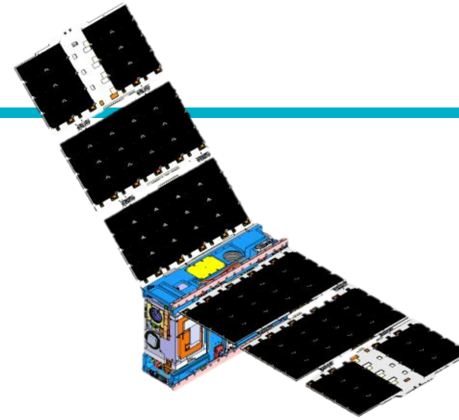


Transfer of Calibration to CubeSat On-board Carbon Nanotube Sources

David Osterman, presenter

Principal Investigator, CIRiS Mission

Co-authors

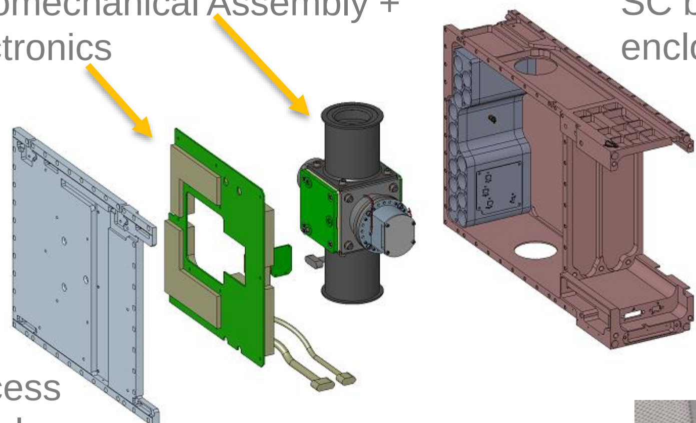
A. Amparan, A. Ghandour, T Kampe, P. Kerrigan, J. Necas, R. Rohrschneider, G. Reavis, M. Veto, R. Warden,

calcon
www.calcon.sdl.usu.edu

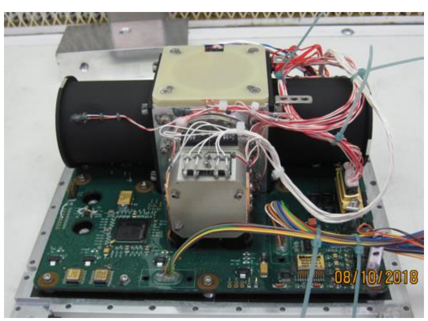
7/1/2019

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



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



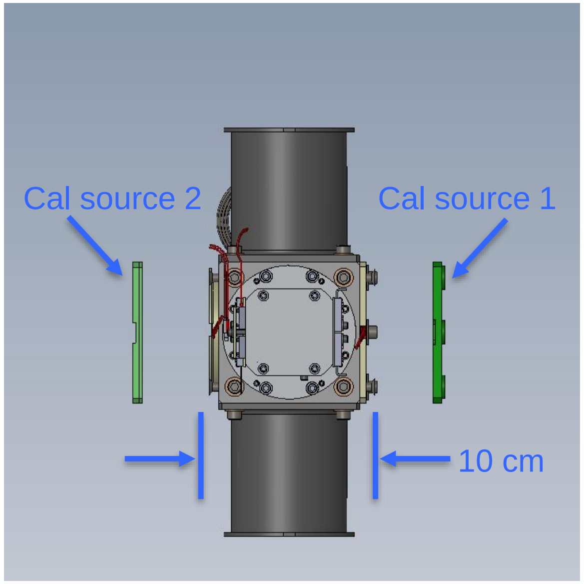
CIRiS instrument on access panel

Instrument + SC bus

Cal source	Calibration temp
On-board CNT	SC temperature (-18 to +18 C)
On-board CNT	Controlled (0 to +40 C)
Deep space	< 10 K

The CIRiS mission objective is technology demonstration, emphasizing on-orbit radiometric calibration of LWIR images

- CIRiS enabling technologies for on-orbit calibration, within the 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
- Launch planned for December 2019



Fit two CNT cal sources in 6U volume

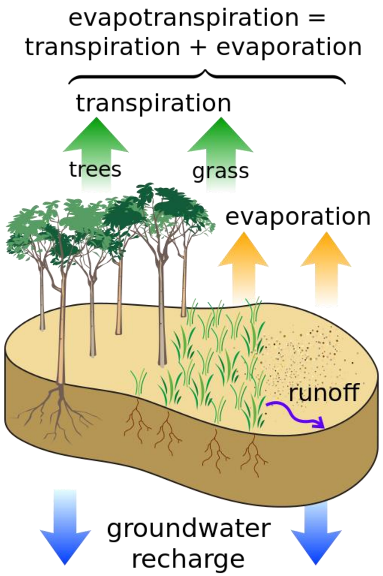
Instrument SWaP	Value
Size	< 20 x 20 x 10 cm^3
Weight	< 2 kg
Instrument power, including heaters (10 minute avg)	9.5 W

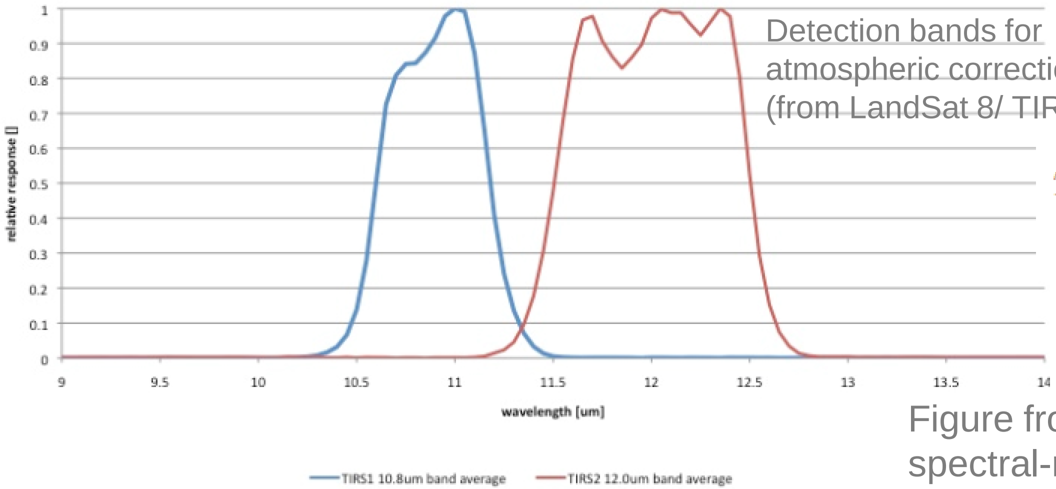
Uncooled operation enables low SWaP

Missions beyond the first CIRiS technology demonstration mission generate future CIRiS calibration performance needs

