ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

Cindy Young[1]

C. Lukashin[1] (PI), T. Jackson[1], T. Stone[2], G. Kopp[3], R. Swanson[4], N. Abraham[5], E. Minda[6]
C. Buleri[6], J. Carvo[7], M. Cooney[1], H. Courrier[4], W. Davis[1], A. Halterman[6], M. Kehoe[4], T. Nguyen[1]
N. Ryan[1], P. Smith[3], M. Stebbins[4]

1 – NASA Langley Research Center, Hampton, VA
2 – USGS, Flagstaff, AZ
3 – LASP University of Colorado, Boulder, CO
4 – Resonon Inc., Bozeman, MT
5 – Goddard Space Flight Center, Greenbelt, MD
6 – Quartus Engineering, San Diego, CA
7 – Blue Canyon Technologies, Inc., Boulder, CO

Funded by ESTO: IIP-QRS-16-0018
SBIR programs: Phase-I & Phase-II

NASA GSFC

ARCSTONE: Team and Contributions

NASA LaRC

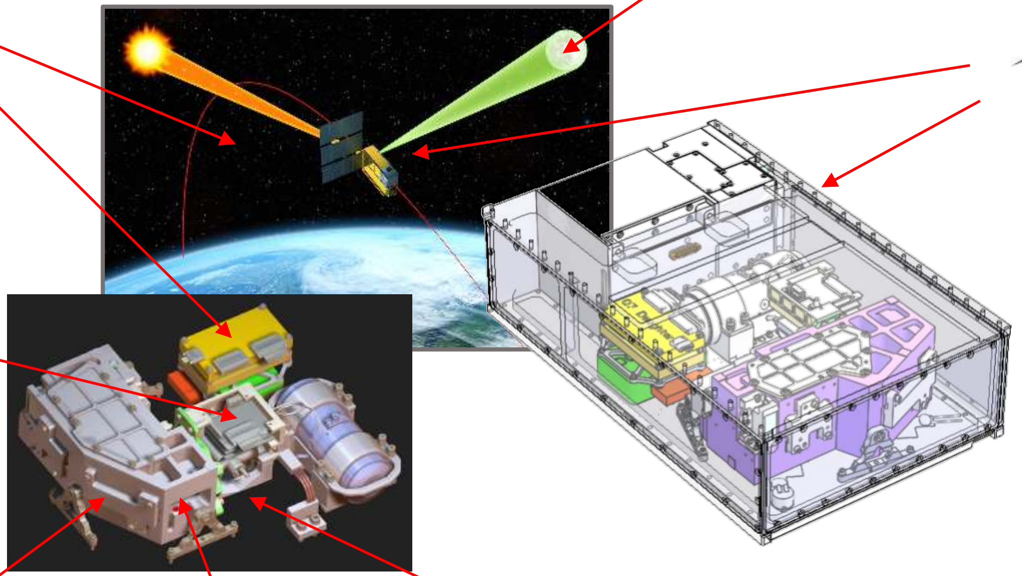
Mission concept & science
Project management *
Engineering coordination
Instrument electronics
Flight and ground software
Mechanical, Thermal & Structural
Environmental testing
* SSAI: sub-contract management

USGS

Lunar calibration approach (ROLO)

BLUE CANYON TECHNOLOGIES

6U CubeSat Bus



LASP

Laboratory for Atmospheric and Space Physics

Instrument concept
Component characterization
Radiometric calibration
Error budget

ARCSTONE TEAM:

- NATIONWIDE COLLABORATION of EXPERTS !
- Collaboration with NIST & UMBC:
  Ground and Airborne lunar measurements

NASA GSFC

Optical black coating

RESONON

Instrument concept
Instrument design
Radiometric modeling
Fabrication
Assembly & alignment
Functional testing

QUARTUS ENGINEERING

Instrument Analysis (STOP, RV, TE)
Input to instrument design
Flexures design

Moon: Potentially Accurate Source for Calibration On-orbit

- Measurement accuracy is directly related to the information content of the dataset. Measurement accuracy is critical to EOS! Current EOS cannot handle data gaps. Need overlapping observations: CERES, MODIS/VIIRS, Landsats, PACE/SeaWIFS, etc.

