T-reX CubeSat Final Report

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Executive Summary

Solar flares cause powerful bursts of radiation that can damage the electronics and disrupt the orbits of active satellites. These bursts of plasma and energy from the Sun can additionally interrupt communication networks and power grids on Earth. The primary mission of T-reX CubeSat is to improve real-time space weather data collection by using X-ray technology to detect these solar storms early. T-reX will collaborate with space weather monitoring companies to actively inform satellite companies of the occurrence and intensity of solar storms, so the companies can adjust the orbits of their satellites accordingly and methodically to avoid collision. Communication and broadcast satellite companies will also be updated on potential breaches in their communication services due to solar radiation, so they can prepare and notify their users. T-reX is a 3U CubeSat that will follow a high, geostationary Earth orbit where it can get an undisturbed, close-up view of the Sun's solar flares. Its primary payload will be an x-ray spectrometer that can detect and record the intensity of solar radiation from charged particles ejected from the Sun. T-reX is expected to be operational for around 5 years and will take around 5 years to engineer from design and ideation to launch. Although there are other CubeSats that similarly utilize x-ray technology to detect solar activity, they operate in a low Earth orbit. In a significantly higher orbit, T-reX has the unique capability to monitor solar flares in real-time with shorter relative eclipse periods, though this higher orbit requires extra thermal control and expenses to launch.

Introduction

1.1 Mission Statement

TreX's will monitor the presence of solar storms using X-ray technology in order to timely warn satellite companies of potential radiation disturbances that can cause damage to electronics or communication breaches.

1.2 Primary and Secondary Mission

T-reX's primary mission is to collect live data on the occurrence and intensity of solar flares via its x-ray flux monitor. This data, if shared timely, can be useful to commercial satellite companies to adjust the orbit of their satellites or communication service providers to predict if there will be a temporary breach in their services.

As a secondary mission, this CubeSat could provide useful data to researchers who are studying space weather and the Sun, enhancing scientific data on solar storms. This could lead to the development of better predictive models of solar phenomena and resulting geomagnetic storms.

ESA's Sunstorm and other existing CubeSats have similar missions of collecting data on X-ray emissions from the Sun, however they operate in low Earth orbits, while T-reX will operate in a high earth orbit. The higher orbit will allow for more continuous monitoring of the Sun as T-reX's observation period will be longer per orbit and there will be less disruptions from space junk and other satellites.

1.3 Users & User Requirements

T-reX's main customers will be large satellite companies, specifically SpaceX, Boeing, SES S.A., and Intelsat S.A., who necessitate data on the occurrence of satellite-damaging solar storms to maneuver their satellites. As of today, the occurrence of these storms is not well-informed, and T-reX will detect these solar storms early to inform satellite companies of their occurrence. Geomagnetic storms, fueled by intense solar flares, cause satellites to unexpectedly drop in altitude as seen in a recent solar storm in May 2024. This poses a risk for satellite collisions to occur when spacecraft are simultaneously dropping in altitude, while others are trying to make their way back into their original orbit. As Elon Musk's Starlink (under SpaceX) plans to launch hundreds of new satellites each month, avoiding collisions becomes all the more important. Additionally, these bursts of plasma and energy released by the Sun can interrupt communication systems on Earth, and Intelsat S.A. and Telsat S.A., broadcast and communication satellite companies, need to be informed of temporary breaches in their services. As a secondary mission, T-reX can provide useful data to NASA researchers who are studying space weather and solar surface activity.

These customers are concerned with the accuracy and timeliness of the data, but aren't concerned with the way the data is collected. Incorporating a high orbit CubeSat can help give real time analysis of the sun's flare patterns and help companies protect their satellites by giving them advanced warning to adjust to a lower orbit.

1.4 Payloads and Major Subsystems

Payload: X-123SSD X-ray Spectrometer

Major Subsystems:

- Primary and secondary structure
  - 3U CubeSat frame
  - Struts, brackets, panels
- Power subsystem
  - 4 30cm x 10cm deployable solar panels
  - ISIS electrical power system, consists of two-cell battery board and daughterboard
- Thermal control subsystem
  - Multilayer insulation
  - High emissivity anodized aluminum surfaces
  - Heat pipes
  - Phase change material positioned near payload and EPS

- Altitude determination and control system
    - XACT-15 Altitude Determination and Control System, consists of 3 reaction wheels, magnetorquers, accelerometers, gyroscopes, and star trackers
    - Sun sensor
- Communication subsystem
    - PULSAR-XTX X-Band Transmitter
    - X-band patch antenna
- Command and data handling subsystem
    - On-board computer

1.5 Expected Operational Life

Expected Operational Life: ~5 years
Design/Development (5 years):
- Ideation
- Securing Funding
- NASA CubeSat Launch Initiative Proposal + Approval
- Physical CubeSat Design
- Mission Planning + Licensing
- Ground Station Design + Development
- Hardware Testing

Launch (3 days):
- CubeSat to Dispenser Integration
- Launch Vehicle Integration + Launch

Mission Operations (5 years):
- Collection of live X-ray data
- Data transmission to ground

End-of-Life Plan: graveyard orbit transfer

The expected operational life of T-reX is around 5 years from launch, typical for a GEO CubeSat, as radiation, thermal fatigue, and mechanical wear will cause its subsystems to degrade over time. T-reX's lithium ion batteries will slowly lose capacity every cycle, and its solar arrays will degrade due to constant charged particle exposure, which will eventually cause T-reX to be unable to power all of its subsystems.

Aerodynamic drag in GEO is insignificant, so T-reX's orbital lifetime is indefinite unless an intentional deorbit system is activated. The easiest way to deorbit a GEO satellite is to transfer it into a graveyard orbit, which is around 300 km above GEO, to move it out of the way of operational spacecrafts.

Subsystem Design

2.1 Mission Planning

This CubeSat will operate in a high, geostationary Earth orbit (GEO), allowing for continuous data collection. Geostationary orbits have an equal rotation period to Earth, so T-reX will stay above the same point on Earth during its entire rotation. GEO orbit times are longer, and there will be a shorter relative eclipse period as well as less disruption from space junk. Additionally, a higher orbit will allow the spacecraft to detect flares earlier as it is closer to the source, though it will require more radiation shielding. Its proximity to the sun also requires it to have more thermal control mechanisms to cool its subsystems during daylight, and to warm it during extreme cold temperatures in the eclipse. Satellites in GEO are significantly more expensive to launch and maintain as it takes more rocket power to transport it into its initial orbit, hence why most CubeSats operate in a low Earth orbit. A higher frequency communication system and more antennas are also required, as the communication signal loses significant power due to free space path loss.

T-reX will operate in an orbit 42,164 kilometers from Earth's center. In a high Earth orbit, aerodynamic, gravity gradient, and solar pressure forces are present, leading to slight changes in the CubeSat's orbit altitude as time goes on. The eccentricity and inclination of T-reX's orbit will be 0, given it will maximize its time out of the eclipse period and provide a consistent, in-plane viewing of the sun. Drag force on the CubeSat will be extremely minimal, if not 0, in GEO, as the atmosphere is extremely thin, emulating a pure vacuum.

Orbital Parameters

Semi-Major Axis (a)	Eccentricity (e)	Inclination (i)	Right Ascension of Ascending Node (Ω)	Argument of Perigee (ω)	True Anomaly (ν)
42164 km	0	0	0	0	0

