Jet Propulsion Laboratory
California Institute of Technology

Low SWaP Radiation Sensor Development and Characterization at JPL

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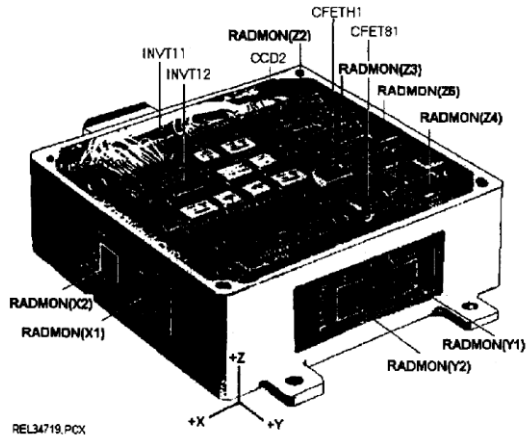
Topics

- JPL’s Radiation Monitors
- Sensors
- Summary

JPL's Radiation Monitor Heritage

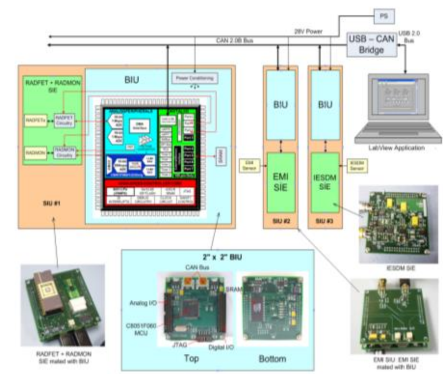
RRELAX

- Instrument successfully flew on the Clementine mission in <u>1992</u>
- Monitored the SEU rates and Total Ionizing Dose (TID)
- Managed by H. B. Garrett



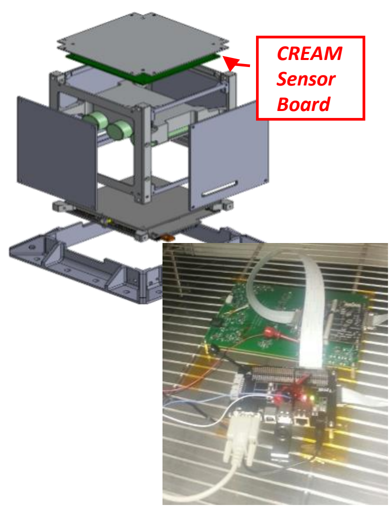
Strategic Initiative <u>2008</u>

- Demonstration of a network of environmental monitoring sensors including design, fabrication and test of a breadboard system
- Measurements of TID, SEU, and a prototype Electrostatic Discharge Monitor



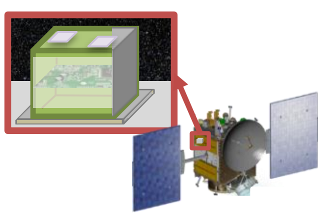
CREAM

- CREAM was an instrument suite part of the MISSE-X CubeSat
- CREAM included TID, temperature, and UV measurements
- CREAM passed PDR at JPL at the time of the MISSE-X cancellation in August <u>2013</u>



Black Box <u>2016</u>

- small environment monitor designed to support mission planning, anomaly investigations, and the design of future JPL missions
- TID, SEU, Charge monitors, and Camera



Environmental Sensors

Sensor	Environment Quantified	Operation Overview	Calibration
Atomic Oxygen (AO) Fluence Monitor	Flux (atoms/cm^2·sec), Fluence (atoms/cm^2)	Provides time-based AO arrival data by using the erosion of a pair of pyrolytic graphite wedges over an ambient lit photodiode.	To improve calibration accuracy, two Kapton covered photodiodes (different film thickness) will provide in-flight calibration verification.
UV Sensor (140 nm - 1100 nm)	Sun-hour from the broad band intensity (W/cm^2) measurement	Measure the current generated by the photodiode responding to the broad band sun spectrum.	Calibrate the photodiode using the solar simulator lamp.
Total Ionizing Dose (TID)	energy deposition by ionizing radiation (J/kg = Gy, rad = cGy)	The threshold voltage of RADFET is shifted according to the total deposited energy in the gate oxide.	Calibrate the threshold voltage shift on ground using known radiation sources such as Co-60 and/or electron beam.
Temperature Transducer	Local temperature (K)	Temperature transducer is an Intergtated Circuit (IC), the design of which results from the fact that semiconductor diodes have temperature-sensitive voltage vs. current characteristics.	The output current is proportional to absolute temperature. (1 μA/K) Will be calibrated on ground.
X-ray Sensor (Soft x-rays: 10-1 nm proposed)	X-ray intensity (W/cm^2)	X-ray Photodiode generated the currents proportional to X-ray intensity. Lower energy photons (UV, VIS, and IR) is blocked by a filter which defines the spectral range.	Calibrate the X-ray photodiode output current with the X-ray source with a known intensity.
Contamination Monitor	Mass of a contamination deposited (g/cm^2)	The frequency of a Quartz Crystal Microbalance (QCM) decreases as the mass deposited on the QCM surface increases.	
Single Event Upset (SEU) Sensor	Number of upset per unit time due to proton flux	Counts the number of bits upset in a memory chip (SDRAM or DRAM) after a unit time and reset the bit value to the original one. Ready for next upset counts.	At the exact flight condition, calibrate the memory chip against the different proton energies and fluences.
Surface Charge Monitor	Potential on sensor surface w.r.t. the S/C ground (V)	The electric field generated by the potential on the surface is attenuated through the hole on ground plane. The attenuated field is sensed using a vibrating electrode driven by a tuning fork that is closed-loop controlled.	The know potential is applied to the sensor plate from a power supply.
Internal ESD Monitor (iESD)	Potential as a function of depth (V)	The potentials along the depth of he dielectric plate are measured through a thin metal meshes imbedded in dielectrics.	The measured potentials are compared with a theoretical model such as NUMIT.

TID – RADFET

- RADFET from REM was used
  - Size of chip carrier: 1.7 x 0.87 cm^2, mass: < 1 g

Example Usage

- Responsivity, Range, and Resolution
  - Responsivity: 0.2 mV/rad(Si) at low dose

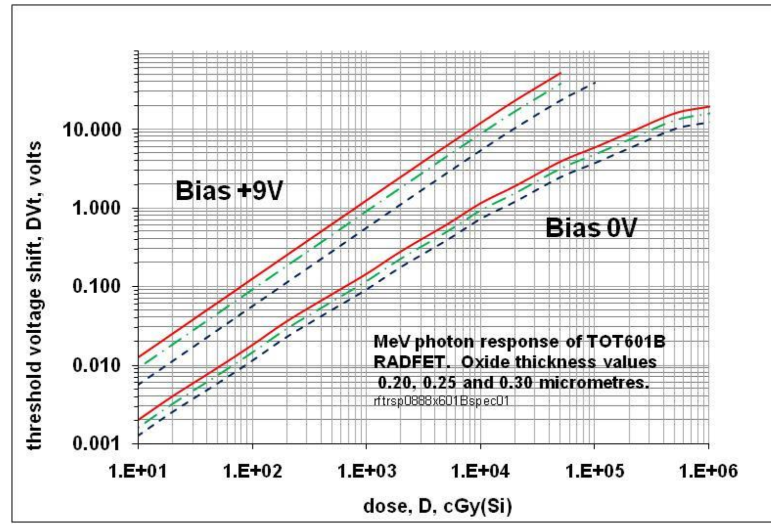
    0.02 mV/rad(Si) at high dose
  - Range: Sensor 1 Mrad (25 V)

