CRaTER
Cosmic Ray Telescope for the Effects of Radiation

Harlan E. Spence, PI, Boston University CSP
Justin Kasper, PS, Harvard-Smithsonian CfA

“Luna Ut Nos Animalia Tueri Experiri Possimus”
(“In order that we might be able to protect and make trial of living things on the Moon”)
CRaTER Objectives from our original proposal:

“To characterize the global lunar radiation environment and its biological impacts.”

“…to address a prime LRO objective and to answer key questions required for enabling the next phase of human exploration in our solar system.”
CRaTER Science Motivation

- Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP) have sufficient energy to penetrate shielding and deposit energy inside an astronaut = crew/mission radiation safety enroute to or on surface of Moon or Mars

- Biological assessment requires not incident GCR/SEP spectrum (available on other mission satellites), but lineal energy transfer (LET) spectra behind tissue-equivalent material

- LET spectra are an important link, currently derived from models; experimental measurements required for critical ground truth – CRaTER will provide this key L2 data product
CRaTER Measurement Concept

- Measurement concept unchanged since PDR
- Two-ended solid-state, particle telescope with TEP views both zenith and nadir
- Sensitive to GCR/SPE primaries and secondaries

**modified** from original CRaTER proposal
CRaTER Telescope Configuration

**Basic concept unchanged since PDR**

- Three, High/Low LET detector pairs (thin/thick) bracket cylinders of tissue-equivalent plastic (TEP)

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NASA’s Goddard Space Flight Center

LRO PSR - CRaTER

Slide - 5
CRaTER Telescope Detectors and Tissue-Equivalent Plastic (TEP)

Telescope in cross-section

A single detector (D5 for EM)

A pair of thin and thick detectors (D5 and D6 for EM)
CRaTER Location on Orbiter
CRaTER Photo Montage
(see backup for detailed images)
Changes Since Mission PER

- None.
Level 1 Mission Requirements and CRaTER L1 Data Products

**Level 1 Requirements**

RLEP-LRO-M10
The LRO shall characterize the deep space radiation environment at energies in excess of 10 MeV in lunar orbit, including neutron albedo.

RLEP-LRO-M20
The LRO shall measure the deposition of deep space radiation on human equivalent tissue while in the lunar orbit environment.

**Level 1 Data Products**

Provide Linear Energy Transfer (LET) spectra of cosmic rays (particularly above 10 MeV), most critically important to the engineering and modeling communities to assure safe, long-term, human presence in space.

Provide LET spectra behind different amounts and types of areal density, including tissue equivalent plastic.
Pre-Delivery Calibration and PSR Instrument Performance Verification

• Pre-delivery Calibration Methods
  – Alpha sources with flight detectors and electronics
  – Internal pulse generation
  – Proton and ion accelerators (used to derive flight calibration and performance verification)

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

• As-delivered Performance Characteristics Met L1 Requirements
  – System linear at 0.1% level
  – Noise level less than 0.15%
  – Temperature dependence less than 0.1%

• Pre-Ship Review Performance Verification
  – Radioactive sources
  – Verifies that performance has not changed through I&T
CRaTER Provides LET Spectra at OPSR

Modeled and actual response of CRaTER to >10 MeV protons in D3 and D4 at MGH in December ‘07; Used to produce absolute calibration

RLEP-LRO-M10

Provide Linear Energy Transfer (LET) spectra of cosmic rays (particularly above 10 MeV), most critically important to the engineering and modeling communities to assure safe, long-term, human presence in space.

Calibrated D4 spectra from that run demonstrates CRaTER ability to provide LET spectra at IPSR

Unchanged Co-60 spectra (in all detectors – D5/6 shown here) since delivery demonstrates CRaTER also provides LET spectra at OPSR
CRaTER Provides LET Spectra Behind Different Amounts of TEP at OPSR

RLEP-LRO-M20

Provide LET spectra behind different amounts and types of areal density, including tissue equivalent plastic.

Co60 spectra taken before instrument delivery, at OPER, and now demonstrate that LET spectra are being measured stably behind different amounts of TEP at OPSR.
Let spectra and LET spectra behind different amounts of TEP demonstrated above using end-to-end measurements obtained during recent MR#1 in December 2008. Also demonstrates readiness of L2 pipeline processing using data from s/c to MOC to SOC.
Instrument Performance, L2 Verification, and Status

Flow of Level 1 to Level 2 Requirements

Level 2 Instrument Requirements

01. Measure the Linear Energy Transfer (LET) spectrum
02. Measure change in LET spectrum through Tissue Equivalent Plastic (TEP)
03. Minimum pathlength through total TEP > 60 mm
04. Two asymmetric TEP components
   1/3 and 2/3 total length
05. Minimum LET measurement 0.2 keV per micron
06. Maximum LET measurement 2 MeV per micron
07. Energy deposition resolution < 0.5% max energy
08. Minimum full telescope geometrical factor 0.1 cm² sr

Level 1 Parent Requirements

RLEP-LRO-M10
Characterize deep space radiation environment

RLEP-LRO-M20
Radiation effects on human equivalent tissue
## Level 2 Requirements Verification
### Summary – All Pass at PSR

