CIRiS: Compact Infrared Radiometer in Space

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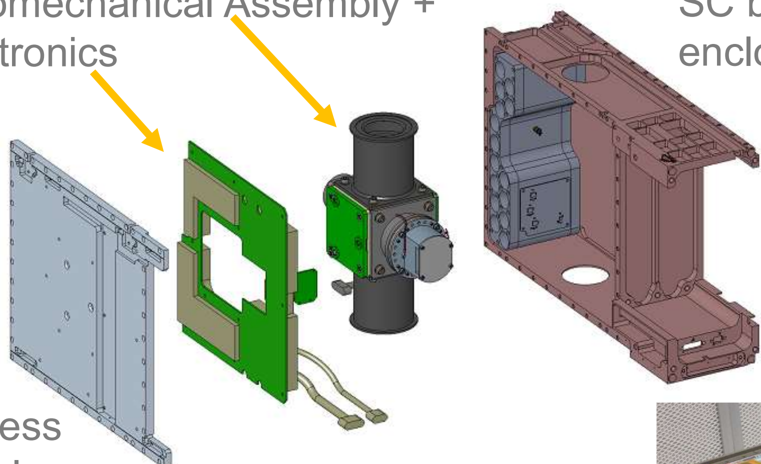
CIRiS is a multispectral LWIR imaging radiometer with on-board calibration system integrated to a CubeSat spacecraft

- CIRiS= Compact Infrared Radiometer in Space
- A “calibration laboratory in space”: multiple calibration parameters selectable on-orbit
- LWIR imaging in 3 bands with NO cryocooling (operating temperatures -20 C to +40 C)

Instrument = Optomechanical Assembly + Electronics

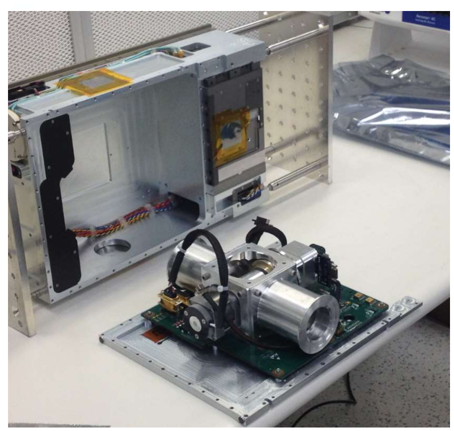
SC bus enclosure (6U)



Access panel

Spec	Value
Frame rate	60 fps
F/#	1.8
FOV	9 x 12 deg
FPA format	640 x 480
Operating temp range	-20 C to +40 C

CIRiS instrument on access panel

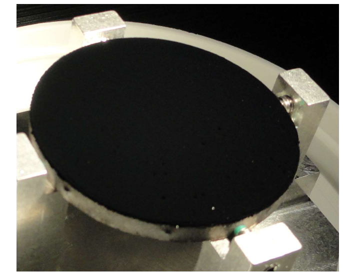


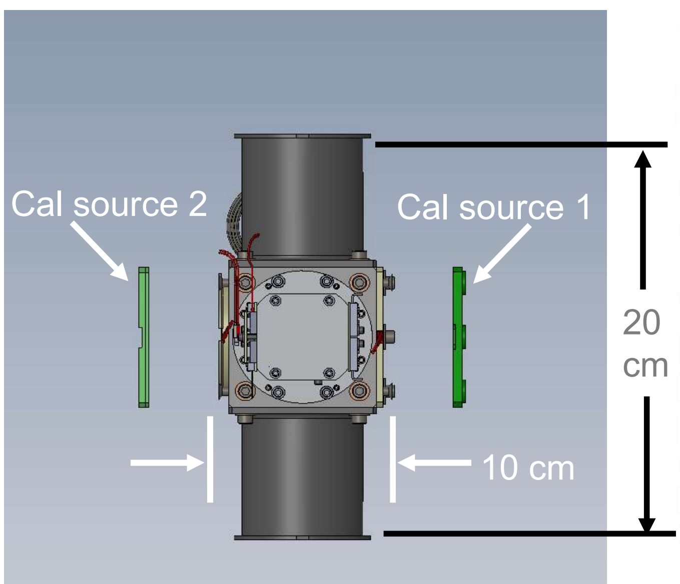
Instrument + 6U Spacecraft bus

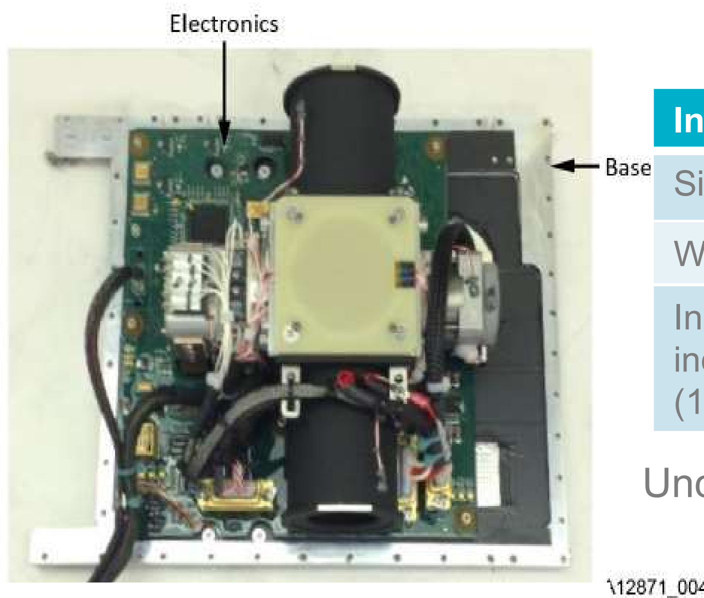
Band	Wavelength range (um)	Bandwidth (um)
1	7.40 to 13.72	6.32
2	9.85 to 11.35	1.50
3	11.77 to 12.60	0.83

The CIRiS mission objective is demonstration of technology for on-orbit LWIR radiometric imaging and calibration on a Cubesat

- CIRiS enabling technologies for on-orbit calibration compatible with size/weight/power constraints of a CubeSat are:
  - On-board carbon nanotube (CNT) calibration sources
    - High emissivity sources on a 1/8 in-thick flat panel substrate
  - New model of an uncooled microbolometer FPA
    - Eliminates power draw, mass, complexity of a cryocooler or cryoradiator





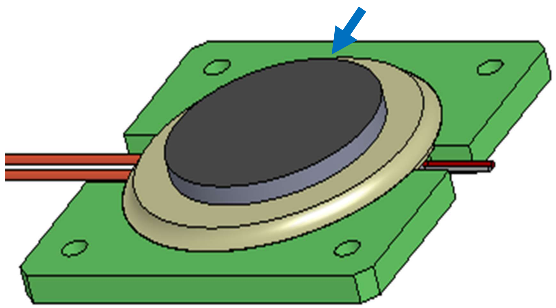


Instrument SWaP	Value
Size	$< 20 \times 20 \times 10\ cm^3$
Weight	< 2 kg
Instrument power, including heaters (10 minute avg)	9.5 W