    ISS Environment < 250 krad (1 year)
  - Resolution: dose resolution

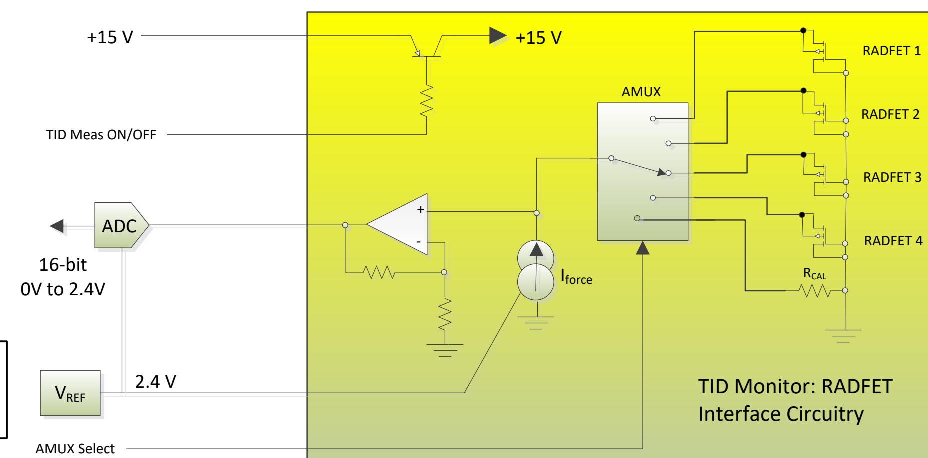
    (50 rad= 1 mV)

    (dose during one orbit, 1.5 hours)

