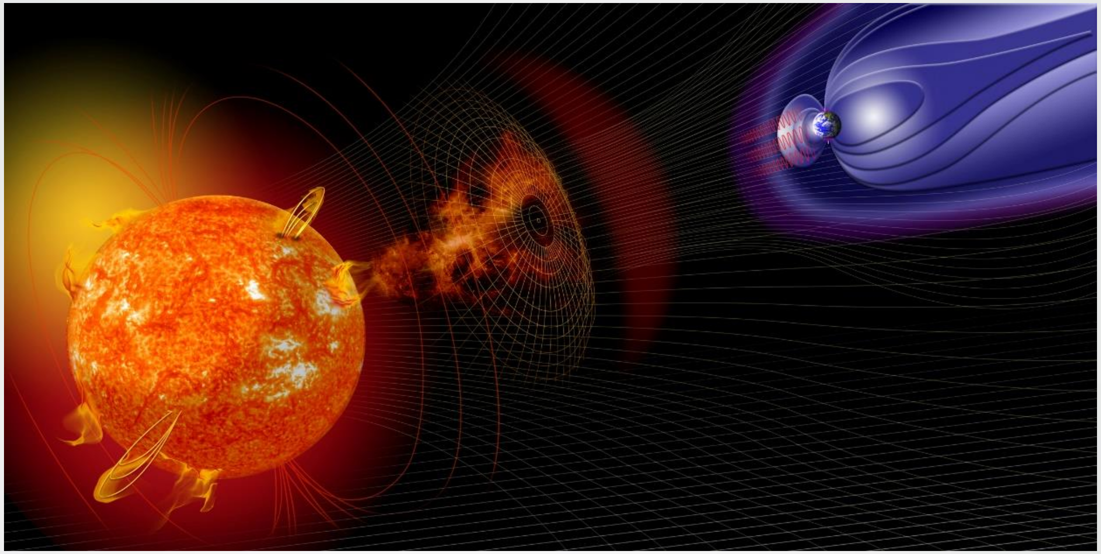
Relativistic **E**lectron **P**recipi**T**ation in Earth's **A**tmosphe**R**e Cubesat

Chris Gilbert, PI; Leah Isaman, PM; Matt Muszynski, SE;

Rory Barton-Grimley, IS; Jonathan Aziz, PS

Motivation



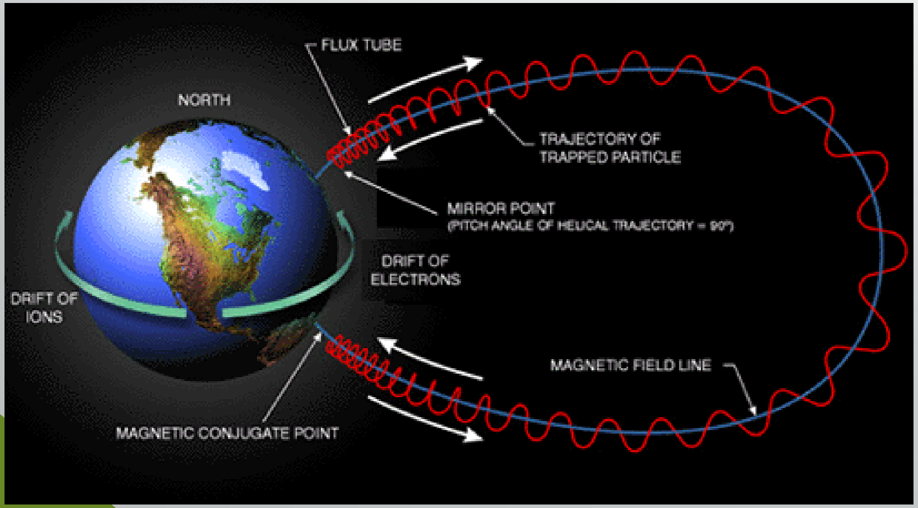
- Energetic electrons are trapped in the Earth’s Van Allen Belts
- Space weather events can cause geomagnetic storms, which empty the Van Allen Radiation belts of electrons at the belt horn points
- These electrons can precipitate onto Earth’s Atmosphere
  - Climate/Weather Models; Atmospheric Chemistry
  - Spacecraft Communication Disruption (GPS)
  - Spacecraft Degradation
- 2013 Decadal Survey, 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.’

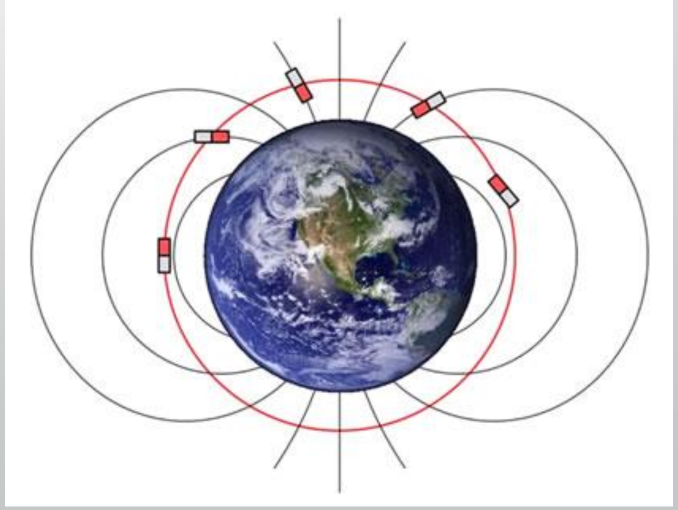
Mission Summary

- REPTAR is a 3U CubeSat, carrying two particle detectors oppositely oriented along the Earth's magnetic field lines.
  - By comparing the rates in each direction, we can constrain the number of electrons lost to the atmosphere
- We have chosen CSSWE's orbit in order to maximize time spent in the horn points of the belts. 478x786 km with 64.7° inclination
- REPTAR will sample the Van Allen Belt loss cones – electrons which are expected to precipitate – for at least 6 months.

[2]

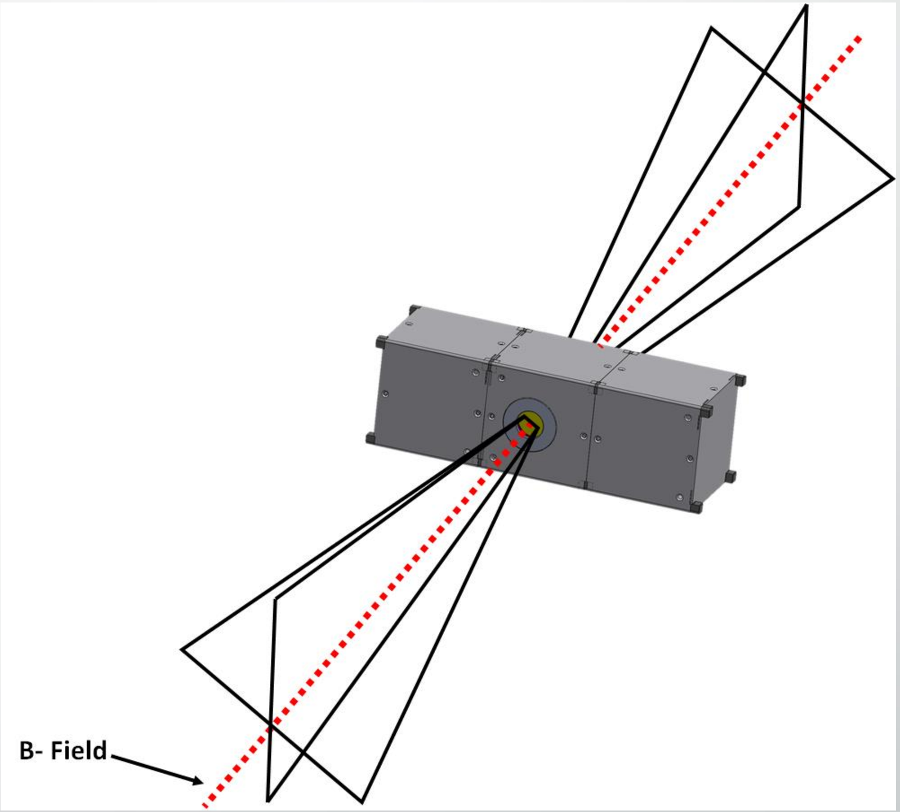
[3]





Instrument Summary

- Two opposite-facing particle detectors for incident electron pitch and energy measurement
    - 4 Silicon Strip Detectors for pitch angle measurement
    - 2 single channel Silicon Pad Detectors for energy discrimination
    - Collimator with ~90 Degrees FOV, Tungsten Baffling, and Be window for Alpha particle rejection
    - Backend electronics similar to those used for the CSSWE REPTile instrument
    - Programmable logic device for timing and energy level histogram binning



