Science Goals to Requirements

Dennis Reuter
NASA/Goddard SFC
Code 693
dennis.c.reuter@nasa.gov
Science Goals Drive System Requirements

• Data must be stable
  – During a given observation, results cannot change as instrument environment changes.

• Data must be reproducible
  – Two or more measurements of the same signal must agree

• Data must be calibrated
  – Performance of onboard calibration systems must be understood

• Data must be capable of being taken over the required dynamic range

• Data must be obtained at the required frequency

• Data must meet the required noise performance

• Data must be flowed to the user community in a timely manner

• Requirements cross system boundaries
Mission Instrument Examples

• Thermal InfraRed Sensor (TIRS) on Landsat 8
  – Very low temperature cryogenic detector
  – Fast data turn-around required
  – Instrument had to be built in ~3 years – ~one year faster than usual

• Ralph instrument on New Horizons Pluto/Kuiper Belt Mission
  – Low light levels very far from the sun (more than 30 times further than the Earth)
  – Very low mass instruments required
  – Very long duration in flight (9.5 years and counting)

• OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) on OSIRIS-REx Asteroid Sample Return Mission
  – Low light levels from dark object (asteroid Bennu < 5% reflectance)
  – Broad spectral range (0.4 – 4.3 \( \mu \)m)
  – Large range of sun-object-spacecraft angles and close in-observations
  – Requirement flow similar to Ralph and won’t be discussed separately
Example 1: Thermal IR Sensor (TIRS) on Landsat 8

- Landsat 8 has two imaging systems
  - The Thermal IR Sensor has 2 channels in the 10-12 μm spectral range (100 meter spatial resolution)
  - The Operational Land Imager (OLI) has 9 spectral channels in the visible to Near-IR range (15 and 30 meter spatial resolution)
  - Both instrument operate in pushbroom mode with 185 km swath

- Product example: TIRS data used to monitor water use on a field-by-field basis in the U.S. West and internationally
  - Evapotranspiration cools vegetation (plants “sweat” as part of photosynthesis)
  - Parametric models use measured vis/NIR and thermal radiation, surface classification and estimates of soil thermal transport to derive soil moisture estimates

- Reliability of product depends heavily on measurement noise
  - Required that radiance measurement noise be ≤ 0.5% @ 300 K
Radiance Detected by TIRS from Surface and Atmosphere

\[ L_s = \frac{\int (B(T, \lambda) \cdot \tau(\lambda) + L_{atm}(\lambda)) \cdot R'(\lambda) \cdot d\lambda}{\int R'(\lambda) \cdot d\lambda} \]

- \( B(T, \lambda) \): Emitted and reflected surface radiance
- \( \tau(\lambda) \): Transmission of atmosphere
- \( L_{atm}(\lambda) \): Emitted and scattered radiance of atmosphere
- \( R'(\lambda) \): Spectral response of detector
- \( L_s \): Detector integrated radiance

Two channel “split window” techniques correct for atmosphere and improve retrieved surface temperature.
Data Product: Water Management Using Surface Energy Balance

\[ R_{NET} = G + ET + H \]

- Soil heat \( (G) \)
- Sensible heat \( (H) \)
- Latent heat \( (ET) \)
- Net radiation \( (R_{NET}) \)

- Net Radiation is the balance between incoming minus outgoing radiation
  - OLI albedo required to calculate the SWup (short wave upwell)
  - TIRS radiance data required to calculate the LWup from surface temperature
Additional TIRS Science

- Mapping urban heat fluxes for air quality modeling (urban heat island)
- Volcanic hazard assessment, monitoring, and recovery
- Cloud detection and screening
- Mapping lake thermal plumes from power plants
- Burnt area mapping / Wildfire risk assessment
- Tracking material transport in lakes and coastal regions
- Identifying mosquito breeding areas and vector-borne illness potential

