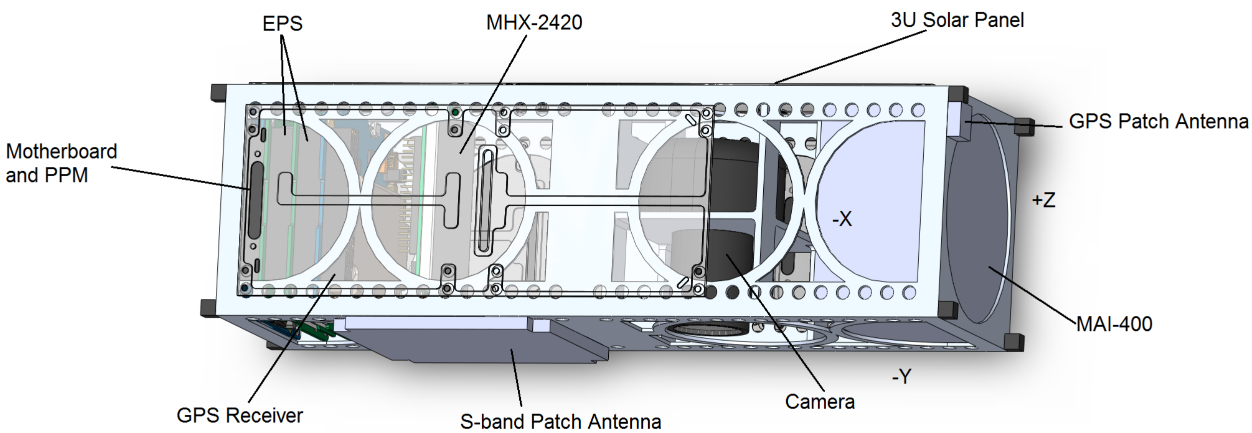

Fig. 9. Full assembly with coordinate planes identified.

Flight Computer/Software

Requirements:

- The flight computer shall operate all hardware of the CaNOP.
- The flight computer shall be composed of space grade material.
- The flight computer shall have space heritage.
- The operating system shall be an RTOS capable of operating with minimal memory.
- The flight computer shall communicate with the ground network via an S-Band radio antenna and transmitter.
- The flight computer shall control the camera.
    - The flight computer shall be able to operate a heater for the camera if necessary.
    - The flight computer shall power on the camera when necessary.
    - The flight computer shall operate the camera to capture hyperspectral data as programmed.
    - The flight computer shall receive and store the hyperspectral cube data produced by the camera.
- The flight computer shall control the ADCS.
    - The flight computer shall power on the ADCS when necessary.
    - The flight computer shall operate the ADCS to de-tumble upon activation.
    - The flight computer shall operate the ADCS to orient the CaNOP CubeSat into the proper position for the camera to capture data.

    - The flight computer shall operate the ADCS to orient the CaNOP CubeSat into the proper position for the antenna to transmit and receive data.
- The flight computer shall be able to read from the GPS system.
    - The flight computer shall be able to determine when to take a picture based on the GPS data.
    - The flight computer shall be able to determine when to downlink data based on the GPS data.
- The flight computer shall read in data from secondary sensors to determine orientation, and whether or not it is in day/night.
- The flight computer shall perform error checks.
    - Upon deployment the flight computer shall be able to run a systems check to ensure that all hardware is functioning properly.
    - The flight computer shall ensure the CaNOP CubeSat does not attempt to overuse power.
    - The flight computer shall keep logs of the results of the system checks.

Flight Software operates the hardware and is referred to as the operating system of a computer. The RTOS will have space heritage and will have minimal memory footprint. The RTOS has no other functionality other than to run the subsystems on the CubeSat.

Drivers on the operating system are utilized in running the subsystems. There will be a driver for each subsystem connected to the motherboard. The subsystems will require USB or another type of Serial Data Communication to “talk” with the motherboard. These act as channels of communication between the motherboard and the subsystems.

The software needs to be able to start a timer for thirty minutes upon deployment. When the timer ends it will run a systems check. It will de-tumble upon successful completion of the checks. When the CubeSat reaches a target location, has power, and is in the sunlight it will prepare the camera and orient itself towards the target. When the appropriate time is reached, it will operate the camera and capture the data. After the data is received it will be prepared for a downlink. The software will then wait for a downlink opportunity. Once it receives a handshake from a NEN station, CaBOP will begin to transmit data. A handshake is confirmed when the CubeSat sends out a ping and the NEN ground station responds with an acknowledgment ping. If it does not complete the transfer before leaving the range of the NEN station, it will wait until it can make contact with another again. This will repeat until the transfer is complete and the downlink is confirmed. Once the downlink is confirmed it will idle, performing system checks after pre-determined amounts of time.

Throughout the flight, the software will monitor power usage. If a subsystem is not operated in a given mode, it will be placed in idle or powered down. If after a power-intensive task is completed, and the battery is below an identified threshold, the CubeSat will be idled (except for attitude control) until the battery charge is above the low charge threshold.

Operational Modes

The flight software will define a finite number of operating modes that will consist of well-defined power profiles, hardware actions, and exit conditions. Each mode is discussed in broad terms here and illustrated in Fig. 10. Details on mode definitions will be provided in the PDR.

Mode 1

The first mode that the CubeSat will be in is Activation Mode (AcM). AcM occurs right after the deployment of the CubeSat from the NanoRacks launcher. The flight computer will start a timer for 30 minutes upon deployment, after this timer reaches zero an extensive set of systems checks will occur to ensure that all of the equipment is functioning and responding correctly.

Mode 2

If a system is not functioning correctly the CubeSat will enter Fail-Safe Mode (FSM) where it will retry checks on the systems that failed the initial check. If possible the subsystem will be rebooted. During FSM the CubeSat will log all possible data and attempt to transmit these logs to the ground. If the CubeSat can finish the AcM sequence without critical errors, it will proceed to turn on the ADCS and stop the tumble of the CubeSat.

Mode 3

After the CubeSat has been oriented it will enter Listening Mode Idle (LMI) where it will be awaiting either a point where it is over a target, or a downlink opportunity. While in LMI the CubeSat will run system diagnostics at constant intervals. It will attempt to downlink these diagnostic logs when it is in the sunlight, within range of a ground station, and has sufficient power.

Mode 4

When approaching a target and the CubeSat has power and is in the sunlight the CubeSat will enter Point of Image Capture mode (PIC) where it will make any orientation adjustments using the ADCS and prepare the camera by powering down any non-essential systems.

Upon arrival it will then power the camera and take the picture. The data from the picture will then be stored on the SD card in the motherboard and the camera will be powered down or placed in idle. It will then run a systems diagnostic test and record its results. After this the CubeSat will enter LMI.

Mode 5

The CubeSat will remain in LMI until a downlink opportunity is presented, then it will enter Downlink mode (DLM) . During this stage the CubeSat will be sending out a constant ping towards the ground station looking for acknowledgment . When the connection is successful the CubeSat will begin to transmit the hyperspectral cube data in packets. After the data is transferred the CubeSat will await a confirmation from the ground station that the files were received. If the CubeSat leaves the range of the ground station before the transfer is complete, it will re-enter LMI and wait for another downlink opportunity, where it will start transmitting from where it left off. Then the CubeSat will then attempt to downlink (using the same steps) the diagnostic log that was generated in PIC. When completed it will enter LMI.

