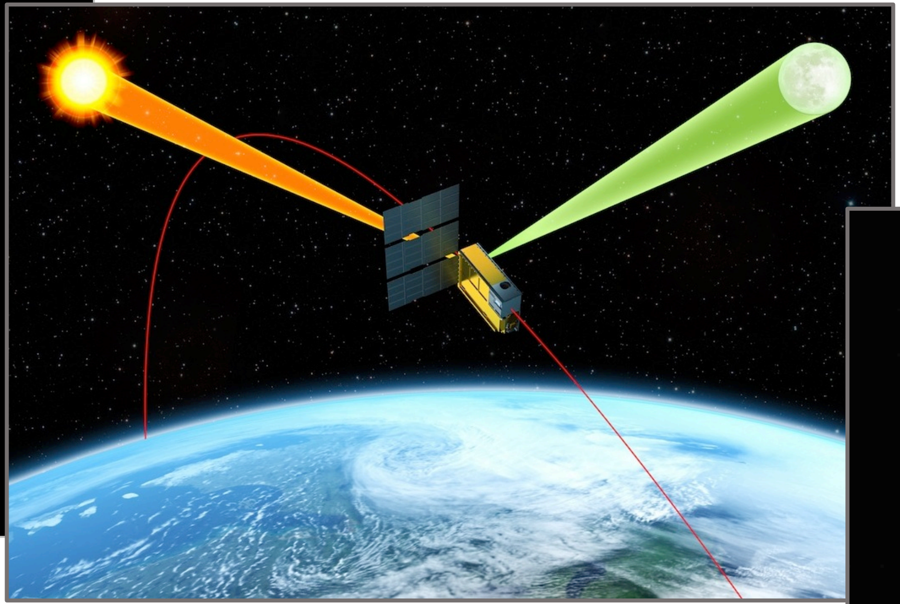
ARCSTONE

T. Stone, C. Lukashin, et al., “Redeveloping the Lunar Reflectance as a High-accuracy Absolute Reference for On-orbit Radiometric Calibration,” input to NRC Decadal Survey, 2017.

ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

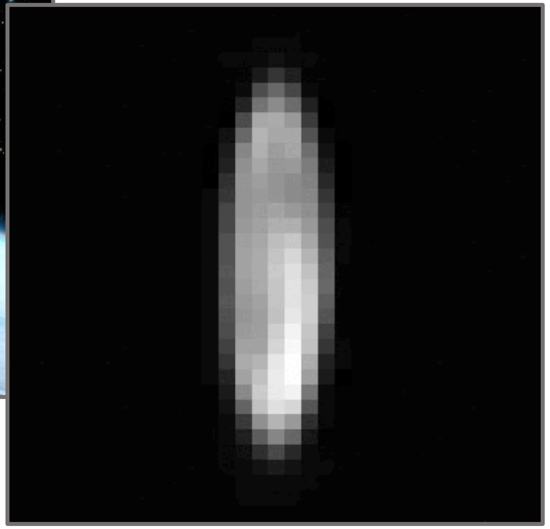
Lunar Surface Reflectance: Invariable < 10^{-8}



Accurate measurements of Lunar Irradiance from Space

Lunar Irradiance Model

Sensor Calibration



ARCSTONE Team

Principal Investigator: Constantine Lukashin[1]

Lead Engineer: Trevor Jackson[1] (presenting)

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3 – LASP Colorado U, Boulder, CO
4 – Resonon Inc., Bozeman, MT
5 – Quartus Engineering, San Diego, CA

PARTNERS:

USGS **LASP** **Resonon** **Quartus Engineering** **Blue Canyon Technologies** **NIST** **GSFC**

ARCSTONE Moon as Solar Diffuser For Instrument Calibration

Current EOS designed on overlapping observations – Cannot handle data gaps !
(CERES, MODIS/VIIRS, Landsat, PACE/SeaWIFS, etc.)

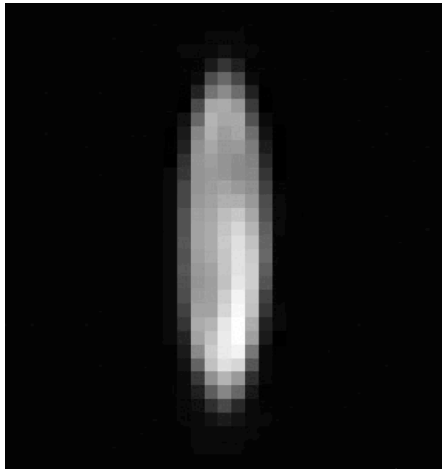
Remote Sensing Calibration Need:

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

Current ROLO Accuracy: estimated 5 – 10%

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

ARCSTONE Applications of the Lunar Calibration Approach

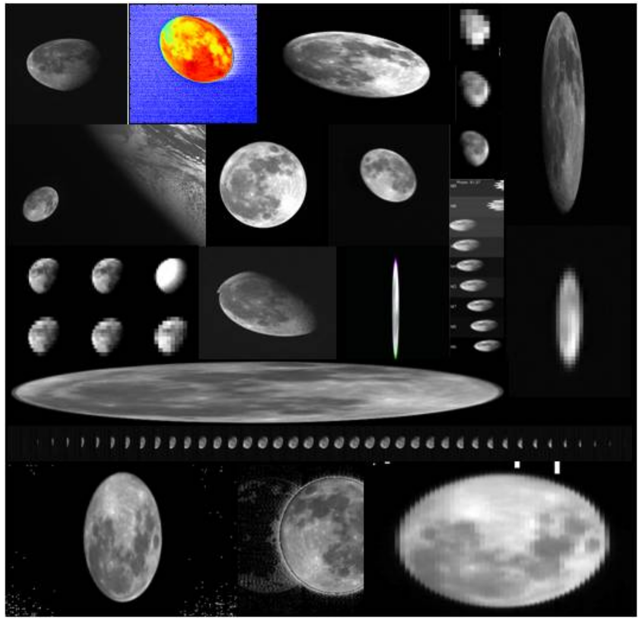
Team	Satellite	Sensor	G/L	Dates	Number of obs	Phase angle range (°)
CMA	FY-3C	MERSI	LEO	2013-2014	9	[43 57]
CMA	FY-2D	VISSR	GEO	2007-2014		
CMA	FY-2E	VISSR	GEO	2010-2014		
CMA	FY-2F	VISSR	GEO	2012-2014		
JMA	MTSAT-2	IMAGER	GEO	2010-2013	62	[-138,147]
JMA	GMS5	VISSR	GEO	1995-2003	50	[-94,96]
JMA	Himawari-8	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)

