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Benefits of Tracking Aids on a 1U CubeSat

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Incoporating active/passive tracking aids into the design of a university/high school CubeSat mission promotes good space stewardship. Tracking aids are necessary for improved tracking covariance of CubeSats. Tracking aid support and design-space cost are covered. Reflectarrays, patch array(s), and deployable antennas show the potential benefit of transmitting data over S-band frequencies and tracking aids that enhance the mission capabilities. Passive and active tracking aids with low impact on the mission provide reduced covariance of CubeSats orbit tracks shown through use of modeling tools.

I. Introduction

THE advantage of CubeSats is their small size, cost, and effort to produce. The problem with CubeSats is their size. Designers often face hard choices with size and power constraints. This conceptual design focuses on the basic necessities while leaving room for a scientific payload in the power and size budget. It also highlights and attempts to codify some "norms" of good space stewardship.

The U.S. Federal Communications Commission, FCC, requires a 25 year disposal plan: at the end-of-life the satellite will de-orbit from Low Earth Orbit, LEO, or Middle Earth Orbit, MEO, or enter a graveyard orbit from Geosynchronous Earth Orbit, GEO. The satellite Owner/Operator(s), O/O, must ensure, unless prevented by technical failures beyond their control, that "all stored energy sources on board the satellite are discharged, by venting excess propellant, discharging batteries, relieving pressure vessels, and other appropriate measures," [1]. The FCC requires O/O to plan for disposal to mitigate orbital debris and ensure the safety of the space environment. "1 in 5 CubeSats Violates International Orbit Disposal Guidelines," a summary of the July 2015 issue of Orbital Debris Quarterly News [2] highlights the large risk that CubeSats play in orbital debris and conjunction analysis. The Joint Space Operations Command, JSpOC, recently recommended "identification markers either physical or signal based," to aid in the cataloging of the satellite. The JSpOC relies on the Space Surveillance Network, SSN, to provide conjunction assessment if the CubeSat is non-maneuverable. "In this case, information from the launch provider and/or O/O is absolutely critical to cataloging the object as soon as possible so that the JSpOC can provide conjunction assessment based on high-accuracy catalog data," [3]. The addition of tracking-aids, reflectors, and other tools into the design to aid cataloging are a soon to be necessary part of orbital debris mitigation.

II. Conceptual Mission Concept and Architecture

A. Mission Statement

The conceptual mission objective is to support a camera for an Earth-imaging mission. The primary objective of this paper is to show that tracking aids can be incorporated into the design of a CubeSat university mission. An Earth-imaging mission by a university represents typical scientific payloads on university CubeSats. The focus is the space segment of the mission.

B. Mission Concept

The mission concept takes the CubeSat conceptual mission through the development, integration and testing, implementation, operations, and disposal of the CubeSat. Each of the mission phases will be highlighted in the following mission concept architecture:

- Concept for accomplishment and utilization of mission objectives
- Technical plan for implementing the mission with all mission elements

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- Mission Operations concept
- Management concept
- Rough cost plan

The example structure provided in [4] is the basis of the mission concept architecture provided in this paper.

1. *Accomplishment and Utilization of Mission Objectives*
   The milestones to accomplish and achieve the full utilization of mission objectives:
   - Prove tracking aids do not affect the science mission of the CubeSat
   - Image Earth and transmit pictures to the ground station

2. *Technical Plan for Implemention the Mission*
   The major mission elements include the launch, space, ground, and program segment. The launch segment comprises the launch system, the launch service, and the necessary infrastructure. The space segment comprises the development of all spacecraft equipment, the payload, the system engineering activities, and tests. The ground segment includes the ground infrastructure, the equipment, the hardware and software for linking the space segment and the mission control center, and the data processing and archiving facilities. The program segment includes the project management, organization, and coordination, product assurance, interfaces, and planning of resources.

For the space segment: the development of the equipment for the CubeSat and the interactions of the payload requirements are of the highest priority. The incorporation of the tracking aids should reflect a subsystem level focus similar to [5-11]. Ref. 5,7, and 8 are of particular interest because of their treatment of tracking aids and subsystem focus: "Development and Design of an AFIT CubeSat Demonstrating Deployable Technology," "An Electric Power Supply Design for the Space Plasma Ionic Charge Analyzer (SPICA) CubeSat," and "CubeSat Deployable Ka-Band Mesh Reflector Antenna Development for Earth Science Missions."