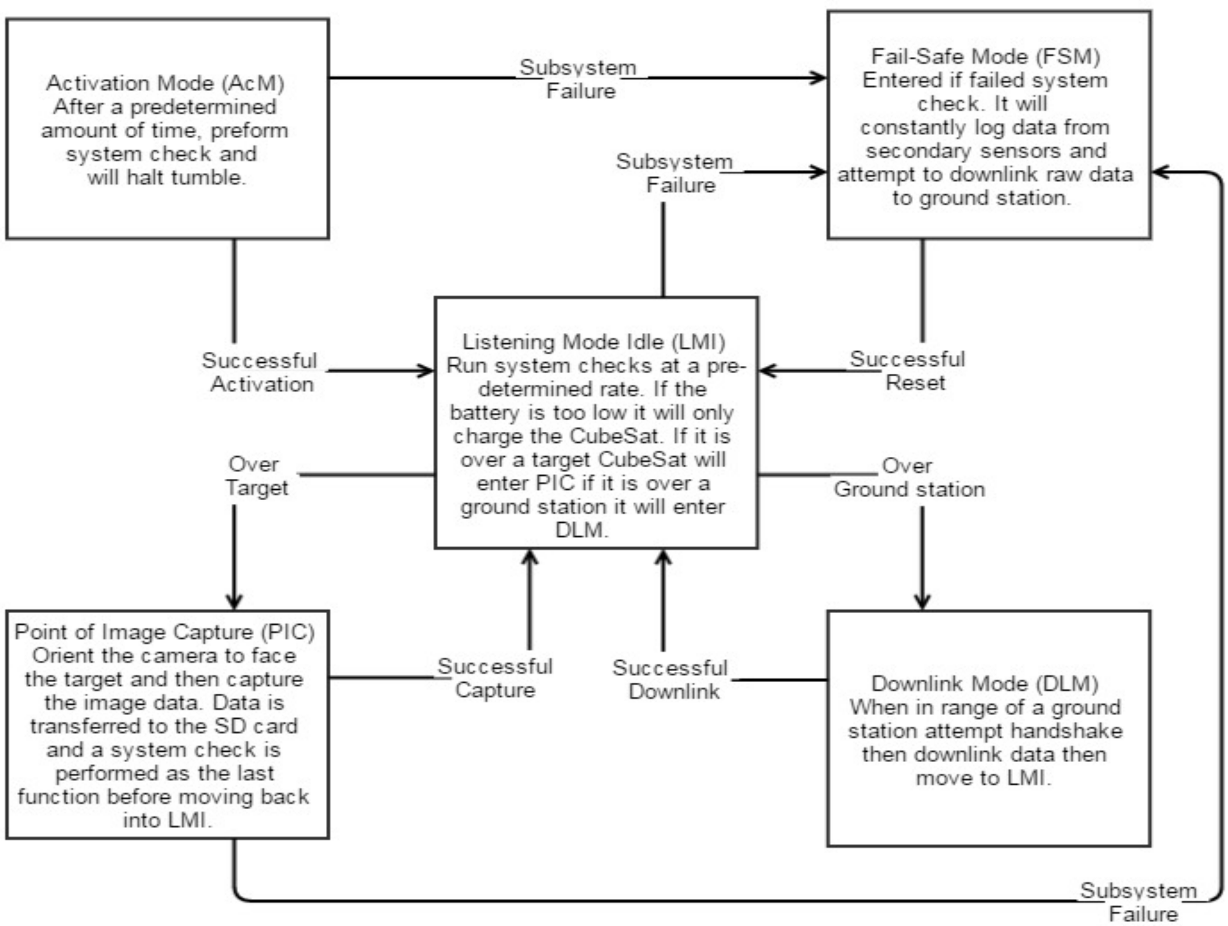

Fig. 10. Software Mode Chart.

The tasks of the software will be broken down first by subsystem, then by the goals of the subsystem, and then as needed into functions by workload. Each function will be created and tested independently to ensure quality and to facilitate debugging of the code. Functions will be delegated to team members whose skills best fit the needs of the function. They will then ensure the proper interfacing of this function with the software program as a whole.

Standard error checking and data validation algorithms will be incorporated into the code in critical functional areas.

Camera

Objective: Utilize a hyperspectral camera to analyze forest regions that, while small in size, will provide the highest quality spectral data cube possible in order to capture precise and accurate data.

Camera Requirements:

- The camera shall be a hyper spectral imaging camera with a minimum of 8 spectral bands across the visible and NIR.
- The camera's spectral bands shall have 5-10 nm bandwidth.
- The camera shall be capable of resolving spatial scales of <100 m from orbit.
- The camera sensor shall be capable of GSD <100 m.
- The camera shall draw no more 4 W of power during operation and shall have an idle power draw of less than 0.7 W.
- The camera shall be entirely contained within a 1U volume.
- The camera shall be activated by a command from the flight computer.
- The camera shall be thermal vacuum tested, in compliance with NASA. regulations for outgassing of materials.
- The camera shall produce hyper spectral cube data that can be compressed using standard algorithms.
- The camera shall use a standard data protocol for the data cube transfer to the flight computer.

The camera is a key component to this project as data cannot be collected without its proper alignment in orbit and calibration. The camera must be able to detect at least 8 spectral bands in order for sufficient data. Each line will detect a different electromagnetic frequency. Each pixel will contain each of the 8 electromagnetic frequencies that we have chosen.

The optical system will be a pushbroom scanner. As the satellite moves, the view plane must be perpendicular to the direction of motion (Hartley, 2015). A linear array of sensors will capture data in the form of a hyperspectral cube (spatial data cubes stacked in spectral bands) to be later transferred to the ground using the MHX-2420 transmitter. As it flies over the desired area each line of pixels captures the intensity of a different wavelength of light, as illustrated in Fig. 11. Each line of pixels is imaged simultaneously and separated into different spectral components before its data reaches the sensor array (Hyspex, 2016). This permits simultaneous acquisition of all spectral bands. Another option is a Whiskbroom sensor. Whiskbroom sensors utilize mirrors to reflect light into a single detector. Using a pushbroom sensor will be more advantageous than a whiskbroom. The pushbroom sensor weighs less than a whiskbroom and is more mechanically stable. Additionally, the pushbroom is able to acquire more light because it hovers over each area for longer period of time.

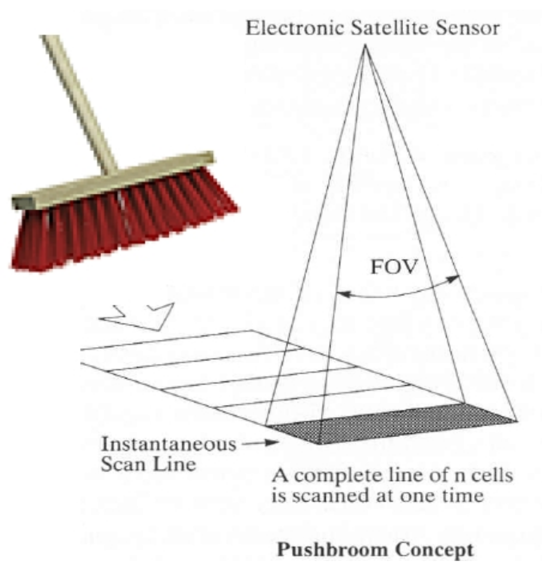

Fig. 11. Pushbroom sensor (Shippert, 2013)

Our current camera preference is the OCI™-M Hyperspectral Camera sold by BaySpec, Inc. (Fig. 12). It is designed for unmanned aerial vehicles such as a CubeSat. The camera unit is 6 cm wide and 8 cm tall, fitting into our required space of 1U. The camera's total mass is 180 grams. The camera has automatic data capturing and processing (BaySpec, 2014). The focal length meets the requirement of 35mm. The camera's dwell (calculated in Table 6, with corresponding formula in Table 5) time at an altitude of 400 km is approximately 8 msec per pixel.

Fig. 12. OCI-M Hyperspectral Camera (Bayspec, Inc.)

Table 5: Camera Formulas. H is orbital altitude.

Index:	Equation
IFOV (mrad)	$\frac{FOV\ (°)}{\#\ of\ pixels} \times \frac{\pi}{180°} \times 1000$
Spatial Resolution (m)	$pixel\ size\ (\mu m) \times 1000 \times\ tan\ (\frac{IFOV\ (mrad)}{1000})$
Ground Sample Distance	$\frac{pixel\ size \times altitude}{focal\ length}$
Scan Width	$L = 2Htan(FOV/2)$
Dwell time (seconds/pixel)	$\frac{GSD}{Orbital\ Velocity}$

Table 6: Camera Data and Calculation Results.