(Images from D. Quattrochi)
## TIRS Driving Requirements

<table>
<thead>
<tr>
<th>RD #</th>
<th>TIRS #</th>
<th>Parameter</th>
<th>L3 Requirement</th>
<th>Systems Affected</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6.2.1</td>
<td>FS-461</td>
<td>NEΔL</td>
<td>$\leq 0.059 \text{ W/m}^2\text{ sr} \mu\text{m} (10.8 \mu\text{m} \text{ channel})$</td>
<td>Optics, Thermal, FPE, FPA</td>
<td>Stability based over 24 second WRS-2 scene</td>
</tr>
<tr>
<td>5.6.4</td>
<td>FS-562</td>
<td>Stability</td>
<td>0.7%</td>
<td>Optics, Thermal, FPE, FPA</td>
<td>Over 40 minutes</td>
</tr>
<tr>
<td>5.5.6</td>
<td>FS-442</td>
<td>Bright Target</td>
<td>$&lt;1%$ radiance outside an $11\times11$ pixel area affected</td>
<td>FPA, FPE, Optics</td>
<td></td>
</tr>
<tr>
<td>5.5.2.1</td>
<td>FS-400</td>
<td>RER</td>
<td>$&gt; 0.007 /\text{m in-track and cross-track}$</td>
<td>Optics</td>
<td></td>
</tr>
<tr>
<td>5.5.2.2</td>
<td>FS-404</td>
<td>Edge Extent</td>
<td>$&lt;150 \text{ m in-track and cross-track}$</td>
<td>Optics</td>
<td></td>
</tr>
<tr>
<td>5.5.1</td>
<td>FS-386</td>
<td>GSD</td>
<td>$&lt;120 \text{ m}$</td>
<td>Optics, FPA, FPE</td>
<td></td>
</tr>
<tr>
<td>5.4.1.2</td>
<td>FS-374</td>
<td>Center Band</td>
<td>Band 10 (Thermal 1) 10.8 $\mu\text{m}$ (± 200nm) Band 11 (Thermal 2) 12 $\mu\text{m}$ (± 200nm)</td>
<td>Optics, FPA</td>
<td></td>
</tr>
<tr>
<td>5.4.1.2</td>
<td>FS-799</td>
<td>Bandwidth</td>
<td>Band 10 - 10.3 $\mu\text{m}$ to 11.3 $\mu\text{m}$ Band 11 – 11.5 $\mu\text{m}$ to 12.5 $\mu\text{m}$</td>
<td>Optics. FPA</td>
<td></td>
</tr>
<tr>
<td>5.4.3</td>
<td>FS-376</td>
<td>Uniformity</td>
<td>Within ± 5% FWHM of measured mean</td>
<td>Optics, FPA</td>
<td></td>
</tr>
</tbody>
</table>

**Radiometry**

**Spatial Performance**

**Spectral Shape**
<table>
<thead>
<tr>
<th>RD #</th>
<th>TIRS #</th>
<th>Parameter</th>
<th>L3 Requirement</th>
<th>Systems Affected</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6.5.1</td>
<td>FS-566</td>
<td>Dead Pixels</td>
<td>&lt; 0.1% dead pixels within any row</td>
<td>FPA</td>
<td>2 for 1 ground pixel selection allowed</td>
</tr>
<tr>
<td>5.6.5.2</td>
<td>FS-570</td>
<td>Inoperable Pixels</td>
<td>&lt;0.25% fail to meet specifications during any WRS-2 scene</td>
<td>FPA, Algorithms</td>
<td>2 for 1 ground pixel selection allowed</td>
</tr>
<tr>
<td>5.7.1</td>
<td>FS-625</td>
<td>LOS</td>
<td>27 microradians per axis</td>
<td>Thermal, Mechanism, Mechanical</td>
<td>Knowledge per 16 day orbit repeat cycle</td>
</tr>
<tr>
<td>5.7.2</td>
<td>FS-179</td>
<td>Timing Accuracy</td>
<td>Timestamp science data within +0.001 seconds of LDCM time stamp</td>
<td>MEB</td>
<td></td>
</tr>
<tr>
<td>5.7.3.1</td>
<td>FS-606</td>
<td>Registration</td>
<td>2 thermal bands co-registered within &lt;18 m after geometric correction</td>
<td>Mechanism, Algorithm</td>
<td>Stability from band to band (2.5 seconds)</td>
</tr>
<tr>
<td>5.7.3.2</td>
<td>FS-608</td>
<td>Geodetic</td>
<td>Pixels at earth's surface located relative to reference system to within 76 m</td>
<td>Mechanism, Algorithm</td>
<td></td>
</tr>
</tbody>
</table>

