# CIRiS: Compact Infrared Radiometer in Space

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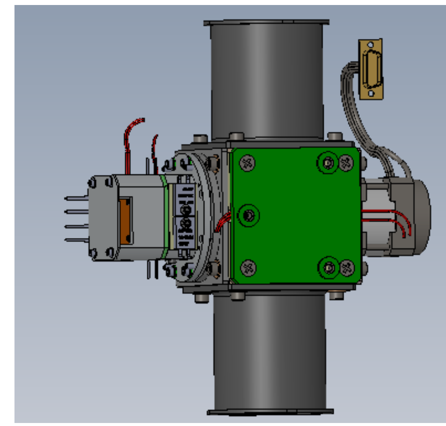
# Overview of the CIRiS instrument and mission

- 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



CIRiS instrument

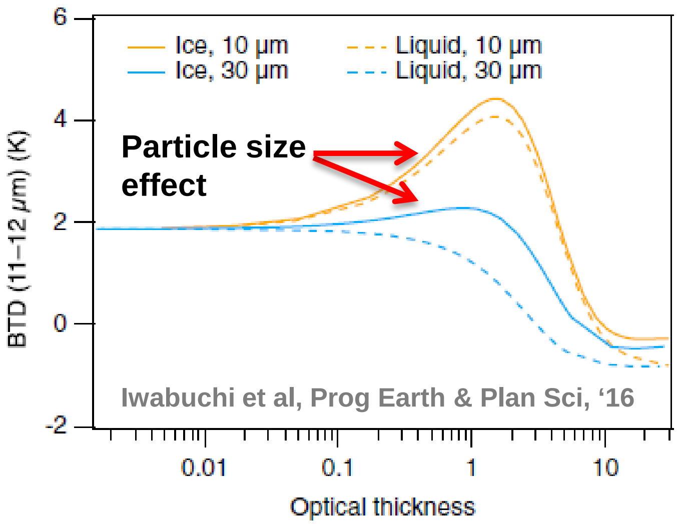
CIRiS spacecraft

# 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



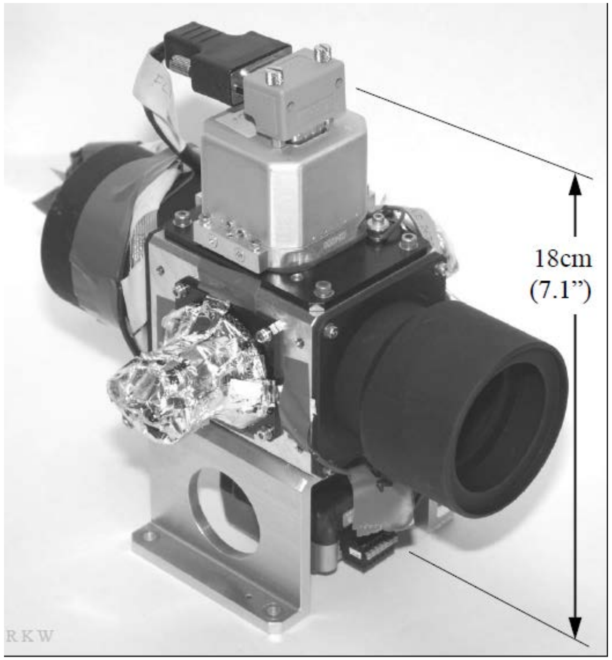

3. Validate climate models
- Local spatial and temporal variations in upwelling radiance, Earth's radiation imbalance

Applications in planetary science:

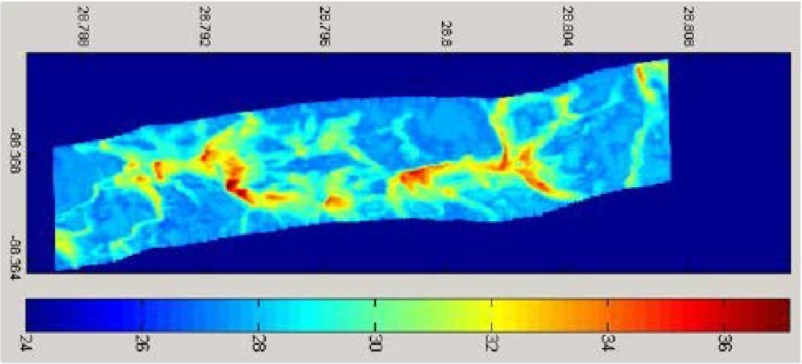
- Surface temperature, plumes, volcanism, tidal heating, ice fracturing and trapped liquid, particle size and compaction, mineralogy, global heat flux