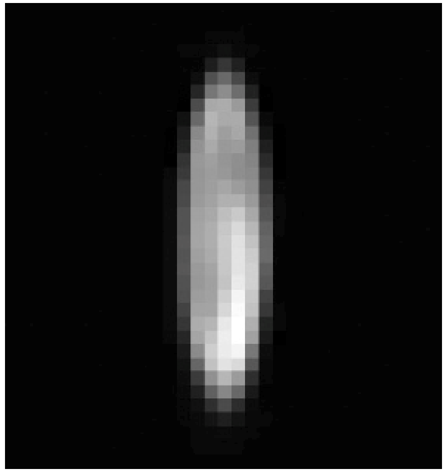
Calibration reference: Lunar Spectral Irradiance (entire disk)

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

- SeaWiFS gain stability: 0.13% (k=1) over 12 years
- Accuracy of current Lunar Model (ROLO): 5 – 10%

On-Orbit Calibration Need:

Absolute accurate spectral irradiance for all lunar phase angles and libration states.



Lunar image by SeaWIFS

Expected Impacts:
- Quality of data products
- Long-term consistency
- Handling data gaps
- Reduces instrument size, mass, power
- Reduce complexity
- Accurate CubeSat sensors

Applications of the Lunar Calibration Approach
(satellite operators worldwide !)

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	

From GSICS (Global Space-based Inter-Calibration System) Lunar Calibration Workshop, December 2014, EUMETSAT.

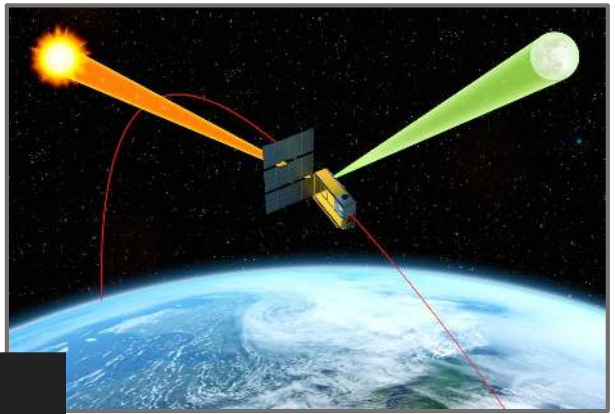
- **Instruments with lunar calibration capabilities participating in the GSICS GIRO (*GSICS implementation of the ROLO model*) program**
- ***List includes sensors with lunar observations submitted to the database at EUMATSAT as of December 2014.***
- ***Next GSICS Lunar Calibration Workshop: November 2020, virtual (?)***

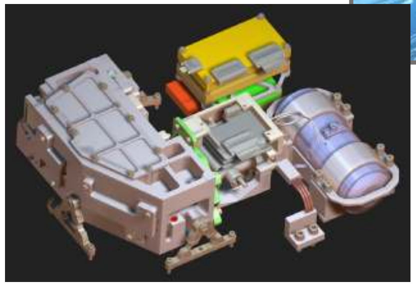
ARCSTONE Objectives:

- *To enable on-orbit high-accuracy absolute calibration for the past, current, and future reflected solar sensors* in LEO and GEO* by providing lunar spectral irradiance as function of satellite viewing geometry and specified wavelength.

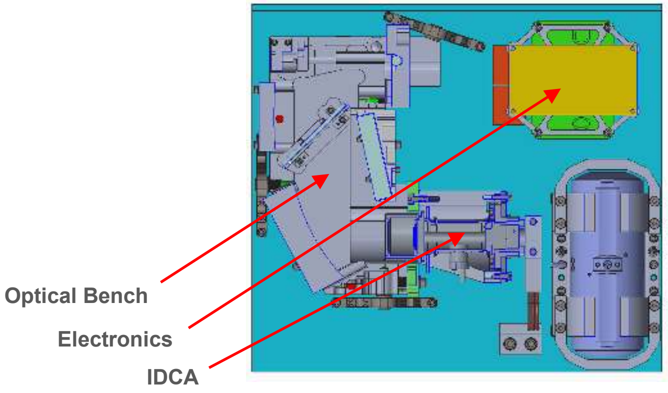
- To design, build, calibrate and validate a prototype instrument, demonstrate *form-fit-function for a 6U observatory with compliance in size, mass, power, and thermal performance*.