Pixel Size (µm)	5.5
Image Length (pixels along track)	2048
Image Width (pixels across track)	1024
Focal Length (mm)	35

IFOV (mrad)	0.157
Cross-track Scene Size (km)	125.7
Ground Sample Distance (km)	63 m
Spectral Resolution (nm)	<5 (for OCI-M)
Dwell Time (seconds/pixel)	0.0083
Shutter Speed (ms)	300

To calculate the time it takes to fly over a particular area of a forest, dwell time is divided by GSD and multiplied by the length of the forest area. If the area is 200 km long, the CaNOP satellite will take approximately 26 seconds to fly over the region.

Definitions:

Scene Size - Scene size is a measure of the distance between the edges of an image, representing the dimension of the image if it were projected onto the Earth's surface.

IFOV (Instantaneous Field of View) - This is a calculation of how much a pixel can see in terms of FOV. The higher the IFOV, the more that will be seen in the image.

FOV (Field of View) - FOV is the angle describing the area that can be observed at any given moment. The larger the angle, the bigger the size of the observable area.

GSD (Ground Sample Distance) - The center-to-center distance of adjacent pixels as projected onto the ground. Larger GSDs have lower spatial resolutions.

Spectral Resolution - The ability to differentiate wavelength intervals and bands into different components. The lower the resolution the more sensitive the system is.

Spectral Bandwidth - The width of the band of light at one half the peak maximum.

Dwell Time - The period of time a sensor has to collect photons from a ground resolution cell.

ADCS

The Attitude Determination and Control System will provide primary orientation information and will include momentum storage and magnetic torquers to adjust the orientation of the CubeSat. An example of a CubeSat ADCS unit is shown in Fig. 13.

ADCS Requirements:

- The ADCS shall de-tumble the CubeSat within a few revolutions.
- The ADCS shall determine the orientation of the CaNOP CubeSat.
- The ADCS shall orient the CaNOP CubeSat with 0.2° pointing accuracy.
- The ADCS shall maintain the orientation of the CaNOP CubeSat with 0.2° pointing accuracy using less than 1.73 W-h per orbit.
- The ADCS shall provide software interface for the CaNOP flight computer.
- The ADCS shall not exceed a mass of 1kg and a volume of 0.5U.
- The ADCS shall have space flight heritage.

Fig. 13. MAI-400 MiniADACS (Maryland Aerospace Inc.).

The ADCS provides and maintains stability and desired orientation for the CubeSat, having the camera and spectral band facing the nadir. Figure 13 shows the ADCS that is being investigated by the CaNOP team is Maryland Aerospace Inc.'s MAI-400 MiniADACS. The system is a 0.5U device with two horizon sensors (Fig. 14), one magnetometer, three momentum wheels, and three electromagnetic torque rods.

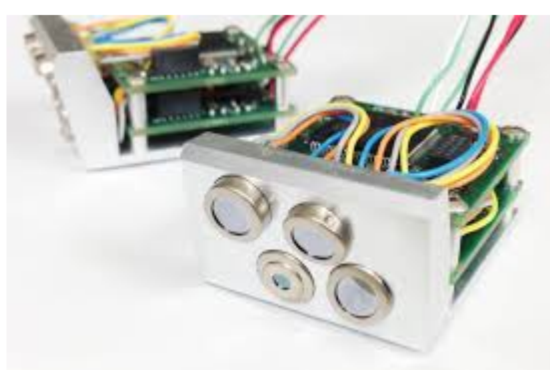

Fig. 14. IR Earth Horizon Sensors (Maryland Aerospace Inc.).

The Static IR Earth Horizon Sensors can partially determine the orientation of the CubeSat through location of the Earth in its relation to the CubeSat. Four thermopile sensors in the IR Earth horizon sensor --three narrow (7° FOV) and one wide (60° FOV) field-- are positioned to detect IR light and locate the Earth's horizon. These readings from the thermopiles will be compared to certain types of light regions: a dark (space), a bright (Earth), and a region with a medium IR brightness (the horizon). Figure 15 shows a visual example of the readings that the horizons sensors will produce. Once the location of the horizon is established, sun sensors from the solar panels can determine the yaw of the CubeSat. When combined, the orientation of the CubeSat can be determined.

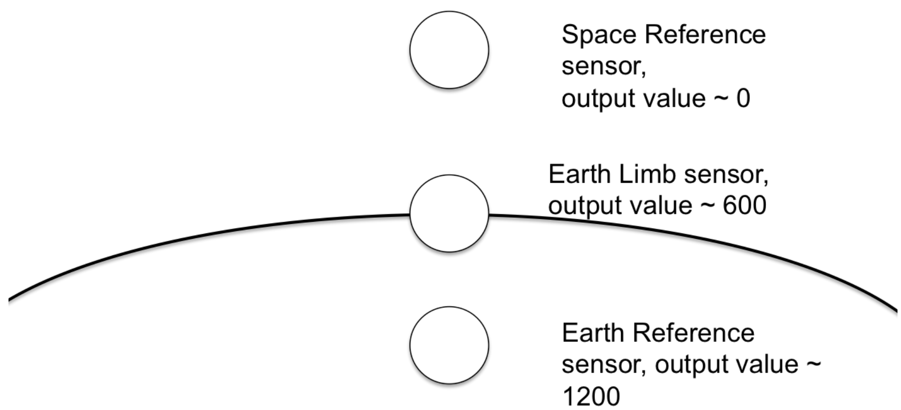

Fig. 15. Differential Thermopile Concept at Zero degrees.

There are constraints surrounding the horizon sensor placement in order to achieve the necessary 0.2° pointing accuracy for the CubeSat. The constraints are that the horizon sensors are not independent of the ADCS and they have to be orthogonal to each other with both having the Earth partially within the sensor's FOV. The CaNOP CubeSat structure has the ADCS on the + z end. Due to structural designs the horizon sensors will be facing the - x and + z directions within the ADCS base.

The magnetometer operates through sensing the Earth's magnetic field. Figure 16 shows the magnetometer and the coordinate frame for the sensor provided by the MAI-400.

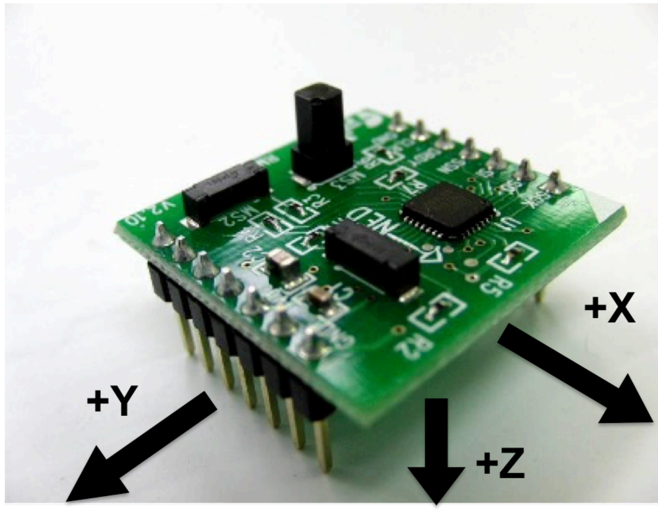

Fig. 16. RM3000 Magnetometer.

A magnetic field drops in intensity with the cube of the distance from the object. The vector magnetometer can detect the magnetic flux, measuring one or more components of the magnetic field at the location of the sensor. With the measurements, the system can determine the attitude of the CubeSat based on the Earth's magnetic field. Complications arise with the magnetometer measurements due to Earth's magnetic field not being constant. The sensor will have to receive data provided by the GPS in order to determine the magnetic field at the location of the CubeSat to accurately sense attitude. Another complication with the accuracy of the magnetometer is its sensitivity to magnetic interference from the other components of the CubeSat. The magnetometer provided by the MAI-400 is specifically required to be placed at least 12.7 cm away from the MAI-400 and other sources of magnetic interference.