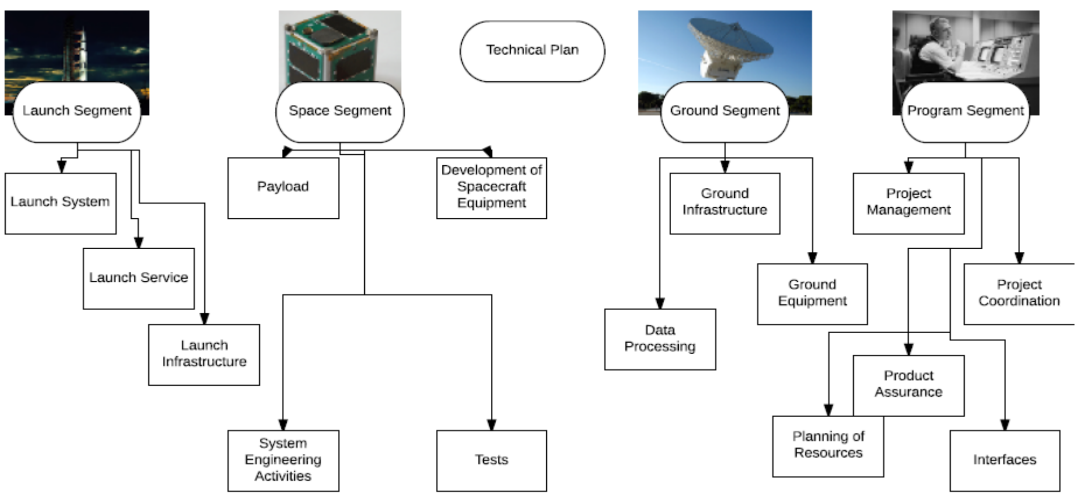

Fig. 1 Technical Plan and All Segments

The development of spacecraft equipment, one of the key components of the space segment, incorporates the development of the Attitude Determination and Control System, ADCS, the power system, the CubeSat bus, and the tracking aids. The system engineering analysis means that sizing, electronics, and thermal considerations must be taken into account when developing the equipment and designing the spacecraft. The spacecraft must undergo a series of tests from the ability of the spacecraft to function autonomously to vacuum testing of individual components. The mission requirements must drive the development of the spacecraft equipment. The pointing, power, thermal, and sizing requirements of the payload will drive the development of the equipment around the payload.

The launch segment will place additional restrictions on the size and mass of the spacecraft. As a secondary payload, the CubeSat will not have control over its injection orbit. This injection orbit will be pre-defined by the primary payload. Launch services will typically charge $22,000-$29,000 per kg for a secondary payload, [4, p. 648].

The ground and program segments support the spacecraft after the launch vehicle has injected the spacecraft into its orbit. Most CubeSats do not have any propulsion devices on-board. This means the injection orbit will be the operational orbit. The ground segment communicates with the spacecraft, tracks the spacecraft, and provides all telemetry. The program segment will allocate resources and provide for the management through the life and end-of-life of the spacecraft.

3. Mission Operations Concept

The mission operations for the space element include commanding the spacecraft, monitoring the status of all subsystems, payload management, operation of the data acquisition systems, reacting to spacecraft anomalies, and trend analysis related to the spacecraft's equipment and subsystems. The mission control center will execute these tasks. As it relates to this paper: the design will incorporate considerations for all of these tasks.

4. Management Concept

The management of the mission will fall to the university. Typical management teams are led by students with a faculty advisor providing stability as students graduate and leave. As an example, the University of Michigan, "M-Cubed," team is led by a student as the Chief Engineer and a Faculty Advisor, Dr. James Cutler, [12]. The other students are divided into subsystem teams for Command and Data Handling, Communications, Electrical and Power Systems, Integration and Testing, Machining, Orbits and Controls, Payload, and Structures. This follows typical mission management structures.

Management of the space element can be decided through management team decisions or autonomously through management software. The Intelligent Payload EXperiment, IPEX, CubeSat validated autonomous operations for the Intelligent Payload Module of the Hyperspectral Infrared Imager, HyspIRI, mission concept. IPEX used machine learning and computer vision to process payload instrument data. IPEX also used the Continuous Activity Scheduler Planner Execution and Re-Planner, CASPER, AI planner/scheduler onboard to determine the most efficient use of IPEX resources from file storage and power to downlink bandwidth, [13]. Autonomous scheduling still requires some ground operations management to handle any spacecraft anomalies and process downlinked data.

5. Cost Estimates

Cost estimates are imperative to any proposal for a CubeSat. While CubeSat missions excel at driving costs down and opening access to space to universities and small commercial interests they can still cost upwards of $100,000. Off-the-shelf electronics are common among CubeSats to keep costs low, [4]. The off-the-shelf electronics used in this conceptual design will be priced and any custom parts will be compared to commercially available parts to create a rough cost estimate of the conceptual 1U CubeSat.

III. Technical Plan: Space Segment

The space segment of the technical plan includes the payload, development of spacecraft equipment, system engineering activities, and tests. The payload requirements will drive the development of spacecraft equipment and system engineering activities. After the development of equipment and system engineering activities are complete tests will be proposed to verify the hardware and software integrity.