Uncooled operation enables low SWaP

The three CIRiS calibration views include views to two carbon nanotube (CNT) sources with emissivity >> 0.99

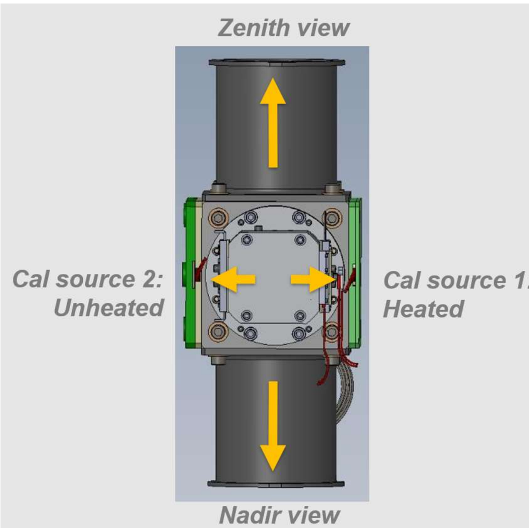
CNT source on substrate, 1/8 in thick, 2.5 in diameter



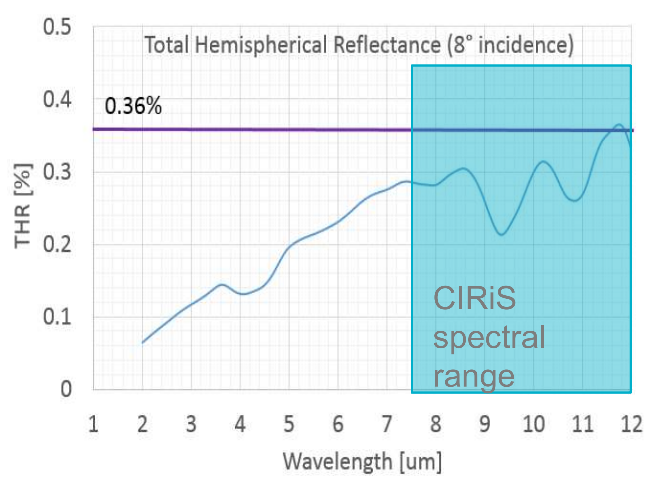
- Three calibration views:
1. CNT source separately heated and temp controlled
2. CNT source at spacecraft temperature
3. View to deep space

- Calibration has been transferred from a NIST traceable source to the two on-board CNT sources

Cal source	Cal Temp range (demonstrated in TVAC)	Temp sensors	PRT Read-out Precision
CNT source 1	0 to +40 C (controlled	2, space qual'd	0.01 C
CNT source 2	-18 to +18 C	2, space qual'd	0.01 C
Deep space	< 10 K	None	0.01 C



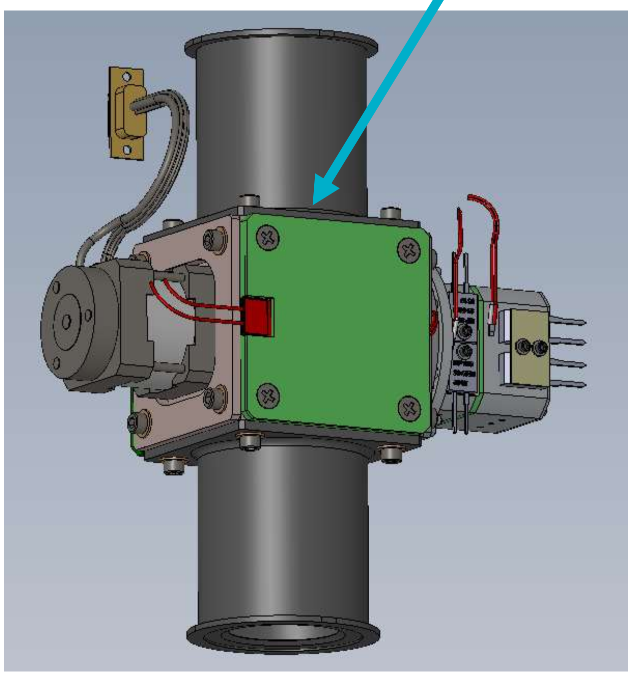
Measured emissivity > 0.9964



The CIRiS instrument has a modular design that facilitates subsystem modification for specific mission needs

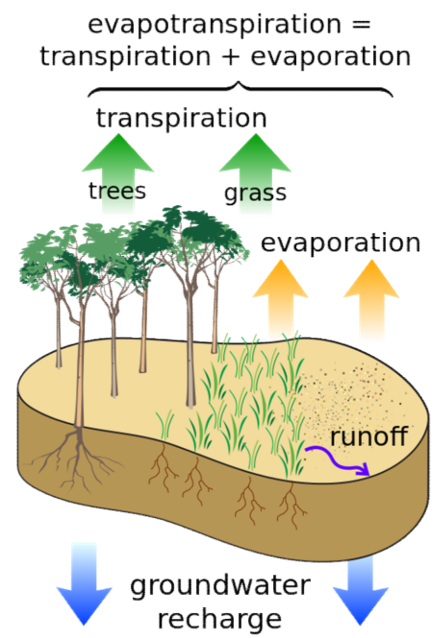
- Subsystems bolt to structural cube enabling modification of one subsystem independent of others

Structural cube

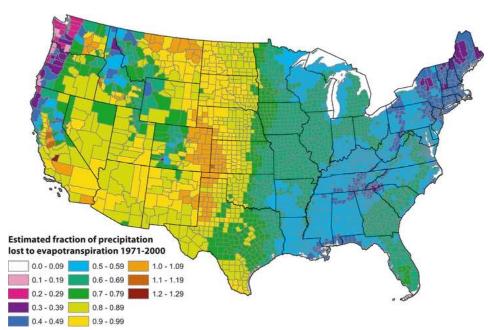


Property	CIRiS	Modifications
Optical System type	Transmissive, single lens	Transmissive or reflective, multi-element
Telescope F/#, EFL	F/1.75, EFL = 36 mm	F/0.5 and above
Spacecraft	CubeSat (6U)	hosted payload, free flier, other
Wavelength bands (#)	3	1 to 5
Frame co-adding	16 frames	> 100
Other modifications		Multiple CIRiS instruments, memory capacity