- One example: a potential surface biology and geology mission for global evapotranspiration measurements
- Primary needs are accurate land surface temperature (1 C or better) and emissivity measurements on spatial/temporal scale of interest
- Calibration requirements driven by need for:

1. Absolute radiance accuracy to determine land surface brightness temperature
2. Relative radiance accuracy between spectral channels to process out impact of atmospheric absorption





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

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

Figure from https://landsat.gsfc.nasa.gov/preliminary-spectral-response-of-the-thermal-infrared-sensor

The CIRiS instrument is entirely uncooled in contrast to traditional cryocooled LWIR instruments

- No cryocooled FPA or cryoradiator
- No cryocooled cold stop in optics

Operating temperatures of CIRiS and existing LWIR radiometric imagers

Radiometric LWIR imagers	Cryocooled	FPA temperature on orbit
Traditional	Cryocooler or cryoradiator	43 K, 58 K, 80 K, 83 K (LandSat TIRS/AIRS/VIIRS/MODIS)
CIRiS	none	255 K to 285 K

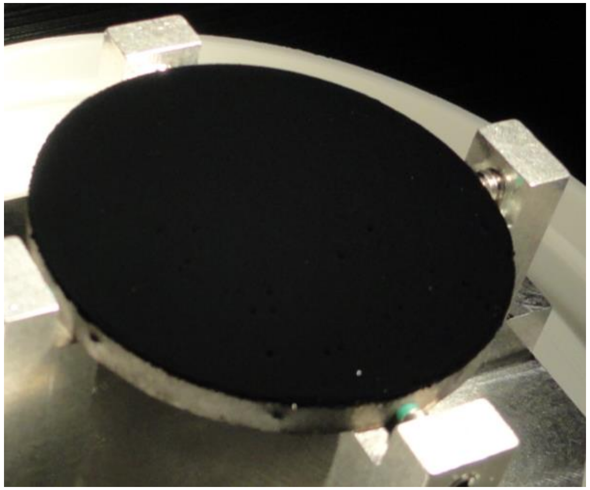
Challenges for on-orbit calibration and imaging from uncooled operation include

- FPA noise and drift
- Stray light and drifting stray light (background radiances)

The CIRiS strategy for addressing these challenges:

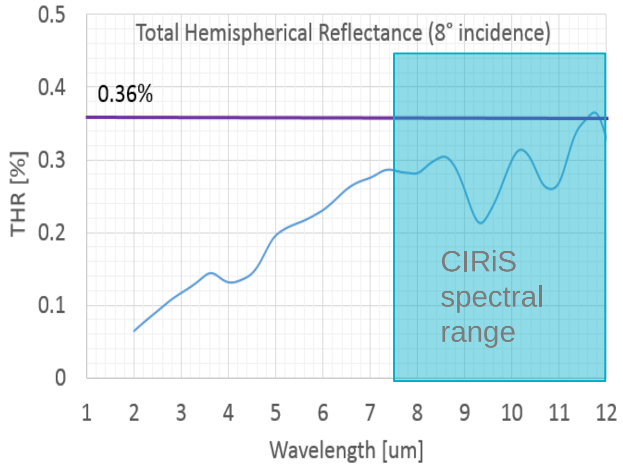
- Noise reduction through averaging (frame co-adding)
- Good system design (suppress stray light, multizone temperature control)
- Algorithms: Based on knowledge of instrument temperatures, measured calibration behavior

The two CIRiS on-board carbon nanotube (CNT) sources enable high emissivity calibration, with reduced reflected stray light

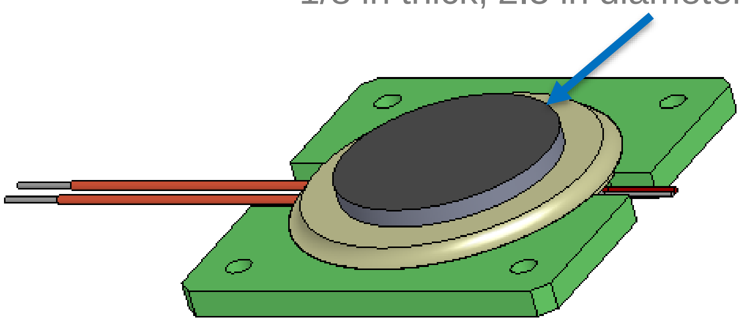


- CIRiS has two on-board CNT sources
1. Heated and temp controlled
2. Unheated, at Spacecraft temperature

CNT measured emissivity > 0.9964



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



CIRiS on-board source subassembly

Heated	Unheated
Two temp sensors (PRTs)	Two temp sensors (PRTs)
PRT near center, near edge	PRT near center, near edge
Space qual'd PRTs (JPSS program)	Space qual'd PRTs (JPSS program)
PRT read-out precision 0.01 C	PRT read-out precision 0.01 C
Film heater	No heater (at SC temp)
Temp control to < 25 mC	No control

The CIRiS lens and 3-band filter assembly are complete and characterized: POINT TO LENS IN CIRiS

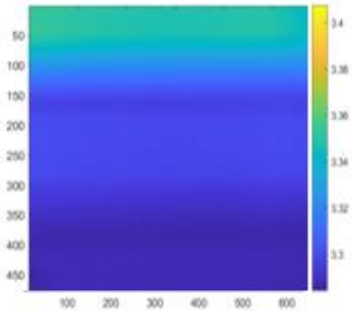
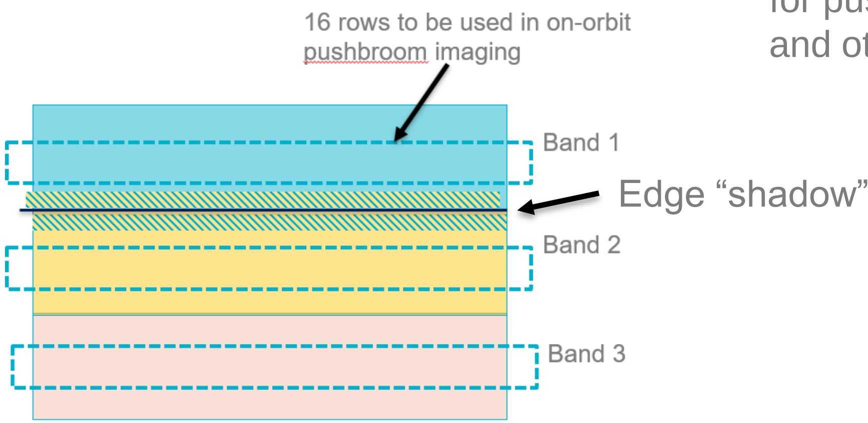
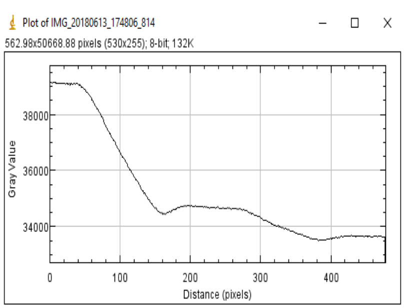