A. Payload

The chosen payload for this conceptual design is an Earth-imaging camera. Due to the availability of data and its small size this mission will use the NanoCam C1U by GOMSpace. The NanoCam C1U using the 35 mm lens has a 2048x1536 pixel resolution for a total size of 3 Megapixels. The lens provides less than 60 m/pixel at 650 km. The data processor features 512 MB of RAM and 2 GB solid-state image storage, [14].

Table 1 The thermal, electrical, and size requirements of the NanoCam C1U

Thermal	Storage: -40ºC to 85ºC Operating: 0ºC to 60ºC
Power	Supply Voltage: 3.3V Supply Current: max 500 mA
Size	Lens size: 35 mm Overall Dimensions: 86.0x 91.7x 57.9 mm

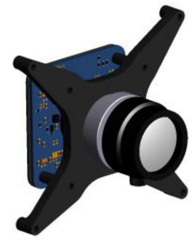

Fig. 2 NanoCam C1U CAD Model of the 35 mm lens attachment.

The requirements for the payload drive the development of the spacecraft equipment, Table 1. The NanoCam C1U, Fig. 2, uses 380 mW in its idle state. During image acquisition mode, less than 5 seconds, the camera consumes 800 mW. While processing the image, less than 10 seconds, the NanoCam consumes 800 mW. During the initial system boot, 15 seconds, the camera consumes 1300 mW.

The camera has no special focus requirements so stringent pointing requirements are not needed. The only pointing requirements will be to keep the camera pointed towards the Earth during orbit.

B. Development of Spacecraft Equipment

The spacecraft will require an ADCS, a power system, a thermal management system, a structure, and tracking aids. The equipment for each system, structure, and tracking aid has been designed specifically for this conceptual design. Depending on specific requirements: these components could be incorporated into other CubeSat missions.

1. Structure

The structure of the CubeSat is made up of the bus. The satellite bus mechanically supports the payload, thermal and power systems, and any additional systems, like the tracking aids or the ADCS equipment. The external structure has already been defined. A CubeSat must fit the Poly Picosatellite Orbital Deployer, P-POD.

The CubeSat standard was developed by professors from Cal Poly and Stanford University [5]. The CubeSat standard defines a satellite with a basic form of 100x100x100 mm, weighing under 1.33 kg, containing anodized edges with a length of 113.5 mm, also known as the 1U configuration, [15]. Everything down to the surface roughness of the CubeSat rails is defined to standardize the satellites and allow for easy access to space. Ref. 15 includes design drawing specifications of the 1U through 3U standards. Common practice is to use Aluminum 6061 as the frame material.

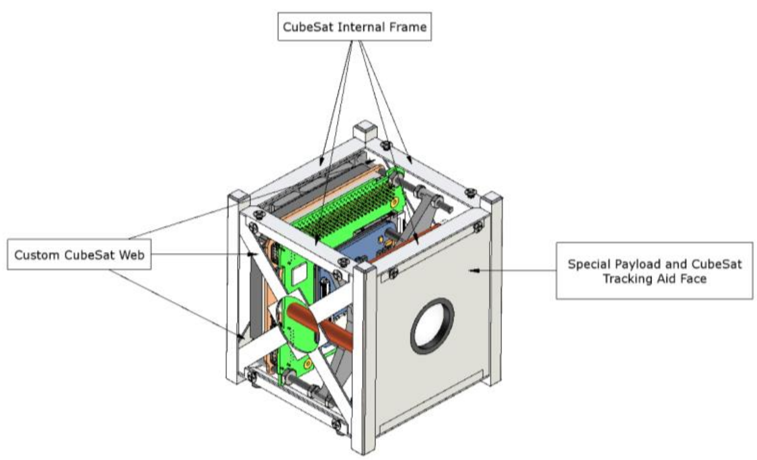

Fig. 3 The satellite bus with surface webs to support external tracking aids, antennas, solar panels, and serve as a slot guide for the camera payload.

The number of internal support frames will vary with the equipment needed to be supported internally. Also, the internal support frames will be used to mechanically interface with surface webs. The surface webs shown in Fig. 3 will support external tracking aids, antennas, and solar panels.

Aluminum 6061 has a relatively long flight history on CubeSats. Pumpkin Inc. has been making the CubeSat Kit chassis using aluminum and has delivered over 150 kits since 2003, [16]. For reference, the CubeSat standard was set in 1999 and the first flight of CubeSats was in 2003 on a Russian Eurorocket, [17]. Aluminum is a good choice: structurally sound and the chance of mass surviving during de-orbit maneuvers is low. Ref. 18 placed the allowable mass of alumnimum at 11.2 kg. The results of the simulation in [18] suggest that for CubeSats launched from the International Space Station, ISS, altitude and lower, the lower the heat of ablation, the more allowed mass. Of the three structural materials compared, Al, stainless steel, Ti, Al has the lowest heat of ablation. The maximum allowed mass for a 1U CubeSat is 1.33 kg, [15], well below the maximum allowable mass of 11.2 kg.