# 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



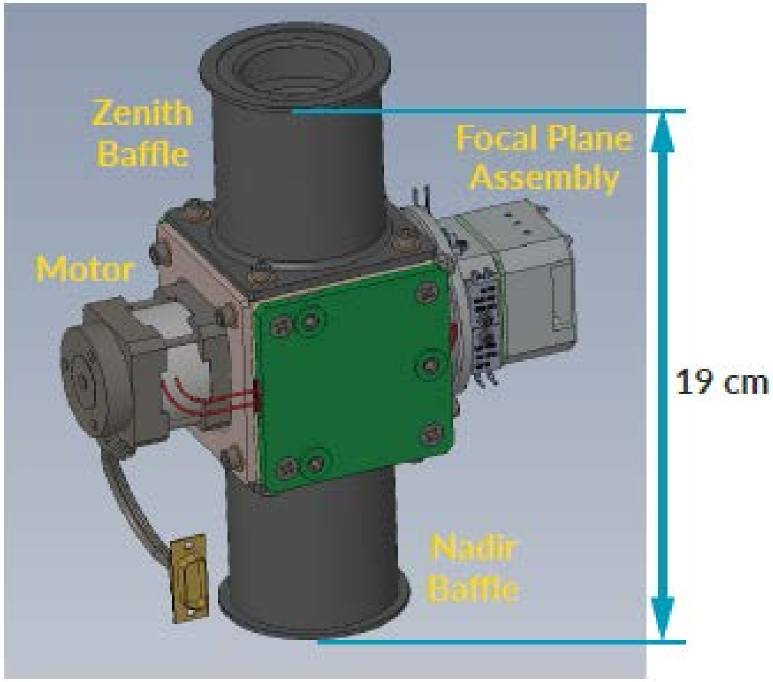

BESST




Temperature image of Gulf of Mexico after oil spill

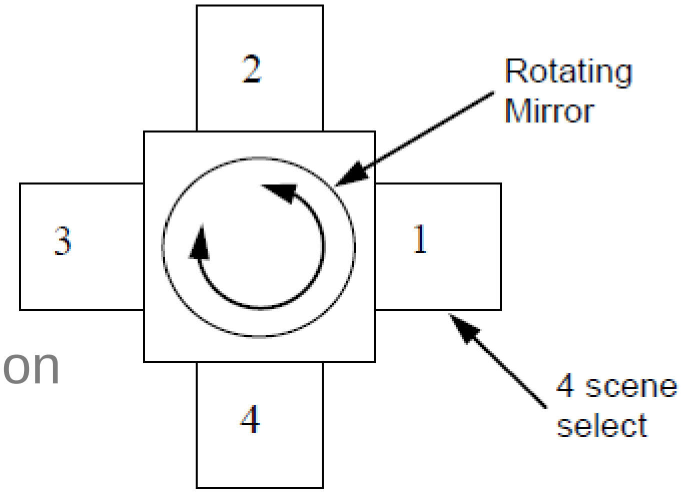
# The CIRiS guiding design objective is high radiometric accuracy in a compact envelope