Table 2.1.1: T-reX orbital parameters

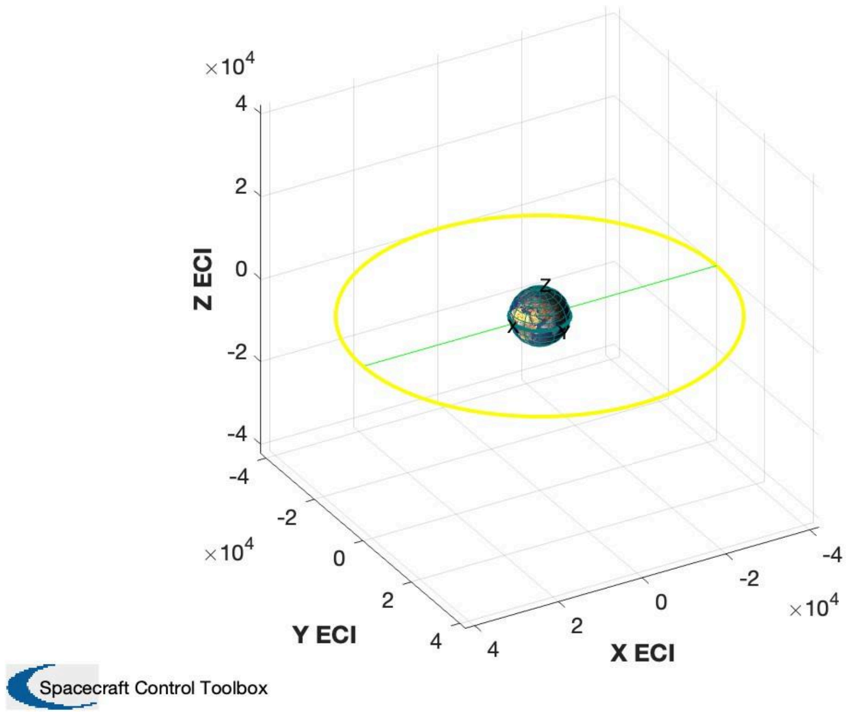

Figure 2.1.1: CubeSat Geostationary Orbit

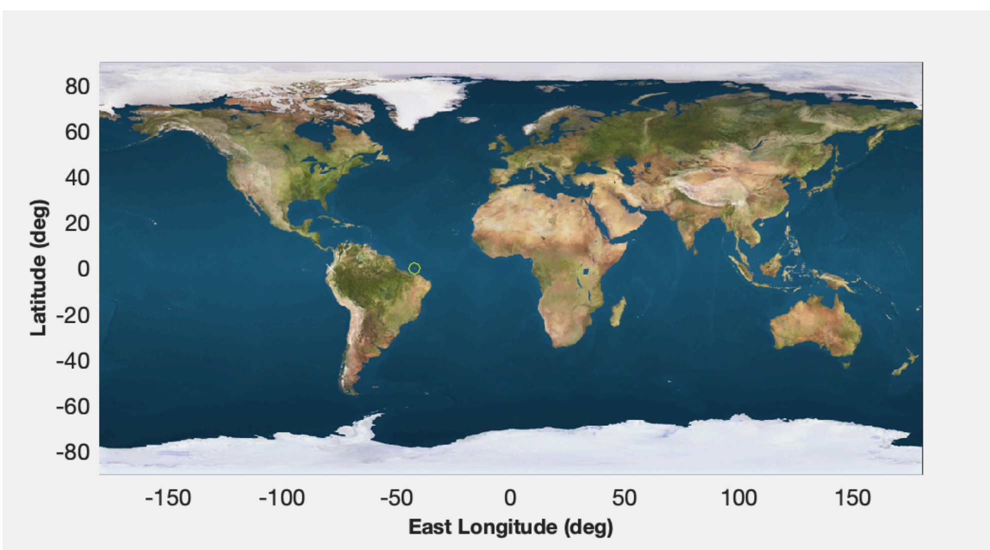

Figure 2.1.2: Trace of Orbit Along Earth's Surface (yellow circle)