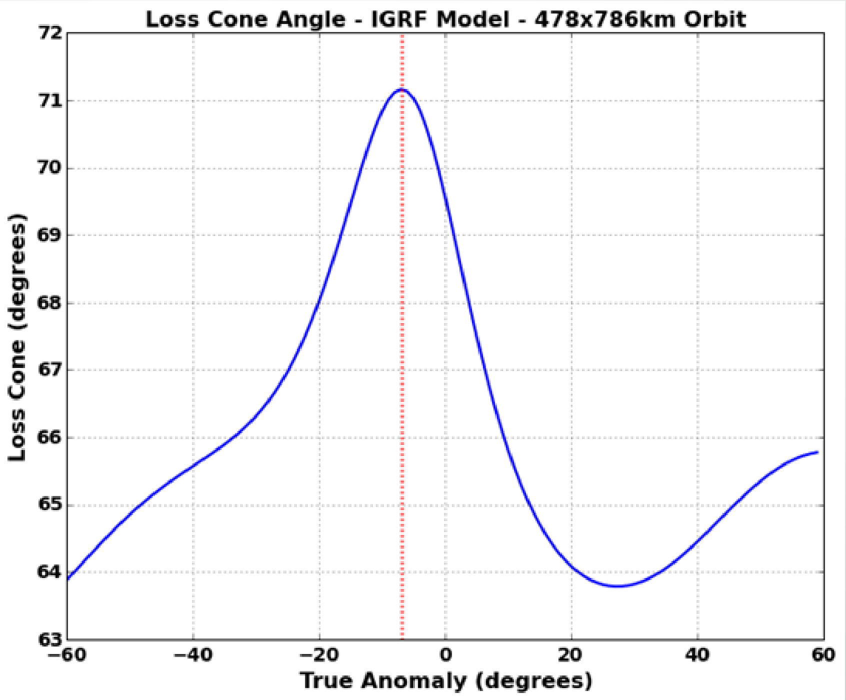
No solar panels or antenna shown

Field of View Requirements

- Detector must not stray out of loss cone – orders of magnitude more flux outside of the loss cone

- Modeling indicates that during an orbit the loss cone half-angle will vary between ~64 degrees and ~71 degrees
  - This drives our detector FOV requirement

- Our passive magnetic attitude control has ~+/- 15 degrees of oscillation, driving a FOV half angle of 45 degrees, ensuring the REPTAR instrument will stay within the loss cone while traversing the radiation belts

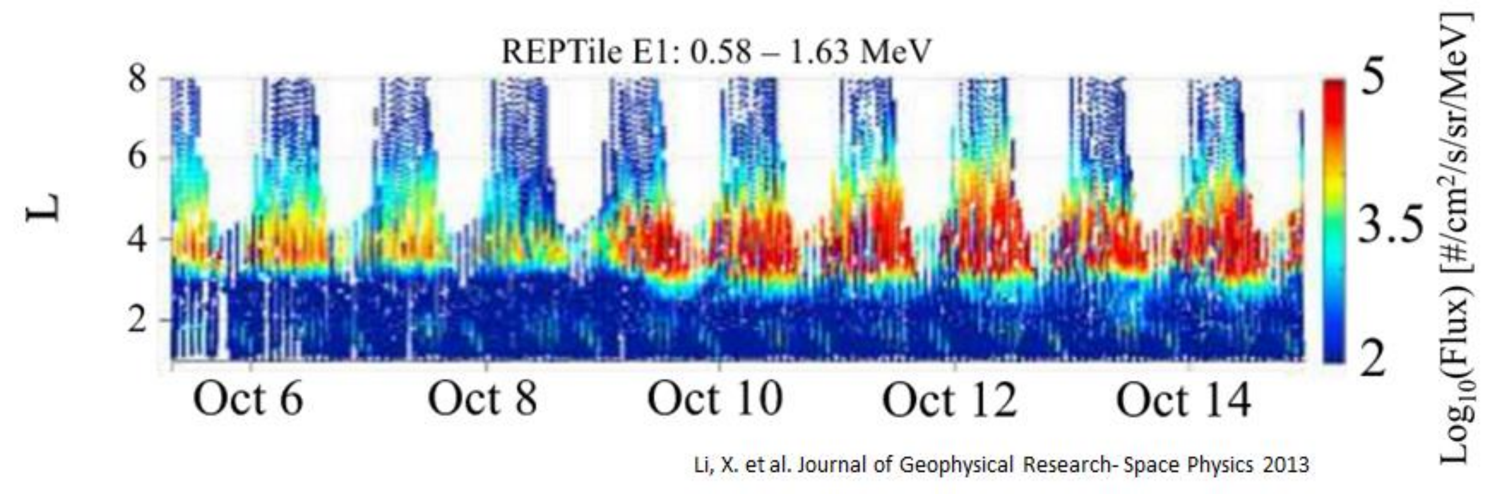


Assumes an inclined elliptical orbit of 64.7 degrees and478x786km, oriented with periapse at the highest latitude

<u>Duration:</u> 31.2816 minutes for -60 to 60 deg True Anomaly

Sampling Requirements

- What electron flux will the REPTAR instrument encounter, and what does this say about the acquisition times?



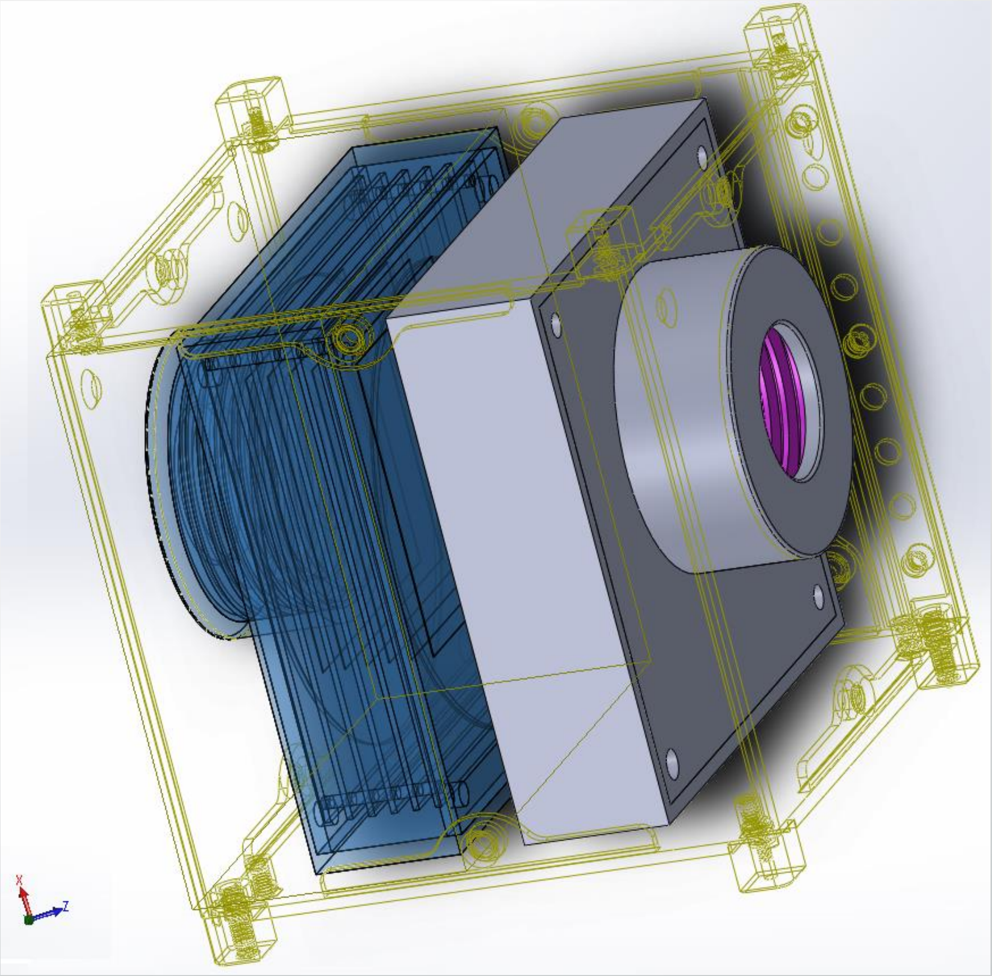
- Assuming a maximum flux of 10^5 #/cm^2/s/sr/MeV we can use the REPTAR geometric factor to determine acquisition times

- 20 microsecond time bin => 1 electron detection
- 40 microsecond time bin => 2 electron detection
- 100 microsecond time bin => ~5 electron detection

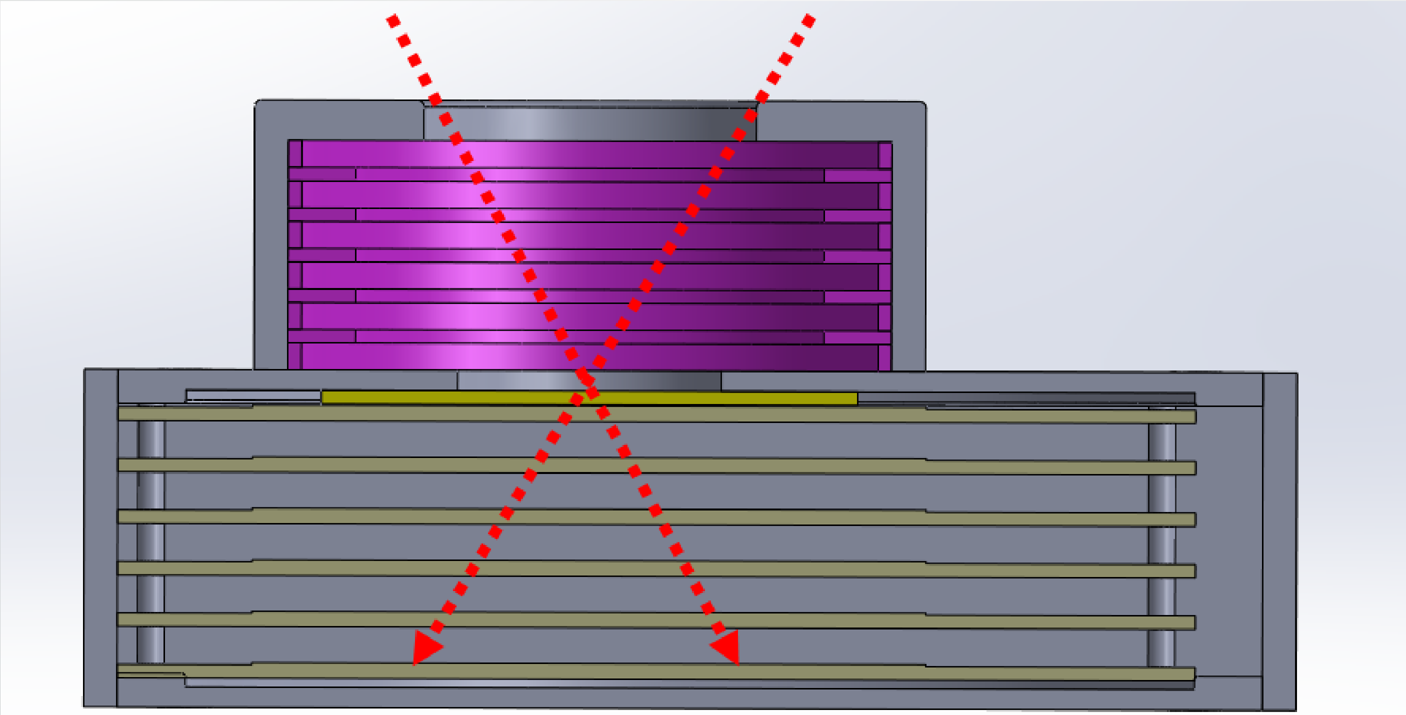
<u>Want to measure between ~0.5-1.6 MeV to complement the CSSWE REPTile measurements</u>

