Space Layer Experiment (SLX) Sensor Calibration

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Abstract

The Space Layer Experiment (SLX) is a sensor that was planned by the US Missile Defense Agency (MDA) to test technology to observe and track objects in space. A detailed and thorough ground calibration of the SLX sensor was planned to support observation and tracking goals, with continuing calibration experiments planned after launch. This presentation provides an overview of the SLX ground calibration that was crafted to use existing SDL calibration equipment and expertise with allowances made for SLX sensor design and program schedule. Preliminary plans that were developed for on-orbit calibration will also be presented with the goal of receiving expert feedback to improve plans for other future calibration efforts.
Presentation Outline

- SLX Sensor Overview
- Calibration Goals & Approach
- Calibration Equipment Overview
- Ground Calibration Measurements
- Ground Calibration Relative Uncertainty Budget
- On-Orbit Calibration Measurements
- On-Orbit Relative Uncertainty Budget
- Summary
What is the Space Layer Experiment?

• Technology Demonstration
  – Track objects in space from orbit
  – Observe objects in multiple bands simultaneously
  – Demonstrate design, fabrication, test, and calibration
Why Do Ground Calibration?

- Verify sensor performance and operation before launch

<table>
<thead>
<tr>
<th>SPECIFICATION</th>
<th>IMPLICATION</th>
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<tbody>
<tr>
<td>The SLX was designed to make observations in the VNIR band</td>
<td>The relative spectral response of the sensor required to be measured over</td>
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<tr>
<td></td>
<td>the full spectral range of the FPA (also required for radiometric responsivity).</td>
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<tr>
<td>The SLX was designed to make observations in the MWIR band</td>
<td>Calibration GSE required to support simultaneous data collection from all</td>
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<td></td>
<td>FPAs.</td>
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<tr>
<td>The SLX was designed to make observations in the MLWIR band</td>
<td></td>
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<tr>
<td>The SLX was designed to make simultaneous observations in each spectral</td>
<td>Calibration GSE required to provide suitable point sources.</td>
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<td>band at the nominal frame rate</td>
<td></td>
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<tr>
<td>The SLX was designed to detect a nominal object in the VNIR band</td>
<td></td>
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<tr>
<td>The SLX was designed to detect a nominal object in the MWIR band</td>
<td></td>
</tr>
<tr>
<td>The SLX was designed to detect a nominal object in the MLWIR band</td>
<td></td>
</tr>
<tr>
<td>The SLX was designed to provide a maximum FOV greater than 1 degree</td>
<td>Calibration GSE required to provide adequate pointing capability.</td>
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</table>

- Ground calibration reduces risk of disappointing performance
  - Some parameters can **only** be measured before launch
Implement Conservative Approach

- Use existing equipment to meet cost constraints
  - Existing equipment is not ideal for sensor
  - Implement pupil underfill baffle to define vignetting (mounted on translation stage to allow direct measurement of pupil-fill correction factor)

- Implement single multifunction configuration to meet schedule
  - Multiple-source collimator
  - Extended Source
Existing Equipment Compromises

- MIC5 collimator is unable to overfill SLX pupil

  Similar size of MIC5 optics to SLX pupil causes beams to vignette as a function of field angle

- Pupil Underfill Baffle simplifies radiometric analysis (pupil overlap correction factor) at the loss of some SNR
Calibration Equipment
(Collimated Blackbody Configuration)

- Collimator with external blackbody
  - Steering mirror to cover sensor FOV
  - Pinhole at MIC5 focus (point source - irradiance)
  - Large aperture at MIC5 focus (extended source - radiance)
Calibration Equipment (Small-Signal Linearity Configuration)

- Internal extended source with Jones source
  - Small signal (constant amplitude on/off Jones source)
  - Large signal (variable extended source temperature)
Calibration Equipment
(Relative Spectral Response Configuration)

- External step-scan interferometer with collimator
  - Steering mirror to cover sensor FOV
  - Large aperture at MIC5 focus (covers many pixels)
  - Sensor records interferogram
Ground Calibration Test Flow

- **Pump/Bakeout/Cool**
- **Focus Verification**
- **Pixel-to-angle mapping, (distortion map)**
- **PRF, IFOV, MTF, array co-alignment**
- **Near Angle Scatter**
- **Closely Spaced Objects**
- **Irradiance Responsivity, Repeatability**

