Overview of new measurements for new lunar modeling

Presented by Stephen Maxwell, NIST

Overview

There is wide agreement that new measurements are needed to create next-generation, SI-traceable lunar calibration models that can provide accurate predictions of lunar irradiance for a given sun-moon-observer geometry

Recognized need for SWIR measurements

Recognized need for polarization measurements

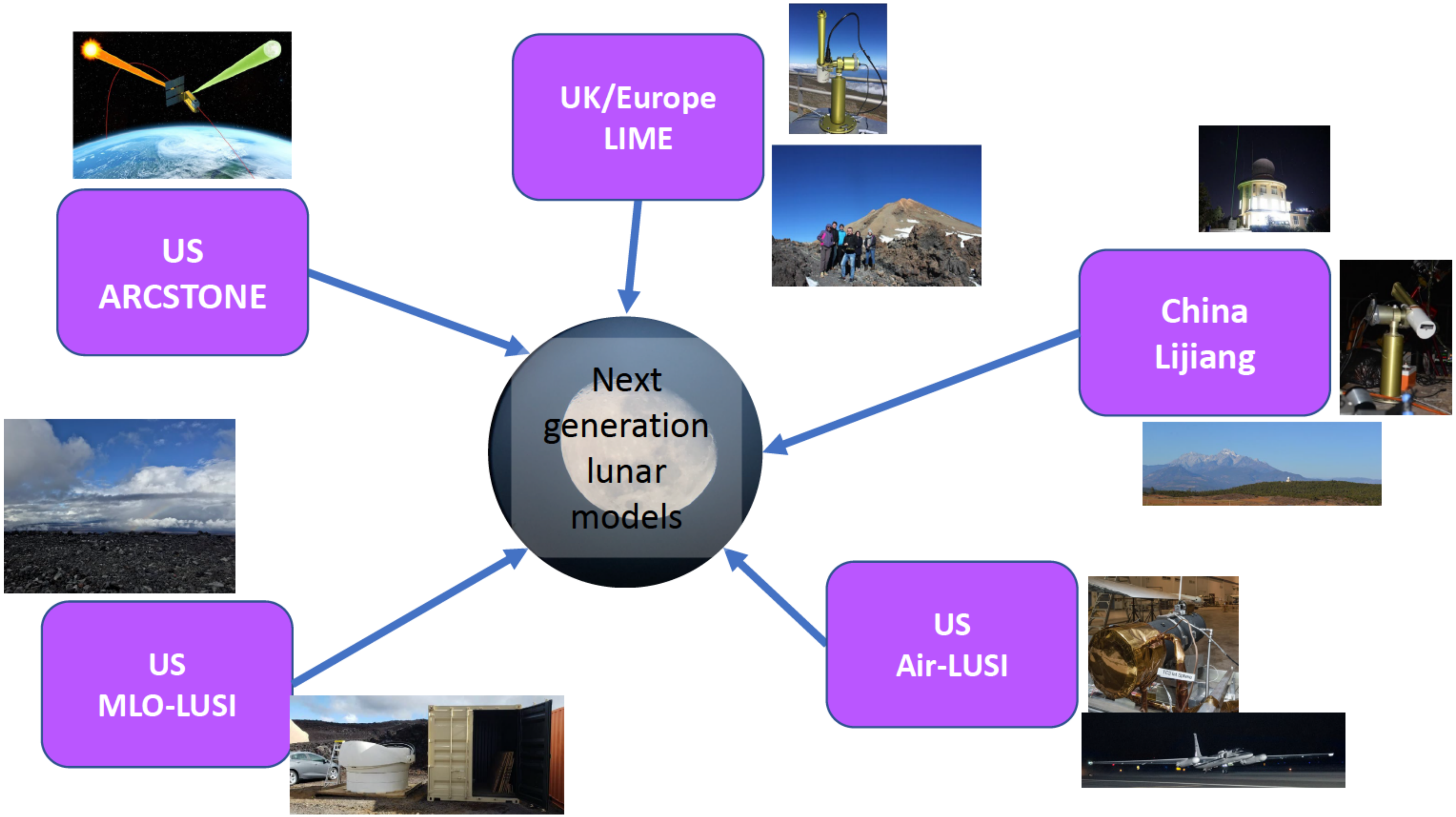
Globally, there are a number of programs whose goal is to acquire SI-traceable observations of lunar irradiance