The MAI-400 has three momentum wheels and three electromagnetic torque rods that control the orientation of the CubeSat. The momentum wheels are masses that are spun to apply a torque to the CubeSat. The momentum wheels are actuated by brushless DC motors. The principle of conservation of angular momentum is applied by the momentum wheels. The momentum wheels continue spinning to concentrate the angular momentum within the wheels rather than the CubeSat. In order to produce the necessary torque to de-tumble, the initial ejection from the NanoRacks, and reorientation of the CubeSat, the wheels will be accelerated in the opposite direction of the desired applied torque.

Electromagnetic torque rods assist the momentum wheels by producing a magnetic field and creating a magnetic dipole. A torque is produced that aids in the orientation of the CubeSat when the rod's magnetic dipole is oriented to have a nonzero cross product with the magnetic dipole of the Earth. The electromagnetic torque rods can also desaturate and transfer the angular momentum from the momentum wheels to the Earth's geomagnetic field as a massive external reference. This allows for the momentum wheels to be brought to a near-idle state, with a significant reduction of power consumption by the ADCS.

While it is difficult to predict the torque necessary to de-tumble the CubeSat at this point in development, the MAI-400 User Manual suggested that the tip-off rates upon launch will be at maximum 5° per second. The de-tumbling should take a “few” revolutions to reach a steady state rate of below 0.2° per second. More precise measurements will be found when more factors can be taken into account.

Power

Objective: The Power subsystem will consist of the Electrical Power System (EPS) and the Solar Panels. These must be able to provide enough power to critical systems during each operational mode of the CubeSat. If the solar panels are unable to provide enough power to complete a task, batteries must provide the necessary power. The solar panels will cover three sides, and will each be three units in length on the outside. If necessary, one of these can be reduced to 2U to accommodate horizon sensors.

Requirements:

- The solar panels shall be capable of providing more than enough power for the system when idle in direct sunlight, so that it can charge the batteries for periods of eclipse.
- The EPS shall provide telemetry data on its status, along with the status of the solar panels and the energy stored in the batteries.
- The EPS shall include an interface for integration with an RBF pin and other activation triggers.
- Battery capacity shall be large enough to provide necessary excess power, and must be able to safely sustain the CubeSat during eclipse.
- The EPS must be able to source enough current during maximum power consumption.
- The EPS and Solar Panels allow for one 2U solar panel to accommodate the horizon sensors of the ADCS

Power Budget: Tables 7 show power consumption by each system during each mode.

Table 7a: Power and Energy for Mode 1, Activation and De-tumbling.

Sub System	**Mode 1a Wait Period (W)**	**Mode 1b De-Tumbling (W)**	**Mode 1c System Checks (W)**
Micro Controller	0.066	0.066	0.066
ADC	0.87	8.47	0.87
GPS and antenna	1.5	1.5	1.5
MHX 2420	0.001	0.001	0.001
Camera	0.7	0.7	0.7
Total Power (W)	**3.14**	**10.7**	**3.14**

Table 7b: Power for Mode 2, Idle Mode.

Sub System	**Mode 2a Idle Mode (W)**	**Mode 2b ADCS Maneuver (W)**	**Mode 2c System Checks (W)**	**Mode 2d Charging (W)**	**Mode 2e Eclipse Heating (W)**
Micro Controller	0.066	0.066	0.066	0.066	0.066
ADC	0.87	8.47	0.87	0.87	0.87
GPS and antenna	1.5	1.5	1.5	1.5	1.5
MHX 2420	0.001	0.001	0.001	0.001	0.001
Camera	0.7	0.7	0.7	0.7	0.7
Total Power (W)	**3.14**	**10.7**	**3.14**	**3.14**	**3.14**

Table 7c: Power for Mode 3, PIC Mode.

Sub System	**Mode 3a ADCS Maneuver (W)**	**Mode 3b Taking Pictures (W)**
Micro Controller	0.066	0.066
ADC	8.47	0.87
GPS and antenna	1.5	1.5
MHX 2420	0.001	0.001
Camera	0.7	4
Total Power (W)	**10.7**	**6.44**

Table 7d: Power consumption for Mode 4, Downlink Mode.

Sub System	**Mode 4a Handshaking Attempt (W)**	**Mode 4b Downlinking (W)**
Micro Controller	0.066	0.066
ADC	0.87	0.87
GPS and antenna	1.5	1.5
MHX 2420	5	5
Camera	0.7	0.7
Total Power (W)	**8.14**	**8.14**

While simulating power consumption during idle mode (2a) and eclipse mode (2e), there was a simulated net gain in stored energy of 0.72 W-h per orbit, as seen in Figure 17. While this simulation assumes ideal solar panel alignment with the sun, future simulations will be performed using STK and Princeton Satellite Solutions simulation software to ensure an accurate energy budget. Trade studies will determine the final power requirements during each mode.

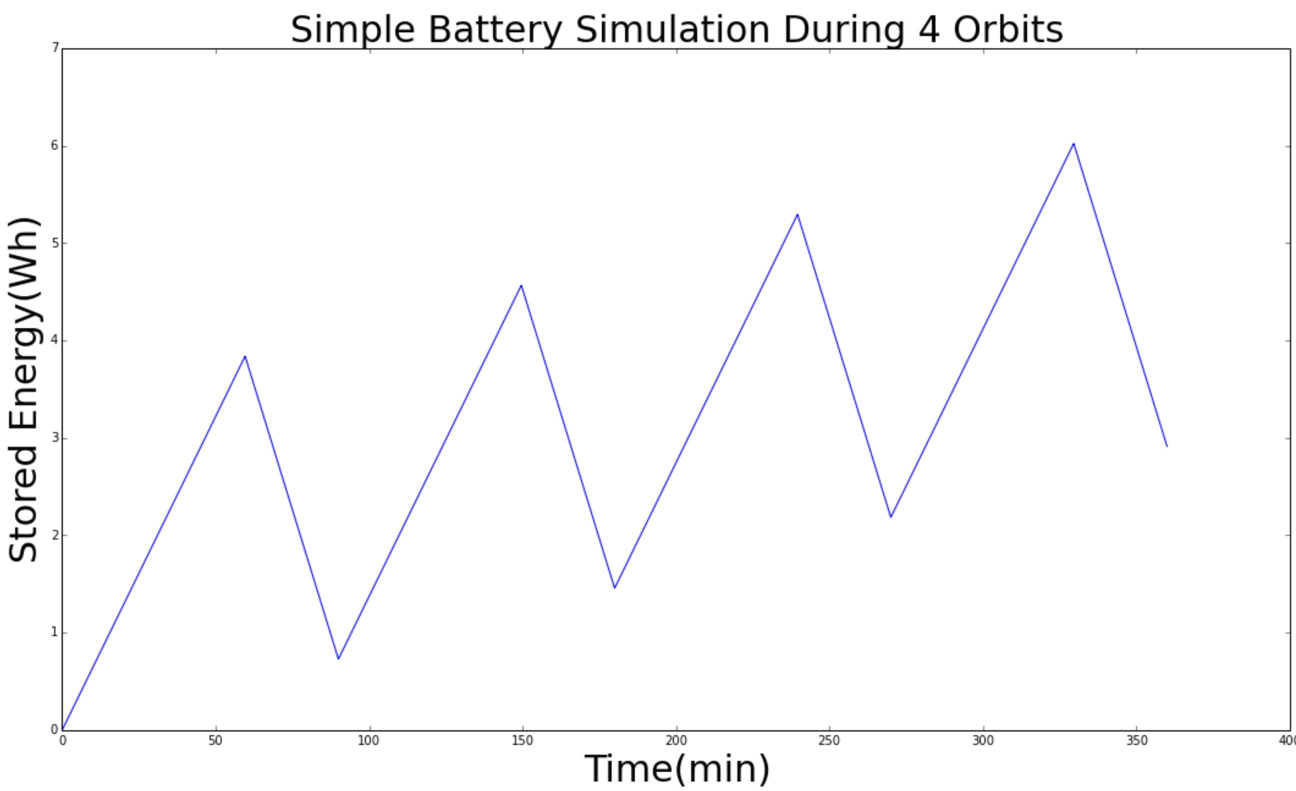

Fig. 17. A simulation of stored battery energy switching between mode 2a when in sunlight and mode 2e when in eclipse.

