CRaTER Pre-Environmental Review (I-PER)

Calibration Test Planning

Justin C Kasper
Smithsonian Astrophysical Observatory

September 10-11, 2007
Outline

- Objective of CRaTER calibration
  - Relate the ADU of the Pulse Height Analysis to the original energy deposited for each detector
- Review results of testing with EM leading to calibration model
  - Sufficient to treat energy deposited as linear function of ADU from Pulse Height Analysis (PHA)
  - Linearity of external pulse generator
  - Noise of analog electronics (less than 2 ADU)
  - Stability of system over time (0.06% variation of internal calibration over 4 months, no trend)
  - Temperature dependence
- Review physics of energy deposition in detectors
  - Models of energy deposition
  - Description of Massachusetts General Hospital Proton Facility
  - Example of MGH observations
- Description of calibration method
  - Demonstration of success with EM
  - Discussion of alternative methods for redundant confirmation of calibration
- Verification of Requirements
  - Level 2 and Level 3
  - Detector specifications
Relevant Documents

• Project Controlled
  – ESMD-RLEP-0010 (Revision A effective November 30 2005)
  – LRO Mission Requirements Document (MRD) – 431-RQMT-00004
  – CRaTER Data ICD – 431-ICD-000104

• CRaTER Configuration Controlled Documents
  – 32-01205 Instrument Requirements Document
  – 32-01206 Performance and Environmental Verification Plan
  – 32-01207 Calibration Plan
  – 32-03010 CRaTER Digital Subsystem Functional Specification
  – 32-05001 Detector Specification Document
  – 32-05002 CRaTER Functional Instrument Description and Performance Verification Plan
CRaTER Layout
CRaTER Telescope Layout

Telescope in cross-section

A single detector (D5 for EM)

A pair of thin and thick detectors (D5 and D6 for EM)

Cosmic Ray Telescope for the Effects of Radiation
Establishing Linearity using External Pulser

The RMS residual from a simple linear relationship is less than 0.1%.
Noise

- The width of the distribution is clearly a linear function of the amplitude of the pulses, or a fixed fraction of the amplitude.

- For these measurements the noise is approximately 0.15% of the pulse amplitude.

- These measurements therefore are an upper limit on the true noise level of the CRaTER analog electronics.
Stability

- Center of a peak generated by the internal pulse generator from four internal calibration runs spaced over four months.

- The instrument response remained steady at the 0.06% level.
Response of EM D1 measurement chain as a function of fixed external pulse generator amplitude for telescope temperatures ranging from -40 to 45°C.

Total change is 0.1% and the noise level appears to increase slightly at lower temperatures.

The temperature dependence may be described sufficiently with two linear functions and a breakpoint at -15°C.

Expect this is due to pre-amplifier and effect may become even smaller with flight parts.
Response Function

• Calibration Requirement
  – Relate ADU to Energy Deposited at 0.5% level

• Experience with EM (FM in progress)
  – System is linear at 0.1% level
  – Noise level is less than 0.15%
  – Temperature dependence is less than 0.1%
  – Drift with time is less than 0.02%/month

• Sufficient Response Function
  – \( E_i = G_i \times (C_i - O_i) \)
  – \( E_i \) is energy deposited [MeV]
  – \( G_i \) is gain [MeV/ADU]
  – \( C_i \) is PHA amplitude [ADU]
  – \( O_i \) is an offset [ADU]
Energy Loss of Protons in Silicon

Simulations of energy deposit

Observations of scattering

Cosmic Ray Telescope for the Effects of Radiation
Signature of Spread Energy Protons in Detector Pair

Simulation (Units of MeV)

Observation (Units of ADU)

Cosmic Ray Telescope for the Effects of Radiation
MGH Beam Testing with EM

Cosmic Ray Telescope for the Effects of Radiation
Example of D1 D2 Observations at MGH
Algorithm for Calibrating Instrument

1. Generate 2D histogram of D1.D2 PHA
2. Compare observed and modeled histograms
3. Sum weighted by model energy distribution
4. Convert model energy deposits into ADU
5. Select model protons in initial energy range
6. Make initial guess for calibration
7. Current best guess calibration
8. Loop over range of initial proton energies
9. GEANT proton model
10. Estimate errors and report results
11. Has model converged?
12. Yes
13. No
14. Make new guess for calibration