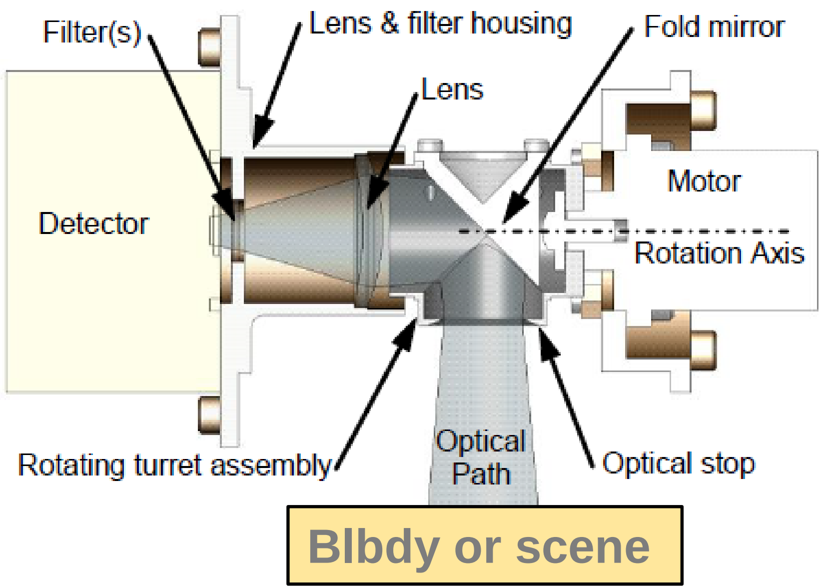
- CIRiS design features for high radiometric performance:
  - Symmetric optomechanical structure to minimize calibration transfer offsets
  - High emissivity (>>0.99) carbon nanotube blackbody sources
  - Three calibration scenes
  - End-to-end on-orbit calibration
  - Knowledge and control of instrument component temperatures



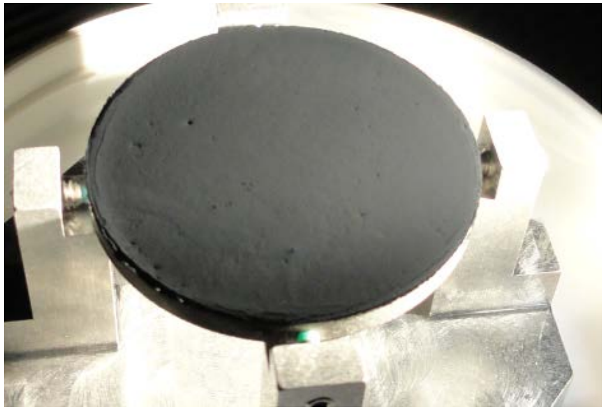
# The CIRiS scene-select mirror points the field of view in one of four directions

- 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

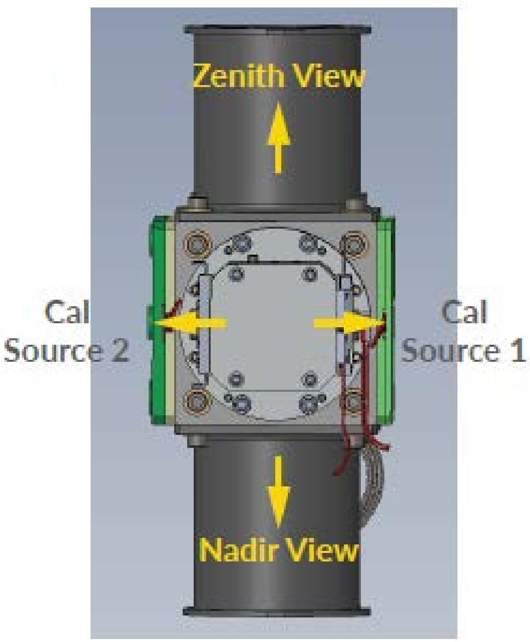


# An enabling technology for high calibration performance in a small volume: Carbon Nanotube (CNT) sources



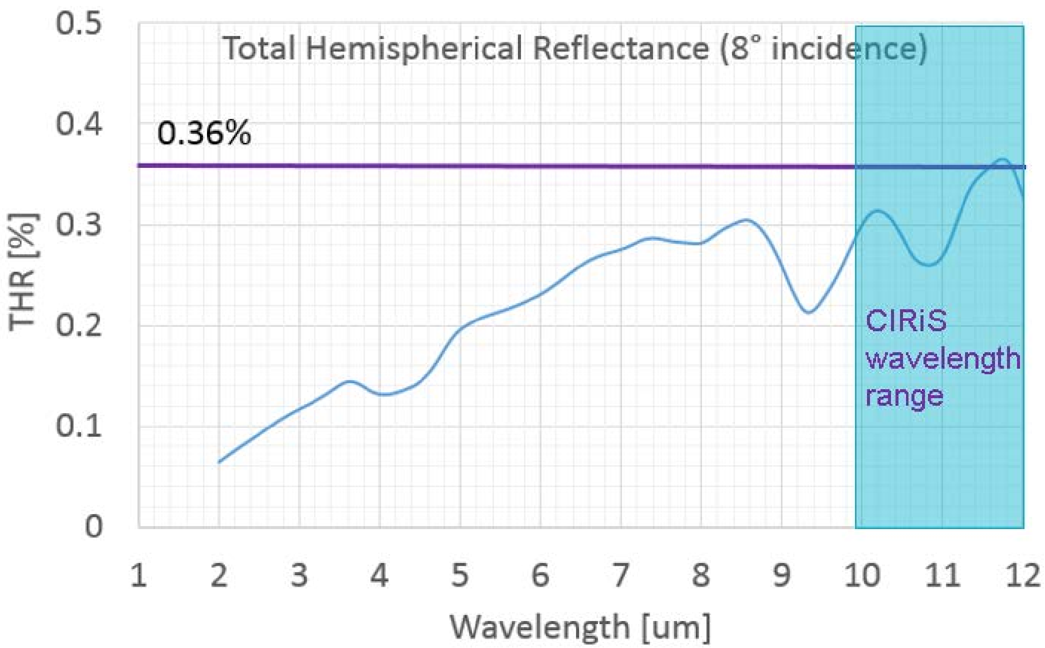
**CIRiS flight sample, 2.5 in diameter**