2. Attitude Determination and Control System, Fig. 4

The Attitude Determination and Control System, ADCS, features four magnetorquers. Three rods are placed in a typical XYZ configuration and the fourth magnetorquer comes with the BAox High Energy Density Battery Array – BAO2S model from the Ecuadorian Space Agency, EXA. The fourth magnetorquer is capable of exerting a moment in the X and Z directions. The attitude feedback and controls are communicated to the Innovative Solutions In Space, ISIS, On-Board Computer, or iOBC. The primary purpose of the ADCS is to keep the NanoCam C1U focused on Earth. The ADCS will also have pointing requirements when passing over ground stations for downlink and uplink communication.

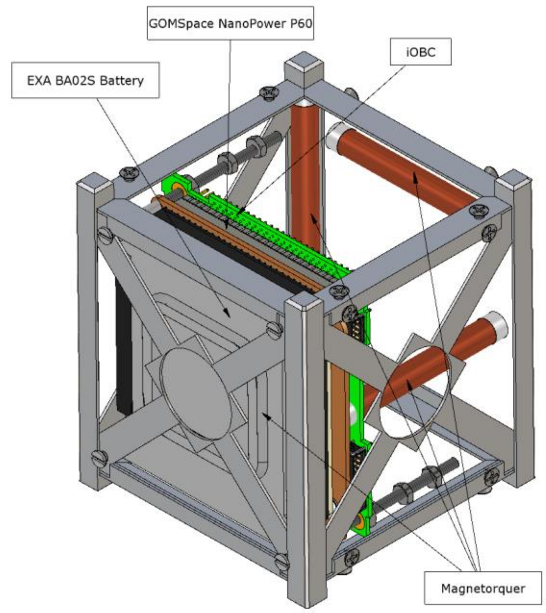

Fig. 4 Attitude and Directional Control System

3. Command and Data Handling

The commands and data management will be handled by the iOBC, ISIS On-Board Computer. The iOBC features a 400 MHz 32-bit ARM9 processor, 64 MB of RAM, data storage up to 128 GB through 2 standard SD Cards, and an operating temperature from -25ºC to 65ºC. The iOBC has flight heritage [19].

The iOBC, Fig. 5, has the option to interface using the I2C, SPI, UART, ADC, PWM, and GPIO protocols. It is also compatible with the Electronic Power System, EPS, from GOMSpace. In order to save space the iOBC will be stacked with the GOMSpace EPS NanoPower-P60.

4. Communications

The iOBC will format the data to be transmitted using a protocol like the AX.25 Protocol. Then the data will be modulated using the PSK technique into a baseband signal with a lower frequency. The baseband signal will then be modulated into a high-frequency carrier signal by the transmitter.

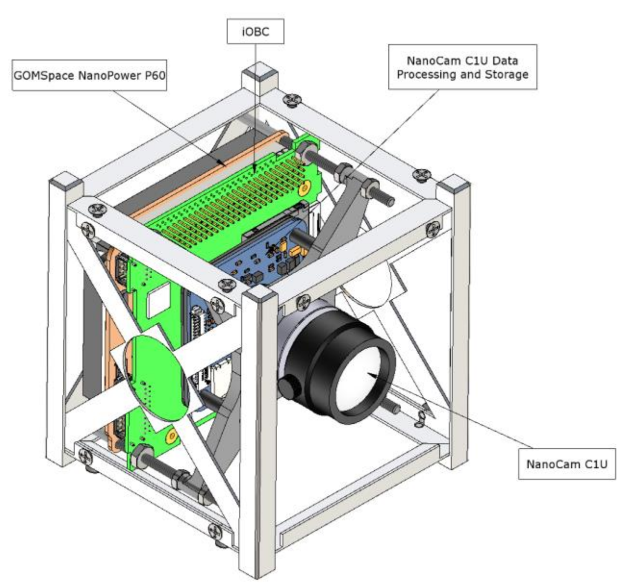

Fig. 5 Command and Data Management System equipment inside the CubeSat.

Then the signal is transmitted through use of the antenna, [4].

The use of patch array(s), a reflectarray, or an inflatable high gain antenna would allow for the use of S-, X-, or potentially Ka-band frequencies as well as UHF for telemetry. The use of such antennas would also for better tracking of the CubeSat. The JSpOC would be able to provide lower covariance on the Two-Line-Elements, TLEs, of a CubeSat utlitizing these tracking aids. Antennas are tracking aids, Fig. 6.