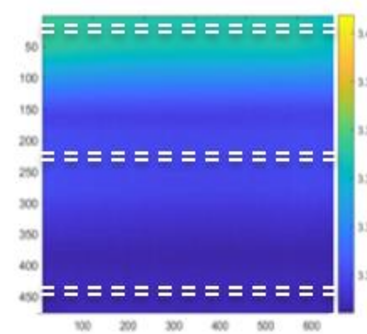
Image acquired of flat field scene

Band	FWHM wavelengths Lower, upper	16 rows selected for pushbroom imaging
1	7.40 um, 13.72 um	10 to 25
2	9.85 um, 11.35 um	225 to 240
3	11.77 um, 12.60 um	445 to 460

- Flat fielding profile used to select FPA pixel rows in each band for pushbroom image free from contamination by filter edges, and other bands



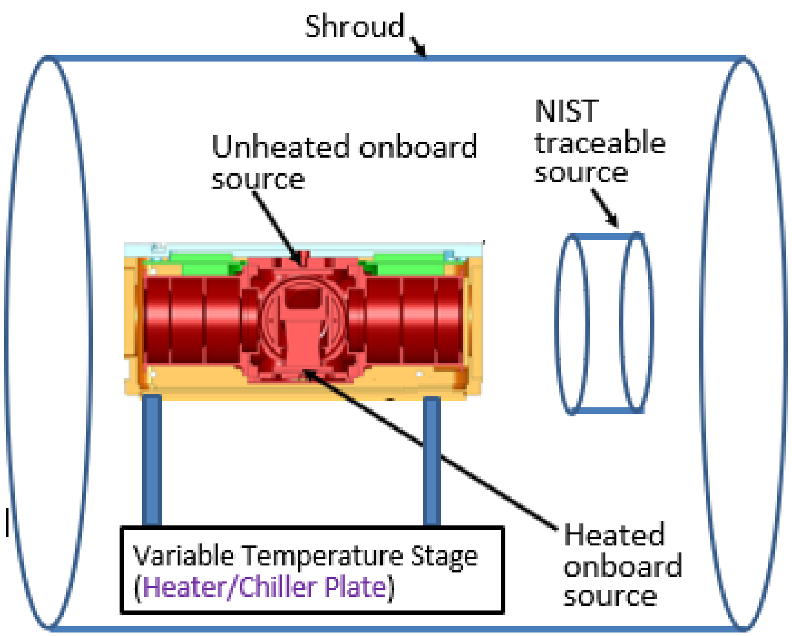


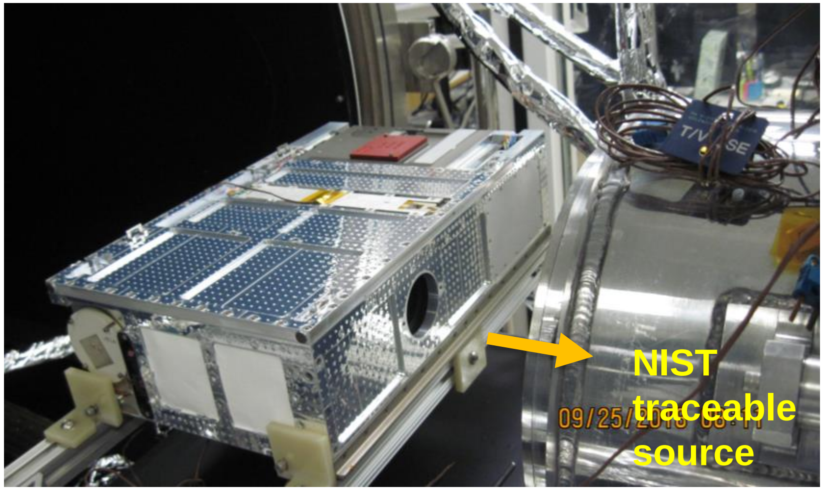


Measured signal down an image column

The TVAC campaign with the integrated CIRiS instrument/spacecraft has served several purposes

- TVAC Objectives:
  - Environmental test
  - Transfer of calibration to on-board calibration sources
  - Characterization of imaging and calibration performance



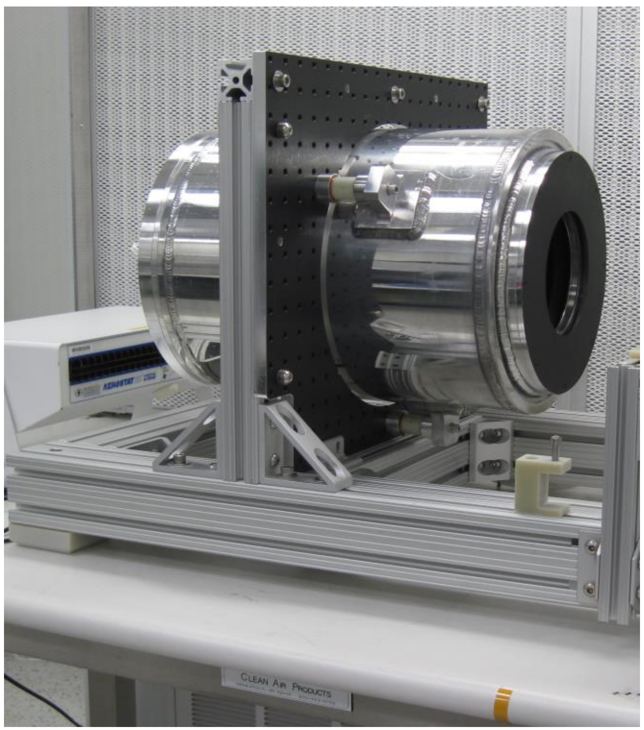


- Shroud and variable temperature stage set temperatures, orbital thermal effects including:
  - Orbital level gradient across SC of 5 to 10 C
  - Orbital-level transients on SC of 5 to 10 C

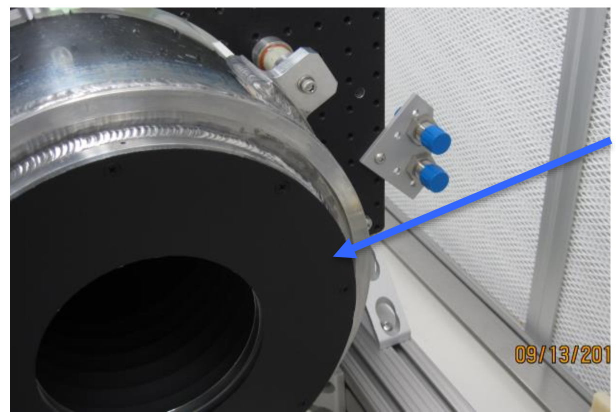
- CIRiS nadir port faces NIST traceable source located inside TVAC chamber

