CIRiS: Compact Infrared Radiometer in Space

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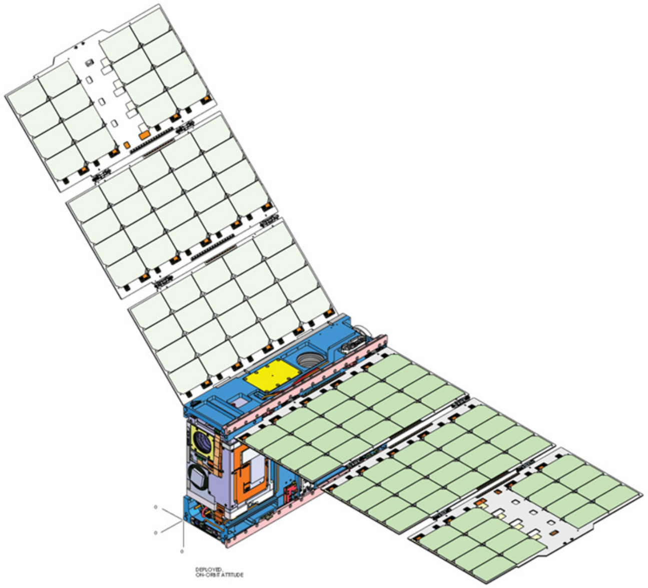
Overview of the CIRiS mission and instrument

- CIRiS is a radiometric thermal infrared (~ 7.5 um to 12.7um) imaging instrument designed to operate on a CubeSat spacecraft
  - Pushbroom imaging in three bands from Low Earth Orbit



- A three year program started in January 2016
  - Launch anticipated in 2018
  - 3 month mission in space
  - Program now in fab and assembly phase

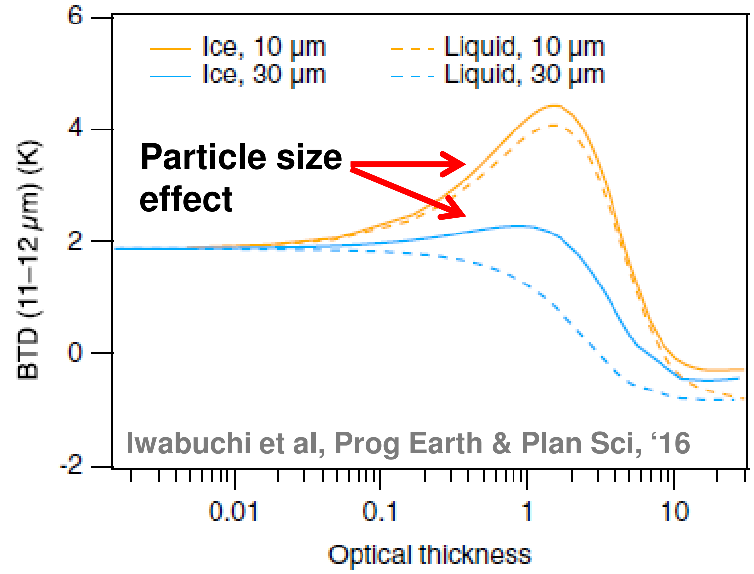
- CubeSat size is 6U

- Objective is technology demonstration with special attention to:
  - New technology for high accuracy, on-orbit calibration
    - Carbon nanotube blackbody sources; uncooled microbolometer FPA
  - Radiometric uncertainty budget validated by measurement
  - Radiometric imaging in three bands

Why radiometric imaging in the thermal infrared?

Scientific and operational applications:

1. Measure optical and physical properties of clouds
- Cloud optical thickness, cloud particle radius, thermodynamic phase
- Measurements contribute to climate model feedback parameters
- Ice cloud properties still not well characterized

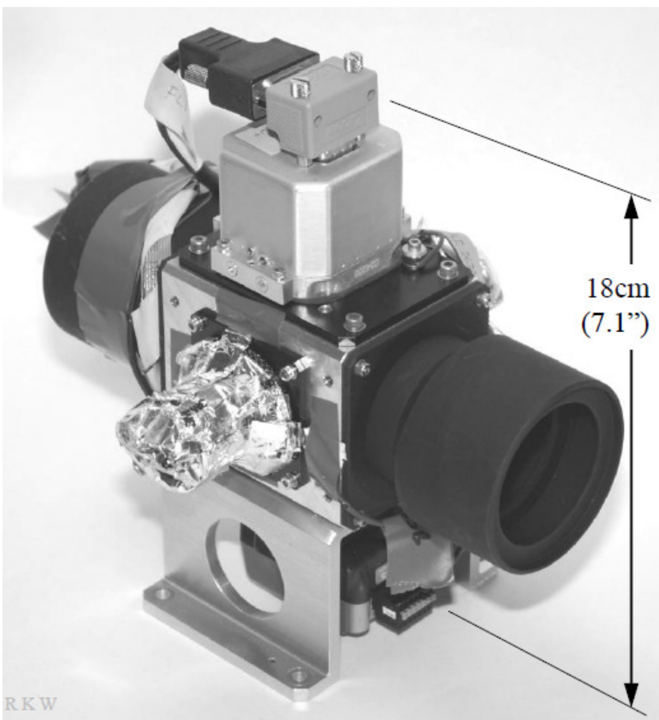


2. Measure Land and Sea Surface temperatures for land management and climate studies
- Evapotranspiration to evaluate drought impact
- Determination of ground water flow on large scales

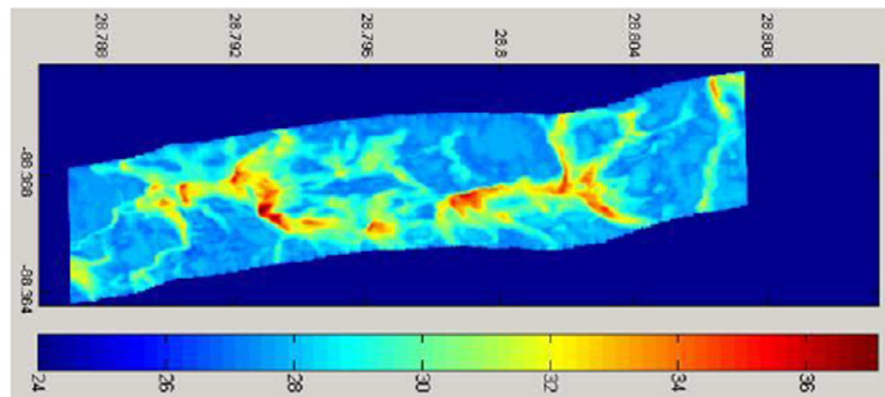
3. Measure earth's radiation budget/validate climate models
- Local spatial and temporal variations in upwelling radiance

