ARCSTONE:

Calibration of Lunar Spectral Reflectance from Space

Funded by ESTO: IIP-QRS-16-0018

Constantine Lukashin[1]

**T.C. Stone[2], G. Kopp[3], T. Jackson[1], R. Swanson[4], C. Buleri[5], J. Beverly[1]
M. Cooney[1], H. Courrier[4], W. Davis[1], M. Kehoe[4], T. Nguyen[1]
G. Rutherford[1], N. Ryan[1], P. Smith[3], M. Stebbins[4], C. Young[1]**

1 – NASA Langley Research Center, Hampton, VA
2 – USGS, Flagstaff, AZ
3 – LASP Colorado U, Boulder, CO
4 – Resonon Inc., Bozeman, MT
5 – Quartus Engineering, San Diego, CA

PARTNERS:

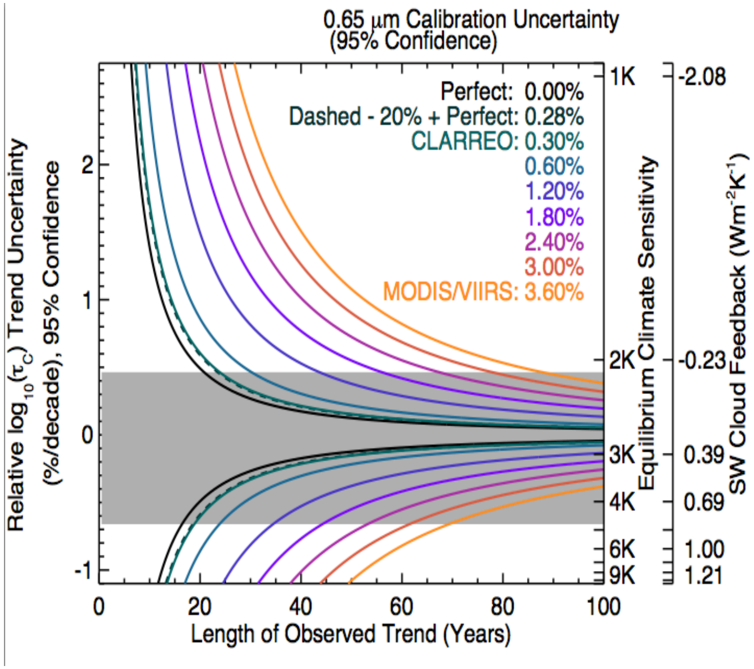
RESONON INC · LASP Laboratory for Atmospheric and Space Physics · USGS · QUARTUS ENGINEERING · BLUE CANYON TECHNOLOGIES · NIST · GSFC

NRC Decadal Survey 2017: Relevance

Inputs to the NRC DS 2017:

1. *Lukashin et al., "Accurate Inter-Calibration of Spaceborne Reflected Solar Sensors," input to NRC Decadal Survey, 2017.*

2. *Stone et al., "Redeveloping the Lunar Reflectance as a High-accuracy Absolute Reference for On-orbit Radiometric Calibration," input to NRC Decadal Survey, 2017.*



The estimated time to detect a relative cloud optical thickness trend (left y-axes) from natural variability is shown here linked to the SW Cloud Feedback and the equilibrium climate sensitivity (right y-axes). *Yolanda Shea et al., 2016*

Obtained information from a measurement is function of measurement uncertainty !

Accuracy (Type B uncertainty) is a key instrument performance parameter !

High absolute accuracy is required to mitigate gaps in observation records (e.g. SeaWIFS/PACE, CERES).

Moon: Solar Diffuser For Instrument Calibration In-orbit

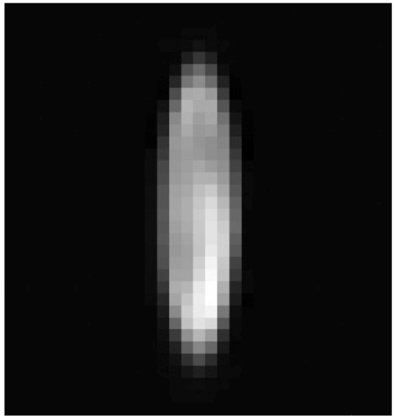
Just One Short Message: Current EOS designed on overlapping observations !
Cannot handle data gaps ! (CERES, MODIS/VIIRS, Landsat, PACE/SeaWIFS, etc.)

Need: Absolute accurate spectral irradiance for all lunar phase and libration states !

Reflectance of Lunar surface stable to < 10^{-8} / year

Calibration reference:
Lunar irradiance (entire disk)

Lunar image by SeaWIFS



SeaWiFS gain stability 0.13% (k=1) over 12 years -- achieved with Lunar calibration

Current ROLO Accuracy: estimated 5 – 10%

Applications of the Lunar Calibration Approach

Team	Satellite	Sensor	G/L	Dates	Number of obs	Phase angle range (°)
CMA	FY-3C	MERSI	LEO	2013-2014	9	[43 57]
CMA	FY-2D	VISSR	GEO	2007-2014		
CMA	FY-2E	VISSR	GEO	2010-2014		
CMA	FY-2F	VISSR	GEO	2012-2014		
JMA	MTSAT-2	IMAGER	GEO	2010-2013	62	[-138,147]
JMA	GMS5	VISSR	GEO	1995-2003	50	[-94,96]
JMA	Himawari-8	AHI	GEO	2014-	-	
EUMETSAT	MSG1	SEVIRI	GEO	2003-2014	380/43	[-150,152]
EUMETSAT	MSG2	SEVIRI	GEO	2006-2014	312/54	[-147,150]
EUMETSAT	MSG3	SEVIRI	GEO	2013-2014	45/7	[-144,143]
EUMETSAT	MET7	MVIRI	GEO	1998-2014	128	[-147,144]
CNES	Pleiades-1A	PHR	LEO	2012	10	[+/-40]
CNES	Pleiades-1B	PHR	LEO	2013-2014	10	[+/-40]
NASA-MODIS	Terra	MODIS	LEO	2000-2014	136	[54,56]
NASA-MODIS	Aqua	MODIS	LEO	2002-2014	117	[-54,-56]
NASA-VIIRS	NPP	VIIRS	LEO	2012-2014	20	[50,52]
NASA-OBPG	SeaStar	SeaWiFS	LEO	1997-2010	204	(<10, [27-66])
NASA/USGS	Landsat-8	OLI	LEO	2013-2014	3	[-7]
NASA	OCO-2	OCO	LEO	2014		
NOAA-STAR	NPP	VIIRS	LEO	2011-2014	19	[-52,-50]
NOAA	GOES-10	IMAGER	GEO	1998-2006	33	[-66, 81]
NOAA	GOES-11	IMAGER	GEO	2006-2007	10	[-62, 57]
NOAA	GOES-12	IMAGER	GEO	2003-2010	49	[-83, 66]
NOAA	GOES-13	IMAGER	GEO	2006	11	
NOAA	GOES-15	IMAGER	GEO	2012-2013	28	[-52, 69]
VITO	Proba-V	VGT-P	LEO	2013-2014	25	[-7]
KMA	COMS	MI	GEO	2010-2014	60	
AIST	Terra	ASTER	LEO	1999-2014	1	-27.7
ISRO	OceanSat2	OCM-2	LEO	2009-2014	2	
ISRO	INSAT-3D	IMAGER	GEO	2013-2014	2	