Images of the Moon from spaceborne sensors



ARCSTONE Mission Concept

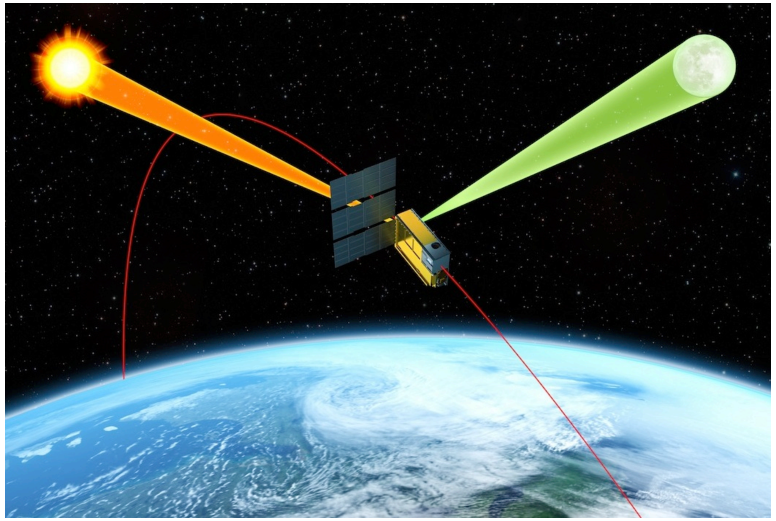
Concept of Operations and Data Products:

- Data to collect: Lunar spectral irradiance every 12 hours, 10 minutes
- Data to collect: Solar spectral irradiance for calibration (at least weekly)
- Combined uncertainty < 0.5% (k=1)
- Grating spectrometer with single field-of-view about 0.6° (no scanning !)
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm
- Sun synchronous orbit at 500 – 600 km altitude

1 year: Improvement of current Lunar Calibration Model (factor > 2);
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.*



6U CubeSat Spacecraft Bus:
courtesy of Blue Canyon Technologies

ARCSTONE CONOPS & Calibration Strategy

Operation Modes:

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

2. Solar Spectral Irradiance observations (solar calibration):
- Every TBD days (e.g. daily)
- 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 offsets):
- Multiple measurements of dark space
- TBD (e.g. daily)

5. Spectral calibration:
- On-board spectral calibration (TBD)
- Occultation measurement of atmosphere (absorption lines)

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

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

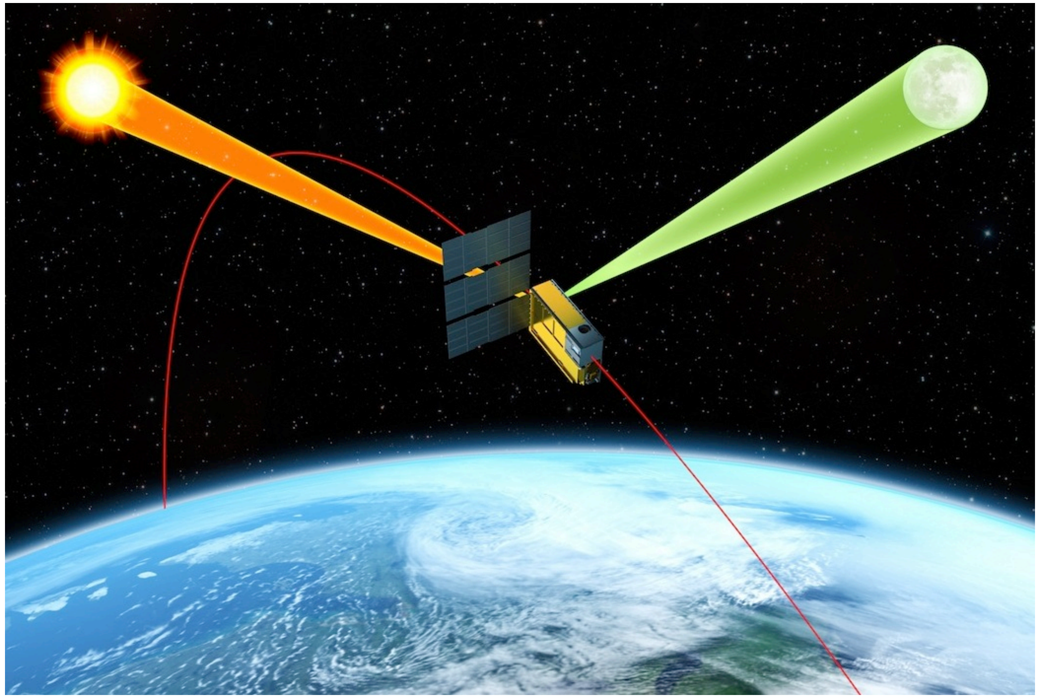
8. Safe mode

9. On-board data processing mode

10. Data downlink mode

ARCSTONE Calibration Strategy:

- Detailed ground characterization
- Absolute calibration on-orbit referencing SSI established by the TSIS/SIM
- Calibration and measurements with the same optical path !