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



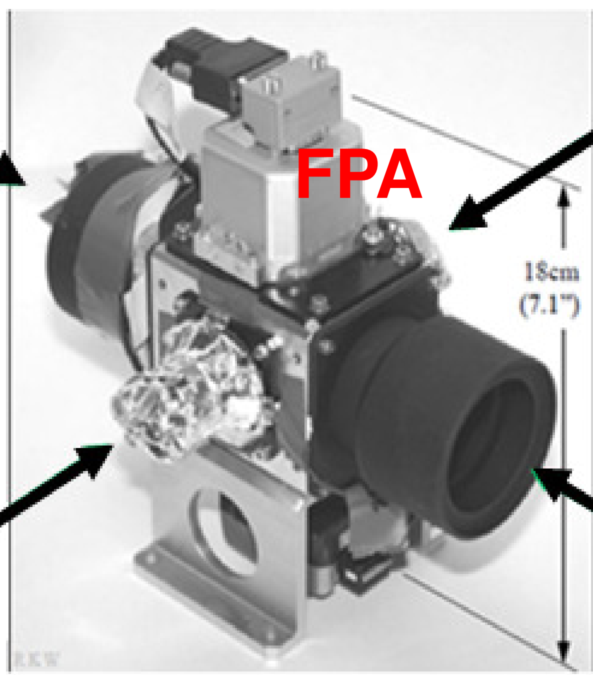
BESST

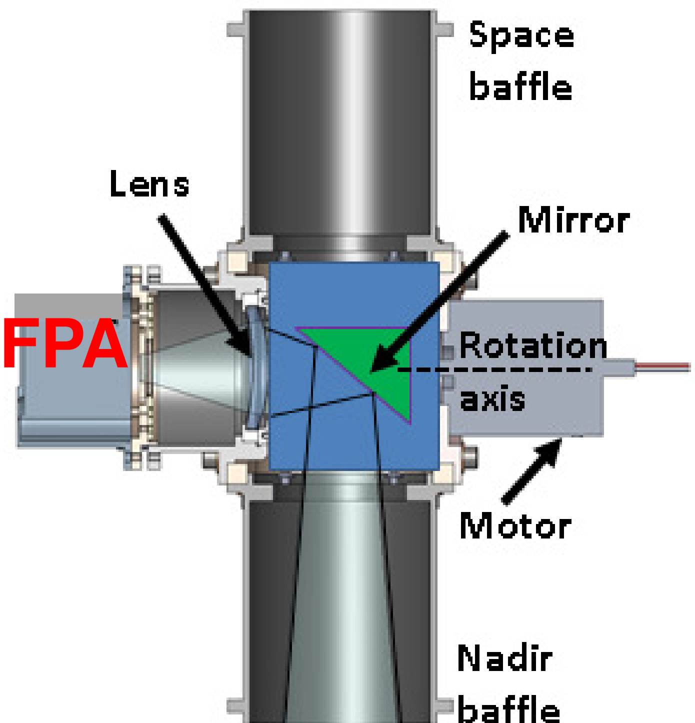


Temperature image of Gulf of Mexico after oil spill

CIRiS adopts the basic structure of the precursor BESST instrument; with additions for space operation

- CIRiS takes from BESST:
  - An uncooled microbolometer FPA
  - A scene-select mirror directing FPA FOV to nadir scene or 3 cal views
  - Two calibration views to on-board blackbody sources
  - A third view to zenith (deep space calibration for CIRiS)
  - Symmetric design maintaining radiometric configuration among four views
  - Modular construction



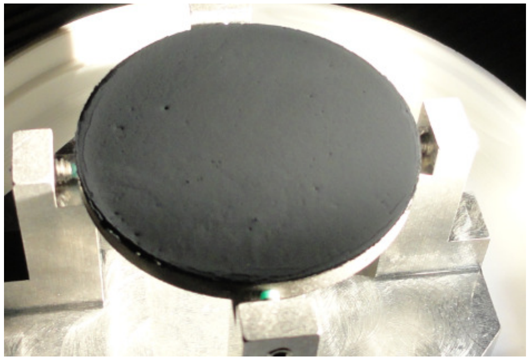


CIRiS (cal sources out of dwg plane)

For space operation CIRiS upgrades and adds to the BESST design

1. Uncooled microbolometer FPA
- Format upgraded from 324 x 256 to 640 x 480
- Pixel size dropped from 38 um to 12 um
- FPA radiation testing (on another program)

2. Two cavity blackbody sources replaced with carbon nanotube (CNT) coated substrates
- High emissivity e> 0.996 in thermal infrared
- Compact 1/8 inch thick substrates



3. Active thermal control and thermal measurement system
- Four controlled temperature zones including one heated cal source
- Twelve temperature sensors throughout instrument and spacecraft

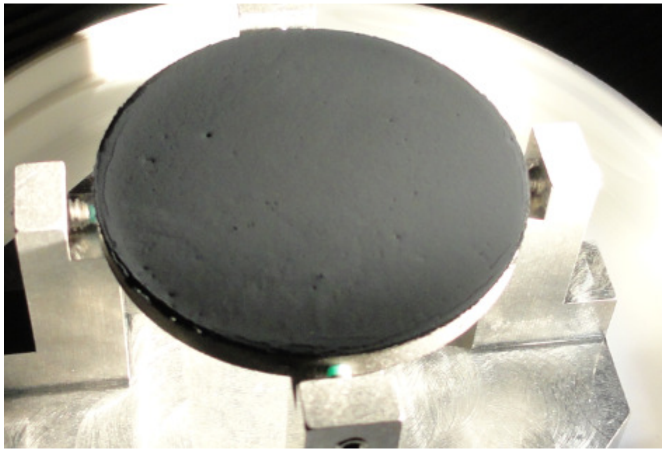
The CIRiS FPA has been chosen after several trades

- Microbolometer FPAs a good choice for thermal IR imaging from a CubeSat
  - No cryocooler; newer commercial versions eliminate stabilizing TEC
  - NEDT < 50 mK adequate for many Earth Science measurements
  - Formats now commercially available up to 1920 x 1200 from US vendors
  - Commercial market and multiple US vendors ensure continued technology advance

- Ball has acquired microbolometer FPAs from four US vendors
  - Extensive characterization for CIRiS and E-THEMIS (Europa mission)
  - Includes radiation testing

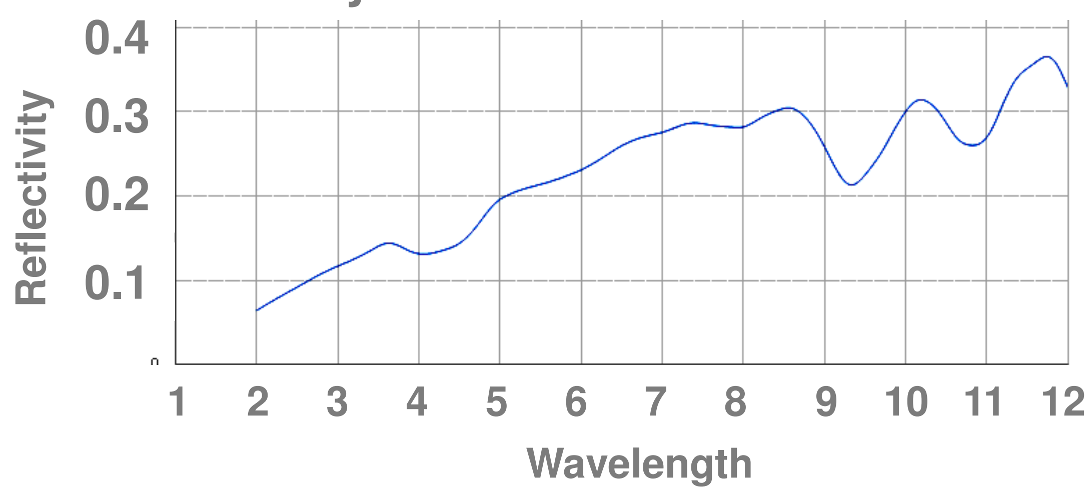
- CIRiS will use a 640 x 480 format, 12 um pixel model, likely with no TEC

Carbon Nanotube (CNT) sources enable high calibration performance in small volume