Detector Overview

- 45 degrees half angle FOV
- Collimator length ~20 mm
- Detector Cavity length~25 mm
- Field Stop - 1 cm^2
- Aperture ~40 mm
- Geometric Factor - 1.84 cm^2-sr
- ~1.7 kg allotted for both detectors
- Extra space allotted in the detector cavity for further shielding if needed (also weight dependent)
- Space between detectors to allow cabling to be run to the detection electronics



Detector General



Incoming electron paths not to scale

- Detectors are separated by ~2.8 mm, but this is changeable and will mainly impact how many channels per detector are actually utilized (discussed further on)
- Field Stop placed at cross over point from 90 degree separated electrons

Detector Stack Details

Strip Detectors

Detector 1 (ZZZ): 100 micron thick, 20 channels
- Total Thickness: 1mm
- Dimensions: 20x7mm
- Active Area: 20mm
- Strip Diameter: 2mm

Detector 2 (ZZZ): 300 micron thick, 20 channels
- Total Thickness: 1mm
- Dimensions: 20x7mm
- Active Area: 20mm
- Strip Diameter: 2mm

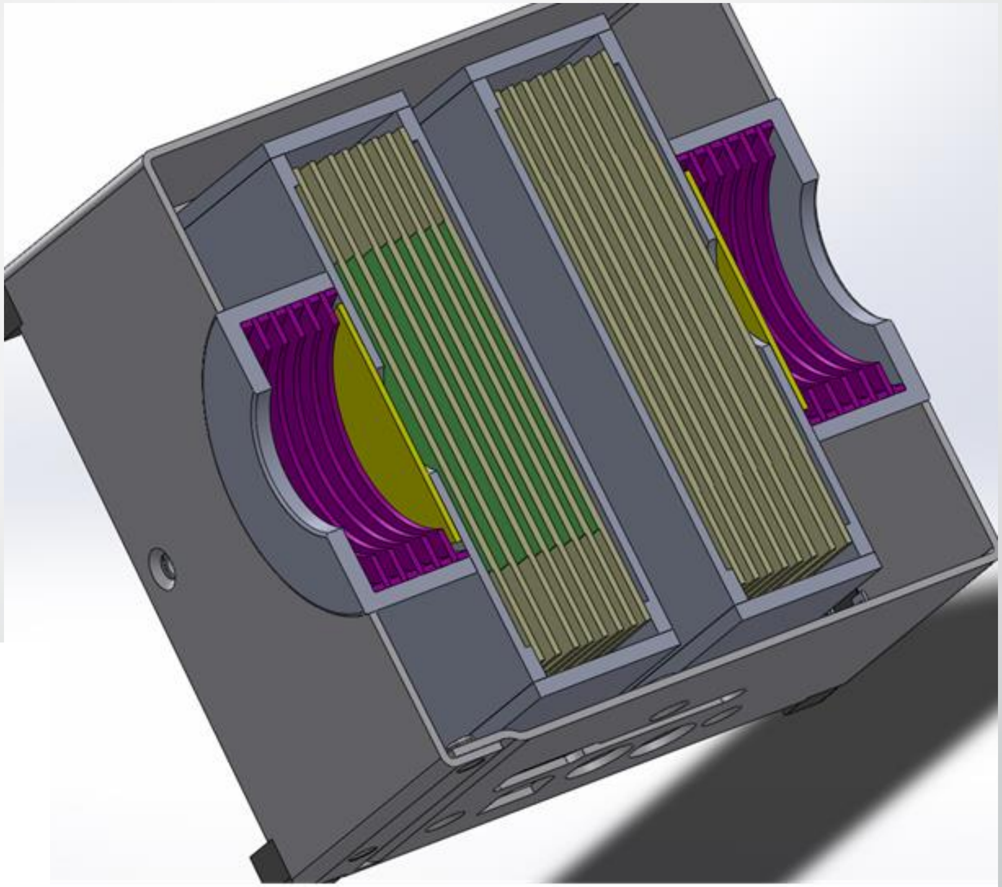
Detector 3 (F): 500 micron thick, 25 channels
- Total Thickness: 1mm
- Dimensions: 50x50mm
- Active Area: 50mm
- Strip Diameter: 2mm

Detector 4 (F): 500 micron thick, 25 channels
- Total Thickness: 1mm
- Dimensions: 50x50mm
- Active Area: 50mm
- Strip Diameter: 2mm

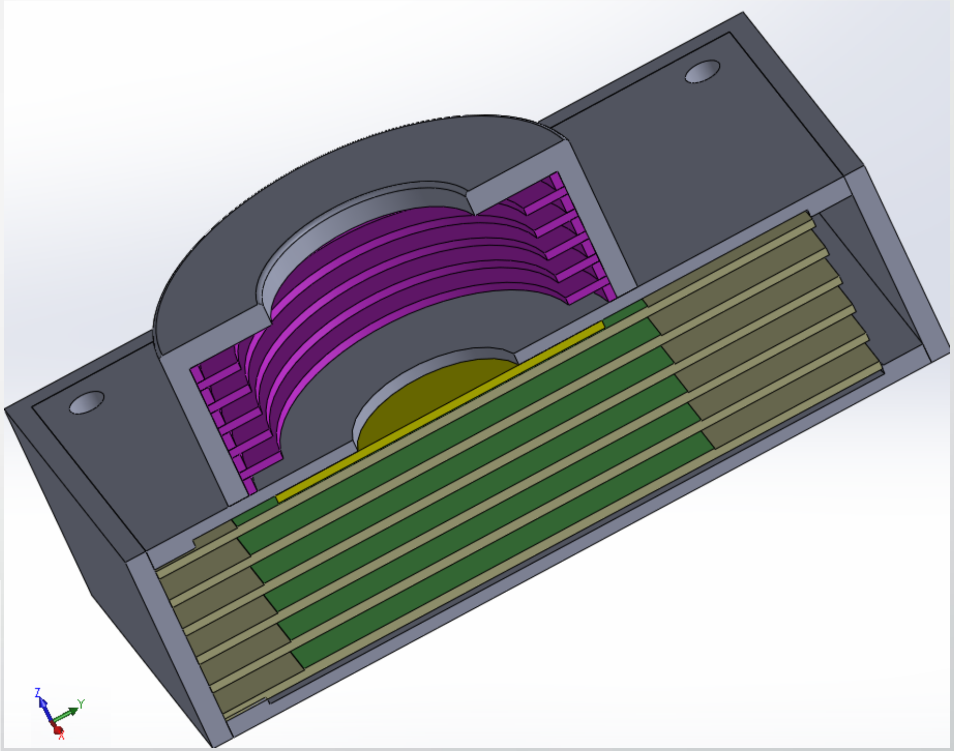
Single Pad Detectors:

Detector 5 (MSX35): 900 micron thick, 1 channel
- Total Thickness: 1mm
- Dimensions: 50x70mm
- Active Area: 50mm

Detector 6 (MSX35): 900 micron thick, 1 channel
- Total Thickness: 1mm
- Dimensions: 50x70mm
- Active Area: 50mm



Detector Stack Details



Strip Detectors

Detector 1 (ZZZ): 100 micron thick, 20 channels
Total Thickness: 1mm
Dimensions: 20x7mm
Active Area: 20mm
Strip Diameter: 2mm

Detector 2 (ZZZ): 300 micron thick, 20 channels
Total Thickness: 1mm
Dimensions: 20x7mm
Active Area: 20mm
Strip Diameter: 2mm

Detector 3 (F): 500 micron thick, 25 channels
Total Thickness: 1mm
Dimensions: 50x50mm
Active Area: 50mm
Strip Diameter: 2mm

Detector 4 (F): 500 micron thick, 25 channels
Total Thickness: 1mm
Dimensions: 50x50mm
Active Area: 50mm
Strip Diameter: 2mm