Instruments with lunar observation capabilities Participating in the GSICS GIRO program: All satellite operators !

From GSICS Lunar Calibration Workshop, December 2014, EUMETSAT.

Not included by GSICS: commercial land imager constellations (e.g. Planet)

Next GSICS Workshop, Fall 2019 , London, UK: ARCSTONE is invited to present .

ARCSTONE Mission Concept

Concept of Operations and Data Products:

- Data to collect: Lunar spectral irradiance every 12 hours, 10 minutes
- Data to collect: Solar spectral irradiance TBD (at least weekly)
- Combined uncertainty < 0.5% (k=1)
- Spectrometer with single-pixel field-of-view about 0.52^o (no scanning !)
- Sun synchronous orbit at 500 – 600 km altitude
- Spectral range from 350 nm trade to 2300 nm, spectral sampling at 4 nm

After 1 year: Improvement of current Lunar Calibration Model (factor > 2);
After 3+ years: New Lunar Irradiance Model, improved accuracy level (factor > 10).

Key Technologies to Enable the Concept:

- Approach to orbital calibration via referencing Sun (TSIS measurements): Demonstration of lunar and solar measurements with *the same optical path using integration time to reduce solar signal -- Major Innovation !*
- Pointing ability of small spacecraft now permits obtaining required measurements *with instrument integrated into spacecraft*

Project Approach:
- Achieve TRL5 by March 2021
- As close to flight as allowed by schedule and budget !

ARCSTONE: Key Mission Performance Parameters

Key Performance Parameters (KPP)	Threshold Value	Goal Value
Accuracy (reflectance)	1.0% (k=1)	0.5% (k=1)
Stability	< 0.15% (k=1) per decade	< 0.1% (k=1) per decade
Orbit	Sun-synch orbit	Sun-synch orbit
Time on-Orbit	1 year	3 years
Frequency of sampling	24 hours	12 hours
Instrument pointing	< 0.2^{o} combined	< 0.1^{o} combined
Spectral Range	380 nm – 900 nm	350 nm – 2300 nm
Spectral Sampling	8 nm	4 nm

* Requirements are captures in a Mission Requirements Doc

* * Threshold Values considered as success criteria

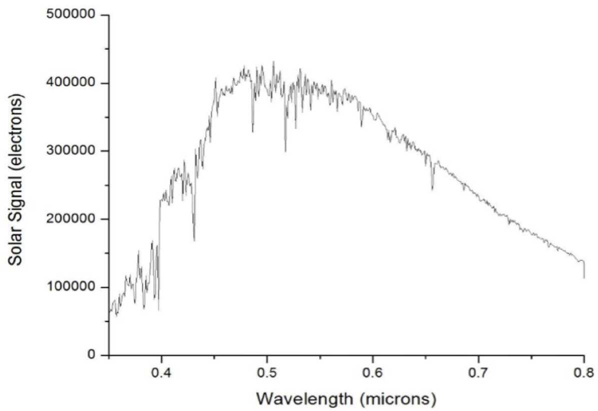
Reference for radiometric requirements (ROLO, T. Stone):
Lunar Phase Angle = 75^{o};
Irradiance = 0.6 (micro W / m^2 nm)
Wavelength = 500 nm

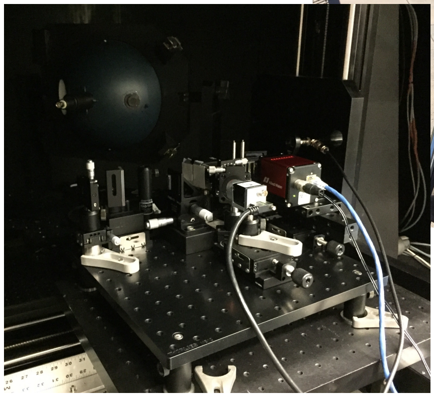
ARCSTONE: Project Timeline and Status

Concept brainstorming: down-select on January 9, 2016
Breadboard design & build by March 2016
Breadboard tested at NIST in April 2016

NASA LaRC et al., IIP proposal funded in March, 2017
Resonon Inc., SBIR Phase-2 funded July, 2017

- Formulation and procurement by August 2017
- Preliminary design, Summer 2017
- Design and STOP analysis completed by March 2018
- Prep. work for fabrication completed by May 2018
- Detectors tested (TVAC included) by Fall 2018
- UVVNIR FPA characterized by January 2019
- Fabrication completed by February 2019
- UVVNIR assembled/aligned by March 2019
- New FSR instrument concept, March 2019
- SWIR IDCA characterization: on going
- SWIR assembly/alignment: on hold
- UVVNIR Characterization: Summer 2019





Breadboard at NIST
April 2016

ARCSTONE: Mission Concept and Week in Life

1. Lunar spectral irradiance observations:
- Every 12 hours
- Close to polar locations
- Multiple measurements within 5– 10 minutes to get required SNR

2. Solar Spectral Irradiance observations (solar calibration):
- Every TBD days (e.g. daily)
- Multiple measurements to get required SNR
- This is radiometric calibration to the TSIS reference