**Daily Benchmark Measurements Throughout**

- **Radiance Responsivity, Repeatability**
- **Integration Time Normalization**
- **Saturation Response**
- **Polarization Response**
- **Response Linearity**
- **In-Band RSR**
- **Out-of-Band RSR**

**Daily Benchmark Measurements Throughout**

- **Radiance Responsivity, Repeatability**
- **Nonuniformity Correction (NUC)**
- **ICU Characterization**

**Shaded blocks indicate low priority tests that will be conducted only if time is available**

**MIC5 Partial-Aperture**
- **Simulated Point-Source Configuration**

**MIC5 Partial-Aperture**
- **Large Spot Extended Source Configuration**

**THOR Full-Aperture**
- **Extended Source Configuration**
Ground Calibration Measurements Detail

• Single Point Source (focus, PRF, IFOV, MTF, irradiance)
  – Single pinhole at MIC5 focus with external blackbody
  – Collect pinhole images at positions spanning FOV (as allowed by schedule and budget)

• Point Source Grid (distortion map, array coalignment)
  – Pinhole array at MIC5 focus with external blackbody
  – Collect overlapping grid patterns covering FOV
Ground Calibration Measurements Detail

• Partial-field extended source (radiance, RSR)
  – Large aperture at MIC5 focus with external blackbody
  – Collect aperture images covering many pixels at positions spanning FOV

• Full-field extended source (NUC, radiance, small-signal linearity)
  – Honeycomb thermal radiator inside THOR chamber overfills pupil and FOV
  – Collect full-frame images
Ground Relative Uncertainty Budget

- **Irradiance Measurement Accuracy (IMA)**
  - 0.5·IMA Irradiance Measurement Precision (IMP)
    - 0.3·IMA Point Source Uniformity Correction over the FOV Unc.
      - Response drift
      - Self-emission drift
    - 0.4·IMA Repeatability (long-term)
  - 0.9·IMA Peak Irradiance Responsivity (PIRR) Uncertainty Over OPL OPS Temperature Range
    - 0.8·IMA PIRR Uncertainty @ Nominal OPL Temperature
      - 0.3·IMA Measurement Uncertainties
      - 0.6·IMA Irradiance Source Uncertainty
      - 0.4·IMA Irradiance Uncertainty due to RSR Uncertainty
    - 0.2·IMA Variation of PIRR with OPL Temperature

Expanded on following slide
Ground Uncertainty Budget Detail

**Measurement Uncertainties**

- 0.1·IMA Std. error of irradiance responsivity coefficient
- 0.2·IMA Irradiance uncertainty due to linearity correction
- 0.1·IMA Irradiance uncertainty due to FPA NUC
- 0.1·IMA Irradiance uncertainty due to gain normalization
- 0.1·IMA Irradiance uncertainty due to background subtraction

**Irradiance Source Uncertainty**

- 0.3·IMA Pupil Overlap Correction Uncertainty (direct measurement)
- 0.5·IMA Collimator Point Source Uncertainty
  - 0.3·IMA Ext BB radiance Unc.
  - 0.2·IMA External relay optics transmittance unc.
  - 0.2·IMA Interface optics transmittance unc.
  - 0.1·IMA Lens contamination unc.
- 0.1·IMA Collimator source port window transmittance unc.
- 0.2·IMA Collimator ND filter transmittance unc.
- 0.2·IMA Collimator reflectance unc.
- 0.1·IMA Collimator diffraction unc.
- 0.2·IMA Aperture area @ LN2 unc.
- 0.1·IMA Collimator focal length @ LN2 unc.
- 0.1·IMA Polarization unc.