ARCSTONE Absolute Calibration On-orbit

ARCSTONE Key Mission Performance Parameters

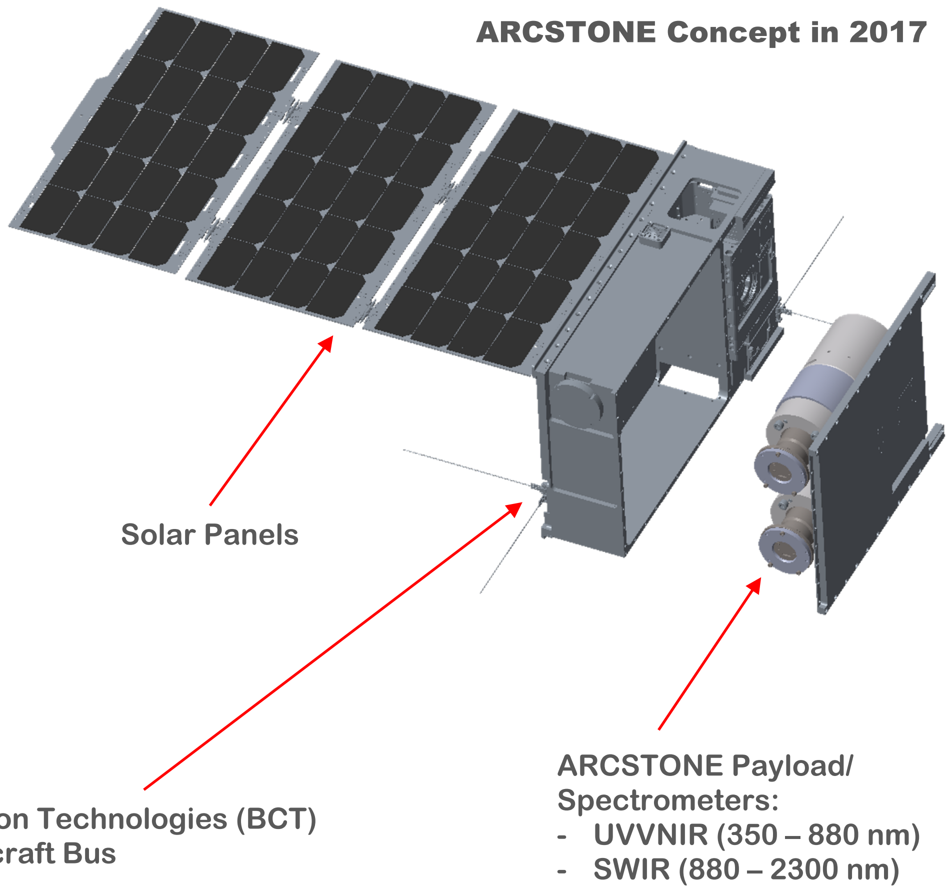
Key Parameters	Threshold Value	Goal Value
Accuracy (reflectance)	1.0% (k=1)	0.5% (k=1)
Stability	< 0.15% (k=1) per decade	< 0.1% (k=1) per decade
Orbit	Sun-synch orbit	Sun-synch orbit
Time on-Orbit	1 year	3 years
Frequency of sampling	24 hours	12 hours
Instrument pointing	< 0.1º combined	< 0.05º combined
Spectral Range	380 nm – 900 nm	350 nm – 2300 nm
Spectral Sampling	8 nm	4 nm

* Requirements are captured in a Mission Requirements Doc

* * Threshold Values considered as success criteria

BCT 6U XB6 Spacecraft pointing:
- **Accuracy 0.002º (1-sigma) in 3 axis**
- **Stability 1 arc-sec over 1 sec**

ARCSTONE Concept in 2017



ARCSTONE Project Timeline

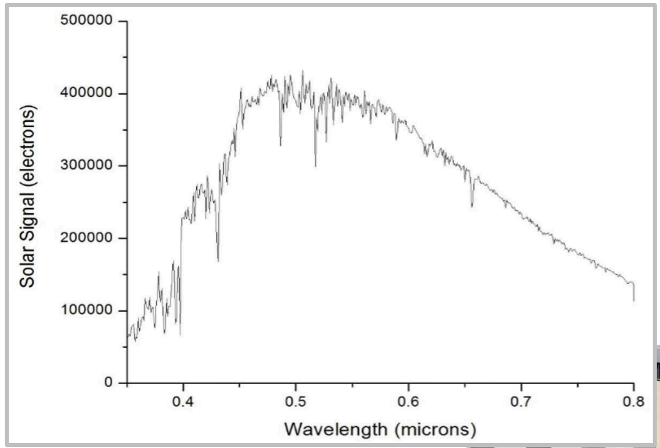
Concept brainstorming: down-select on January 9, 2016
Breadboard design & build by March 2016
Breadboard tested at NIST in April 2016

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

- Formulation and preliminary design, Summer 2017
- Design and STOP analysis completed by March 2018
- Prep. work for fabrication completed by May 2018

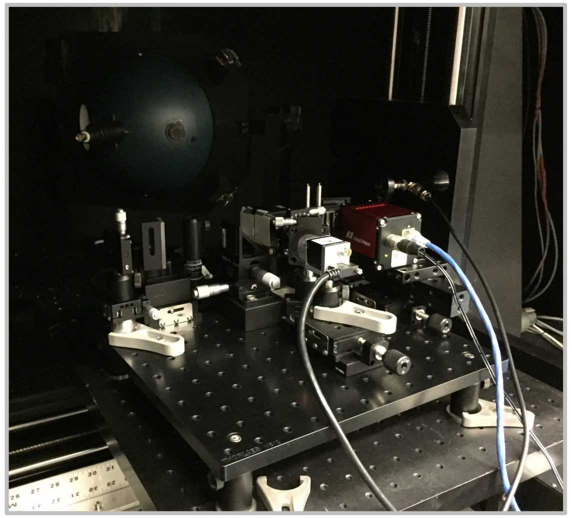
- UVVNIR detector TVAC tested by Fall 2018
- UVVNIR FPA characterized by January 2019

- Fabrication completed by February 2019
- UVVNIR assembled/aligned by March 2019
- New FSR instrument concept, March 2019
- SWIR assembly/alignment: on hold
- SWIR IDCA characterization, July 2019
- UVVNIR Characterization: Summer 2019