Programs contributing to this talk:

US programs – ARCSTONE, MLO-LUSI, air-LUSI

European/UK program – LIME

Chinese program – Lijiang site, including at least 4 lunar measuring instruments


UK/Europe
LIME
US
ARCSTONE
China
Lijiang
Next generation lunar models
US
MLO-LUSI
US
Air-LUSI

Air-LUSI Objectives

Primary:

To make very accurate, SI-traceable lunar spectral irradiance measurements with high spectral resolution from above about 95% the atmosphere. Target uncertainty is <0.5% (k=1).

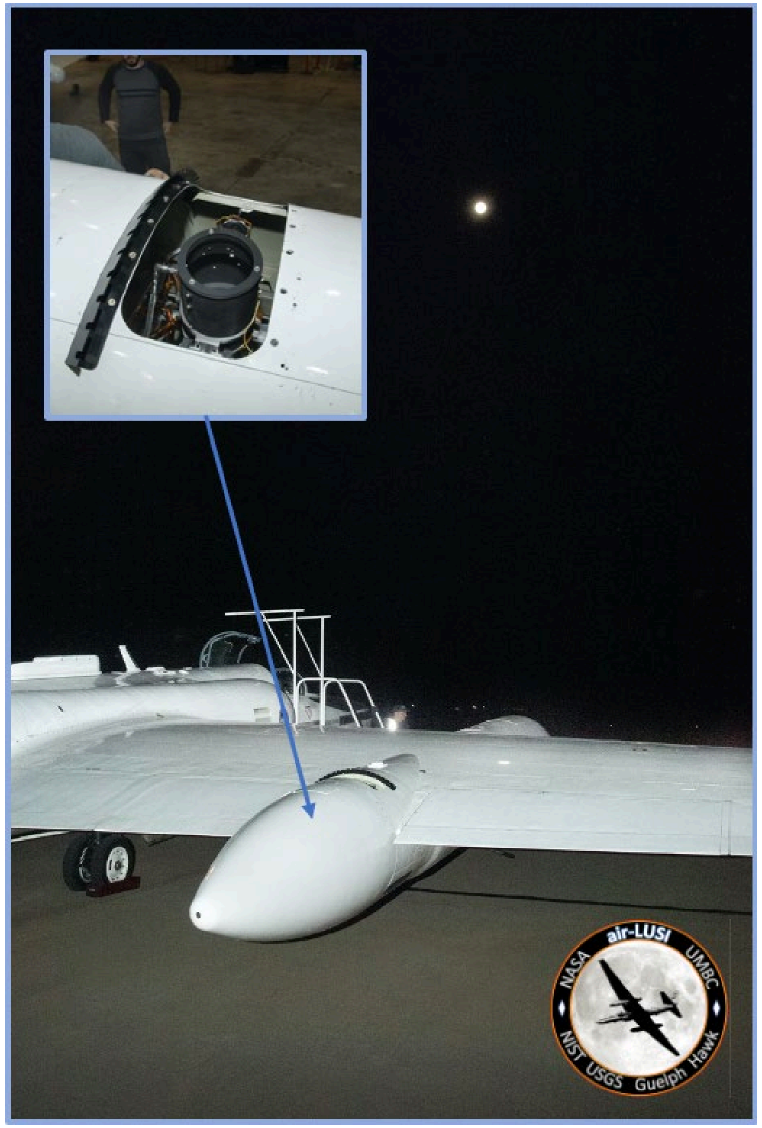
Secondary:

To improve satellite lunar calibration via a high accuracy, absolute lunar model and provide to a validation resource for similar efforts. Air-LUSI also intends to improve its measurement accuracy with each campaign.