    A/D converter: 16 bit

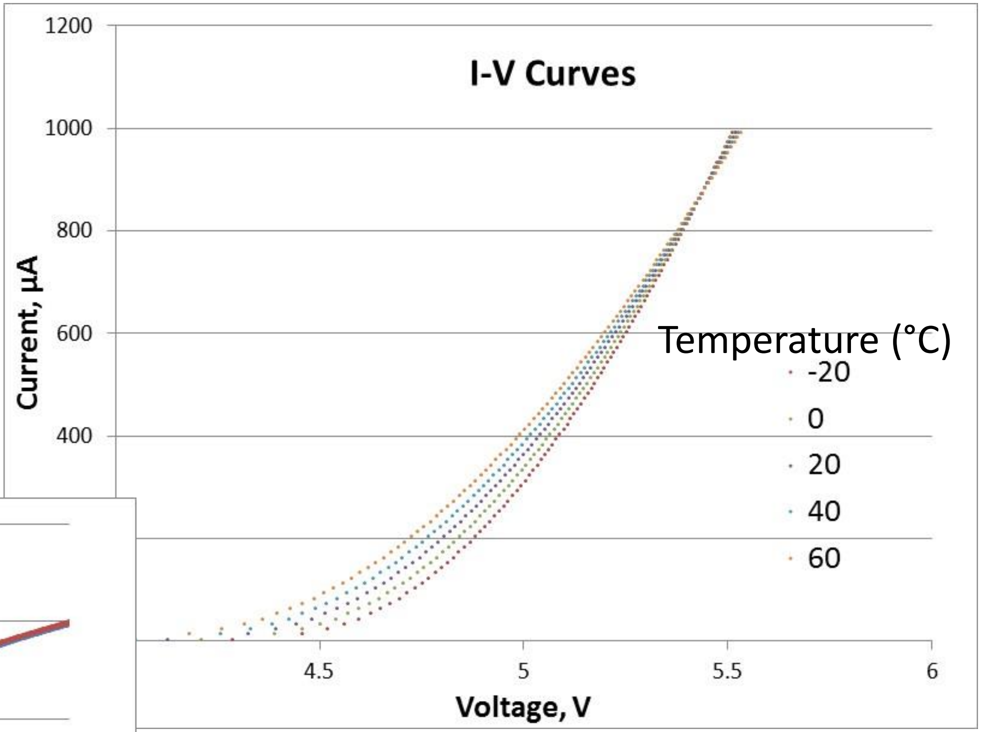


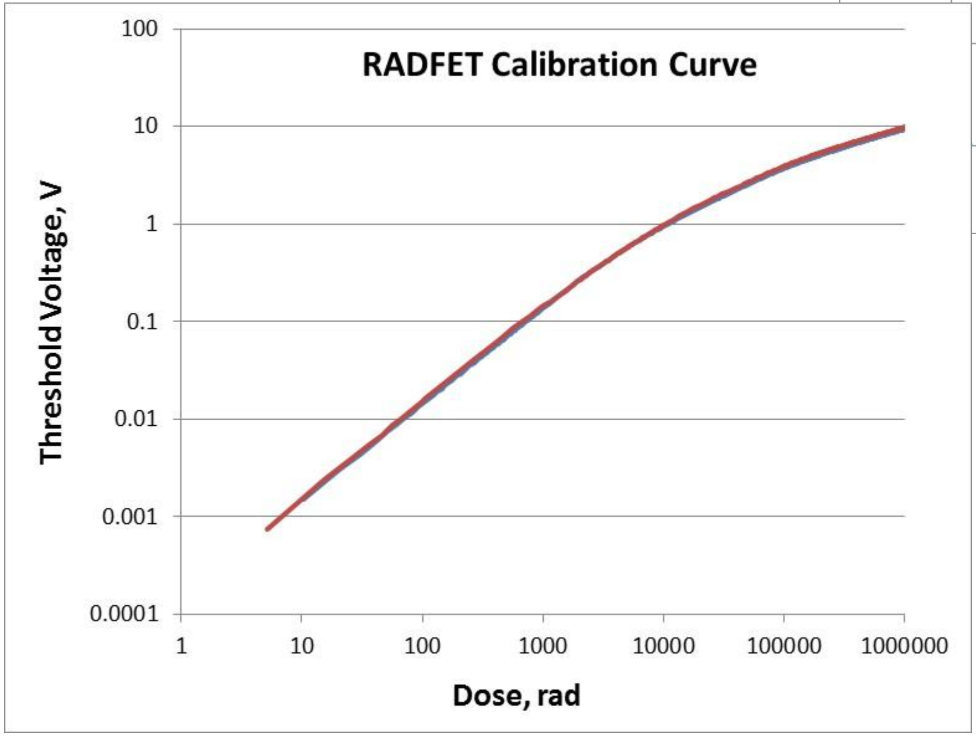
Example Circuitry



Calibration of TID sensor

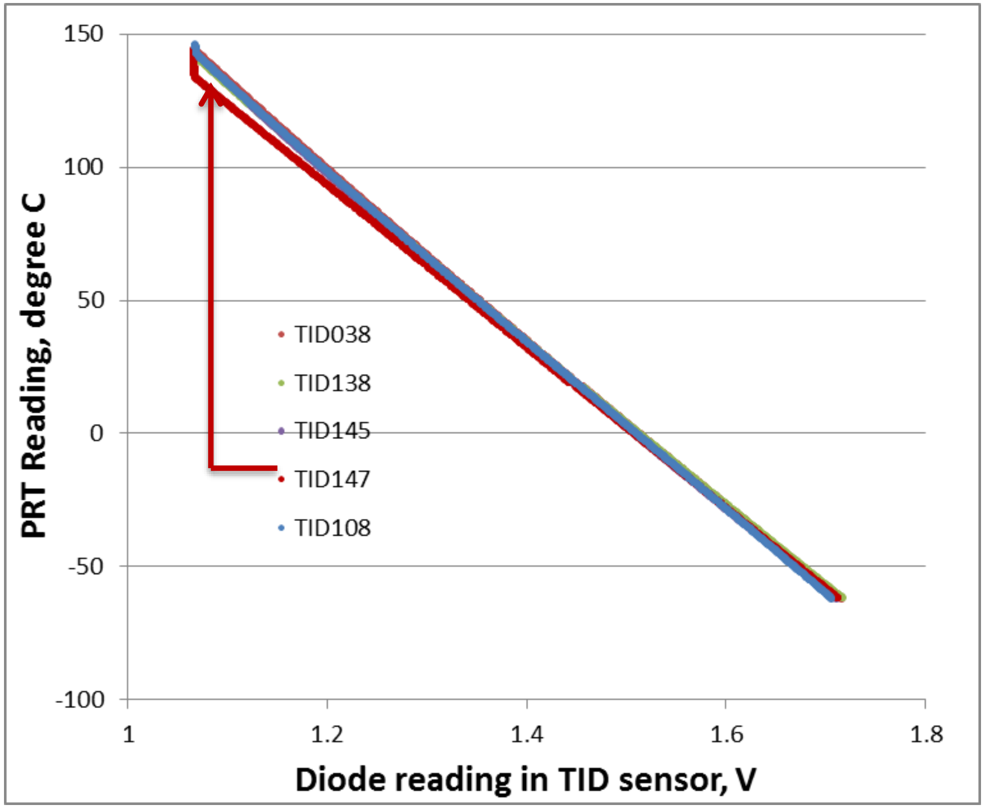
- I-V curve at several temperatures
- zero temperature coefficient (ZTC) point
  - Measurement current
  - ZTC changes with dose
  - used for the preselection of RADFETs





- Calibration curves for two RADFETs
- Zero bias
- Room temperature
- Current at ZTC point
- Pre-selected based on I-V curve
- Two RADFETs showed similar curves

Calibration – built-in diode in TID sensor



TID Sensor Designator	Slope	Intercept
038	-316.98	479.92
138	-312.76	473.46
145	-314.08	473.53
147	-303.15	457.00
148	-314.07	475.16
155	-312.49	473.38
158	-312.25	472.45
160	-317.45	480.63
165	-318.11	481.33
108	-318.31	480.65

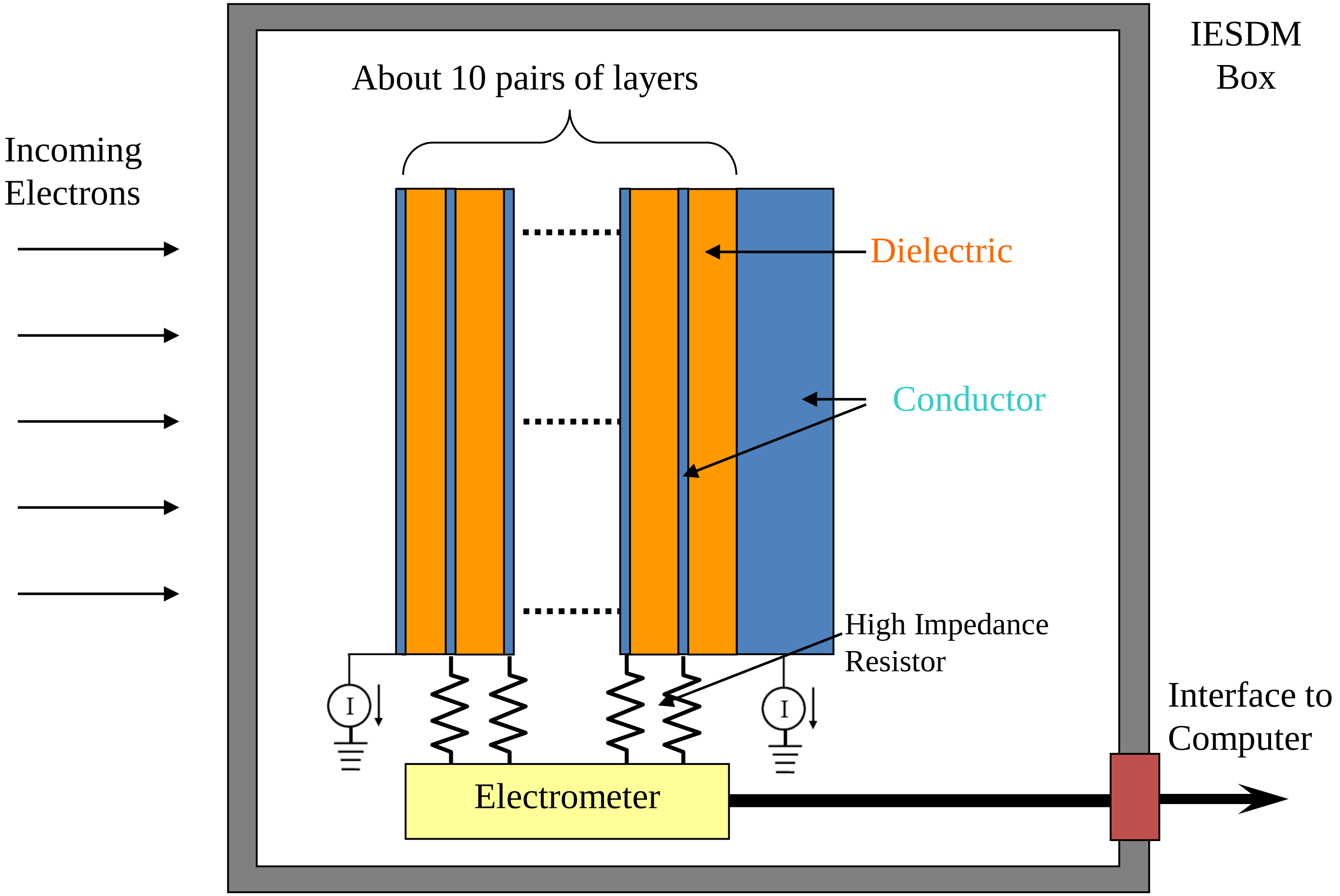
- TID 147 shows large deviation. The rest nine sensor show similar curves.
- The diode outputs show linear relationship with the temperature except for high temperature region (130 ~ 150 ˚C).
- TID sensors with similar temperature calibration curves (and similar I-V characteristics) were selected for the further tests.

Low SWaP Adjustable Dosimeter

- Developing with ASU (Hugh Barnaby and David Allee)
- A low size (<25 cm^2), weight (<200 g), and power (<1 W) dosimeter system which is capable of adjusting its sensitivity (and maximum range) between 10 mrad (10 krad) and 1 rad (1 Mrad).
- Designing proto-type adjustable dosimeter system using REM Model TOT601B RADFETs combined with a dual slope Nyquist-rate A/D converter with built-in sync filter assembled with radiation hardened components.
- System will be able to sample between 2 rad and 1 Mrad of ionizing dose