3. Dark images:
- Multiple measurements with closed shutter
- Before every lunar and solar observations

4. Dark field (to calibrate out shutter temp):
- Multiple measurements of dark space
- TBD (e.g. daily)

5. Field-of-view sensitivity characterization:
- Calibration of instruments alignment
- TBD (e.g. weekly)

6. Spectral calibration:
- Fraunhofer lines (TBD)
- On-board spectral calibration (TBD)

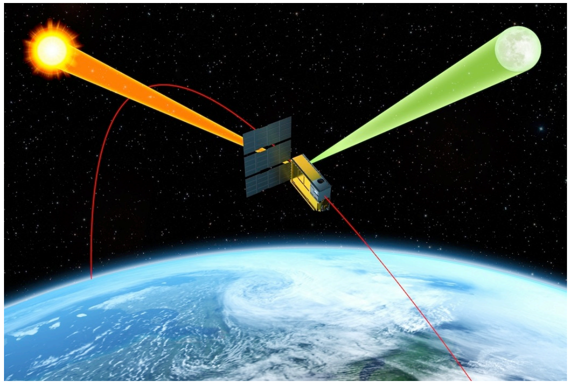
7. Spacecraft pointing calibration (and other checks):
- Defined by the BCT for calibration of spacecraft functions

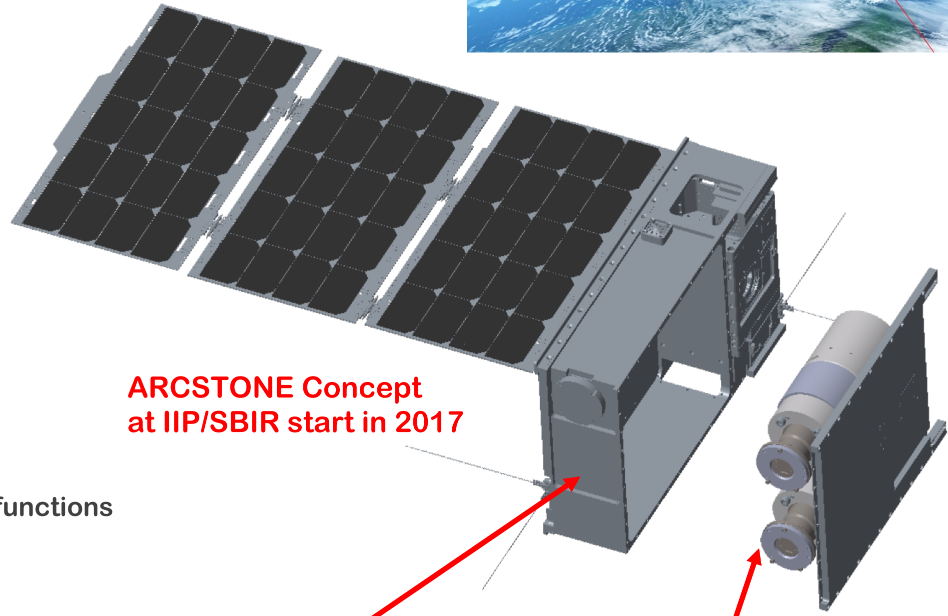
8. Stand by mode:
- Mode between lunar and solar observations