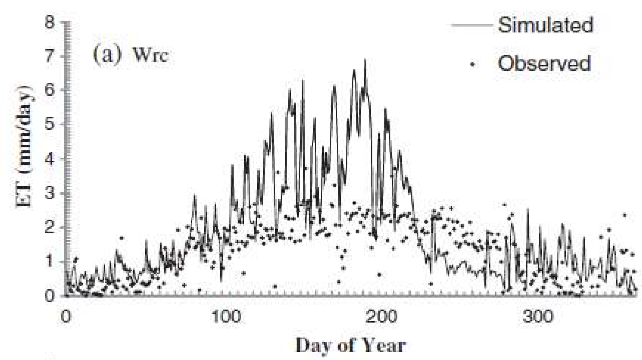
One potential CIRiS application in surface biology and geology: remote sensing of evapotranspiration (ET)



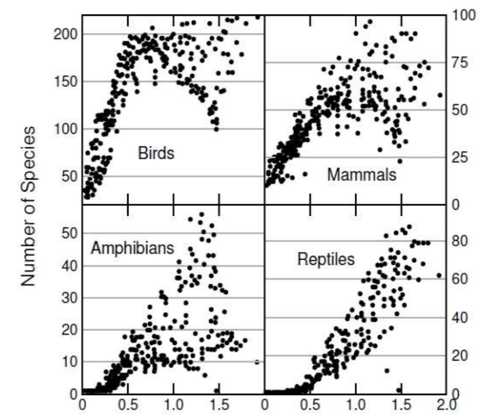
- Evapotranspiration, a key Earth Science variable, combines:
  - Evaporation from the earth's surface
  - Transpiration, the release of water vapor from plant cell surfaces
- ET returns the majority of precipitation falling on land to the atmosphere
- ET varies substantially spatially AND temporally
- ET contributes significantly to a variety of local and global phenomena including local climate, weather, carbon cycle, earth's energy balance, biodiversity



ET across CONUS,1971 -2000 avg



Daily ET variation, ground measurement



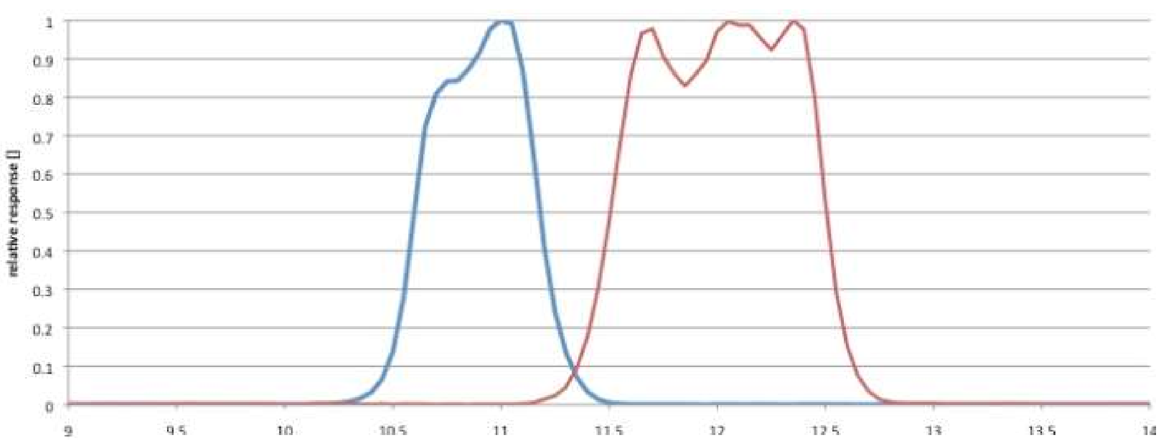
ET vs number of species US & Canada

References, CW from top right: M.W. Toews, 2007, D.J. Currie, 1991, M. Liu et al, 2013, W.E. Sandford and D.L. Selnick, 2012

Evapotranspiration measurement from Low Earth Orbit utilizes multispectral radiometric LWIR imaging

- Quantities required for remote determination of ET are
  - accurate emissivity and land surface temperature (1 C or better), on spatial/temporal scale of interest
  - meteorological data (air temperature, water vapor pressure) on regional scale
- Required measurements from LEO
  - LWIR radiance in specific wavelength bands from 8 to 13 um (2 to 4 bands)
- Required processing
  - Removal of spurious effects of atmosphere (water vapor)
  - A method of scene emissivity determination

Detection bands for atmospheric correction (from LandSat 8/ TIRS)



$$T_s = T_i + c_1(T_i - T_j) + c_2(T_i - T_j)^2 + c_0 + (c_3 + c_4 w)(1 - \varepsilon) + (c_5 + c_6 w)\Delta\varepsilon$$

Regional and Global Evapotranspiration Measurements have high value in several areas

1. Science value

- Evapotranspiration cited in 2017 Earth Science Decadal Survey (National Academy of Science) in questions driving Most Important Objectives:

Are changes in evapotranspiration and precipitation accelerating…and how are these changes expressed in the space-time distribution…?

- ET identified as an interest for all five Decadal Survey focus areas

2. Land/water Management

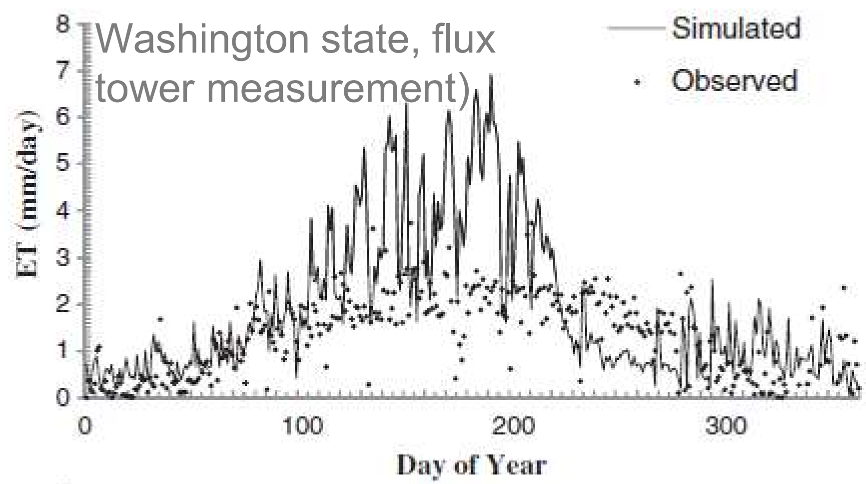
- "water loss" side of sustainable water management, water quality enhancement, drought prediction including "flash drought", ground water management, irrigation sufficiency