- CNT films on solid substrates are blackbody sources exhibiting very high emissivity in a much smaller volume then 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**)**

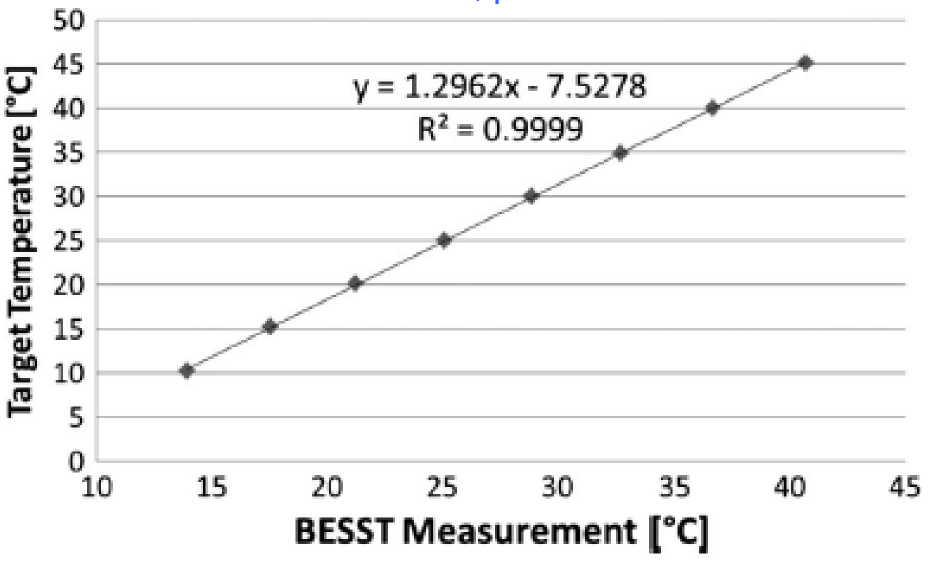



NIST measurements of a CIRiS carbon nanotube source shows reflectance < 0.36%, resulting in emissivity > 0.996

# CIRiS on-orbit radiometric accuracy is dependent on ground calibration accuracy

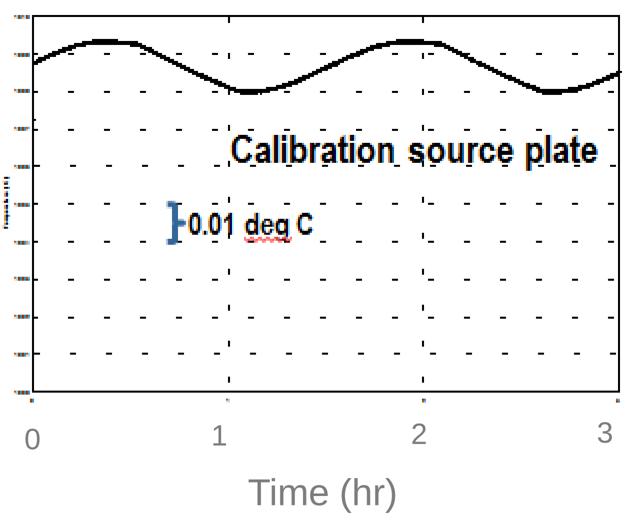
- Pre-launch ground calibration procedure uses a NIST traceable blackbody source
- The CIRiS on-board CNT sources transfer the ground calibration to space
- A radiometric uncertainty model is now being developed to predict CIRiS ground and on-orbit calibration accuracy
- This procedure has been implemented 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