Cosmic Ray Telescope for the Effects of Radiation
Demonstration of Best-Fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 Gain</td>
<td>0.0768051</td>
<td>MeV/ADU</td>
</tr>
<tr>
<td>D1 Offset</td>
<td>1.62984</td>
<td>ADU</td>
</tr>
<tr>
<td>D2 Gain</td>
<td>0.0249125</td>
<td>MeV/ADU</td>
</tr>
<tr>
<td>D2 Offset</td>
<td>-4.22239</td>
<td>ADU</td>
</tr>
<tr>
<td>Beam Peak</td>
<td>19.2745</td>
<td>MeV</td>
</tr>
<tr>
<td>Beam Width</td>
<td>25.2324</td>
<td>MeV</td>
</tr>
<tr>
<td>Intensity</td>
<td>0.118187</td>
<td>$10^6$ protons</td>
</tr>
<tr>
<td>D1 Spread</td>
<td>1.58370</td>
<td>%</td>
</tr>
<tr>
<td>D2 Spread</td>
<td>4.80770</td>
<td>%</td>
</tr>
</tbody>
</table>
Complementary Calibration Methods

- (1) Brookhaven National Laboratory
  - EM only (radiation, cleanliness, scheduling concerns)
  - Verified stability at high rates of heavy ions
  - Scattered silicon and iron beams
  - Secondary fragmentation spectra
- (2) Radioactive sources of alpha radiation
  - FM at Aerospace during integration
- (3) Calibrated charge injection
  - Use a stable and calibrated charge injector to insert known amplitude pulses after detectors
  - FM at Aerospace during integration
  - Equipment brought to MIT for measurements with full instrument
- Initial measurements with FM S/N 2 using (2) and (3) show FM meeting requirements
Tests at Aerospace

Additional tests make use of calibrated external pulse generator and radioactive alpha sources

Cosmic Ray Telescope for the Effects of Radiation
<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Quantity</th>
<th>Method</th>
<th>EM</th>
<th>S/N 2 Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRaTER-L2-01</td>
<td>Measure the Linear Energy Transfer (LET) spectrum</td>
<td>LET</td>
<td>A</td>
<td>Verified instrument measures LET using energetic particle beams, radioactive sources, models</td>
<td>Initial verification using radioactive alpha sources, cosmic ray muons, external and internal pulser. Beam test soon</td>
</tr>
<tr>
<td>CRaTER-L2-02</td>
<td>Measure change in LET spectrum through Tissue Equivalent Plastic (TEP)</td>
<td>TEP</td>
<td>A</td>
<td>Measured spectra consistent with modeled energetic particle energy deposition</td>
<td>MGH test next week</td>
</tr>
<tr>
<td>CRaTER-L2-03</td>
<td>Minimum pathlength through total TEP</td>
<td>&gt; 60 mm</td>
<td>I</td>
<td>81 mm total TEP used</td>
<td>80.947 mm as measured +/- 0.001 mm</td>
</tr>
<tr>
<td>CRaTER-L2-04</td>
<td>Two asymmetric TEP components</td>
<td>1/3 and 2/3</td>
<td>I</td>
<td>27 and 54 mm sections of TEP</td>
<td>26.980 mm and 53.967 mm sections of TEP used, both +/- 0.001 mm measured with micrometer</td>
</tr>
<tr>
<td>CRaTER-L2-05</td>
<td>Minimum LET measurement</td>
<td>&lt; 0.25 keV per micron</td>
<td>T</td>
<td>D2 0.145 KeV/micron using measured detector thickness and calibration</td>
<td>0.089 KeV/micron typical determined at Aerospace with radioactive source, beam test next week</td>
</tr>
<tr>
<td>CRaTER-L2-06</td>
<td>Maximum LET measurement</td>
<td>&gt; 2 MeV per micron</td>
<td>T</td>
<td>D1 2.13 MeV/micron using measured detector thicknesses and calibration</td>
<td>MGH test next week</td>
</tr>
<tr>
<td>CRaTER-L2-07</td>
<td>Energy deposition resolution</td>
<td>&lt; 0.5% max energy</td>
<td>T</td>
<td>&lt;0.1% electronics from external pulser, &lt;0.06% detectors using width of alpha source</td>
<td>Pulser test analysis in progress, electronics noise expected to decrease</td>
</tr>
<tr>
<td>CRaTER-L2-08</td>
<td>Minimum D1D6 geometrical factor</td>
<td>&gt; 0.1 cm^2 sr</td>
<td>I</td>
<td>0.57 cm^2 sr derived from mechanical drawings</td>
<td>0.57 cm^2 sr derived from mechanical drawings</td>
</tr>
</tbody>
</table>