Solar Spectral Irradiance measured by ARCSTONE

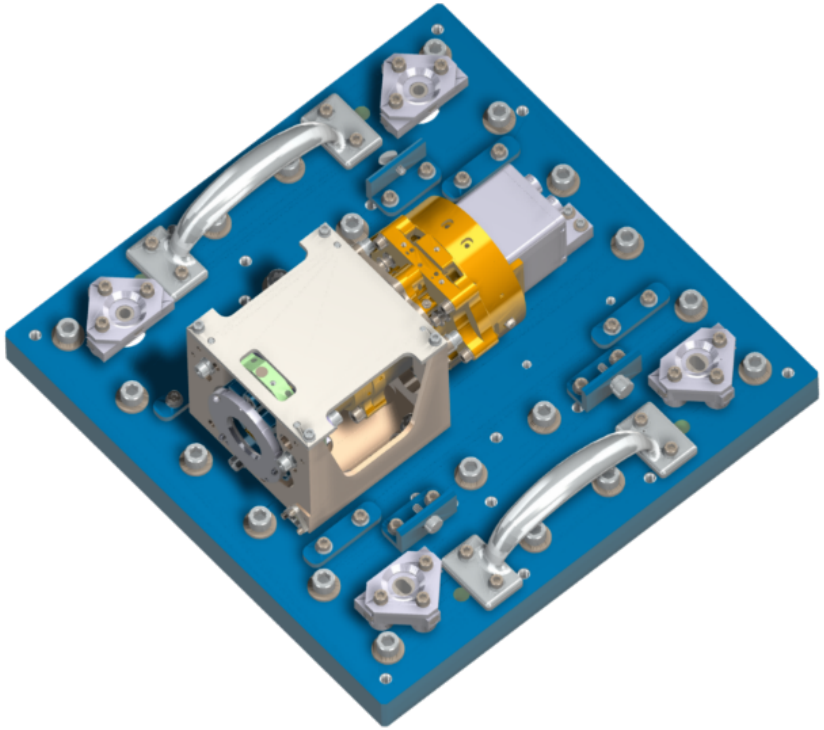
Breadboard at NIST SIRCUS Facility, April 2016



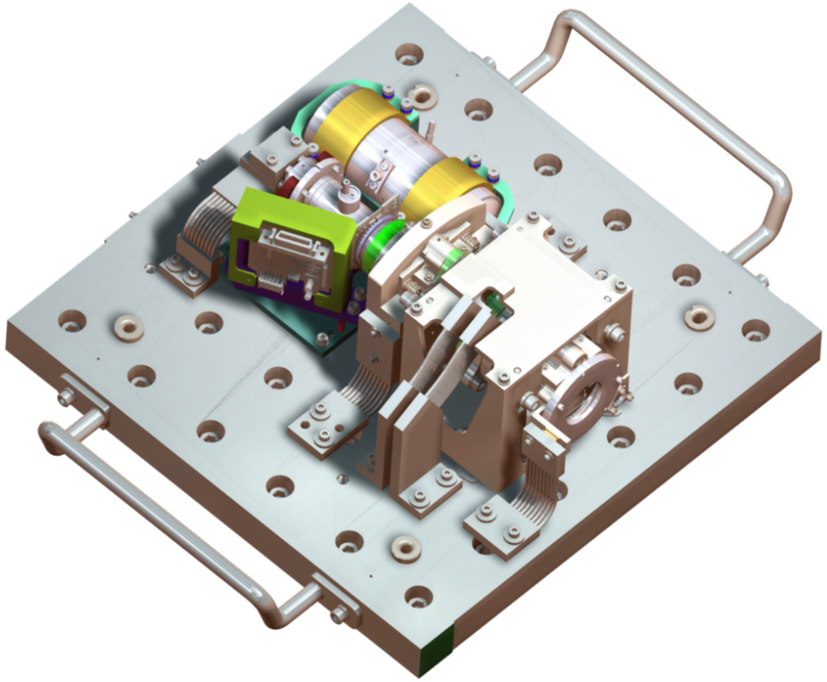
Breadboard at NIST's roof, April 2016

ARCSTONE IIP designed Instruments (EDU)

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



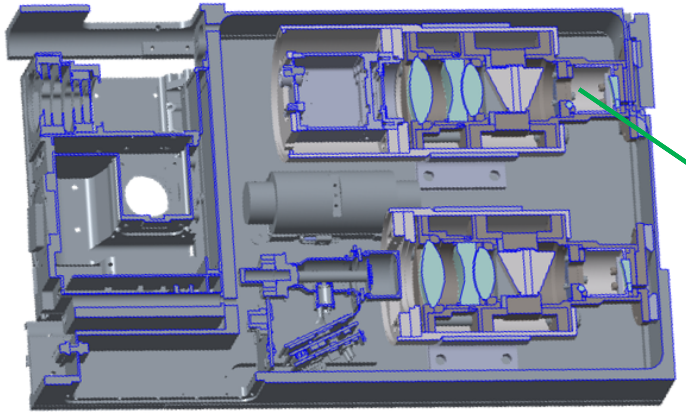
UVVNIR Spectrometer – Ultraviolet Visible Near Infrared
350-880 nm
Transmission Grating Spectrometer
Uncooled FPA and Optic Train