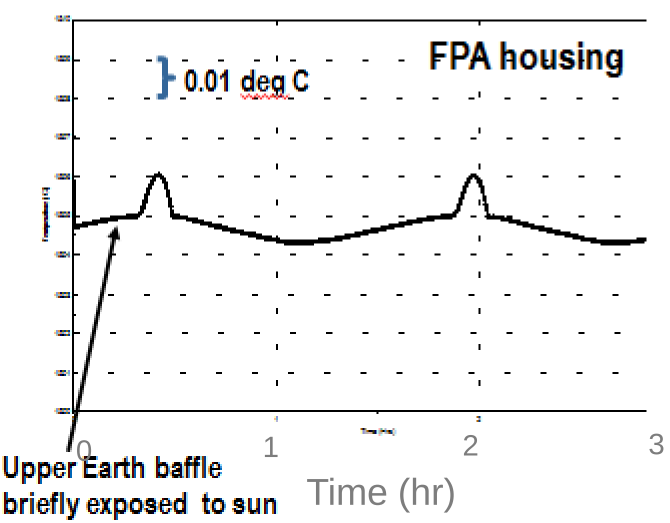
Results of ground calibration on BESST aircraft instrument, precursor to CIRiS

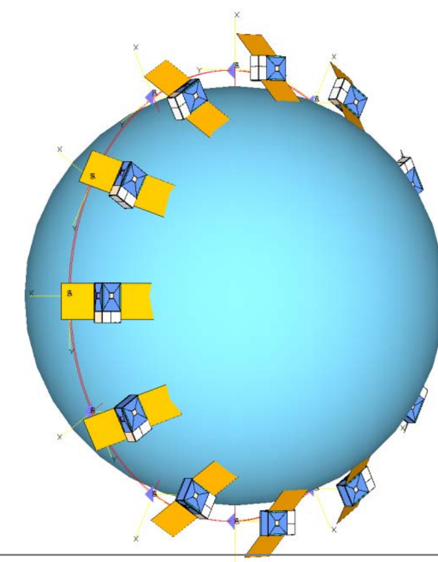


# The CIRIS thermal subsystem contributes to overall radiometric performance

- 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

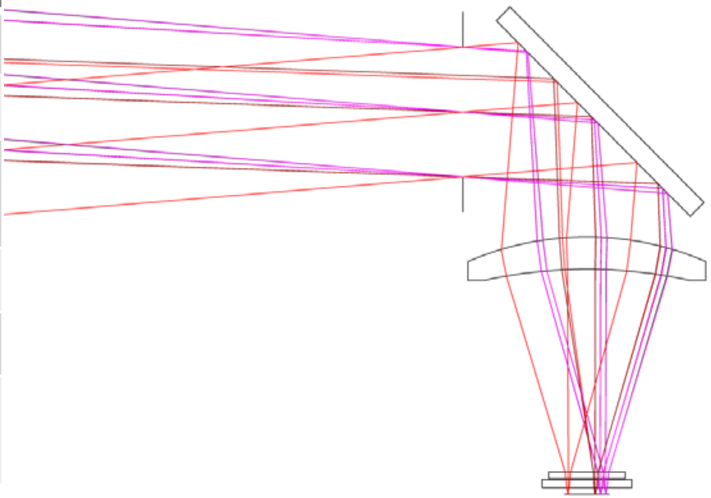
| CIRiS FPA | |
|---|---|
| Format | 640 x 480 |
| Pixel Size | 12 um |
| Frame rate | 30 fps or 60 fps |
| Noise Equivalent Temp Difference (NEDT) | < 50 mK (F/1, 290 K) |
| Volume | 26 x 26 x 33 mm |
| Mass | 40 gm |
| Power | < 1 W @ 30 fps |

- Formats of commercial uncooled microbolometer FPAs now available up to 1024 x 768 format.