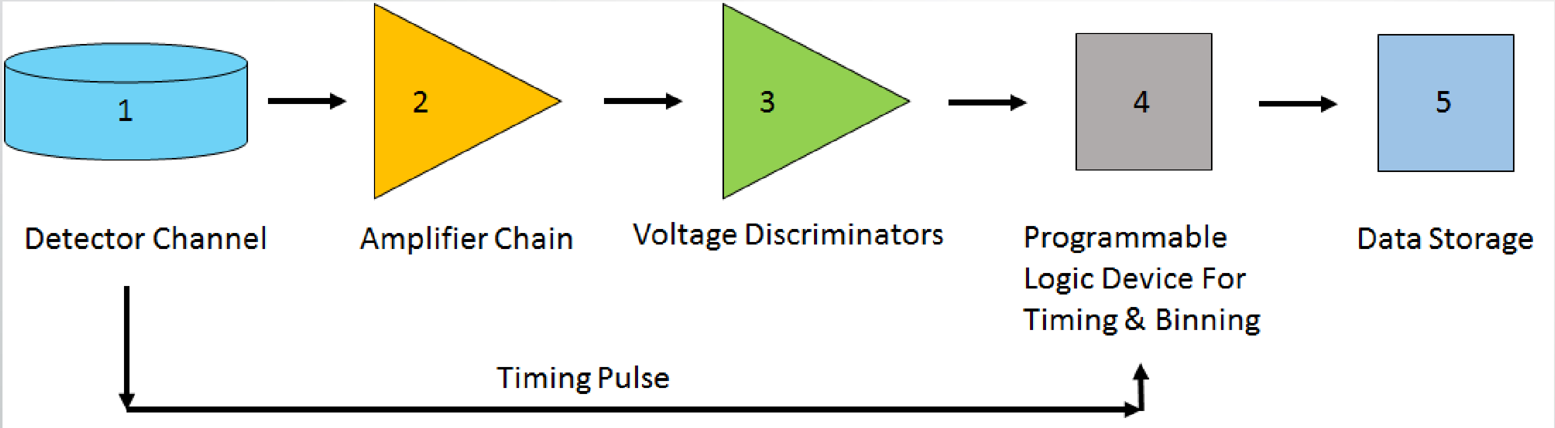
Single Pad Detectors:

Detector 5 (MSX35): 900 micron thick, 1 channel
Total Thickness: 1mm
Dimensions: 50x70mm
Active Area: 50mm

Detector 6 (MSX35): 900 micron thick, 1 channel
Total Thickness: 1mm
Dimensions: 50x70mm
Active Area: 50mm

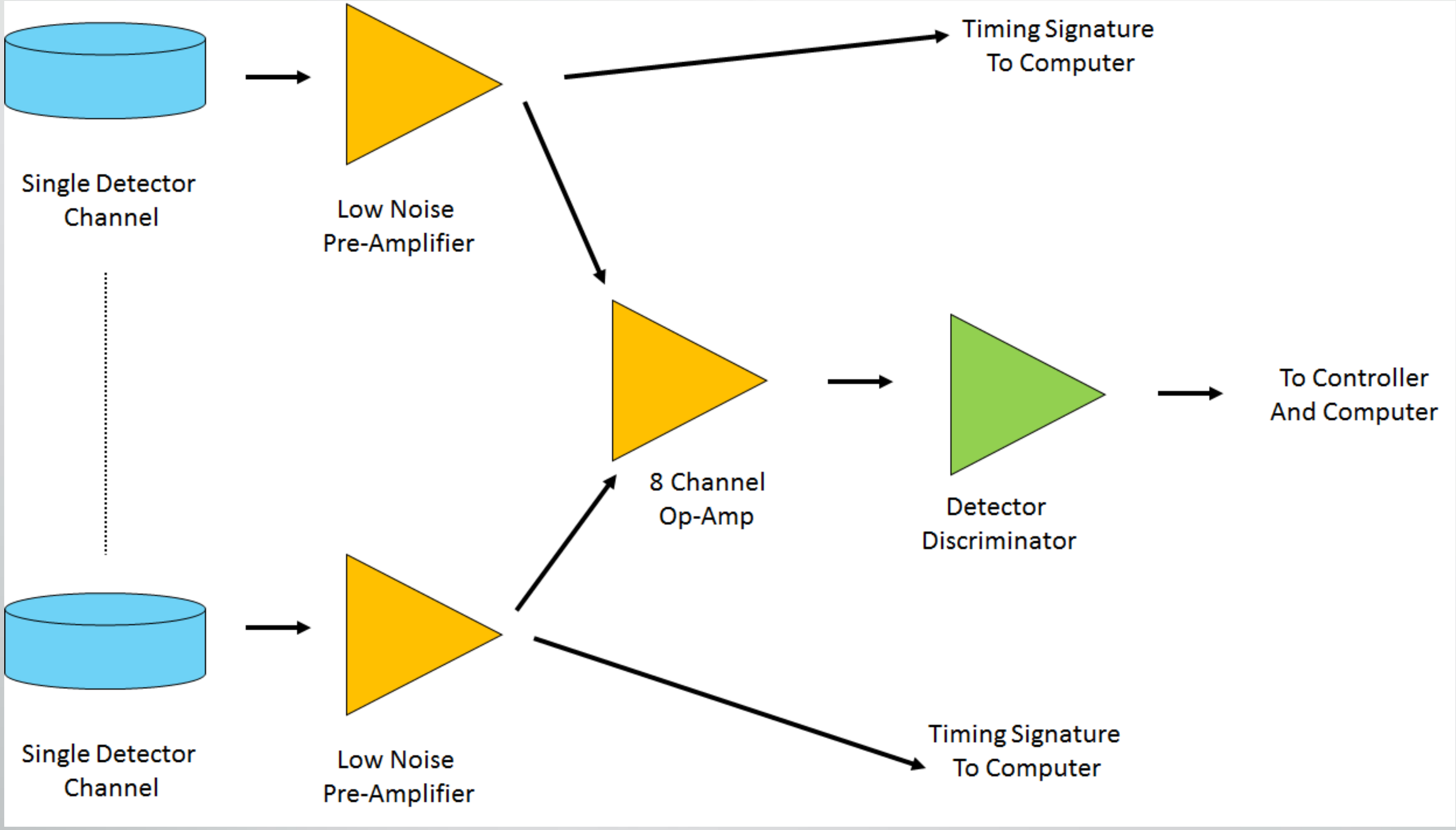
Electronic Architecture

General back-end electronics flow



1) Detector channel (single strip or strip detectors)
2) Low noise amplifier with pulse shaping and timing pulse into Op-Amp for added gain
3) Programmable discriminators
4) Timing Unit and Computer to control voltage thresholding and binning
5) Onboard data storage

Electronic Architecture



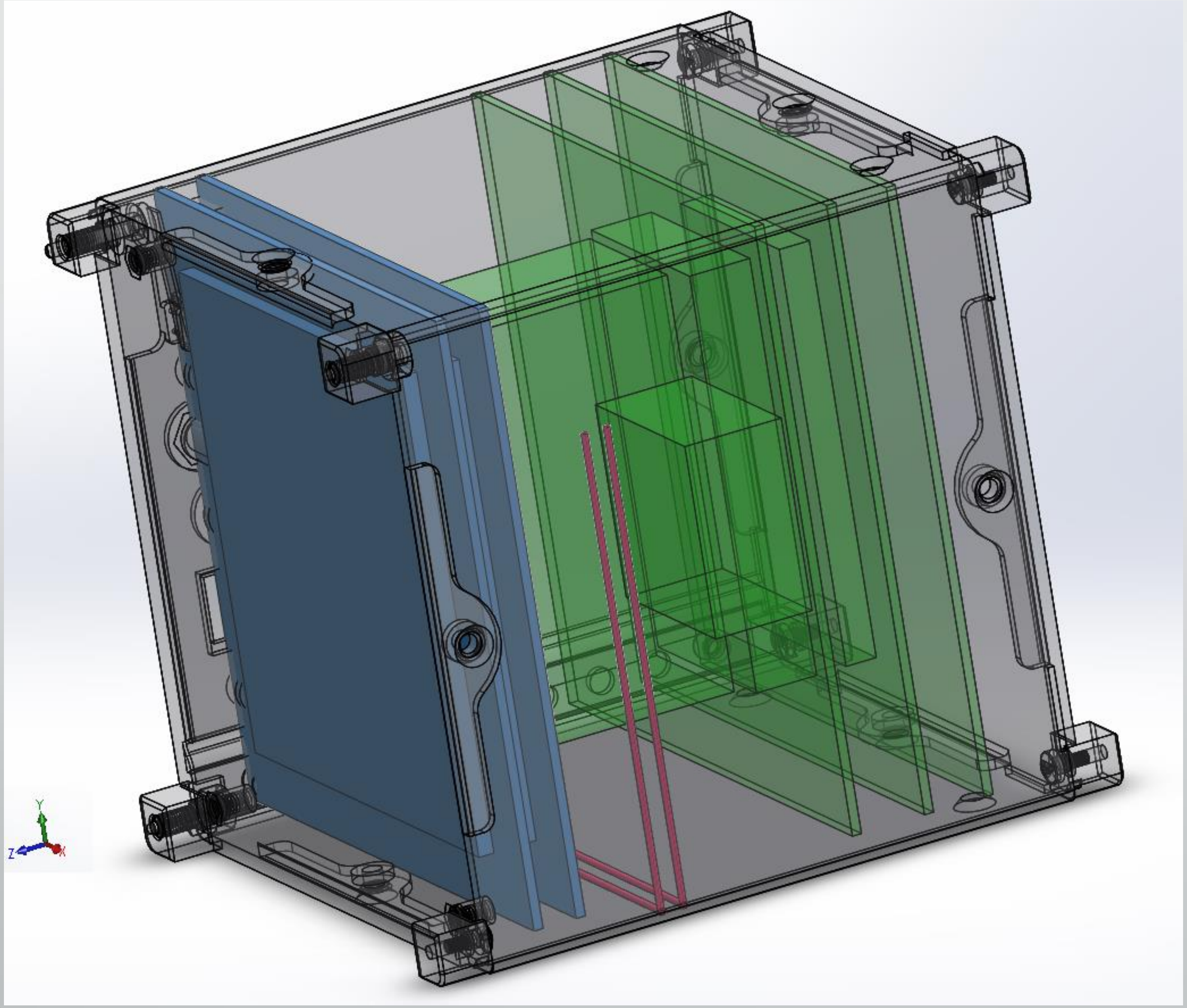
- Low Noise Amplifier: Amp-Tek A225 (as used with REPTile)
- 8 Channel Op-Amp: Not chosen, but available through many suppliers
- Single Discriminator for each of the 6 detectors