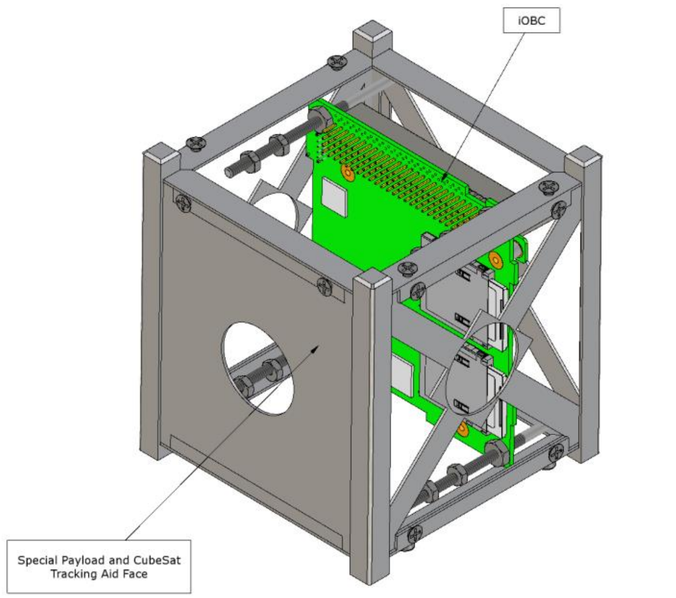

Fig. 6 Communications is governed by the iOBC and the patch array on the front of the CubeSat.

5. Power System

The power to the CubeSat is supplied by 7 solar panels. The P110B and P110A panels were manufactured by GOMSpace. They feature two solar cell assemblies connected in series. They also feature a coarse sun sensor to aid in attitude determination and temperature sensor to help gauge temperature drift. The P110 series panels can produce up to 2.3 W in LEO and operate from -40ºC to 85ºC, [20]. Assuming full sunlight in LEO, the solar panel will produce 4.84 – 4.64 V, 508 – 490 mA, and 2400 – 2270 mW. Some of the solar panels will produce for roughly 60 minutes each orbit before falling into complete shadow for 30 minutes, [4, p. 702]. All the solar panels will not experience full illumination at the same time which reduces the maximum output below 16800 mW.

The CubeSat must continue to provide power to its systems in moments of shadow. Lithium-ion batteries are preferred because of their high energy density. The CubeSat will utilize the BAox High Energy Density Battery Array, the BAO2S unit, from the Ecuadorian Space Agency, EXA, and two custom Lithium-ion batteries. The EXA-BAO2S can output 3.7 V, 5400 mAh, and 19.9 Whr. The operating temperature is -30ºC to 80ºC, [21, 22]. EXA has shown remarkable resiliency with this particular battery type which is needed for a CubeSat as events are likely. After six months of no signal, EXA recovered their KRYSAOR spacecraft's signal and was able to recharge the battery array despite being completely depleted on recovery, [22].

The two custom Lithium-ion batteries are based off GOMSpace's P-series Lithium-ion batteries. The P-series batteries are movable and contain their own heating element. Placement next to the NanoCam C1U should help maintain operating temperature and allow efficient utilization of space. The custom batteries are designed to give 8.4-6 V and produce 2600 mAh at 7.4 V. The operational temperature is -20ºC to 60ºC, [23]. The additional

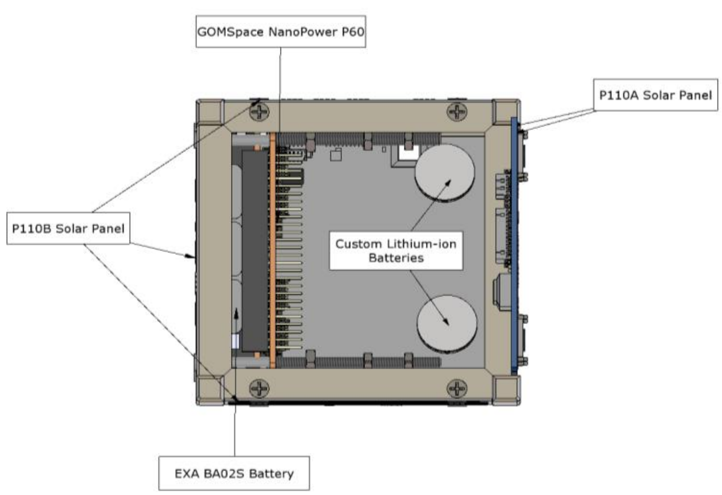

Fig. 7 Overview of the power system equipment on the CubeSat.

batteries also provide redundancy in case of failure.

An Electrical Power System, EPS, regulates, conditions, and distributes the energy from the batteries and solar panels through an onboard planner and optimization system directly from the iOBC or through a dedicated board. In this design the GOMSpace EPS – NanoPower P60 system is used. The P60 system features a Power Distribution Unit, PDU, and Array Conditioning Unit, ACU. The ACU converts the photovoltaic cells power. The PDU and ACU are both built on the standard GOMSpace Dock which supports GOMSpace's on-board computer and communications hardware. The PDU will distribute power as needed or directed and limit current and voltage to prevent damage to subsystems. The IPEX CubeSat used CASPER, an AI planner/scheduler to make the most efficient use of power resources to support spacecraft activities, [13]. This conceptual design makes no assumptions about the power management system but assumes efficient choices, either through uplinked commands or autonomous decisions, will be made.