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

- Vacuum compatible, conical cavity blackbody source
- Calibrated against NIST standard over 235 K to 350 K
- Emissivity measured with NIST standard: 0.9981 +/- 0.0001
- Includes LN2 cooled annular shield to minimize stray light
- Blackbody may be flooded with liquid nitrogen for 80 K scene (not NIST traceable
- 12.7 cm aperture
- Temperature accuracy ≤ 0.2 K (2 σ)
- Temperature gradient ≤ 0.05 K



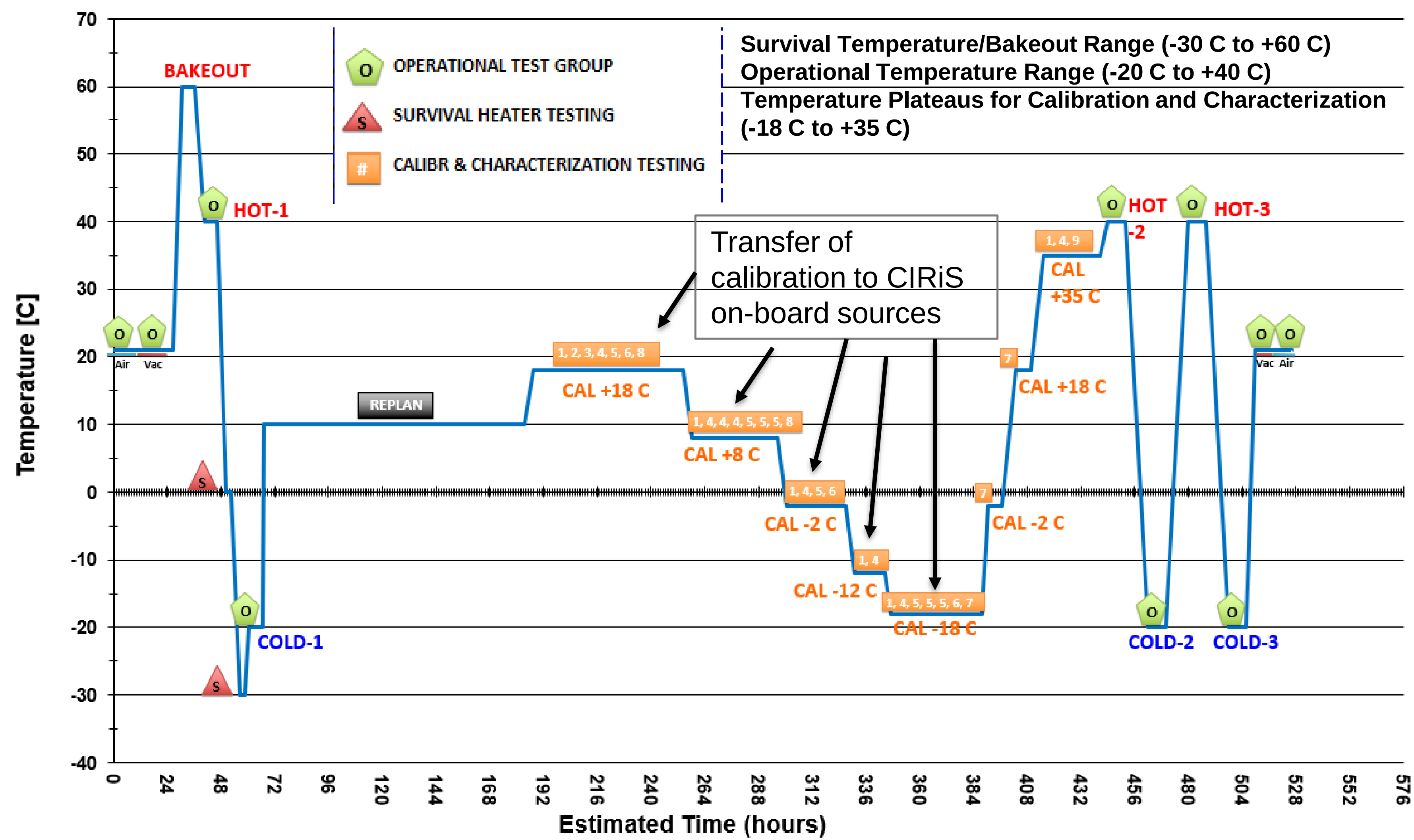
LABB mounted for TVAC



LN2 cooled annular ring for thermal IR stray light control

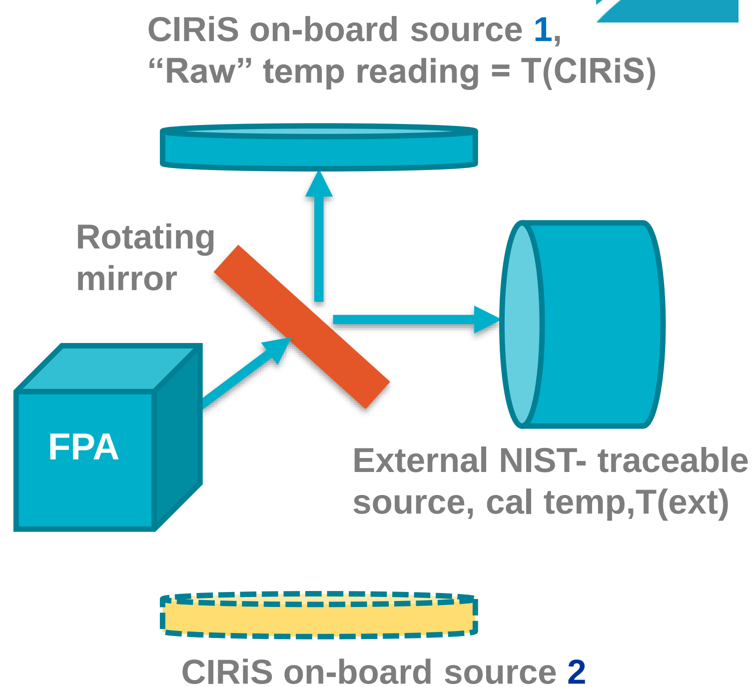
Performance of LABB1 verified by NIST TXR measurement in 2013, S. Collins et al, Calcon 2013