3. Commercial value

- Improvement in quality of fruit and other crops

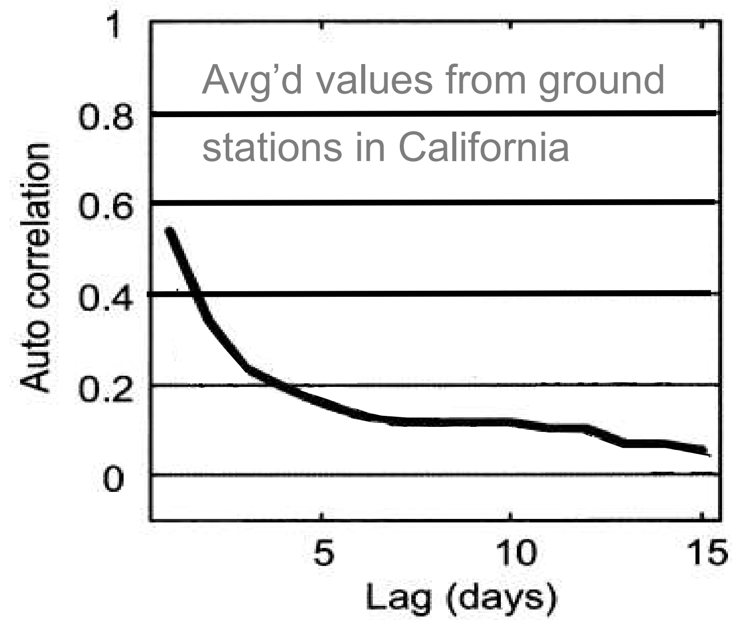
CIRiS instruments could provide high add-on science value, at low cost, by complementing ET measurements from larger SWAP instruments

- A potential role for constellations of CIRiS instruments in measuring ET temporal variability on critical time scale < 5 days
  - As sample time increases beyond 5 days, ET is increasingly uncorrelated (statistical fluctuation)
- Complementary measurements to larger SWAP instruments that have better spatial resolution
- CIRiS also provides high calibration performance to bound uncertainty in ET measurement



ET temporal variations reflect hourly, daily, seasonal, annual effects

M. Liu, et al., 2013

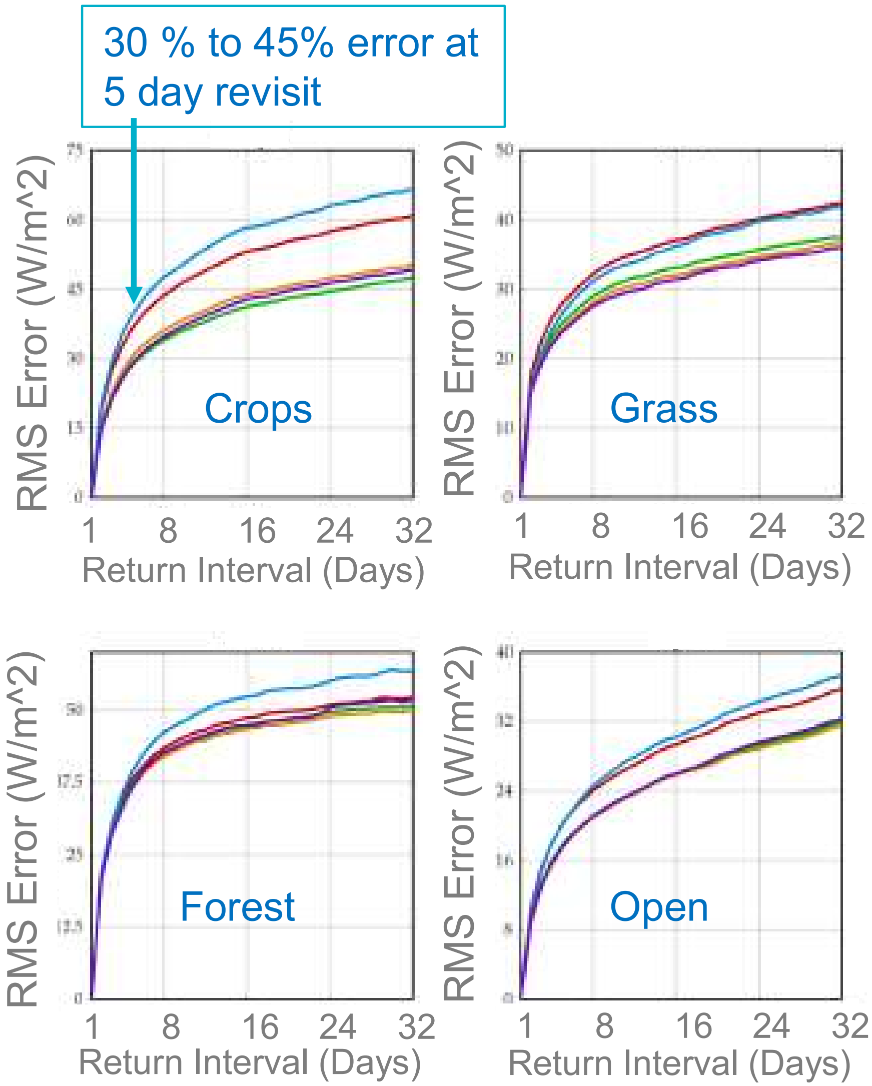


The autocorrelation function of ET drops rapidly from 1 to 5 days

After H. Hidalgo et al., 2005

Shortened revisit times significantly improve ET measurement accuracy

- Error in ET, as reconstructed from temporal samples, improves rapidly with reduction in revisit times below 5 days
- Multiple spacecraft provide a route to reduced revisit times



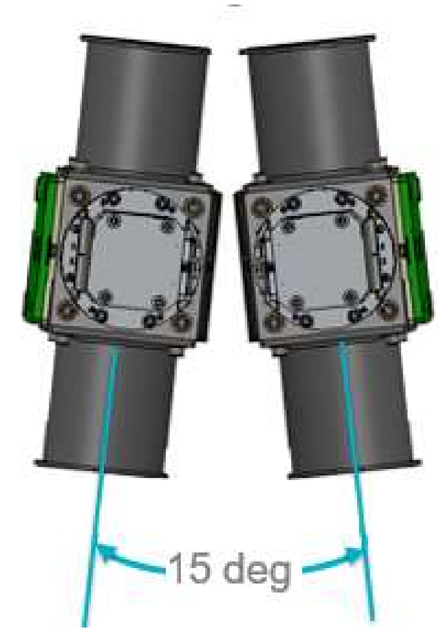
Left: RMS Error in reconstructed ET and ET-related physical variables, vs revisit times,

From J.G. Alfieri et al,, Effect of the revisit interval and temporal upscaling methods on the accuracy of remotely sensed evapotranspiration estimates, 2017

Some sample ET mission architecture generate short global revisit times by means of constellations of small spacecraft

- These solutions are optimized for short revisit times over the entire globe
- Revisit times are the same for daylight observations, and for nighttime
- Other design versions possible