Electronic Architecture

- A total of 97 individual channels from all detectors, all of which would need their own amplifier chain if utilized.
- Due to geometric factor chosen for the instrument only ~37 channels receive signal, greatly reducing the back-end electronics needed.
- Two 9x9 cm^2 electronics cards can house the 37 Amp-Tek A225 pre-amplifiers and 5 eight channel Op-Amps. (shown on next slide)
- Each A225 can draw ~10 mW of power, which will generate a significant amount of heat. This can be disposed of conductively through thermally conductive card rails, allowing the heat to be dissipated to the space craft body.

Electronic Architecture

- Detector electronics cards shown in blue



CubeSat Subsystems Summary

- Power
  - Clyde Space CS-SBAT3-10 – 30 Wh Battery
  - Clyde Space SP-L-S3U-0016-CS-MGT Solar Panels
  - Clyde Space CS-3UEPS3-NB EPS Motherboard
- ACS
  - Passive Magnetic Attitude Control (PMAC)
- C&DH
  - TI MSP430 Series microcontroller
  - Salvos Real-Time Operating System (RTOS)
- COMM
  - Astronautical Development's Li-1 Radio
- Bus
  - Pumkin Inc's CubeSatKit MISC 3U Cubesat bus

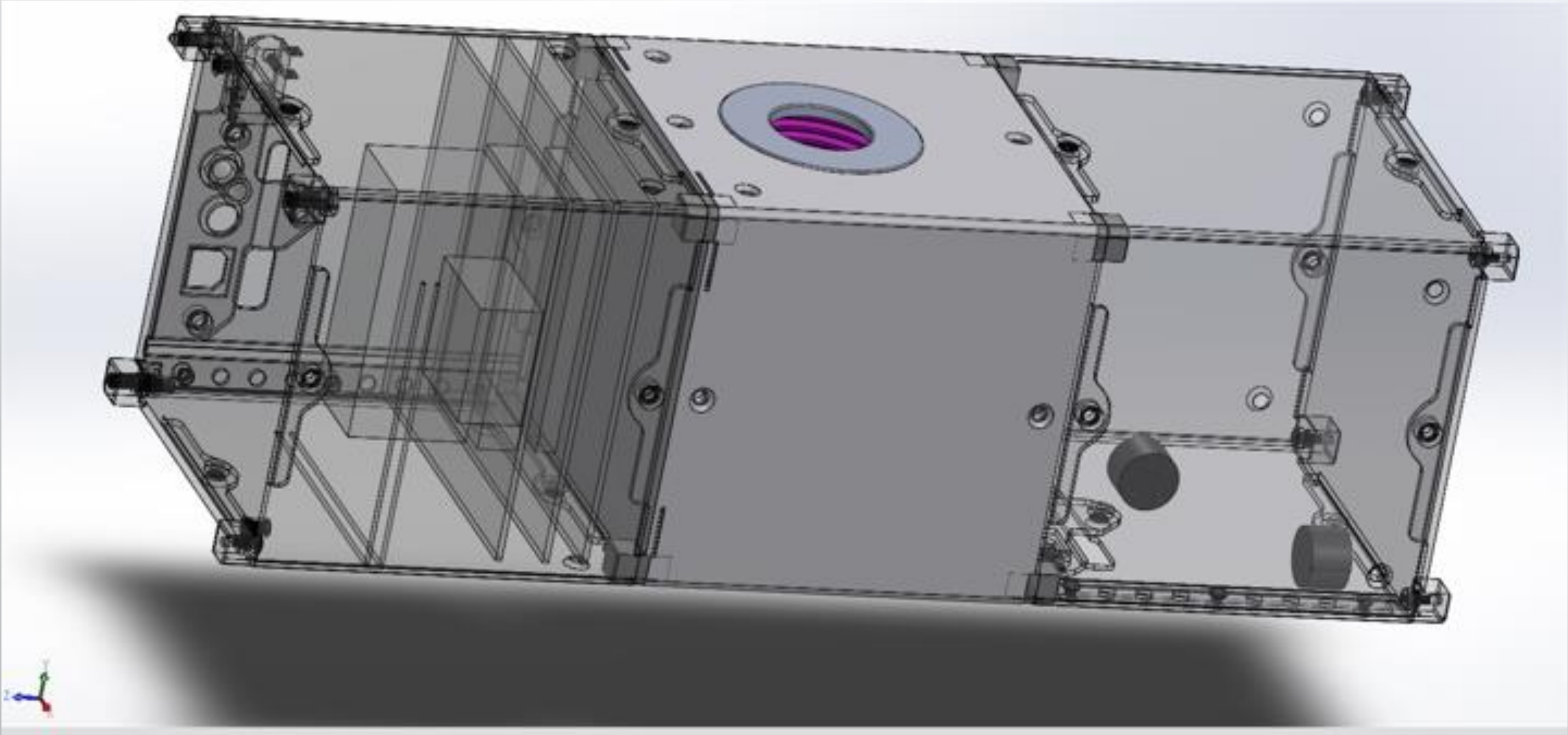
PMAC/ADCS

- REPTAR spacecraft uses Passive Magnetic Attitude Control (PMAC)
  - Single bar magnet aligns REPTAR with Earth's magnetic field
  - Ferromagnetic hysteresis rods dampen oscillation of the spacecraft
  - Pointing performance is ±15 degrees from the local magnetic field
- Magnetometer gives orientation
  - Honeywell HHMC6343
  - Orientation with respect to local field is known within 1 degree.
- PMAC/Magnetometer combination was chosen to save power and weight.

Mass, Power, and Volume

Subsystem	Mass (g)	Power (mW)	Volume (cm^3)
REPTAR	1500	2000	1000
Magnetometer	200	400	52
PMAC	20	0	18
C&DH	100	400	30
EPS	232	200	85
Radio	52	500	21.45
Chassis	317	0	300
Solar Panels	560	n/a	n/a
Total	2981	3500	1506.45
Available	4000	5500	3400
Margin	25.47	36.36	55.69

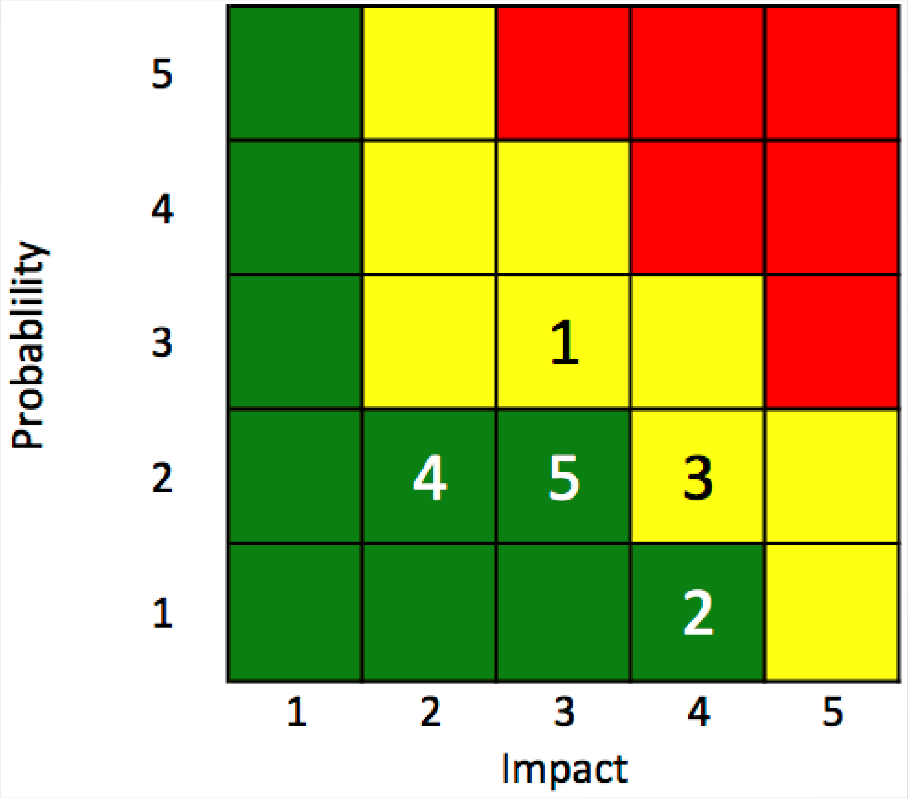
Spacecraft Configuration



Communication

- REPTAR Record rates:
  - 30 minutes of horn time per orbit
  - 10 Mb horn data written per day
- Astronautical Development's Li-1 Radio
  - Supports 9.6 kbps downlink
  - 23 minutes of downlink per day
  - 14Mb daily downlink
  - 40% Downlink margin for retransmits, blown passes, late AOS/early LOS
- Ground Support provided by LASP ground station used for CSSWE and MinXSS.