**FPE (Focal Plane Electronics)**
**FPA (Focal Plane Assembly)**
**MEB (Main Electronics Box)**
TIRS Block Diagram
TIRS on Landsat 8 Spacecraft

- Deployable Earth Shield (Stowed)
- Sensor Unit Connector Bulkhead
- Cryocooler Electronics
- MEB
- OLI
TIRS FOVs and Telescope Detail

- Deployed Earthshield
- Nadir View
- Telescope Radiator
- Scene Select Mechanism
- Spaceview
- FPE
- Flexures (1 of 3)
- Cryocooler
- Telescope Assembly
- Cryocooler Radiator
- Scene Select Mechanism
- Telescope/FPA
- Cryocooler
TIRS Focal Plane Layout (3 QWIPs)
Leaving Goddard Space Flight Center

On the Spacecraft, Showing Views (Earth View – Space View) = Source Radiance
Requirements Flowdown

**LDCM Level 3 Specifications**
- RD
- SCTR
- OBS-IRD
- LEVR
- IMAR

**TIRS Level 4 Specifications**
- Flight Specification
- Simulator/EGSE Specification
  - Calibration Test Plan
  - Environmental Test Plan

**Subsystem Level 5 Specifications**
- Telescope
- Focal Plane Assembly
- Focal Plane Electronics
- Main Electronics Box
  - Thermal
  - Mechanism
- Cryocooler
- Algorithms
- Mechanical
- Harness

- Level 3 requirements specify
  - Mission performance
  - Mission environment
  - Testing (instrument and subsystem)
  - Design process

- Level 4 specifications capture TIRS instrument, algorithm, simulator and testing requirements
- Predicted performance and margin shown against Level 4
- Instrument verification will be performed against Level 4
  - Verification by analysis, test, inspection, design or some combination
- Level 5 specifications are populated with allocated or derived requirements
  - Captures specific subsystem requirements necessary for subsystem buy-off
- PDLs are responsible for verification before delivery to I&T
  - Verification by analysis, test, inspection or some combination
## Level 3 to 4 Requirements Trace

<table>
<thead>
<tr>
<th>Requirement</th>
<th>LDCM TIRS RD</th>
<th>LDCM O-IRD</th>
<th>LDCM LEVR</th>
<th>LDCM I-MAR</th>
<th>LDCM SCTR</th>
<th>LDCM TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIRS Flight System Specification</td>
<td>182</td>
<td>190</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>372</td>
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<tr>
<td>TIRS GSE Specification</td>
<td>70</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>70</td>
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<tr>
<td>TIRS Calibration/Validation Plan</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>TIRS I&amp;T Plan</td>
<td>-</td>
<td>-</td>
<td>606</td>
<td>-</td>
<td>-</td>
<td>606</td>
</tr>
<tr>
<td>TIRS MAIP</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>398</td>
<td>-</td>
<td>398</td>
</tr>
<tr>
<td>N/A</td>
<td>5</td>
<td>196</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>204</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>257</strong></td>
<td><strong>386</strong></td>
<td><strong>606</strong></td>
<td><strong>400</strong></td>
<td><strong>54</strong></td>
<td><strong>1703</strong></td>
</tr>
</tbody>
</table>
TIRS Noise Drives Thermal Requirements

- TIRS noise is a function of inherent signal variance (electron “shot noise”), system instability noise, electronics and array noise (“read noise”) and quantization noise – terms dependent on thermal system
- For an integration time $t$, Source flux $F(S)$, Background flux $F(B)$, Scene Select Mirror flux $F(M)$, Optics flux $F(O)$ and detector dark current $I(D)$
- $N = \left\{ 2g^t(F(S) + F(B) + F(M) + F(O) + I(D)) + \\
(\frac{t^2}{2}((\frac{\delta F(B)}{\delta T})^2 +(\frac{\delta F(M)}{\delta T})^2 +(\frac{\delta F(O)}{\delta T})^2 + (\frac{\delta I(D)}{\delta T})^2)) \\
\right\}^{1/2}$