Mission Design	CIRiS (now)	ET mission
CIRiS instruments on SC	1	2
# of SC	1	3 to 6
Telescope spec	F/1.8, XT FOV = 12.2 deg	F/1.8 XT FOV = 15.4 deg
Payload XT FOV	12.2 deg	2 x 15 = 30 deg
Filter bands	3	4
# of frames avg'd	16	64
instrument processing memory capacity	20 MB (SRAM)	256 MB (SDRAM)
Orbital altitude	500 km	400 to 500 km
Orbit type	ISS orbit	Sun synchronous



Two CIRiS instruments on one spacecraft achieve 30. deg XT FOV

Results of the sample ET missions for short revisit times

- Revisit times down to 2 days over the entire globe are feasible with up to 6 spacecraft
- All spacecraft have the same equator crossing time
- A second solution set trades larger GSD to achieve shorter time revisit times than shown below

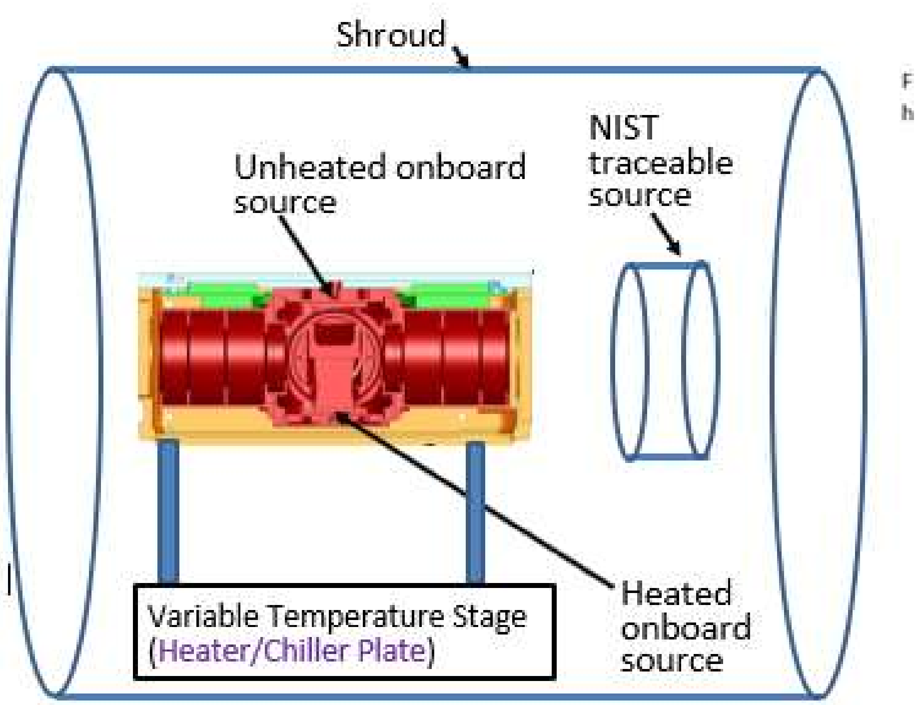
# of spacecraft	Altitude (km)	GSD at nadir (m)	Revisit time for global coverage (days)*
3	467	156	4
4	446	149	3
6	417	139	2

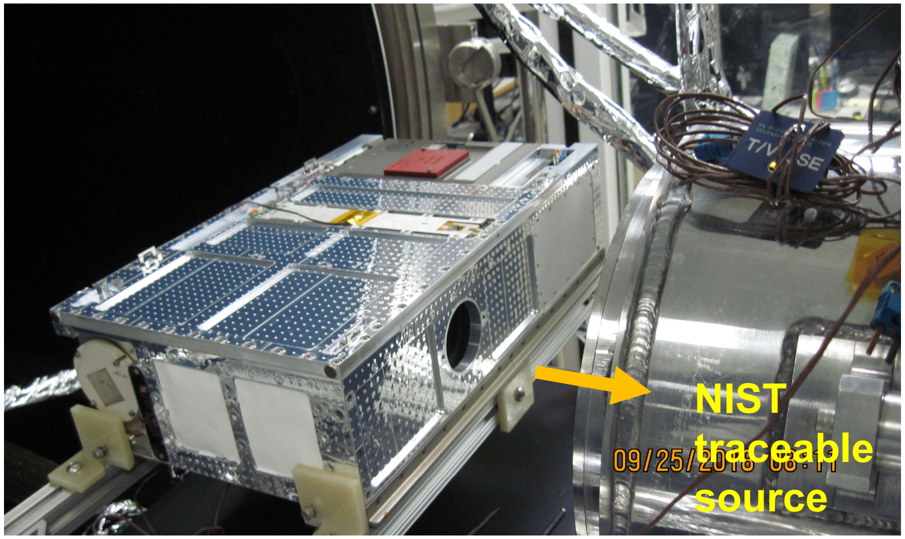
Also:

Specification	Performance
NEDT, 300 K scene, representative band, 10.3 to 10.8 um.	0.46 K

The integrated CIRiS instrument/spacecraft has completed a successful TVAC campaign

- TVAC Objectives:
  - Transfer of calibration to on-board calibration sources
  - Characterization of imaging and calibration performance
  - Environmental test
- TVAC configuration set to emulate on-orbit thermal effects, as derived from on-orbit thermal model::
  - Spacecraft thermal gradient of 5 to 10 C
  - Orbital-level transients on SC of 5 to 10 C





- CIRiS nadir port faces NIST traceable source located inside TVAC chamber

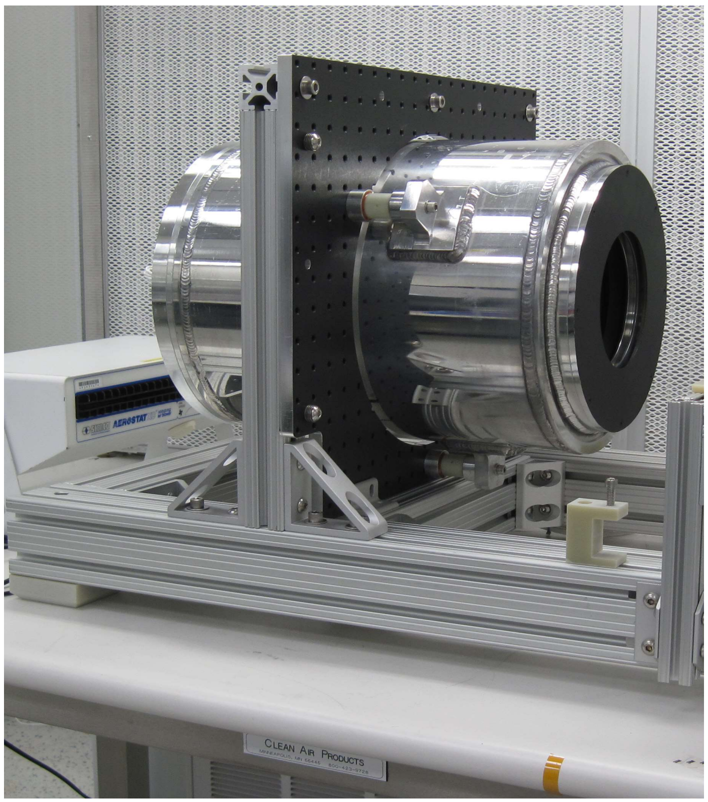
Data acquired in TVAC testing includes extensive characterization of CIRiS instrument performance