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Quantity</th>
<th>Method</th>
<th>As Delivered</th>
<th>OrbiterPSR</th>
<th>Pass/Fail</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>Verified instrument measures LET using Co60 source and ground level cosmic rays</td>
<td>Pass</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>MGH Beam Run September</td>
<td>Verified instrument measures LET using Co60 source and ground level cosmic rays in all six detectors</td>
<td>Pass</td>
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<tr>
<td>CRaTER-L2-03</td>
<td>Minimum pathlength through total TEP</td>
<td>&gt; 60 mm</td>
<td>I</td>
<td>80.947 mm as measured +/- 0.001 mm</td>
<td>Not testable after delivery; no mechanical change</td>
<td>Pass</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>26.972 mm and 53.992 mm sections of TEP used, both +/- 0.001 mm measured with micrometer</td>
<td>Not testable after delivery; no mechanical change</td>
<td>Pass</td>
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<tr>
<td>CRaTER-L2-05</td>
<td>Minimum LET measurement</td>
<td>&lt; 0.25 keV per micron</td>
<td>T</td>
<td>0.09, 0.16, 0.09 (thicks)</td>
<td>Verified through system gain and noise comparison using internal pulser and Co-60 source</td>
<td>Pass</td>
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<tr>
<td>CRaTER-L2-06</td>
<td>Maximum LET measurement</td>
<td>&gt; 2 MeV per micron</td>
<td>T</td>
<td>2.2, 2.2, 2.2 (thins)</td>
<td>Verified through system gain comparison</td>
<td>Pass</td>
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<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, &lt;0.25% gain uncertainty from beam calibrations at MGH</td>
<td>Verified through system noise comparison</td>
<td>Pass</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>Not testable after delivery; no mechanical change</td>
<td>Pass</td>
</tr>
</tbody>
</table>
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 ($\Delta E$) locally, per unit path length ($\Delta l$), when the particle traverses a silicon solid-state detector.

Modeled and actual response of CRaTER to >10 MeV protons in D3 and D4 at MGH in December ’07; Used to produce absolute calibration

Calibrated D4 spectra from that run demonstrated CRaTER ability to measure LET spectra at IPSR
CRaTER-L2-02 Measure LET Spectrum after Passing through TEP

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

**Illustration**

- Iron nuclei enter D1
- Iron breaks up within first section of TEP
- Breakup of iron into fragments after passing through TEP measured at BNL
- Iron nuclei enter D3
- Spectra from heavy ions runs demonstrate CRaTER ability to measure LET spectra after passing through TEP (D1 and D3 shown) at IPSR
CRaTER-L2-01 and -02 Still Satisfied at OPSR

CRaTER’s FM response to $^{60}$Co source at delivery (blue), at OPER (green) and just prior to OPSR (red)

- Noise levels have changed by < ~0.1 ADU RMS
- Negligible change is at the resolution limit of our measurements and well below required limit

- Both L2-01 and L2-02 requirements still met at OPSR
CRaTER-L2-03 Minimum Pathlength through total TEP Still Satisfied at OPSR

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

<table>
<thead>
<tr>
<th>Value</th>
<th>Requirement</th>
<th>Units</th>
<th>SN02 (FM1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Length</td>
<td>mm</td>
<td></td>
<td>26.97988</td>
</tr>
<tr>
<td>Large Length</td>
<td>mm</td>
<td></td>
<td>53.96738</td>
</tr>
<tr>
<td>Ratio</td>
<td>ratio</td>
<td></td>
<td>0.333301955</td>
</tr>
<tr>
<td>Total Length</td>
<td>60 mm</td>
<td></td>
<td>80.94726</td>
</tr>
</tbody>
</table>

The total lengths of the long and short TEP components on both flight instruments are measured to be greater than 80.9mm exceeding the 60 mm requirement.

- Not directly testable after delivery
- No mechanical change expected
- No net change in performance detected
- Requirement remains satisfied
CRaTER-L2-04 Two Asymmetric TEP Components Still Satisfied at OPSR

• **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.

Inspected the mechanical diagrams and confirmed that the specified lengths of TEP are 27 mm and 54 mm. Confirmed through measurements of the TEP segment lengths.

<table>
<thead>
<tr>
<th>Value</th>
<th>Requirement</th>
<th>Units</th>
<th>SN02 (FM1)</th>
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<tbody>
<tr>
<td>Small Length</td>
<td>mm</td>
<td></td>
<td>26.97988</td>
</tr>
<tr>
<td>Large Length</td>
<td>mm</td>
<td></td>
<td>53.96738</td>
</tr>
<tr>
<td>Ratio Small/Total</td>
<td>0.333333</td>
<td>ratio</td>
<td>0.333301955</td>
</tr>
<tr>
<td>Total Length</td>
<td>60</td>
<td>mm</td>
<td>80.94726</td>
</tr>
</tbody>
</table>

• Not directly testable after delivery
• No mechanical change expected
• No net change in performance detected
• Requirement remains satisfied
**CRaTER-L2-05/-06 Minimum/Maximum LET measurement**

- **Requirements**
  - 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/µm in the Silicon.
  - 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/µm in the Silicon.