CIRiS flight sample, 2.5 in diameter

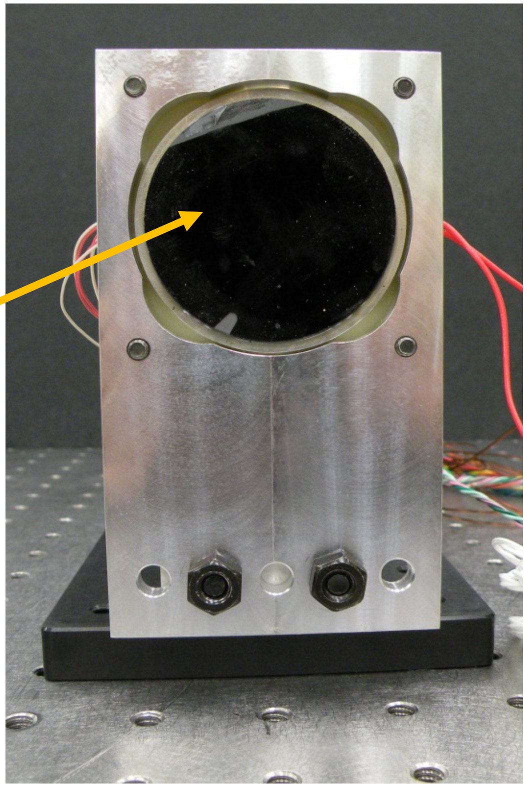
- Two CNT sources on 1/8 inch thick substrate fit in spacecraft 10-cm dimension
- Emissivity >0.996 contributes to high radiometric calibration accuracy two ways:
  1. Reduces error from emissivity uncertainty
  2. Reduces stray light reflection during cal
- NIST measures hemispherical reflectivity on CIRiS flight lot characterization sample
  - Result shows reflectivity < 0.0035; emissivity >0.9965



Extensive testing conducted on CNT source Engineering Design Unit

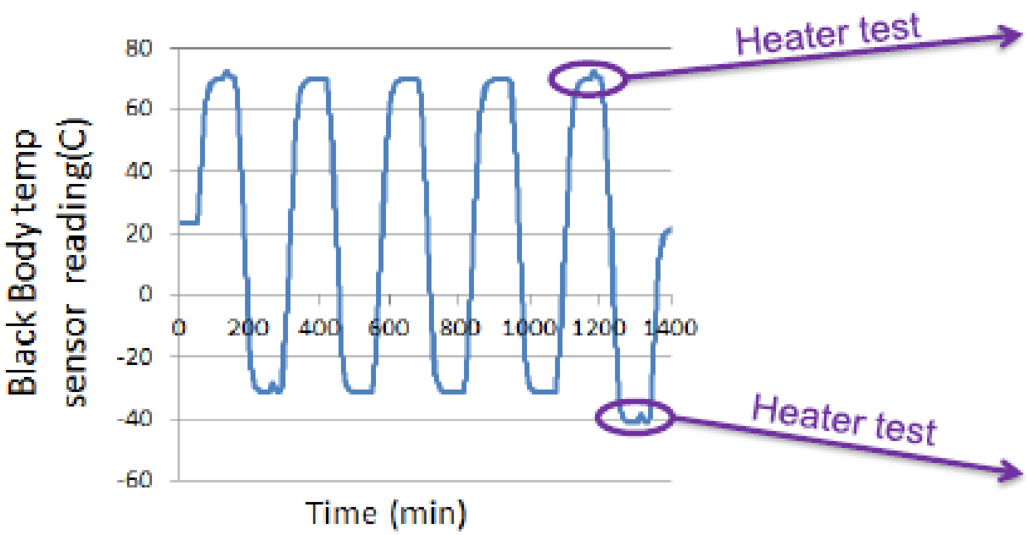
- Three temperature sensors embedded in EDU behind CNT substrate for nonuniformity measurement
- Flight temperature sensors are space-qualified; procured from another Ball space program
- EDU subjected to thermal cycling in air, thermovac, radiometric imaging
  - Establishing workmanship, thermal performance,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

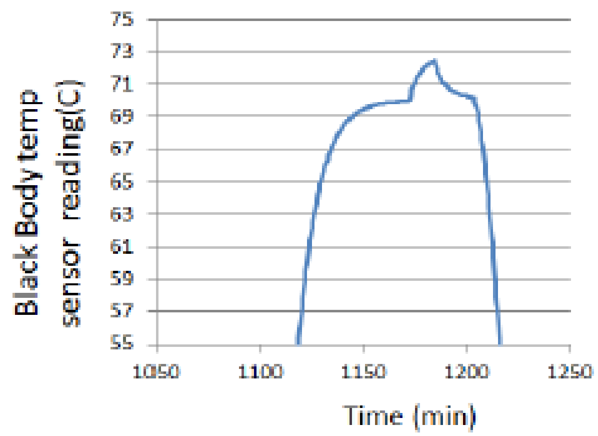
CNT on 1/8 in thick substrate

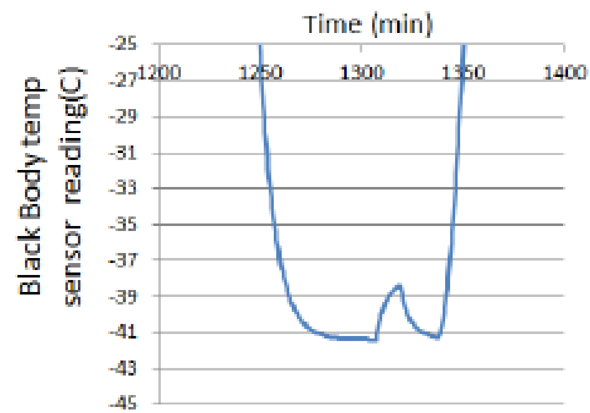


CNT calibration source EDU cycled over qualification thermal range to verify workmanship quality