**Cosmic RAd Telescope for the EEffects of Radiation**
<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Quantity</th>
<th>Method</th>
<th>EM</th>
<th>S/N 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRaTER-L3-01</td>
<td>Thin and thick detector pairs</td>
<td>140 and 1000 microns</td>
<td>I</td>
<td>148, 148, 148, 988, 988, 988 microns as measured</td>
<td></td>
</tr>
<tr>
<td>CRaTER-L3-02</td>
<td>Minimum energy</td>
<td>&lt; 250 keV</td>
<td>T</td>
<td>140 keV as measured based on calibration</td>
<td>219 keV using Alpha source MGH test next week</td>
</tr>
<tr>
<td>CRaTER-L3-02</td>
<td>Nominal instrument shielding</td>
<td>1524 microns Al</td>
<td>I</td>
<td>Verified by inspection of instrument and mechanical drawings</td>
<td>Verified by inspection of instrument and mechanical drawings</td>
</tr>
<tr>
<td>CRaTER-L3-03</td>
<td>Nadir and zenith field of view</td>
<td>762 microns Al</td>
<td>I</td>
<td>Designed to 762 microns</td>
<td>Measured to be 812.8 microns zenith and 810.3 microns nadir</td>
</tr>
<tr>
<td>CRaTER-L3-04</td>
<td>Telescope stack</td>
<td>Shield, D1D2, A1, D3D4, A2, D5D6, shield</td>
<td>I</td>
<td>Verified by inspection of instrument and mechanical drawings</td>
<td>Verified by inspection of instrument and mechanical drawings</td>
</tr>
<tr>
<td>CRaTER-L3-05</td>
<td>Pathlength constraint</td>
<td>10% for D1D6</td>
<td>I</td>
<td>Using geometry of telescope and uniform distribution on sky &lt; 5%</td>
<td>Using geometry of telescope and uniform distribution on sky &lt; 5%</td>
</tr>
<tr>
<td>CRaTER-L3-06</td>
<td>Zenith field of view</td>
<td>&lt;34 degrees D1D4</td>
<td>I</td>
<td>33 degrees from mechanical drawing</td>
<td>33 degrees from mechanical drawing</td>
</tr>
<tr>
<td>CRaTER-L3-07</td>
<td>Nadir field of view</td>
<td>&lt;70 degrees D3D6</td>
<td>I</td>
<td>69 degrees from mechanical drawing</td>
<td>69 degrees from mechanical drawing</td>
</tr>
<tr>
<td>CRaTER-L3-08</td>
<td>Calibration system</td>
<td>Variable rate and gain</td>
<td>T</td>
<td>Verified by use of the internal calibration system</td>
<td>In process</td>
</tr>
<tr>
<td>CRaTER-L3-09</td>
<td>Event selection</td>
<td>64-bit mask</td>
<td>T</td>
<td>Verified by testing in a beam and by using ambient cosmic ray muons</td>
<td>MGH beam test next week</td>
</tr>
<tr>
<td>CRaTER-L3-10</td>
<td>Maximum event transmission rate</td>
<td>1,200 events/sec</td>
<td>T</td>
<td>Verified using internal calibration operating at high rate and beam</td>
<td>In process</td>
</tr>
</tbody>
</table>

**Cosmic Ray Telescope for the Effects of Radiation**
CRaTER-L2-01 Measure the LET Spectrum

**Requirement**

- The fundamental measurement of the CRaTER instrument shall be of the linear energy transfer (LET) of charged energetic particles, defined as the mean energy absorbed (ΔE) locally, per unit path length (Δl), when the particle traverses a silicon solid-state detector.