9. Safe mode (TBD)

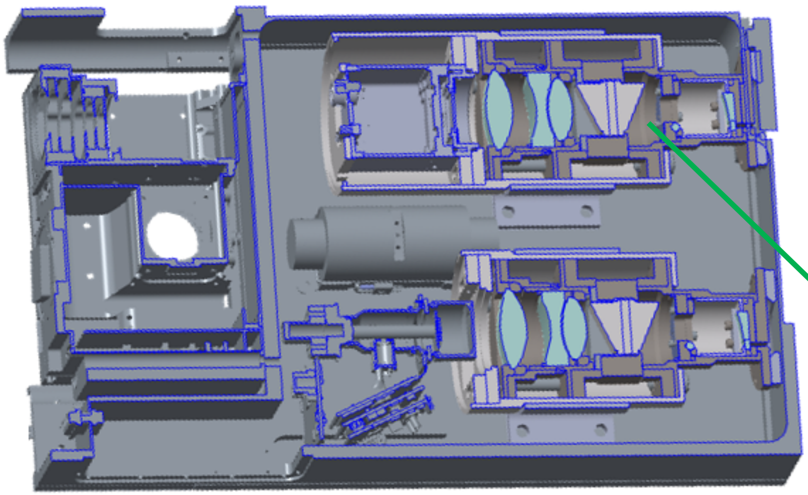
10. On-board data processing mode

11. Down-link data mode



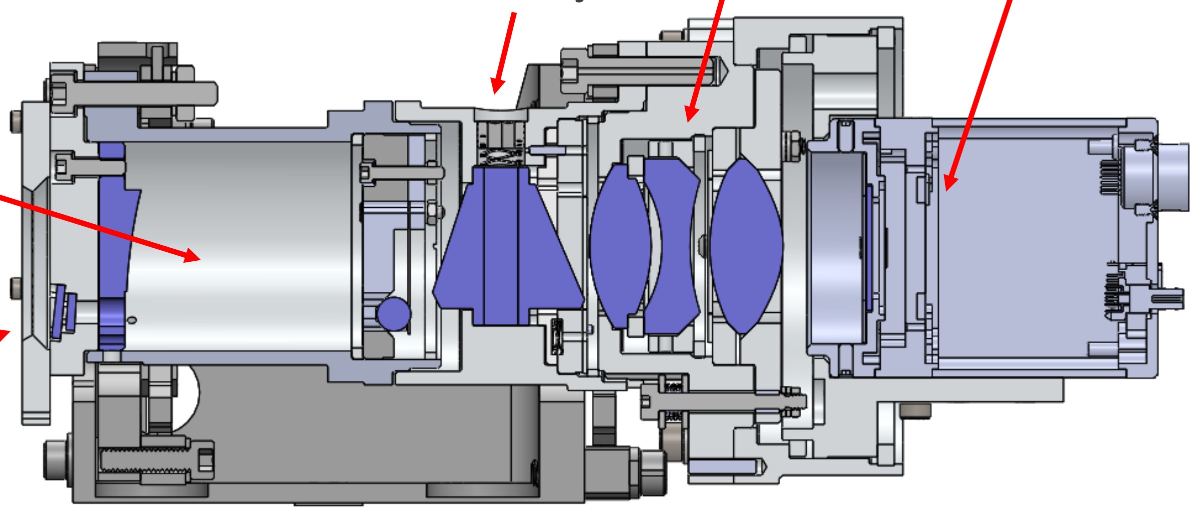


ARCSTONE: Observatory and Instrument Design



Cubesat 6U bus:
Courtesy of Blue Canyon Technologies

Preliminary System Design



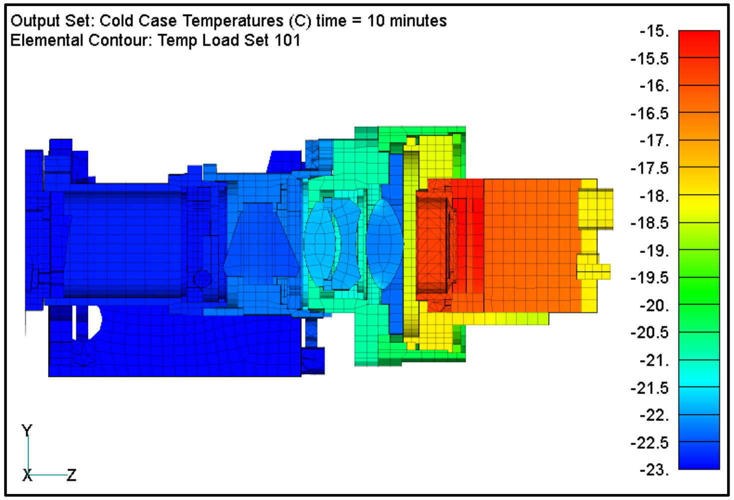
Prototype of ARCSTONE UVVNIR Instrument

ARCSTONE: STOP Analysis by Quartus & Resonon, Inc.

Orbital States from LaRC team →

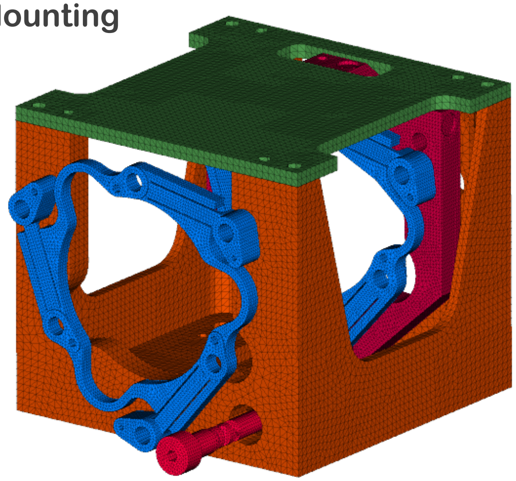
Current design assumes large thermal changes in orbit !

Thermal Modeling
Temperature Mapping
Thermoelastic Modeling
Nonlinear Analysis Considerations
Zernike Calculation
Zemax Modeling
Thermoelastic Changes of Lenses
Optical Effects of Thermal Stress
Mount Modifications of Lenses