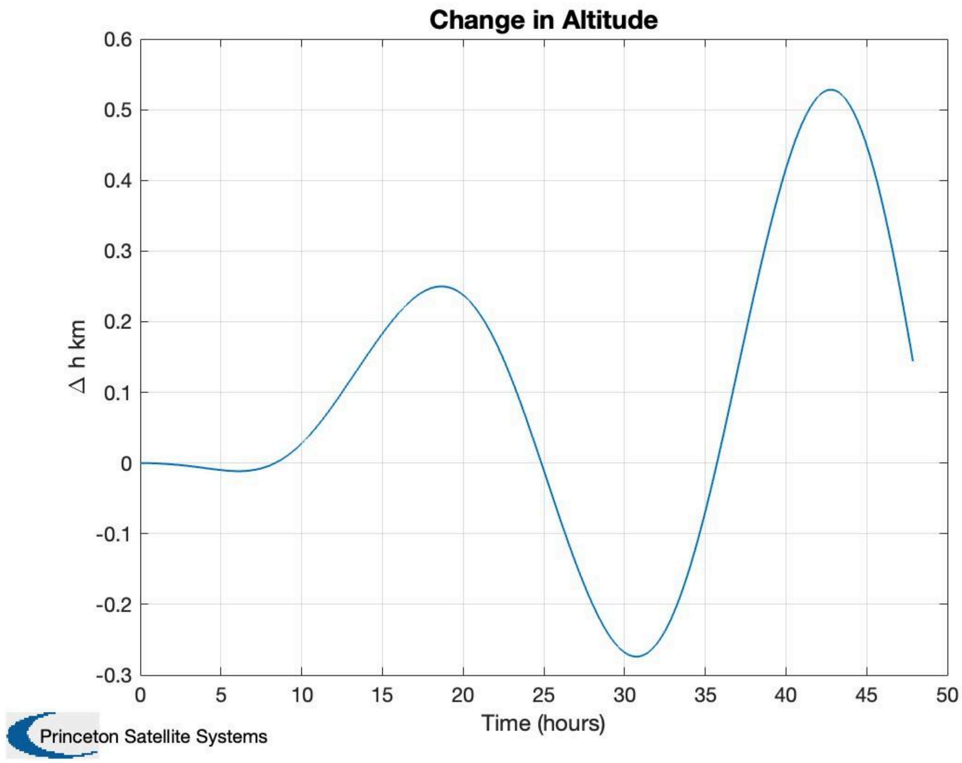

Figure 2.1.3: CubeSat change in altitude over time due to surface disturbances

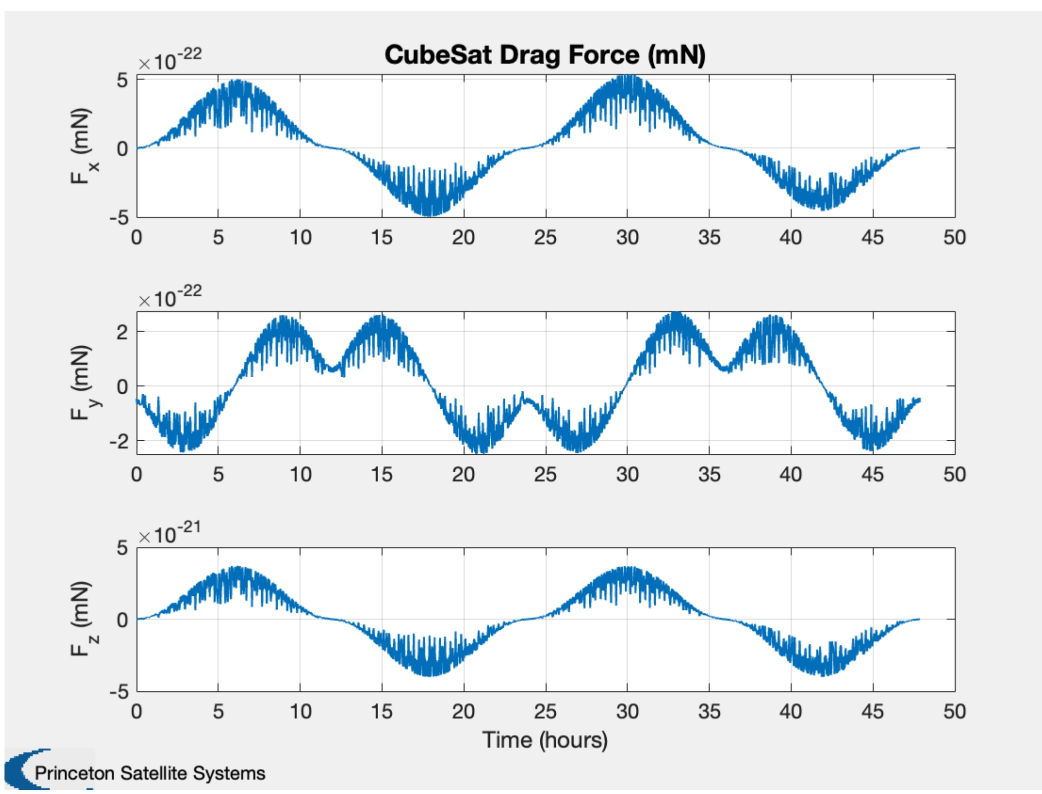

Figure 2.1.4: CubeSat drag force over 2 periods

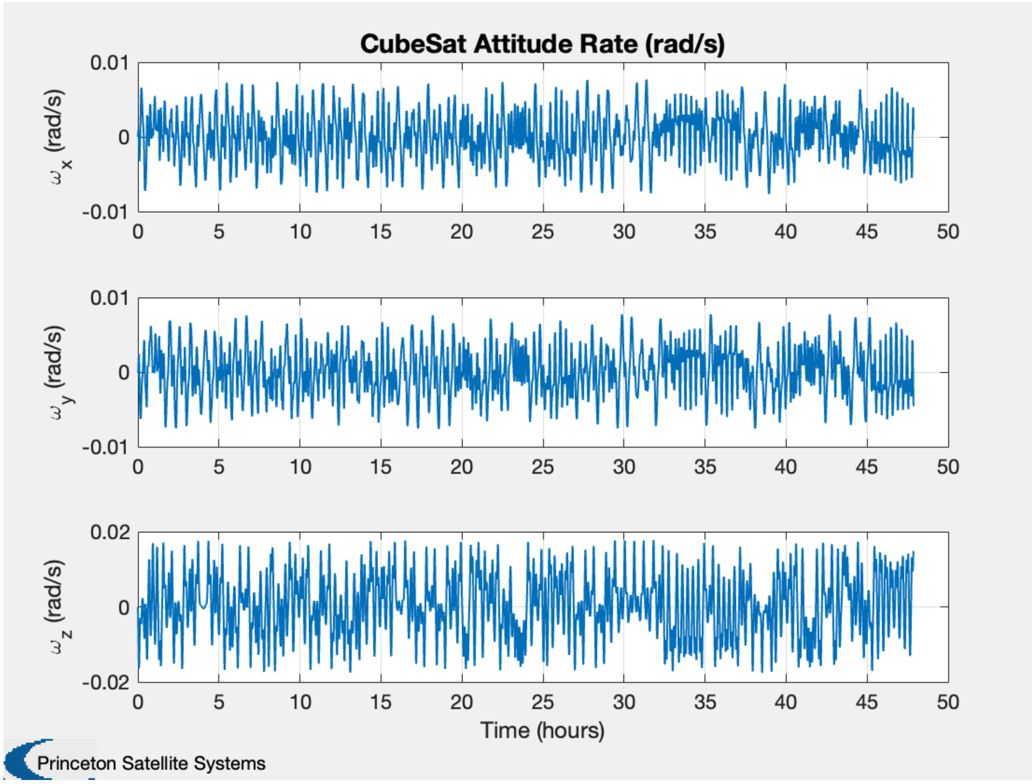

Figure 2.1.5: CubeSat altitude rate for 3 axis over 2 periods

2.2 Structure and Mechanism

This CubeSat will have a 3U structure (1 1 3), allowing it to house all the necessary payloads and subsystems without being overly complex or costly. 3U structures are the most common for CubeSats, making them compatible with most launch vehicles. Using a 3U structure will additionally allow the CubeSat to house a more heavy, robust ADCS subsystem, which is necessary as the payload data relies heavily on the consistency of T-reX's orientation towards the Sun. The additional volume a 3U structure provides also allows more room for thermal control mechanisms such as phase change materials, multilayer insulation, and heat pipes, which are necessary for the temperature fluctuation T-reX will face in GEO.

4 solar panels will be utilized for this CubeSat to maximize power generation, which is integral to storing enough energy to operate the X-ray flux detector and power all subsystems during the entire orbit. They will be deployed at a 90 degree angle to the lateral faces of the CubeSat at the operational phase to reduce drag during launch and in orbit. 4 patch antennas will also be placed on each x and y face of the CubeSat.

Structural Breakdown (bottom to top): 0.5U Altitude Control System, 1.5U System Electronics, 1U Payloads

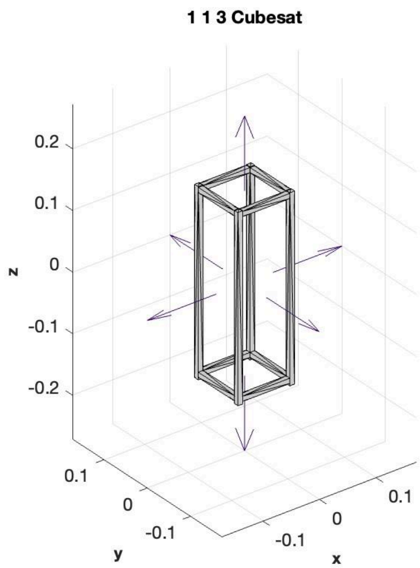

Figure 2.2.1: CubeSat primary structure

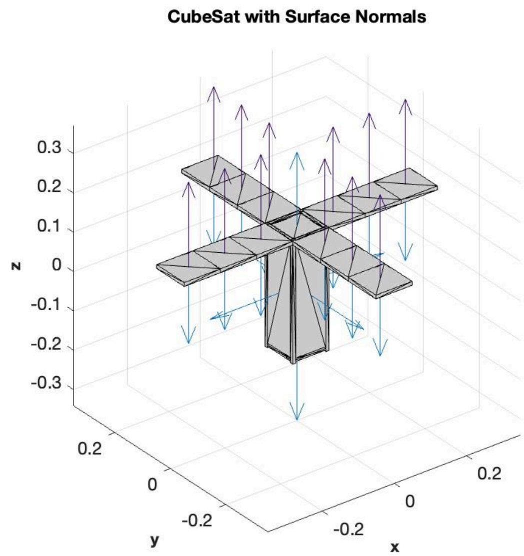

Figure 2.2.2: CubeSat structure including aluminum x/y panels and deployed solar panels

Volume Budget:

Subsystem	Volume (cm^2)	Volume Percentage
OBC	8.64	0.288%
ADCS	500	16.67%
Sun Sensor	3.249	0.108%
EPS/Li-Ion Batteries	233.606	7.79%
X-Band Transmitter	101.088	3.37%
X-ray Spectrometer	175	5.83%
Frame and Secondary Structure	300	10%
Deployable Solar Panels	-	-
X-Band Antenna	-	-
Panel X+ & X-	-	-
Panel Y+ & Y-	-	-

Panel Z+	-	-
Panel Z-	-	-
Heat Pipes	20	0.667%
MLI	25	0.833%
Phase Change Material	150	5%
Total Subsystem Volume	1516.583	51%
Max 3U Cubesat Volume	3000	100%

Table 2.2.1: CubeSat volume budget

Deployable solar panels, exterior aluminum panels, and antennas are not included in the internal volume of the CubeSat. All interior components have a length and width of <10 cm and can stack inside a 10 cm by 10 cm cross sectional CubeSat.

The internal subsystems of T-reX only take up around 51% of its maximum volume capacity, leaving empty pockets for additional mechanical structures and wiring channels. This significant amount of free space offers flexibility in arranging the components of T-reX for maximum stability and center of gravity control.

Mass Budget:

Subsystem	Mass (g)	Mass Percentage
OBC	80	2.40%
ADCS	890	26.73%
Sun Sensor	5	0.15%
EPS	184	5.53%
Li-Ion Batteries	165	4.96%
X-Band Transmitter	120	3.6%
X-ray Spectrometer	180	5.41%
Frame and Secondary Structure	290	8.71%
Deployable Solar Panels	440	13.22%
X-Band Antenna x4	80	2.40%

Panel X+ & X-	300	9.01%
Panel Y+ & Y-	300	9.01%
Panel Z+	50	1.5%
Panel Z-	120	3.6%
Heat Pipes	15	0.45%
MLI	10	0.3%
Phase Change Material	100	3.0%
Total	3.329 kg	100%

Table 2.2.2: CubeSat mass budget

2.3 Thermal Control Subsystem

In a high earth orbit, satellites undergo more extreme heat fluctuations, as they experience intense solar radiation when their orbit sweeps closer to the sun and experience freezing cold temperatures during the eclipse period. To protect from infrared radiation during periods closer to the Sun, this CubeSat will utilize passive thermal control including multilayer insulation, high emissivity surfaces, radiators, and heat pipes. A radiator will be placed on the Z- wall of the CubeSat to dissipate excess heat from the spacecraft, and thin, flat heat pipes will help transport the heat from hotter parts of the CubeSat to the anti-sunward side for the radiator to emit. The X sides of the CubeSat will be covered in high-emissivity anodized aluminum (absorptivity = 0.14, emissivity = 0.84) and the Y sides of the CubeSat will be covered in polished aluminum (absorptivity = 0.09, emissivity = 0.03); both will be lined and insulated with gold foil. The combination of anodized and polished aluminum will ensure that the CubeSat doesn't overheat from absorbing too much solar radiation, but still accepts enough heat to stay at an operational temperature range.

When T-reX is in the eclipse period, its payloads and other subsystems will be heated by phase change materials, functioning as a thermal battery to mitigate the extreme cold temperatures that can cause malfunctions or material fracture. One phase change material will be placed near the payload, and another will be placed near the EPS and battery system. The CubeSat's MLI will also assist in reducing heat loss. During an eclipse period, T-reX will no longer be able to detect solar flares, so the payload will not need to be operational, it will just need to maintain in working condition.