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**Table: LET Measurement Requirements**

<table>
<thead>
<tr>
<th>Param</th>
<th>Units</th>
<th>Required</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
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<tr>
<td>Thickness</td>
<td>microns</td>
<td>150/1000</td>
<td>148</td>
<td>1000</td>
<td>149</td>
<td>1000</td>
<td>149</td>
<td>1000</td>
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<tr>
<td>Gain</td>
<td>KeV/ADU</td>
<td></td>
<td>81.55</td>
<td>22.21</td>
<td>82.90</td>
<td>22.44</td>
<td>80.60</td>
<td>22.20</td>
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<tr>
<td>Offset</td>
<td>ADU</td>
<td></td>
<td>-0.34</td>
<td>0.91</td>
<td>-0.47</td>
<td>-2.24</td>
<td>-0.41</td>
<td>0.88</td>
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<tr>
<td>Min E</td>
<td>KeV</td>
<td>250</td>
<td>435.83</td>
<td>90.82</td>
<td>453.54</td>
<td>162.36</td>
<td>436.43</td>
<td>91.57</td>
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<tr>
<td>Max E</td>
<td>MeV</td>
<td></td>
<td>334.04</td>
<td>90.97</td>
<td>339.61</td>
<td>91.95</td>
<td>330.18</td>
<td>90.91</td>
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<tr>
<td>E Error</td>
<td>MeV</td>
<td>0.50%</td>
<td>0.17</td>
<td>0.20</td>
<td>0.19</td>
<td>0.18</td>
<td>0.18</td>
<td>0.20</td>
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<tr>
<td><strong>Min LET</strong></td>
<td>KeV/µm</td>
<td>0.25</td>
<td>2.94</td>
<td>0.09</td>
<td>3.04</td>
<td>0.16</td>
<td>2.93</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Max LET</strong></td>
<td>MeV/µm</td>
<td>2</td>
<td>2.26</td>
<td>0.09</td>
<td>2.28</td>
<td>0.09</td>
<td>2.22</td>
<td>0.09</td>
</tr>
</tbody>
</table>

**Verified at delivery through system gain and noise comparison using internal pulser and Co-60 source**
Insignificant (< 10% of required) changes in system gain and noise using internal pulser and Co-60 source demonstrates that max/min LET requirements still met at OPSR.

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LRO PSR - CRaTER
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.

- Verified through system noise measured at instrument delivery
- Upper limit on system noise is less than $0.15\% < 0.5\%$
CRaTER-L2-07 Energy Deposition Resolution Still Satisfied at OPSR

- Verified at OPSR through system noise calculation and comparison with pre-ship values using the internal pulser
- System noise change is far less than requirement limit
- No change at OPSR compared to verified values demonstrated at instrument delivery

- Histograms of primary science output in D1-D6 with pulser at 64 and 128
- Blue curve from as-delivered; red curve at OPSR
- Shows ability to measure LET repeatably and stably to +/- ~0.25%
CRaTER-L2-08 Geometrical Factor Still Satisfied at OPSR

**Requirement**

- The geometrical factor created by the first and last detectors shall be at least 0.1 cm$^2$ sr.

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

*Derived from assembly drawings*

- $r_1 = 1.75$ cm
- $r_6 = 1.75$ cm
- $Z = 12.71 - 0.25 = 12.46$ cm

$G = 0.57 > 0.1$ cm$^2$ sr

- Not directly testable after delivery
- No mechanical change expected
- No net change in performance detected
- Requirement remains satisfied
• 31 Testable Requirements

• 29 Already Verified

• 2 “Pending”
  – FN_080: done by analysis
  – IF_040: our requirements to receive these data are listed in the External Systems ICD for LRO GS; some of the SPICE data are already received on a daily basis (as verified during MR1 and MR4)
  – “Pending” items are essentially done just awaiting documentation in the scorecard

• All Detailed Verification Scorecard Charts (5) Provided in Back-up Material
SOC Development Status
CRaTER SOC Hardware/Network Architecture

- CRaTER Hardware and Network Architecture
  - Unix workstations and RAID array receive, process, store, and distribute real-time telemetry and downloaded instrument data
  - Security and risk managed by segregating workstations/user access into 3 groups
    - SOC-A (only sysadmin access)
    - CRaTER-A (only software team+ access)
    - CRaTER-Work-A (only mission support+ team access)
    - CRaTER-Science (science team+ and other designated users)
SOC Development Status
CRaTER SOC Hardware/Network Architecture

• CRaTER Hardware/Network Architecture
  – Additional security and risk management steps
    • on-going maintenance support from Redhat for bug fixes and security patches
    • logs automatically collected and analyzed for evidence of problems or (attempted) intrusions
      – CRaTER-Logger
    • NO group user accounts; password expirations
    • all software changes/patches tested first on development system before installation on other operational workstations
      – CRaTER-Devel
SOC Development Status
CRaTER SOC Hardware/Network Architecture