Risks



ID	Description	Impact	Probability
1	Pitch angle determination failure	3	3
2	Antennas fail to deploy	4	1
3	Battery malfunction	4	2
4	Fabrication delays	2	2
5	Cost overruns	3	2

Schedule/ Budget

- Schedule:
  - Design Phase: 120 Days
  - Fabrication Phase: 275 Days
  - Final Testing/Calibration Phase: 90 Days
  - Operations: >180 days
  - Total: 2 Years
- Budget
  - Instrumentation: $30 000
  - Spacecraft: $50 650
  - Labor/Overhead: $1 388 750
  - Total: $1 352 150 over two years

References

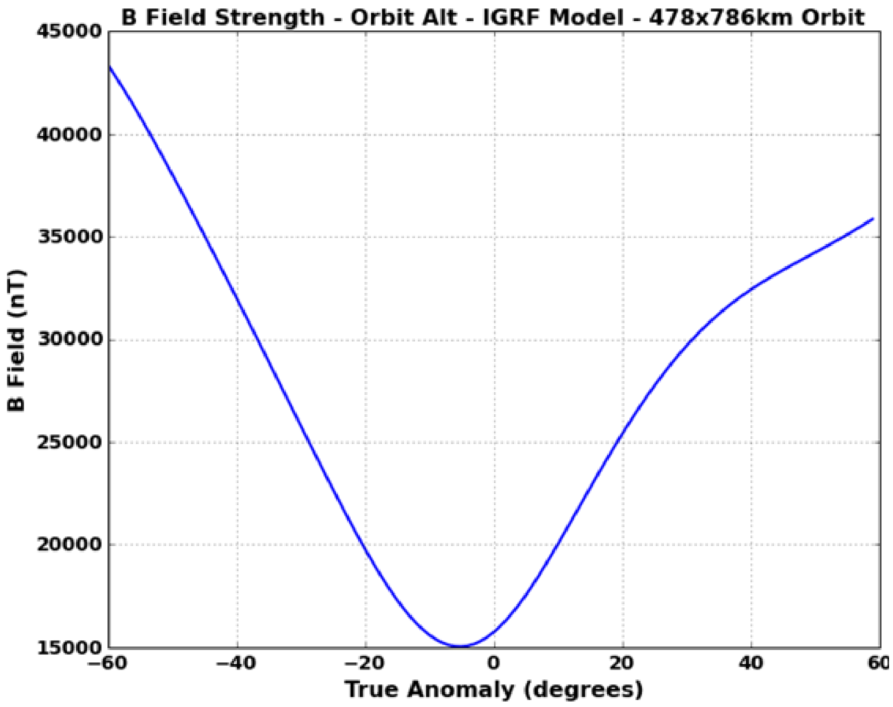
[1] http://i.space.com/images/i/000/047/698/original/525022main_FAQ12.jpg?1432006371

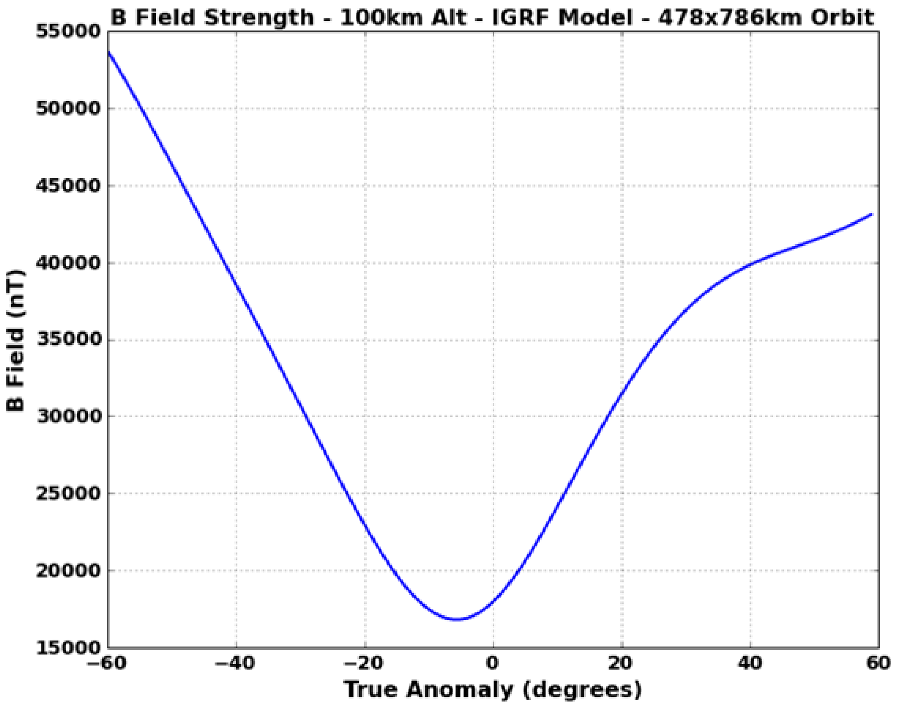
[2] http://lasp.colorado.edu/home/csswe/files/2012/06/ADCS2.jpeg

[3] http://pluto.space.swri.edu/image/glossary/drift_bounce3.gif

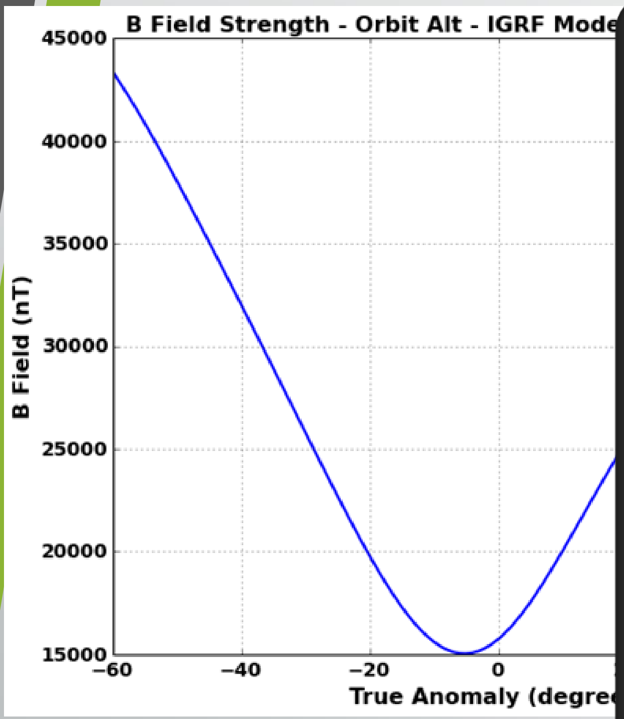

REPTAR

B-Field Strength throughout a radiation belt pass





B-Field Strength throughout a radiation belt pass



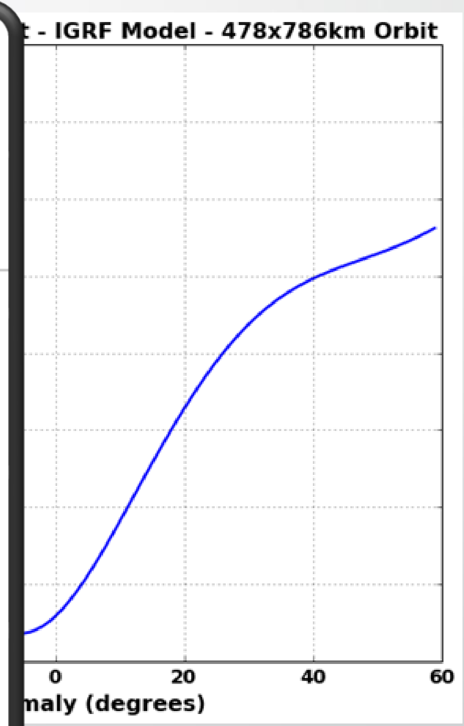
Input parameters:
Year= 2015
latitude= 64.24, longitude= 110.37, height= 478.56

Pofile name: Height
Profile parameters: start= 100., stop= 1000., step= 50.

