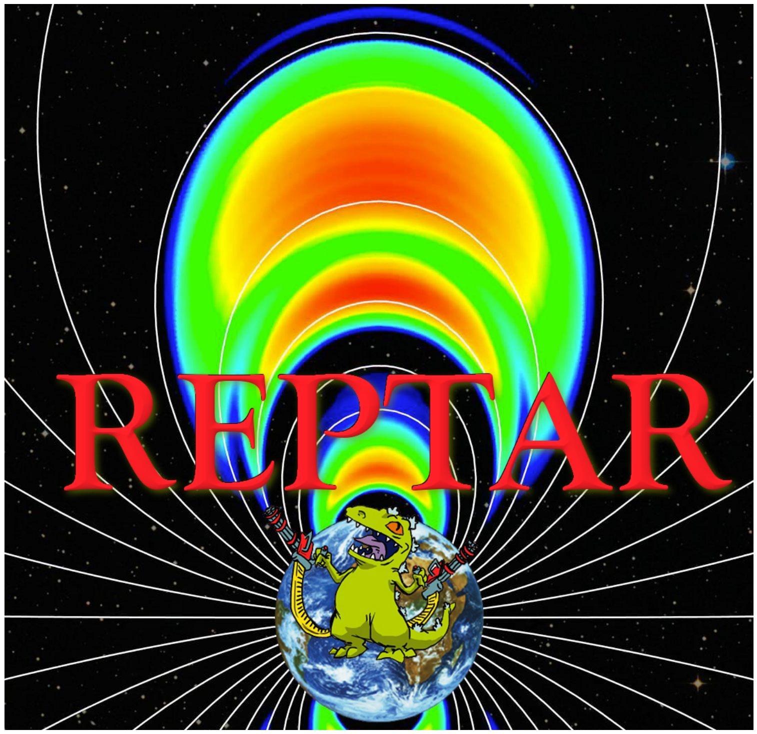

REPTAR: Relativistic **E**lectron **P**recipi**T**ation in Earth's **A**tmosphe**R**e

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REPTAR CubeSat Mission Summary

Objectives. The Relativistic Electron Precipitation in Earth's Atmosphere (REPTAR) CubeSat is being designed by students at the University of Colorado Boulder. Its primary objective is to understand the rate at which energetic electrons are deposited into Earth's atmosphere as they are lost from the Van Allen Belts. During geomagnetic storms, caused by forcing from energetic solar events like solar flares and Coronal Mass Ejections (CMEs), the populations of these belts drop significantly. There are two primary loss mechanisms: the electrons can fall to Earth near the horn points of the radiation belts, or they can be lost to space as the increased magnetic pressure from the Sun causes the Earth's magnetopause to overlap with the belt. Previous missions that measured the populations of these belts were unable to distinguish between these two loss mechanisms. Consequently, we are not currently able to constrain the flux into the atmosphere.

REPTAR will measure the differential downflowing versus upflowing electron flux near the horn points of the belts, providing the first direct measurement of atmospheric electron precipitation. The effect of geomagnetic storms on precipitation rates will be studied, which drives a mission lifetime requirement of six months to ensure that measurements are taken during at least two storms. These measurements are important for a variety of reasons: When electrons enter the ionosphere, they can degrade or disrupt spacecraft communications, including disruption of vital GPS coverage; they are a source of damaging radiation to spacecraft components and understanding the distribution of precipitation will help inform future spacecraft shielding requirements; and the energy deposited into the atmosphere is a vital input to terrestrial climate and weather modeling. Correlating REPTAR measurements with solar activity will assist in the production of predictive models to guide responses to energetic solar events.

REPTAR's baseline mission includes an attempt to make the first measurements of the pitch angle of radiation belt electrons. This novel information will provide a much more detailed understanding of electron behavior, including determination of the exact altitude at which electrons precipitate. This measurement is extremely difficult to make, and the mission is conceived as a technology readiness demonstration. In the event that this novel measurement fails, however, our instrument design is such that we will still be able to achieve our threshold science objective of determining total electron atmospheric precipitation.

Methodology. REPTAR is a 6U CubeSat that will use the Blue Canyon XACT system to orient itself along the magnetic field lines of the Van Allen Belts. The payload consists of two particle detectors oppositely oriented along the magnetic field line. The instruments will measure electrons with energies from 100 keV to 1.6 MeV, and pitch angles from 0 to 45 degrees. These detectors are derived from the REPTile instrument on the Colorado Student Space Weather Experiment(CSSWE), another CubeSat mission developed at the University of Colorado in Boulder. REPTAR thus benefits from strong heritage both instrumentationally and institutionally.

1 Science Motivation and Relevance to NASA

REPTAR's mission is to determine the energy flux and pitch angle distributions of Earth's radiation belt electrons near their mirror points to assess upper atmosphere interactions during both geomagnetic activity and quiescent times. This objective will address the 2013 Decadal Survey for Heliophysics Key Science Goal #2,

> "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." [1]

1.1 Science Background

Earth's magnetosphere contains the Van Allen Radiation Belts, consisting of an inner proton belt and outer electron belt. Both toroidal regions of trapped particles are centered on the magnetic equator. Energetic protons accelerated by cosmic ray interactions with the atmosphere fill the proton belt, extending approximately from L values of 1.5 to 2.5, with protons having typical energies of 100 keV to 100 MeV. Electrons from both the atmosphere and solar wind, with typical energy from 100 keV to a few MeV, occupy the electron belt between L values of about 4 to 6.

Charged particles in a magnetic field follow cyclotron paths with velocity components both parallel and perpendicular to magnetic field lines. The angle between the particle velocity and the magnetic field is the pitch angle, given by:

$$\alpha = \tan^{-1}\left(\frac{v_\perp}{v_\parallel}\right) \tag{1}$$

Pitch angle is an instantaneous property of an energetic particle. While traveling along converging magnetic field lines, the particle's parallel velocity gradually becomes perpendicular velocity. The mirror point is the location where the pitch angle reaches 90° (i.e., where the particle's velocity is entirely perpendicular to the field line), and the particle reverses direction. An energetic particle that mirrors at a low enough altitude will precipitate into the atmosphere and deposit its energy, manifested as ionization and atmospheric heating. Increased ionization influences both ground and spacecraft communications. Atmospheric heating increases atmospheric density at high altitudes, which increases satellite drag in low-Earth orbit. The loss cone is defined by the limiting pitch angle within which particles are expected to precipitate. That critical angle is dependent on the local magnetic field strength, so the loss cone varies spatially in a dipole magnetic field and temporally due to field variations.

$$\sin^2 \alpha_{loss} = \frac{B}{B_M} \tag{2}$$

Once the local field strength is measured, the loss cone pitch angle can be calculated. The magnetic field strength at the mirror point, B_M, can be obtained from the International Geomagnetic Reference Field (IGRF) [2] or similar models for an assumed 100 km altitude, below which particles should precipitate.