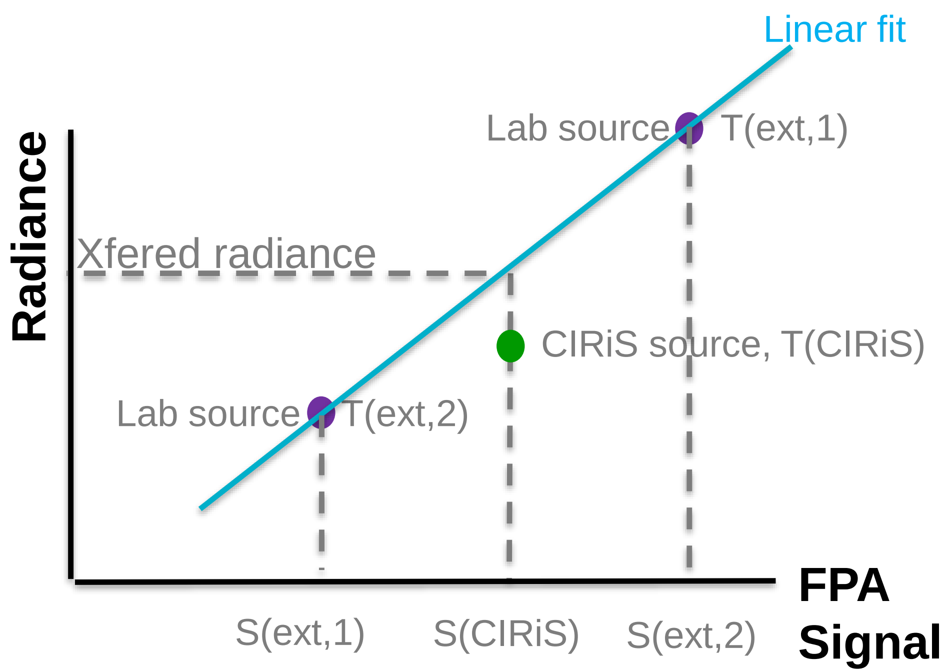
The TVAC temperature profile encompassed bakeout, and ranges for instrument survival, calibration and characterization testing



Transfer of calibration method is applied separately to each of two CIRiS on-board source

- FPA alternately views CIRiS source (T(CIRiS)) and external source (T(ext)), acquiring images
- Procedure implemented twice, with T(ext, 1) and T(ext, 2) ~ T(CIRiS) +/- 1 C

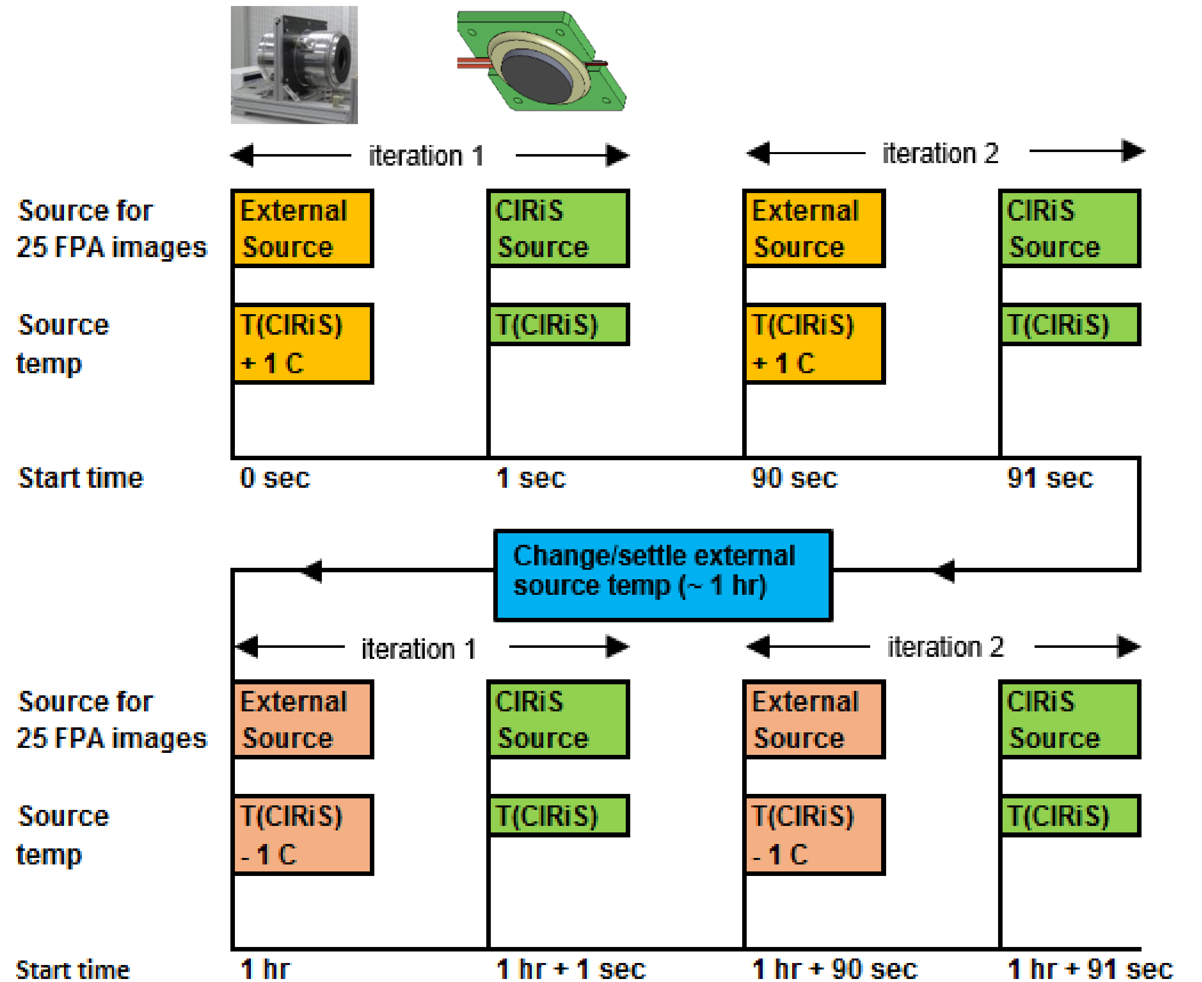


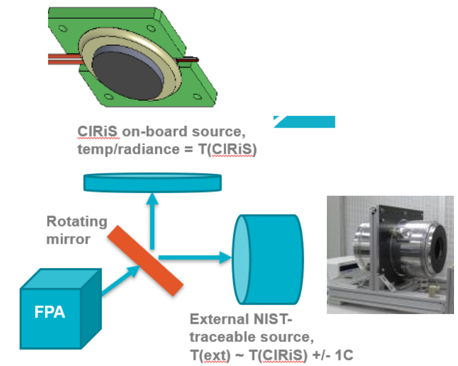


L(Xferred) =

$$\frac{[L(ext,2) - L(ext,1)]}{[S(ext,2) - S(ext,1)]} * [S(CIRiS) - S(ext,1)]$$

Transfer of calibration to one CIRiS 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

The CIRiS FPA is the source of the dominant temporal noise component impacting the transfer of calibration

- Temperature sensors (Platinum Resistance Thermometers) and FPA noise are sources of Type A uncertainty in transfer of calibration
- Depending on radiance levels and band, FPA noise dominates the other noise sources, moderately to significantly
- FPA noise amplitude can be reduced through frame averaging
  - On ground or on-orbit (frame shift and co-add in LEO orbit)