• CRaTER Hardware/Network Architecture
  – Minimize outages/time to recover from hardware failures
  • main workstations installed in a secure, environmentally controlled room with automatic fire suppression
  • redundant workstations at all three levels
    – SOC-B/CRaTER-B/CRaTER-Work-B
  • spares for other key hardware
    – firewall router, RAID array drives
  • automated system-wide backups
    – off-site storage
SOC Development Status
Real-time and Processed Data Distribution

• Real-Time (VC0) Data Distribution
  – Process on SOC-A continuously listening for telemetry
    • rtserver
  – All raw data recorded to data files
  – Data decom’d and passed through firewalls to CRaTER-A
  – Process on CRaTER-A distributes to applicable clients
    • rtserver
• Real-Time (VC0) Data Distribution
  – Very flexible system
  – Input from 1 stream output to many streams
  – Clients “register” with \textit{rtserver}
    • default set of clients
      – always receive data whenever \textit{rtserver} is running
    • additional clients added/removed via the command line
  – Clients specify
    • protocol (UDP or TCP), format (ascii, binary), content (all or a subset of available ApIDs)
SOC Development Status
Status Monitors

CRaTER Status
Power: On
Last Updated: 2008-01-28 - 18:31:27

Power
Orbiter Supplied Voltage ..... 32.5 V
CRaTER Current Used ..... 0.198 A
CRaTER Power Used ..... 6.435 W
Thin Detector Bias ..... 21.2 V
5V Digital Monitor ..... 4.933 V
-5V Analog Monitor ..... 4.992 V
-5V Analog Monitor ..... 4.990 V

Test Mode
High Test Mode On? ..... No
Low Test Mode On? ..... Yes

Detector Rates
Deep Space Side
Detector 1 ..... 8 cts/sec
Detector 2 ..... 10 cts/sec

Middle of Telescope
Detector 3 ..... 8 cts/sec
Detector 4 ..... 10 cts/sec

Moon Side
Detector 5 ..... 8 cts/sec
Detector 6 ..... 10 cts/sec

Total Cold Counts ..... 8 cts/sec

Temperatures
Case ..... 23.9 C
Telescope ..... 39.6 C
Power Supply ..... 31.1 C

Display during MR4 (21-25 Jan 2009)
SOC Development Status
Real-time and Processed Data Distribution

- **Real-Time (VC0) Data**
  - Tested during numerous mission readiness tests and mission rehearsals
    - MRT-5a, MRT-6a (2008-06-26)
    - MR-1 (2008-12-15)—2 day test, MR-4 (2009-01-21)—4 day test
  - Performed without problems
• Data Processing Pipeline
  – Tested with instrument data and FDF/MOC products delivered during Mission Rehearsal #1
  
• No issues
SOC Development Status
Data Archiving

- Archive creation tools and delivery process tested during PDS Archive Delivery Tests
  - Test 1 2008/02/15
  - Test 2: 2008/03/26
  - Test 3: 2008/04/23

- Successfully completed all tests
SOC Development Status
Staffing: Staff + Grad + Undergrad Students

Principal Investigator
H. Spence

SOC Lead
M. Golightly (S)
SOC Deputy
D. Bradford (S)

PDS PPI Node
M. Sharlow (UCLA IGPP)

System Administration
D. Bradford (S)
E. Wilson (S)
J. Sanborn (S)

Software Development/Maintenance
E. Wilson (S)
T. Case (GS)
A. Boyd (UgS)

SOC Operations
M. Golightly (S)
T. Case (GS)
A. Boyd (UgS)
TBD 1 (UgS)
TBD 2 (UgS)

E/PO
N. Gross (S)

Hire by end of Spring ’09 semester
<table>
<thead>
<tr>
<th>Document</th>
<th>Title</th>
<th>Current Status</th>
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<tr>
<td>32-01213</td>
<td>Science Operations IT Risk Assessment</td>
<td>Rev B: 06/01/2007</td>
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<tr>
<td>32-01211</td>
<td>Standard Product Data Record and Archive Volume SIS (includes EDR and RDR data product and archive volume software interface specifications)</td>
<td>Rev D: 01/19/2009</td>
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<td>PDS/PPIs EDR/Pipeline RDR SIS Peer Review</td>
<td>11/06/2007</td>
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<td>Inputs to CRaTER Instrument User’s Manual for MOC</td>
<td>Prior to FORR</td>
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SOC Development Summary

- CRaTER SOC ready to proceed to FORR!
Significant Instrument PRs/PFRs

- CRaTER has no problem reports
Flight Software Status

- CRaTER flight software is flashed-burned into onboard instrument FPGAs.
- No updates or changes are possible because none are needed.
Ongoing Development Tests with CRaTER E/M

- Still using well-characterized EM unit (flight equivalent) now and even during prime mission; calibrated flight spare remains in bonded storage
  - Simulated SEP spectrum tests (bottom left) at Massachusetts General Hospital and Brookhaven National Laboratory (BNL)
  - Continued LET measurements at BNL (bottom right) using additional heavy ions
  - >20 MeV neutron beam testing at Lawrence Berkeley National Labs (last week!)
CRaTER Trending Summary