Characteristics:

- High accuracy: < 1.0% (k=1), 415 -1000 nm (target <0.5%)
- High spectral resolution: 3.7 nm with 0.8 nm sampling (300 – 1100 nm)
- Small atmospheric correction: ~ 3% from molecular scatter and O_3 over small region

- Calibration checked before and after use
- Calibration monitored up to the point of data collection



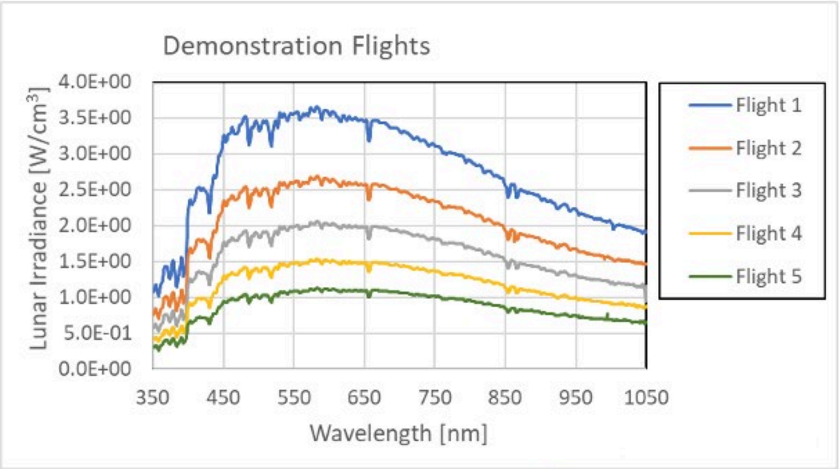
UMBC NIST USGS NASA UNIVERSITY of GUELPH

Air-LUSI Results & Status

- Demonstration Flight Campaign November 2019 was successful.
  - Lunar Spectral Irradiance for 5 nights at phases: 10°, 21°, 34°, 46° and 59°
  - Error budget gives an uncertainty of < 1.0 % (k=1), which can be improved

  Air-LUSI is ready for operational use

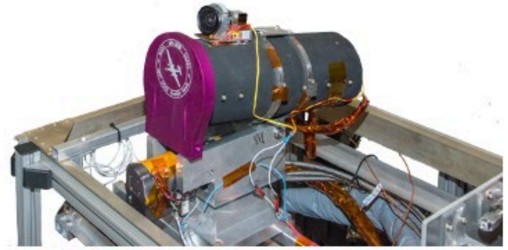
- Post-Campaign Activities
  - Wrapping up data reprocessing and ROLO comparison
  - Doing initial work on repairs and maintenance
  - Some tasks dependent on lab access were delayed efforts b/c of COVID



- Current Applications
  - Comparing Air-LUSI to ESA LIME model and data from Tenerife
  - Can compare to CNES PLEIADES and NASA Terra MODIS
  - GSICS community expressed strong interest in more comparisons at Lunar Workshop

- Future data collection depends on funding and aircraft availability

- Because of aircraft availability, we may be delayed until FY22



MLO-LUSI Objectives

Primary:

To collect a high spectral resolution, SI-traceable dataset of the lunar spectral irradiance in the visible, near-infrared, and short-wave infrared over a densely sampled and broad range of sun-moon-observer configurations.

To collect measurements sufficient to enable lunar spectral irradiance model redevelopment.

Secondary:

To advance the metrology of lunar spectral irradiance measurement (e.g., testing new calibration techniques, identifying systematics that may apply to systems such as Air-LUSI, etc.).

To identify and pursue scientific measurements enabled by a semi-permanent lunar observatory (e.g., lunar polarization, nighttime aerosols).