The Radiation Belt Storm Probes (RBSP) mission has helped to increase understanding of acceleration, global distribution, and variability of radiation belt electrons and ions [3]. The dynamics and coupling of those particles with the atmosphere has not been adequately addressed. The electron belt is characterized with polar-region horns that extend down to low altitudes, where particle-particle interactions are observed. CSSWE complemented RBSP by measuring the flux of protons from solar energetic particle events and radiation belt electrons within the horns [4]. These recent missions have contributed to the study of space weather and Earth's radiation belts, but there has been no direct measurement of energy deposition into the atmosphere.

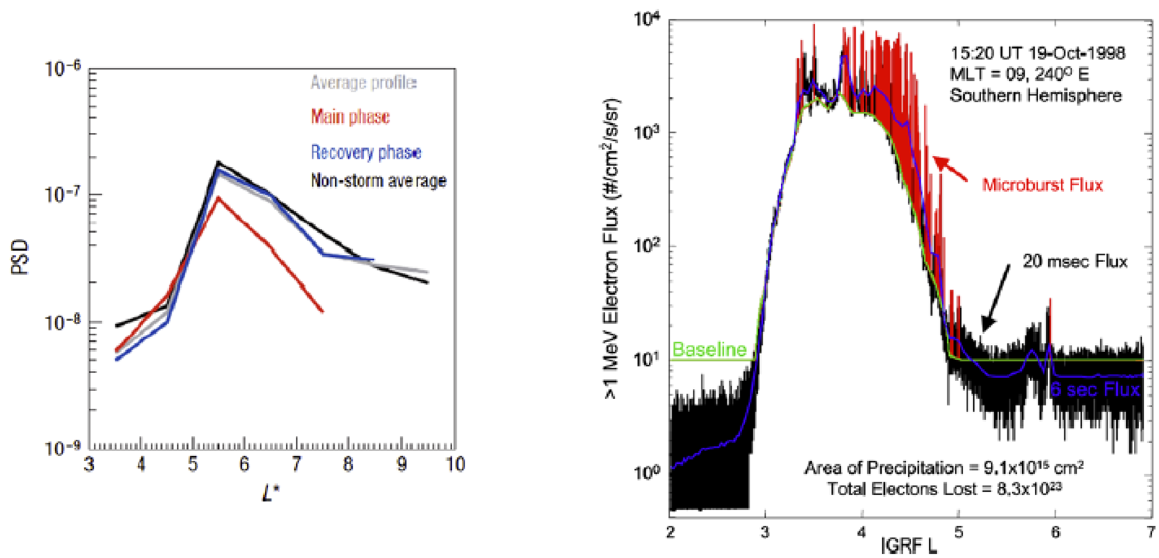


Figure 1: Storm effects on radiation belt electrons [5]. Left: Phase space density (PSD) of energetic electrons for a constant third adiabatic invariant L^* (slightly lower than L-shells, e.g. $L^* = 5.5 \sim L = 6$). Right: Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) observations of microburst input to the electron belt.

Figure 1 depicts the response of trapped electron populations to geomagnetic storms, where both depletions and enhancements are evident. REPTAR seeks to address questions about what the energy input from loss cone electrons into the atmosphere is in quiescent times an how geomagnetic storms change this dynamic by in situ electron detection within the loss cone. Measuring both the incoming and outgoing electron energy yields the energy flux from the electron belt into the atmosphere. Pitch angle measurements yield the altitude of electron precipitation, which connects energy deposition to processes in atmospheric chemistry and ionization. Furthermore, the REPTAR mission aims to identify pitch angle dependent population growth and loss processes. Connections between the trapped and precipitating electron populations can be made by surveying the edge of the loss cone.

2 Science Mission

2.1 Orbit

The REPTAR mission will target a 478 × 786 km orbit inclined at 64.7°, but any orbit with an inclination exceeding 55° ensures passes through the electron belt horns and above 400 km satisfies mission lifetime requirements. This orbit is of the same configuration as CSSWE's orbit, and was chosen because it maximizes time spent inside the horn points and will deorbit within 25 years, satisfying NASA space debris control regulations.

2.2 Measurements

REPTAR seeks to measure energy and pitch angle of both incoming and outgoing electrons within the loss cone at the electron belt horns. Magnetic field measurements are necessary to identify and orient with the loss cone, and to resolve electron pitch angles.

Electron energy measurements should encompass the entire electron belt population with typical energy from 100 keV to 1.6 MeV. A 30% energy resolution resolves the known spectral features of the electron belt and is consistent with RBSP. Integral flux measurements above 1.6 MeV cover the extreme energy population [5].

Instrument requirements for pitch angle and magnetic field measurements are derived from Eq. 2. The REPTAR mission aims to measure loss cone electrons exclusively, so the angular range of the instrument must be no larger than the smallest lost cone angle. This occurs when the ratio B/B_M is at a minimum. B can be minimized using a dipole model of Earth's magnetic field.

$$B = \frac{B_0}{r^3}\sqrt{1 + 3\sin^2\lambda} \tag{3}$$

Earth's surface equatorial field strength is approximately $B_0 = 31,000$ nT. The interior of the electron belt is $L = 4$, and REPTAR's orbit reaches a magnetic latitude $\lambda = 58°$ when computed at apogee. The corresponding magnetic field strength is then $B = 38,870$ nT. For a 100 km mirror point on the same field line, $B_M = 52,570$ nT, and the pitch angle measurement requirement is $\alpha_{loss} \leq 59.3°$.

Pitch angle resolution requirements are driven by wave-particle interactions above the gyrofrequency and geomagnetic disturbances on longitudinal drift timescales. High-frequency waves above the gyrofrequency can accelerate electrons in or out of the loss cone. Of course this is pitch angle dependent, as the gyrofrequency is conditional on the perpendicular velocity. Loss mechanisms in longitudinal drift are also pitch angle dependent. Electrons maintaining the third adiabatic invariant and remaining on the same drift surface can be lost on the dayside due to magnetopause compression. They can also be accelerated out the magnetotail on the nightside by electric fields. Both mechanisms result from the solar wind acting on the magnetosphere. Data analysis from the Combined Release and Radiation Effects Satellite (CRRES) connected pitch angle distributions to various physical processes using a 5° resolution [6]. REPTAR's instrument requirement is to match or improve upon that 5° resolution.