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



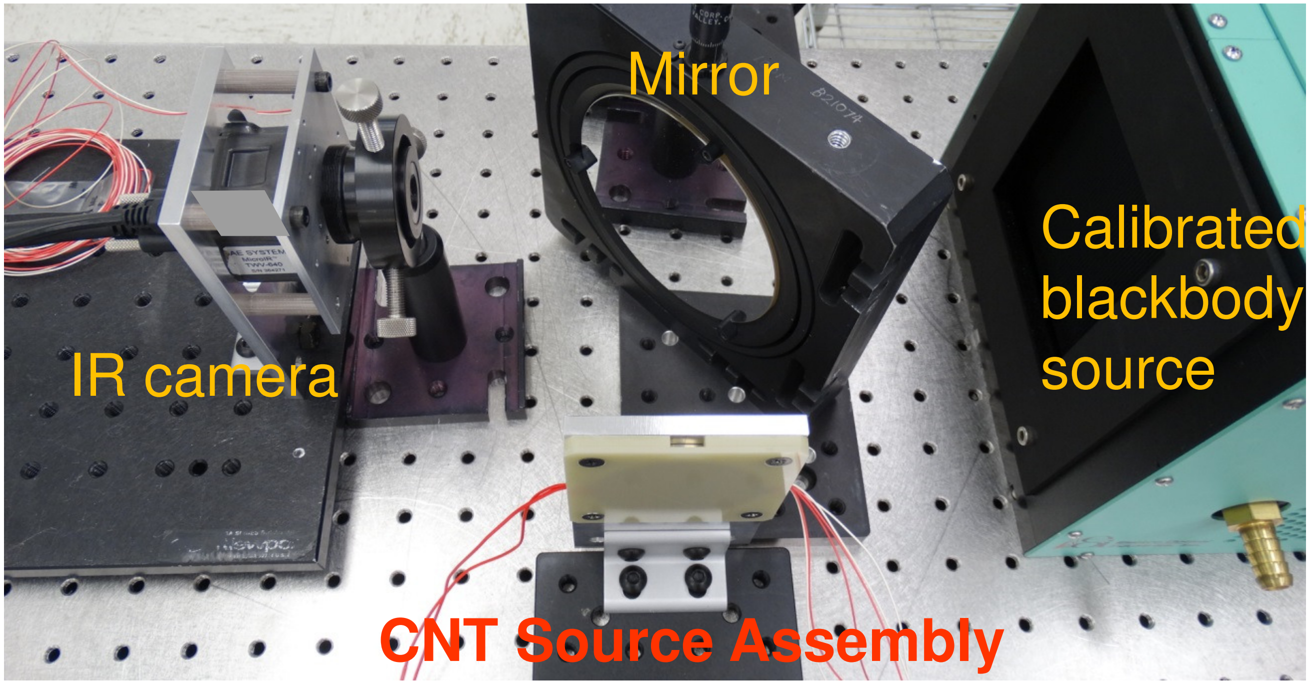




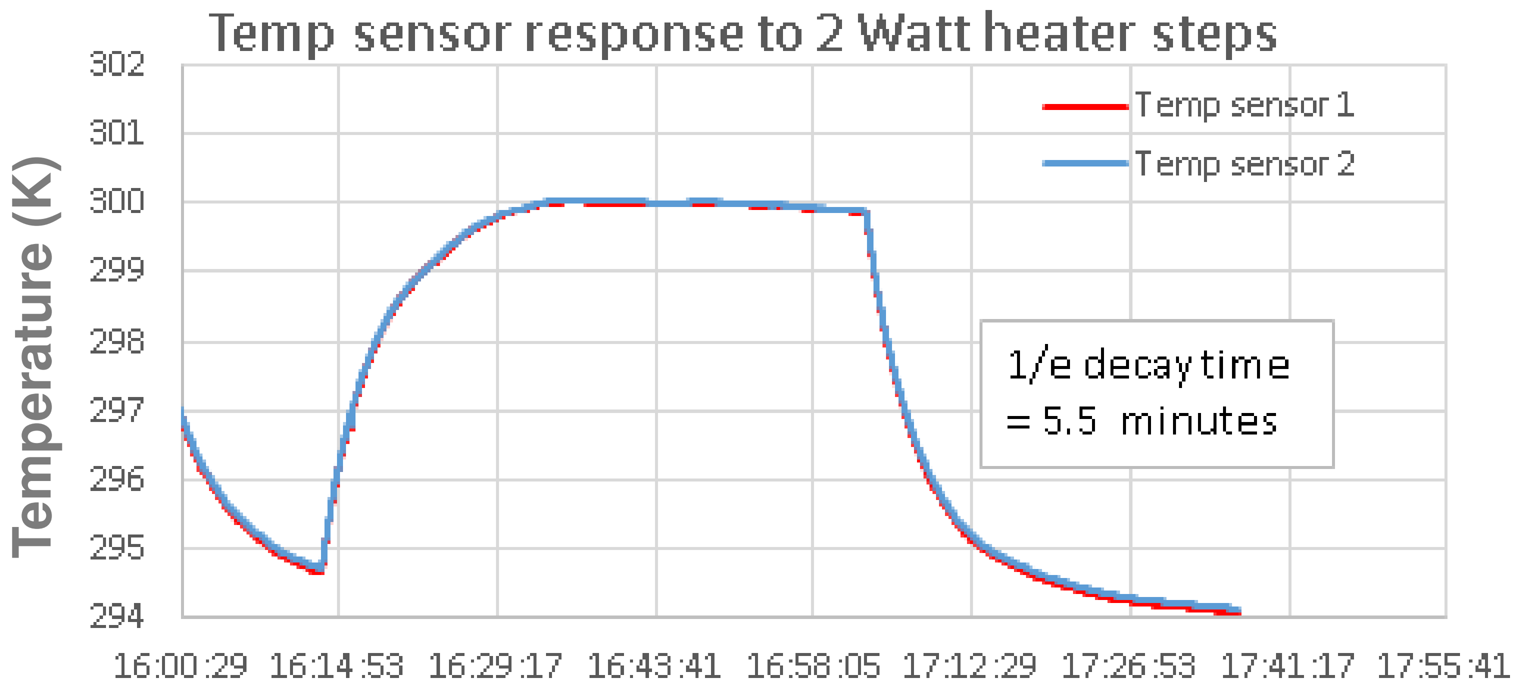
Output of one temperature sensor

Microbolometer FPA tested in thermovac chamber with CNT source

- FPA calibration validated in air prior to moving into thermovac
- Characterization tests in thermovac include:
  - Thermal sensitivities of FPA
  - Thermal uniformity of FPA and CNT source
  - Radiometric uncertainty terms- FPA signal drifts, thermal and non-thermal

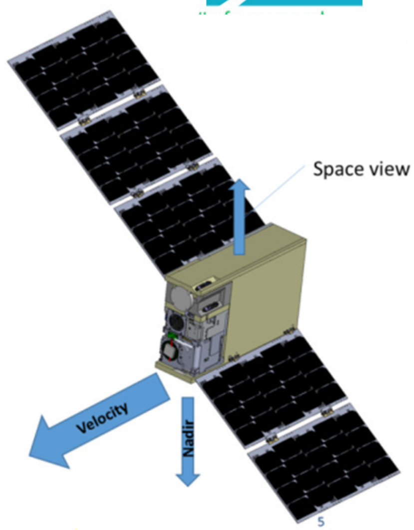


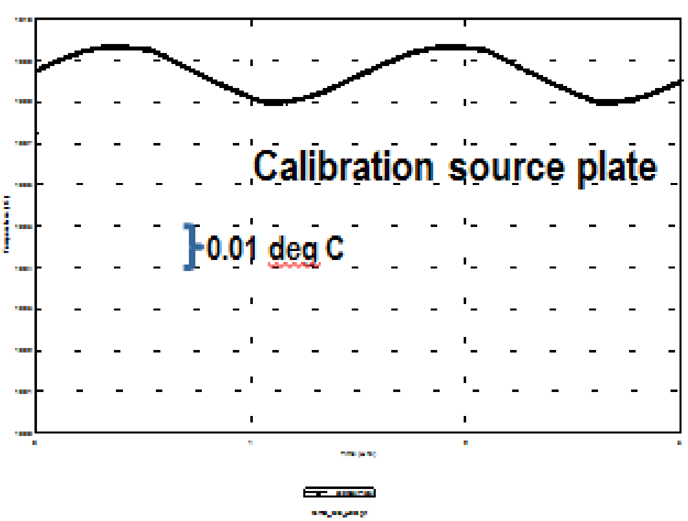
Long thermal time constant designed into CNT calibration assembly to minimize temperature drift during calibration

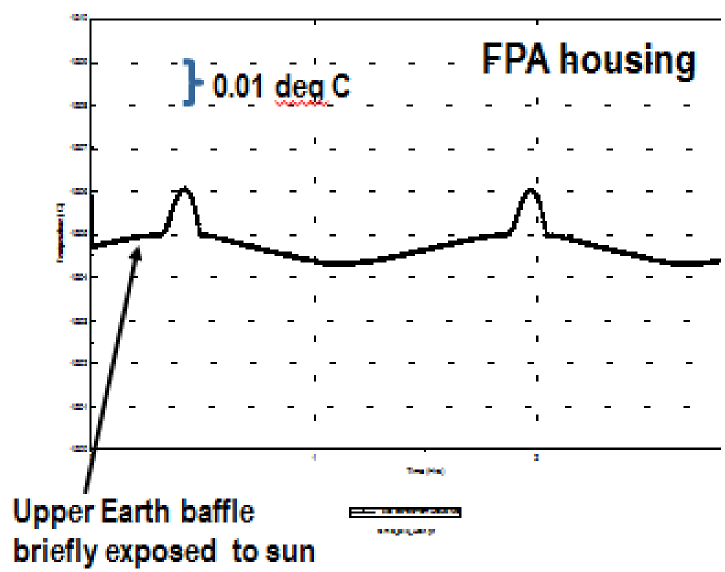


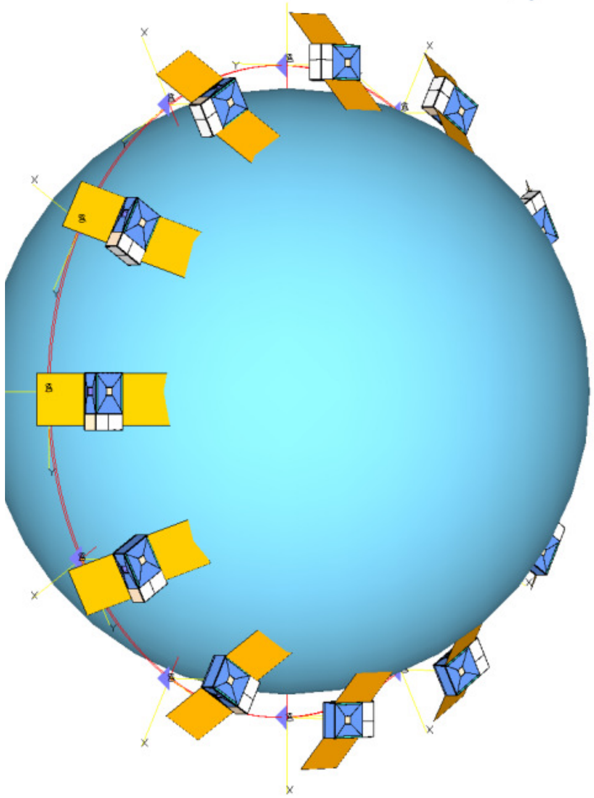
On-orbit thermal models developed for instrument (Ball) & SC bus (BCT)