$F(S) = B(S)CE\tau_l\tau_f r_m \pi/(1+(2f)^2)$, $F(B) = B(B)CE\tau'_f \pi(\Omega_b-1)/(1+(2f)^2)$, $F(M) = B(M)CE\tau_l\tau_f \varepsilon_m \pi/(1+(2f)^2)$, $F(O) = B(O)CE\tau_f \varepsilon_o \pi/(1+(2f)^2)$,

$B(x) =$ appropriate radiance integral for temperature $x$

$ID = K\exp(-1.4388*cutoff/T_d)[K$ and cutoff depend on array], $RD = \text{detector read noise}$

$RE = \text{electronics read noise}$, $Q = 12$ bit quantization noise $= (\text{well depth}/4094)/(12)^{1/2}$

$CE = \text{conversion efficiency}$, $\tau_l = \text{lens transmittance}$, $\tau_f = \text{filter transmittance}$, $f = f/#$

$r_m = \text{mirror reflectance}$, $\varepsilon_m = \text{mirror emittance}$, $\varepsilon_o = \text{optics emittance}$, $\tau'_f = (1+\tau_f)/2$

$\Omega_b = \text{solid angle above cold shield}$, $g = \text{photoconductive gain}$
Noise terms of particular note

- Long wavelength cutoff of detector requires very low temperature operation to reduce dark current
  - Poisson statistics give a noise term whose variance is proportional to the charge collected
- Large derivative in dark current with temperature requires very stable detector temperature (milli-Kelvin stability) to reduce noise contribution
- Long wavelength operation also means thermal emission signal from the instrument is significant
  - Again, Poisson statistics give a noise term whose variance is proportional to the charge collected
  - Also requires stable instrument temperature to reduce noise
- Used photoconducting detector because it gave best uniformity
  - But also has both charge regeneration and recombination noise terms giving rise to factor of $\sqrt{2}$ in the flux noise term.
- Numerous trades available
  - Detector temperature, instrument temperature, electronic noise, f/#, etc. etc…
**TIRS Detectors: 10-13.5 µm Quantum Well IR Photodetectors**

- QWIPs operate as “particle in a box” [quantum well] photoconductors
- TIRS: bound to quasibound QWIPs
- IR photon excites electron from lower, bound states to states near conduction band
- Thermal energy excites electrons too
- E-Field causes excited electrons to conduct and be counted as signal

\[ \lambda_c = 13.4 \, \mu m \]

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Carrier Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>20000 Å GaAs</td>
<td>1 x 10^{18} cm^{-3}</td>
<td></td>
</tr>
<tr>
<td>50 Å AlGaAs (x = 0.16) undoped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 Å GaAs</td>
<td>0.6 x 10^{18} cm^{-3}</td>
<td></td>
</tr>
<tr>
<td>700 Å AlGaAs (x = 0.16) undoped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 Å GaAs</td>
<td>0.6 x 10^{18} cm^{-3}</td>
<td></td>
</tr>
<tr>
<td>50 Å AlGaAs (x = 0.16) undoped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2500 Å GaAs</td>
<td>1 x 10^{18} cm^{-3}</td>
<td></td>
</tr>
<tr>
<td>GaAs n+ SUBSTRATE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Thermal Zones:
- Warm End
  - Scene Select Mechanism
  - Scene Select Mirror & Baffles (≤293K)
    - Stability ±1K (35 sec)
    - Stability ±2K (44 Min)
  - Blackbody Calibrator (270 to 320K)
    - Stability ±0.1K (35 sec)
- Cold End
  - Tel Stage: Tel Assembly (185K)
    - Stability ±0.1K (35 sec)
    - Stability ±0.25K (44 Min)
  - Warm Stage: FPA Shroud (<88K)
    - Stability ±0.01K (35 sec)
    - Stability ±0.02K (44 min)
TIRS Uses T-dependent Index of Refraction of GE to Adjust Focus

- 100 µm shift of focus smears the image by ~ 40%
- Requirement for focus adjustment caused requirement that lens temperature be adjustable from 180 to 190 K
  - Corresponds to ~ ± 75 µm focus shift.
  - Required lens temperature stability ± 2 K
- Noise stability required is more stringent
TIRS Surface Temperature Map – Salton Sea, CA

10.8 µm Radiance [W/m²/sr/µm]