**MGH proton measurements**

Simulation (Units of MeV)  
Observation (Units of ADU)
CRaTER-L2-02 Measure LET Spectrum after Passing through TEP

**Requirement**

- The LET spectrum shall be measured before entering and after propagating though a compound with radiation absorption properties similar to human tissue such as A-150 Human Tissue Equivalent Plastic (TEP).

---

**Cosmic Ray Telescope for the Effects of Radiation**
CRaTER-L2-03 Minimum Pathlength through total TEP

• **Requirement**
  - The minimum pathlength through the total amount of TEP in the telescope shall be at least 60 mm.

FM S/N 2
Short TEP: 26.980 mm
Long TEP: 53.967 mm
Total Length: 80.947 mm as measured +/- 0.001 mm
Greater than 60 mm
CRaTER-L2-04 Two asymmetric TEP components

- **Requirement**
  - The TEP shall consist of two components of different length, 1/3 and 2/3 the total length of the TEP. If the total TEP is 61 mm in length, then the TEP section closest to deep space will have a length of approximately 54 mm and the second section of TEP will have a length of approximately 27 mm.

  FM S/N 2
  Short TEP: 26.980 mm
  Long TEP: 53.967 mm
  \[
  \frac{26.98}{26.98 + 53.967} = 0.333304508 = \frac{1}{3}
  \]
CRaTER-L2-05 Minimum LET measurement

• **Requirement**
  - At each point in the telescope where the LET spectrum is to be observed, the minimum LET measured shall be no greater than 0.25 keV/ micron in the Silicon.

  From the EM Beam Calibration at MGH
  D2 Gain 0.0249125 MeV/ADU
  D2 Offset -4.22239 ADU
  D2 thickness 988 microns
  D2 Min E 0.143934709 MeV
  D2 Min LET 0.145682904 KeV/micron
  0.14 KeV/micron < 0.25 KeV/micron
CRaTER-L2-06 Maximum LET measurement

• **Requirement**
  - At each point in the telescope where the LET spectrum is to be observed, the maximum LET measured shall be no less than 2 MeV/ micron in the Silicon.

From the EM beam calibration at MGH
D1 Gain 0.0768051 MeV/ADU
D1 Offset 1.62984 ADU
D1 Thickness 148 microns
D1 Max E 314.7188696 MeV
D1 Max LET 2.126478849 MeV/micron
  
  2.13 MeV/micron > 2 MeV/micron
CRaTER-L2-07 Energy deposition resolution

**Requirement**

- The pulse height analysis of the energy deposited in each detector shall have an energy resolution better than 1/200 the maximum energy measured by that detector.

Upper limit on system noise is less than 0.15% < 0.5%
CRaTER-L2-08 Geometrical Factor

• Requirement
  – The geometrical factor created by the first and last detectors shall be at least 0.1 cm² sr.

\[
G = \frac{1}{2} \pi^2 \left( r_1^2 + r_6^2 + z^2 - \sqrt{r_1^2 + r_2^2 + z^2} \right) - 4r_1^2 r_2^2
\]

\[
r_1 = 1.75 \text{ cm} \\
r_2 = 1.75 \text{ cm} \\
Z = 12.71 - 0.25 = 12.46 \text{ cm} \\
G = 0.57 > 0.1 \text{ cm}^2 \text{ sr}
\]
CRaTER-L3-01 Thin and thick detector pairs

• **Requirement**
  
  – The telescope stack shall contain adjacent pairs of thin and thick Silicon detectors. The thickness of the thin detectors will be approximately 140 microns and the thick detectors will be approximately 1000 microns.

  Thickneses of each detector measured by Micron and reported as part of the delivery
  For the EM: 148, 148, 148, 988, 988, 988 microns
CRaTER-L3-02 Minimum Energy

**Requirement**
- The Silicon detectors shall be capable of measuring a minimum energy deposition of 250 keV or lower.

D2 Gain 0.0249125 MeV/ADU
D2 Offset -4.22239 ADU
Evaluate at ADU of 10
D2 Min E 0.143934709 MeV
144 keV < 250 keV
CRaTER-L3-03 Nominal instrument shielding

• Requirement
  - The equivalent shielding of the CRaTER telescope outside of the zenith and nadir fields of view shall be no less than 1524 microns (0.060 inches) of aluminum.