* Planetary instruments: OSIRIS Rex Camera suite [Golish et al., 2020]





ARCSTONE Concept: Accurate measurements of Lunar Irradiance from Space with an Instrument flying on 6U CubeSat (courtesy BCT) in LEO.



Progress of ARCSTONE instrument Design

$TRL_{current} = 4$ $TRL_{out} = 5$

ARCSTONE Mission Concept

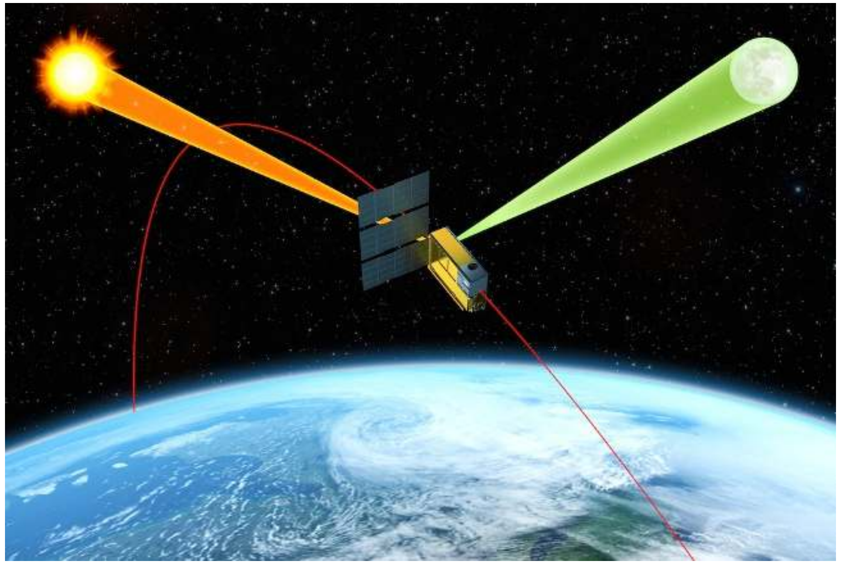
Concept of Operations and Data Products:

- Data to collect: Lunar spectral irradiance every 12 hours, 10 minutes
- Data to collect: Solar spectral irradiance for calibration (daily)
- Combined uncertainty < 0.5% (k=1)
- Spectrometer with single-pixel field-of-view about 0.7^o (no scanning !)
- Sun synchronous orbit at 500 – 600 km altitude
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm

1 year: Improvement of current Lunar Calibration Model (factor of 2 – 4);
3+ years: New Lunar Irradiance Model, improved accuracy level (factor of 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 spacecraft now permits obtaining required measurements *with instrument integrated into spacecraft.*



6U CubeSat Spacecraft Bus:
courtesy of Blue Canyon Technologies (BCT)

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

ARCSTONE

ARCSTONE Mission: Key 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	< 0.2^{o} combined	< 0.1^{o} combined
Spectral Range	380 nm – 900 nm	350 nm – 2300 nm
Spectral Sampling	8 nm	4 nm

