The CaNOP Cubesat Mission

Andrew Santangelo
sci_Zone, Inc.
Rio Rancho, New Mexico; (505) 205-8315
andrew_santangelo@mac.com

Dr. Kevin Crosby
Carthage College
Kenosha, Wisconsin; (262) 914-3166
kcrosby@carthage.edu

ABSTRACT

The CaNOP Cubesat Mission is a student based cubesat mission based out of Carthage College. The purpose of the mission is to test a method for multispectral imaging, image changes in the rain forest on Earth, and visualize changes in urban night lighting due to the growth in low power LED street lights. The 3U Cubesat camera system is designed to replicate early Landsat remote sensing capabilities. For this mission CaNOP is using a commercial four-band multispectral push-broom imager designed for precision agriculture applications. This imaging system reproduces a subset of the visible and near-IR Landsat and MODIS spectral imaging channels at a ground pixel size of 60m at an orbital altitude of 400 km. CaNOP will be deployed from the ISS in Fall 2019. Communications will be through our LinkStar-STX3 and LinkStar duplex radios which link the satellite through the Globalstar network providing global beaconing and positioning, command and control, and image download. We will be able to control swaths to image based on known location via our web ground interface. For this presentation we will discuss the mission plan and mission science, provide comparison figures of merit for CaNOP, present the new PC104 based BeagleBone Black interface and architecture and how it was integrated with the cubesat, and how data from the mission will be collected and shared with the community.

CANOP MISSION OVERVIEW

Forests currently absorb as much as 30% of annual global anthropogenic carbon dioxide emissions.[1] 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.[2] 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.[3] 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.[4] 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.[5] 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.

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.[6] 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 Figure 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.

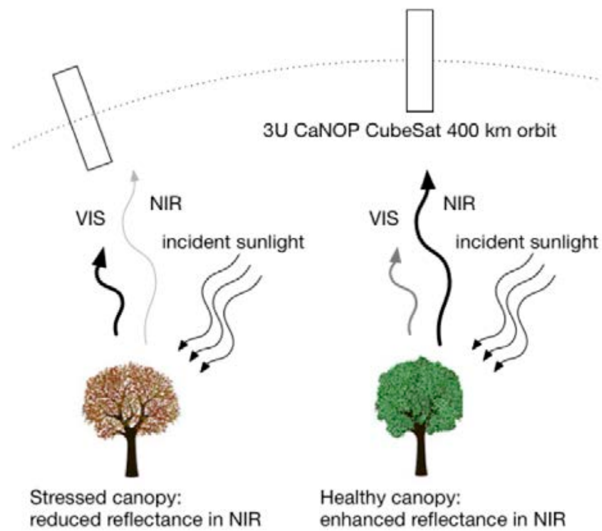

Figure 1: Mission Concept

SCIENCE REQUIREMENTS[7]

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:

- *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 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.
- <u>*Photochemical Reflectance Index (PRI).*</u> 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 are

- <u>*Derived Index: LAI*</u>. 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 $LAI = (3.618 * EVI - 0.118)$.
- <u>*Derived Index: FAPAR*</u>.
  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.
- <u>*Gross Primary Production*</u>
  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 secondary science requirement of the CaNOP mission is to image urban areas at night and measure qualitatively the change to LED based outdoor lighting over the 2 year mission life. Target cities include Portland, Oregon; Albuquerque, New Mexico; Kenosha, Wisconsin; Chicago, Illinois; Paris, France; and Perth, Australia.

IMAGING[7, 8]

A *Spectral Devices msCAM*™ hyperspectral camera will be used for imaging on the mission. The camera can image at 450, 550, 650, and 750 nm at 2048 unmixed pixels per band. Figure 2 presents the *msCAM* without the lens; Figure 3 shows the camera mounted in the cubesat frame with the f/1.4 lens.

Figure 2: msCAM multispectral camera used on CaNOP.

The design specifications of a nominal push broom 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 is used in the analysis.