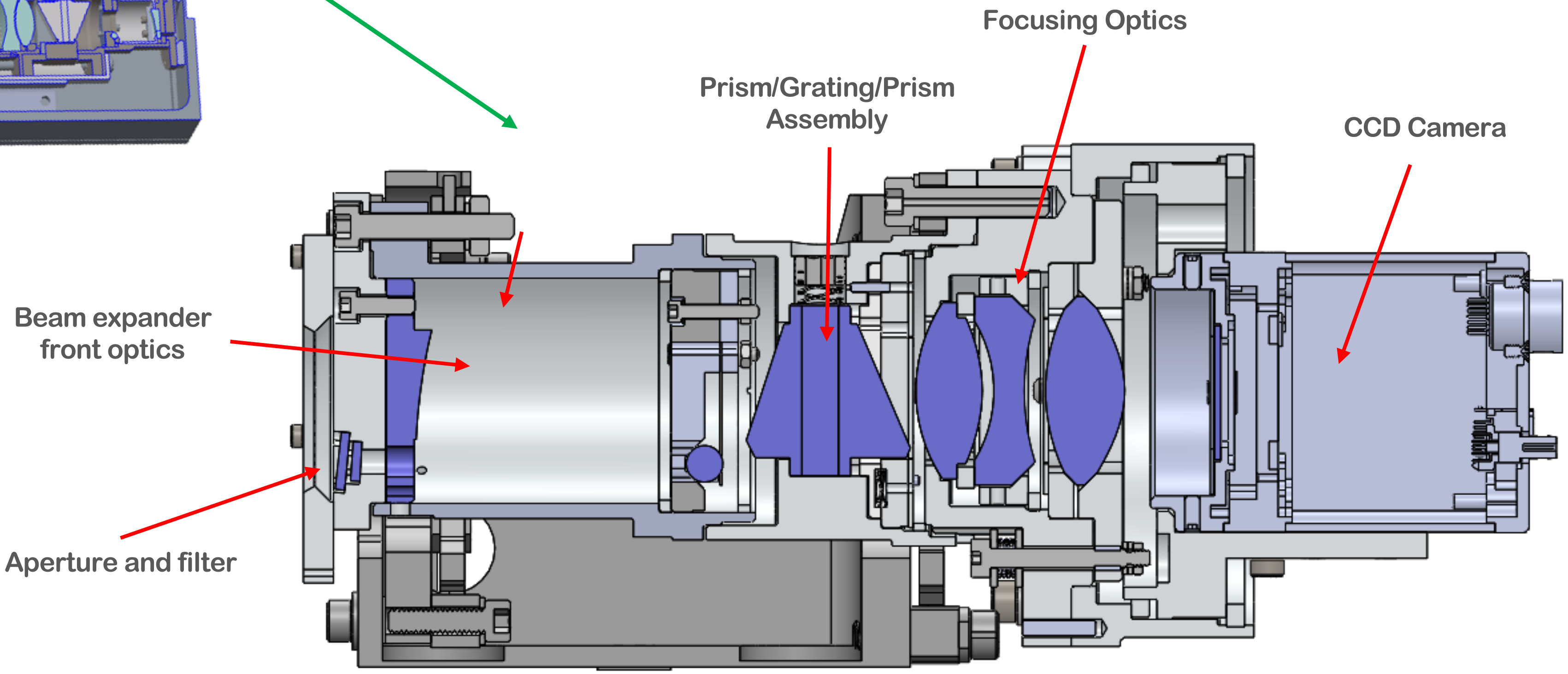
SWIR Spectrometer – Short Wave Infrared
880-2300 nm
Transmission Grating Spectrometer
Cooled FPA and Optic Train

ARCSTONE Observatory and Instrument Design

Cubesat 6U bus:
Courtesy of Blue Canyon Technologies



Preliminary System Design



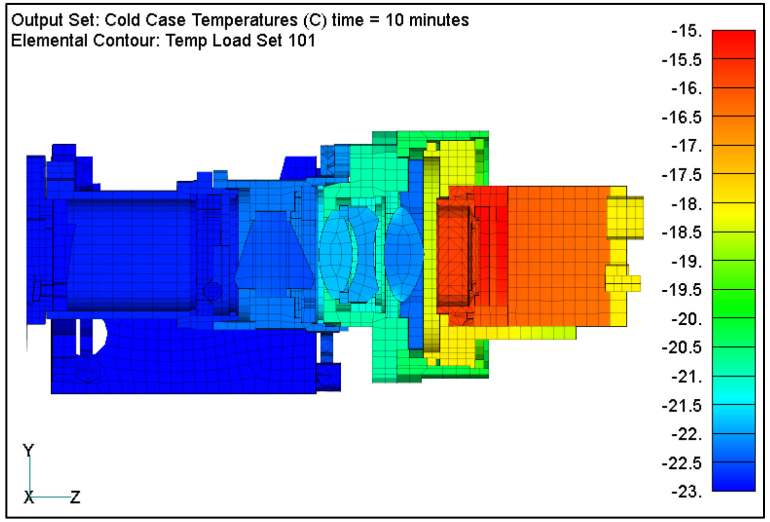
Prototype of ARCSTONE UVVNIR Instrument

ARCSTONE STOP Analysis by Quartus Engineering

Current design assumes large thermal operational range in-orbit !

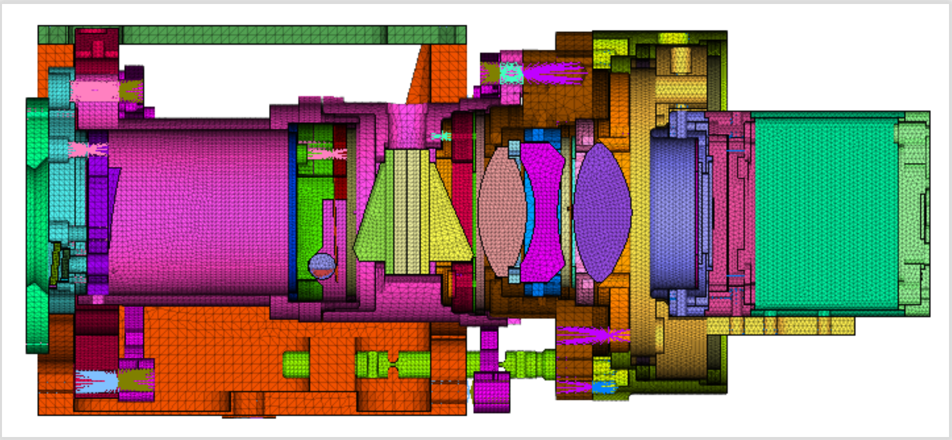
Orbital States from LaRC team →

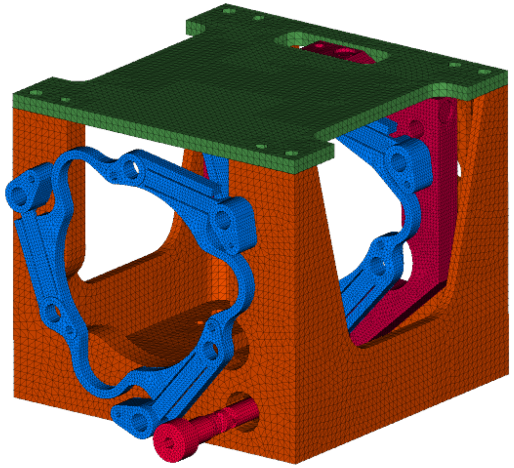
Thermal Modeling
Temperature Mapping
Thermoelastic Modeling
Nonlinear Analysis Considerations
Zernike Calculation
Zemax Modeling
Thermoelastic Changes of Lenses
Optical Effects of Thermal Stress
Mount Modifications of Lenses