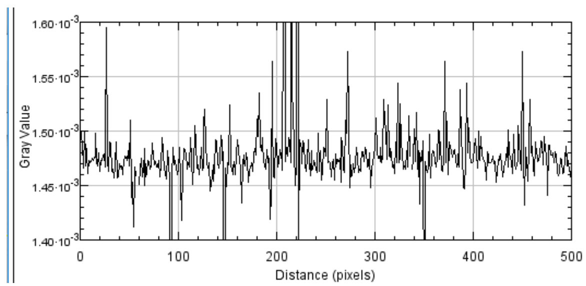
Sensor	Uncertainty (sensor reading)	Uncertainty (radiance W/m^2-sr)	
CIRiS temp sensor	+/- 5 mK	≤ 1 e -6	
LABB temp sensor	+/- 5 mK	≤ 1 e -6	
FPA	4 to 10 counts	1 e -6 to 1 e -5	Dominates

Effects of FPA temporal noise on transfer of calibration can be isolated, measured and parametrized

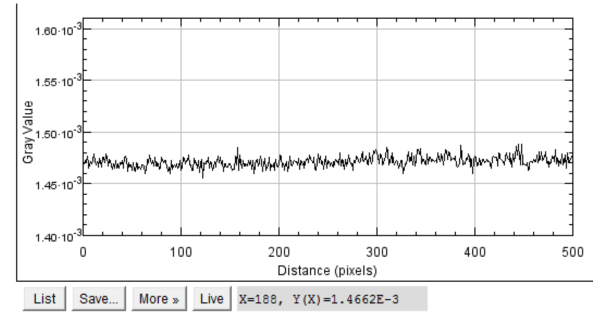
- Can measure FPA temporal noise effect in transfer of calibration data
  - Appears as standard deviation across any FPA pixel row that declines with frame averaging

Transfer of calibration to heated cal source at + 30 C, band 2, row 225

Xfered calibration (W/m^-sr)



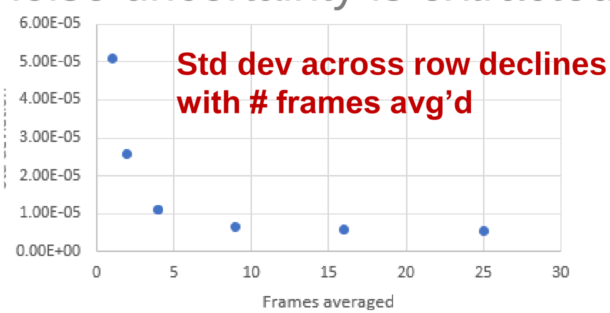
Xferred calibration across row, from single FPA frame



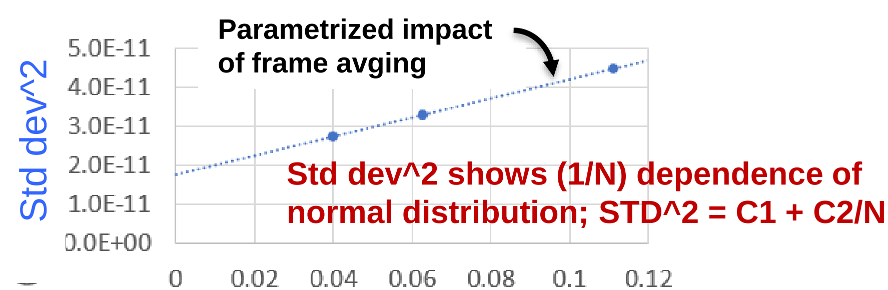
Xferred calibration across row, from 25 FPA frames averaged

- FPA noise uncertainty is extracted from standard deviation vs # of frames averaged

Stdt dev across row, in Xferred cal,



N frames averaged

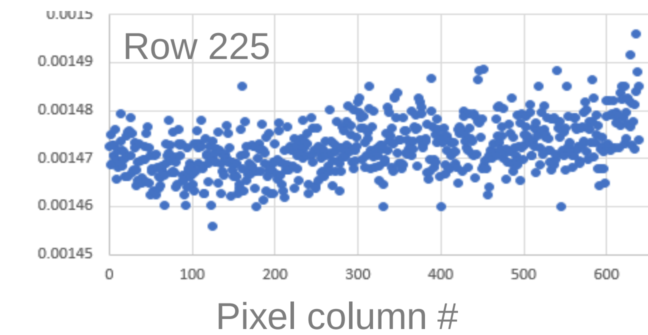


1/(N frames averaged)

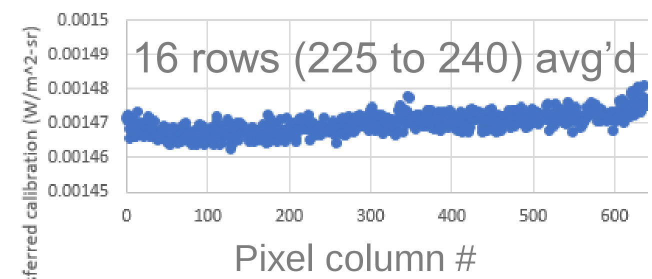
Several options exist for reducing FPA noise in transfer of calibration

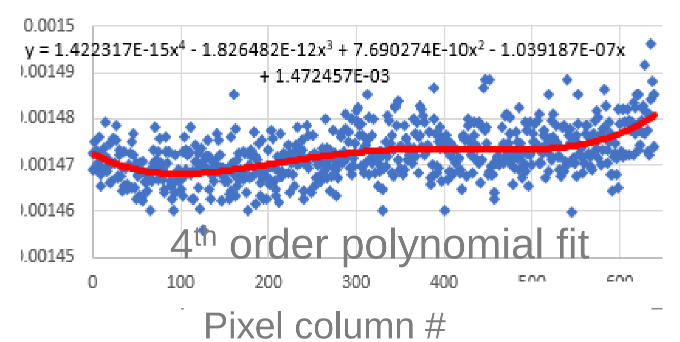
Transferred calibration across FPA columns, band 2, source temp +30.0 C

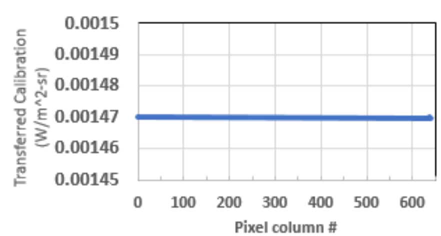
- Temporal averaging: Average 25 frames for each temperature and iteration



- 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)