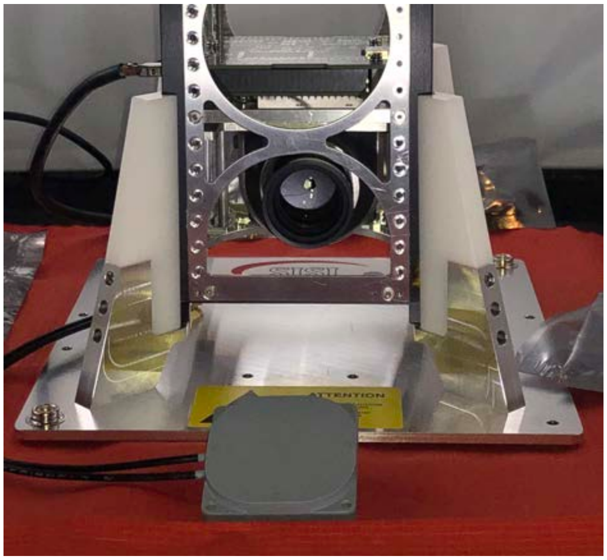

Figure 3: msCAM multispectral camera with lens integrated into the cubesat structure

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

<u>Field of View:</u> 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

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

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

<u>Swath Width:</u> 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.

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

<u>Ground Sample Distance:</u> The GSD is the ground projected pixel size:

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

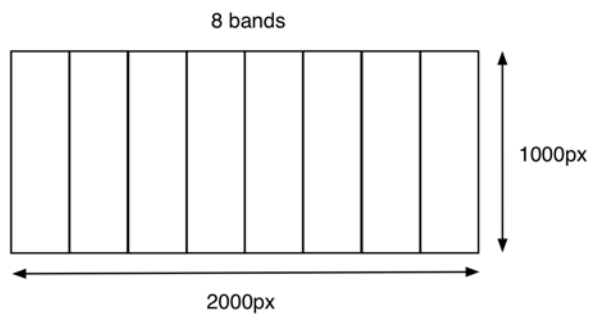

Figure 4: Push broom sensor showing the arrangement of 2 Mpx into 8 spectral bands.

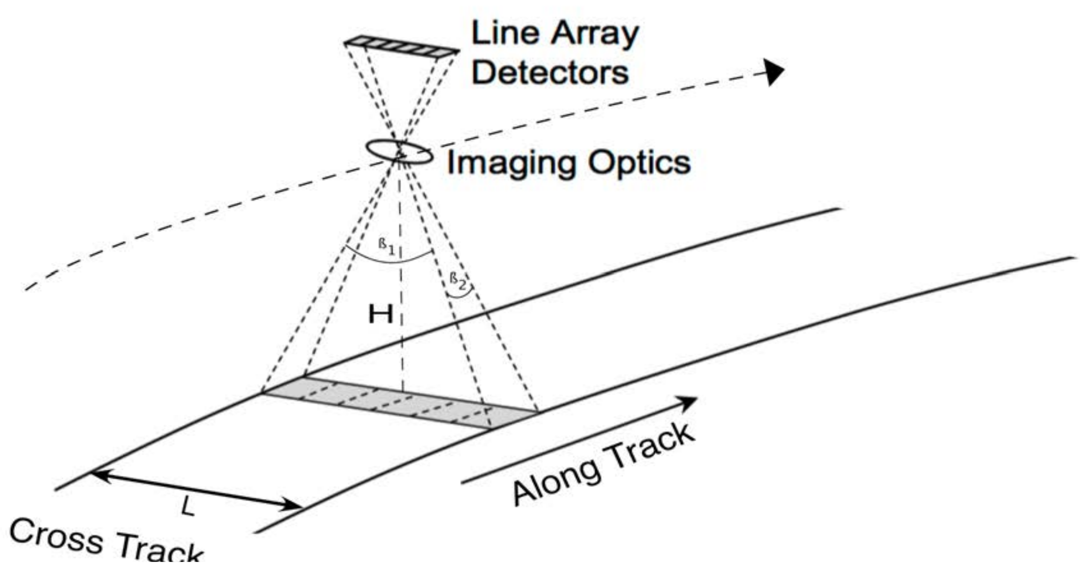

Figure 5: Push broom imaging geometry.