Selected parameters are:
1 Height, km
2 B_total, nT
3 L_value, Re

1	2	3
100.	58437.6	3.887
150.	57006.3	3.903
200.	55623.0	3.920
250.	54285.7	3.938
300.	52992.4	3.955
350.	51741.1	3.973
400.	50530.1	3.991
450.	49357.6	4.009
500.	48222.2	4.028
550.	47122.3	4.048
600.	46056.4	4.067
650.	45023.2	4.087
700.	44021.4	4.107
750.	43049.8	4.127
800.	42107.2	4.148
850.	41192.4	4.168
900.	40304.5	4.189
950.	39442.4	4.211
1000.	38605.1	4.232

http://omniweb.gsfc.nasa.gov/vitmo/igrf_vitmo.html



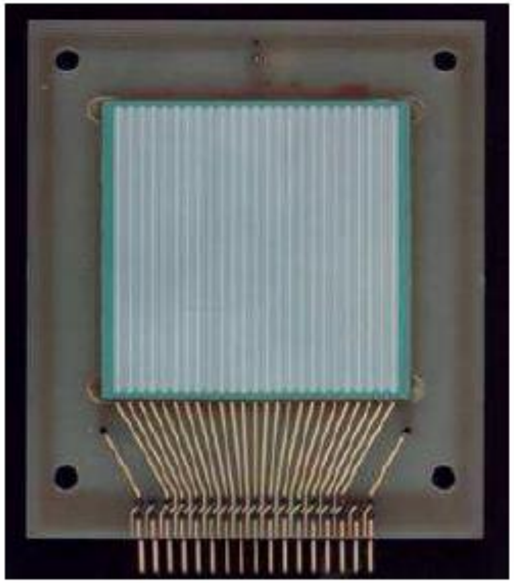
MICRON SEMICONDUCTOR

Single Alphabet Design

DESIGN F

SPECIALIST DETECTORS FOR NUCLEAR PHYSICS

SILICON DETECTOR TYPE:	TOTALLY DEPELTED SILICON MICROSTRIP DETECTOR WITH OVER VOLTAGE OPERATION.
TECHNOLOGY:	4 INCH SILICON
Nº of ELEMENTS:	25
Nº of OUTPUTS:	25
ELEMENT ACTIVE LENGTH:	50 mm
TOTAL ACTIVE WIDTH:	50 mm
ELEMENT SEPARATION:	25 µm
ELEMENT PITCH:	2 mm
THICKNESS:	65 µm, 140 µm, 300 µm, and 500 µm
RISE TIME:	20 ns maximum
ELEMENT CAPACITANCE:	185 – 25 pF subject to thickness
NOMINAL INTERSTRIP RESISTANCE:	100 MΩ
ALPHA RESOLUTION	Junction 55 KeV FWHM maximum Ohmic 75 KeV FWHM maximum
MAXIMUM NOISE PER ELEMENT (µs T.C):	20 KeV



MICRON SEMICONDUCTOR

DESIGN ZZZ

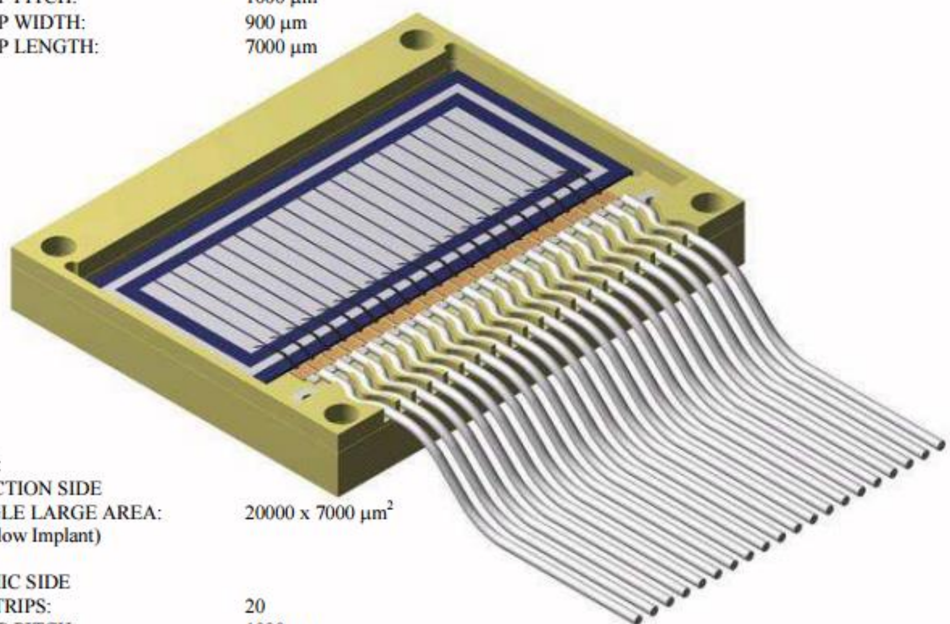
SINGLE SIDED DC MICROSTRIP DETECTOR

SILICON DETECTOR TYPE:	DC coupled ion implanted totally depleted silicon microstrip detector which can be tailored for single sided p-n devices or n-n double sided devices. Microstrip device with a multi-guard ring design for high radiation environment operation.
TECHNOLOGY:	3 inch wafer technology for n-n design 4 inch wafer technology for p-n design
DESIGN:	Microstrip device with a multi-guard ring design for high radiation environment operation.
THICKNESS:	65 -1000 μm

P-N DEVICE:

JUNCTION SIDE

Nº STRIPS:	20
STRIP PITCH:	1000 μm
STRIP WIDTH:	900 μm
STRIP LENGTH:	7000 μm



N-N DEVICE:

JUNCTION SIDE

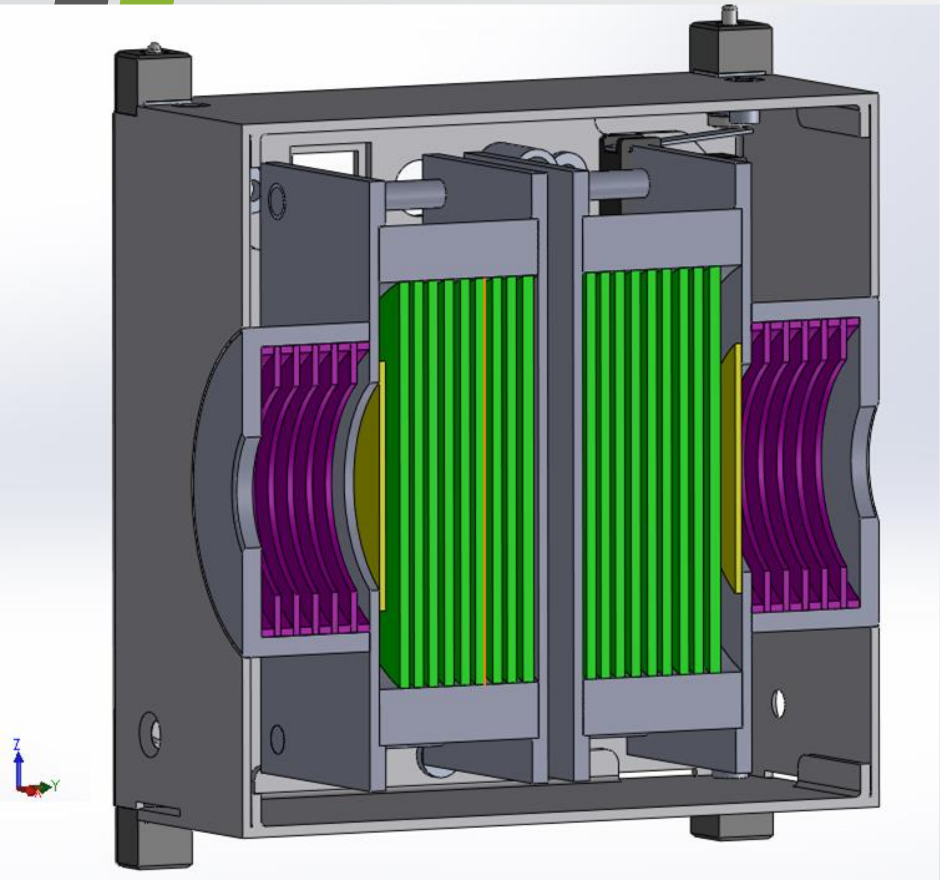
SINGLE LARGE AREA: (Shallow Implant)	20000 x 7000 μm^2