- Driving requirements are:
  - **< 15 W average payload heater power while collecting data**
  - **FPA baseline temperature in range of +15 º C to +20 º C**
  - **FPA operating temp stability = +/- 1 º C**
  - **Cal Source and FPA housing stabilities +/- 0.1 º C**
- Instrument thermal model example: orbit resulting from ISS launch
  - **440 km altitude**
  - **Polar orbit, 98 degree inclination**
  - **45 degree sun beta angle**



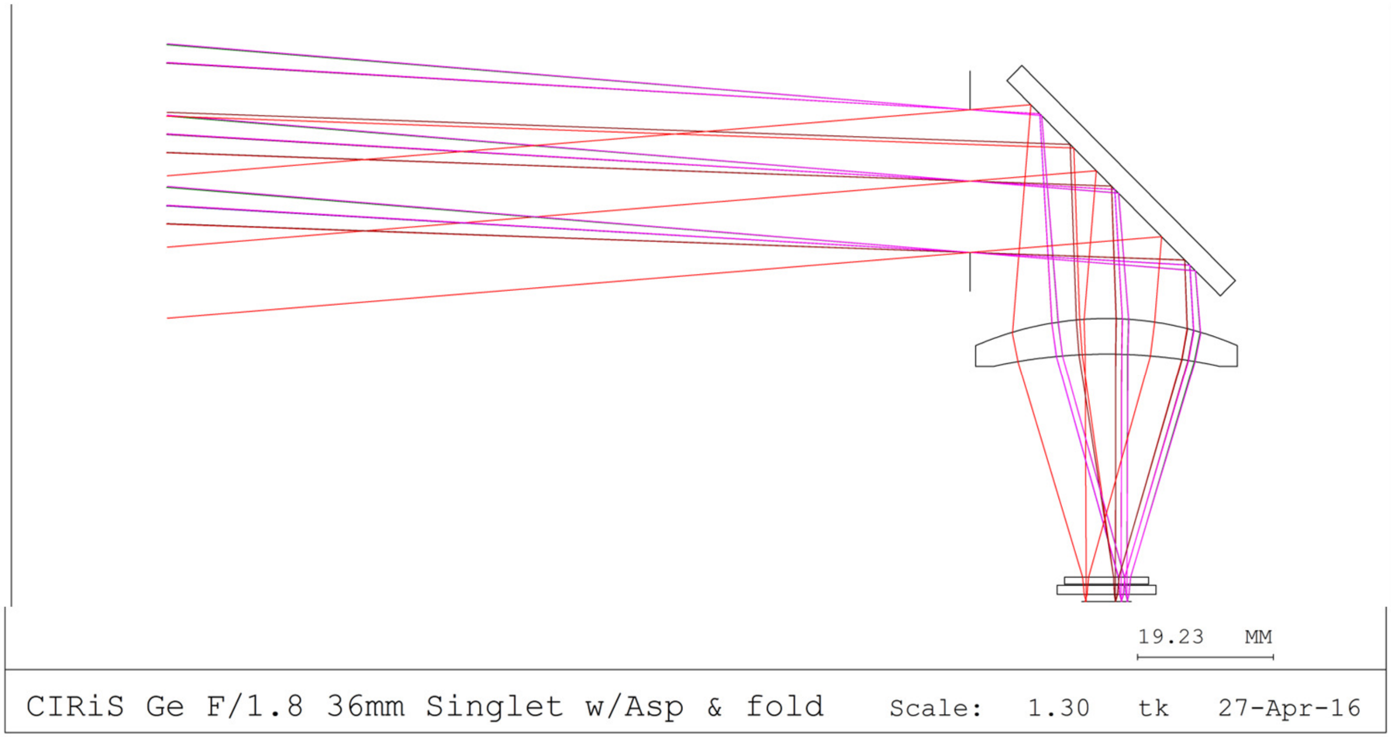






The CIRiS optical system comprises a mirror, single lens and optical filters

- The single lens has one aspheric surface for improved off-axis performance
- F/1.8 design is reduced from BESST (F/2.0) for improved SNR
- Limitation on F/# reduction is volume of 6 U Cubesat