6. Thermal Management

The thermal management of the spacecraft is accomplished both passively and actively. The two custom lithium-ion batteries feature self-heating elements that help keep them operational. The batteries are strategically placed next to the NanoCam C1U to keep it at operational temperature through passive heating. The electronics heat will be enough to maintain the operational temperature of the EXA – BAO2S battery, [22]. In this way, the electronics undergo active heating through their own resistive elements, the 2 Lithium-ion batteries maintain their own operational temperature, and the other elements are passively heated through the operation of these components.

Typical LEO orbits place CubeSats in-between -20ºC and 20ºC and when in direct sunlight up to 80ºC, [4, p. 702]. The EPS and iOBC will monitor temperature fluctuations and shut-down or start up sub-systems when necessary to maintain operational temperature limits of -20ºC and 60ºC, [23].

C. Tracking Aids

Tracking aids for CubeSats vary widely in space, power consumption, and sub-system properties. Tracking aids considered for this 1U CubeSat are classified as either passive or active systems depending upon whether power is consumed solely to aid in the identification/tracking of the CubeSat.

1. Passive Systems

Passive systems include patch array(s), a reflectarray, a mesh reflector, and an inflatable antenna. The addition of antennas that provide a higher gain also positively impacts the ability of the SSN to track such objects. Correlation is much easier and covariance can be reduced through accurate TLE output in the catalog. Patch array(s) are arranged directly on the side of the CubeSat which limits the power sub-system: a side of the CubeSat that could have been used for a solar panels is being used for communications. The EnduroSat patch array features S-Band capabilities, 2.4-2.45 GHz range, and an RF output of up to 4.0 W, [24]. A reflectarray is a series of printed panels on the unused side of a deployed solar array. These panels reflect narrow radio signals to the precise location of a specified receiver. A reflectarray functions in much the same way that a parabolic dish reflector does except that the reflectarray is flat. The ISARA spacecraft, 3U CubeSat, utilized this antenna for a projected data rate of 100 Mbps, [25].

Mesh reflectors and inflatable antennas require power for their initial deployment mechanism but offer high gain available for larger spacecraft and smaller storage volume. Chahat et. al, designed a deployable mesh reflector for the RainCube project from NASA Jet Propulsion Laboratory, [8]. The RainCube mission requires a 6U CubeSat with a fixed nadir-pointing profile at Ka-band, with a minimum detectable reflectivity better than +12dBZ at 250 m range resolution and 10 km horizontal resolution at an altitude of 450-500 km. The high-gain antenna, >42dBi, is designed to fit in less than 1.5U space. The 0.5 m diameter Ka-band high-gain antenna is deployed through the use of a gas to lift the antenna slightly and a spring to finish the one-time transition, [8]. Placing the deployment container for the mesh reflector in a suitable location proved difficult. Space is limited and the NanoCam C1U takes up a large percentage of useable volume.

Current CubeSat communication systems primarily use frequencies ranging from VHF to S-Band through the use of dipole and patch antennas, with a peak gain generally of 6 dB. The transceivers typically use limited transmission power, about 1.0 W. Inflatable antennas for CubeSats, specifically a 1.0 m design in the S-Band, has a estimated gain of 24.9 dB allowing a CubeSat to transmit data at 100 kps from an orbit close to GEO [26, p. 323]. If the inflatable antenna has 100 holes, 10 µm in diameter, and the orbital temperature is constant at 373 K: with only 1 g of benzoic acid as the sublimating powder the antenna will stay inflated for approximately 430 days, [26, p. 329]. The antenna pointing required is within 8.75º. The current ADCS system with magnetorquers is sufficient for this purpose. Babuscia et. al, proposed operation of the inflatable antenna is untenable at altitudes less than 800 km. Drag torque is more than sufficient to de-orbit the vehicle [26, p. 330]. The idea of using inflatable devices at the end-of-life of CubeSats to de-orbit the spacecraft is popular. The FuusenBrake system was deployed on the EarthSCAN mission to de-orbit the CubeSat constellation at end-of-life. When deployed the inflatable balloon will cause a 3U CubeSat to de-orbit in 73 days from a 500 km orbit, [27, p. 8]. A CubeSat using a 1.7 m diameter spherical inflatable device would be de-orbited in 328 days from a 800 km circular orbit, [28, p. 54]. Large inflatable antennas are not viable for a 1U CubeSat without a propulsion system to correct for drag effects in LEO.