12.0 µm Radiance [W/m²/sr/µm]
Dark greens indicate higher ET and blues and beiges progressively lower ET.
Example 2: Ralph Instrument on New Horizons Pluto/Kuiper Belt Mission

- Passively cooled Ralph instrument has two components: MVIC and LEISA

- **MVIC (Multi-spectral Visible Imaging Camera)**
  - Panchromatic (400 – 975 nm) channel and four color channels
    - Blue (400–550 nm)
    - Red (540–700 nm)
    - NIR (780–975 nm)
    - Methane (860–910 nm)
  - Focal plane < 175 K
  - Color channels and two panchromatic channels operate in TDI (Time Delay and Integrate) mode

- **LEISA (Linear Etalon Imaging Spectral Array)**
  - 1.25 μm to 2.5 μm spectral imager with resolving power (λ/δλ) ~ 225
  - 2.1 μm to 2.25 μm spectral imager with resolving power (λ/δλ) ~ 545
  - Operates in push-frame mode
  - Focal plane < 115 K
New Horizons Mission Objectives

**PRIMARY OBJECTIVES:**
- Characterize global geology and morphology of Pluto and Charon
- Map surface composition of Pluto and Charon (< 10 km)
- Characterize the neutral atmosphere of Pluto and its escape rate

**SECONDARY OBJECTIVES:**
- Characterize time variability of Pluto’s surface and atmosphere
- Image Pluto and Charon in stereo
- Map terminators of Pluto & Charon at high res
- Map composition of selected areas of Pluto and Charon at high res
- Characterize Pluto’s ionosphere and solar wind interaction
- Search for neutral species, hydrocarbons, and nitriles in Pluto’s upper atmosphere
- Search for atmosphere around Charon
- Determine Bond albedos for Pluto and Charon
- Map surface temperatures of Pluto and Charon

**TERTIARY OBJECTIVES:**
- Characterize energetic particle environment of Pluto and Charon
- Refine bulk parameters (radii, masses, densities) and orbits of Pluto and Charon
- Search for magnetic fields of Pluto and Charon
- Search for additional moons and rings
Average of the best *ground-based* (whole disk) spectra of Pluto (including the light from Charon) from 65 data sets obtained from 2001 to 2013 in a monitoring program (Grundy et al., 2013). Reproduced courtesy Elsevier. Weak spectral features (e.g. N$_2$) drove LEISA sensitivity requirements including enclosure and detector temperatures.
(Left) Model of the Ralph instrument with principle structures labeled. (Right) Picture of Ralph, looking down the aperture, before the addition of most of the multi-layer insulation (MLI)
Ralph: Two Cameras in One Box

**MVIC FOV**

**LEISA FOV**

- High Res: 2.1 μm
- Low Res: 2.2 μm
- NIR, CH4, Red, Blue, Pan1, Pan2

- 0.037°, 0.070°, 0.15°
(Left) Raytrace diagram showing the path to the LEISA and MVIC focal planes and the Field of View (FOV) of both systems. (Right) Spacecraft rotation provides the image motion needed for scans.
### Ralph MVIC Specifications & Requirements

<table>
<thead>
<tr>
<th>Field of View (FOV)</th>
<th>5.7° x 0.83°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation Transfer Function (MTF)</td>
<td>&gt; 0.15 (Pan over 5.7° x 0.2°) at 20 cycles/mRad</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.15 (NIR over 3.7°) at 20 cycles/mRad</td>
</tr>
<tr>
<td><strong>MVIC Color/Pan Bands S/N Specifications</strong></td>
<td></td>
</tr>
<tr>
<td>Panchromatic</td>
<td>400 - 975 nm</td>
</tr>
<tr>
<td>Blue</td>
<td>400 - 550 nm</td>
</tr>
<tr>
<td>Red</td>
<td>540 - 700 nm</td>
</tr>
<tr>
<td>Near IR</td>
<td>780 - 975 nm</td>
</tr>
<tr>
<td>Methane</td>
<td>860 - 910 nm</td>
</tr>
<tr>
<td><strong>Optical Navigation Requirements</strong></td>
<td></td>
</tr>
<tr>
<td>Image Pluto and at least 4 stars with a S/N &gt; 7</td>
<td></td>
</tr>
<tr>
<td>90% encircled energy diameter &lt;36 microns</td>
<td></td>
</tr>
<tr>
<td><strong>Alignment</strong></td>
<td></td>
</tr>
<tr>
<td>Ralph shall have an alignment cube</td>
<td></td>
</tr>
<tr>
<td>Ralph line-of-sight with respect to alignment cube</td>
<td>&lt; 3.2 mRad</td>
</tr>
<tr>
<td><strong>Aperture Cover</strong></td>
<td></td>
</tr>
<tr>
<td>Ralph shall have an aperture cover</td>
<td>One-time operation with transparent window</td>
</tr>
<tr>
<td><strong>Temperatures</strong></td>
<td></td>
</tr>
<tr>
<td>Housing</td>
<td>&lt; 230 K</td>
</tr>
<tr>
<td>MVIC Detector</td>
<td>&lt; 180 K</td>
</tr>
</tbody>
</table>
Ralph LEISA Specifications & Requirements