- Analysis of characterization data in progress

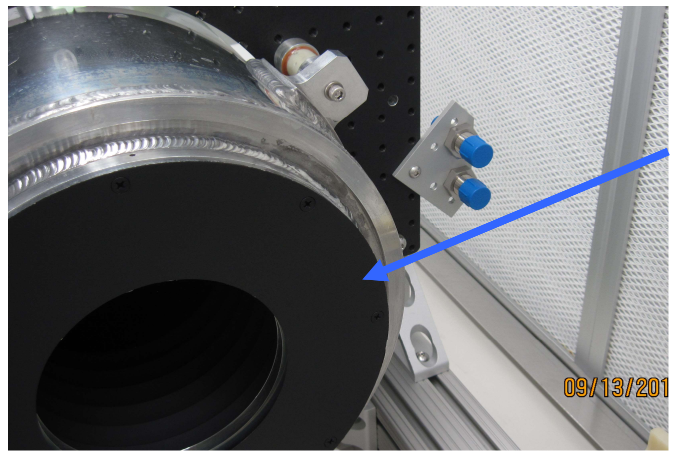
TVAC Characterization Measurement
Measure FPA gain variation with FPA operating temperature (in TVAC chamber)
Measure nonlinear correction to linear calibration
Measures baseline signal drift in fixed thermal environment
Measures signal drift due to FPA temperature changes
Measures signal drift due to SC temperature changes
Measure signal drift over full orbit SC temperature changes
Measure signal transients from scene select changes
Identify optimal calibration timing sequence
Measure signal repeatability
Measure signal reproducibility

Calibration transferred to CIRiS carbon nanotube sources from Ball's NIST-traceable Large-Area BlackBody (LABB-1)

- Vacuum compatible, conical cavity blackbody source
- Calibrated by NIST TXR facility from 235 K to 350 K
- Temperature accuracy ≤ 0.2 K (2σ)
- Temperature gradient ≤ 0.05 K
- Emissivity measured with NIST standard: 0.9981
- Includes LN2 cooled annular shield to minimize stray light