Flight filters for the three CIRiS wavelength bands have been procured

- Filter selection guided by wavelength bands and budget considerations
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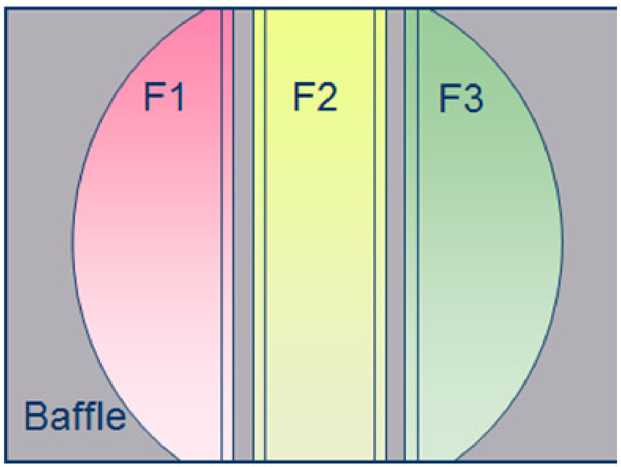
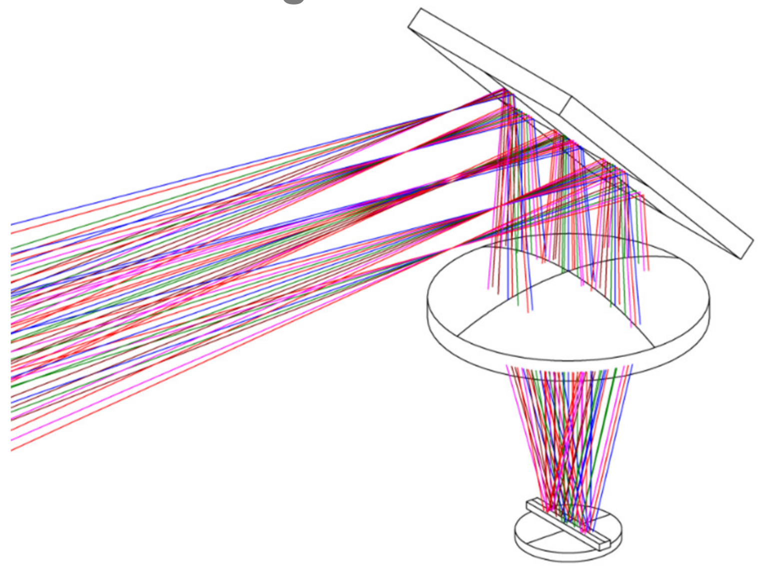
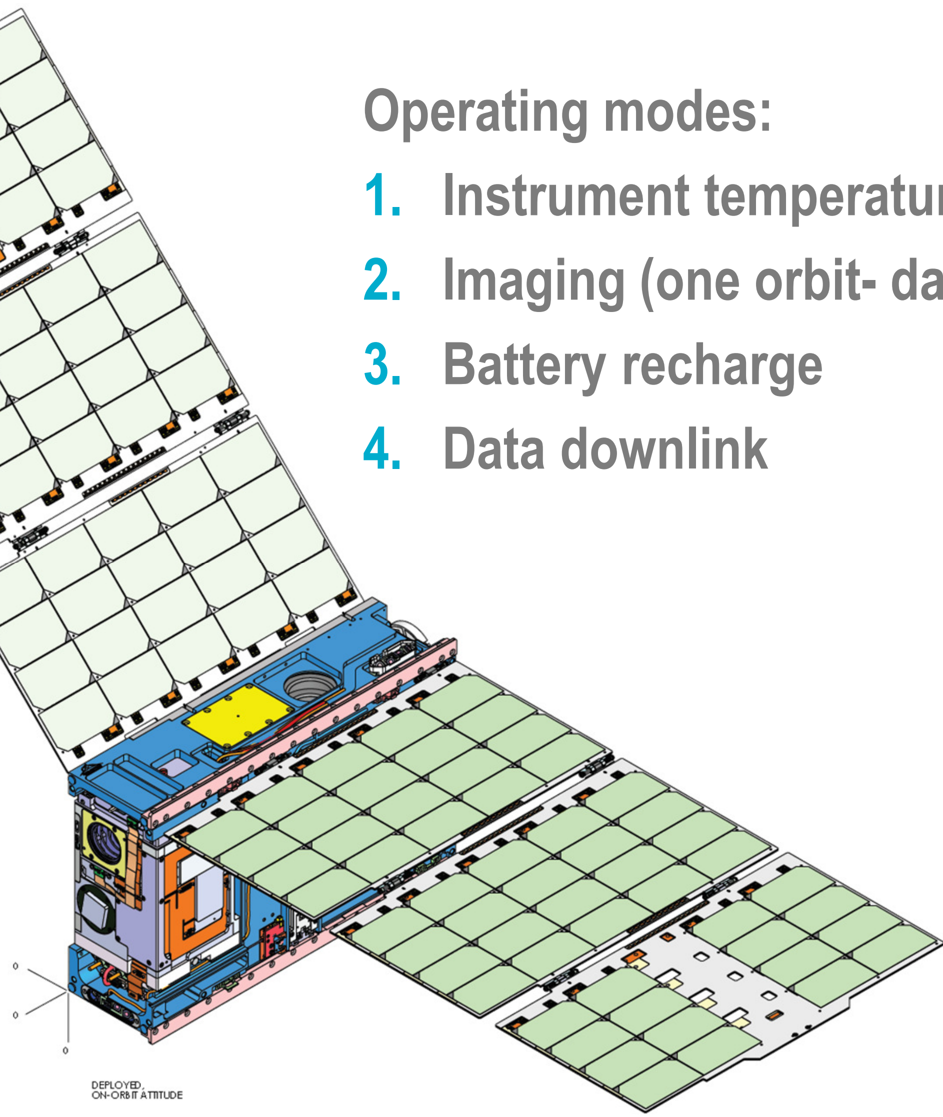




Function	Band (um)	Center wavelength (um)	Band pass (um)
Split window band 1 (atmospheric correction)	9.85 to 11.35	10.6	1.5
Split window band 2	11.77 to 12.6	12.23	0.91
High signal for thermal imaging	7.5 to 13.0	10.25	5.5

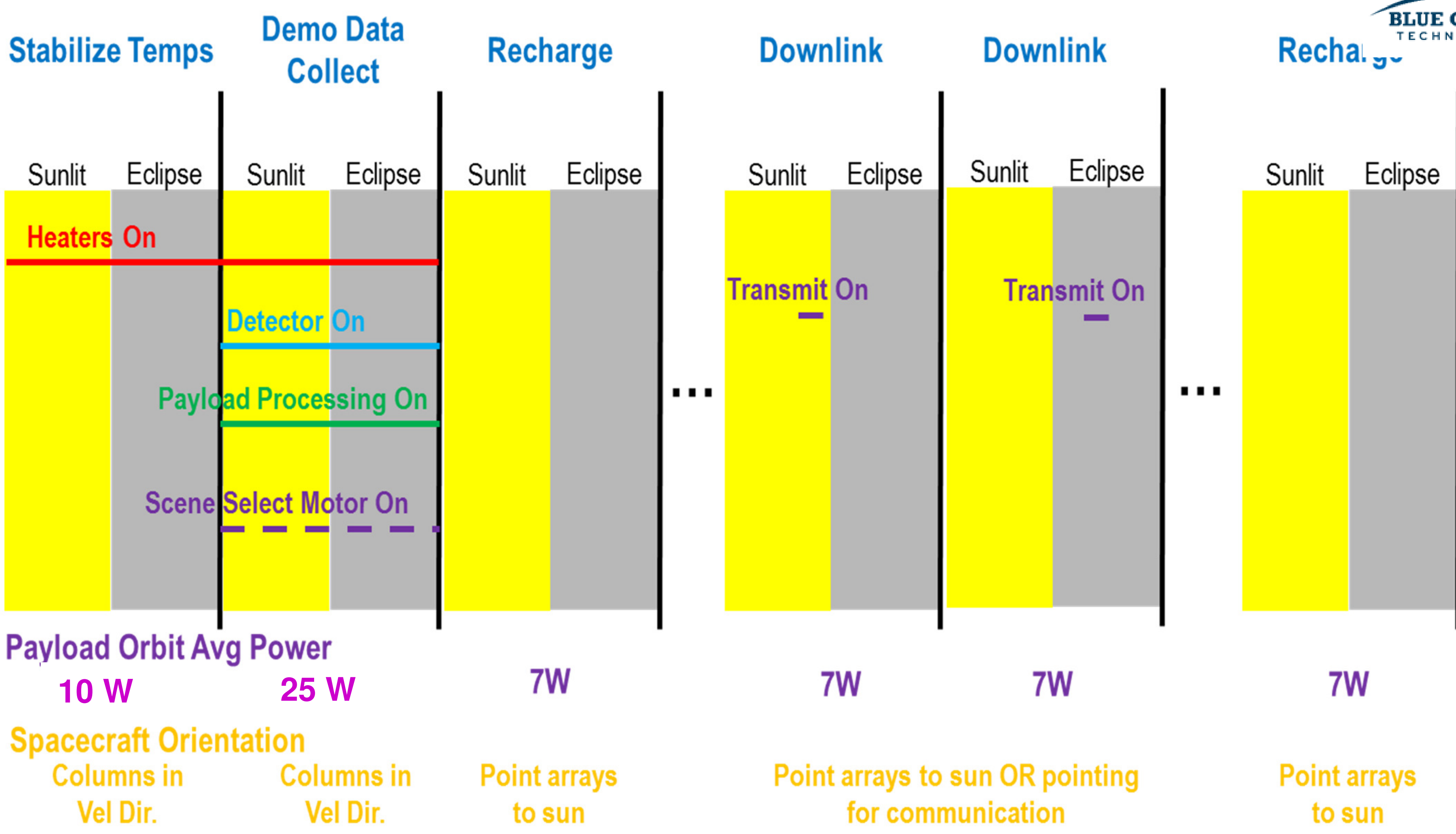
On-orbit operations comprise four operating modes



Operating modes:

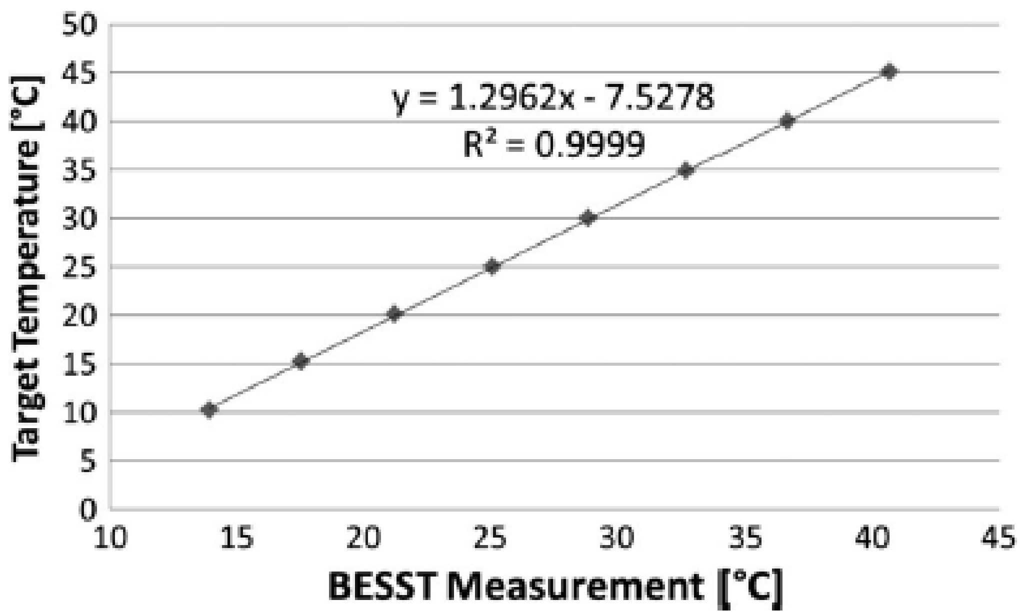
1. Instrument temperature stabilization (one orbit)
2. Imaging (one orbit- day and night side)
3. Battery recharge
4. Data downlink

On-orbit Concept of Operations



Ground calibration prior to instrument delivery establishes baseline radiometric precision and accuracy

- Ground calibration procedure prior to launch will use a NIST traceable blackbody source
- Calibration is transferred to space vis CNT sources
- Accuracy at time of ground calibration is a baseline for on-orbit accuracy
- For BESST this procedure achieved:
  - accuracy of 0.3 deg C
  - precision of 0.16 deg C
- CIRiS is expected to improve on this



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

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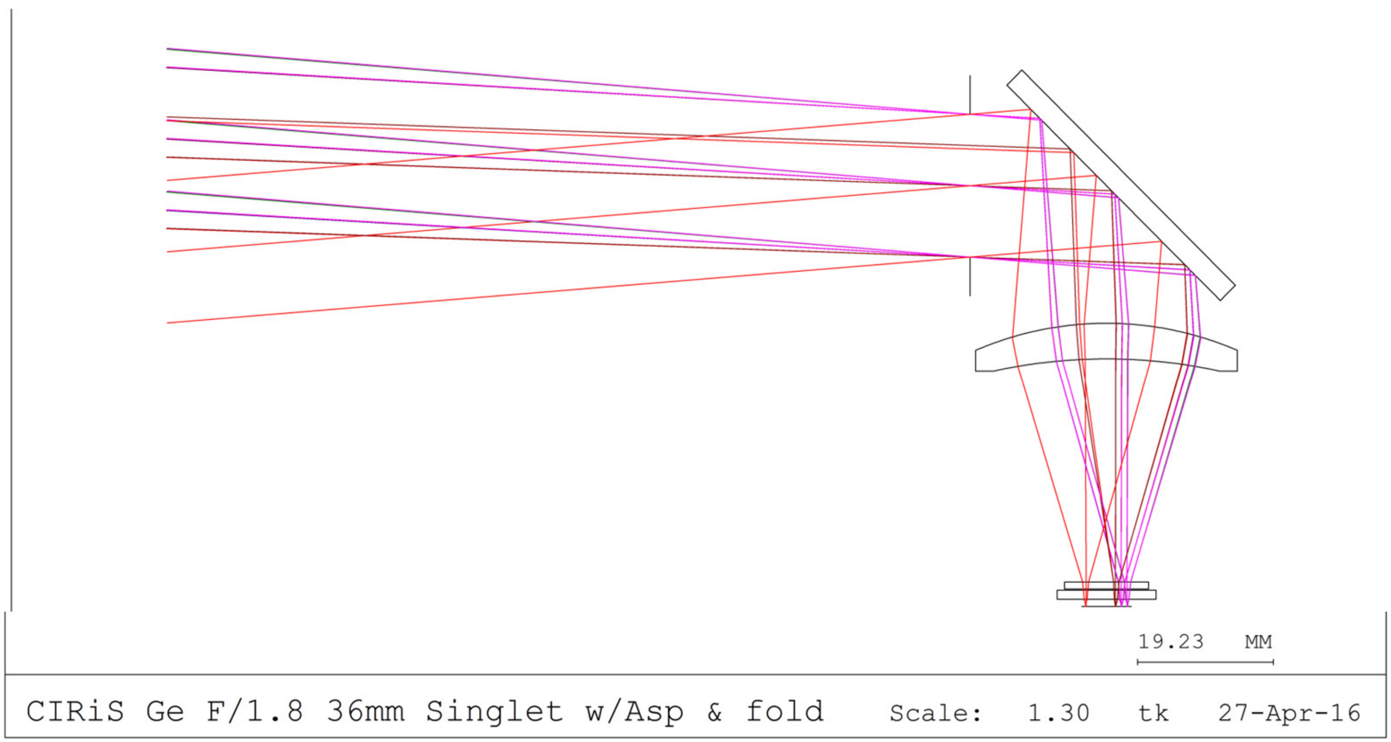

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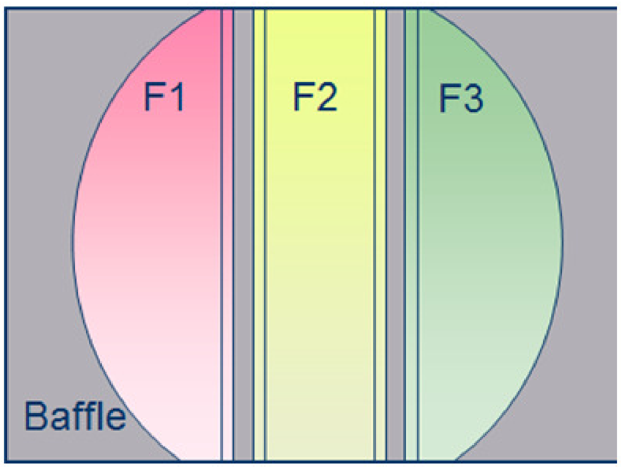