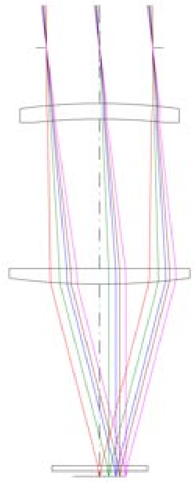
# The CIRiS optical system is intentionally simple for the CIRiS mission technology demonstration

- 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

| Parameter | Value |
|---|---|
| F/# | F/1.8 |
| Focal Length | 36.0 mm |
| Entrance Pupil Aperture | 20.0 mm |
| Angular resolution | 0.00122 radians |
| Field of View | 12.2 x 9.2 deg |
| GSD from 400 km altitude (one pixel) | 0.133 km |



CIRiS optical system with one lens

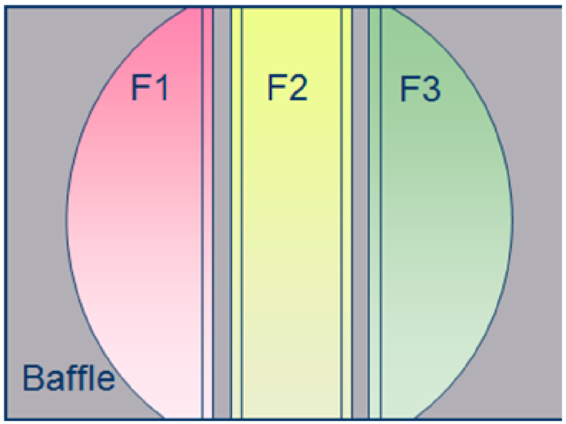


Two lens design

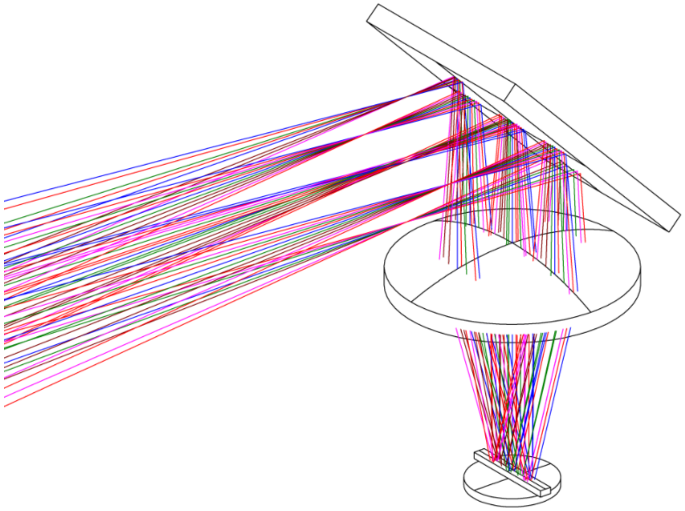
# The butcher block filter geometry combines three dielectric filters

- Images acquired in all three wavelength bands by pushbroom scanning

Scan direction




Butcher block filter assembly



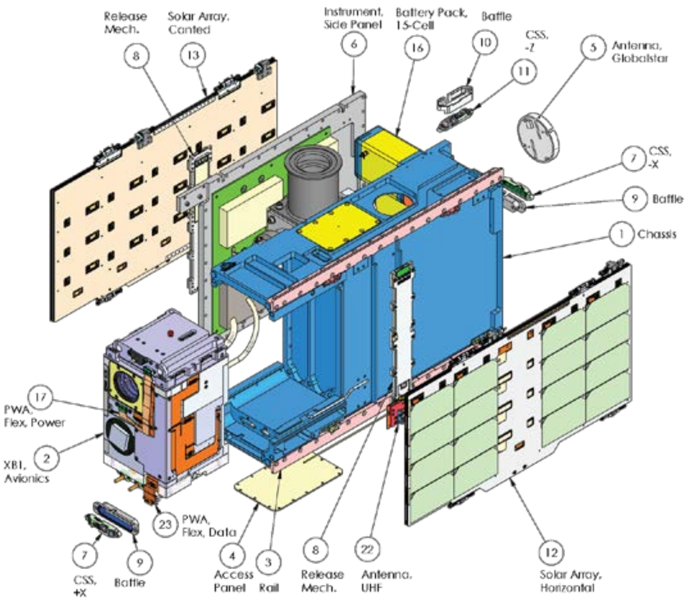
| Function | Band (um) | Band pass (um) | Center wavelength (um) |
|---|---|---|---|
| Split window band 1 (atmospheric correction) | 9.85 to 11.35 | 1.5 | 10.6 |
| Split window band 2 | 11.77 to 12.6 | 0.91 | 12.23 |
| High signal for thermal imaging | 7.5 to 13.0 | 5.5 | 10.25 |