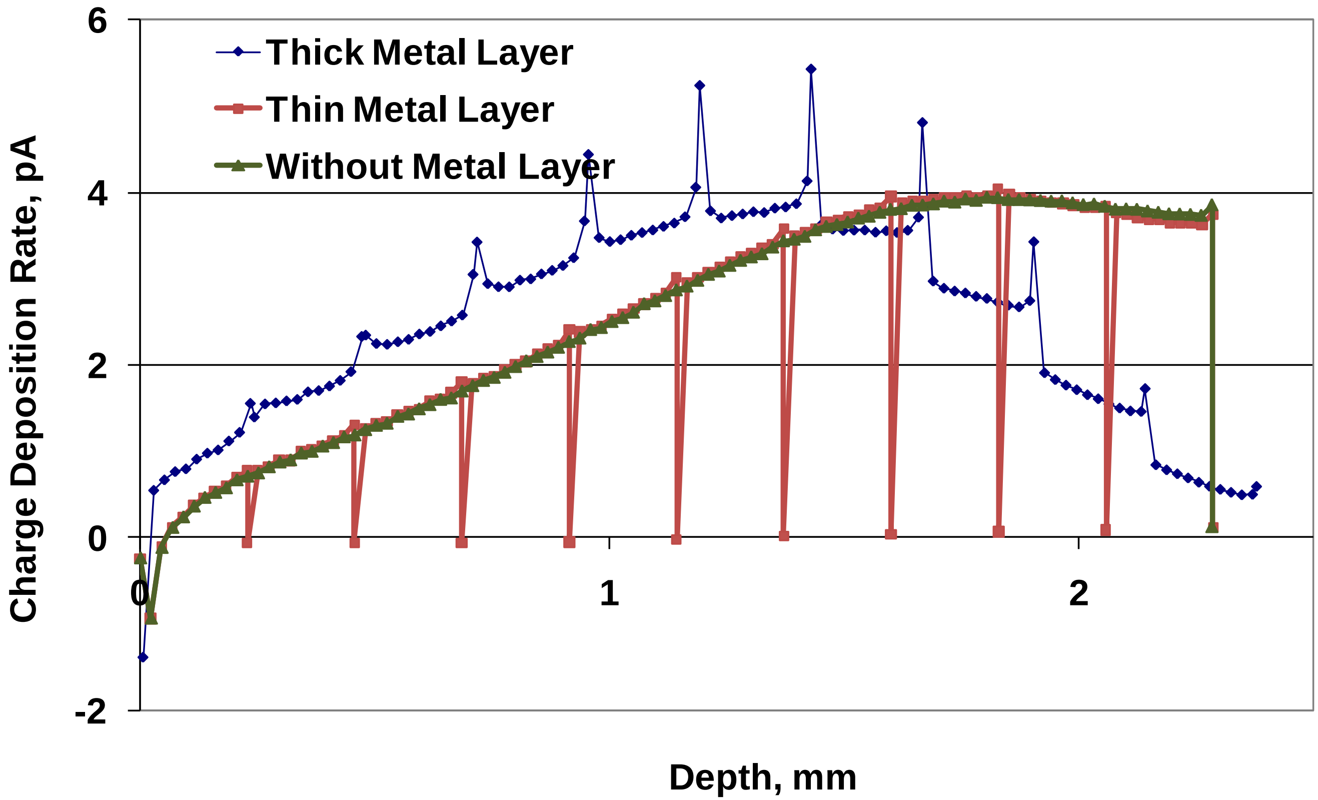
Internal Electrostatic Discharge Monitor (IESDM)

The IESDM was designed to emulate a multi-layer circuit board. Very thin metallic layers (meshes) were inserted between the dielectric layers

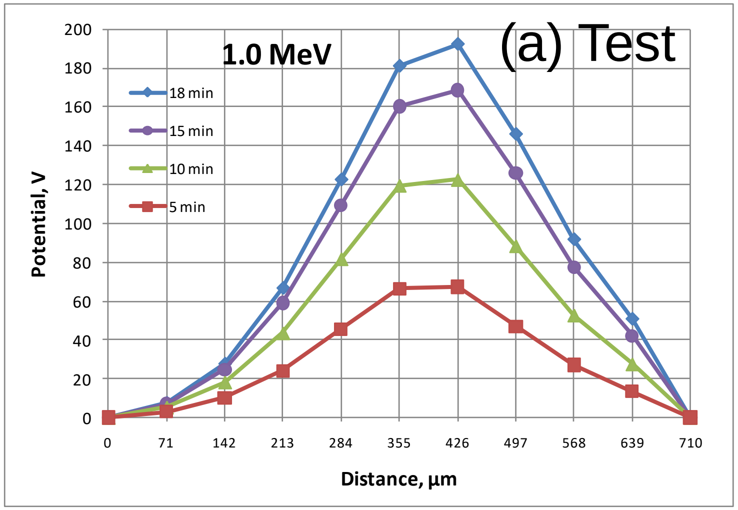


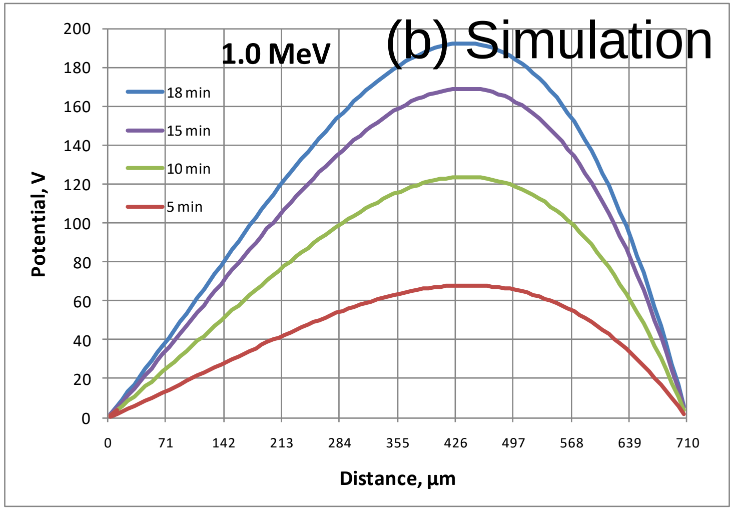
Internal Electrostatic Discharge Monitor

Example Monte Carlo (TIGER) simulation result – 1 MeV, 300 pA
Show that insertion of thin metal layers does not change the charging profile



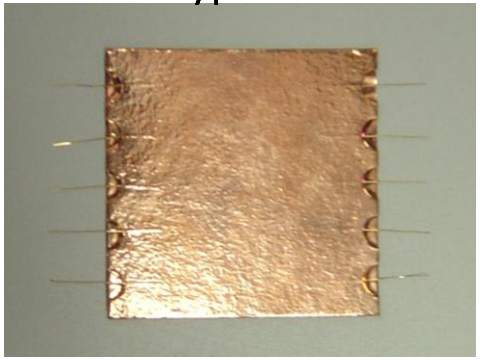
Internal Electrostatic Discharge Monitor





Dark conductivity: 3.1×10^{-16} $ohm^{-1}m^{-1}$
RIC coefficient: 2.0×10^{-16} sec $ohm^{-1}m^{-1}rad^{-1}$