<u>*Instantaneous Field of View:*</u> The IFOV measures the angular image cone of a single pixel and is given by

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

<u>*Dwell Time:*</u> 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.

$$t_d = GSD/V = 63\ m/(7.67\times10^3 m/s) = 8.2\ msec.$$

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 ($2x10^6$px) = $1.6x10^8$ bits = 20 MB.

LINKSTAR SYSTEM[9, 10]

Where the *msCAM* and supporting software is the heart of the payload, the *LinkStar* system is the heart of the satellite. The *LinkStar* system hosts the *QuickSAT/Vehicle Management System (VMS)* which controls satellite and payload operations, manages all communications, provides location services, and manages the power of the payload, GPS, and on board radios. The primary board of the *LinkStar* system is the *LinkStar-STX3-PC104* as shown in Figure 6. The *LinkStar-STX3*-PC104 supports the CubeSat bus architecture allowing for communications and control with other devices on the CubeSat bus. A modified *BeagleBone Black* is used as the principal flight computer and interfaces with the board from underneath via the *BeagleBone Black* cape interface and architecture.

The *LinkStar-STX3-PC104* has integrated with it the *Globalstar* STX3 packet radio module which provides one way (downlink) messaging service through the *Globalstar* satellite network with over 95% Earth coverage. Messages can be up to 144 bytes in length and can be broadcasted as little as every 5 minutes in 9 byte packets. For the CaNOP mission we will be broadcasting to the ground vehicle and payload health and location.

Figure 6: The LinkStar-STX3-PC104 Radio System.

A connector is provided on the *LinkStar-STX3-PC104* board to support both *NovAtel OEM700 series GPS* for space and advanced ground use and the *Adafruit Ultimate GPS* for ground use and testing plus high altitude balloon applications. When connected to the board the *QuickSAT/VMS* system automatically communicates with the GPS. *QuickSAT/VMS* can obtain all information from the GPS including location services, system time, GPS configuration, and signal quality. *QuickSAT/VMS* can build an ephemeris from the GPS and support geofences to turn devices like the *msCAM* on and off. For this mission we are using the *NovAtel OEM719* with the COCOMs removed.

The *LinkStar-STX3-PC104* also supports the *LinkStar GSP-1720* duplex radio system which provides for the uplink of commands and the transmission of data to the ground including the large image files generated from the *msCAM* (Figure 7). The *GSP-1720* communicates also through the *Globalstar* satellite network communicating with their satellites in orbit via bent pipe communications to the ground. This provides approximately 45% communications coverage in LEO. Figure 8 shows the approximate coverage area for the *LinkStar GSP-1720*. The *LinkStar* system communicates via PPP connecting the CaNOP to the internet; the CaNOP satellite when connected is treated like a node on the internet and communicates directly with a secure ground server.

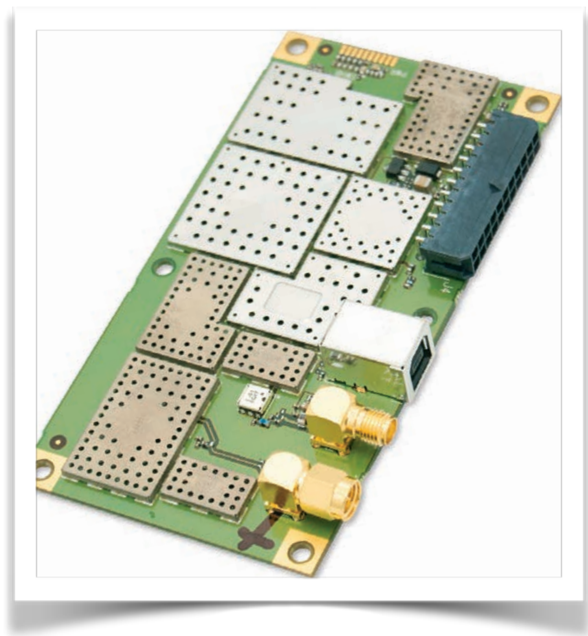

Figure 7: The *LinkStar GSP-1720* duplex radio providing internet based communications.