2. Passive System Analysis

Using FreeFlyer, STK, and analytical tools from [29] for correlation of orbit tracks we can determine in a the upper bounds of probability that a CubeSat with a passive system installed is more likely to be correlated than a CubeSat without a passive system installed. Fig. 8, gives the percentage of time that a satellite in a sun-synchronous

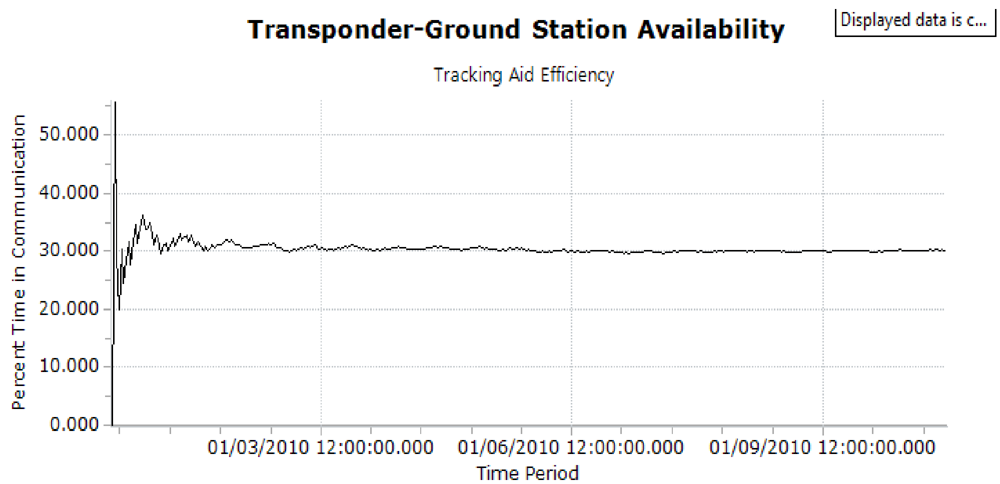

Fig. 8 CubeSat Communication Sensor Contact with Ground Stations

orbit in a polar inclination will see three ground stations, McMurdo, Antarctica, White Sands, NM, and Cape Canaveral, FL.

The average time-per-day spent in contact with the ground stations is 30% per day over a ten-day period. The number of contacts, Table 2, allow the determination of the number of contacts-per-day and the sensor points obtained-per-day.

Table 2 Number of contacts over a ten-day period

Item	Value
Number of White Sands Contacts	61
Number of Cape Canaveral Contacts	60
Number of McMurdo Contacts	122

The number of contacts-per-day for White Sands is 6.1, contacts for the Cape are 6.0, and the McMurdo contacts-per-day are 12.2. This means that McMurdo sees the satellite for about 15% of the day while the Cape and White Sands see the satellite for only about 7.5%. The circularized orbit at 8000 km provides about 17.78 min in contact with each ground station.

Table 3 Ground Station Contacts-per-Day

Ground	Contacts	Percentage	Time (hrs)	t-per-pass(min)
WS	6.10	7.531%	1.807	17.78
Cape	6.00	7.407%	1.778	17.78
MM	12.2	15.06%	3.615	17.78
Total	24.3	30.00%	7.200	17.78

[29, p. iii] allow for a simplified analysis of the probability of a track being associated with the correct measurement. The probability is a function of the object density in the focal plane normalized by the error. Assuming single-scan sensors from each ground station and a Chapman analytical model for atmospheric effects we can estimate and predict the track purity. Track purity is defined as the number of scans with correct measurement assignments (multiple objects in focal plane) over the total number of scans in a given set *K*, [29, p. 34]. Mis-detections are ignored for a more holistic analysis. Assuming a conservative estimate of 30% correct assignments over one measurement per pass per day; the track purity can be estimated to be about 29.1% per day. While dependent on the sampling interval the normalized standard deviation is expected to converge to about 1σ, [29, p. 40].

3. Active Systems

Active systems include transponders, as they can be used solely for tracking purposes, GPS receivers, radio frequency, RF, identification tags, pulsed LEDs, and beacons emitting laser light. All of these systems require interaction with ground stations by either outputting the information, GPS receivers, or allowing ground stations to make calculations based on the observations of the CubeSat. Transponders allow for range and flight velocity measurements. Range measurements can be taken by measuring the latency of a looped uplink signal. Flight velocity can be measured through measurements of Doppler frequency shifts between transmitted and received signals. GPS receivers use modified triangulation information when available to update deterimination estimates and reduce the error associated with normal TLE propagation.

4. Active System Analysis

The primary driver for active system analysis is the power system cost to the satellite. The systems for the imaging mission power cost, Table 4, will drive the availability for active tracking aids.