Temperature Mapping Results

Thermoelastic Results





UVVNIR Mount Random Vibration

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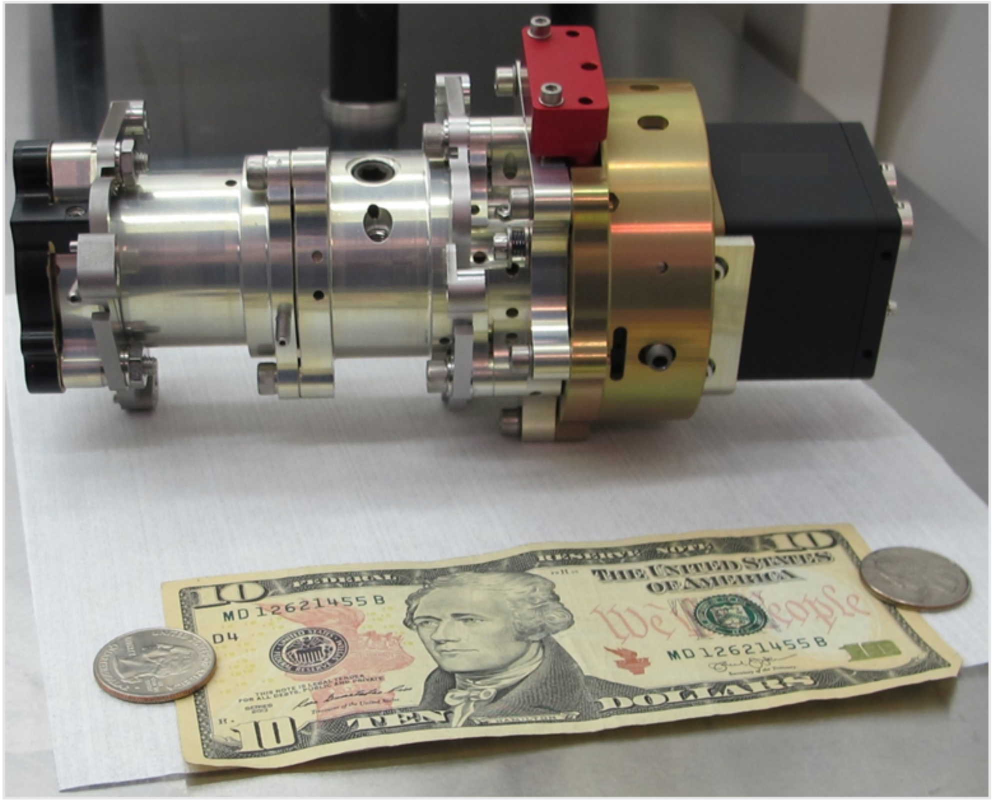
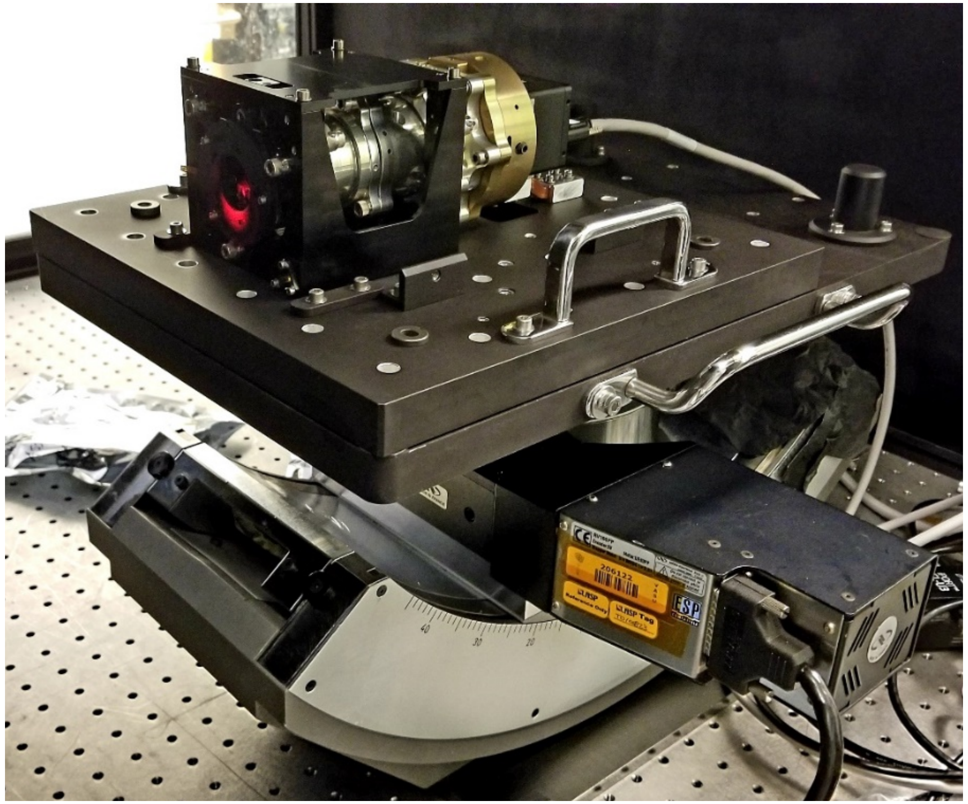
Fabricated & Assembled UVVNIR

Path Forward for UVVNIR Spectrometer: Field campaigns and vibe/TVAC tests





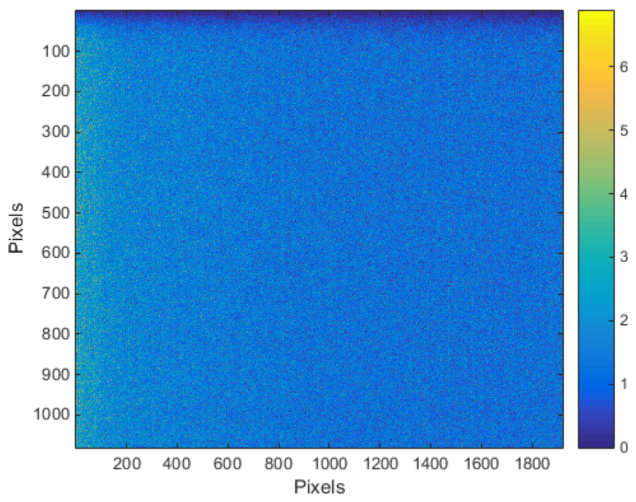
UVVNIR Instrument:
- CCD characterized
- Assembly & Alignment completed