Time resolution requirements are similarly derived from flux measurements of past missions. REPTAR's detector requires a 10 ms cadence to account for the expected on orbit flux up to 10^5 cm^{-2}/s/sr/Mev, as CSSWE measured [4]. Also consistent with CSSWE, REPTAR will downlink 6 second histogram bins to satisfy the science goals. [7].

Finally, magnetic field measurements will allow REPTAR to identify when it is in an electron belt horn and the approximate loss cone orientation, allowing for proper instrument alignment. Equation 3 establishes the magnetic field strength range requirement, $38,870$ nT $\leq |B| \leq 44,602$ nT, corresponding to the minimum field strength if the apogee occurs in the $L = 6$ shell, and the maximum if perigee is in the $L = 4$ shell. Equation 2 yields the required magnetic field resolution of 100 nT for 2.5° pointing accuracy to resolve 5° in pitch angle.

3 Instrument Design

3.1 Science Traceability Matrix

NASA Science Goal	Investigation Science Goal	Science Measurement Requirements		Instrument Performance		
		Physical Parameters	Observable	Parameter	Requirement	Projected
2013 Decadal Survey for Heliophysics: "Determine the coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs	Determine the energy and pitch angle distributions of Earth's radiation belt electrons near their mirror points to assess upper atmosphere interactions during both geomagnetic activity and quescent times	Radiation Belt Electron Populations	1) Electron Pitch Angle	Angular Range	≤ 55 degrees half angle	45 Degrees half angle
				Angular Resolution	≤ 5 degrees	5 degrees
			2) Electron Energy Spectrum	Range	100 keV - 1.6 MeV	40 keV - 1.6 MeV
				Resolution (dE/E)	< 30%	25% (12.5% from 40 keV to 1.2 MeV)
				Measurement Cadence	10 ms	20 microseconds
				Histogram Cadence	6 seconds	6 seconds
		Magnetic Field	3) Local Magnetic Field Strength	Range	38,870 nT - 44,602 nT	+/- 200,000 nT
			4) Local Magnetic Field Orientation	Resolution	< 2.5 degree	0.1 degree

3.2 Measurement Technique and Requirements

To generate a measurement of an incident electron's energy and pitch angle in the forward and aft directions, we have decided to pursue a dual detector design. Each of the two detectors will consist of six totally depleted silicon detectors, representing six distinct energy levels that can be measured. Of the six detectors, the first four will have an active area subdivided into distinct individual channels. These first four detectors will be used to determine the electron's incident pitch angle and provide the first four energy levels. The last two detectors, used to extend the energy measurement bandwidth, will each have a single channel pad. Fabrication of a complete detector assembly with the desired characteristics can by done by employing detectors from Micron Semiconductors that are readily available off the shelf components. The arrayed detectors are at TRL 4 and the single channel detectors are at TRL 8 (by way of the CSSWE REPTile instrument [8]). The first two years of the REPTAR mission will be dedicated to improving the TRL of the arrayed detector stack from level 4 to level 6 in preparation for flight.

The use of stacked silicon detectors has been employed in many successful particle detection missions, such as CU Boulder CSSWE mission where the REPTILE instrument employed a silicon detector stack to measure electron energy. The operation for each detector is as follows: as an electron hits each detector, it dissipates ΔE of its energy to that detector, and continues depositing energy into each detector until the electron has been totally depleted. By adding up the number of detectors an electron has passed through, its energy can be determined. As mentioned detectors have a minimum energy detection of approximately 40 keV, and the detector stack will have the ability to fully deplete an electron with 1.6MeV, allowing for a total telescope minimum energy detection of 50 keV and a maximum energy detection of 1.6 MeV, if the electron registers signal on all six detectors.

For the proposed orbit we have been able to model the projected loss cone half angles, using the IGRF magnetic field model [2] and an orbit propagator, for when the CubeSat will be in the radiation belts. With perigee oriented at the maximum latitude point of the orbit, we find that the range of loss cone half angles varies from 64 degrees to 71.5 degrees. These values, combined with previous flux measurements from the CSSWE mission provide specifications for the REPTAR instruments' fields of view.

3.3 Mechanical Design

The center 2U of the REPTAR spacecraft is allotted to the instruments and the ADCS, which takes up $\frac{1}{2}$U. With ample space for each of the two detectors, instrument development is not limited by the stringent requirements of fitting within 1U of a CubeSat. This allows ample shielding to be employed and still maintain weight and size margins. The extra space also ensures the ability to fit all back-end electronics in the 1.5U allotted for the instruments, and further shield from other on-board components that could contribute noise or interference.

Looking at the silicon detector stack, the first four detectors will be responsible for providing an estimate of the electrons incident pitch angle, which can be generated by segmenting each layer into millimeter wide arrays. Commercial off the shelf components from Micron Semiconductor give us approximately 25 distinct arrays on the an active area of 25 mm. The last two detectors of the stack are of a single pad single channel design, similar to those flown on the REPTile instrument, with 50 mm active areas. Using the convention that 2 mm of silicon material will completely deplete 1 MeV of energy, the distribution of thickness across the detector gives the REPTAR instrument a upper bound on the detection energy bandwidth of 1.6 MeV. This will be carefully modeled and verified during the instrument development phase of the project. The minimum detection energy for each detector layer is about 50 keV, giving us a lower bound of energies our detector stacks will be capable of measuring.

As an electron travels through the detector stack, it will hit distinct arrays in each of the six detectors, thus giving us a track of its trajectory. Using a look up table, we can estimate a bounding measurement of the incident angle based off of the trajectory. Instantaneous measurement of the electron's pitch angles relies on accurate understanding of REPTAR's attitude and pointing characteristics. We anticipate being aligned with a magnetic field line to properly measure the incoming angle of the incident electron, and this will be done by way of the Blue Canyon XACT ADCS system, which will give better than $\pm 1°$ pointing accuracy.

To avoid measurements of incident electrons from outside of the loss cone and mitigate detector saturation, a collimator and field stop are being incorporated in the front of each detector stack. The field of view half angle of the detector stack is designed to be 65°. Models indicate that half angles range from 64.5° to 71.5° over our projected orbit. A field of view of 65°, when combined with our pointing capabilities, has the ability to fully span the loss cone when the CubeSat is traversing the radiation belts. Knowing the field of view of the detectors, we defined a field stop with an area of 1 cm^2, giving an $A\Omega$ for each instrument of approximately 3.627 $cm^2 - str$. With the geometry of the instrument and fluxes examined from the REPTile instrument [4], it the acquistion for single electron detection will need to be on the order of 50 microseconds. An image of the detector layout with the collimator, baffling, window, and detector stack.