# 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)

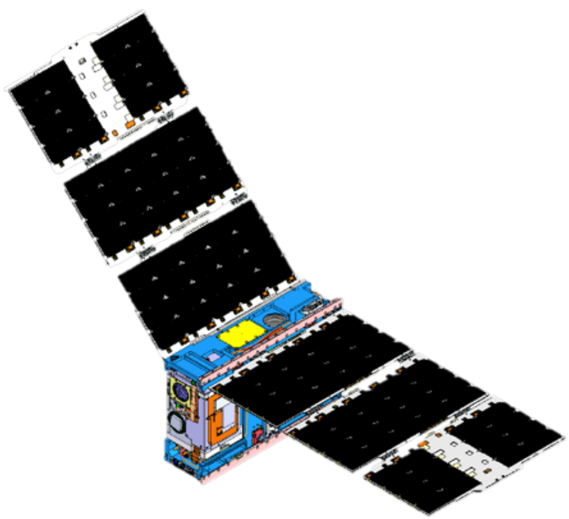
- Variables to be investigated:
  1. Calibration views used and their order: 1,2 or 3
  2. Temperature setting of heated calibration source: 280 K to 300 K
  3. Time between calibrations
  4. Dwell time/averaging time at each calibration

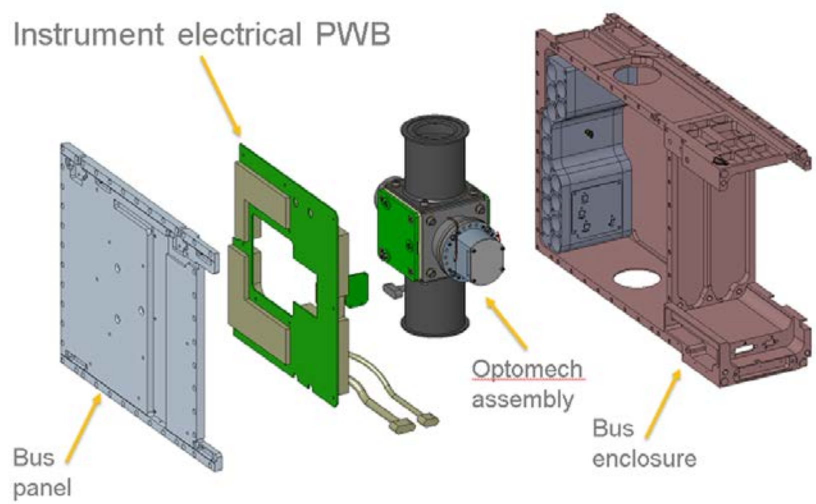
# CIRiS is integrated to a 6U CubeSat spacecraft bus