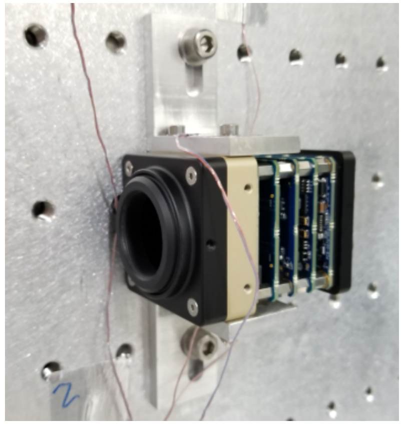
UVVNIR Instrument:
- Undergoing characterization at LASP

ARCSTONE UVVNIR CCD 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)

Average Dark Image





- UVVNIR CCD camera characterized at LASP
- UVVNIR CCD camera TVAC tested at LaRC

UVVNIR CCD Camera Conclusions:

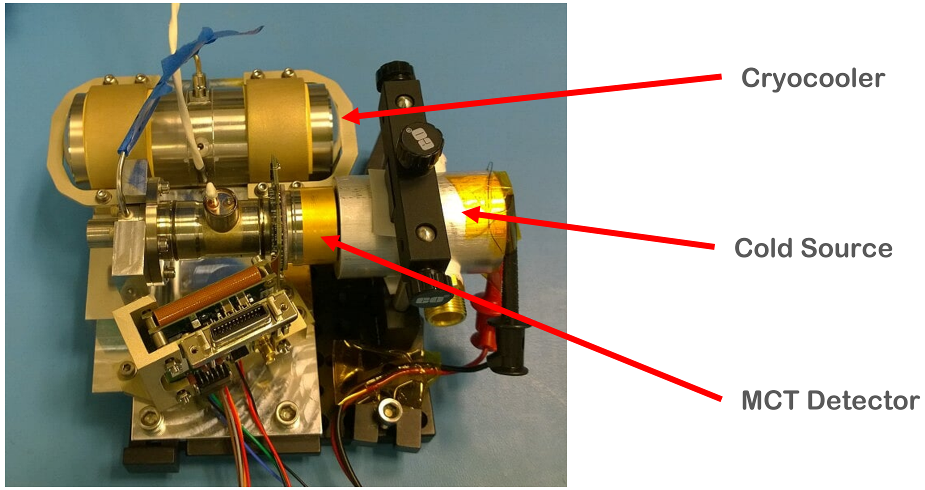
- Camera is consistent to be usable in high-accuracy measurements, with ~0.1% – 0.3% (k=1) uncertainty
  - ✧ *Final uncertainty values will depend on number of pixels used for averaging*
- Dark current is much lower than expected
- There are a number of features that can be overcome through dark-image subtraction and flat-field correction

Integration time stability and linearity over 10^5 range !

ARCSTONE

SWIR Camera Characterization
MCT Integrated Detector Cooler Assembly (IDCA)

- 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



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

SWIR IDCA Camera Conclusions:

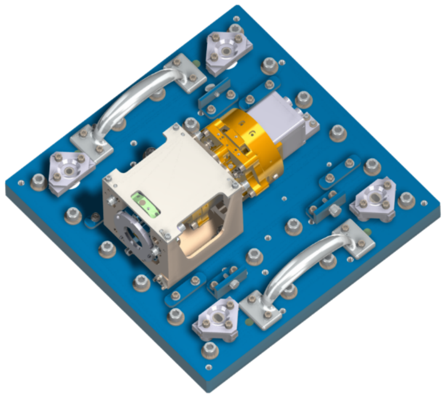
- Camera is expected to be usable with 0.3% - 0.4% uncertainty depending on signal level:
  - ✧ *Primary contributor to uncertainty is variation in the offset value between its measurements (repeatability)*
  - ✧ *Offset value variation is a systematic uncertainty that cannot be mitigated through increased averaging, but may be lower during real data collecting operations,*

    e.g. measuring offset before every lunar observation
- Camera linearity is better than expected
- **Final random uncertainty values will depend on number of pixels used for averaging**

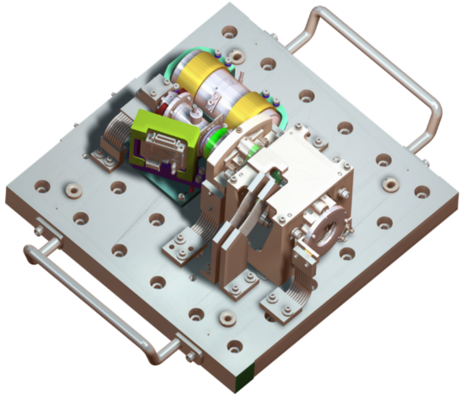
Integration time from 10^{-4} to 3.3 seconds !

ARCSTONE Full Spectral Range (FSR) Instrument

Ultraviolet Visible Near Infrared (UVVNIR)