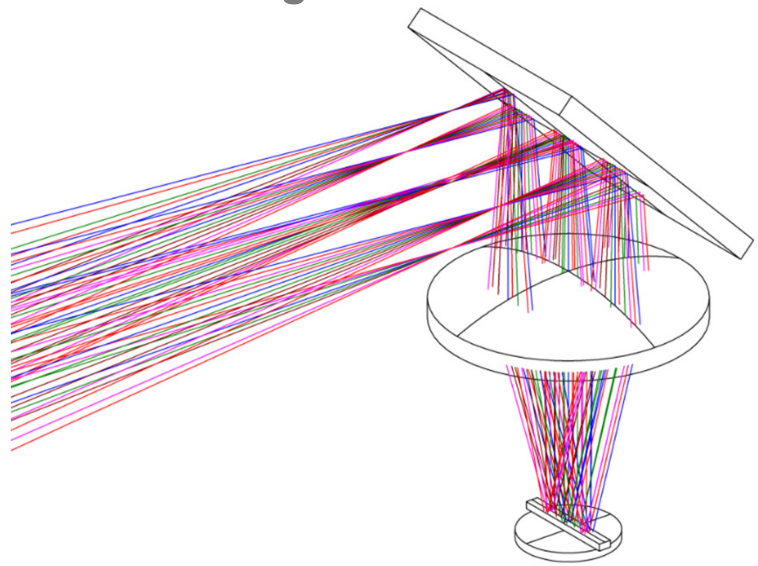

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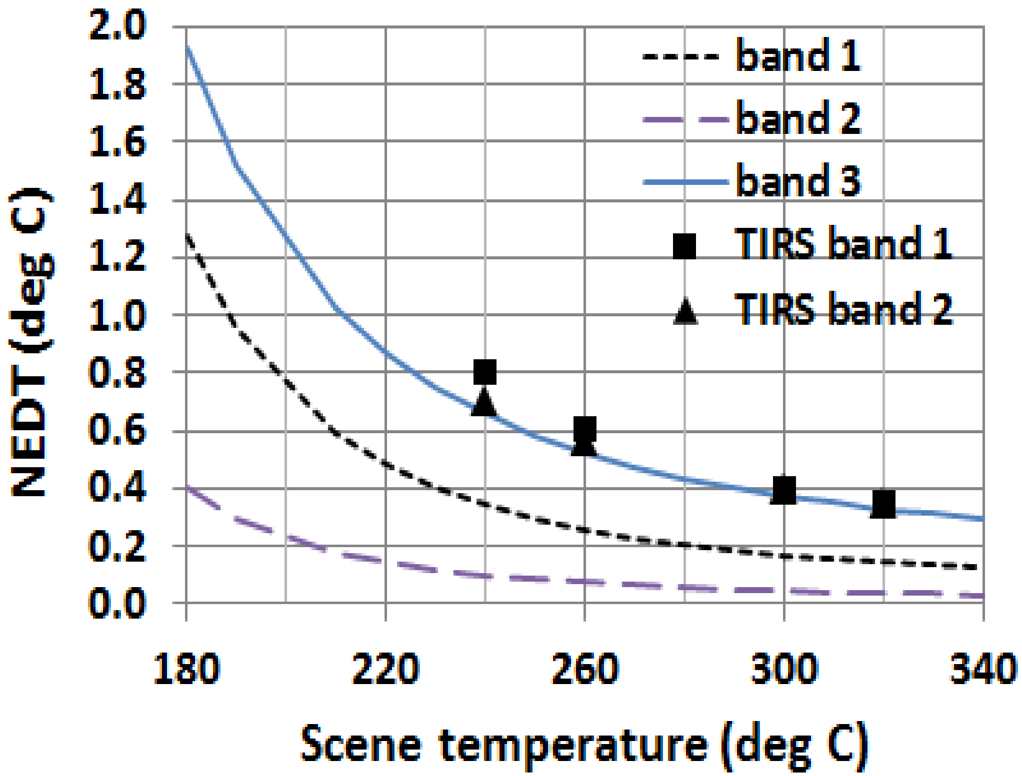
Calculated instrument precision (End-to-end Noise Equivalent Difference Temperature = NEDT) compliant with needs of many applications

- NEDT improved with 2x2 pixel binning; has little impact on image quality for F/1.8 lens design
- Potential for further NEDT improvement by co-adding adjacent image frames with row shift (NEDT improves as sqrt of # of frames added)

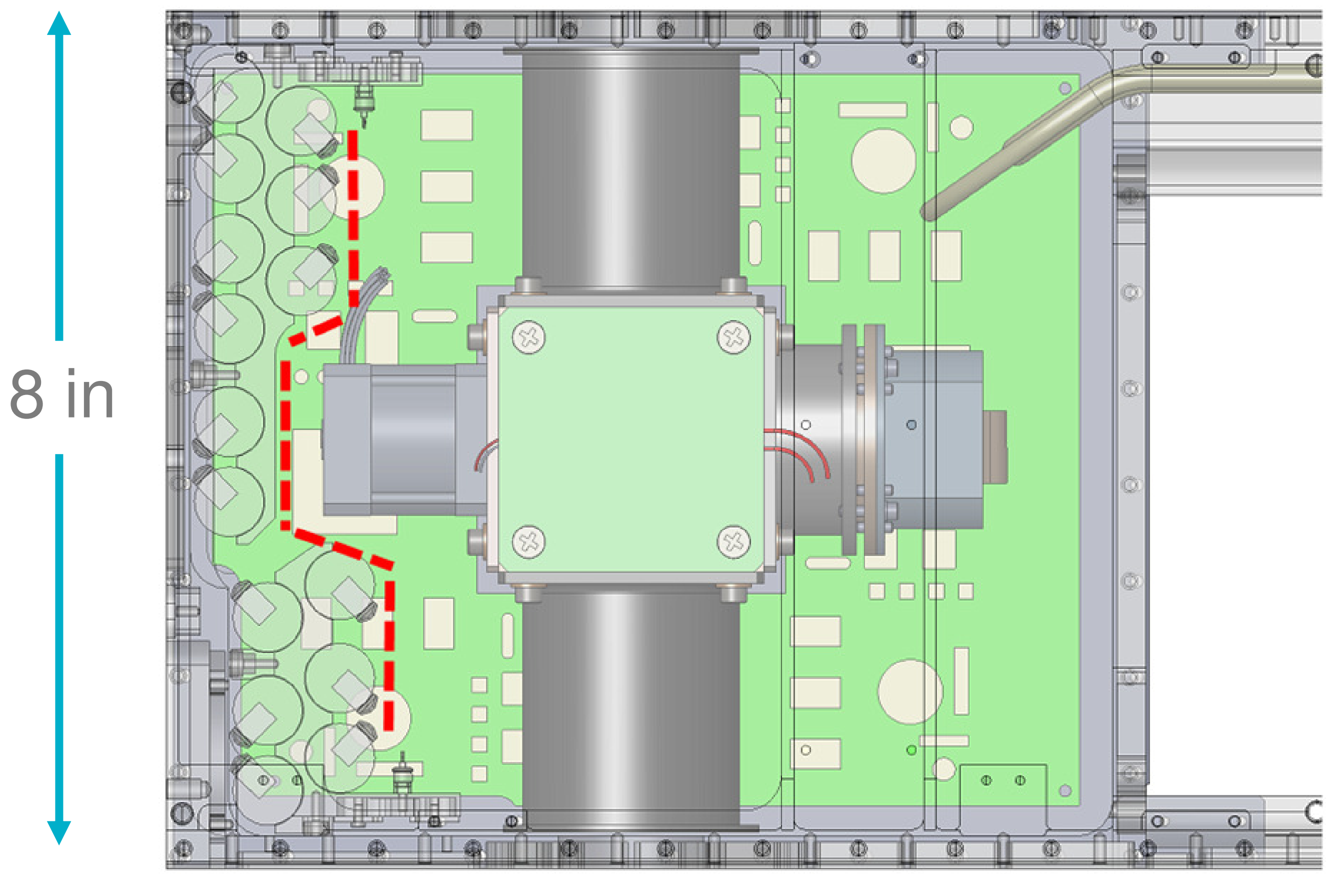


Binned GSD = 270 met from 410 km altitude (ISS launch)

Swath = 85 km

Interface design between the spacecraft and instrument is complete

- Packing many components in small 6U volume requires careful design
- Small volume of FPA and two CNT sources helps a lot
  - Need to position: instrument structure, batteries, electronics board, electronic parts, baffles, solar panel latches



CIRiS Status, mid-June 2017

- 90% of mechanical parts fabricated
- Procured flight CNT sources, flight FPAs, flight optics
- Spacecraft electronics EDU delivered
- Optical coatings being applied (mirror, high emissivity surfaces)
- Electronics layout complete

- Waiting to hear launch date and orbit

Acknowledgements

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The Ball team:

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- Bill Good
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- David Osterman
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- Bob Warden

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