- Imaging Performance (MTF @ Nyquist) not specified by will be higher than MVIC due to larger pixels, smaller field, longer wavelength

<table>
<thead>
<tr>
<th>Detector Element</th>
<th>40 μm by 40 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (IFOV)</td>
<td>62 μR/pix</td>
</tr>
<tr>
<td></td>
<td>⇒ 650 mm EFL</td>
</tr>
<tr>
<td>FOV</td>
<td>0.90 deg x 0.90 deg</td>
</tr>
<tr>
<td>MTF</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>will be &gt;30% @ Nyquist</td>
</tr>
</tbody>
</table>

**LEISA S/N Specifications at specific wavelengths**

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>S/N Specification</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250 nm</td>
<td>S/N &gt; 31/pix</td>
<td>0.35</td>
</tr>
<tr>
<td>2000 nm</td>
<td>S/N &gt; 27/pix</td>
<td>0.35</td>
</tr>
<tr>
<td>2150 nm</td>
<td>S/N &gt; 18/pix</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Spectral Performance**

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Range</td>
<td>1250 to 2500 nm</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>Δλ/λ &gt; 220</td>
</tr>
<tr>
<td></td>
<td>at 1250 - 2500 nm</td>
</tr>
<tr>
<td></td>
<td>Δλ/λ &gt; 520</td>
</tr>
<tr>
<td></td>
<td>at 2100 - 2250 nm</td>
</tr>
</tbody>
</table>

**Temperature**

| Detector               | < 130 K                     |

**Alignment**

| LEISA with-respect-to MVIC | None | will be <1 mrad |
New Horizons Spacecraft with Instruments

New Horizons Spacecraft showing the positions of all seven instruments. The Ralph MVIC and LEISA images are obtained by scanning the fields of view across the target by spacecraft motion.

Ralph instrument swathed in MLI in preparation for mounting on spacecraft. Boresight is facing forward in this picture.
LEISA Noise Drives Thermal Requirements

- LEISA noise is also a function of inherent signal variance (electron “shot noise”), system instability noise, electronics and array noise (“read noise”) and quantization noise – terms dependent on thermal system
- For wavelength $\lambda$, an integration time $t$, Source flux $F_{S\lambda}$, Background flux $F_{B\lambda}$, Optics flux $F_{O\lambda}$ and detector dark current $I(D)$
- $N(\lambda) = \{[t*(F_{S\lambda} + F_{B\lambda} + F_{O\lambda} + I(D))] +$
  
  $[t^2*(((F_{B\lambda}(B)/T)\Delta T(B))^2 + ((F_{O\lambda}(B)/T)\Delta T(B))^2 + ((I(D)/T)\Delta T(D))^2)]$