Equilibrium Surface Temperature (Solar Panels):

$$T_{\text{eq}} = \left(\frac{\alpha S}{\sigma \varepsilon}\right)^{1/4}$$

$$T_{eq} = (\frac{0.85\times1367}{5.67\times10^{-8}\times0.8})^{1/4} = 400.06K$$

Eq 2.3.1: Solar panel equilibrium surface temperature

Equilibrium Surface Temperature (Anodized Al Lateral Panels):

- Radiant energy from the Sun is 0 because the aluminum x and y panels are always facing perpendicular to the Sun: $q_{sol} = \alpha S A_{proj} = 0W$
- Assumed Albedo factor ~ 0.3
- Solar energy reflected by Earth based on estimated view factor: $q_{albedo} = \alpha A_f S A_{proj} F_{ES} = 0.3 \times 1367 \times 0.03 \times 0.3 = 3.69W$
- Radiation emitted by Earth based on estimated view factor: $q_{infrared} = \sigma\varepsilon T_E^4 A_{proj} F_{ES} = 5.67 \times 10^{-8} \times 0.84 \times 255^4 \times 0.03 \times 0.3 = 1.812W$
- Total CubeSat power consumption: $Q_{gen} = 19.326W$
- $q_{solar} + q_{albedo} + q_{infrared} + Q_{gen} = Q_{out,rad} = 24.73W$
- Surface area of panels: $A_{surf} = 2 \times 0.3 \times 0.1 = 0.06m^2$

$$T_{eq} = (\frac{Q_{out,rad}}{\sigma\varepsilon A_{surf}})^{1/4} = (\frac{24.73}{5.67\times10^{-8}\times0.84\times0.06})^{1/4} = 304.04K$$

Eq 2.3.2: Anodized aluminum lateral panels equilibrium surface temperature

Equilibrium Surface Temperature (Polished Al Lateral Panels):

$$T_{eq} = (\frac{Q_{out,rad}}{\sigma\varepsilon A_{surf}})^{1/4} = (\frac{24.73}{5.67\times10^{-8}\times0.03\times0.06})^{1/4} = 701.6K$$

Eq 2.3.3: Polished aluminum lateral panels equilibrium surface temperature

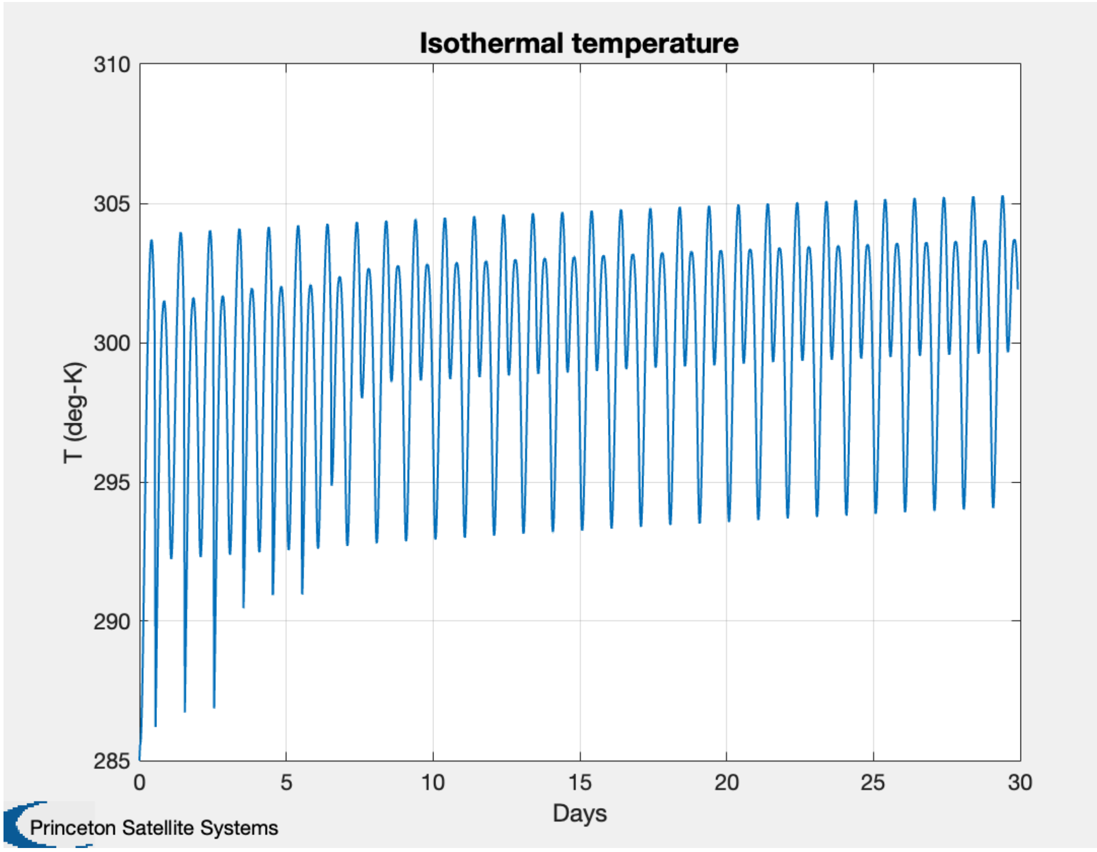

Figure 2.3.1: Isothermal temperature of entire CubeSat over the course of 30 days (aluminum and radiator on X/Y/Z surfaces accounted for, phase change materials, MLI, and heat pipe effects not included)

2.4 Power Subsystem:

This subsystem consists of the CubeSat's solar panels and electrical power system. T-reX's solar panels will capture energy from photons of sunlight, and its EPS will store the energy collected by the solar panels in electrical form. This CubeSat will utilize the ISIS electrical power system, consisting of a 2-cell battery board and a daughterboard to supply energy to the entire CubeSat, including the payloads, and ensure continuous operation even during eclipse periods. This EPS utilizes semiconductor technology to improve the efficiency of solar power conversion and is equipped with maximum power point tracking hardware.

T-reX's 4 solar panels will be deployed in orbit, and will each be 30 cm by 10 cm in area. They will be deployed outward from each lateral side at a 90 degree angle to form the shape of a cross. These solar cells will have a 30% efficiency, and due to the nature of the sun sensor, will always be surface normal to the Sun.

This CubeSat will utilize commercial lithium ion batteries (Li-Ion). Li-Ion batteries are more lightweight and smaller than commonly used nickel cadmium (NiCad) batteries and can operate in a broad range of temperatures. They also have a longer lifetime, which is integral for a satellite in HEO that will go much longer periods without making contact with the ground.

Power Budget:

Component	Power Consumption (W)	w/ 5% Contingency	Margin	Total (W)
Command & Data Handling				
OBC-Cube-Polar	3	3.15	20%	3.78
Altitude Determination and Control				
XACT-15 Altitude Control System	2.82	2.961	20%	3.553
NXSS2v01 Sun Sensor	0.0205	0.0215	10%	0.0237
Communication				
PULSAR-XTX X-Band Transmitter	7	7.35	20%	8.82
Electrical and Power				
ISIS iEPS Type A	~0	0	20%	0
Payload				
X-123SDD X-ray Spectrometer	2.5	2.625	20%	3.15
Total	15.34	16.108		19.326

Table 2.4.1: CubeSat power budget

Total power consumption during daylight period: 19.326 W
Total power consumption during eclipse (see table 3.2.2): 7.333 W

Battery Capacity Requirement:

- $\eta_{DOD(Li-Ion)} = 0.85$
- $V_d = 3.3$ V
- Time in eclipse ~ 50 min
- Battery Load-to-loss ~ 3%

$$C = \frac{P_n T_n}{X_{b\to l}\eta_{DOD}V_d}$$

$C = \frac{7.333 \times 50/60}{0.97 \times 0.85 \times 3.3} = 2.25Ah$

Eq 2.4.1: Battery capacity requirement during eclipse

Energy Capacity of 2 Li-Ion Batteries:

- Battery Capacity = 3 Ah

$$E_b = NC_bV_d$$

$E_b = 2 \times 3 \times 3.3 = 19.8Wh$

Eq 2.4.2: Total energy capacity of 2 Li-Ion batteries

Battery Mass:

- Specific energy of Li-Ion Battery = 120 Wh/kg

$$m_b = \frac{E_b}{S_b}$$

$m_b = \frac{19.8}{120} = 0.165\ kg$

Eq 2.4.3: Mass of 2 Li-Ion batteries

Solar Power Generation (Operational Conditions):