Temperature Mapping Results

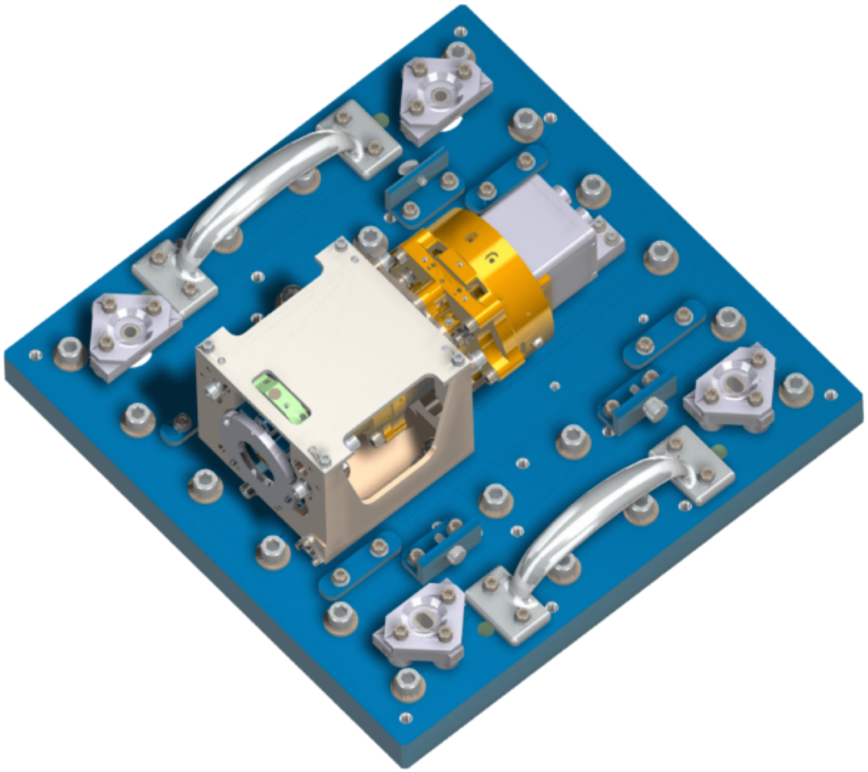
Flexure Mounting



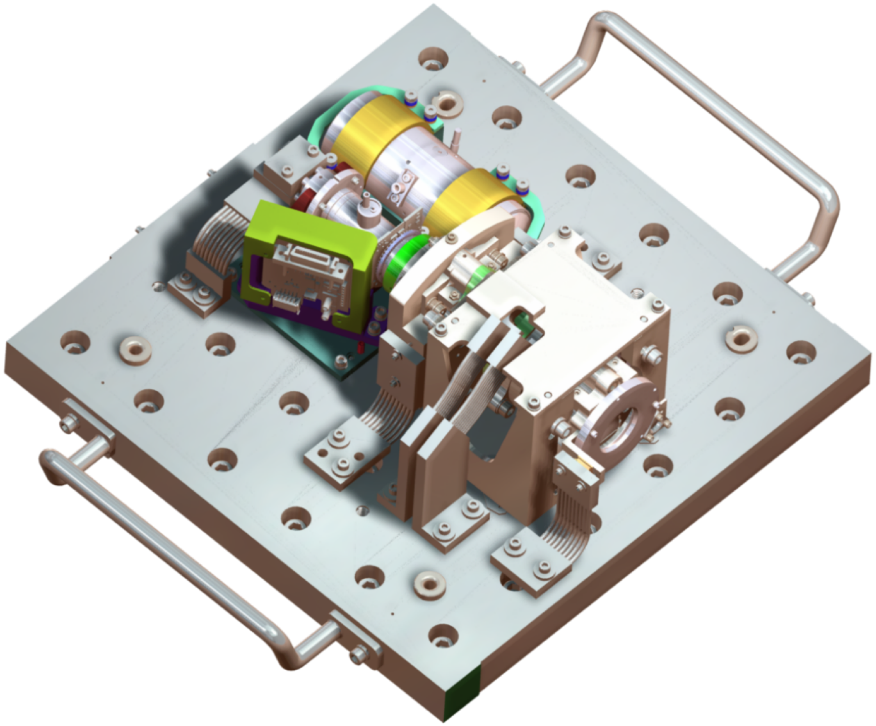
Thermoelastic Results

ARCSTONE: IIP designed Instruments (EDU)

- Designed for Development Vibe/TVAC but not flight hardware, complete in March 2018
- This is what went into fabrication in April/May 2018, completed in February 2019

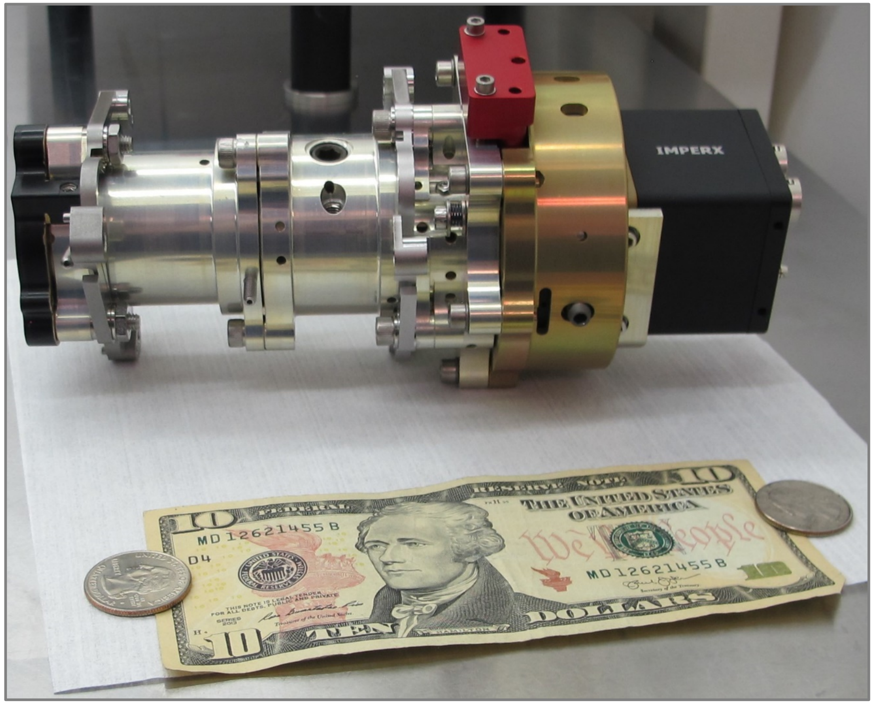


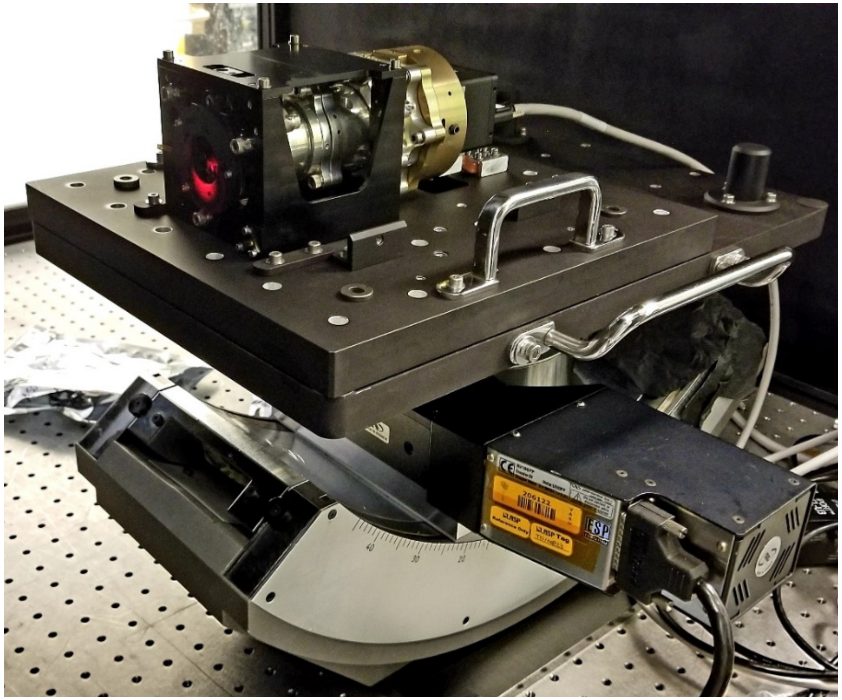
UVVNIR Spectrometer – Ultraviolet Visible Near Infrared 350-900 nm
Transmission Grating Spectrometer
Uncooled FPA and Optic Train



SWIR Spectrometer – Short Wave Infrared 880-2300 nm
Transmission Grating Spectrometer
Cooled FPA and Optic Train