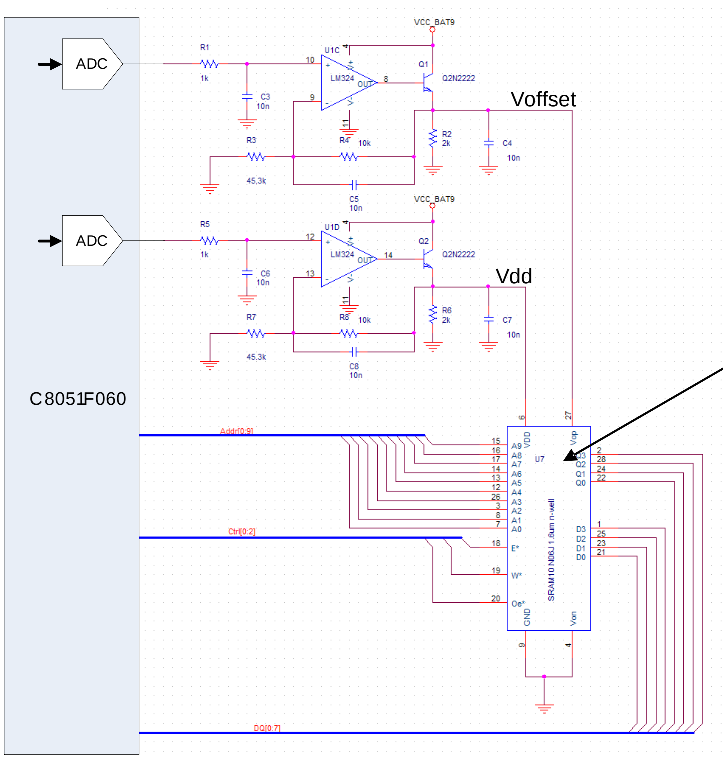
Prototype IESDM

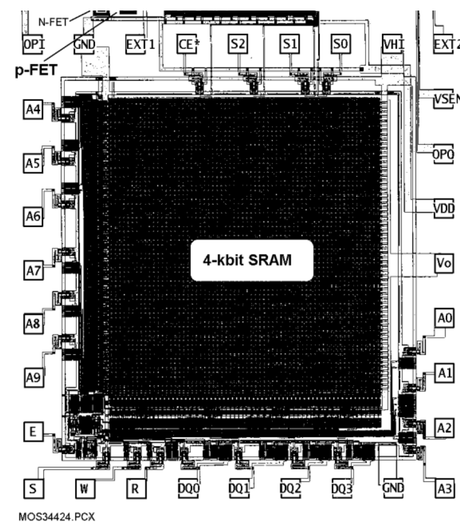


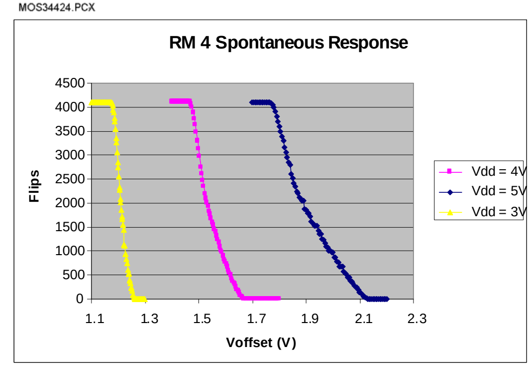
Test Setup

SEU Sensor

- Will use a commercial SRAM. This SRAM can be sensitized to SEUs by lowering V_{dd} (as was done for the RADMON). So we eliminate the V_{offset} adjustment channel, but keep the V_{dd} adjustment channel. If we only want two values (nominal V_{dd} value for read/write and lower sensitizing value for SEU "stare" time), the DAC can be replaced with a 2-1 AMUX feed by voltage dividers.







- RADMON chips used for two bin particle spectrometer in RRELAX boxes flown on Clementine (1994)
- Critical charge sensitivity to SEUs is tunable via Voffset and Vdd .

SEU Sensor - RRELAX

A signal level will strongly depend on shielding, integration time, pixel size, radiation hardness, threshold voltage as well as an exposed environment.

Refer to the previous experiment; RADMON on Clementine RRELAX (4 kbit)

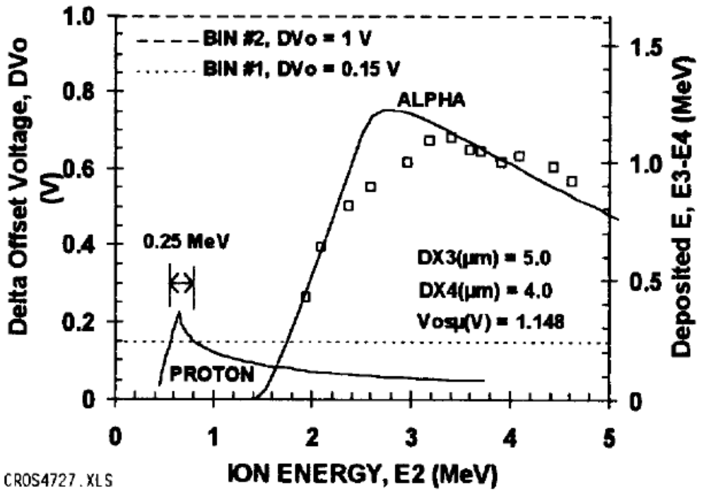


Figure 6. Calibration curves and operational thresholds for the SRAM particle detector.

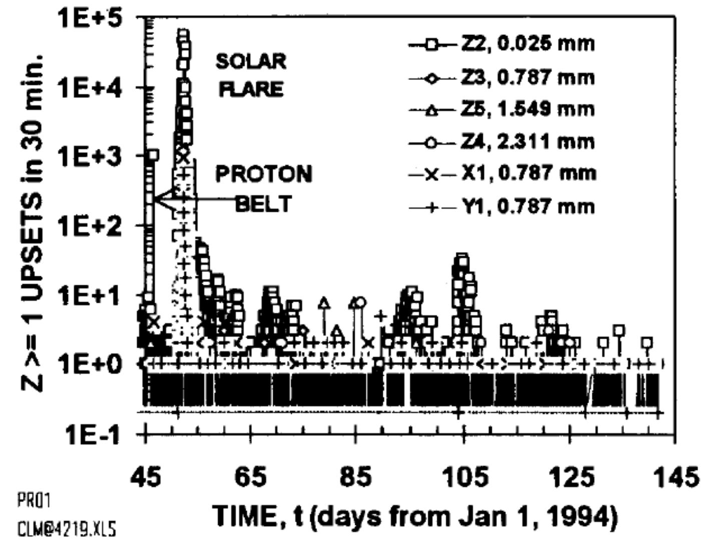


Figure 7. Overview of the Z≥1 upsets for S/C Z2, Z3, Z5, Z4, X1, and Y1 SRAMs.

With the threshold voltage of 0.15 V, Protons with 0.55 MeV < E < 0.8 MeV and heavier ions upset the RADMON.

Upset Rate of RADMON;
Solar Flare: up to 6E4 SEU/30min
Normal: ~ 2 SEU/30min

M. G. Buehler, G. A. Soli, B. R. Blaes, J. M. Ratliff, and H. B. Garrett, "Clementine RRELAX SRAM Particle Spectrometer," IEEE Transaction on Nuclear Science, vol. 41, pp. 2404, 1994.