- Solar cell total area = $12 \times 0.01 \times 0.01 = 0.12\ m^2$
- Incidence angle = 0 deg (assumed normal)
- Efficiency = 30%
- *Power in lab conditions*: $P_{L,\,total} = A \times Scosi\eta = 0.12 \times 1367 \times cos0 \times 0.3 = 49.2\ W$

$$P_c = P_L\left(\eta_{rad}\eta_{uv}\eta_s\eta_{cy}H_I\eta_m\eta_I\eta_{con}\eta_t L_p\right)$$

$P_{c,\,total} = 49.2(0.8 \times 0.98 \times 1 \times 0.99 \times 1 \times 0.975 \times 0.98 \times 0.9 \times 0.86 \times 0.996) = 28.13\ W$

Eq 2.4.4: Total power generation of solar panels

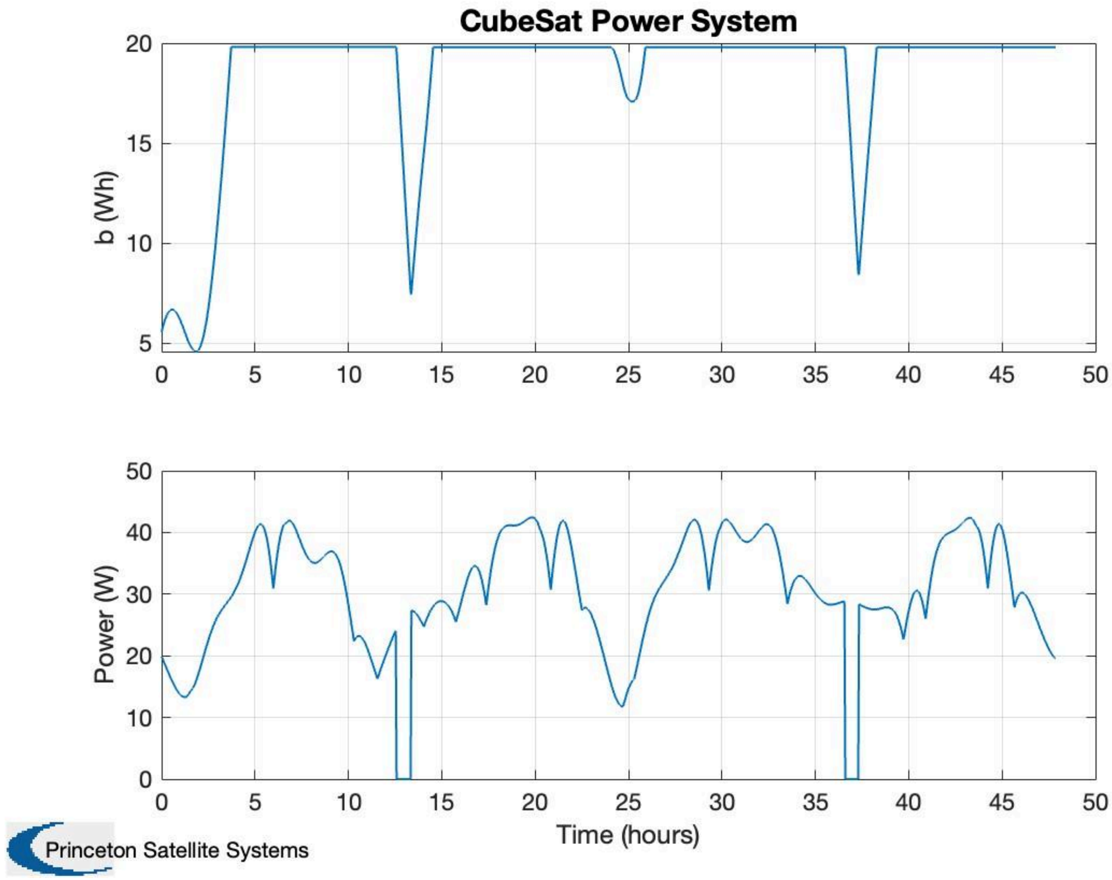

Figure 2.4.1: Power system model showing battery capacity and solar power generation of the CubeSat over a 48 hour period. Sections in graphs with zero solar power generation represent eclipse periods (relatively short in GEO), where the battery is the only source of power for the CubeSat. This graph does not account for all power losses in the solar array whilst in operational conditions.

The battery capacity, b, is full during daylight periods when receiving an influx of power from the solar panels, as seen in the bottom graph. The dips in the battery capacity graph happen during eclipse periods, which can be interpreted from the graph as when solar power generation is zero. This is when the CubeSat solely relies on battery power to power its subsystems.

2.5 Altitude Determination and Control System

T-rex will utilize Blue Canyon Technology's XACT-15 altitude and determination control system that employs various sensors and actuators to precisely measure and control its altitude.

XACT-15 contains star trackers that precisely provide 3-axis attitude determination (with accuracies of $\pm$ 0.003 degrees and $\pm$ 0.007 degrees) relative to stellar bodies with known positions. It additionally contains a coarse sun sensor that assists with estimation and provides basic vector information about the Sun's relative location to the spacecraft. A magnetometer is also employed to assist in altitude determination by measuring the strength of magnetic fields around the spacecraft. XACT-15 also includes accelerometers and gyroscopes to report continuous data on the spacecraft's linear acceleration and angular velocity. Since the payload data heavily relies on the CubeSat's orientation to the Sun, an additional sun sensor will operate in conjunction with XACT-15 to ensure that the x-ray spectrometer is always directly pointing towards the Sun.

XACT-15 contains 3 micro-sized reaction wheels to control the CubeSat's altitude over 3 axes. Blue Canyon's RWP015 reaction wheels are used in XACT-15, and they generate a maximum momentum of 0.015 Nm/s and a maximum torque of 0.004 Nm. XACT-15 also contains 3 magnetorquers to manage the spacecraft's angular momentum and orientation by generating a dipole moment to interact with Earth's magnetic field. The magnetorquers can produce a torque to change the spacecraft's altitude or orientation.

In GEO, reaction wheels are the main contributors to altitude control, and the magnetorquer does minimal work (~0.1 μT) as Earth's magnetic field strength is much more insignificant at high orbits. Magnetorquers in GEO primarily only assist with reaction wheel desaturation, which is the process of creating a torque in the opposing direction to the reaction wheels to relieve them of excess momentum that builds up. Although the exact specifications for the magnetorquers in XACT-15 are not specified, the model below represents the basic specifications necessary for a theoretical magnetorquer in T-reX.

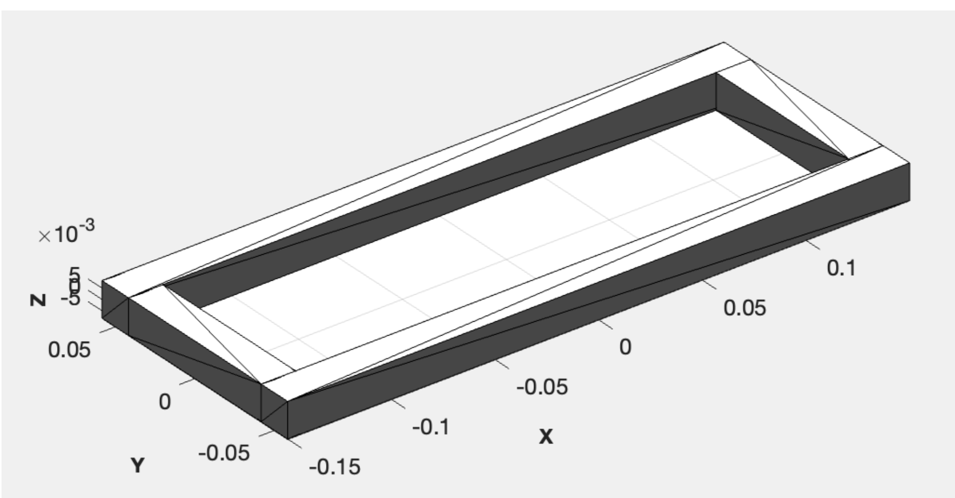

Figure 2.5.1: Magnetic torquer design

If 3 of these magnetorquers are used to provide altitude control for each axis, the graph below represents the magnitude of magnetic torques overtime that the CubeSat's ADCS will provide.