  Verified by inspection of mechanical drawings
• **Requirement**
  
  – The zenith and nadir fields of view of the telescope shall have no more than 762 microns (0.030) of aluminum shielding.

EM built to 762 microns

FM S/N 2 end caps specified to be 0.030” +/- 0.002”, or 762 +/- 51 microns

Measured to be 812.8 microns zenith and 810.3 microns nadir

812 and 810 microns > 762 microns

Within the design tolerance of the mechanical drawing, but nonetheless is slightly greater than the requirement specified. We have filed a Non-conforming Material Report (NMR).

The science team feels that this difference in thickness does not affect the quality of the measurements made, since it is still sufficiently thin to allow protons to enter the telescope over the desired energy range, as long as the thickness is measured so it can be fed into the models.
CRaTER-L3-05 Telescope stack

**Requirement**

- The telescope shall consist of a stack of components labeled from the zenith side as zenith shield (S1), the first pair of thin (D1) and thick (D2) detectors, the first TEP absorber (A1), the second pair of thin (D3) and thick (D4) detectors, the second TEP absorber (A2), the third pair of thin (D5) and thick (D6) detectors, and the final nadir shield (S2).

Verified by direct inspection
CRaTER-L3-06 Full telescope pathlength constraint

**Requirement**
- The root mean squared (RMS) uncertainty in the length of TEP traversed by a particle that traverses the entire telescope axis shall be less than 10%.

RMS from Monte Carlo is $0.78\% < 10\%$
CRaTER-L3-07 Zenith field of view

• **Requirement**
  - The zenith field of view, defined as D2D5 coincident events incident from deep space using the naming convention in CRaTER-L3-04, shall be less than 34 degrees full width.

By inspection $33 < 34$ degrees
CRaTER-L3-08 Nadir field of view

- **Requirement**
  - The nadir field of view, defined as D4D5 coincident events incident from the lunar surface, shall be less than 70 degrees full width.

By inspection, $69 < 70$ degrees
CRaTER-L3-09 Calibration system

- **Requirement**
  - The CRaTER electronics shall be capable of injecting calibration signals at with different amplitudes and rates into the measurement chain.

---

**Cosmic Ray Telescope for the Effects of Radiation**
CRaTER-L3-10 Event selection

• Requirement
  – A command capability shall exist to allow specification of detector coincidences that will be analyzed and sent to the spacecraft for transmission to the ground.

Shown that this works using proton beam at MGH
CRaTER-L3-11 Maximum event rate

**Requirement**
- CRaTER will be capable of transmitting primary science data, namely the energy deposited in each of the detectors, on at least 1000 events per second.

Verified by exposure to proton and iron beams, and by running internal calibration system at 2kHz
# Detectors

Table 1.1 of Detector Specification (32-05001 Rev E)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area</td>
<td>9.6 cm² circular - Reference</td>
</tr>
<tr>
<td>Active diameter</td>
<td>35 mm</td>
</tr>
<tr>
<td>Active diameter tolerance</td>
<td>+/- 0.1 mm</td>
</tr>
<tr>
<td>Thickness (detector)</td>
<td>Thin = 140 um, Thick = 1000 um</td>
</tr>
<tr>
<td>Thickness tolerance</td>
<td>+/- 10 um thin, +/- 35 um thick</td>
</tr>
<tr>
<td>Thickness uniformity</td>
<td>+/- 10 um</td>
</tr>
<tr>
<td>Window implantation</td>
<td>5 um each ohmic and junction</td>
</tr>
<tr>
<td>Metallization - junction</td>
<td>3% grid of 3000 Å +/- 1000 Å</td>
</tr>
<tr>
<td>Metallization - ohmic</td>
<td>100% surface coverage; 3000 Å +/- 1000 Å</td>
</tr>
<tr>
<td>Full depletion (FD)</td>
<td>Thin = 10 – 60V, Thick = 100 – 200V</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>Thin = Thick = FD + 30V</td>
</tr>
<tr>
<td>Capacitance (typical)</td>
<td>Thin = 700 pF, Thick = 100 pF</td>
</tr>
<tr>
<td>Leakage current max (20C)</td>
<td>Thin = 300 nA junction, 200 nA guard</td>
</tr>
<tr>
<td></td>
<td>Thick = 2,000 nA junction, 2000 nA guard</td>
</tr>
<tr>
<td>Drift (max leakage @ 40C)</td>
<td>8 x Ileak @ 20C</td>
</tr>
<tr>
<td>Stability</td>
<td>Thin = 1% Ileak @ 40C for 168 hours in Nitrogen</td>
</tr>
<tr>
<td></td>
<td>Thick = 1% Ileak @ 40C for 21 days in vacuum</td>
</tr>
<tr>
<td>Alpha resolution (²⁴¹Am) - junction</td>
<td>Thin = 3%, Thick = 1.5% (line width)</td>
</tr>
<tr>
<td>Alpha resolution (²⁴¹Am) - ohmic</td>
<td>Thin = 3%, Thick = 1.5% (line width)</td>
</tr>
</tbody>
</table>
# Detector Verification Summary