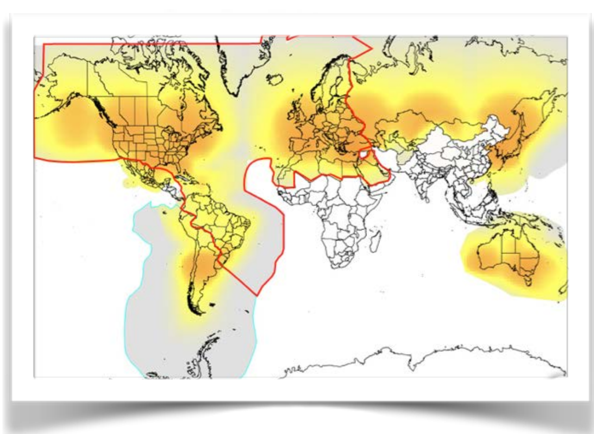

Figure 8: Approximate coverage area of the *LinkStar GSP-1720* duplex radio.

Figure 9 shows a computer model of the CaNOP cubesat with all the components integrated including the *LinkStar* system, *msCAM*, *NovAtel OEM719* and supporting systems. The structure, solar panels, ADCS, battery, OBC and EPS are *Clyde Space* components; all systems on the stack communicate through the CubeSat bus.

MISSION OPERATIONS[7, 11, 12, 13]

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 51° and altitude 400 km as would be provided by deployment from the International Space Station.

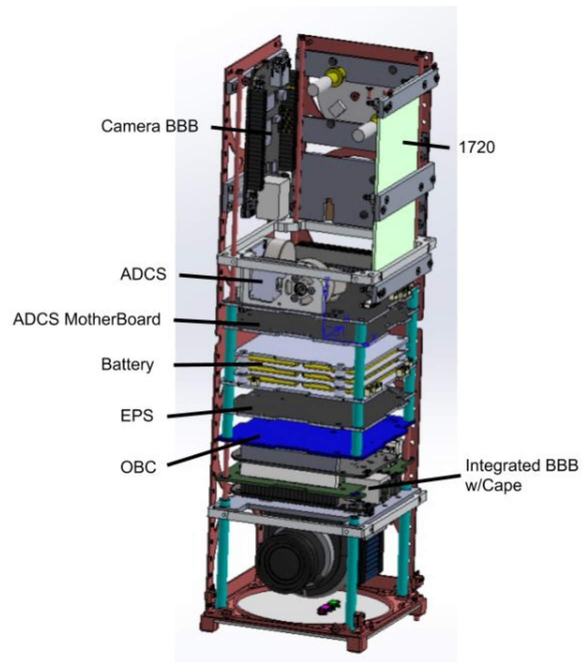

Figure 9: The *CaNOP* satellite and supporting systems.

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; the *LinkStar* system will begin to beacon data as allowed within FCC parameters upon deployment (radio fully controllable from the ground and antenna pointing away from Earth). 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 *LinkStar* antenna pointing at the zenith and the *msCAM* pointing at 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 orientation for the camera and *LinkStar* antennas. During this period *QuickSAT/VMS* will build the on board ephemeris based on data from the onboard GPS receiver data for use in lieu of the GPS to save on power when applicable. When in the coverage area of the *Globalstar* satellite network, *QuickSAT/VMS* will power on the *GSP-1720,* connect the satellite to the internet, and connect to the *QuickSAT/VMS* ground server. The system will 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 "fenced" areas for imaging. 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 turned on to begin image acquisition. The data will be transferred from the separate camera *BeagleBone Black* to the *QuickSAT/*VMS database on the *LinkStar BeagleBone Black*. Once the satellite leaves the "fenced area" and all data is transferred to the *QuickSAT/*VMS database, the camera and its supporting *BeagleBone Black* will be turned off.

The *CaNOP LinkStar* duplex radio connects directly to the ground station cloud based server via the internet. A web interface is provided to the user to monitor data, send commands, and move files up and down from the satellite. The images are initially sent automatically as thumb nails to the ground. The user can then select from the image thumbnails which images are to be transmitted to the ground.

IMAGING TARGETS[7]

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 Table 1, 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.

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).

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.

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