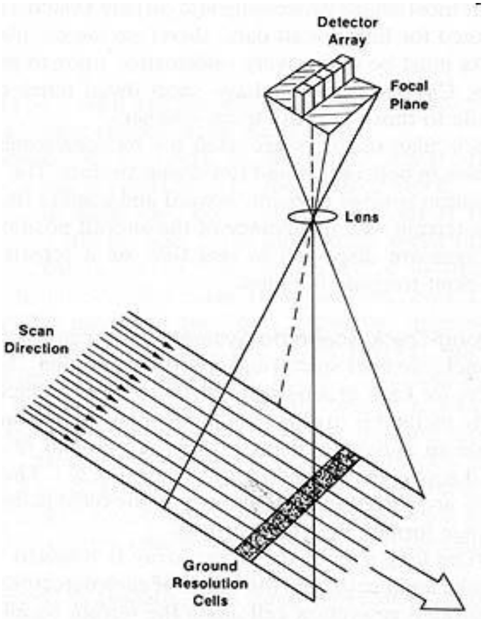






A note on CIRiS frame averaging (temporal averaging) for improved SNR

- CIRiS has been designed to frame average on orbit, in pushbroom mode, for improved SNR
  - Electronics implements on-board co-adding of consecutive frames, with row shift to compensate for nadir scan, (like TDI in CCDs)
  - Implemented independently in each spectral band
- Number of frames co-added, is selectable on-orbit
  - Up to 16 frames on-orbit, up to 25 frames on ground
  - Limitation on number of frames co-added is imposed by SRAM used in demonstration design



C. ALONG–TRACK SCANNER.

- A future CIRiS implementation will have capacity to co-add 100 X more frames, if desired, for greater SNR improvement

*Figure from https://www.slideshare.net/pramodgpramod/remote-sensing-scanners

Uncertainty analysis, Type A (statistical components) for different averaging approaches: 1

I. Frame averaging only (temporal averaging)

- Impact of frame averaging on scene temperature uncertainty depends on band because of different signal levels in bands

CIRiS band	Frames averaged	Uncertainty (radiance W/m^2-sr)	Uncertainty (scene temp C)	Note
1	25 frames	2.78e-6	0.03 C	measured
	100 frames	1.39e-6	0.015 C	extrapolated*
2	25 frames	2.62e-6	0.11 C	measured
	100 frames	1.31e-6	0.06 C	extrapolated
3	25 frames	1.33e-5	1.18 C	measured
	100 frames	6.64e-6	0.59 C	extrapolated

- All value iteration 2

*Extrapolation to 100 frames assumes SNR continues to improve as √# of frames.

Uncertainty analysis, Type A (statistical components) for different averaging approaches:2

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

- All value iteration 2

*Extrapolation to 100 frames assumes SNR continues to improve as √# of frames.

Uncertainty analysis, Type A (statistical components) for different averaging approaches: 3

III. Frame averaging (temporal averaging) AND average all pixels in band

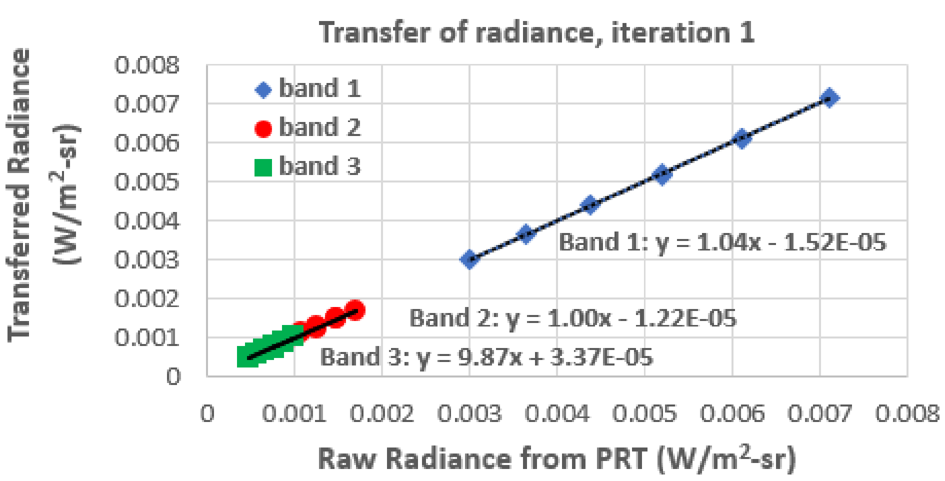
CIRiS band	Frames averaged	Uncertainty (radiance W/m^2-sr)	Uncertainty (scene temp C)	Note
1	25 frames	2.78e-6*	0.001 C	measured
2	25 frames	2.62e-6	0.003 C	measured
3	25 frames	1.33e-5**	0.03 C	measured

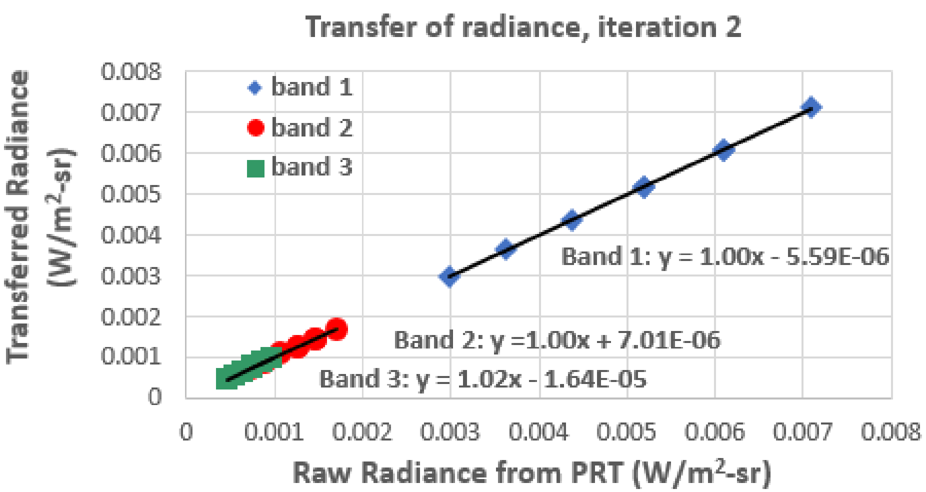
- All value iteration 2

Transfer of calibration relation when averaging over all pixels shows consistent behavior in all three bands

Observations:

- R^2 for all fits (iteration 1 and 2, all bands) > 0.99
  - R^2 for iteration 2, (all bands) > 0.998
- Iteration 2 slopes closer to 1.0, smaller (or equal) intercepts, higher R^2