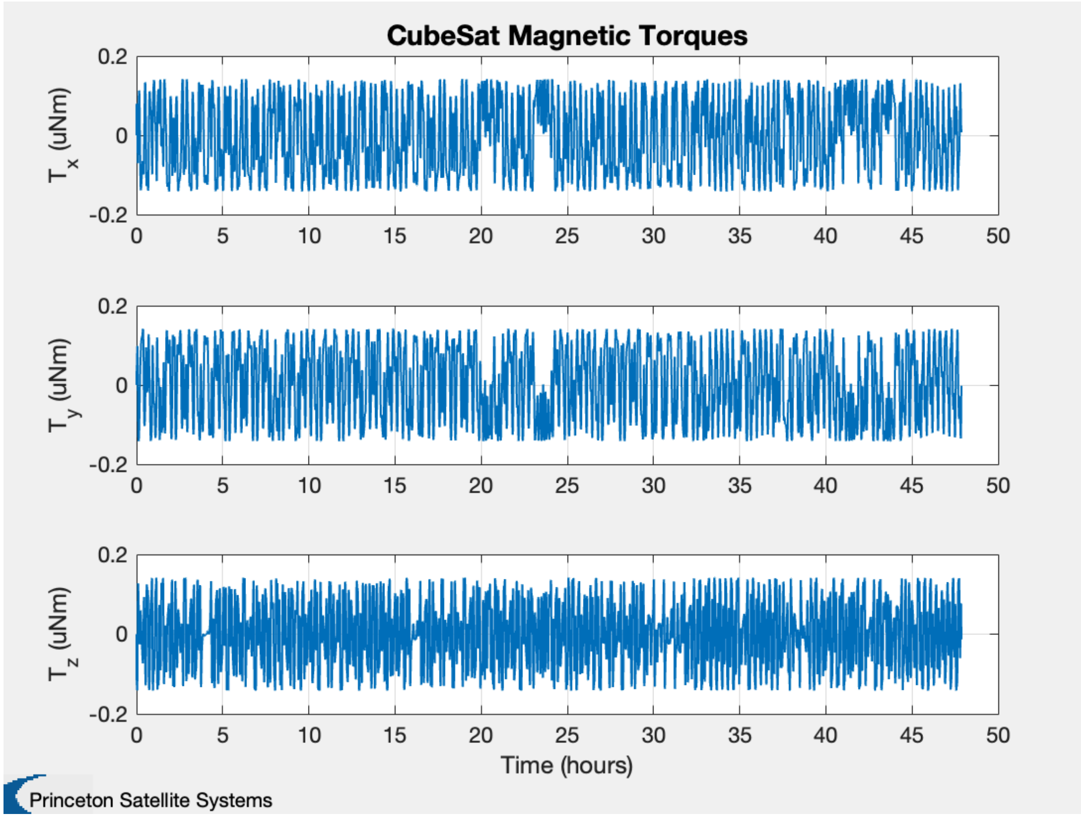

Figure 2.5.2: CubeSat magnetic torques over 3 axis

Pointing Budget

Component	Target	Axis to Align and Frame of Axis	Accuracy	Precision	Function
Command & Data Handling					
OBC-Cube-Polar	N/A	N/A	N/A	N/A	N/A
Altitude Determination and Control					
XACT-15 Altitude Control System	N/A	N/A	0.007 deg	0.003 deg	Provides Control and Estimation
NXSS2v01 Sun Sensor	N/A	N/A	N/A	N/A	Provides Estimation
Communication					
PULSAR-XTX	N/A	N/A	N/A	N/A	N/A

X-Band Transmitter					
X-Band Antenna	Ground Station	(+,-) X or Y Axis of Spacecraft to be aligned with Earth Nadir	5 deg	1 deg	Needs Pointing
Electrical and Power					
ISIS iEPS Type A	N/A	N/A	N/A	N/A	N/A
Deployable Solar Panels	The Sun	(+) Z Axis pointing to Sun Zenith	N/A	N/A	Needs Pointing
Thermal					
Heat Pipes	N/A	N/A	N/A	N/A	N/A
Phase Change Material	N/A	N/A	N/A	N/A	N/A
Payload					
X-123SDD X-ray Spectrometer	The Sun	(+) Z Axis pointing to Sun Zenith	N/A	N/A	Needs Pointing

Table 2.5.1: CubeSat pointing budget

2.6 CDH and Communication Subsystem

2.6.1 Command and Data Handling

An on board computer (OBC) will be placed inside T-reX to process telemetry data, store critical payload data, monitor the health of subsystems, receive commands from the ground station, and control the power use of different subsystems. The payload data takes up the most amount of capacity on the OBC, as a real-time stream of data from the x-ray spectrometer is being uploaded to the CubeSat. T-reX will use CAVU Aerospace's OBC-Cube-Polar; this specific OBC is lightweight, takes up minimal space on the CubeSat, and has a radiation-tolerant design which is important in GEO. It also contains high speed data ports and is powerful enough to handle real-time tasks, making it suitable to support the x-ray spectrometer, which will generate a significant amount of data. It has a maximum memory of 4GB and has ECC protection, meaning that it automatically detects and corrects bit errors from radiation.

Data Budget

Component	Data Rate (kbps)	Margin	Data Rate with 5% Contingency (kbps)
Payload (X-123SDD List Mode)	320	5%	336
ACDS Telemetry	10	5%	10.5
EPS Telemetry	5	5%	5.25
Thermal Telemetry	5	5%	5.25
Communications Housekeeping	0.1	5%	0.105
OBC Housekeeping	5	5%	5.25
Command Uploads	1	5%	1.05
Total	346.1		363.405

Table 2.6.1.1: CubeSat data budget

The amount of GB per day the OBC needs to store its telemetry, communication, and payload data can be calculated from the total data rate of the CubeSat.

$$363.405kbps \cdot \frac{1000bits}{1kb} \cdot \frac{1byte}{8bits} = 45.425kB/s$$

$$45.425kB/s \cdot 3600 \cdot 24 = 3.924GB/day$$

Eq 2.6.1.1: CubeSat total GB usage per day

OBC-Cube-Polar’s maximum memory is 4GB, so it will have enough onboard storage to accommodate T-reX’s daily data budget, though the margin is slim.

2.6.2 Communication Subsystem

T-reX’s communication subsystem will consist of an X-band transmitter and 4 patch antennas to increase its communication signal. T-reX will use the PULSAR-XTX X-Band Transmitter that allows bidirectional communication between the CubeSat and the ground station; the ground station can simultaneously collect telemetry data, collect logs from the payload and send commands to the CubeSat. X-band transmitters are more suited for CubeSats in GEO orbit than

UHF or S-band transceivers, as they have higher data transmission rates which will be necessary for T-reX to transmit continuous data from the x-ray spectrometer to the ground station over a long distance. Compared to even higher frequency Ku and Ka-band transmitters, X-band transmitters suffer less atmospheric loss and are compact and simply designed, making them ideal for CubeSats with limited power and space. Four X-band patch antennas, thin 6 by 4 centimeter panels, will be placed on each X and Y side of the CubeSat. Patch antennas are especially valuable during launch as they are flat to the sides of the CubeSat and compact, not interfering with the launch vehicle, and are often more lightweight than regular antennas.

T-reX's ground station will be stationed in Quito, Ecuador for optimal satellite communication in a GEO orbit. GEO orbit satellites operate directly above the equator, and stay in the same position above the earth as it rotates. Quito is very close to the equator, with a latitude of 0.1807 degrees South and a longitude of 78.4678 degrees West, and has a high elevation of 2850 meters above sea level, allowing for optimal communication with the satellite. It is also located near T-reX's launch site in Florida, which could be useful during the beginning stages of operation when the CubeSat's telemetry data needs to be updated and established quickly.

According to Transcelestial, (ref) a "good" bit error rate is considered less than 1e-5, so link budget analysis is performed below to assess whether the current communication system can achieve a bit error rate of less than 1e-5. Values in the link budget table were found from the data sheets of PULSAR-XTX X-Band Transmitter and IQ Spacecom X-Band Antenna, or assumed based on a satellite in GEO orbit. Bit rate was calculated in table 2.6.1.1.