MLO LUSI Results & Status

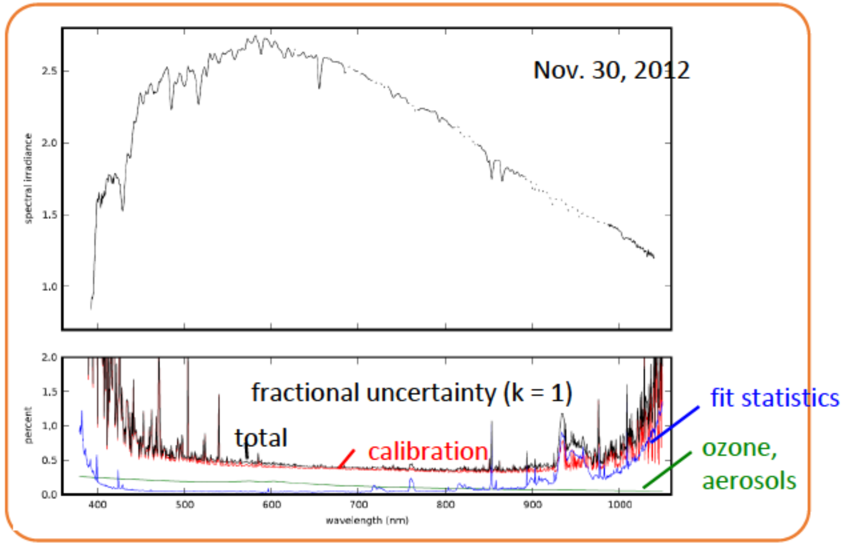
Technique proven over many measurement campaigns with prototype system carried out at Mt. Hopkins (Air-LUSI technique is derivative of this).

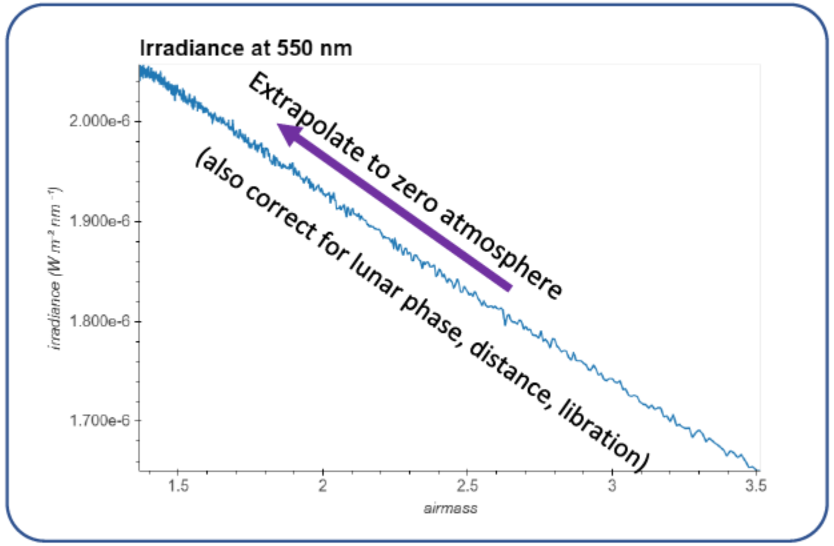
Two measurement campaigns with prototype carried out at MLO (2017, 2019).

Telescope dome and calibration hut at MLO site

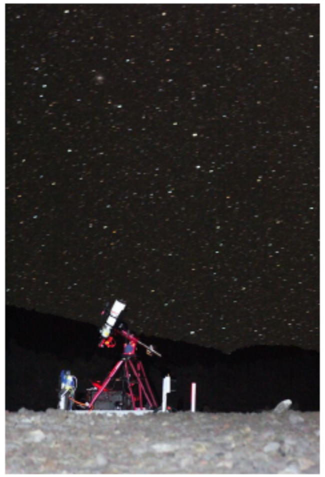
Certified engineering drawings are now in hand (new this week)

MLO-LUSI commissioning is planned for Summer 2021.

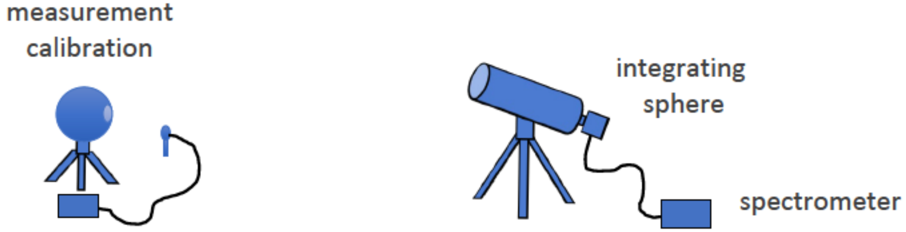




MLO-LUSI measurement principle



- 106 mm refracting telescope
- Lunar disk imaged into FOV limiting aperture
- Integrating sphere scrambles incident light – image and polarization
- Light directed into spectrograph via fiber bundle