ARCSTONE: Fabricated & Assembled UVVNIR





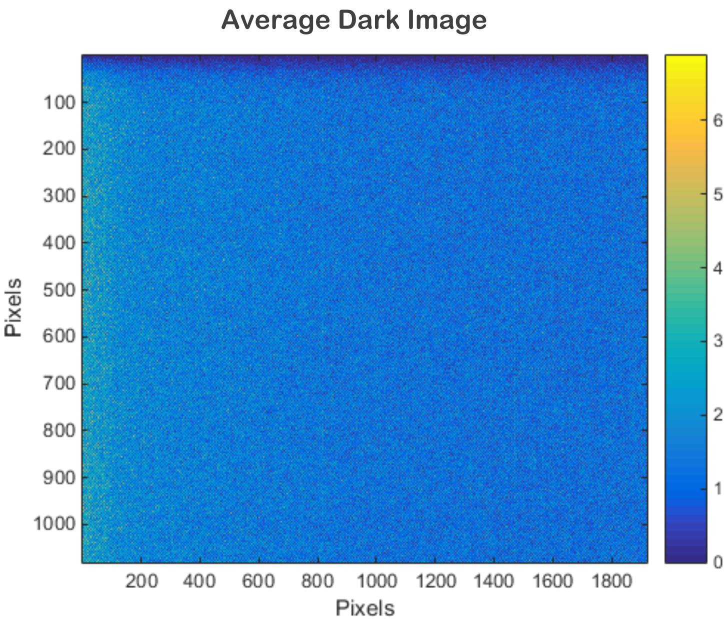
UVVNIR Instrument:
- CCD characterized
- Assembly /Alignment completed

UVVNIR Instrument:
- Ready for characterization at LASP

Path Forward: Future Field campaigns and vibe/TVAC tests

ARCSTONE UVVNIR: Camera Characterization

- Sensor is remarkably uniform
  - *No hot pixels*
  - *No dead pixels*
  - *Only 10's of pixels with > 5σ average noise*
- Narrow band (20-30 pixels) of pixels with lower fixed-pattern noise offset at top of sensor
- Appears to have ~1 DN electronic checkerboard pattern noise (correctable via dark-image subtraction)

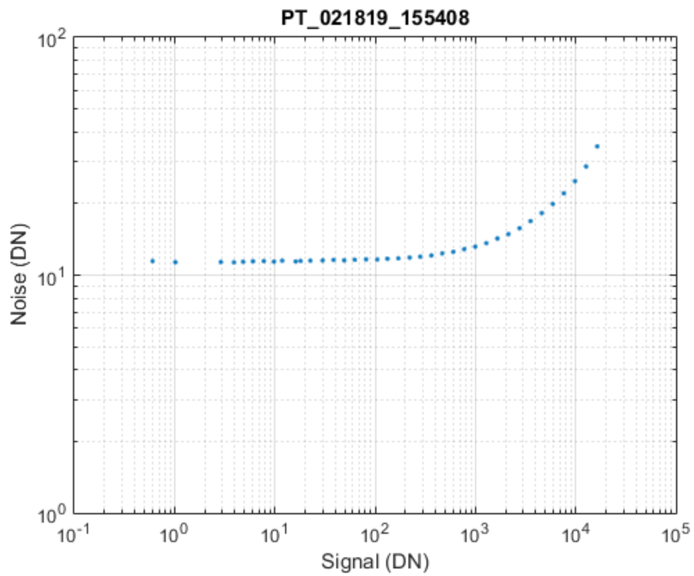


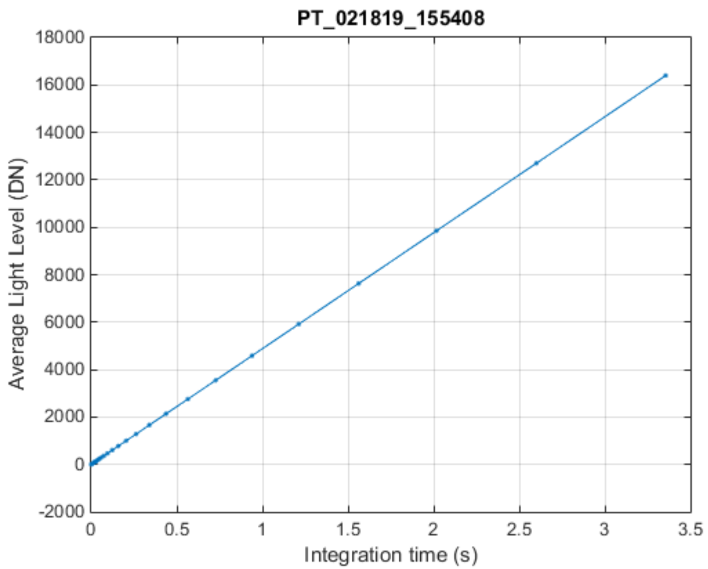
Imperx Camera Conclusions

- Camera is consistent enough to be usable in high-accuracy measurements, with ~0.1% – 0.3% (k=1) uncertainty
  - *Final uncertainty values will depend on number of pixels used for averaging*
- There are a number of features that can be overcome through dark-image subtraction and flat-field correction
  - *Non-uniform fixed-pattern noise*
  - *Standard deviation on pixel gains is $0.47\ e^-/DN$*
- Dark current is much lower than expected from spec sheets

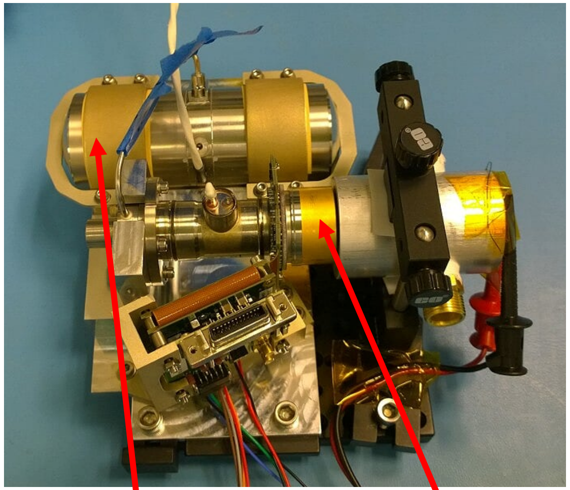
- Imperx camera characterized at LASP
- Imperx camera TVAC tested at LaRC