* * Threshold Values considered as success criteria

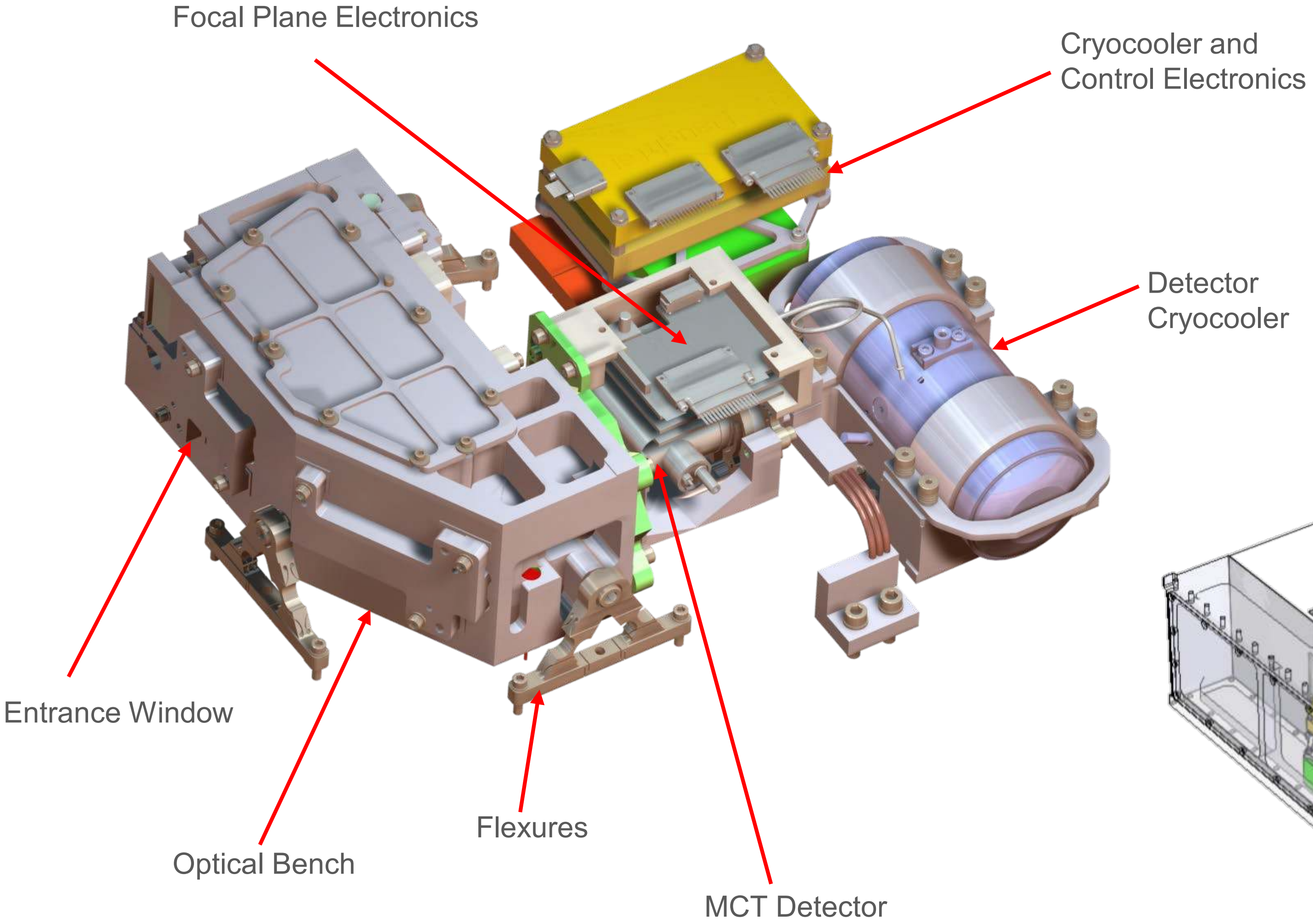
Reference for radiometric requirements (ROLO, T. Stone):
Lunar Phase Angle = 75^{o};
Irradiance = 0.6 (micro W / m^2 nm)
Wavelength = 500 nm

ARCSTONE MISSION CONOPS:

1. Lunar spectral irradiance observations:
   - Every 12 hours
   - Close to polar locations
   - Multiple measurements within 5– 10 minutes to improve SNR
2. Solar Spectral Irradiance observations (solar calibration):
   - 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
5. Field-of-view sensitivity characterization:
   - Calibration of instruments alignment
6. Spectral calibration:
   - On-board spectral calibration
7. Spacecraft pointing calibration and other checks:
   - Defined by the BCT for calibration of spacecraft functions
8. Stand by mode:
   - Mode between observations
9. Data Downlink Mode
10. Safe Mode (if required)

