CIRiS: Compact Infrared Radiometer in Space

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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
Radiometric imaging in the thermal infrared has applications from Earth science to planetary science

- The upcoming CIRiS mission is most directly applicable to Earth science:
  - Surface temperature, cloud microphysics, soil moisture, vegetation health

Potential applications of a CIRiS instrument adapted to planetary science include:

- High resolution (spatial, temperature) surface temperature imaging:
  - Active thermal phenomena: plumes and plume vents, volcanism
  - Subsurface thermal phenomena: tidal heating, ice fracturing, trapped liquid water

- High accuracy radiometric measurement:
  - Global heat flux
  - Cryogenic surface temperatures and flux

- Thermal inertia
  - Particle size and compaction, block abundance, regolith properties

- Minerology
  - Surface composition, rock forming minerals
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 $< +/\!/-0.01 \text{ deg C}$
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>
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<tbody>
<tr>
<td>Format 640 x 480</td>
</tr>
<tr>
<td>Pixel Size 12 µm</td>
</tr>
<tr>
<td>Frame rate 30 fps or 60 fps</td>
</tr>
<tr>
<td>Noise Equivalent Temp Difference (NEDT) &lt; 50 mK (F/1, 290 K)</td>
</tr>
<tr>
<td>Volume 26 x 26 x 33 mm</td>
</tr>
<tr>
<td>Mass 40 gm</td>
</tr>
<tr>
<td>Power &lt; 1 W @ 30 fps</td>
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- 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>
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CIRiS optical system with one lens

Two lens design
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 (atmospheric correction)</td>
<td>9.85 to 11.35</td>
<td>1.5</td>
<td>10.6</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>
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</table>
The CIRiS Electronics consists of a single board

Electronics functions:
- Power
- Temperature sensor read-out; thermal control
- Camera Interface, command/control, image data acquisition
- Spacecraft Interface
- Memory for image data storage
- Time stamping of image
- Motor Control
- Telemetry

Electronics processing:
- Binning
- Frame averaging
- Frame shift and co-add,
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**
CIRIS’ modular construction facilitates changes in individual assemblies

- Assemblies may be modified independently of remainder of instrument, as required for planetary missions
  - E.g., modify FPA, telescope (refractive, reflective), filter bands
  - Microbolometer FPA detects from 7 um to 50 um (E-THEMIS)
CIbS has a variety of advantages for planetary science

- Small size, weight and power
- Customize calibration to mission: timing, combination of calibration views
- High accuracy in calibration increases value of science data for:
  - Low signals (e.g., thermal mapping of cryogenic surfaces):
  - High dynamic range signals (e.g., limb measurements, hot plumes against cold surroundings, thermal inertia of small bodies)
  - Fundamental quantities (e.g., global heat flux)
Example of CIRiS in a planetary application: investigate asteroid regolith structure via thermal inertia

- Likely asteroid surface temperature ranges from 150 K to 350 K
- Use CIRiS without modification (filter bands, FPA, telescope)
- Sweep FOV across asteroid surface to image in three bands

![Graph of temperature vs longitude for 1999 JU3](image1)

Calculated temperature of 1999 JU3 vs longitude (Koschny, 2009)

![Graph of NEDT vs scene temperature for CIRiS](image2)

Calculated CIRiS temperature sensitivity (Noise Equivalent Difference Temperature- NETD)

GSD = 0.7 met from 1 km range

Swath = 200 met
Extensive thermal cycling and thermal vacuum testing has been conducted on the CNT blackbody source EDU and the FPA

- CNT EDU subjected to thermal cycling, thermovac, radiometric imaging
  - Establishes workmanship, thermal performance, factors affecting calibration
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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