ARCSTONE SWIR: IDCA Characterization





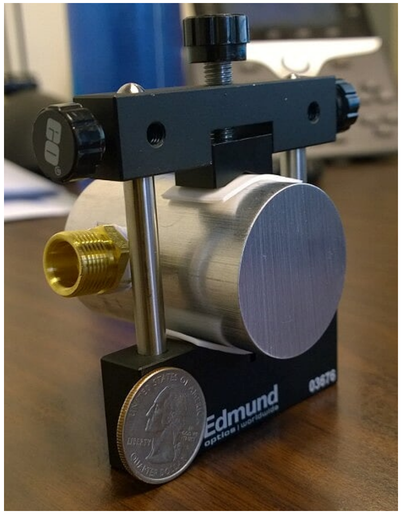
- The transfer gain would be approximately 25.8 e-/DN, and the full well would be approximately 1.18 Me^-



SF070 Cryocooler (AIM)

Mini-Nyx 640 MCT Detector (AIRS)

Cold source by P. Smith:

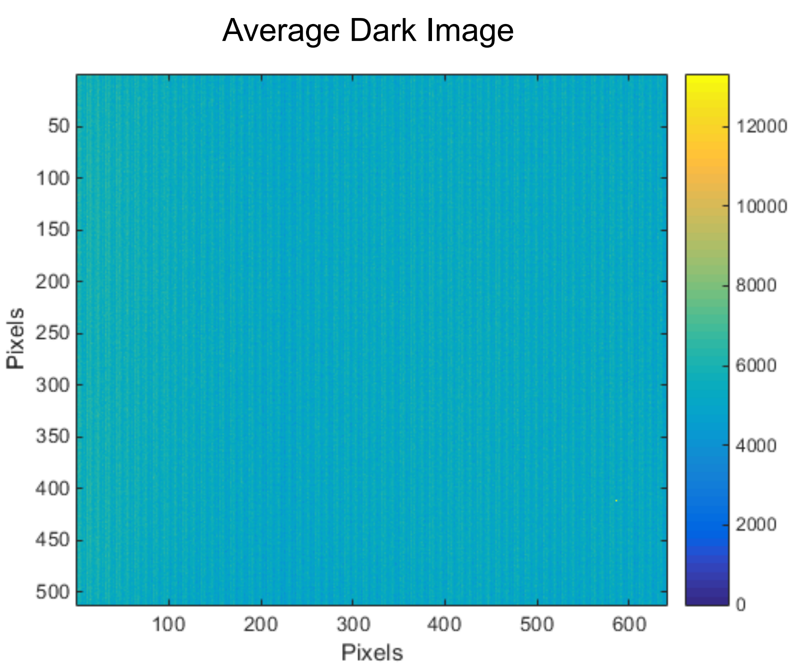


Major Credits:

- IDCA selection/acceptance: Mike Cooney (NASA LaRC)
- Mechanical design: Trevor Jackson (NASA LaRC)
- IDCA characterization: Paul Smith (LASP, CU)

Sensor Uniformity

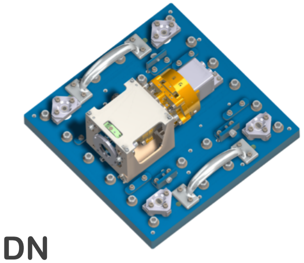
- Sensor is uniform
  - *745 hot/dead pixels*
  - *Only 2 pixels with no normal surrounding pixels*
- Vertical banding apparent in both dark and light images
  - *Eliminated through dark subtraction*



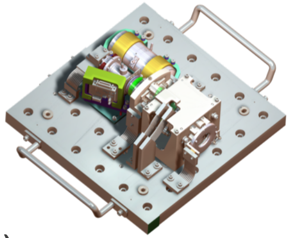
SWIR IDCA Conclusions

- Camera has exhibited offset behavior that limits its usability to *1-2%* accuracy:
  - *Root cause of behavior is unknown*
  - *With additional study time, it may be possible to correlate behavior with another factor (cryo power, temperature, etc.) and create a correction*
  - *However, the camera has moved to the integration phase due to schedule pressure*
- Other random noise sources together are small enough to make *the camera usable in the 0.3% uncertainty range if the offset uncertainty is discovered*
  - *Final uncertainty values will depend on number of pixels used for averaging*
- *Future camera studies will benefit from the investigation of the camera settings and the equipment and experiment setup used to measure this sensor. Work in progress…*
- *Integration time from 10^{-4} to 3.3 seconds !*

ARCSTONE: Engineering Summary



- **Ultraviolet Visible Near Infrared (UVVNIR) Channel**
  - 350-900 nm transmission grating spectrograph, uncooled FPA and optical train
  - Volume: 211.9 mm x 97.0 mm x 91.9 mm, Mass: 1.288 kg (instrument channel alone)
  - Detector Performance: Average Dark Current at 40° C: ~1 e-/s/pixel, Average Read Noise: 2.9 DN, Full Sensor Linearity: less than a 0.2% correction from 0 – 12000 DN (73% of the dynamic range), Average Transfer Gain: 2.3 e-/DN
  - Optical Performance*: Spectral line-width determination, Wavelength calibrations, Sensitivity to polarization, Field-of-view sensitivity, Stray light characterization, Moon shape sensitivity (via analysis)
  - Environmental Testing*: Vacuum bakeout, vibration, instrument performance at varying temperatures, go/no go functional test pre and post each environmental test
  - Data readout format: Intensity values

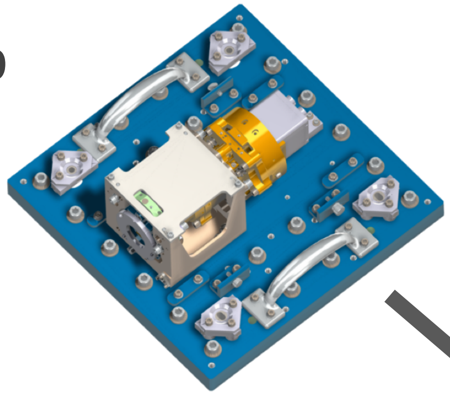


- **Short Wave Infrared (SWIR) Channel**
  - 880-2300 nm transmission grating spectrograph, cooled FPA and optical train
  - Volume: 249.9 mm x 149.5 mm x 96.2 mm, Mass: 2.35 kg (estimated, instrument alone)
  - Detector Performance: Average Dark Current at 140 K: 3800 e-/s/pixel, Average Read Noise: 10.9 DN, Full Sensor Linearity: Less than a 0.2% correction from 0 – 50,000 DN (76% of the dynamic range), Average Transfer Gain: 25.8 e-/DN
  - Optical Performance*: Spectral line-width determination, Wavelength calibrations, Sensitivity to polarization, Field-of-view sensitivity, Stray light characterization, Moon shape sensitivity (via analysis)
  - Environmental Testing*: Vacuum bakeout, vibration, instrument performance at varying temperatures, go/no go functional test pre and post each environmental test
  - Data readout format: Intensity values

