CIRiS: Compact Infrared Radiometer in Space
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Presented by Hansford Cutlip

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Overview of the CIRiS instrument and mission

- The CIRiS instrument is a radiometric thermal infrared imaging instrument integrated to a 6U CubeSat spacecraft
  - Three imaging bands from 7.5 um to 12.7um

- CIRiS will be launched into Low Earth Orbit

- The mission objectives are to:
  1. Demonstrate new technologies for high accuracy, on-orbit calibration compatible with Smallsats
  2. Optimize radiometric calibration for science and operational applications

- The CIRiS instrument is modular, by design, to facilitate specialized implementations
  - The design may be optimized for specific planetary science objectives
Why radiometric imaging in the thermal infrared?

Scientific and operational applications for Earth observations:

1. Land management
   - Land surface temperature – analyze for soil moisture and drought impact
   - Infrared reflectance- analyze for plant health and stress

2. Cloud microphysical effects for weather research
   - Particle radius, thermodynamic phase, optical thickness

3. Validate climate models
   - Local spatial and temporal variations in upwelling radiance, Earth’s radiation imbalance

Applications in planetary science:
   - Surface temperature, plumes, volcanism, tidal heating, ice fracturing and trapped liquid, particle size and compaction, mineralogy, global heat flux
The CIRiS instrument adapts the design of a prior aircraft mounted Ball Aerospace instrument

- **BESST**: Ball Experimental Sea Surface Temperature Radiometer
  - Used primarily as a remote radiometric thermal imager for Sea Surface Temperature
- Operated on aircraft and UAV campaigns
- A radiometric imager with two on-board blackbody sources
The CIRiS guiding design objective is high radiometric accuracy in a compact envelope

- CIRiS design features for high radiometric performance:
  - Symmetric optomechanical structure to minimize calibration transfer offsets
  - High emissivity (>>0.99) carbon nanotube blackbody sources
  - Three calibration scenes
  - End-to-end on-orbit calibration
  - Knowledge and control of instrument component temperatures
The CIRiS scene-select mirror points the field of view in one of four directions

- Three calibration scenes, one science scene
  - One source at on-board ambient temp: 280 K
  - One source at controlled temperature: 280 K to 300 K
  - View to deep space
- Four-fold symmetry minimizes background variation during transfer of calibration to science view
- Calibration is end-to-end: FPA to front aperture
An enabling technology for high calibration performance in a small volume: Carbon Nanotube (CNT) sources

- CNT films on solid substrates are blackbody sources exhibiting very high emissivity in a much smaller volume than conventional cavity black sources.
- CNT sources on 1/8 inch thick substrates enable two sources to fit in the short dimension of a 6U spacecraft (< 10 cm).
- CNT sources are rugged:
  - Measurements on Ball CNT sources show no BRDF or visual change after thermal cycling (-30 C to +50 C).
  - Almost no particulates after vibration testing.
The measured emissivity of CIRiS flight CNT samples is > 0.996

- The high emissivity contributes to high radiometric calibration accuracy in two ways:
  1. Reduces error from emissivity uncertainty
  2. Reduces stray light reflection during calibration (R < 0.0036)

NIST measurements of a CIRiS carbon nanotube source shows reflectance < 0.36%, resulting in emissivity > 0.996
CIRiS on-orbit radiometric accuracy is dependent on ground calibration accuracy

- Pre-launch ground calibration procedure uses a NIST traceable blackbody source.
- The CIRiS on-board CNT sources transfer the ground calibration to space.
- A radiometric uncertainty model is now being developed to predict CIRiS ground and on-orbit calibration accuracy.
- This procedure has been implemented for an aircraft mounted instrument (BESST) from which the CIRiS design was derived. The measured BESST calibration achieves:
  - In-flight accuracy of 0.3 deg C
  - In-flight precision of 0.16 deg C
- CIRiS is expected to improve on this.
The CIRIS thermal subsystem contributes to overall radiometric performance

- Thermal control implemented in 4 separate zones
- Temperature knowledge collected from 12 sensors around instrument for additional background correction if necessary
- Thermal model for representative LEO orbits shows temperature excursions of blackbody sources and FPA housing < +/-0.01 deg C

440 km altitude
Polar orbit,
98 degree inclination
45 degree sun beta angle
The CIRiS detector is an uncooled microbolometer FPA

- No cryocooler or TEC necessary
- Ball has tested microbolometer FPAs from four US vendors
  - FPA characterization performed for CIRiS and the E-THEMIS instrument (Europa mission/ASU) program includes radiation testing

<table>
<thead>
<tr>
<th>CIRiS FPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format</td>
</tr>
<tr>
<td>Pixel Size</td>
</tr>
<tr>
<td>Frame rate</td>
</tr>
<tr>
<td>Noise Equivalent Temp Difference (NEDT)</td>
</tr>
<tr>
<td>Volume</td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>Power</td>
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</table>