**Flight Detector Performance Test Summary**

Rev 1.0 6/18/2007 package provided to B. Klatt from Micron

## Post Environmental Testing

<table>
<thead>
<tr>
<th>Thickness (µm)</th>
<th>Operating Voltage (V)</th>
<th>Junction Leakage (nA)</th>
<th>Guard Leakage (nA)</th>
<th>Capacitance (pF)</th>
<th>Forward Voltage at 10mA (V)</th>
<th>Ip Voltage from Cap. Plot (V)</th>
<th>Ip Voltage from Measurement (V)</th>
<th>Leakage Current at VCP=300 (nA)</th>
<th>Gas Voltage at 100mA (V)</th>
<th>AM241 Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Junction Side</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Peak=5.498MeV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ohmic Side</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Peak=5.498MeV)</td>
</tr>
</tbody>
</table>

| D001 | 150 | 40 | 64 (71) | 20 (48) | 772.3 | 0.58 | 10 | 11 | 54 | 60 | 64.8 | 52.1 | 38.5 | 71.2 | 52.8 | 47.7 |
| D002 | 150 | 38 | 24 | 21 | 766.45 | 0.59 | 8 | 9 | 25 | >100 | 64.5 | 52.1 | 38 | 72.6 | 52.2 | 50.4 |
| D003 | 147 | 38 | 20 | 21 | 742.5 | 0.58 | 8 | 7 | 10 | >100 | 74.5 | 69.5 | 26.8 | 80.7 | 69.3 | 41.3 |
| D004 | 147 | 38 | 15 | 16 | 749.95 | 0.58 | 8 | 7 | 4.5 | >100 | 64.3 | 50.3 | 40.1 | 76.5 | 50.2 | 57.7 |
| D005 | 148 | 40 | 91 | 47 | 756.85 | 0.6 | 10 | 7 | 50 | 50 | 56.8 | 45 | 34.6 | 60.47 | 44.2 | 41.26 |
| D006 | 148 | 38 | 11 | 12 | 766.75 | 0.58 | 8 | 6 | 20 | >100 | 68.5 | 52.3 | 44.2 | 72.1 | 52.4 | 49.5 |
| D007 | 149 | 39 | 16 | 13 | 753.45 | 0.6 | 9 | 7 | 4 | >100 | 75.2 | 60.3 | 44.9 | 81.7 | 60 | 55.4 |
| D008 | 149 | 39 | 13 | 14 | 748.95 | 0.59 | 9 | 7 | 15 | >100 | 70.2 | 62.5 | 31.9 | 74.5 | 62.4 | 40.7 |
| D009 | 152 | 38 | 315 | 253 | 755.3 | 0.58 | 8 | 7 | 300 | n/a | 81.3 | 64 | 50.1 | n/a | 63.6 | 65.36 |
| D010 | 152 | 38 | 21 | 22 | 758.05 | 0.6 | 8 | 6 | 10 | >100 | 60.3 | 46.4 | 39.5 | 66.1 | 46.3 | 49.9 |

**Cosmic RAY Telescope for the Effects of Radiation**
Conclusions

- We have a documented calibration plan, justified by our experience with prototypes, models, and the EM
- The calibration has been applied to the EM
- Additional tests have been applied to the EM to verify the success of the calibration plan
- We are in the process of conducting the same calibration with the FM, with the key measurements occurring next week at Brookhaven, but initial measurements at Aerospace indicating the the instrument meets the requirements