Transceiver

Objective: To transmit hyperspectral data cubes that come from BaySpec OCI™ - Hyperspectral camera to NASA's Near Earth Network (NEN).

Requirements:

- The transceiver shall transfer and transmit two to three hyperspectral image cubes weekly to NASA's NEN ground stations.
- The transceiver shall include a radio transmitter that has a 2.4 GHz transmission frequency range for S-Band downlink.
- The transceiver shall include a radio receiver capable of receiving S-Band transmission commands and messages coming from ground station.
- Communications system shall be able to relay hyperspectral images within a satellites passing range.
- The radio transmitter and receiver shall be capable with interfacing with several flight components, including flight computer.
- Radio transmitter shall be able to operate and transmit at the orbital location of 400 km above the Earth.

In order to transmit hyperspectral data cubes, CaNOP will utilize the MHX-2420, a radio transmitter that has a transmission frequency of 2.4 GHz. This frequency range can often be called *S-Band transmission* and is a common receiving frequency for ground stations in NASA's Near Earth Network (NEN). Likewise in communication systems, CaNOP must also have a way to receive information for command handling protocols. CaNOP will utilize the S-Band Patch Antenna provided by EnduoSat, which features a frequency range of 2.3-2.5 GHz. Downlink and uplinking information will be heavily reliant on GPS and mission planning; ground station transmitters will uplink information regarding best location for CaNOP to make a "data dump".

Through Systems Tool Kit (STK) mission simulations,as seen in Fig.18 our team can accurately gauge how long CaNOP has to transmit according to its position relative to a NEN ground station receivers. We will not be capable of downlinking during the entire hatched areas. In the PDR we will have a more accurate representation of downlink opportunities.

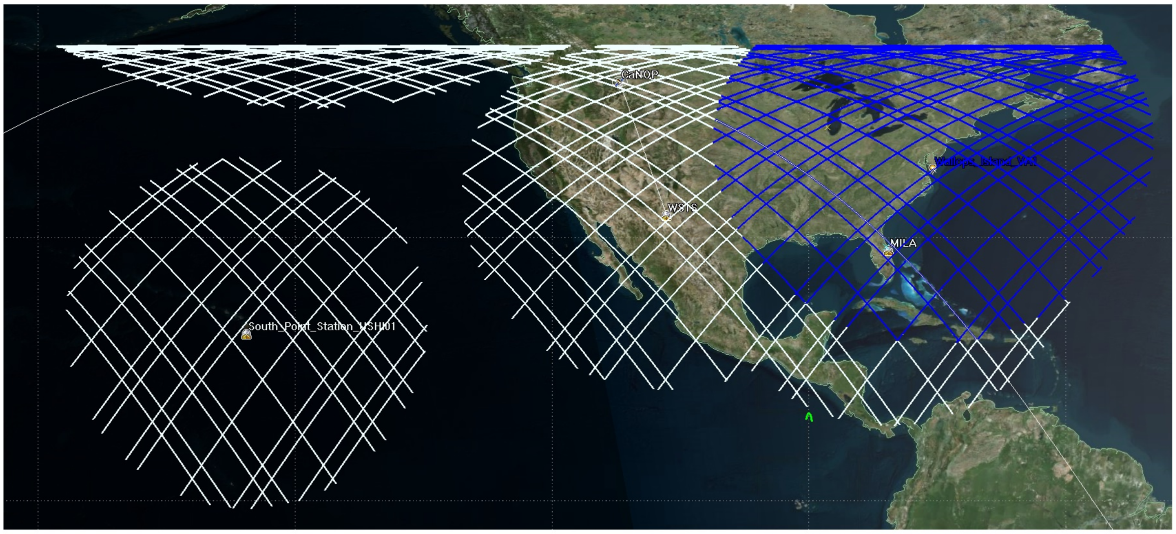

Fig. 18. STK simulated downlink opportunities over a 5-day period. Hatched patches represent line-of-sight downlink opportunities with NASA NEN ground stations.

Link Budget

In order to calculate the received power at the ground station we use the link equation, $P_{received} = EIRP + G_r - Losses$ (Langton, Charan 1998). Here the EIRP is the Equivalent Isotropic Radiative Power, which represents the transmit power plus the gain of the transmitting antenna. The other terms in the link equation are identified below.

$$EIRP = P_t + G_t$$

$$Losses = L_t + L_r + L_{freespace} + L_{cable}$$

G_r is the receiver gain, which is given in Table 8.
P_t is the transmitter power, which is 30 dBW.
G_t is the transmitter gain, which is 8.3 dBi.
L_t is the loss in the transmitter, which is 0.6 dB.
L_r is the loss in the receiver, which is 1.7 dB.
$L_{freespace}$ is the loss due to traveling through free space, which is 147 dB directly overhead a receiving antenna and 162 dB at maximum transmission distance.
L_{cable} is the loss due to the connector cable between the transmitter and the antenna, which is 0.1 dB.

The anticipated EIRP for CaNOP S-band communications is 38.3 dBW.

Received power from the CaNOP transmitter for the Near Earth Network groudn station assets are provided in Table 8. In the data presented in Table 8, “Minimum Received Power” corresponds to maximal line-of-sight distance between CaNOP and ground station. Likewise, “Maximum Received Power” corresponds to CaNOP directly over the ground station.

Table 8. NEN Ground Stations and received power from CaNOP.

Name of receiver	G_r **(dBi)**	**Maximum Received Power from CaNOP (dBm)**	**Minimum Received Power from CaNOP (dBm)**	**Location of receiver**
ASF 10M	45.0	-66.345	-81.512	64° N 147° W
ASF 11M	44.8	-66.545	-81.712	64° N 147° W
AUWA01	47.1	-64.245	-79.412	29° S 115.3° E
LEO-T	38.6	-72.745	-87.912	38° N 75° W
USHI01	47.1	-64.245	-79.412	19° N 155.7° W
USHI02	47.1	-64.245	-79.412	19° N 155.7° W
WGS	44.8	-66.545	-81.712	38° N 75° W

From data provided in the Space Network Users Guide (SNUG) we can calculate that an average acquisition threshold is -217.4 dBm as we can see from Table 8 even the minimum power received from CaNOP is above this margin, therefore CaNOP transmissions will be received by the ground stations. Provided consistently above-threshold received power and the data rate associated with S-Band communications, we can estimate total downlink data volumes. These values are shown in Table 9.

Table 9: Daylight Access Times for 6 NEN Ground Stations that receive S-band transmissions

	Wallops Flight Facility (WFF)	**White Sands (WS1S) (can't use at 2.4 GHz)**	**South Point Station USHI01**	**Dongara Station AUWA01 STDN AUWS**	**Alaska Satellite Facility (ASF) 11m STDN ASFS**	**Merritt Island Launch Annex (MILA) (can't use at 2.4 GHz)**
Total time in 1 year (sec)	9.69×10^5	8.58×10^5	5.52×10^5	7.03×10^5	4.39×10^5	6.90×10^5
Average Time (sec)	468	410	451	430	356	433
Max Time (sec)	646	643	641	643	495	643
# of downlinks	2068	2091	1223	1637	1232	1594
Average Downlink per pass at 115 kbps (MB)	6.73	5.90	6.49	6.18	5.12	6.22

Given the data in Table 9, we estimate that we will need to allocate 3-4 downlink opportunities to acquire a single a 20 MB spectral datacube.