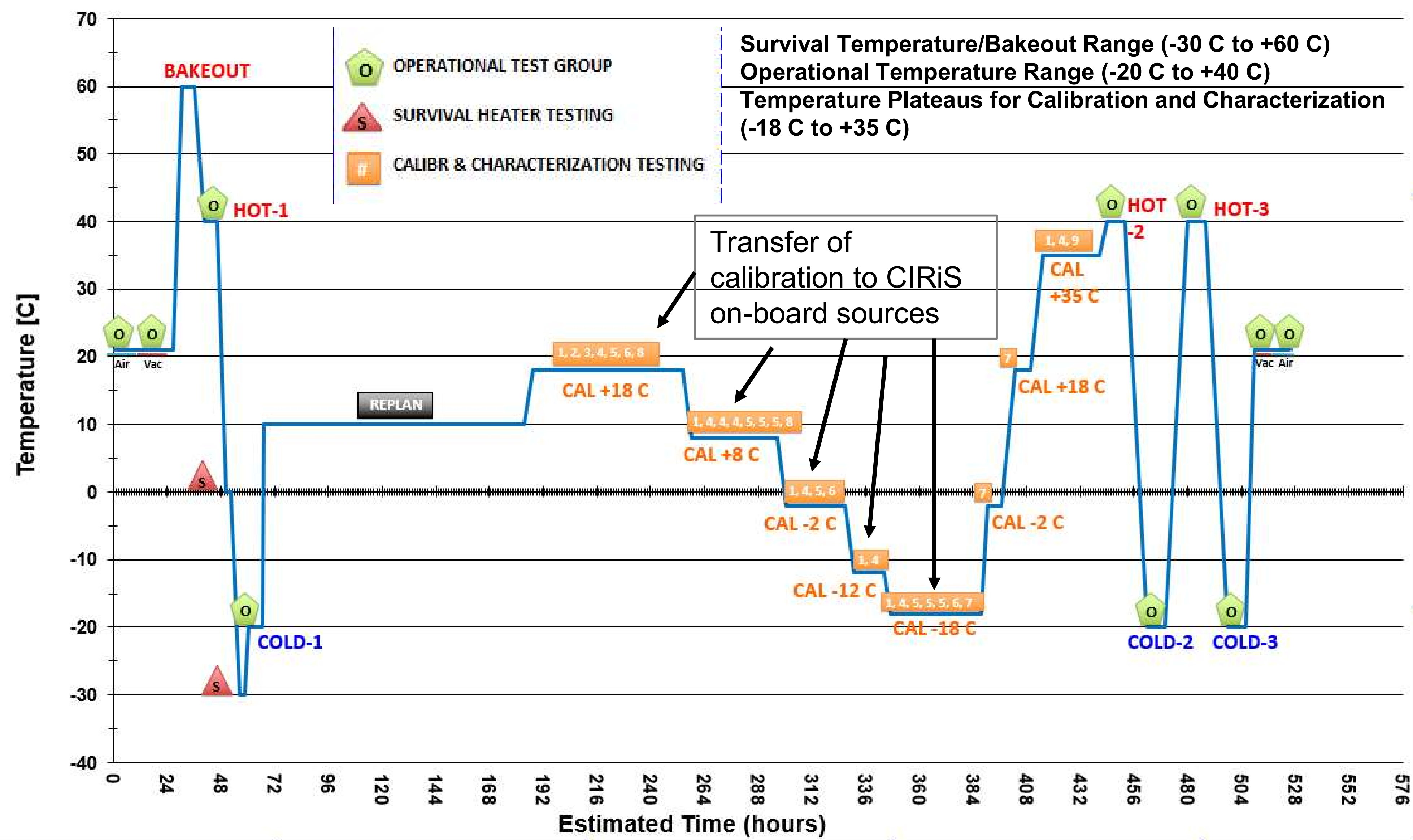


LABB-1 mounted for TVAC

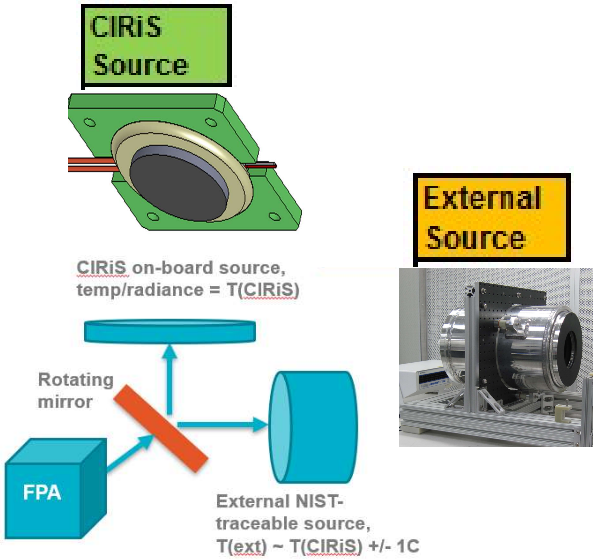


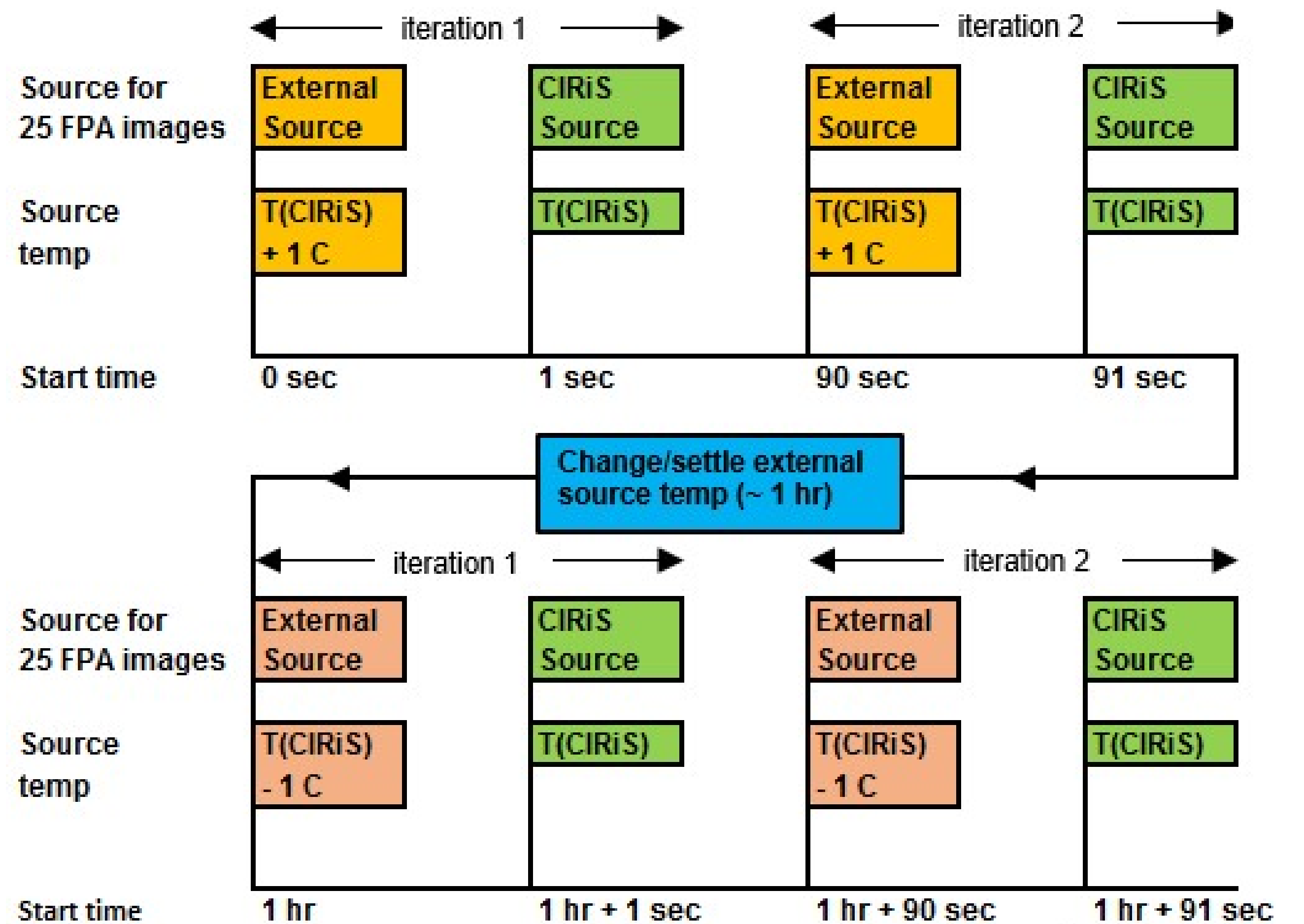
LN2 cooled annular ring for thermal IR stray light control

The TVAC temperature profile encompassed bakeout, and ranges for instrument survival, calibration and characterization testing



Transfer of calibration to one CIRiS CNT source, at one source temperature, implemented twice over ~ 1 hour



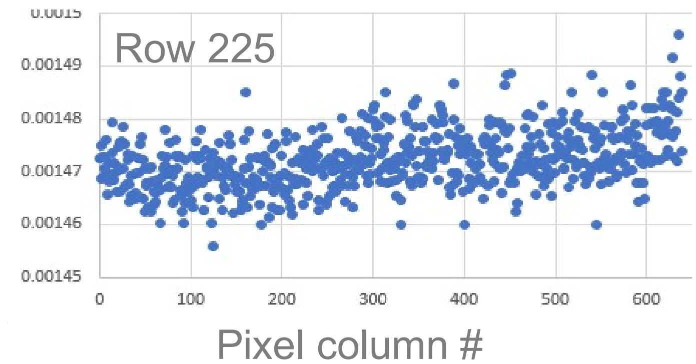


- Each view of a CIRiS calibration source lasts 1 sec, acquiring 25 FPA images frames in 0.5 sec
- Changing to a 2nd external, NIST-traceable source temp, and settling to 25 mK, takes ~ 1 hour

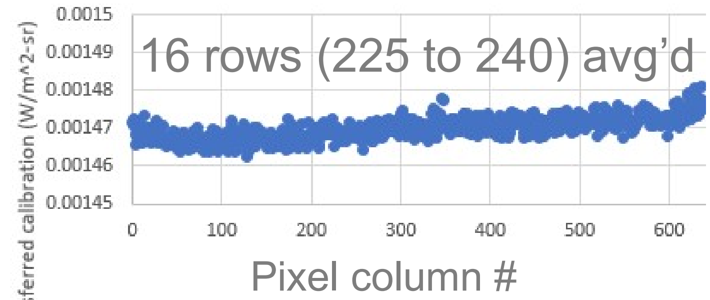
Several options exist for reducing FPA noise in transfer of calibration