**Irradiance Uncertainty due to RSR Uncertainty**

- 0.4·IMA In-band RSR uncertainty
- 0.3·IMA Average RSR uncertainty
- 0.2·IMA RSR variation across FPA
- 0.1·IMA RSR variation with temperature

**Out-of-Band RSR Uncertainty**

- 0.2·IMA Variation of PIRR with OPL Temperature

**Variation of PIRR with OPL Temperature**

- Cryocooler interface temperature stability
- Payload interface temperature stability
- Electronics temperature stability
- Baffle temperature stability
- Telescope temperature stability
- Cold box temperature stability
- FPA temperature stability
## On-Orbit Calibration Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Correction Method</th>
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<tbody>
<tr>
<td>Irradiance Responsivity &amp; Uniformity</td>
<td>Standard reference star</td>
</tr>
<tr>
<td>Pixel-to-object-space angle</td>
<td>Star field</td>
</tr>
<tr>
<td>Point Response Function, IFOV</td>
<td>Standard reference star</td>
</tr>
<tr>
<td>Array &amp; boresight-to-spacecraft coalignment</td>
<td>Star field</td>
</tr>
<tr>
<td>Radiance Responsivity</td>
<td>ICU, cross check to reference stars</td>
</tr>
<tr>
<td>Bad pixel map</td>
<td>All available data</td>
</tr>
<tr>
<td>Non-Uniformity Correction</td>
<td>ICU, Earth-limb &amp; lunar observations</td>
</tr>
<tr>
<td>Responsivity trend correction</td>
<td>ICU, cross check to reference stars</td>
</tr>
<tr>
<td>Dark background</td>
<td>Cold shutter, deep space look</td>
</tr>
<tr>
<td>Spectral Response</td>
<td>On-orbit update not possible</td>
</tr>
<tr>
<td>Polarization Sensivity</td>
<td>On-orbit update not possible</td>
</tr>
<tr>
<td>ICU characterization</td>
<td>Cross check to standard reference stars</td>
</tr>
<tr>
<td>Non-linearity correction</td>
<td>Possibly ICU test, questionable</td>
</tr>
</tbody>
</table>
On Orbit Relative Uncertainty Budget

IMA Irradiance Measurement Accuracy (IMA) On-Orbit

0.5-IMA Irradiance Measurement Precision (IMP)

0.3-IMA Updates to Point Source Uniformity Correction Uncertainty (2)
0.3-IMA Updates to Repeatability (2)

Spacecraft Pointing Jitter
Sensor Noise / Repeatability
Cosmic rays
Zodiacal or earth limb background effects
Point-Source Extraction (PSE) Algorithm Processing Effects
Contamination / Ice Buildup on FPAs

0.9-IMA Peak Irradiance Responsivity (PIRR) Uncertainty Over OPL OPS Temperature Range (2)

0.8-IMA On-Orbit PIRR Uncertainty @ Nominal OPL Temperature (2)

0.3-IMA Star Irradiance Measurement Uncertainties (2)
0.3-IMA Irradiance Uncertainty due to RSR Uncertainty (1)
0.2-IMA On-Orbit Variation of PIRR with OPL Temperature (2)

(1) Gound Measurements
(2) On-Orbit Measurements

Expanded on following slide
On Orbit Uncertainty Budget Detail

0.3·IMA Star Irradiance Measurement Uncertainties (2)
- 0.1·IMA Standard error of irradiance responsivity coefficient (1,2)
- 0.1·IMA Irradiance uncertainty due to spacecraft pointing jitter (2)
- 0.1·IMA Irradiance uncertainty due to algorithm effects (2)
- 0.2·IMA Irradiance uncertainty due to linearity correction (1,2)
- 0.1·IMA Irradiance uncertainty due to FPA NUC (1,2)
- 0.1·IMA Irradiance uncertainty due to gain normalization (1,2)
- 0.1·IMA Irradiance uncertainty due to background subtraction (1,2)

0.3·IMA Irradiance Uncertainty due to RSR Uncertainty (1)

0.2·IMA On-Orbit Variation of PIRR with OPL Temperature (2)
- Cryocooler interface temperature stability
- Payload interface temperature stability
- Electronics temperature stability
- Baffle temperature stability
- Telescope temperature stability
- Cold box temperature stability
- FPA temperature stability
Summary

• Viable calibration plan established using existing equipment
  – Partial-pupil approach minimizes equipment interaction and simplifies analysis
  – Additional uncertainty introduced by partial-pupil approach addressed in uncertainty budget

• Highest priority ground calibration measurements identified and included in plan
  – Ground data collection iteration and parameter coverage minimized to limit data volume and test schedule

• Uncertainty budgets identify interactions and effects considered in calibration planning
  – Ability to address dominant uncertainties limited by equipment, schedule, etc.
  – On-orbit calibration measurements and updates planned