Uplink budgets will be developed in the PDR.

GPS

Objective: To accurately and precisely locate the CaNOP CubeSat so the motherboard can tell the camera to take pictures of target areas when located at the latitude and longitude required. The motherboard will also be able to turn on the transceiver when the CubeSat is within range of a ground station. This will allow the CaNOP CubeSat to conserve power by leaving the transceiver and camera off until it is necessary for the CubeSat to downlink or take pictures.

Requirements:

- The GPS shall be capable of receiving either the L1 signal, L2C signal, or both signals.
- The GPS shall be capable of discerning the CaNOP CubeSat's location with an accuracy of 1 meter at a 65% confidence level.
- The GPS shall be either space-grade or thermal vacuum tested.
- The GPS shall be activated by software command from the flight computer.
- The GPS shall have a mass on no more than 150 grams.
- The GPS receiver module shall have dimensions no larger than 100mm x 100mm x 25mm.
- The GPS shall draw no more than 1.5W during operation and shall draw no more than 0.01W when the GPS is unpowered.

In order to achieve the objective while fulfilling the requirements CaNOP shall be using a GPSRM 1 GPS Receiver Module from Pumpkin Inc depicted in Figure 19. The GPS Receiver is capable of receiving the L1 and L2C GPS signals. By receiving the two different frequencies the receiver can receive a more accurate location than if it could receive only one of the signals (GPS World, 2015). The receiver also conforms to the mass, size, power, and communications requirements. The GPS antenna that we are considering is the ANT-

GPS Active GPS Antenna from SpaceQuest Ltd. although we have not finished a trade study on the GPS antenna.

Fig. 19. GPSRM 1 GPS Receiver Module.

Subsystem Dependencies

The CaNOP subsystems communicate by data protocols that will be fully defined in the PDR. A notional schematic of the protocols and dependencies is shown in Fig. 20.

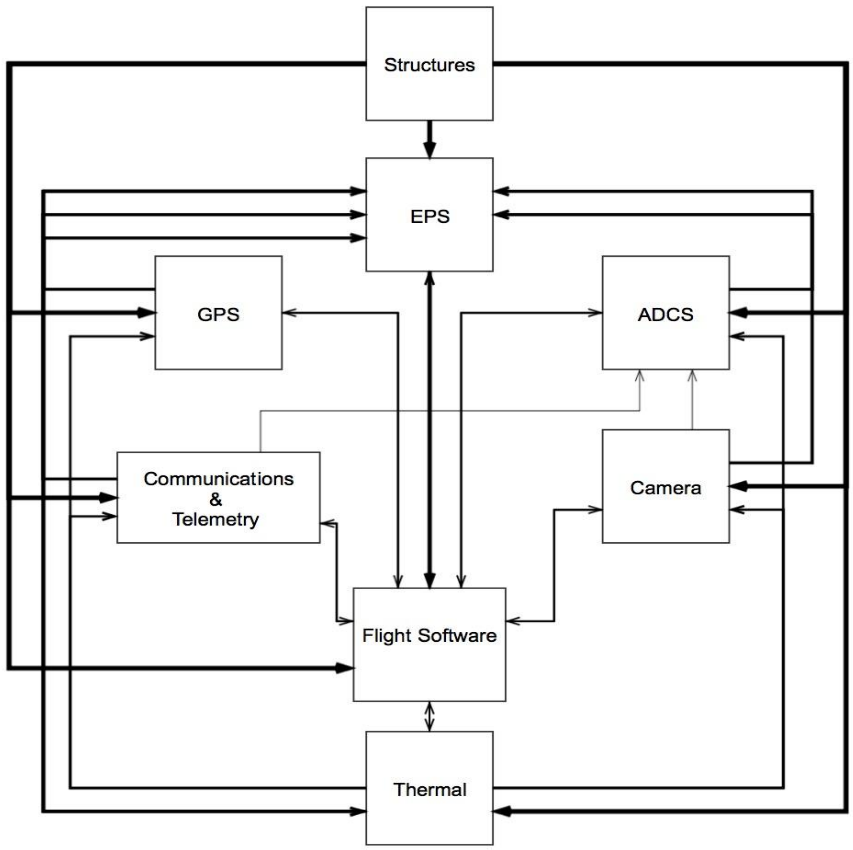

Fig. 20. Subsystem Dependency Block Diagram

Structures depend on information from every subsystem that has hardware. Information on how each subsystem component is mounted and the mass and dimensions of each component must be given to structures in order to design the CaNOP CubeSat in compliance with the CubeSat Design Specification and the NRCSD Interface Control Document requirements. In turn, each technical subsystem depends on the structure to contain and organize all components of the CubeSat.

All technical systems rely on the thermal and EPS subsystems to some degree. The thermal subsystem maintains the temperature of the CaNOP CubeSat, assuring that the average temperature is within each subsystem's temperature range for operation to prevent warping, cracking, and other technical malfunctions. EPS powers all systems on the CubeSat (including thermal) and obtains and directs power from the solar panels. The thermal and EPS subsystems depend on commands from the flight software subsystem. For thermal, flight software dictates when to activate and measure the temperature of the CubeSat. Flight software commands EPS when and to which system to direct power.

Flight software depends on the collected data from the GPS, the sun sensors from EPS, and the magnetometer and horizon sensors from ADCS. The provided data flight software would then be able to determine the current location, attitude, and power supply of the CubeSat, and move into the appropriate mode. In order to know when to activate PIC mode, flight software needs both the data surrounding the target forest located collected from the science team and GPS to define where those locations are in relation to the CubeSat. Flight software depends on the communications and telemetry subsystem for downlink and handshake. The flight software's LMI and Activation modes collect the data provided from all technical subsystems for status updates.

ADCS relies on the computed data from flight software that was collected by the solar panel's sun sensors, and the onboard horizon sensors and magnetometer for attitude determination. The ADCS switches into the proper mode performing control maneuvers for attitude orientation through flight software commands.

The camera needs the ADCS to keep the CubeSat in proper orientation, having the camera face the nadir direction. The science team identifies which bands of light the camera will measure. Flight software commands the camera to capture an image and then enables data collection of the image.

The communication and telemetry system depends on commands from flight software to know when to handshake, transmit data, and accept uplinks. The communication and telemetry system also depends on the ADCS to maintain consistent proper orientation that enables communication.

CubeSat Requirements Compliance

The CubeSat will adhere to the requirements set forth by the CubeSat Design Specification and the NRCSD Interface Control Document. In the case of a conflict, the more limiting requirement will be used.

Mass

The mass budget below displays the masses for all components. The maximum mass will be less than 4 kg, which is the maximum mass for a 3U CubeSat as set forth in the CDS document. The center of gravity will be found by modeling the satellite in SolidWorks. It may be necessary to add counterweights in order to ensure that the center of gravity is within 2cm of the center, as required by NanoRacks.

Volume

The CubeSat will not exceed 100 ± .1 mm in the +X Direction, 100 ± .1 mm in the +Y direction and 340.5 ± .3 mm in the +Z direction, as outlined in the CDS and NRCSD ICD.

Any protrusions from the body will be less than 6.5mm away from the body in each direction.

Materials

In accordance with the out-gassing criterion provided by NASA, the materials used will be approved by NASA, and will have a Total Mass Loss (TML) ≤ 1.0%, and a Collected Volatile Condensable Material (CVCM) ≤ 0.1%.
Hazardous materials shall conform to Air Force Space Command Manual (AFSPCMAN) 91-710, Volume 3.

Power

The batteries will not have a stored chemical energy greater than 100 Wh. The current through the RBF Pin and activation switches will not be greater than 10A.

Interface/ICD

There will be no Interface Control Document.

Activation

The Satellite will be activated using an RBF pin alongside three mechanical deployment switches. The CubeSat will not power up until thirty minutes after the removal of the RBF pin, and this timer will be stopped and reset if the pin is replaced.