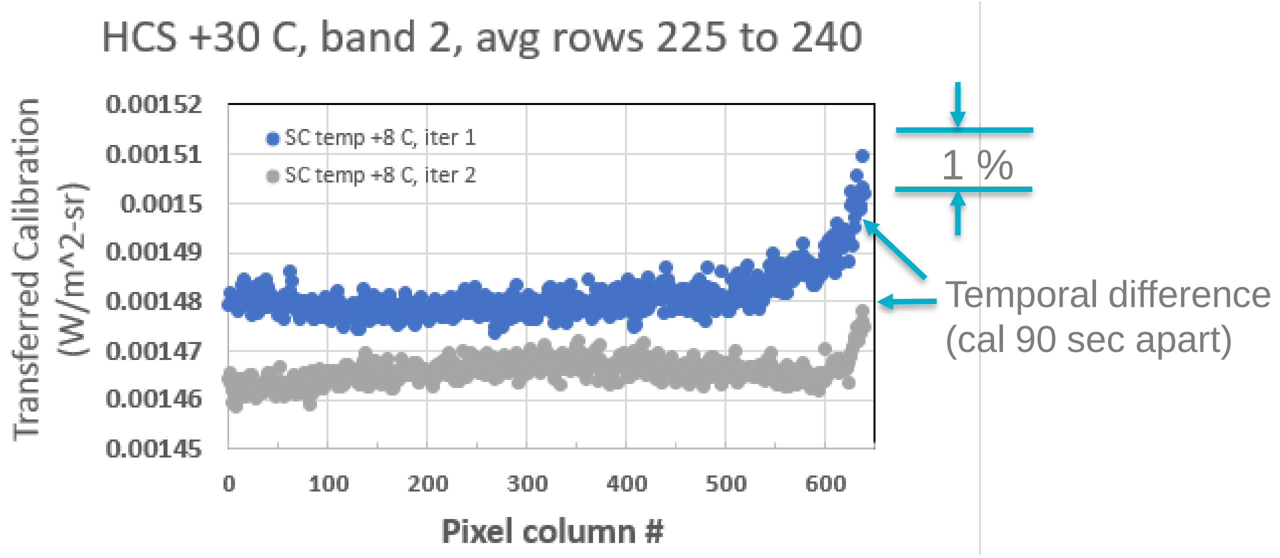


	Band 1			Band 2			Band 3		
	Slope	Inter cept	R^2	Slope	Inter cept	R^2	Slope	Inter cept	R^2
Iteration 1	1.005	1.2e-5	0.9998	0.9875	3.4e-5	0.9901	1.045	1.5e-5	0.9960
Iteration 2	1.001	0.56e-5	0.9999	1.001	0.70e-5	0.9982	1.028	1.6e-5	0.9984

Averaging the transfer of calibration over 16 rows in each band enables identification of small factors in calibration

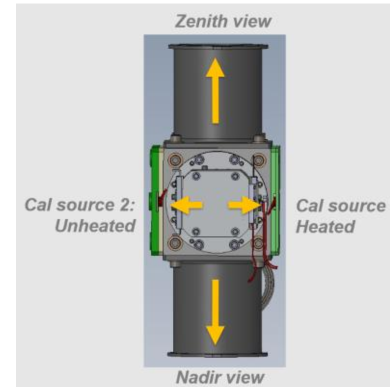
- Improve SNR in calibration transfer process by averaging 16 rows in each column
  - 16 averaged rows are those to be used on-orbit for pushbroom imaging

- Can observe impact on transferred calibration of:
  - spatial nonuniformity
  - Temporal differences (calibration performed 90 sec apart)

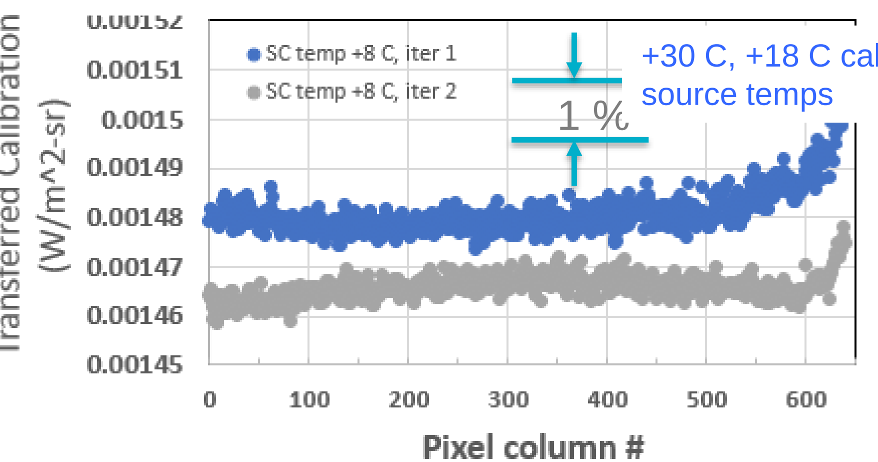


Reducing the difference in the CIRiS calibration source temperatures greatly reduces spatial nonuniformity, temporal effects and other nonideal effects

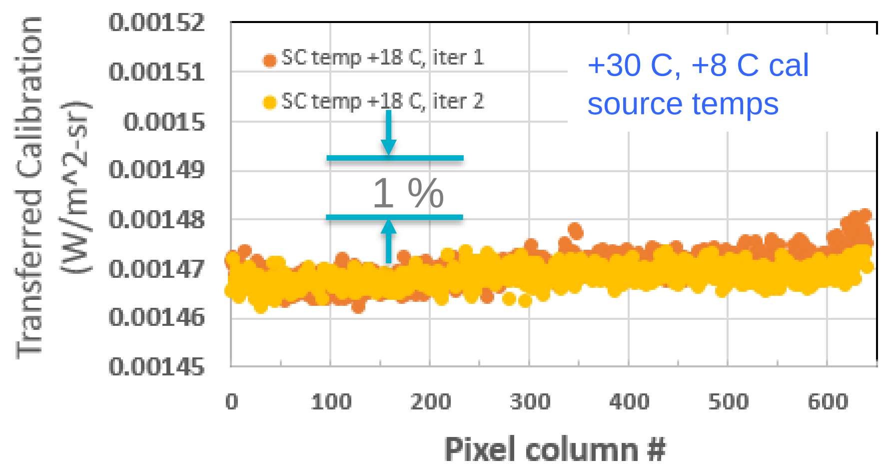
- With a +12 C difference in on-board cal source temperatures, nonuniformity of transferred calibration across FPA FOV is < 1%
- Change in transferred calibration with spacecraft temperature (+8 C to +18 C) is < 1 %
- Difference in transferred calibration between iteration 1 and iteration 2 is < 1 %
- With a +22 C difference in on-board cal source temperatures, these non-deal effects become larger



+22 C temperature difference between on-board cal sources



+12 C temperature difference between on-board cal sources



Conclusions

- A campaign of ground calibration, characterization and environmental testing on the CIRiS instrument/CubeSat spacecraft has been completed
- The testing included transfer of calibration from a NIST traceable source to the two CIRiS on-board carbon nanotube sources
- Several levels of processing have been applied to reducing statistical (noise) uncertainty in the transfer of calibration to the on-board sources
- Averaging 25 consecutive image frames and 16 image rows in each band results in noise uncertainty in the transferred calibration equivalent to < 0.3 C scene temperature in all bands
- Analysis of the ground calibration and characterization data continues
- Launch is scheduled for December 2019