First, the signal-to-noise ratio must be solved for based on the bit error rate (R_{be}).

$$\frac{E_b}{N_0} = -2ln(2R_{be}) = -2ln(2 \cdot 1e - 8) = 21.64$$

Eq 2.6.2.1: CubeSat desired signal to noise ratio

Next, the path loss due to space propagation must be calculated. Since the spacecraft is in GEO, this loss is significant due to its distance from the ground station.

$$L_s = 20log_{10}(\frac{4\pi df}{c}) = 20log_{10}(\frac{4\pi \cdot 35783150 \cdot 8.025 \cdot 10e9}{3 \cdot 10e8}) = 201.604\, dB$$

Eq 2.6.2.2: CubeSat communication path loss due to space propagation

The required transmitter power to achieve the target bit error rate can be solved for using the variables below.

$$P_t = \left(\frac{E_b}{N_0}\right)\frac{R_b L_s k T_s}{L_t L_m G_t L_p L_a G_r}$$

$$P_t = (21.64)\frac{363.405 \cdot 10e3 \cdot 1.45e16 \cdot 1.38065e-23 \cdot 290}{0.794 \cdot 0.794 \cdot 10 \cdot 1 \cdot 1 \cdot 45} = 1.609W$$

Eq 2.6.2.3: CubeSat required transmitter power for communication to ground

The received power by the ground station can be calculated from the transmitter power as follows.

$$P_{EIR} = P_t + G_t = 1.387 + 10 = 11.387 dBW$$

$$P_r = P_{EIR} - L_s + G_r = 11.387 - 201.6 + 45 = -145.213 dBW = 3.015 fW$$

Eq 2.6.2.4: Received power from transmitter to ground station

Link Budget

	Value	Unit	Loss Factor
Transmitter			
Modulation Attenuation (L_m)	-	-	0.794
Line Attenuation (L_t)	-	-	0.794
Antenna Gain (G_t)	10	dB	-
Bit Rate	363.405	kbp	-
Propagation Path			
Space Attenuation (L_s)	201.6	dB	1.45e16
Polarisation Attenuation (L_p)	~0	dB	1
Atmospheric Attenuation (L_a)	~0	dB	1
Receiver			
Antenna Gain (G_r)	45	dB	-
System Noise Temperature (T_s)	290	K	-
Required Transmitter Power (P_t)	1.609	W	
Received Power at Ground	3.015	fW	

Station (P_r)			
Transmit Power Margin Factor	0.6126	W	
Transmitter Power per Antenna	0.5	W	
Total Transmitter Power	2	W	

Table 2.6.2.1: CubeSat link budget

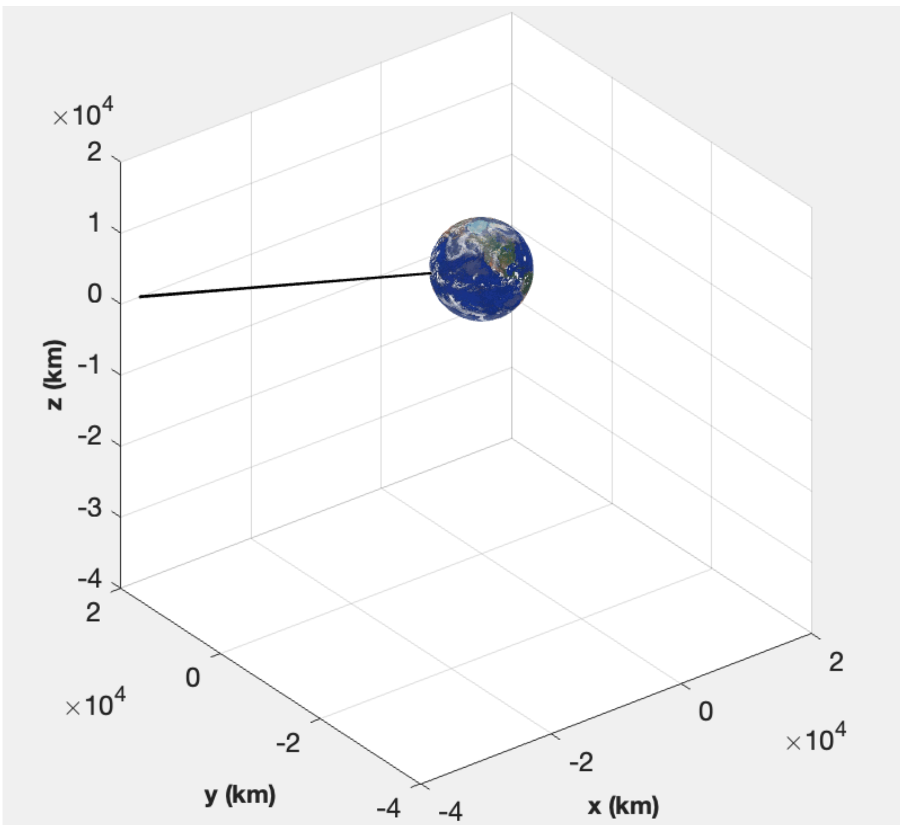

Figure 2.6.2.1: Satellite visibility from ground station

The CubeSat is in a geostationary orbit, so it should stay in the same location above Earth at all times.

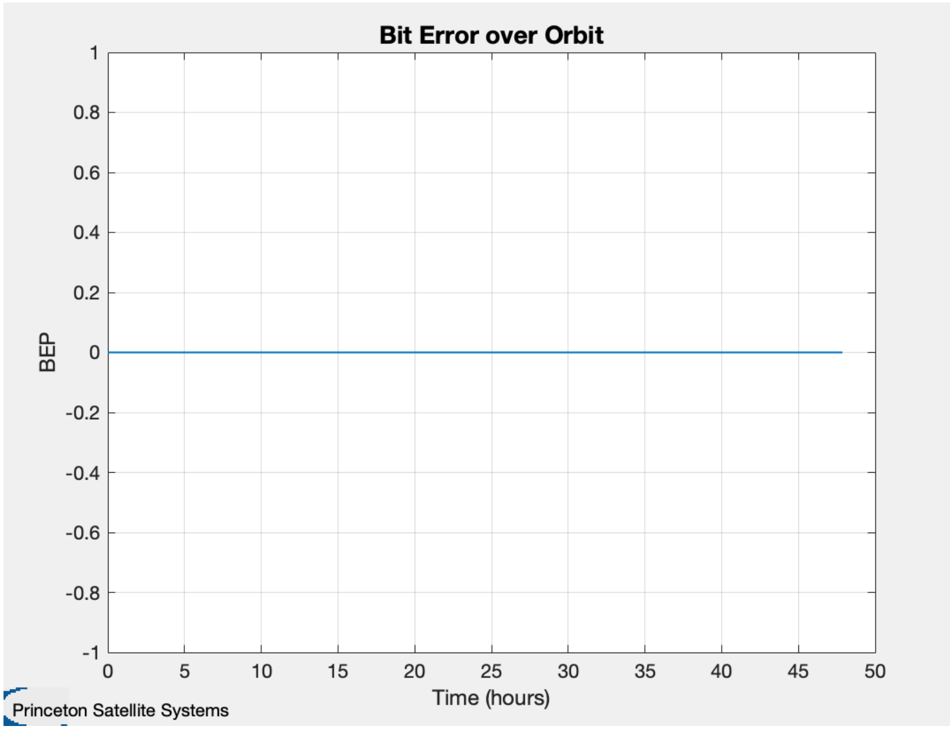

Figure 2.6.2.2: Bit error over orbit (1e-5)

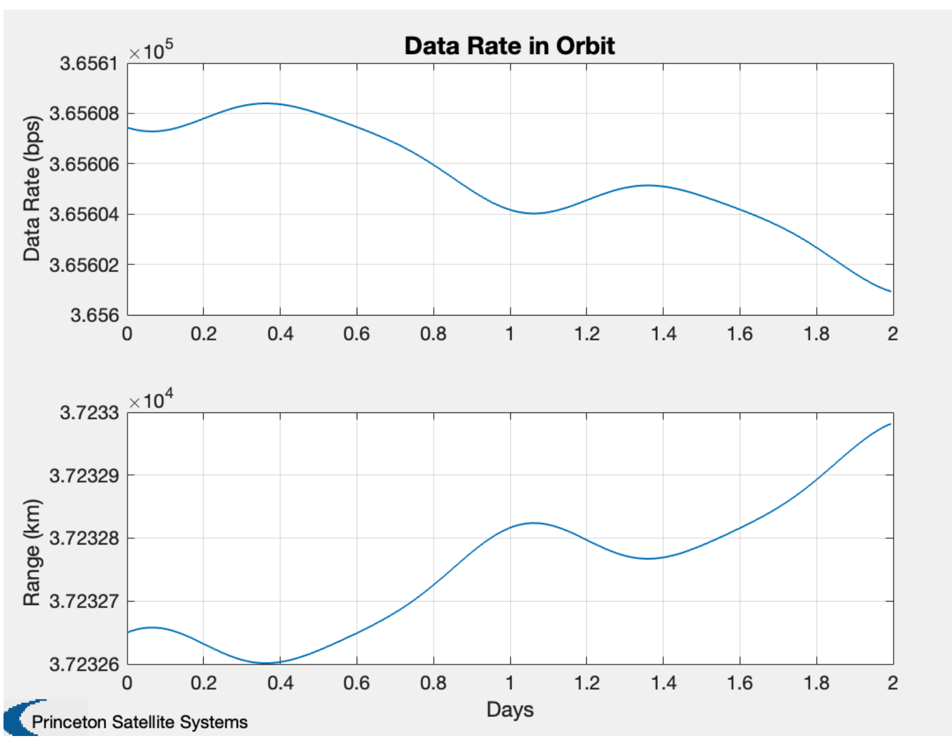

Figure 2.6.2.3: Data rate in orbit when providing transmit power enough to achieve a desired data rate of ~363.405 kbps

2.5 Payload

X-ray Spectrometer
- Mass: 180 g
- Dimensions: 7 x 10 x 2.5 cm
- Power Requirements: 2.5 W

Figure 2.5.1: Ametek X-123SDD Complete X-Ray Spectrometer with Silicon Drift Detector (SDD)

The x-ray spectrometer will be able to report the strength of solar flares via measuring solar radiation, which can indicate the early stages of solar storms when unusually high. The x-ray spectrometer consists of a silicon drift detector along with a digital pulse processor and a power supply. The silicon drift detector works by measuring the energy of incoming charged particles by the ionization they cause from knocking off electrons from atoms in the material. The digital pulse processor in the spectrometer digitizes the output of the drift detector, records peak amplitude of the radiation, and then records it in its histogram memory. The recorded x-ray spectrum is then transferred over to the CubeSat's OBC.