Testing, Modeling, and Simulation

Testing

The CaNOP team will implement module testing on all subsystems and flight code. The purpose of the module testing is to ensure the functionality and to characterize the operational modes of each of the subsystems and the flight code functions. Module test procedures will be developed during the CDR process, and will be implemented according to the project timeline prior to systems testing and integration.

The components that are not space-grade shall be thermal vacuum tested under hard vacuum and operational temperature cycles. The integrated CaNOP CubeSat will also undergo thermal vacuum testing, as well as vibration testing per specifications that will be developed for the CDR.

The transceiver modem will be characterized to ensure the communications equipment works as intended with proper range and signal strength.

The Camera team uses a prototype pushbroom camera to characterize the operational limits (temperature, power) for the camera. the team will take images of trees while on the ground to ensure that the data reduction process is workable.

Critical Technologies and Risks

Full risk assessments and mitigations will be provided in the PDR. Initial risk areas include:

- COTS camera does not have space heritage.
- COTS camera has not been validated at LEO temperatures in vacuum.
- Mission requires higher downlink data rates than is typical with CubeSat missions.

- Image acquisition with pushbroom sensor is a complex process and requires higher levels of attitude control, determination than is typical in CubeSat missions.
- CubeSat ADC system technology is relatively new and untested.
- CaNOP power requirements are at the upper limit of what can be provided without deployable solar panels.
- Project build costs are higher than is typical for CubeSat missions.
- ITU/FCC licensing is increasingly difficult for CubeSat missions.

Modeling and Simulations

The CaNOP CubeSat mission operations and power and link budgets will be modeled and simulated in Systems Tool Kit (STK), MATLAB, and SolidWorks. NASA Debris Assessment Software (DAS) will be used to estimate orbital lifetime and debris collision probabilities.

STK will be the primary mission simulation tool. STK provides well-known mission operations support, including launch and orbit profiles, downlink budgets, gravity torques, and limited on-orbit power modeling. STK will also provide estimates of how long the CaNOP CubeSat will be directly over a targeted forest region; and the time periods of when the CaNOP CubeSat will be in direct sunlight, penumbra, and umbra.

SolidWorks will be used as the primary design tool for the structural design of the CaNOP CubeSat, including moment and mass distributions. SolidWorks will also be used for stress analyses and Finite Element Modeling (FEM) as needed.

MATLAB and the Princeton Aerospace CubeSat code will be used to model the thermal environment of the CaNOP CubeSat, as seen in Figure 21. Currently, the CaNOP is being simulated with the 4 3U sides covered in solar panels, and the 2 1U ends covered in a gold foil. The simulation includes a constant 3W of internal power consumption by the CaNOP. These conditions will be modified as the design evolves.

Thermal simulations will be used to set the extremes for thermal vacuum testing of the CaNOP CubeSat.

ArcGIS and ArcMAP will be used to develop NDVI and EVI models of our target forests. The GIS tools will allow the operations team to practice the data reduction techniques developed for CaNOP data.

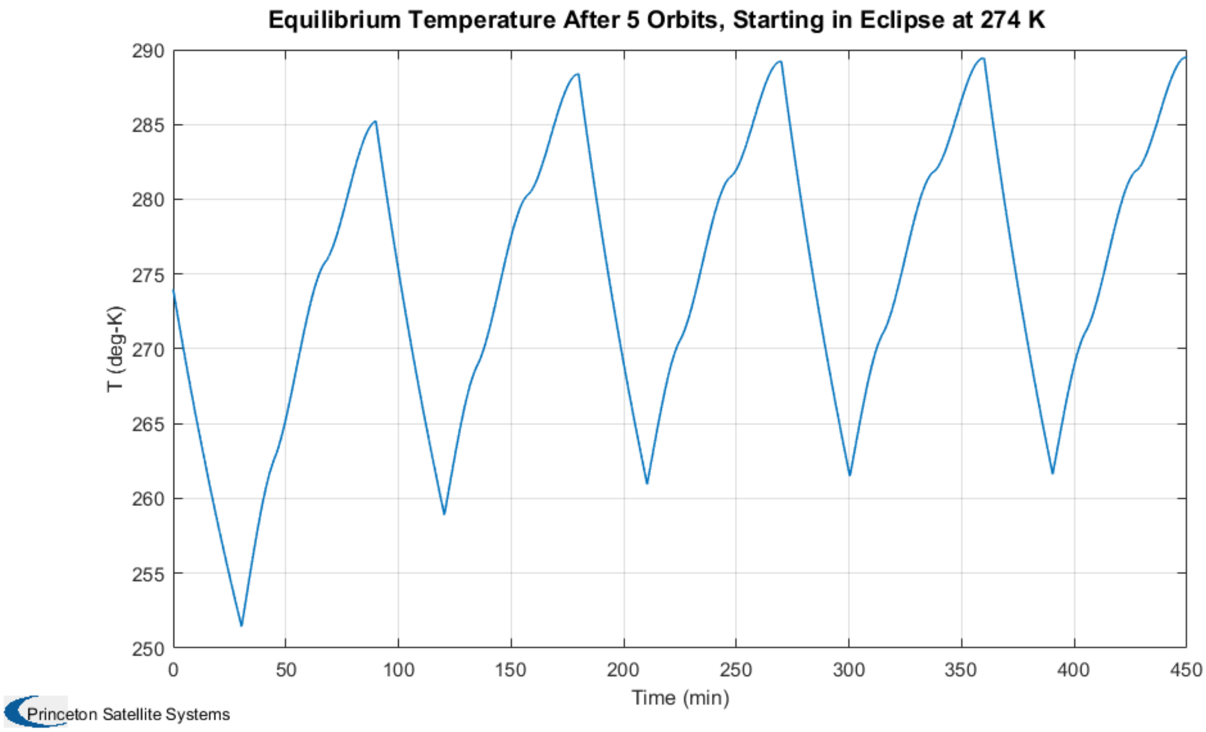

Fig. 21. Initial thermal simulations. The temperature of the simulated CaNOP fluctuates between 260K and 290K.

Education and Outreach

A crucial aspect of the project is the promotion of CaNOP's mission, goals, and scientific context to the local and greater community while also providing an educational experience. CaNOP, through a combination of social media outreach and educational outreach, will achieve and maintain the promotion of the project throughout the duration of the project.

The CaNOP team will construct and maintain a social media presence. Social media is a proven tactic to spread information quickly and easily; it is convenient for not only CaNOP but also for the target audience to utilize. This target audience includes all genders aged 13-65+.

A Facebook page will be created and maintained under the name CaNOP and will be employed as the main platform through which information will be spread. The Facebook page will provide educational videos in regards to the project as well as updates on the team. The goal is to make the page informational, but also fun and visually appealing.

CaNOP's target demographic will be reached as all groups can be found on the platform. A YouTube channel will accompany the page to hold all the videos posted. Educational videos will be linked from Youtube.

Instagram and Snapchat also provide social platforms on which CaNOP will operate, but will not be as significant as Facebook. Photos will be posted of the team and their adventures on Instagram. Snapchat will be utilized by the team as a team building exercise and ensure some laughter for the audience. These social media platforms are meant to be fun as to entice the audience to follow us and vicariously learn as they become intrigued. Instagram and Snapchat also allow the team to further connect to their audience.

CaNOP will visit local schools, giving presentations and demonstrations of the mission's outline and related scientific background. The goal of the presentations is to spread awareness of CaNOP's objectives and garner community support for this endeavor. To accomplish this, members of the team will visit primary, secondary, and specialty schools in the Kenosha/Racine area.

Another aspect of outreach will be to that of the scientific community both at Carthage and abroad. Teams will travel to Aerospace and CubeSat conferences to give talks about the project, its mission, goals, and the researcher's methodology. The project may also host open house where members of the Carthage community can come and learn about the different subsystems, as well as the progression of the project as a whole.