SEU Sensor

Typical modern memory chip has 4 Mbit (1000 time higher than RADMON) and area of about 1 cm^2.
Expected upsets calculating from RADMON data;
Solar Flare: up to 2E6 SEU/min
Normal: ~ 70 SEU/min

Calculation from Proton Environment:
Bin flux between 0.5 MeV < E < 1 MeV (twice of that of RADMON case)
No Shielding

- Normal

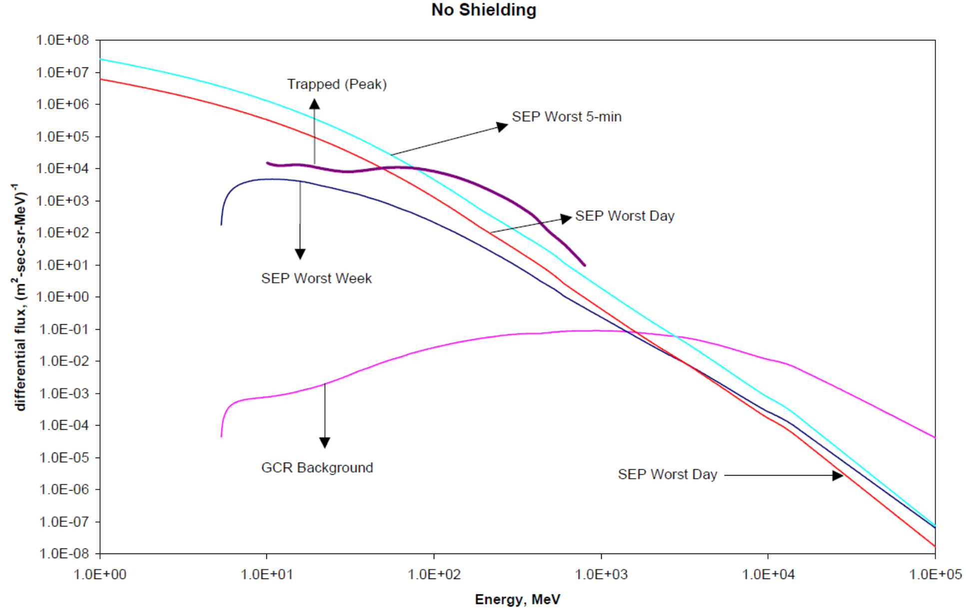
AP8MAX: 9.5E2 hits/min
AP8MIN: 8.6E3 hits/min

- Solar flare

From the left graph
proton flux is ~ 3E7/(m^2 s sr MeV)
Converted to 5E5 /(cm^2 min)

Assuming 1% upset per measurement, 2E6 SEU/min can be done by a measurement per every second

Figure 14. CREME96 High Energy Proton Differential Spectra for ISSA LTMPF
No Shielding

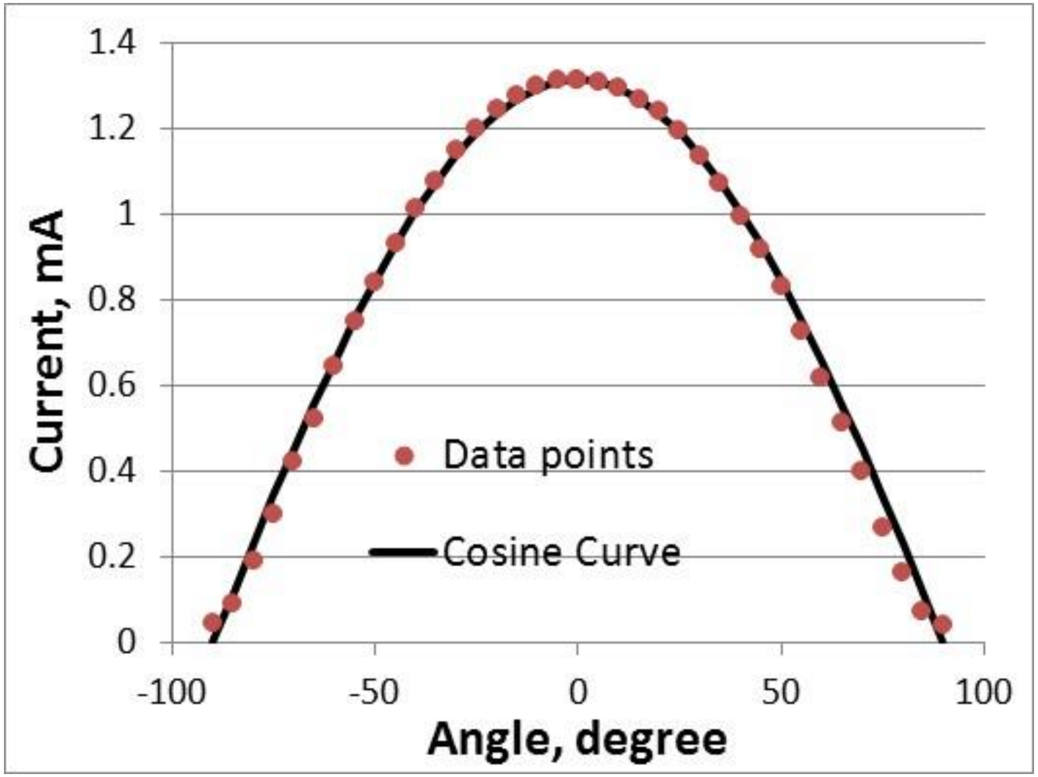


Insoo Jun, "Ionizing Radiation Environment for the ISSA Low Temperature Microgravity Physics Facility (LTMPF)", JPL IOM 5132/5052-01-122, May 31, 2001

UV Sensor

- A photodiode UVG12 from OptoDiode Corp. was selected
  - A direct measurement of the UV irradiance will be strongly interfered with by "contamination".
  - Measure broad band UV-VIS irradiance
    - Very small interference from contamination
    - Depends on the sun angle and shade
    - Measure Sun-Hour
  - Extract Ly-α irradiance from the measured sun hour and the reported daily Ly-α irradiance
    - The daily Ly-α irradiance is being measured in SOLSTICE instrument on SORCE satellite and reported in the website http://lasp.colorado.edu/lisird/sorce/sorce_ssi/.
  - Some flight histories, Readily available
  - Spectral range: 140 ~ 1100 nm
  - Apply reverse bias (0 – 50 V) and read a current
  - Size: 1.0 x 1.0 cm^2, mass: < 10 g
  - At normal, the expected irradiance is ~ 0.1 W/cm^2.

UV Sensor Calibration - Angle



- Measured the output current at 1 AU irradiance
- Current measured as a function of the angle of the UV sensor.
  - Follows the cosine curve well
- Good for the local UV irradiance measurement

X-ray Sensor

- Expected environment from SSP 30425

TABLE 7.2–1 SOLAR ELECTROMAGNETIC RADIATION

Type	Wavelength (nm)	Energy (keV)	Level (W/m^2)
UV	100–150		7.5E–3
EUV	10–100		2E–3
X–RAYS	1–10	1.2 – 0.12	5E–5
FLARE X–RAYS	0.1–1	12 – 1.2	1E–4

There are two possible cases depending on spectral range of interest.

1) 1 nm – 10 nm (1.2 keV – 0.12 keV)
   Difference with and without flare is only few times.
   Too many hits to use a pulse counting mode.
   → Current Measurement
2) 0.1 nm – 1 nm (12 keV – 1.2 keV)
   Difference with and without flare is several orders of magnitude.
   Current due to electron and proton is larger than the current due to x-ray in normal condition (without flare)
   → Pulse Counting

X-ray Sensor

- **Contamination from electrons and protons.**

(From AE8MAX and AP8MIN and stopping powers from NIST)
Assuming the detector (Si) thickness of 100 µm

Energy deposition due to electrons: 6.6 E6 keV/(cm^2 s)
Energy deposition due to protons: 2.8 E5 keV/(cm^2 s)
Total ~ 6.9 E6 keV/(cm^2 s) which is ~ 1 E-5 W/m^2

Case 1), current measurement mode,
the contamination due to the electrons and protons will be less than 20 %.
Case 2), pulse counting mode,
the contamination from electron and proton can be distinguished by different pulse height.