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

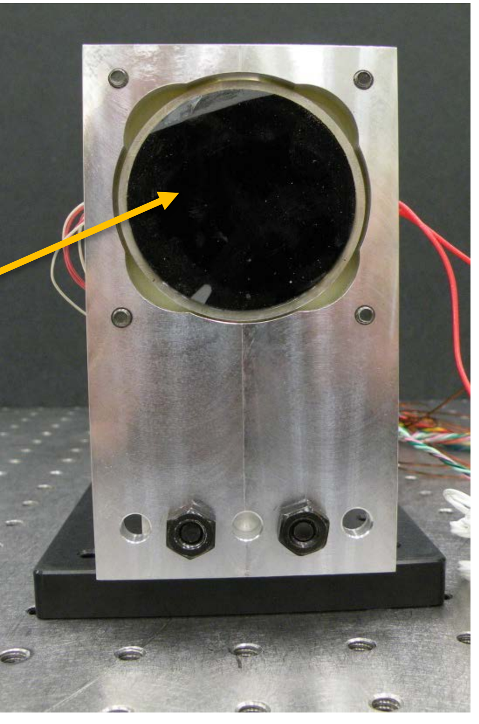




## Extensive testing conducted on CNT source Engineering Design Unit

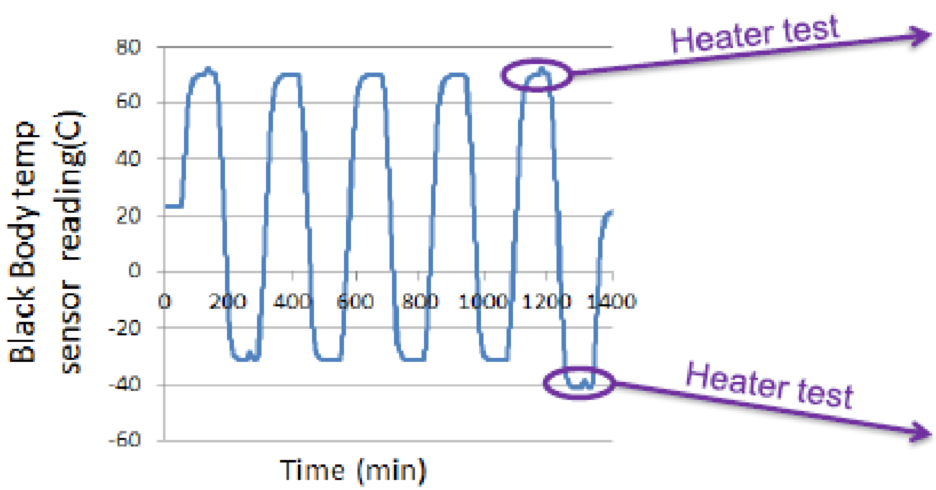
- Three temperature sensors embedded in EDU behind CNT substrate for nonuniformity measurement
- Flight temperature sensors are space-qualified; procured from another Ball space program
- EDU subjected to thermal cycling in air, thermovac, radiometric imaging
  - Establishing workmanship, thermal performance,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

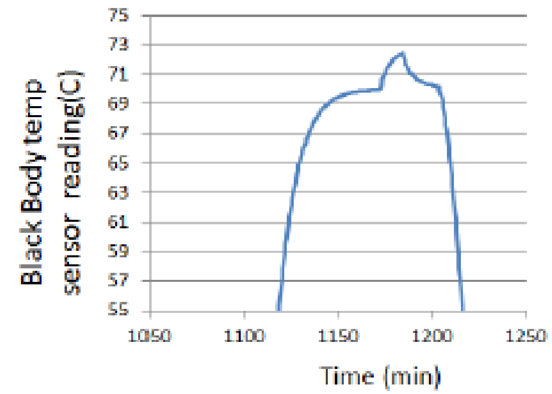
CNT on 1/8 in thick substrate

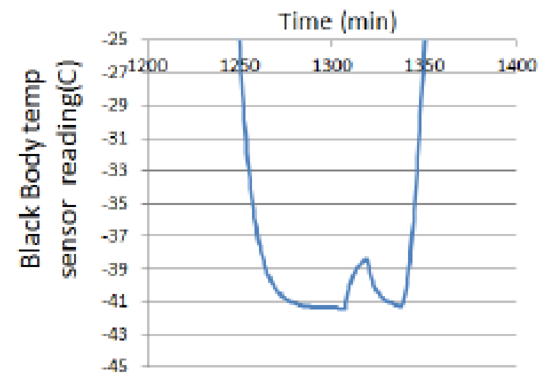


# CNT calibration source EDU cycled over qualification thermal range to verify workmanship quality

- 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

| | BESST | CIRiS |
|---|---|---|
| Weight (kg) | 1.35 | 1.05 |
| Avg power (W) | 20 | 10 |
| Envelope ($cm^3$) | 18x19x9 | 18x19x9 |

| | BESST | CIRiS |
|---|---|---|
| FOV | 29 deg x 22 deg | 12.2 deg x 9.2 deg |
| FPA Pixel Size | 38 um | 12 um |
| FPA Format | 324 x 256 | 640 x 480 |
| FPA NEDT | < 65 mK | < 50 mK |
| Frame rate | 4 Hz | 30 Hz/60 Hz |
| Band 1 | 10.2-10.9 um | 9.9 – 11.4 um |
| Band 2 | 8.0 - 12.0 um | 7.5 -13.0 um |
| Band 3 | 11.3 – 12.1 um | 11.8 to 12.7 um |

# 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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The Ball team:

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