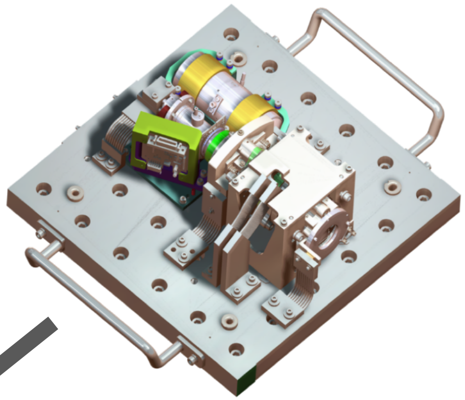
*to be completed

ARCSTONE: Full Spectral Range (FSR) Instrument

2017 – 2019
IIP work

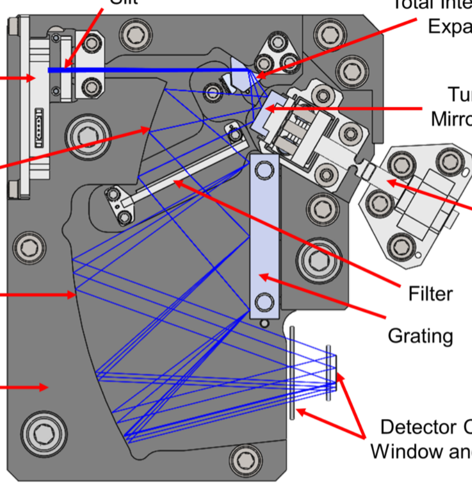


Ultraviolet Visible Near Infrared (UVVNIR)



Short Wave Infrared (SWIR)

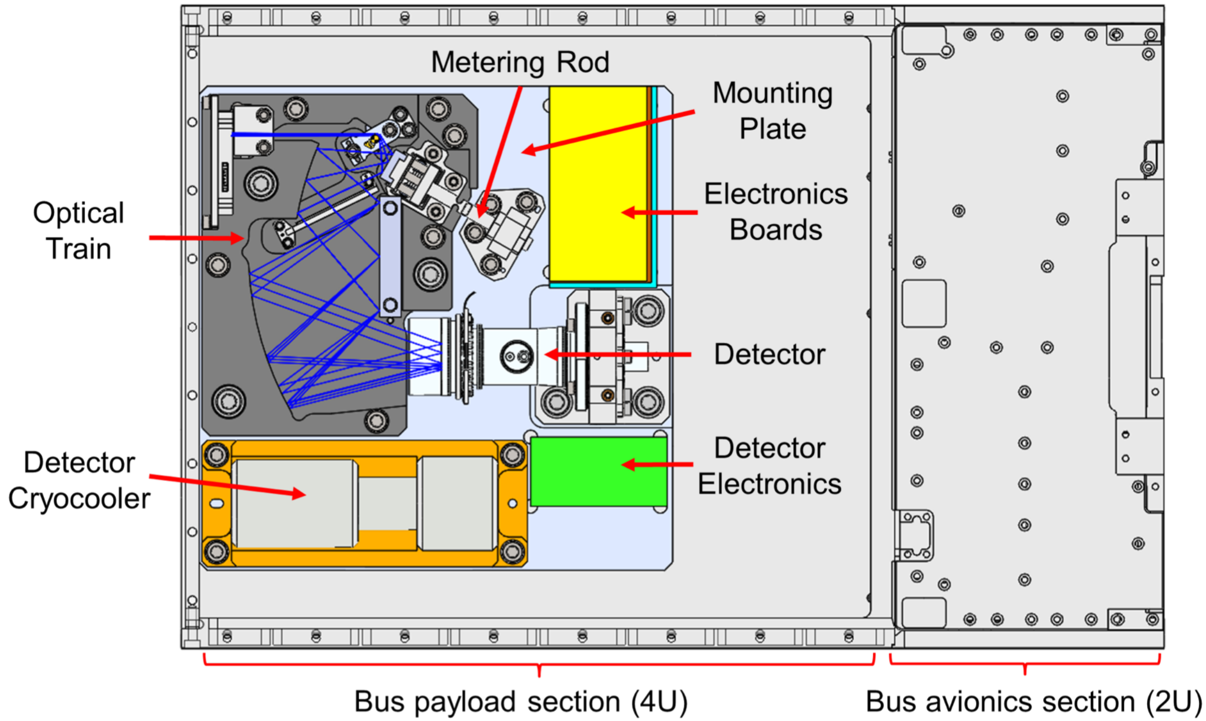
2019 – 2021
IIP work



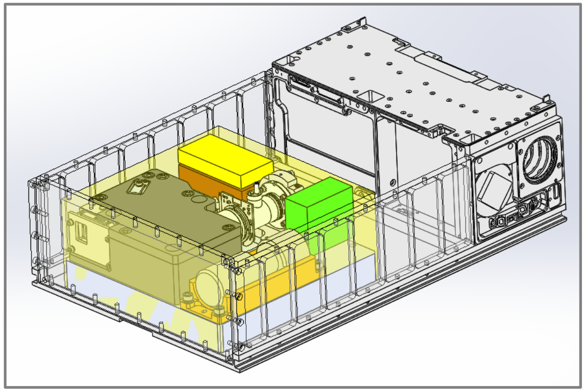
******Single channel system*, thinned MCT detector covers 350 – 2300 nm wavelength range**

ARCSTONE 2019: FSR Instrument

New Design based on concept from Mission Development Lab: Oct. 2018 at LaRC



Blue Canyon Technologies (BCT) XB6 Spacecraft Bus (6U)



Volumetric margin: 52%

- LaRC et al., IIP extended to Q2 / FY21
- Resonon et al., SBIR Phase-2, FY19 – FY21

ARCSTONE FSR Status:
Optomechanical Design and STOP Analysis by end of FY19.

ARCSTONE Web, *http://arcstone.larc.nasa.gov*

THANK YOU !