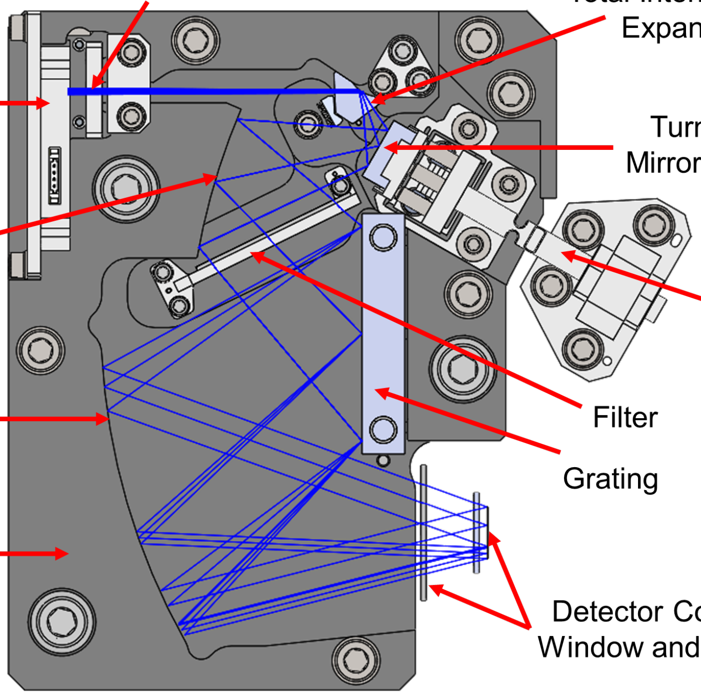


2017 – 2019 IIP work



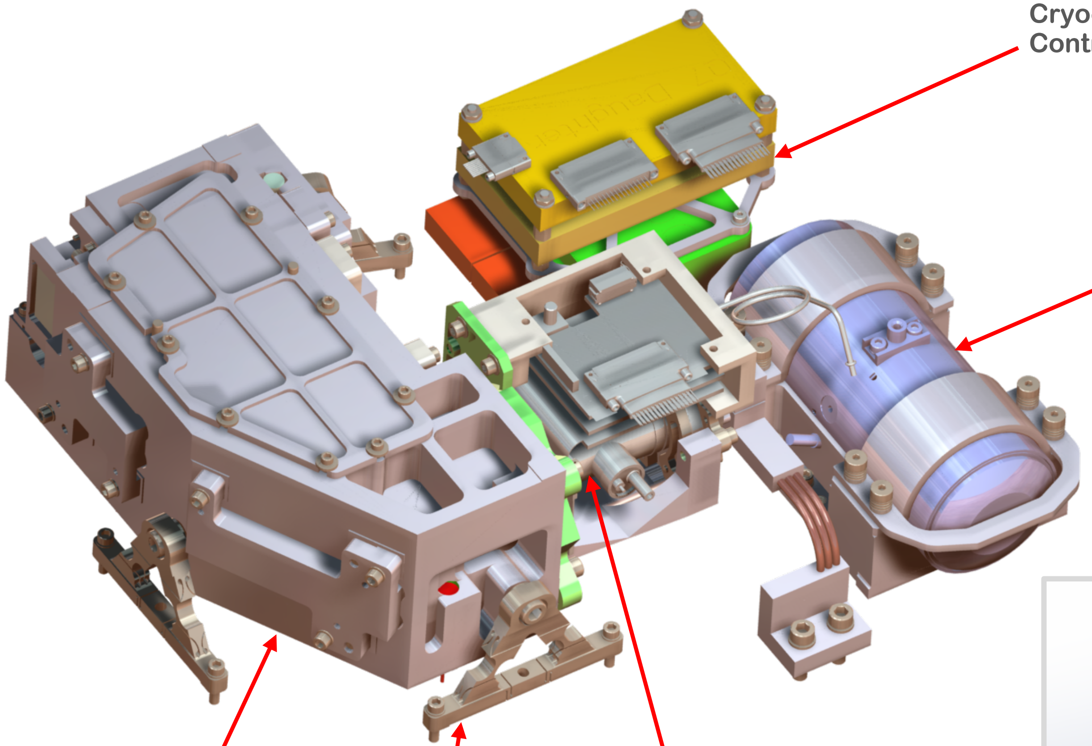
Short Wave Infrared (SWIR)

ARCSTONE FSR: All in ONE !



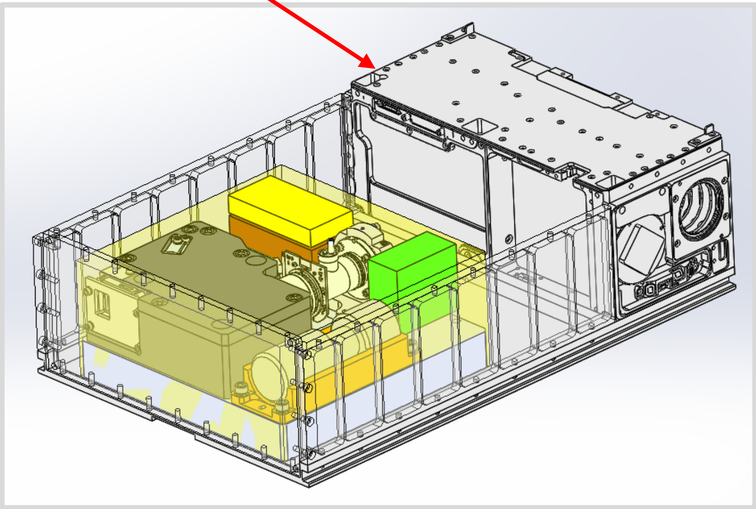
Single channel system, based on new product:
- Thinned MCT detector
- Wavelength range from 350 to 2300 nm

ARCSTONE Full Spectral Range (FSR) Instrument



Project Approach:

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



ARCSTONE FSR Status:

- Optomechanical Design
- STOP Analysis in FY19

- LaRC: IIP-QRS-16-0018
- Resonon: SBIR Phase-2

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

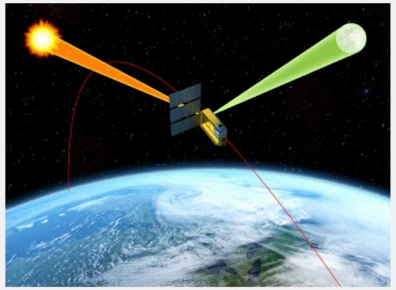
Home About Team Contact

ARCSTONE

Achieving Instrument High Accuracy In-Orbit

One of the most challenging tasks in remote sensing from space is achieving required instrument calibration accuracy on-orbit. The Moon is considered to be an excellent exoatmospheric calibration source. However, the current accuracy of the Moon as an absolute reference is limited to 5 - 10%, and this level of accuracy is inadequate to meet the challenging objective of Earth Science observations. ARCSTONE is a mission concept that provides a solution to this challenge. An orbiting spectrometer flying on a small satellite in low Earth orbit will provide lunar spectral reflectance with accuracy sufficient to establish an SI-traceable absolute lunar calibration standard for past, current, and future Earth weather and climate sensors.

LEARN MORE



The ARCSTONE observatory is shown in low Earth orbit with the spectrometer viewing the Sun and Moon. The spacecraft rotates in order to view the Moon or the Sun.

"The Moon is available to all Earth-orbiting spacecraft at least once per month, and can be used to tie together the sensor radiance scales of all instruments participating in lunar calibration without requiring near-simultaneous observations."

– HUGH KIEFFER & TOM STONE

THANK YOU !