A primary source of noise for the REPTAR detectors will be from shield-penetrating particles, where the aluminum casing proves to be transparent to certain energy electrons and protons. This is most prominent for the area surrounding the detector stack, so extra shielding will be incorporated along this area, which could consist of Tungesten or other radiation hardened materials — this portion of the design process will follow suite of the REPTile instrument. Suppression of noise becomes an issue in the CubeSat environment as mass is highly restricted. The detector housing will be primarily 6061-T6 aircraft aluminum, due to its cheap cost and high strength. Layers of tungsten will have to be incorporated to further bolster shielding against unwanted particles. Tungsten proves to be good for shielding has it has a low kick off rate of particles when it is hit. The collimator is designed to have internal baffling to prevent incidence of electrons from outside the loss cone on the detector stack and will also be made of Tungsten. To prevent issues with detector electronics being struck by unwanted particles, we will house the back-end electronics within the aluminum casing behind the detectors. Combining this shielding with circuit components similar to those that flew on with the REPTILE instrument proven to withstand the radiation environment, we are maximizing suppression of noise and ensuring the ability to withstand a impact event that could cripple the mission.

The instruments will be on the order of 1.5-2.0 kg, with a nominal weight of of 1.7 kg being the target for a combined weight of the two instruments. As both need to fit into 2U of the total 6U area, we have only have minor demands on the full instrument size. The complete length of each instrument is approximately 6 cm. They will placed back to back in the 2U space, with electronics contained between. The 6 centimeter length includes the detector stack and feed horn, with approximately a 60-40% split for collimator and detector stack. The diameter of the collimator will be close to 5 cm, but this is tied to the previously calculated $A - \Omega$, and can be scaled as needed to ensure fit into the 2U space and maintain the correct field of view. Diagrams of how the detectors and their electronics fit into the 6U space craft are shown in the appendix of the document.

3.4 Electronics Design

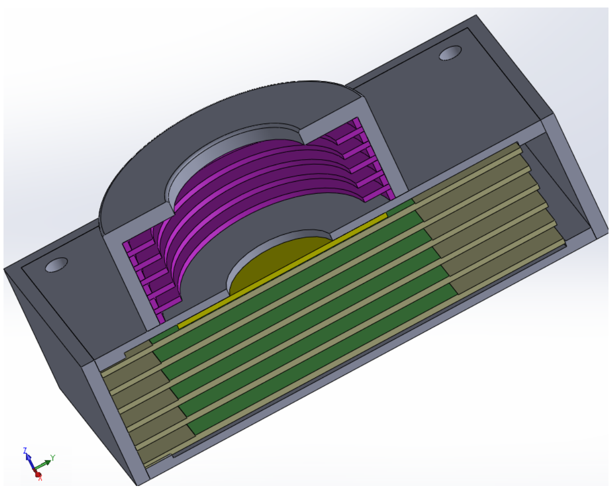


Figure 2: Shown is the design for the REPTAR detectors. The collimator is lined with Tungsten baffling, shown in purple, then after the field stop is a Be window to facilitate unwanted particle blocking, and finally the six silicon detectors

For each electron detection registered, the silicon detector stack gives off a series of voltage pulses. Because every detector gives off an individual pulse, the number of pulses leaving the stack is dependent on the penetration depth of the electron. These pulses are at low voltage levels, so they are susceptible to noise. In order to reduce noise concerns and establish distinguishable voltage bands for the different energy levels, the detector output is fed into an amplifier chain. The amplified waveform enters voltage discriminators for pulse height analysis, and is then fed into the programmable logic device. The amplifier chain also gives off a timing pulse that is simultaneously fed into the programmable logic device. The logic device bins the pulses by time and energy level and passes the information to the SD card used for data storage.

The signal first enters a charge sensitive pre-amplifier, chosen to be the Amptek Inc. IC A225, following in the footsteps of the REPTile instrument as space-graded electronics with flight heritage are of utmost importance. The A225 outputs a timing pulse, which is fed into the programmable logic device to keep a timing record, and an amplified waveform which then enters the second stage of amplification for further energy level separation. The second stage amplifier can be any generic Op-Amp with flight heritage, as the waveform is now large enough to mitigate low noise issues. The complete amplifier chain takes the waveform from a low millivolt pulse to a multi-volt range, which is needed for thresholding.

Thresholding is controlled by the programmable logic device. The discriminators establish energy thresholds that the voltage pulses are interrogated against. The discriminator output is a TTL pulse, which is then fed into the programmable logic device housing the timing to digital converter chip (TDC). Under high electron fluxes, analog to digital converters with flight heritage will not be fast enough to mitigate breakdown of signal analysis. For this reason, the use of a multi-channel Constant Fraction Discriminator (CFD) will be employed. CFDs are similar to a simple voltage comparator, but instead have the ability to provide extremely accurate and stable timing signatures (picosecond resolution).

Due to the desired field of view and the field stop needed to maintain measurements within the loss cone, not all measurement channels will be illuminated by incident electrons. As we are using off the shelf components, we will have unused measurement channels in the first four detectors. All though this seems as a waste of active area on the detector, use of off the shelf components with a predetermined active area, that does not necessarily match our desired field of view, outweighs custom detectors in price and heritage.

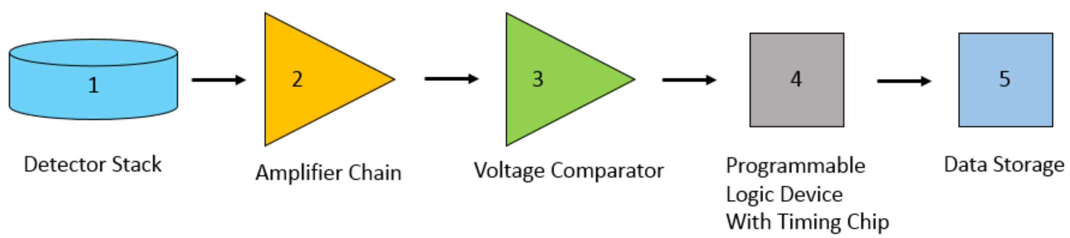


Figure 3: Shown is the flow of the backend electronics consisting of: detector stack, amplifier chain, comparator for discriminating voltage pulses, programmable logic device for binning the signals, and then on-board data storage and further processing if needed.