• Housekeeping telemetry

• Derived parameters from science data, directly relate to L1 measurements
  – Processed signal amplitudes and system noise using internal pulser
    • Stimulates nearly entire analog and digital system (signal injected just downstream from the solid state detectors)
    • Internal test can be conducted under any conditions, and so is the most typical test used for science trending
  – Co-60 radionuclide spectra
    • Absolute spectral shape tests entire analog and digital system from end to end, including solid state detectors
    • Test requires placement of radionuclide source near CRaTER aperture, and so is done only during CPTs

• Trends of both engineering housekeeping and science data demonstrate no measurable or significant changes since instrument delivery
Housekeeping Trends – All Engineering Vital Signs are Nominal

<table>
<thead>
<tr>
<th>Date</th>
<th>Delta (days)</th>
<th>Temp (C)</th>
<th>Bias Voltage (V)</th>
<th>Detector Leakage Current (µAmps)</th>
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<tr>
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<td></td>
<td></td>
<td>Thin</td>
<td>Thick</td>
</tr>
<tr>
<td>Nominal Value</td>
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<td>Limits</td>
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<td>±~10</td>
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<td>-</td>
<td>22</td>
<td>217.5</td>
<td>74.1</td>
</tr>
<tr>
<td>(As delivered)</td>
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<tr>
<td>(PER)</td>
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<td>12/29/08</td>
<td>350</td>
<td>22</td>
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<td>74.1</td>
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<tr>
<td>(PSR)</td>
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</tbody>
</table>
Peak location (ADU) (and peak width) in each detector using the internal pulser as a function of time spanning instrument environmental testing to orbiter pre-ship review.

Histogram of pulser in D1: Peak location (ADU) and width (noise in ADU) determined for each detector during a test.
Primary science peak deviates by less than ±1 ADU out of 4095 for same pulser amplitude.

Green range represents maximum variation (+/- 10 ADU or 0.25%) within which measurements meet L1 requirements; Requirements met at each major instrument and mission milestone review, including at this Orbiter Pre-Ship Review.

Note: temperature variations from run to run account for measurable but insignificant test-to-test differences:
1. 24.53 °C
2. 25.59 °C
3. 20.40 °C
4. 23.54 °C
5. 28.34 °C
Primary Science Trends – System Gain From Co60 Source

Co-60 Histograms (Total Counts Normalized)

ADU
Absolute radionuclide spectrum before delivery and at OPSR shows that probability of system gain change is infinitesimal at outer limits of acceptable range, and <~1% likely at even a trifling gain shift of 1 ADU.
Overview of Launch Site Processing

• CRaTER does not require any instrument specific launch site processing
CRaTER Orbiter-level Calibration

- CRaTER calibration can only be performed through beam testing.
  - Consequently, no orbiter level calibration was performed.
  - Instrument-level calibration was performed at Massachusetts General Hospital Proton Therapy Center with supporting characterization measurements taken at Brookhaven National Laboratory.
  - Stability of calibration verified on orbiter through comparisons between pre-delivery and OPSR responses to Co60, ground-level cosmic rays, and internal pulser.
IRD Performance Waivers

• CRaTER has no performance waivers
Summary – CRaTER Ready to Ship!

- CRaTER performance at OPSR continues to meet easily L1 requirements
- All system indicators are nominal
- L2 data products already generated in CRaTER SOC from recent mission rehearsal
- No outstanding issues or concerns
- CRaTER is ready to ship to the Cape!

CRaTER’s webpage:  http://crater.bu.edu
CRaTER’s Facebook name:  Crater Lro
Back-up Material
## LRO Payload Provides Broad Benefits

<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>Measurement</th>
<th>Exploration Benefit</th>
<th>Science Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRaTER Cosmic Ray Telescope for the Effects of Radiation</td>
<td>Tissue equivalent response to radiation</td>
<td>Safe, high performance, lighter weight space vehicles</td>
<td>Radiation boundary conditions for biological response</td>
</tr>
<tr>
<td>DLRE Diviner Lunar Radiometer Experiment</td>
<td>Better than 500m scale maps of Temperature, surface ice, mineralogy</td>
<td>Determines conditions for systems operability, resource including water-ice location</td>
<td></td>
</tr>
<tr>
<td>LAMP Lysim Alphas Mapping Project</td>
<td>Maps of frosts in permanently shadowed areas, etc.</td>
<td>Locate potential water-ice on the surface, image shadowed areas</td>
<td>Source, history, migration and deposition of polar volatiles</td>
</tr>
<tr>
<td>LEND Lunar Exploration Neutron Detector</td>
<td>Maps of hydrogen in upper 1 m of Moon at 10km scales</td>
<td>Locate potential water-ice in lunar soil</td>
<td></td>
</tr>
<tr>
<td>LOMA Lunar Orbiter Laser Altimeter</td>
<td>~50 m scale polar topography at &lt; 10 cm vertical, roughness</td>
<td>Safe landing sites and surface navigation</td>
<td>Geodetic topography for geological evolution</td>
</tr>
<tr>
<td>LROC Lunar Reconnaissance Orbiter Camera</td>
<td>1000’s of 50cm/pixel images (125km2), and entire Moon at 100m in UV, Visible</td>
<td>Surface landing hazards and some resource identification</td>
<td>Tectonic, impact and volcanic processes, resource evaluation, and crustal evolution</td>
</tr>
<tr>
<td>Mini-RF Technology Demonstration</td>
<td>X&amp;S-band Radar imaging and radiometry</td>
<td>Demonstrate new lightweight SAR and communication technologies, locate potential water-ice</td>
<td>Source, history, deposition of polar volatiles</td>
</tr>
</tbody>
</table>
CRaTER Flight Model During Assembly

CRaTER analog section alpha testing at The Aerospace Corp.