  $+ [R_D^2 + R_E^2 + Q^2] \}^{1/2}$

- $F_{S\lambda} = R_{S\lambda} \times Q_E \times \tau_f \times r_m \times \pi / (1 + (2f)^2)$,
- $F_{B\lambda} = B_{\lambda}(B) \times Q_E \times \tau_f' \times \pi \times (\Omega_b - 1) / (1 + (2f)^2)$,
- $F_{O\lambda} = B_{\lambda}(B) \times Q_E \times \tau_f' \times 3 \times \varepsilon_m \times \pi / (1 + (2f)^2)$,
- $R_{S\lambda}$ = Reflected solar flux at wavelength $\lambda$, $B_{\lambda}(x)$ = Planck radiance at $\lambda$ for temperature $x$
- $I_D = K \times \exp(-1.4388 \times \text{cutoff}/T_d)[K \text{ and cutoff depend on array}, \text{RD} = \text{detector read noise}$
- $R_E = \text{electronics read noise}$, $Q = 12 \text{ bit quantization noise} = (\text{well depth}/4094)/(12)^{1/2}$
- $Q_E = \text{Quantum Efficiency}$, $\tau_f = \text{filter transmittance}$, $f = f/\#$, $r_m = \text{mirror reflectance}$
- $\varepsilon_m = \text{mirror emittance}$, $\tau_f' = (1 + \tau_f) / 2$, $\Omega_b = \text{solid angle above cold shield}$
- $g = \text{photoconductive gain} = 1$
Noise terms are similar to TIRS but some differences

• The wavelength cutoff of detector requires low temperature operation to reduce dark current
  – Because this is a passively cooled system this is a very significant driver

• Temperature stability is not a significant driver
  – Small temperature changes don’t affect dark current or background as much

• Thermal emission signal from the instrument is significant but, because a wedged filter is used to obtain spectra, only the longer wavelengths are affected

• Used photovoltaic detector because increased QE is very important at low light levels
  – Also only has both charge generation noise term so no factor of sqrt(2) in the flux noise term.
  – At 2.5 micron cutoff, HdCdTe detectors give decent uniformity and stability.

• Again, numerous trades available
  – Detector temperature, integration time, electronics noise, QE, f/#, etc. etc…..
In photovoltaic detectors an applied voltage induces a large junction region from which photons can eject carriers into the conduction band with essentially no recombination loss. The well depth is the number of carriers required to remove the depletion layer. (Left) The 256 x 256 pixel LEISA detector. The active area of the array is the central dark region. (Right) The full LEISA focal plane assembly with the wedged filter shown mounted above the array.
Pluto Methane Map Obtained with LEISA Shows Spatial Differences

(Left) an image of Pluto showing the methane distribution obtained using IR spectra generated by Ralph/LEISA. (Right) Examples of Pluto relative reflectance spectra. The blue spectrum shows absorption bands characteristic of solid methane (CH₄). The red spectrum, while showing evidence of the methane bands, is broader and has much less structure. It may be representative of absorption by water and/or a mixture of species known as tholins in addition to CH₄. The spatial resolution of these data is on the order of 150 km. Later observations of Pluto obtained spectra at a spatial resolution of about 6 km, or roughly 25 times higher than that shown here.
This July 13, 2015, image of Pluto and Charon is presented in false colors to make differences in surface material and features easy to see. It was obtained by the Ralph instrument, using three filters to obtain color information, which is exaggerated in the image. The apparent distance between the two bodies has been reduced. (Right) The bright heart-shaped region of Pluto includes areas that differ in color characteristics. The western lobe, shaped like an ice-cream cone, appears peach color in this image. A mottled area on the right (east) appears bluish. Even within Pluto's northern polar cap, in the upper part of the image, various shades of yellow-orange indicate subtle compositional/ differences. (Left) The surface of Charon is viewed using the same exaggerated color. The red on the dark northern polar cap is attributed to hydrocarbon materials including a class of chemical compounds called tholins. The mottled colors at lower latitudes point to the diversity of terrains on Charon.
Some Closing Thoughts

• Once defined, the science goals are a significant driving force in defining the system requirements
  – Of course, implementation and survival requirements are critical, but they are relative to the system being designed to obtain the science

• However, there is typically some leeway in the science goals, and it behooves all to recognize this.
  – The degradation of a product typically starts slowly when requirements are exceeded
  – When 10% of the goal is causing 90% of the implementation problems, it is time to have a discussion

• Effort should be made to meet the requirements at a subsystem level

• However, the system performance is dependent on all requirements – there is usually an opportunity to make sub-system level trades
  – It is very important that there be open communication about problems

• Please let the system engineers and the scientists know when meeting a particular requirement is becoming problematic.
  – We are ready to believe you.