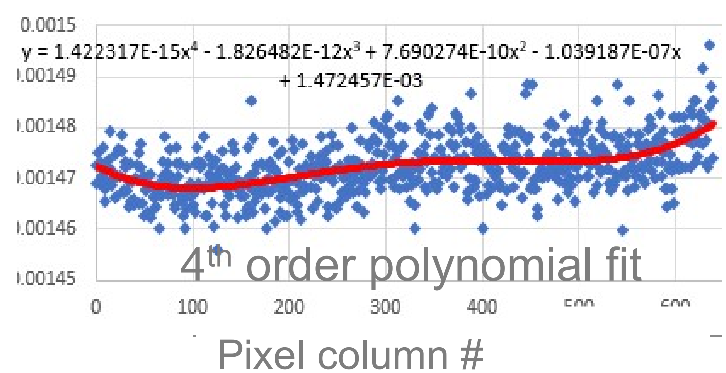
Transferred calibration across FPA columns, band 2, source temp +30.0 C

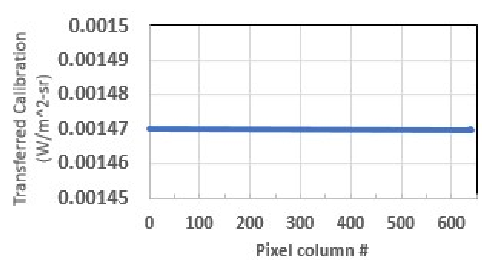
- Temporal averaging: Average 25 frames for each temperature and iteration



- Spatial averaging applied separately to each band
  1. Column averaging within the band (16 rows for 4X noise reduction)
  2. Polynomial fit across columns (>20 x noise reduction)
  3. Column and row averaging (>20 x noise reduction)







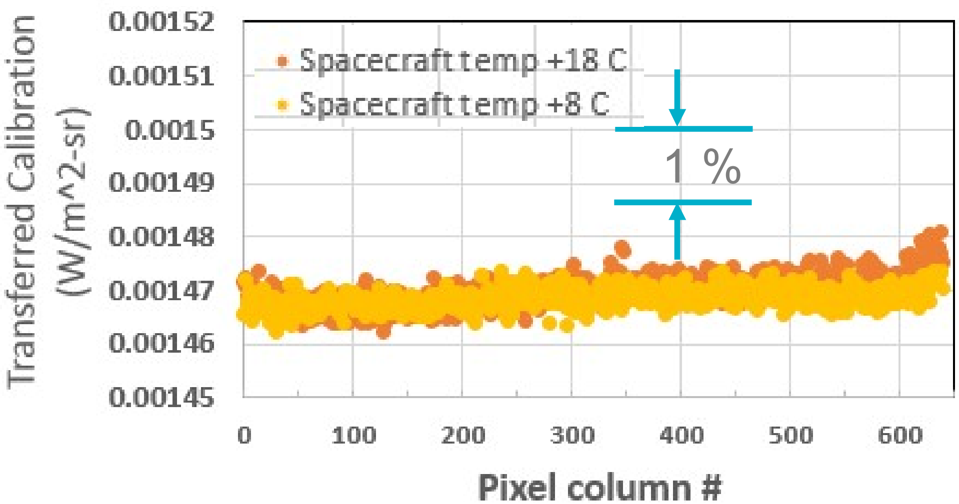
Statistical uncertainty (type A), including FPA noise

II. Frame averaging (temporal averaging) AND average 16 adjacent rows

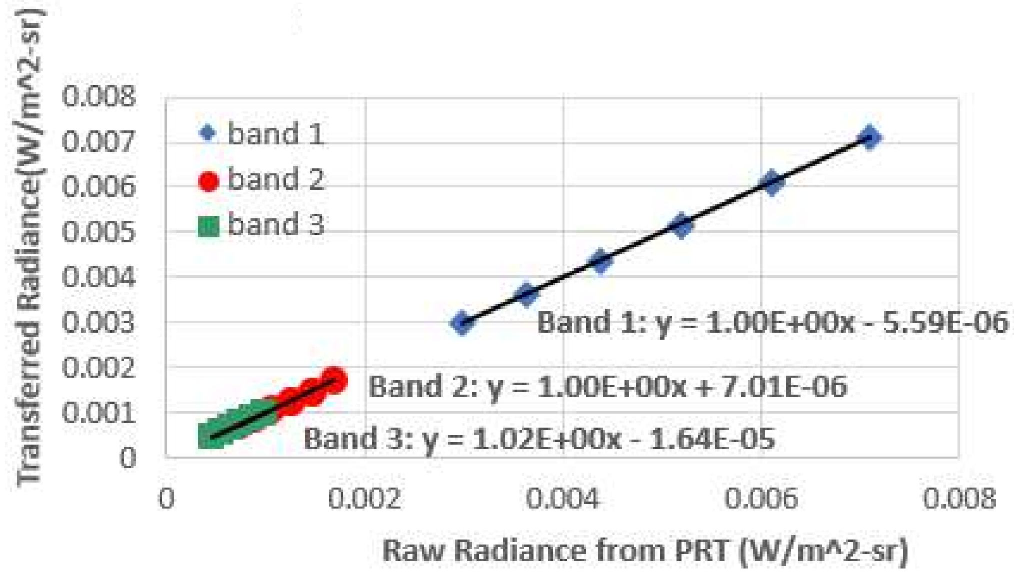
CIRiS band	Frames averaged	Uncertainty (radiance W/m^2-sr)	Uncertainty (scene temp C)	Note
1	25 frames	2.78e-6	0.01 C	measured
	100 frames	1.39e-6	0.004 C	extrapolated
2	25 frames	2.62e-6	0.03 C	measured
	100 frames	1.31e-6	0.015 C	extrapolated
3	25 frames	1.33e-5	0.3 C	measured
	100 frames	6.64e-6	0.15 C	extrapolated

Results of transfer of calibration to carbon nanotube source show good performance

- Nonuniformity of transferred calibration is < 1% across an image row
- Dependence on spacecraft temperature is < 1%



- Quality of linear fit is very good: R^2 >0.998 for all bands



Band	1	2	3
R^ 2	0.9999	0.9982	0.9984

Conclusions

- Science applications of the CIRiS instrument to Surface Biology and Geology include Evapotranspiration measurement from LEO
- Revisit times as short as 2 days are possible with CIRiS instruments in constellations of up to 6 spacecraft
- Initial results from TVAC testing of CIRiS are looking promising for high radiometric performance and calibration
- CIRiS launch is scheduled for December 2019