* 6U CubeSat accommodation Study is completed

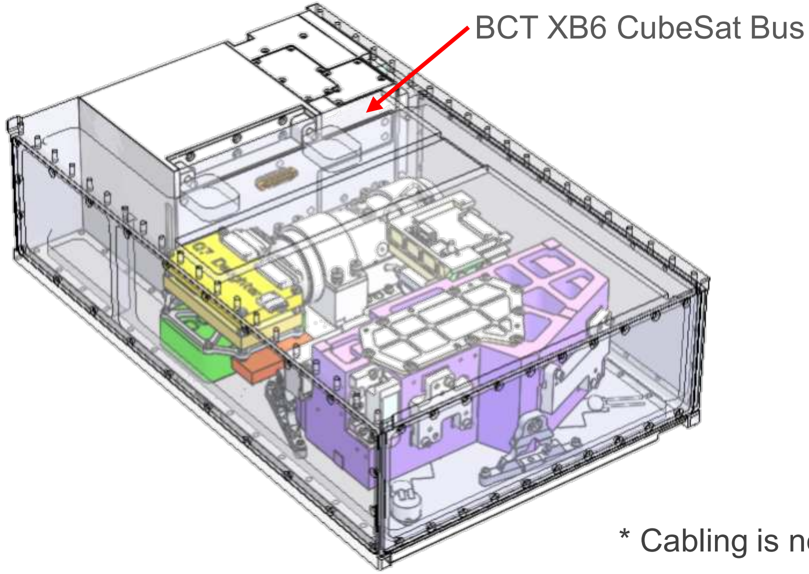
ARCSTONE Instrument in Fabrication



Volume:
Fits within up-to-date spacecraft bus CAD from BCT with at least 0.5mm clearance from all payload walls/features

Mass:
4.13 kg (*6 kg payload allowable*)

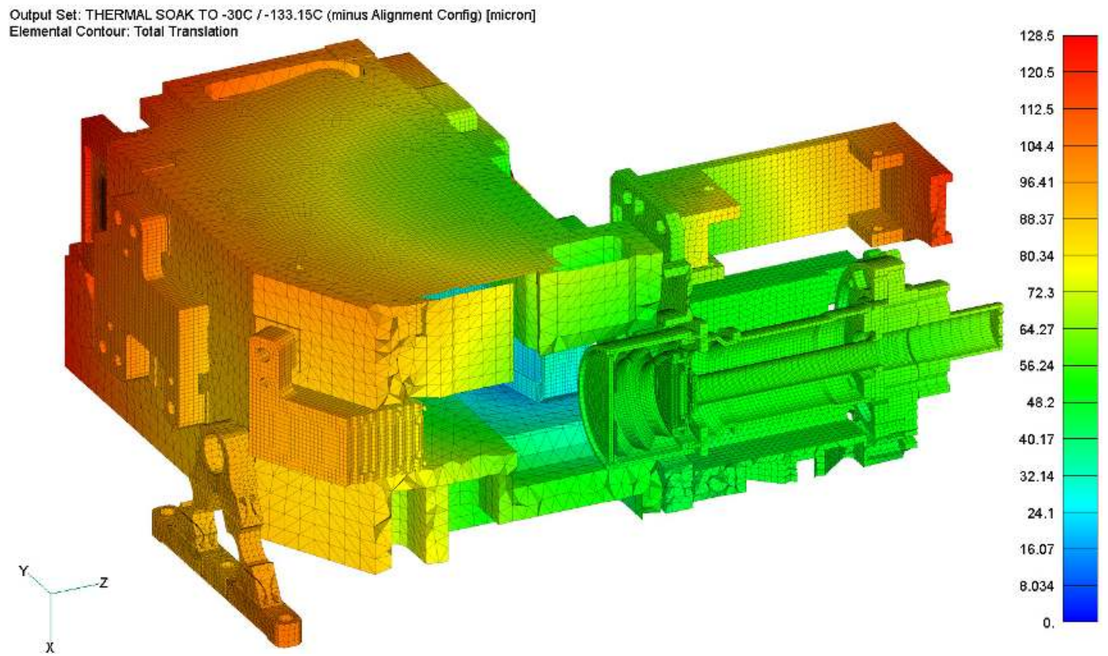
Power (all worst cases):
Science Mode: 23.83 W (*118 W peak allowable*)
Data Downlink Mode: 34.07 W
Stand By Mode: 15.5 W