3.5 Technology Readiness Level Table

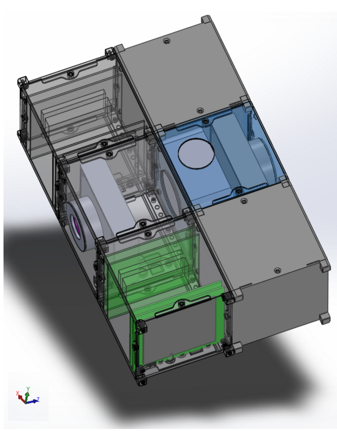
Component	Manufacturer	TRL
CubeSat Bus	Pumpkin	9
Micro processor	Microchip	8
EPS	Clyde Space	8
Solar Panels (1U)	Clyde Space	9
Solar Panels (3U)	Clyde Space	9
Radio	Astronautical Development	8
ADCS	Blue Canyon Tech	7
Flight Software	Salvo	9
Detector	Custom	4*

* The detector assembly will increase to a TRL of 6 after the two-year instrument development and testing phase of the mission

4 Spacecraft Design

4.1 Overview

REPTAR Mission Traceability Matrix			
Mission Life	**Driving Mission Requirements** > 3150 orbits of science observation (20 minutes science data per orbit) Reentry Plan: Atmospheric drag will cause deorbit within 25 years	**Mission Design Requirements** Mission Duration: 210 days (<30 commisioning + 180 science) Number of satellites: 1 Orbit (CSSWE): 478 x 768 km, 64.7 deg inclination	
Spacecraft Accomodation	**Driving Mission Requirements** Desired resolution of measurements: CSSWE 6 sec count rate Desired pointing accuracy: 1 degree Desired attitude knowledge (relative to B-field): 1 degree	**Spacecraft Requirements** 6 Watts Data Storage : 32 Gb total storage Spacecraft Size: 6U Maximum Mass: 4kg	**Operations Reqirements** S/C Modes: Safe, Science, Standby
Mission Communications Accomodation	**Driving Mission Requirements** Science data: 10Mb / day produced Housekeeping data: 650kb / day produced	**Spacecraft Requirements** Daily Data Downlink: 14 Mb Downlink Rate: 9.6kbps Bit error rate ≤ 1e-5 Comm Frequency: 70cm Band (437 MHz)	**Ground System Requirements** Comm Frequency: 70cm band (437 MHz) Downlink contacts: 4 daily Downlink duration: 23 min daily Spacecraft and Science data destination: MOC Bit error rate ≤ 1e-5



The REPTAR spacecraft borrows heavily from the heritage of CSSWE and MinXSS (the Miniature X-ray Solar Spectrometer), both of which were made at CU-Boulder. REPTAR is a 6U CubeSat designed to conform to the Cal Poly CubeSat design specification. Attitude is controlled via Blue Canyon Technology's XACT system, the same system as used by MinXSS. The spacecraft communication subsystem is based on those from CSSWE and MinXSS, and the same ground system will be shared between all three missions (although there is no overlap in the missions, so there is co possibility of conflict). Power is provided by solar panels on each 10cm $\times$ 30cm and 20cm $\times$ 30cm side of the spacecraft. A 6U bus was chosen rather than 3U to ensure ample margin is available, particularly in mass.

4.2 Configuration and Structure

The main structure of REPTAR is a Pumpkin Inc. SUPERNOVA 6U chassis, which measures 65 mm $\times$ 239.2mm $\times$ 105.6 mm. The CubeSatKit bus was selected because of it high level of compatibility with other systems both from Pumpkin Inc. and from other vendors.

The REPTAR instruments will be in the the central 2U of the spacecraft, but will only fill

1.5U. The remaining 0.5U at the center will be used by the XACT ADCS system. The radio, C&DH, EPS, and battery will be mounted in one of the free regions of the spacecraft. Clyde space solar panels will be mounted on each 30cm $\times$ 10 cm and 30 cm $\times$ 20 cm face. The total mass of the spacecraft as proposed is 5214 g, giving a 32.82% mass margin below the 8 kg constraint. The total volume of spacecraft components is 2265.45 cm^3, 68.05% below the 7000 cm^3 capacity of the 6U structure.

4.3 Pointing/ADCS

REPTAR will use XACT High Performance ADCS unit from Blue Canyon Technologies, which will be flight tested on CU-Boulder's MinXSS mission, to be deployed from the ISS in late 2015. The MinXSS team expects XACT to offer arcsecond pointing accuracy, well below REPTAR's 1° pointing requirement. The ground operations team will use NORAD Two Line Elements along with the IGRF magnetic field model to produce pointing commands for REPTAR on the ground that will be uplinked once per day. The REPTAR instruments will point along the magnetic field lines while flying through the horn points, and will point for optimal solar panel performance everywhere else in the orbit.

REPTAR Mass, Power, and Volume Budgets			
Subsystem	Mass (g)	Power (mW)	Volume (cm^3)
REPTAR	1500	2000	1000
XACT ADCS	850	2830	500
C&DH	100	400	30
EPS	232	200	85
Radio	52	408	21.45
Chassis	1640	0	600
Solar Panels	840	N/A	N/A
Total	5214	5838	2236.45
Available	8000	11000	7000
Margin (%)	34.82	46.92	68.05

4.4 Power

REPTAR's power system will use solar panels on each 10 cm $\times$ 30 cm and 20 cm $\times$ 30 cm side of the spacecraft (with gaps for instrument apertures), a EPS system capable of delivering 3.3 V, 5 V, and 12 V power supplies, and a 30 Wh battery, all provided by Clyde Space.

Over an orbital day, REPTAR will average greater than 16.5 W, giving 11 W orbit averaged power draw. REPTAR's total power consumption is 5.8 W with the engineering systems using 3.8 W and the instrument using 2 W, giving 46.92% margin in the power budget. The orbit averaged power draw for the Li-1 Radio is 408 mW, reflecting a 200 mW nominal power draw and half an hour a per day of transmission at 10 W.

4.5 Communication

Following the heritage of CSSWE and MinXSS, REPTAR will use a two deployable spring steel antennas, one coming out of each 10 cm $\times$ 20 cm face, and Astronautical Development LLCs Lithium-1 Radio UHF module. By using the same on-board systems as CSSWE and MinXSS, REPTAR will be able to easily interface with the ground station infrastructure that has been used by those missions and by the Laboratory for Atmospheric and Space

Physics (LASP) at the University of Colorado.

The Li-1 Radio supports a downlink rate of 9.6 kbps. Given the orbital inclination of 65°, apogee of 770 km and perigee of 470 km (roughly CSSWEs orbital parameters at start of mission), predictions give an average of 3.9 daily contacts with an average length of 6 minutes and 23 seconds. This gives an average daily downlink time of 24 minutes and 53 seconds. Given the 9.6kbps of the Li-1, REPTAR will be able to support a downlink of over 14 Mb per day. Assuming that REPTAR takes data in the horns for about 30 minutes per orbit, it will generate about 11 Mb of data per day while in the horns, allowing for 100% downlink of horn data plus 40% margin for late AOS, early LOS, retransmission of data, and other inefficiencies in a given pass. Housekeeping data will be minimal and will fit easily within the 40% margin.