TEP integrated on structures before going into telescope

Zenith endcap and thick/thin detector stack being inserted into telescope assembly

View into telescope before adding TEP and detectors

Integrated telescope assembly and analog board
CRaTER Flight Model During Final Calibration

CRaTER flight unit (bagged and purged) during final calibration at MGH Proton Facility

CRaTER flight unit at MGH with proton beam spot centered on telescope aperture
CRaTER Flight Model At Delivery and Initial I&T

CRaTER As-Delivered and Calibrated Flight Model
Before Instrument Pre-Ship Review

CRaTER (aka, LRO’s “Hood Ornament”) perched on diving board after integration
Co-60 radionuclide source positioned on CRaTER's nadir telescope aperture during August 30th EMI testing.

CRaTER blanketed in preparation for orbiter-level environment testing. The kapton tape which makes a small circle on the GBK is covering CRaTER's nadir telescope aperture.
<table>
<thead>
<tr>
<th>SOC Requirement</th>
<th>Method</th>
<th>Status</th>
<th>Date</th>
<th>Engineer</th>
<th>Additional Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN_010</td>
<td>T</td>
<td>P</td>
<td>2009/01/14</td>
<td>Case/Golightly</td>
<td>Processed CRaTER data and FDF files delivered as part of LRO Mission Rehearsal #1 (15-16 Dec 2008).</td>
</tr>
<tr>
<td>FN_020</td>
<td>I</td>
<td>P</td>
<td>2008/10/24</td>
<td>Case/Golightly</td>
<td>Verified CRaTER data processing pipeline can be manually executed with user-supplied input data file names—this will permit any necessary reprocessing.</td>
</tr>
<tr>
<td>FN_030</td>
<td>T</td>
<td>P</td>
<td>2009/01/14</td>
<td>Case/Golightly</td>
<td>Processed CRaTER data and FDF files delivered as part of LRO Mission Rehearsal #1 (15-16 Dec 2008).</td>
</tr>
<tr>
<td>FN_040</td>
<td>T</td>
<td>P</td>
<td>2008/02/15</td>
<td>Wilson/Golightly</td>
<td>Verification completed during PDS Archive Delivery Tests 1, 2, &amp;3.</td>
</tr>
<tr>
<td>FN_050</td>
<td>I</td>
<td>P</td>
<td>2008/03/26</td>
<td>Bradford</td>
<td>Applies to following machines: crater-a, crater-b, crater-devel, and crater-science</td>
</tr>
<tr>
<td>FN_060</td>
<td>T, I</td>
<td>P</td>
<td></td>
<td>Bradford/Golightly</td>
<td>Applies to following machines: crater-a, crater-b, crater-devel, and crater-science</td>
</tr>
</tbody>
</table>

**SOC Development Status**

**Requirements Verification Scorecard**

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Method</th>
<th>Status</th>
<th>Date</th>
<th>Engineer</th>
<th>Additional Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN</td>
<td>Shall perform measurement data processing to produce CRaTER standard data products.</td>
<td>T</td>
<td>P</td>
<td>2009/01/14</td>
<td>Case/Golightly</td>
<td>Processed CRaTER data and FDF files delivered as part of LRO Mission Rehearsal #1 (15-16 Dec 2008).</td>
</tr>
<tr>
<td>FN</td>
<td>Shall perform measurement data reprocessing to update CRaTER standard data products as required by the science team.</td>
<td>I</td>
<td>P</td>
<td>2008/10/24</td>
<td>Case/Golightly</td>
<td>Verified CRaTER data processing pipeline can be manually executed with user-supplied input data file names—this will permit any necessary reprocessing.</td>
</tr>
<tr>
<td>FN</td>
<td>Shall create the following CRaTER primary data products:</td>
<td>T</td>
<td>P</td>
<td>2009/01/14</td>
<td>Case/Golightly</td>
<td>Processed CRaTER data and FDF files delivered as part of LRO Mission Rehearsal #1 (15-16 Dec 2008).</td>
</tr>
<tr>
<td></td>
<td>a. Time-ordered listing of event amplitude in each detector (L1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. Linear Energy Transfer (LET) for each processed event (L2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. Time-ordered listing of secondary science data (L1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d. Time-ordered listing of housekeeping data (L1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FN</td>
<td>Shall provide the CRaTER data products (CRATER_FN_030) and L0 data to the PDS PPI Node for archive and distribution</td>
<td>T</td>
<td>I</td>
<td>2008/02/15</td>
<td>Wilson/Golightly</td>
<td>Verification completed during PDS Archive Delivery Tests 1, 2, &amp;3.</td>
</tr>
<tr>
<td></td>
<td>data to the PDS PPI Node for archive and distribution</td>
<td></td>
<td></td>
<td>2008/03/26</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2008/04/23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FN</td>
<td>Shall provide sufficient disk space for:</td>
<td>I</td>
<td>P</td>
<td>2008/03/26</td>
<td>Bradford</td>
<td>Applies to following machines: crater-a, crater-b, crater-devel, and crater-science</td>
</tr>
<tr>
<td></td>
<td>a. 10 days of incoming data from the MOC</td>
<td></td>
<td></td>
<td>2008/04/23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. 10 days of L1 derived products</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. 10 days of L2 derived products</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FN</td>
<td>Shall provide backup storage for disk space used for software development, user accounts and on-line disk space used for analysis</td>
<td>T</td>
<td>I</td>
<td>2008/03/26</td>
<td>Bradford/Golightly</td>
<td>Applies to following machines: crater-a, crater-b, crater-devel, and crater-science</td>
</tr>
<tr>
<td>FN</td>
<td>Functional Requirement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF</td>
<td>Interface Requirement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF</td>
<td>Performance Requirement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## SOC Development Status Requirements Verification Scorecard