- Formats of commercial uncooled microbolometer FPAs now available up to 1024 x 768 format.
The CIRiS optical system is intentionally simple for the CIRiS mission technology demonstration

- A single Ge lens with one aspheric surface for improved off-axis performance
- Low F/# = 1.8 for high SNR
  - Limitation on F/# reduction is 6 U Cubesat envelope
- The CIRiS optomechanical structure is compatible with a range of other optical designs, both refractive and reflective

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>F/#</td>
<td>F/1.8</td>
</tr>
<tr>
<td>Focal Length</td>
<td>36.0 mm</td>
</tr>
<tr>
<td>Entrance Pupil Aperture</td>
<td>20.0 mm</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.00122 radians</td>
</tr>
<tr>
<td>Field of View</td>
<td>12.2 x 9.2 deg</td>
</tr>
<tr>
<td>GSD from 400 km altitude (one pixel)</td>
<td>0.133 km</td>
</tr>
</tbody>
</table>
The butcher block filter geometry combines three dielectric filters

- Images acquired in all three wavelength bands by pushbroom scanning

<table>
<thead>
<tr>
<th>Function</th>
<th>Band (um)</th>
<th>Band pass (um)</th>
<th>Center wavelength (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split window band 1</td>
<td>9.85 to 11.35</td>
<td>1.5</td>
<td>10.6</td>
</tr>
<tr>
<td>(atmospheric correction)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Split window band 2</td>
<td>11.77 to 12.6</td>
<td>0.91</td>
<td>12.23</td>
</tr>
<tr>
<td>High signal for thermal imaging</td>
<td>7.5 to 13.0</td>
<td>5.5</td>
<td>10.25</td>
</tr>
</tbody>
</table>
The CIRiS on-orbit concept of operations will implement variants on a basic calibration procedure

- **Goals of calibration investigation:**
  - Space validation of calibration procedures
  - Optimization of calibration procedures (accuracy, dynamic range, time between cals)

- **Variables to be investigated:**
  1. Calibration views used and their order: 1, 2 or 3
  2. Temperature setting of heated calibration source: 280 K to 300 K
  3. Time between calibrations
  4. Dwell time/averaging time at each calibration
CIRiS is integrated to a 6U CubeSat spacecraft bus

Spacecraft functions include:

- **Guidance, Navigation & Control**
  - 3-axis control, star tracker
- **Power Subsystem**
  - Power distribution, solar panels, battery storage
- **Spacecraft command and Data Handling**
  - Command control, data storage, telemetry
- **RF communication**
  - Globalstar Radio
- **Payload electrical interface**
Extensive testing conducted on CNT source Engineering Design Unit

- Three temperature sensors embedded in EDU behind CNT substrate for nonuniformity measurement
- Flight temperature sensors are space-qualified; procured from another Ball space program
- EDU subjected to thermal cycling in air, thermovac, radiometric imaging
  - Establishing workmanship, thermal performance, factors affecting calibration
CNT calibration source EDU cycled over qualification thermal range to verify workmanship quality

- The fifth cycle went 10°C below the cold qualification temperature

Output of one temperature sensor
CIRiS reduces size, weight and power relative to the aircraft mounted BESST

<table>
<thead>
<tr>
<th></th>
<th>BESST</th>
<th>CIRiS</th>
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<tbody>
<tr>
<td><strong>Weight (kg)</strong></td>
<td>1.35</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Avg power (W)</strong></td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td><strong>Envelope (cm³)</strong></td>
<td>18x19x9</td>
<td>18x19x9</td>
</tr>
<tr>
<td><strong>FOV</strong></td>
<td>29 deg x 22 deg</td>
<td>12.2 deg x 9.2 deg</td>
</tr>
<tr>
<td><strong>FPA Pixel Size</strong></td>
<td>38 um</td>
<td>12 um</td>
</tr>
<tr>
<td><strong>FPA Format</strong></td>
<td>324 x 256</td>
<td>640 x 480</td>
</tr>
<tr>
<td><strong>FPA NEDT</strong></td>
<td>&lt; 65 mK</td>
<td>&lt; 50 mK</td>
</tr>
<tr>
<td><strong>Frame rate</strong></td>
<td>4 Hz</td>
<td>30 Hz/60 Hz</td>
</tr>
<tr>
<td><strong>Band 1</strong></td>
<td>10.2-10.9 um</td>
<td>9.9 – 11.4 um</td>
</tr>
<tr>
<td><strong>Band 2</strong></td>
<td>8.0 - 12.0 um</td>
<td>7.5 -13.0 um</td>
</tr>
<tr>
<td><strong>Band 3</strong></td>
<td>11.3 – 12.1 um</td>
<td>11.8 to 12.7 um</td>
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CIRiS Status as of August 1 2017

- All mechanical parts fabricated
- All procurements completed
- Flight CNT source assemblies fabricated
- Electronics board on-order
- Spacecraft electronics EDU delivered
- Spacecraft in functional test

- Launch anticipated late 2018; waiting to hear date
Acknowledgements

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