Like CSSWE and MinXSS, REPTAR will use AX.25 packetization for science data. Each packet will contain a 1 byte header, a single sample from REPTAR (3 byte timestamp, 238 bytes of raw data, 6 bytes of magnetometer data), and a two byte checksum. This leaves the final 6 bytes of each packet free for margin in future development of the REPTAR science data product. Housekeeping packets will be 256 bytes and will contain the same header, timestamp, and checksum, and 80 3-byte telemetry data points with 10 extra bytes open for later development. Because there will likely be far fewer than 80 housekeeping telemetry points, the timestamp will used as a mini-epoch with part of each 3-byte point containing seconds since the timestamp. In this way telemetry points can have arbitrary cadences relative to the cadence of housekeeping packets.

4.6 Data Handling

4.6.1 Processor

REPTAR uses a Pluggable Processor Module (PPM) equipped with a Microchip PIC33 microcontroller to run all C&DH functions, including binning data collected by the primary detector, collecting and transmitting housekeeping data, coordinating the ADCS system, and relaying any commands sent from the mission operations center. The MC PIC33 was chosen because of its flight heritage (MinXSS) and low power requirements (3 mA when operational and up to 1 mA when idle). Connecting the microcontroller to the rest of the spacecraft is a motherboard that maintains a real-time clock (RTC) and contains a backup 3-volt battery that can be used to power the PPM in case of EPS failure.

4.6.2 Flight Software

The motherboard-mounted microcontroller will run a version of Salvos Real-Time Operating Software (RTOS) optimized for the PIC33. Not only has this software flown on multiple missions (e.g., CINEMA), but the software is also very familiar to those at University of

Colorado who will be doing the bulk of the programming. The software itself will be responsible for binning data, selecting which data to transmit based on timestamps so that only data in and near the horns is sent, and receiving/implementing commands from the ground.

4.6.3 Data Flow

Having access to the REPTILE flux data in the energy range that we propose to measure in, we can do a dynamic range analysis and determine what length our initial time bins will be. The REPTILE mission gives a maximum of roughly $10^5 \#/cm^2/str/s/MeV$. Using this number, our previously calculated $A\Omega$, and assuming a time bin of 0.5 milliseconds, we will see that within one acquisition we will have approximately 65 registered counts on the detector. We can then assuming that the timing units will have an equivalent dead time after detection (though modern timing units quote nanosecond dead-time, but to our knowledge flight heritage has not been established), giving us a total measurement cadence of approximately 1 millisecond. With the orbit we have chosen, which is designed to be equivalent to that of the REPTILE instrument, we will have close to 30 minutes in the radiation belts as we pass through the periapse point, which we are orienting to be at the maximum latitude point of approximately 64 degrees. Having a 1 millisecond measurement cadence will provide the instrument with an abundance of data to be summed into 6 second histograms for downlink. See next section for more details on what data will be sent.

Each histogram that is produced will consist of 56 bins: 8 energy bins 150 keV wide and 7, five degree angular bins.

5 Ground Segment

5.1 Ground Station

REPTAR's ground station will be the facility at LASP that was originally designed and build for CSSWE and will be used for MinXSS. The spacecraft and ground station will communicate at 437.345 MHz, the chosen frequency of the International Amateur Radio Union. The ground station consists of the Kantronics KAM XL terminal node controller, Two M2 436CP42 cross Yagi antennas and a Yaesu G5500 azimuth-elevation rotator. The ground station is located in Boulder, Colorado.

5.2 Concept of Operations

REPTARs concept of operations will require ground operators to fulfill two primary duties creating and uplinking command products, and ensuring that all expected data reaches the ground. State vectors will be uploaded to ensure optimal pointing for science data collection while in the horns and for solar pointing at other times.

Following from the operations of CSSWE, downlinks will be scheduled whenever the spacecraft is visible above a 10 degree mask at the Boulder ground station. Predictions will be made on a weekly basis using AGI's Systems Tool Kit (STK). The duration of each contact as given by STK will be used to determine how many packets can be downlinked in each contact. Each contact, the spacecraft will be commanded to dump as much data as can be transmitted from horizon to horizon, with a small overlap from the previous pass. Each data packet will contain a sequence number, all of which should make it to the ground. Ground operators will be responsible for ensuring that all sequence numbers are present. Any packets found to be missing will be added to the downlink queue for the next orbit. Because of REPTARs modest data recording rate - about 5.5 Gigabits per year there is no concern of overfilling the 32 GB recorder, and no packets will be overwritten over the lifetime of the mission.

5.3 Modes

REPTAR will use three modes, science, safe, and standby. Science mode will be used to take data while in the radiation belts while standby mode will be used at all other times in a nominal orbit. Because the REPTAR instrument may saturate without causing any damage, safe modes will only result from anomalous behavior.

6 Mission Schedule and Management

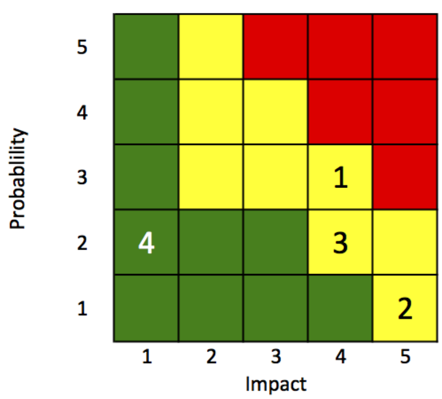
6.1 Schedule

REPTARs mission schedule can roughly be divided into six phases: instrument development, subsystem fabrication and testing, overall assembly, final testing and calibration, operations, and analysis. Though this proposal gives an in-depth road map for the construction, design, and scientific data gathering components of the mission, a lengthy development phase is required to finalize schematics, personnel, facilities, and schedules. Once production has begun, components and subsystems will be made and tested repeatedly, culminating in final pre-launch calibrations. The total time from the start of the development phase to the competition of final testing is 3.25 years, after which REPTAR will be ready to launch on the first available vehicle. Once in orbit, REPTAR will take five days to prepare for data collection. REPTAR's operational duration is six months, during which REPTAR is likely to take data during at least two solar storms, if not more. While the data collected will be processed while the spacecraft is still flying, there will be a dedicated three-month science data analysis period following REPTAR's decommissioning.