Outreach Requirements

- Social Media
    - Facebook
        - Facebook shall feature educational content that targets a wide range of people.
        - Videos shall be posted frequently regarding information pertaining to various subsystems.
        - Team Updates shall be posted often.
        - Facebook shall be open and inviting to create a fun atmosphere that has potential to spark intellectual growth.
    - Instagram, Snapchat
        - Instagram and Snapchat shall be updated frequently.
        - Instagram and Snapchat shall be open and inviting.
        - All CaNOP members shall contribute photos and videos to both platforms.

- Educational Outreach
  - Information presented shall be presented in a manner that can be understood at the target educational level (demographics presented in Table 10).
  - Presentations shall be modified to fit the appropriate educational level.
  - The curriculum shall be set forth as follows:
    - Elementary School - project members will introduce rudimentary information with the aid of visual and sensory items:
      - What a satellite is.
      - What a satellite does.
      - What CaNOP's objective is.
    - Middle School - project members will introduce the mission's conceptual design as well as the information found in the elementary schools presentations:
      - The basic forest ecology and carbon content surrounding selected target forests.
      - How CaNOP will communicate with the satellite.
      - The basic scientific principles utilized in the project.
    - High School - project members will introduce the same information found in the lower educational level presentations and add more complex information like mission design and scientific background:
      - The calculations utilized in various teams.
      - The scientific principles utilized.
    - Specialty Schools - depending on the nature of the school, members will introduce more technical concepts including orbital information and vegetation indices.
    - CaNOP and Carthage College shall be promoted at all events.
      - Elementary and Middle school students will receive a take home sheet.
      - High school students will receive promotion verbally.
  - Schedule - The Education and Outreach team has already discussed several schools in Kenosha which they will like to visit though, in total, there are 72 schools in the area being considered for presentations:
  - The optimal goal is to present at the majority, if not all, schools in each district: though in an event where that is not possible, the visits will take place at schools selected upon by population size, academic leanings, and plausible interest in the material.
- Conferences/Open House
  - Frequency:

        - Present at 2-3 conferences over the life of the project
        - Hold 1-2 open house
    - Curriculum
        - Conferences
            - Should include both space technology and science conferences
            - Should be regional or national in scope
        - School Open House
            - Each subsystem will prepare a presentation of their work
                - General information
                - Design process
                - Pertinence to the project
            - It will take place in a general fair format

Table 10. Local Schools in Kenosha and Racine Wisconsin.

School District	Specialty	High Schools	Middle Schools	Elementary Schools	Total
Kenosha	4	3	5	23	35
Racine	N/A	5	7	21	33

(Kenosha Unified School, 2015), (Racine Unified School District, 2015)

Management

The CaNOP Management Team consists of the P.I. and The WSGC Program Manager. The reporting and responsibility relationships between management, mentors, and the student team are as indicated in the WBS of Fig. 22, with each subsystem consisting of three students, one of who serves as the lead on the particular subsystem. Each student, except the System Engineer, serves on three teams. The subsystem leads report to the System Engineer who in turn reports to the appropriate mentor and/or P.I. The specific responsibilities for the subsystem leads are to (weekly) communicate the subsystem team's progress through formal status updates and progress assessments, to lead the development of design documentation for their subsystem, and to serve as the POC for the Systems Engineer and the Integration and Testing Lead.

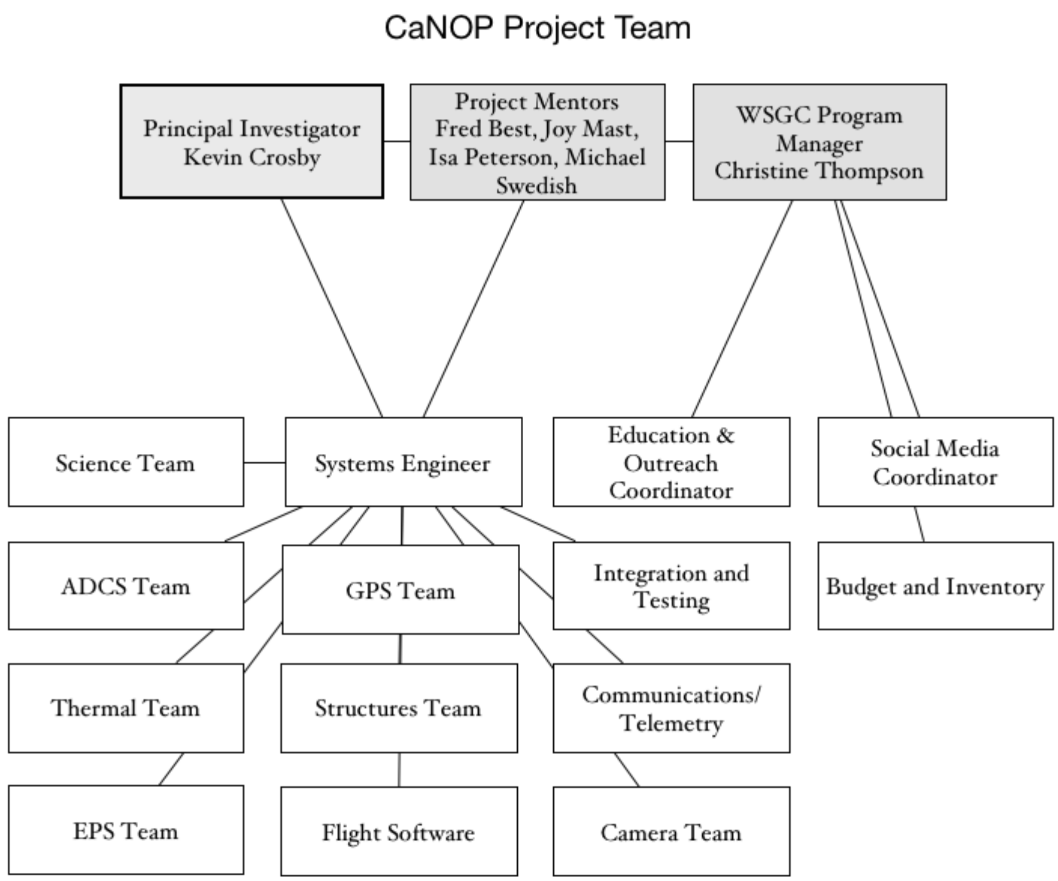

Fig. 22. Team Structure and reporting lines.

Remaining Issues before PDR

ADCS Issues

- Understand how the horizontal (-Y direction towards the nadir) orientation of the CubeSat will affect the ADCS
- Calculate a more precise estimate of the duration for the de-tumbling process.
- Have a better understanding of the sun sensors and how they operate by discussing them with the EPS team
- Determination of the sources of magnetic interference within the CubeSat that will affect the accuracy of the magnetometer.

Science Team Issues

- Topographic correction for use in NDVI and EVI calculations
- Correlation of NDVI and EVI to GPP
- Acquisition of additional target forests
- Cloud cover interference

Testing, Modeling, and Simulation Issues

- Have a complete STK simulation of the CaNOP CubeSat
- Have a complete Power simulation of the CaNOP CubeSat
- Have a complete Thermal simulation of the CaNOP CubeSat
- Finish modeling the structure of the CaNOP CubeSat
- Have a complete schedule for testing to be done on the CaNOP CubeSat

Comm. System Issues

- ITU and FCC licensing
- Accurate downlink budgets for high data-rate comms.

Summary

The CaNOP CubeSat mission is an ambitious attempt to reproduce some of the capabilities and data workflow associated with a large multispectral observing program such as Landsat in a 3U CubeSat form factor with an interdisciplinary team of undergraduate students. The team will follow standard engineering design processes, developing detailed design documents, pursue coordination with NASA Near Earth Network assets for downlink and telemetry support, and will work with the NASA CSLI program for launch manifest.

Four faculty-industry mentors who will provide guidance on subsystem technologies and testing and integration operations support the undergraduate team.

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