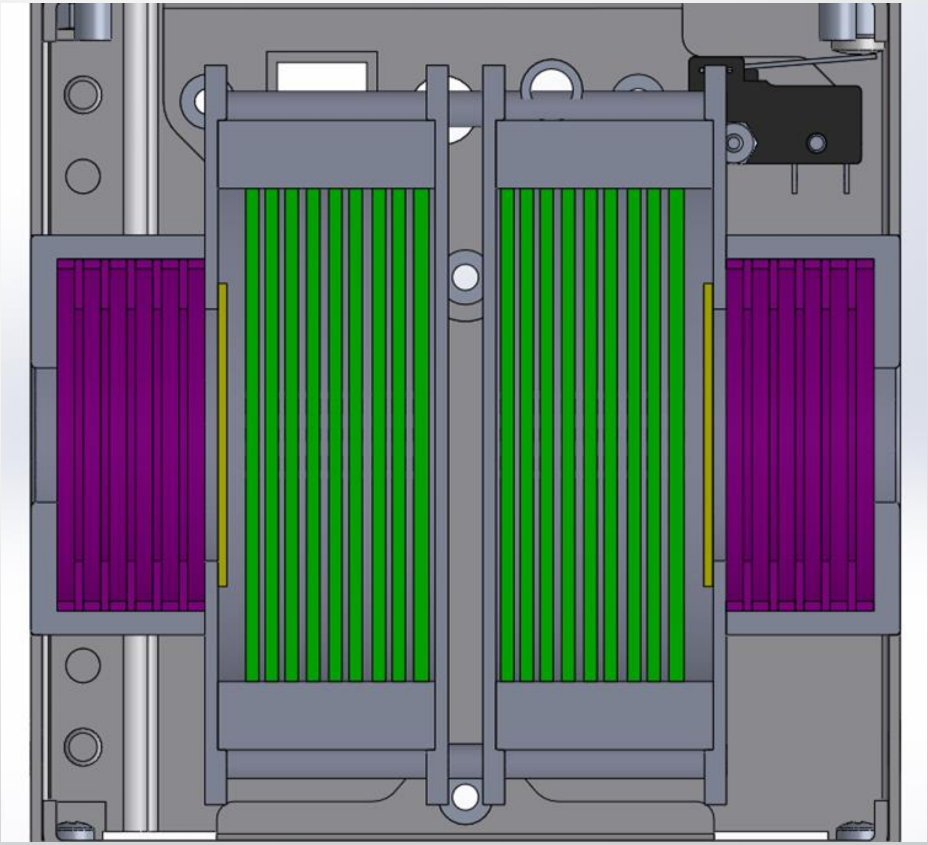
OHMIC SIDE

Nº STRIPS:	20
STRIP PITCH:	1000 μm
STRIP WIDTH:	900 μm
STRIP LENGTH:	7000 μm

CHIP DIMENSIONS: 20000 x 7000 μm^2

Hamamatsu SSD - Circular Detector Face - 100+ detector channels



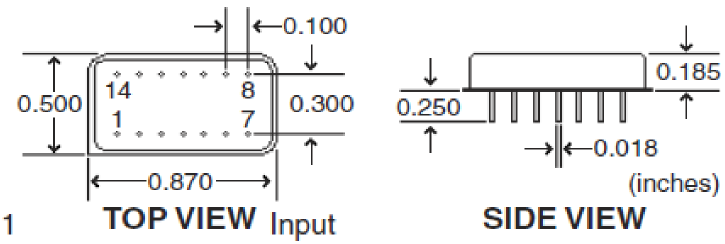


AMPTEK®

CHARGE SENSITIVE PREAMPLIFIER AND SHAPING AMPLIFIER

A225

Package and Pin Configuration



Pin 1	Input
Pin 2, 9	Case
Pin 3, 6, 7, 10, 13	NC
Pin 4	Input GND and Case
Pin 5	Output GND
Pin 8	Output
Pin 11	Vs = +4 to +25 VDC
Pin 12	Timing Pulse
Pin 14	Compensation (see notes)

Features

- Operates from -55 to +125 °C.
- Small size (14 pin hybrid DIP) allows mounting close to the detector.
- Ultra low power (as low as 10 mW)
- Wide range single supply voltage (+4 to +25 VDC)
- Pole-zero cancellation (internal)
- Two outputs available (timing pulse and shaped unipolar)
- High reliability screening
- One year warranty

Input Characteristics

Sensitivity:	240 mV/Mev (Si) 300 mV/Mev (Ge) 195 mV/Mev (CdTe) 206 mV/Mev (HgI2) 5.2 V/pC 0.83 μV/electron
Noise:	2.5 keV FWHM (Si) 2.0 keV FWHM (Ge) 3.1 keV FWHM (CdTe) 2.9 keV FWHM (HgI2) 4.5 x 10^{-17} C rms 280 electrons rms

General

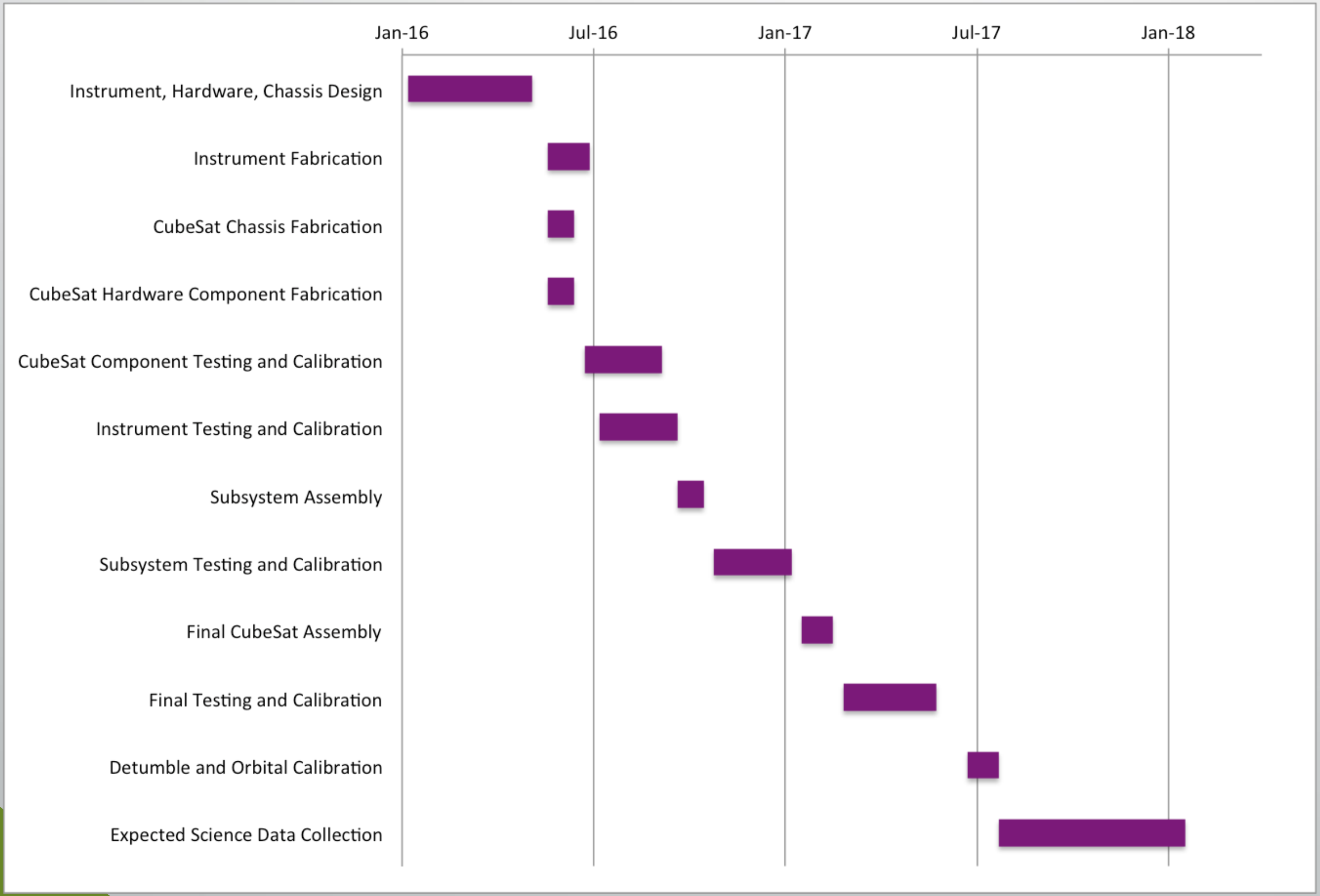
Weight:	.14 oz, 4 g
Operating Voltage:	Vs = +4 to +25 VDC
Operating Current:	2.3 mA independent of Vs
Variation of Sensitivity with Supply Voltage:	< 0.07% /Volt, 4 to 10 Volts < 0.005% /Volt, 10 to 25 Volts
Temperature:	-55 to +125 °C Operational
Temperature Stability:	0.02% / °C at 25 °C typical ±2% from -25 to +75 °C
Screening:	Amptek High Reliability
Package:	14 pin hybrid DIP (metal)
Radiation Resistance:	100k rad(Si)
Warranty:	One year
Test Board:	PC-25

Component	Manufacturer	P/N	TLR	Flight Heritage
CubeSat Structure and Hardware	Pumpkin	711-00499	9	CSSWE, RAX, RAX-2
Solar Panels	Clyde Space	SP-L-S3U-0016-CS-MGT	7	
EPS Motherboard	Clyde Space	CS-SBAT3-10 – 30	7	
Battery	Clyde Space	CS-3UEPS3-NB	7	
Radio	Astronautical Development	Li-1	8	CSSWE
ACS	Permanent bar magnet and hysteresis rods		9	CSSWE
Si Detector Assembly	Developed at CU		7	CSSWE
Magnetometer	Honeywell Microelectronics & Precision Sensors	HMC6343	7	CSSWE

Risk Mitigation

ID	Description	Mitigation Strategies
1	Angle determination failure	Mission focuses on counts alone (still valid science mission)
2	Antennas fail to deploy	Limiting data transmission
3	Battery malfunction	Limiting night-side operations; Limiting transmission times
4	Fabrication delays	Schedule overestimates time required
5	Cost overruns	Utilize low-cost student labor

Detailed Schedule



Labor Cost Breakdown

Position	Equivalent FT Work (Years)	Yearly Salary ($)	Total ($)
Principal Investigator	1.75	80 000	140 000
Project Manager	1.25	75 000	93 750
Systems Engineer	1.75	75 000	131 250
Instrument Scientist	1.25	75 000	93 750
Project Scientist	1.00	75 000	75 000
Students (x5)	2 = 4 semesters	8500 per semester	170 000

REPTAR Science Traceability Matrix							
NASA Science Goal	Investigation Science Objectives	Science Measurement Requirements		Instrument Performance			Mission Requirements (Science Driven)
		Physical Parameters	Observable	Parameter	Requirement	Projected	
2013 Decadal Survey, 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."	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 quiescent times.	Radiation Belt Electron Populations	1) Electron Pitch Angle	Angular Range	<= 55 degrees half angle	45 Degrees half angle	Must be able to maintain pointing along magnetic field lines
				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	Need 6 months of data to observe geomagnetic storms
				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	

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	**Operations Reqirements**
Spacecraft Accomodation	**Driving Mission Requirements** Desired resolution of measurements: CSSWE 6 sec count rate Desired pointing accuracy: < 15 degrees Desired attitude knowledge (relative to B-field): < 2 degrees	**Spacecraft Requirements** 5 Watts Data Storage : 32 Gb total storage Spacecraft Size: 3U Maximum Mass: 4kg	**Operations Reqirements** S/C Modes: Safe, Science, Maintanence Keep out zones (duty cycling wrt beta angle)
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 Orbit events prediction for downlink (times in horns)