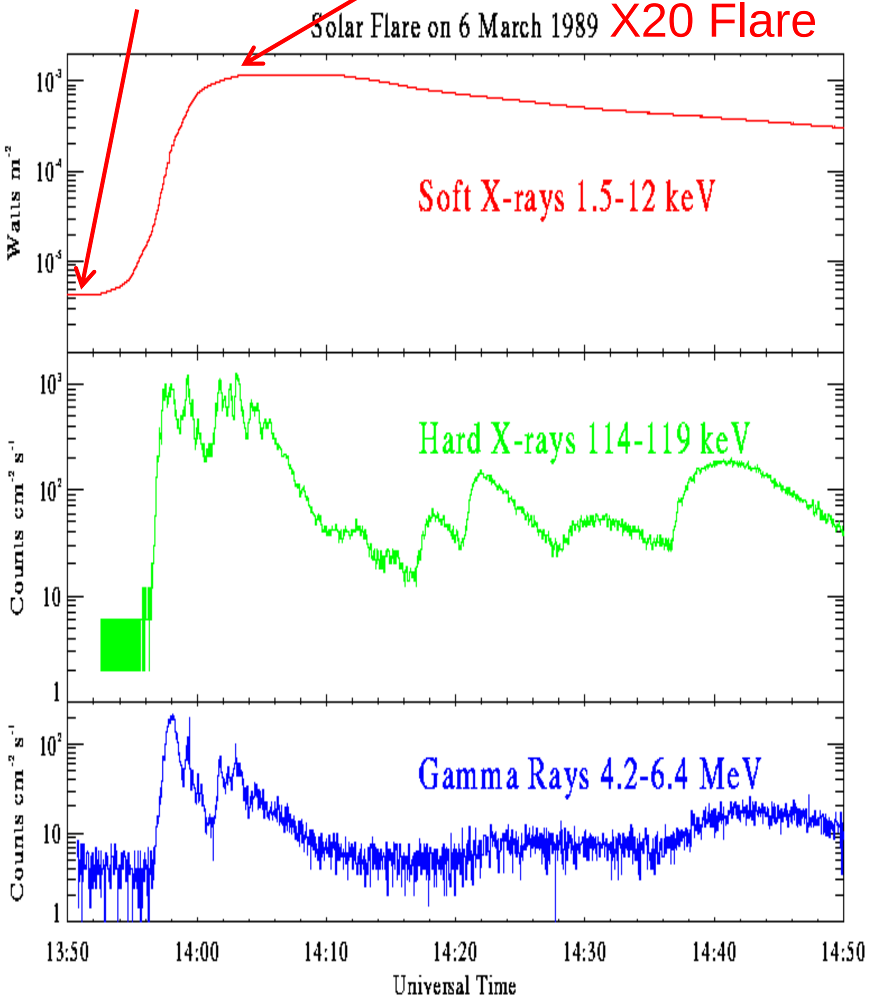
X-ray: less than 10 keV
Electron: 50 – 100 keV
Proton: 100 – 1000 keV

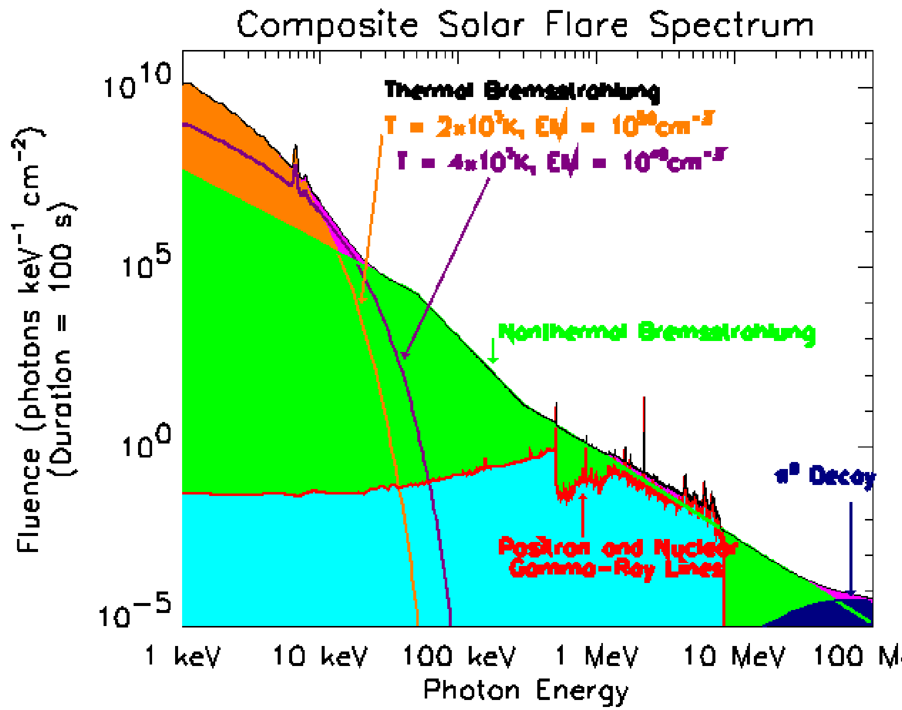
X-ray Sensor

Normal
4E-6 W/m²

Flare
1E-3 W/m²

X20 Flare





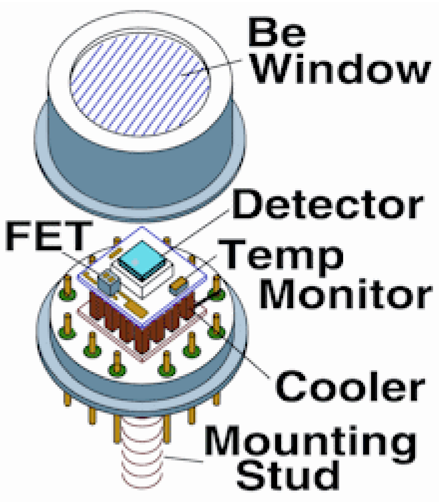
Case 1) about 1E8 photons/(cm² s)
Case 2) about 5E6 photons/(cm² s)

From
http://hesperia.gsfc.nasa.gov/hessi/flares.htm

X-ray Sensor

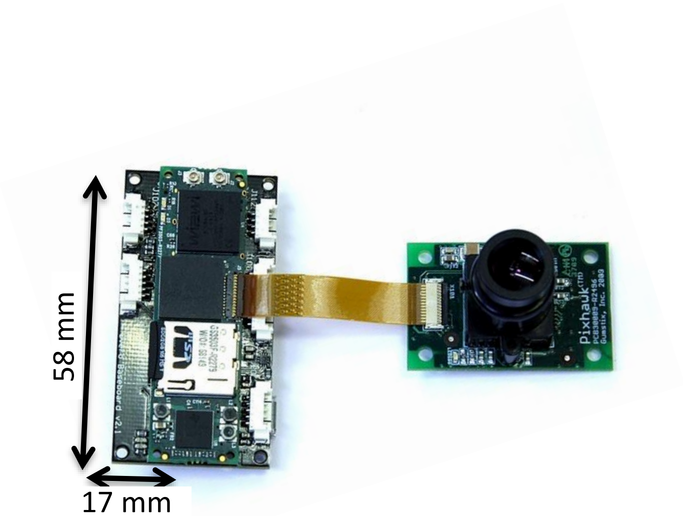
Case 1)
Sensor: AXUV100 from OptoDiode Inc,
sensor area 1 cm^2, Responsivity 0.28 A/W
Expected current: 1.4 nA

Case 2)
Sensor: Si-PIN from Amptek,
sensor area 6 mm^2, thickness 500 µm,
1.0 mil Be Window
Maximum pulse counting rate: 1 E6 pulses/sec
Expected pulse rate at solar flare: 3E5 pulses/sec