Table 4 Power Consumption

Maximum Consumption and Output Measured Using Average Sunlight Time with Shadow Considered							
Device		Consumption			Output		
# of Components	Components	Power [Wh]	Voltage [V]	Current [mAh]	Power [Wh]	Voltage [V]	Current [mAh]
7	Solar Panels - P1	554.4	23.1	168000	2.772090323	4.84	586.7591183
1	Camera - NanoC	0.03	3.6	8.333333333	0	0	0
1	Computer - On-E	13.2	3.3	4000	0	0	0
1	Battery - Baox H	0	0	0	19.9	3.7	5400
3	Magnetorquer Ro	14.4	15	72000	0	0	0
1	Frame - Aluminur	0	0	0	0	0	0
4	Solar Panels - To	0	0	0	0	0	0
2	Battery - Custom	0	0	0	26.64	7.4	3600
1	EPS NanoPower	39.6	3.3	12000	0	0	0
	Static Componen	52.83		Power Available	49.31209032		

With an average time in sunlight of 69.3 min, the CubeSat produces 49.3 Wh. With all systems on the CubeSat will require 52.83 Wh. This will require creative power schedules or choosing new components to meet the power requirements. Power consumption is a stringent demand on the 1U CubeSat. Active devices under stringent power budget restraints are a liability to the mission.

GPS receivers considered as the truth information show TLE has a mean error of 0.832 m and a standard deviation of 444 m. GPS is only available for 213.5 min of an orbit when operating on the PSSCT-2 of The Aerospace Corporation, [30]. More investigation into the power schedule and demand on the pico-satellite is required.

Orbit determination accuracies for satellite-to-satellite tracking using transponders, [31], have a high resolution of up to 2 m in range and less than 1 mm/s in range rate for 0.1 Hz. [31] reported these results based on the ATS-6/GEOS-3 and the ATS-6/NIMBUS-6 satellite-to-satellite determination experiments. Transponders could be highly valuable in this regard but it is expected that a creative power schedule will require activation by radar detection or integrated commands when in certain regions of orbit.

IV. Rough Cost Plan

A rough cost estimate of all components used in the conceptual design of the 1U CubeSat are included below. Some of the tracking aids: the patch array(s), reflectarray, and the inflatable high gain antenna are not available commercially. They are still in the development stages and are often custom built for individual spacecraft. Therefore, they were not included in the cost plan presented in Table 5. The ground station costs and university staff and student costs were considered negligible in this rough cost estimate.

Table 5 does not include the launch costs: launch services typically charge $22,000-$29,000 per kg for a piggyback launch, [4, p. 648]. Prior to the addition of tracking aids with communication capabilities the CubeSat has

Table 5 Rough component cost estimates for the conceptual 1U CubeSat.

Manufacturer	Sub-System	Item	Quantity	Unit Cost	Total Cost
GOMSpace	Power	Solar Panels - P110B	7	~€5,500	$41,354.39
GOMSpace	Payload	Camera - NanoCam C1U	1	~€18,000	$19,334.52
ISIS	Command & Data Handling	Computer - On-Board Computer (iOBC)	1	~€4,400	$ 4,726.22
EXA	Power/ADCS	Battery - Baox High Energy Density Battery Array BAO2S	1	~€6,300	$ 6,767.08
NewSpace	ADCS	Magnetorquer Rod	3	$1,600.00	$ 4,800.00
OnlineMetals/UA Machine Shop	Structure	Frame - Aluminum 6061 Sheet/Cutting/Shaping	1	$ 25.40	$ 25.40
UA Machine Shop	Structure	Solar Panels - Torsional Hinges for Deployment	4	$ 8.99	$ 35.96
UA ARP Lab	Power	Battery - Custom Lithium Ion Batteries	2	$5,000.00	$10,000.00
GOMSpace	Power	EPS NanoPower P60 - Power Management System	1	$4,900	$ 4,900.00
					$91,943.57

a mass of 6.22×10^{-1} kg. Assuming the worst case scenario: launch costs would be $18,038. *The total cost estimate to build and launch this 1U CubeSat would be $110,000.*

V. Conclusion

The active tracking aids have significant drawbacks due to their power demands. The stringent power costs on a 1U CubeSat make it difficult to justify an active tracking aid device except to benefit from multiple roles in the mission. The passive devices have the opportunity to supplement mission goals and not detract from the science mission. Passive devices should be implemented to practice good space stewardship and supplement CubeSat capabilities.

Active devices often provide a significant reduction in error. With GPS as a secondary system, used only for 213 min of the orbit reduced the error of a picosatellite to 0.832 m when using only TLE propagation and Monte Carlo methods as a means of estimating true position. Satellite-to-satellite tracking, using Doppler shifts, found true range within 2 m and within less than 1 mm/s for a sampling rate of 0.1 Hz. Passive devices, like a large reflectarray can increase the object density in a sensor's focal plane. This will increase the likelihood of correct measurements being assigned and reduce the error to within 1 standard deviation as measurements are taken over time.

The authors plan to focus on introducing more realistic scenarios to test the assumption that passive devices will perform better as a design choice. The power budget for a 1U CubeSat will be re-examined.

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