* Cabling is not shown

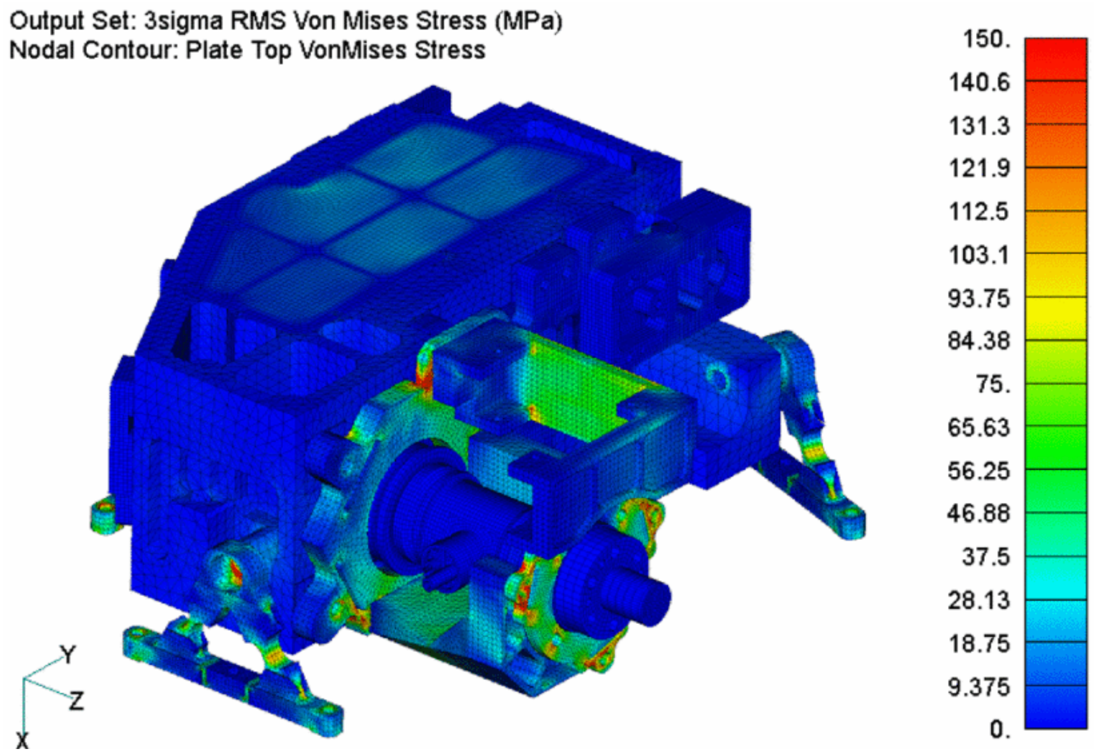
ARCSTONE Instrument Analysis

Performed Analysis:
STOP, Thermoelastic, Random Vibe



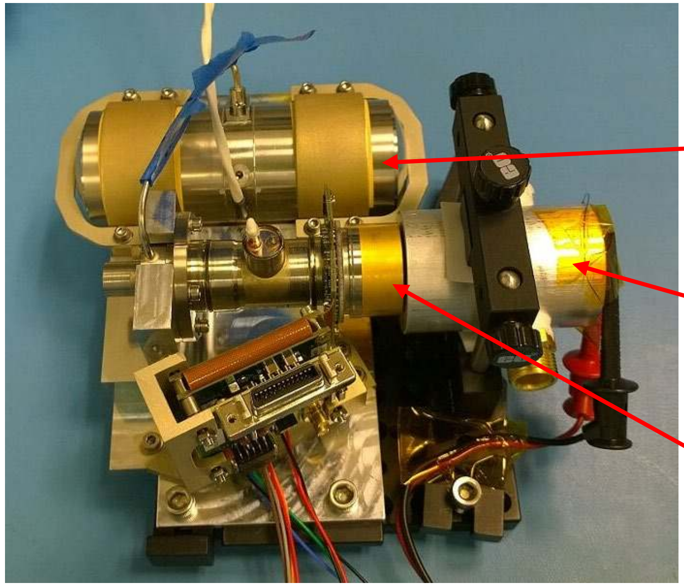
Optic bench displacements [microns] at −30°c.
Cutaway shows interior of camera dewar/cold finger.

Optic bench random vibration analysis.



ARCSTONE: SWIR IDCA (1 – 2.3 µm) Characterization

- **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



Cryocooler

Cold Source

MCT Detector

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

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

SWIR IDCA Characterization Conclusions:

(1) SWIR IDCA *usable at 0.3% - 0.4% uncertainty level:*

- *Primary contributor to uncertainty is variation in the offset value between its measurements (repeatability over a few days).*
- *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.*

(2) Camera linearity: *better than expected at 0.1% !*

(3) Initial Vacuum tests: *positive results !*

Full Spectral Range IDCA is essentially the same as SWIR IDCA (except for detector, OB filter, and integration time extended to 16 seconds)

ARCSTONE IIP: Status and Next Steps

Status:

- Design and STOP analysis completed for EDU instrument
- 6U CubeSat accommodation study completed
- Fabrication of instrument is in progress