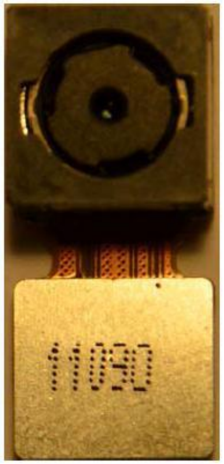


Camera

- Optional module
- Low mass, volume, and power
- Could include Gumstix (image processing) and local memory within the module
- Candidate detectors:
    - 5MP Aptina MT9P031
    - Mouser 931-LI-5M05CMAF
    - 0.3 MP Aptina MT9v032 (MarCO's detector)
- Autofocus vs fixed lens



Gumstix module and 5 MP Aptina-based camera module



Mouser 931-LI-5MO5CMAF

MarCO camera
(Gumstix module and 0.3 MP Aptina-based camera module)

Summary

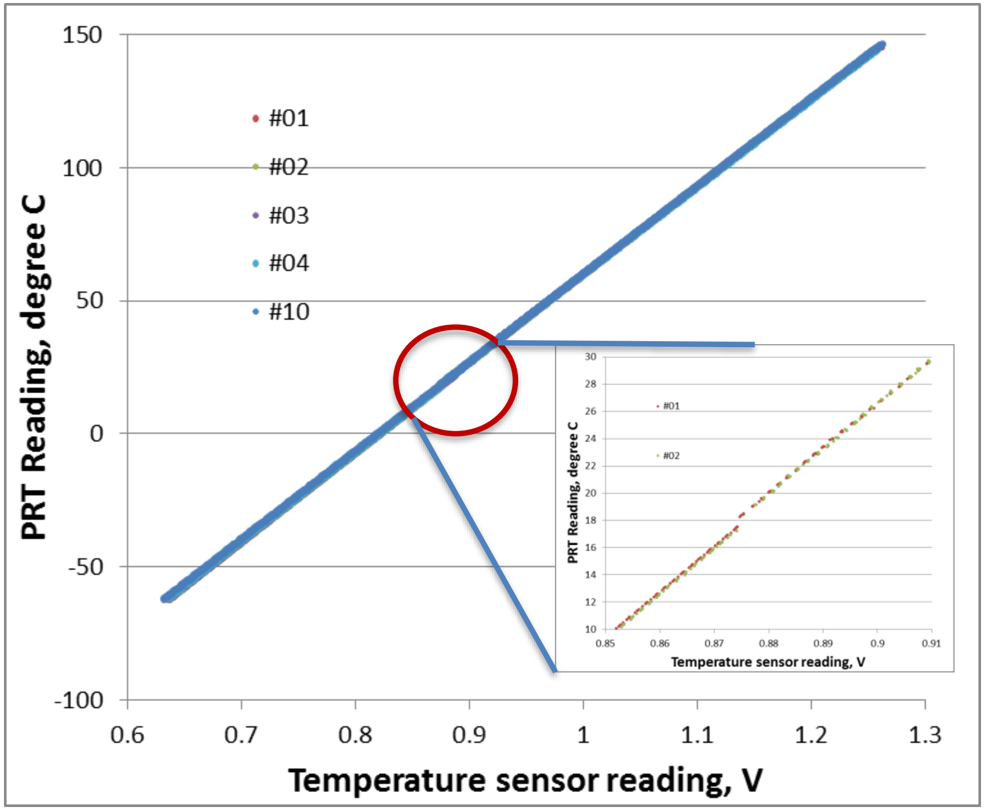
- At JPL, compact radiation monitor activities have been going on.
- Several sensor were considered and calibrated.
- In a future, we hope that every JPL missions have the radiation monitor.

THANK YOU!

QUESTIONS?

BACKUP

Test Results – Temperature sensor



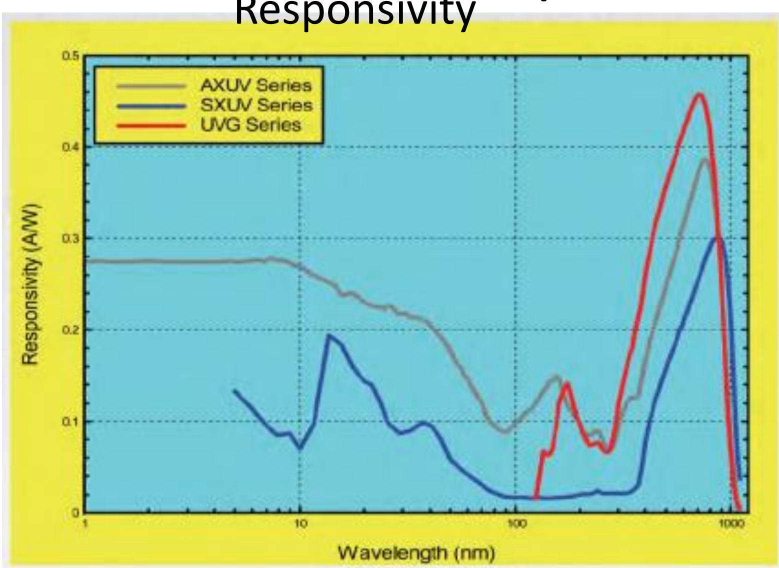
Temp Sensor Designator	Slope	Intercept
1	332.25	-273.06
2	333.10	-273.85
3	333.79	-273.99
4	331.07	-271.86
5	333.89	-274.01
6	332.85	-273.47
7	332.08	-272.88
8	332.72	-273.43
9	332.75	-273.45
10	330.78	-271.13

- All ten sensors show very similar calibration curves.
- There is a small discontinuity at 20 ˚C.
  - Most likely due to configuration difference between high and low temperature calibration setups.
  - Final temperature calibration is needed as the final flight configuration: Test As You Fly (TAYF)

UV Sensor – UVG12

- Responsivity, Range, and Resolution
  - Average Responsivity: 0.25 A/W
  - Expected maximum signal (when the surface is normal to Sun): 3 mA
  - Range: Sensor 10 mA (linear up to 3.1 mA)
    Environment 3 mA
  - Resolution: ~ 10 µA

Responsivity



Responsivity w.r.t intensity

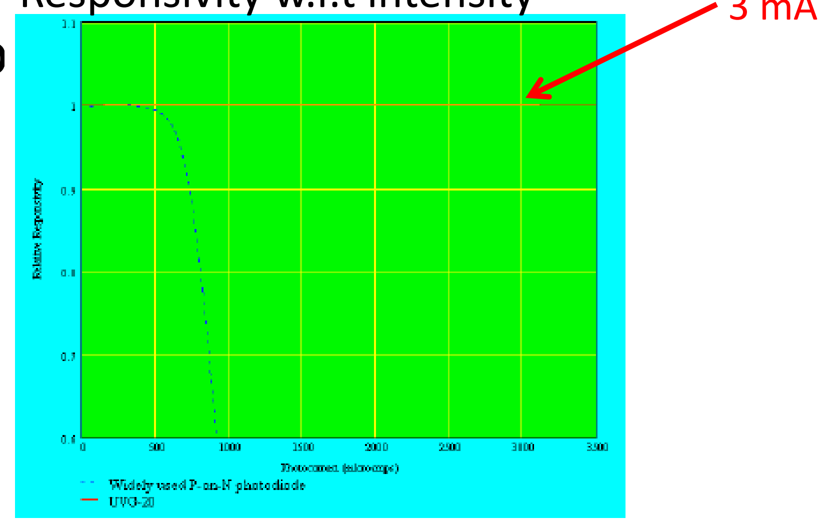


Fig. 15: Typical linearity of Opto Diode photodiodes and a widely used P-on-N photodiode when tested at 430 nm.