Phase	Description	Duration	Milestones
1	Instrument Development	2 Years	Instrument TRL increased to 6
2	Subsytem/Instrument Fabrication, Assembly, and Small-Scale Testing	0.75 Years	Subsystems assembled and tested (overlaps with phase 1)
3	Overall Assembly	0.25 Years	All subsystems and instruments integrated into CubeSat structure
4	Final Testing and Calibration	0.75 Years	CubeSat becomes flight-ready
5	Operations	0.5 Years	One month of detumble and in-orbit calibration; Data collection
6	Data Analysis	0.25 Years	None

6.2 Risk Management

CubeSats are inherently riskier than larger satellites, but REPTAR seeks to minimize these risks by using flight-tested systems with a high degree of heritage. Moreover, many of the components used in REPTAR (antenna, flight software, etc.) have been used to construct previous CubeSats at CU-Boulder. The experience gained by these previous missions reduces the overall risk for REPTAR. Only the detectors are new, and they have an extensive development and testing program in place to give REPTAR a high probability of success.



Rank	Description	Mitigation Strategies
1	Instrument not at TRL 6 at the end of the two year development period	The instrument scientist (and a cadre of graduate students) will be working full-time on testing and improving the instrument design for two years. If the instrument is still at a TRL below 6 at this point, the mission will be descoped to use COTS detectors to measure flux (no angle determination).
2	Deployable antenna fails to deploy	Learn from other CU CubeSats that used this antenna (CSSWE and MinXSS) and include extensive pre-flight testing. Cable holding in antenna will degrade after one month in space, at which point the antenna will deploy.
3	Pitch angle determination fails after launch	Extensive development and testing (2+ years) will minimize the risk. The descope science mission (flux counts) can still be performed as long as at least one detector strip is functional.
4	Cost overruns	Utilize the extensive experience at CU with regard to CubeSat development. Buy COTS when possible.

6.3 Descope Option

Our baseline mission is to measure electron flux and pitch angle distribution. In the event that our novel pitch angle measurement fails due to inability to determine spacecraft angle relative to the field lines, failure of the software to reliably extract pitch angles from the instrument, or any other instrument failure, we will still be able to measure total energy flux. This means that we will still be able to meet our threshold science objective, which will provide novel data, as no mission has yet been able to constrain atmospheric precipitation.

6.4 Budget

1. CubeSat Components - $115 550

   - Chassis and supporting hardware - $17 800
     Pumpkin is a well-known manufacturer and retailer of CubeSat components with a record of successful satellites. Buying a kit (of which Pumpkin manufactures many) reduces the possibility of incompatible parts and defective structures. This cost includes the structure, as well as development boards and modules for testing.
   - Motherboard, Card Library, and Pluggable Processor Module (C&DH) - $2450
     This combination of Pumpkin motherboard with Microchip PIC33 microprocessor flew on the MinXSS mission, as well as numerous others. The PPM requires little power, and the motherboard has a built-in backup battery.
   - Clyde Space Solar Panels - $35 400
     We are using four 3U panels on the sides of REPTAR as well as four 1U panels on the ends. These models of solar panels have flight heritage and are able to recharge the main battery even after a nighttime radio downlink to the ground. As described above, the ADCS will orient the spacecraft for maximum solar coverage when not in the horns, so power generation should not be a problem.
   - Clyde Space EPS - $4900
     The Clyde Space EPS is a reliable system with the heritage of many successful CubeSats. It is not prone to unexpected latching or unlatching, and features short-circuit protection on switches and buses that are a part of the system.
   - Li-1 Radio - $5000
     Many CubeSats have flown with the Li-1, including the recent CSSWE.
   - Blue Canyon Tech. XACT (ADCS) - $50 000
     The XACT ADCS provides the precise pointing necessary to determine electron pitch angles. The sub-degree accuracy of the XACT more than meets the <1 degree requirement. This pointing system will also allow for the spacecraft to be positioned to maximize solar panel power production while not recording data.

2. Instruments - $70 000

   - Si Detector Test Fabrications - $40 000
     REPTAR is in part a mission about proving the flight-worthiness of these novel silicon detectors. The detectors will progress through up to four iterations during their two-year development. Each stage will cost approximately $10 000 to manufacture.
   - Si Detector Assembly - $30 000
     Two instruments will fly on REPTAR. The detectors will progress to TRL 6 during the development phase in preparation for their use on REPTAR. This cost includes all supporting electronics for the detector stacks, as well as the 32 GB SD card that serves as the data recorder.

3. Other Costs - $202 100

    - Off-Site Testing Fees - $25 000
      Not all testing can be done in the CU labs: some will need to take place in nearby specialty test chambers.
    - Salvo 4 Pro Real Time Operating Software (RTOS) - $2100
      The basis for the flight software on REPTAR, the Salvo RTOS was recently used in the same capacity on MinXSS. Not only does it have flight heritage, but it is also familiar to the software engineers at CU-Boulder who will be working with it. The license will need to be renewed once over the course of testing and operations.
    - General Hardware - $25 000
    - LASP Ground Station (1 Year) - $150 000

4. Labor - $2 562 500

Position	FTE				Salary	Total
	Y1	Y2	Y3	Y4	Per Year	
Principal Investigator	0.5	0.5	0.75	1	80000	220000
Project Manager	0.25	0.5	0.5	0.5	75000	131250
Systems Engineer	0.25	0.5	1	0.75	75000	187500
Instrument Scientist	1	1	0.6	0.5	75000	232500
Project Scientist	0.5	0.5	0.5	0.5	75000	150000
Graduate Students	3	4	3	2	30000	360000
Overhead						1281250

Four Year Total - $2 950 150

7 References

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8 Appendix A: Supplementary Instrument Figures

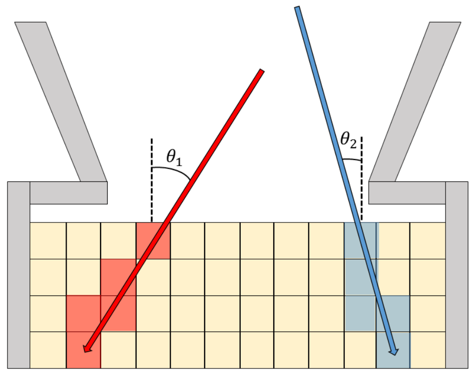

Figure 4: This diagram shows how different arrays are illuminated by an incident electron. For a given illuminated arrays, the onboard computer can compute what the probable incident pitch angle was. Also, as each detector will deplete some energy, ΔE_{layer}, how far the electron penetrates into the stack gives an indication of what the total energy of the incident electron was.