The x-ray spectrometer only requires a 5V power supply from the CubeSat's EPS and a connection to a communication/data collection interface, which will be primarily the CubeSat's OBC, to function. The on board computer (OBC) will manage the data collection and transmission of the CubeSat, as well as control its main operations. T-reX's communication subsystem will allow the spacecraft to continuously transmit data from the OBC to the ground station. The CubeSat's altitude control subsystem will stabilize its orbit and ensure that the spectrometer is facing the right direction toward the Sun. T-reX will use Blue Canyon Technology's XACT-15 Altitude control system and will use a sun sensor to detect the position of the Sun relative to the spacecraft.

3. Operational Life

3.1 Launch Option

Every year, in an effort to inspire scientists of the next generation, NASA's CubeSat Launch Initiative selects CubeSats proposals from educational institutions and non profits to launch into space at a low cost. As T-reX was designed at an educational institution, it qualifies to be selected for this initiative, which could streamline launch processes and minimize cost. Each CubeSat pairs with NASA's Launch Services Program, which will accommodate the CubeSat's planned orbit as well as any other special considerations. T-reX will be manufactured in the US and will be launched at Cape Canaveral Space Force Station in Florida, which is one of NASA's primary launch sites and is ideal for spacecrafts going into equatorial orbit. T-reX is projected to launch around June 2029 after the CubeSat and ground station are fully developed, proper licensing is acquired, and necessary hardware testing is done. Cape Canaveral Station has launch vehicles that can be used to carry CubeSats into space; T-reX will be launched from the Atlas V rocket Aft Bulkhead Carrier, which offers a rideshare program for small satellites, and will stay in the rocket's carrier until it reaches its necessary height for a GEO orbit. Typically, this rideshare program would cost around 300,000 dollars, but NASA's CubeSat Launch Initiative would cover most of it, though it doesn't specify online what the remaining total would be exactly.

3.2 Daytime Operation

Daytime Power Budget (Includes Passive Systems)

Component	Operational?	Power Consumption (W)	w/ 5% Contingency	Margin	Total (W)
Command & Data Handling					
OBC-Cube-Polar	Yes	3	3.15	20%	3.78
Altitude Determination and Control					
XACT-15 Altitude Control System	Yes	2.82	2.961	20%	3.553
NXSS2v01 Sun Sensor	Yes	0.0205	0.0215	10%	0.0237
Communication					
PULSAR-XTX	Yes	7	7.35	20%	8.82

X-Band Transmitter					
X-Band Antenna	Yes	0	0	20%	0
Electrical and Power					
ISIS iEPS Type A	Yes	~0	0	20%	0
Deployable Solar Panels	Yes	0	0	20%	0
Thermal					
Heat Pipes (Passive)	Yes	0	0	20%	0
Phase Change Material (Passive)	No	-	-	-	-
Payload					
X-123SDD X-ray Spectrometer	Yes	2.5	2.625	20%	3.15
Total		15.34	16.108		19.326

Table 3.2.1: Daytime power budget

During the daytime, when the CubeSat has a clear view of the Sun, all subsystems requiring power are operating at their maximum output as the payload is actively working and real-time data is being collected and sent to the ground station. The only system that is not actively operating is the phase change material, that is absorbing heat from the Sun, but not actively releasing any energy as the CubeSat is warmed by the Sun's radiation.

3.3 Nighttime Operation

Nighttime Power Budget (Includes Passive Systems)

Component	Operational?	Power Consumption (W)	w/ 5% Contingency	Margin	Total (W)
Command & Data Handling					
OBC-Cube-Polar	Yes (reduced)	1	1.05	20%	1.26
Altitude Determination and Control					
XACT-15 Altitude	Yes	2.82	2.961	20%	3.553

Control System					
NXSS2v01 Sun Sensor	No	-	-	10%	-
Communication					
PULSAR-XTX X-Band Transmitter	Yes (reduced)	2	2.1	20%	2.52
X-Band Antenna	Yes	0	0	20%	0
Electrical and Power					
ISIS iEPS Type A	Yes	~0	0	20%	0
Deployable Solar Panels	No	-	-	20%	-
Thermal					
Heat Pipes (Passive)	No	-	-	-	-
Phase Change Material (Passive)	Yes	0	0	20%	0
Payload					
X-123SDD X-ray Spectrometer	No	-	-	20%	-
Total		5.82	6.111		7.333

Table 3.2.2: Nighttime power budget

During the eclipse period, most subsystems still need to be operational to continue to monitor and report the CubeSat's health and telemetry data. The OBC and X-band transmitter will operate at a reduced power (~20%) to conserve battery power, as they do not need to be actively uploading and transmitting payload data, which is the most significant part of their duty during the daytime. However, the x-ray spectrometer and sun sensor do not have to be actively powered as T-reX is no longer in direct view of the Sun. Similarly, the deployable solar panels are no longer collecting power when not exposed to the Sun's radiation, and the passive heat pipes no longer need to distribute excess heat around the CubeSat to the radiator. The CubeSat's phase change material will start to release heat during the eclipse period to ensure that its key electronics do not freeze and maintain their operating temperature.

3.4 End of Life Operations

At the end of its operational life, T-reX will move into a graveyard orbit from its geosynchronous orbit to avoid becoming space junk and interfering with other operational satellites. Since T-reX does not contain an active propulsion system, it will utilize a drag sail to slowly transition into a graveyard orbit. This drag sail will be deployed once the CubeSat is no longer operational and will produce a consistent, small drag force on the CubeSat and cause it to lose its orbital momentum. The drag force will be weak, since the atmosphere is thin in GEO, so this process could take years, but T-reX will eventually be pushed further and further outward into the graveyard orbit, around 300 km above GEO.

Conclusion

T-reX will enhance real-time solar storm observation by using X-ray technology to detect solar flares early in their development. Operating in a geostationary earth orbit, this CubeSat will provide uninterrupted, real-time data to satellite companies and researchers to warn them of potential threats to their satellites and communication systems. This data will aid satellite companies in finding a system to adjust their orbits without collisions as satellite traffic increases drastically. In addition to the x-ray spectrometer that will be used to detect solar flares, T-reX will consist of an on-board computer, an electronic power system, a thermal control subsystem, an altitude control system, and a X-band transmitter with patch antenna for communication. Solar panels will be deployed during orbit to streamline launch efforts. The satellite will be launched by NASA's CubeSat Launch Initiative (CSLI), which provides low-cost space access to chosen CubeSat projects from eligible organizations. The design, testing, and launch processes combined should take around 5 years, and the expected operational life of the CubeSat should also be 5 years. After the CubeSat is no longer operational, it will be transferred into a graveyard orbit, away from active operational zones.

Throughout the process of designing T-reX, insights were gained into the difficulty of launching and maintaining a CubeSat in a high geosynchronous orbit. Key lessons were learned in the importance of managing limited power, the importance of a highly efficient communication subsystem, and the need for intensive and methodic thermal control to prevent CubeSat electronics from overheating. Additionally, each subsystem has significant effects on one another; replacing one subsystem can affect the whole CubeSat's power needs, thermal control needs, and communication links, which makes it challenging to make adjustments further into the ideation process. In future CubeSat design, margins for battery capacity, data storage capacity, and communication power may need to be higher, as space and launch conditions can often cause unexpected damage or operational environments. Overcompensating for the CubeSat's operational needs can ensure its operation upon launch and long-term mission success.

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