<table>
<thead>
<tr>
<th>SOC Requirement</th>
<th>Test Method</th>
<th>Status</th>
<th>Date</th>
<th>Engineer</th>
<th>Additional Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN_070 Shall provide sufficient disk resources to stage PDS deliverables</td>
<td>T, I</td>
<td>P</td>
<td>2009/01/26</td>
<td>Bradford/Wilson</td>
<td></td>
</tr>
<tr>
<td>FN_080 Shall support priority assignment of processing jobs based on input from the science team</td>
<td>T</td>
<td>P</td>
<td>2009/01/26</td>
<td>Bradford/Wilson</td>
<td></td>
</tr>
<tr>
<td>FN_090 Shall be capable of providing operational and testing configurations</td>
<td>T, I</td>
<td>P</td>
<td>2009/01/26</td>
<td>Bradford/Wilson</td>
<td></td>
</tr>
<tr>
<td>FN_110 Networking connections shall be capable of capturing, storing and processing CRaTER science and housekeeping at the maximum data rate possible</td>
<td>T</td>
<td>P</td>
<td>2009/01/26</td>
<td>Bradford/Wilson/Golightly</td>
<td>Verified during Mission Rehearsal #4 (21-25 Jan 2009)</td>
</tr>
<tr>
<td>FN_500 Shall provide resources to support the development and maintenance of CRaTER measurement data processing software</td>
<td>T, I</td>
<td>P</td>
<td>2009/01/30</td>
<td>Bradford/Wilson/Case/Golightly</td>
<td>CRaTER-Devel--dedicated SOC ops software development and test system. CRaTER-Science—BU CRaTER team computer which supports development and testing of higher-level CRaTER data products.</td>
</tr>
<tr>
<td>FN_510 Shall provide resources to support testing with the LRO Ground System</td>
<td>T</td>
<td>P</td>
<td>2008/12/16, 2009/01/24</td>
<td>Golightly/Wilson</td>
<td>Verified by successfully supporting all required Mission Readiness Tests, Simulations, and Mission Rehearsals.</td>
</tr>
<tr>
<td>FN_520 The SOC shall provide resources to support testing with the PDS PPI Node</td>
<td>T</td>
<td>P</td>
<td>2008/02/15, 2008/03/26, 2008/04/23</td>
<td>Golightly/Wilson/Sharlow</td>
<td>Verified by successfully completing PDS Archive Delivery Tests 1, 2, &amp;3.</td>
</tr>
</tbody>
</table>