Next Steps:

- Complete 6U CubeSat/Payload thermal study (September 2020)
- Complete fabrication of instrument (October 2020)
- Characterize Full Spectral Range IDCA (January 2021)
- Assemble instrument (February 2021)
- Calibrate instrument (May 2021)
- Field-test instrument with Sun and Moon measurements (TRL5, June 2021)

Testing ARCSTONE field equipment at NASA LaRC

ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

Recent Publications:

Swanson, R., C. Lukashin, M. Kehoe, M. Stebbins, H. Courrier, T. Jackson, M. Cooney, G. Kopp, P. Smith, C. Buleri, T. Stone, “The ARCSTONE Project to Calibrate Lunar Reflectance,” *IEEE Aerospace Proceedings,* 2020

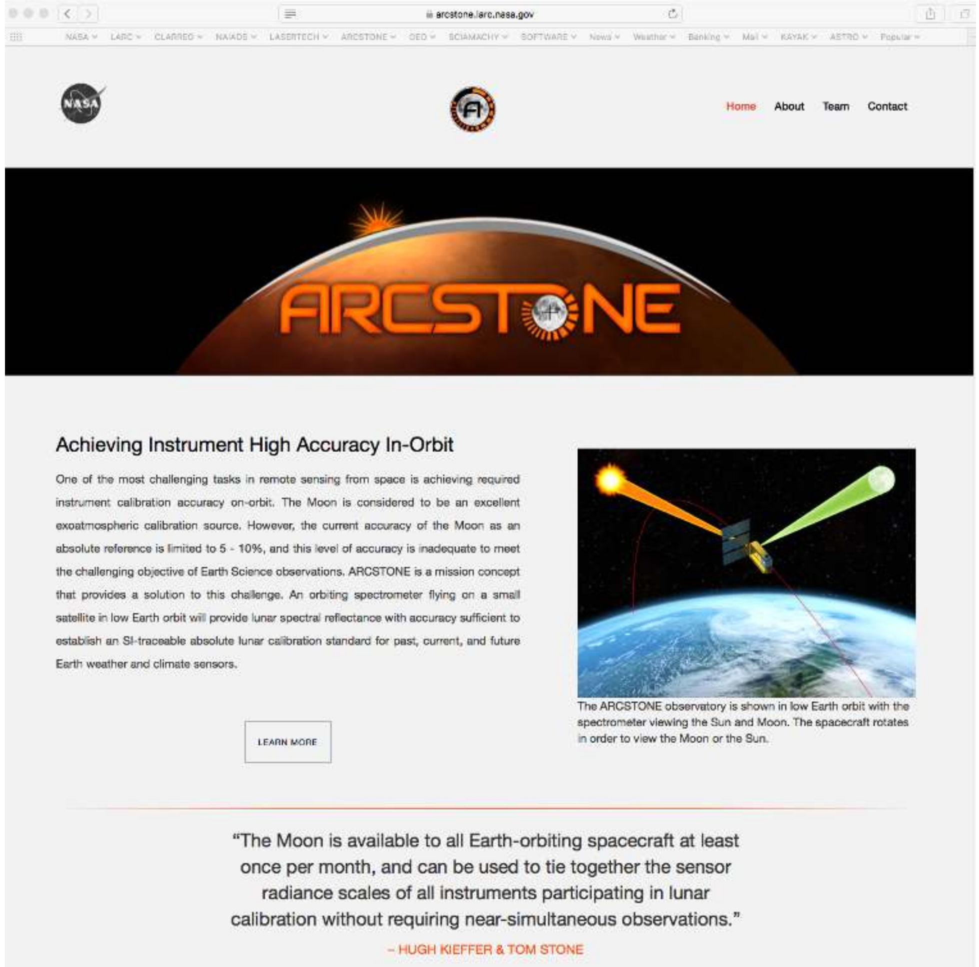
Available online: https://ieeexplore.ieee.org/abstract/document/9172629

Stone, T.C., H. Kieffer, C. Lukashin, K. Turpie,
“The Moon as a Climate-Quality Radiometric Calibration Reference,” *Remote Sens.,12*, 1837, 2020

Available online at https://www.mdpi.com/2072-4292/12/11/1837

ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

http://arcstone.larc.nasa.gov



THANK YOU !