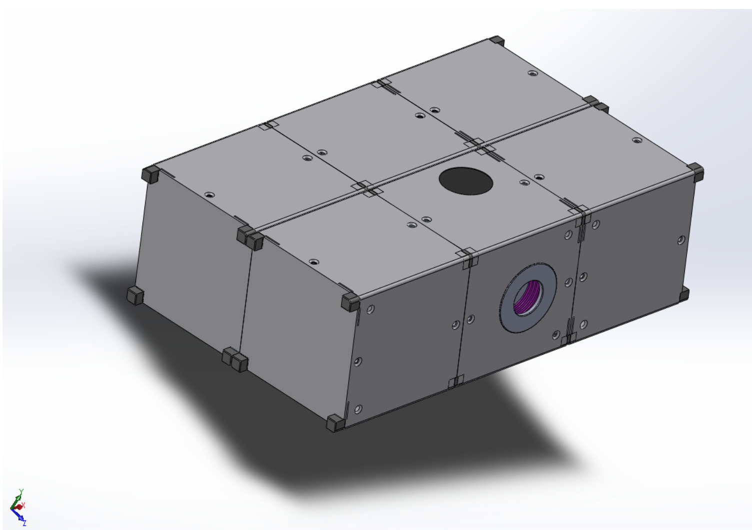

Figure 5: Image showing the detector port and star tracker port on the aft side of the space craft. Antennas and solar panels not shown.

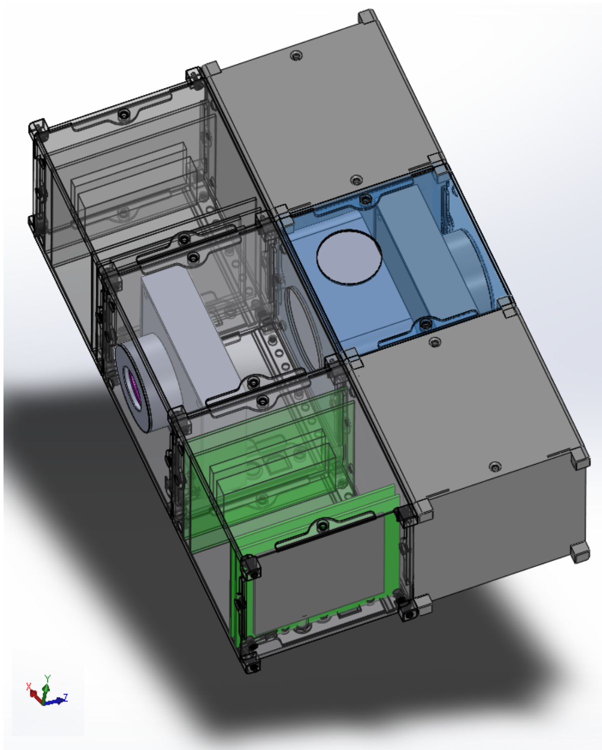

Figure 6: Image showing the boards for the space craft and the detectors back end electronics. Also shown is the ACDS system with port for star tracker, and the two detector assemblies. Antennas and solar panels not shown.

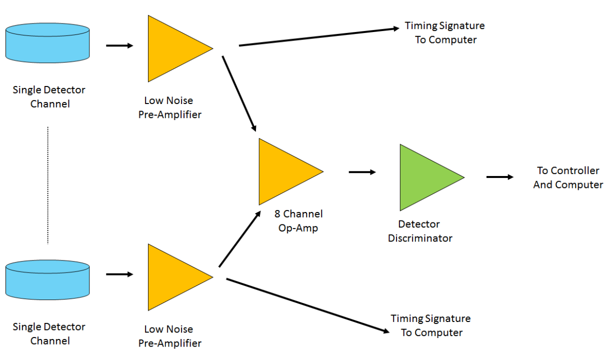

Figure 7: Figure showing back end electronics and how each channel will have its own low noise preamplifier, but will share a common high gain op amp with seven other channels. This signal is then fed into the discriminators and then to the onboard computer.

9 Proposal Responsibilities

9.1 Chris Gilbert, Principal Investigator

Proposal Sections:
Cover Page
Logo
Mission Summary
2.1 Orbit (with PS)
5.3 Modes
6.3 Descope Option

Other:
Managed formatting and figure placement
Guided development of many sections

9.2 Matt Muszynski, Systems Engineer

Proposal Sections:
4.1 Spacecraft Design Overview
4.2 Spacecraft Configuration and Structure
4.3 Pointing/ADCS
4.4 Power
4.5 Communication
5.1 Ground Station
5.2 Concept of Operations
5.3 Modes

Other:
SWAP Table
Physical layout of spacecraft
Link budget, access predictions and total daily downlink calculation
Investigated alternative orbits
  We originally had considered something far more elliptical in order to maximize time in the the radiation belts
Investigated alternative ground stations.
  If the LASP GN wasnt enough, I considered partnering with another school in order to get a seconds place GN and share LASP operations expertise with another institution. This fell by the wayside when we found we didnt need the extra downlink time.
Redesigned spacecraft from 3U to 6U in order to accommodate ADCS
  Changed passive ADCS system to Active
  Changed power predictions
  Changed CONOPS (added stored pointing commands)

9.3 Jonathan Aziz, Project Scientist

Proposal Sections (with input from PI and iteration with Instrument Scientist):
1 Science Motivation and Relevance to NASA
1.1 Science Background
2. Science Mission
2.1 Orbit
2.2 Measurements

Other:
STM Development
  Science goal → Instrument Requirements
orbit investigation
survey of past missions (RBSP, CSSWE, DEMETER, CRRES, SAMPEX)

9.4 Rory Barton-Grimley, Instrument Scientist

-Python program to use IGRF Model combined with orbit propagator to understand measurement enviroment and what the design to requirements for the instrument were (fluxes, loss cone half angles etc.). This included looking at REPTile radiation belt data for comparison to my script (mainly for flux calculations)

-All instrument hardware design and calculations (including detector geometry model written in Python for geometric factor calculations and physical dimensions for dector cavity within the allotted space for the instruments). Notable recent 3U to 6U change

-All instrument electronics design and calculations (amplifier chain power draw, thresholding design, timing etc, some of this was mainly for a macroscopic understanding of how the backend of the detectors would actually function.)

-Writing for instrument section

-Generated all SolidWorks images of space craft lay out for proposals and presentations.

9.5 Leah Isaman, Project Manager

Proposal Sections:
  4.6.1 Processor
  4.6.2 Flight Software
  6.1 Schedule
  6.2 Risk Management
  6.4 Budget

Other:
  Proposal editing
  Scheduling
  Itemized line budget
  TRL Chart