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I: Inspect  
P: Pass  
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yyyy/mm/dd
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<tr>
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<th>Description</th>
<th>Method</th>
<th>Status</th>
<th>Date</th>
<th>Engineer</th>
<th>Additional Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF_010</td>
<td>Shall obtain on a per orbit basis CRATER instrument L0 science data from the LRO MOC</td>
<td>I</td>
<td>P</td>
<td>Golightly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_020</td>
<td>Shall obtain on a per orbit basis CRATER instrument housekeeping data from the LRO MOC</td>
<td>I</td>
<td>P</td>
<td>Golightly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_030</td>
<td>Shall obtain real-time housekeeping data provided by the MOC</td>
<td>T</td>
<td>P</td>
<td>Wilson</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_030</td>
<td>Shall obtain the daily stored command load from the LRO MOC</td>
<td>T</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_040</td>
<td>Shall obtain LRO SPICE SPK data from the LRO MOC on a monthly basis</td>
<td></td>
<td>NT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_050</td>
<td>Shall obtain LRO SPICE CK data from the LRO MOC on a monthly basis</td>
<td></td>
<td>NT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_060</td>
<td>Shall obtain CRATER L0 data needed for reprocessing from the LRO MOC</td>
<td>I</td>
<td>NT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_070</td>
<td>Shall obtain LRO SPICE SCLK, LSK and FK kernels from the LRO as needed</td>
<td>T</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IF_500</td>
<td>Shall provide the PDS PPI Node with the following CRATER data products:</td>
<td>T</td>
<td>P</td>
<td>Wilson/</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a. Energy deposited in each detector for every processed event.</td>
<td></td>
<td></td>
<td>Golightly/Sharlow</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. Linear energy transfer in each detector for every processed event.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. CRaTER mass model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
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<th>Engineer</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>IF_510</strong></td>
<td>T, I</td>
<td>P</td>
<td></td>
<td>Wilson/Goelicky/Goeke/Sharland</td>
<td></td>
</tr>
<tr>
<td><strong>PF_020</strong></td>
<td>T, I</td>
<td>P</td>
<td>2009/01/20</td>
<td>Wilson/Goelicky</td>
<td>CRaTER SOC-A machine continuously monitoring and recording VC0 telemetry streams from the MOC for 6 months. Eval period includes several Mission Readiness Tests, Sim-29, Mission Rehearsal #1, and Mission Rehearsal #4.</td>
</tr>
<tr>
<td><strong>PF_030</strong></td>
<td>A</td>
<td>P</td>
<td></td>
<td>Golightly/Bradford</td>
<td></td>
</tr>
<tr>
<td><strong>PF_040</strong></td>
<td>A</td>
<td>P</td>
<td></td>
<td>Golightly/Bradford</td>
<td></td>
</tr>
<tr>
<td><strong>PF_050</strong></td>
<td>A</td>
<td>P</td>
<td></td>
<td>Golightly/Wilson/Sharland</td>
<td></td>
</tr>
<tr>
<td><strong>PF_060</strong></td>
<td>A</td>
<td>P</td>
<td></td>
<td>Bradford</td>
<td></td>
</tr>
</tbody>
</table>

**FN = Functional Requirement**  
**IF = Interface Requirement**  
**PF = Performance Requirement**  

<table>
<thead>
<tr>
<th>T: Test A: Analysis P: Pas F: Fail NT: Not Testable</th>
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<th>Status</th>
<th>Date</th>
<th>Engineer</th>
<th>Additional Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF_070</td>
<td>Shall provide adequate on-line storage to buffer 10 days of outgoing data</td>
<td>A</td>
<td>P</td>
<td></td>
<td>Bradford</td>
<td></td>
</tr>
<tr>
<td>PF_080</td>
<td>SOC shall provide adequate on-line storage for 10 days of CRATER standard data products</td>
<td>A</td>
<td>P</td>
<td></td>
<td>Bradford</td>
<td></td>
</tr>
<tr>
<td>PF_100</td>
<td>Shall provide a mechanism for the science team to validate incoming data</td>
<td>T, I</td>
<td>P</td>
<td></td>
<td>Case/Goeke/Wilson</td>
<td></td>
</tr>
<tr>
<td>PF_110</td>
<td>Shall provide performance and trending information</td>
<td>T, I</td>
<td>P</td>
<td></td>
<td>Case/Goeke/Wilson</td>
<td></td>
</tr>
</tbody>
</table>

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**NASA’s Goddard Space Flight Center**

**LRO PSR - CRaTER**

**Slide - 65**
Flow of Requirements

Level 2 Parent Requirements

01
- Thin and thick detector pairs 140 & 1000 μm
02
- Minimum energy < 250 keV
03
- Nominal instrument shielding > 1524 μm Al
04
- Nadir and zenith field of view shielding < 762 μm
05
- Telescope stack
06
- Pathlength constraint < 10% for D1D6
07
- Zenith field of view < 33°
08
- Nadir field of view < 70°
09
- Calibration system
10
- Event selection
11
- Maximum transmission rate > 1000 events/second
Calibration Parameters for Flight and Flight Spare CRaTER Units

<table>
<thead>
<tr>
<th>Var</th>
<th>Unit</th>
<th>Flight Model S/N 02 (Selected for delivery to NASA)</th>
<th>Flight Model S/N 01</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>D1</td>
<td>D3</td>
</tr>
<tr>
<td>Offset</td>
<td>ADU</td>
<td>-0.3</td>
<td>-0.5</td>
</tr>
<tr>
<td>Gain</td>
<td>KeV/ADU</td>
<td>81.6</td>
<td>82.9</td>
</tr>
<tr>
<td>Min E</td>
<td>KeV</td>
<td>435.5</td>
<td>453.5</td>
</tr>
<tr>
<td>Max E</td>
<td>MeV/um</td>
<td>334.1</td>
<td>339.6</td>
</tr>
<tr>
<td>Thick</td>
<td>um</td>
<td>148</td>
<td>149</td>
</tr>
<tr>
<td>Min LET</td>
<td>KeV/um</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Max LET</td>
<td>MeV/um</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Max/Min</td>
<td>#</td>
<td>24847</td>
<td>14028</td>
</tr>
</tbody>
</table>
Primary science peak deviates by less than ±1 ADU out of 4095 for same pulser amplitude.

Temperatures vary from run to run:
1. 24.53 °C
2. 25.59 °C
3. 20.40 °C
4. 23.54 °C
5. 28.34 °C