- lab-calibrated spectrometer monitors sphere → transfer standard → → → traceable to the NIST primary SI standards

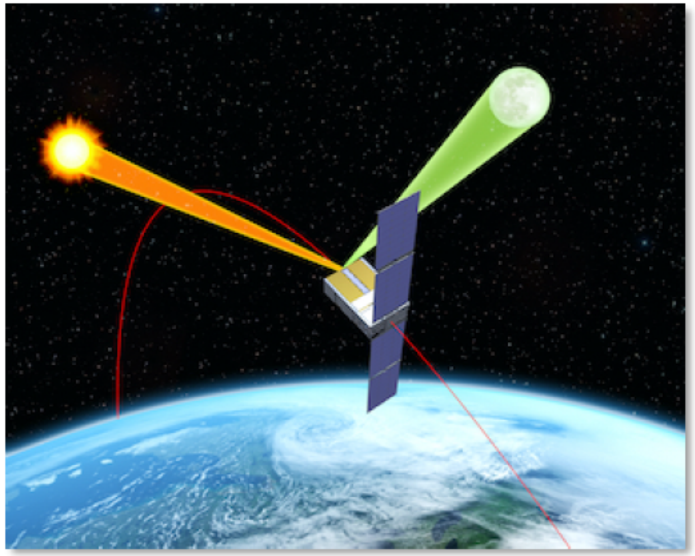
ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

PI: Constantine Lukashin (NASA LaRC)

OBJECTIVES

- The ARCSTONE objective is 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

- The ARCSTONE IIP objective is to design, build, calibrate and validate a prototype instrument, potentially to be integrated into a 6U CubeSat bus. Display *form-fit-function for a 6U observatory with compliance in size, mass, power, and thermal performance*



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

BCT 6U XB6 Spacecraft pointing (3 axis, 2 trackers):
- Accuracy +/- 0.002°
- Stability 1 arcsec over 1 sec

Funded by NASA ESTO: IIP-QRS-16-0018
NASA SBIR programs: Phase-I, Phase-II, and Phase-E

$TRL_{current} = 4$ $TRL_{IIP} = 5$ (July 2021)

ARCSTONE Mission Concept

Concept and Operations:

- Spectrometer with single-pixel field-of-view about 0.7° (no imaging !)
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm
- 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)
- Sun synchronous orbit at 500 – 600 km altitude

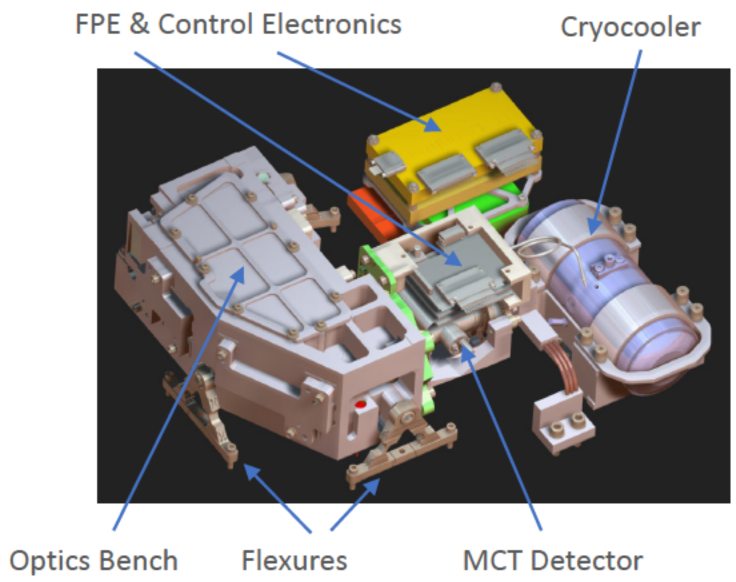
3+ years: New Lunar Irradiance Model, improved accuracy level (factor of 10)

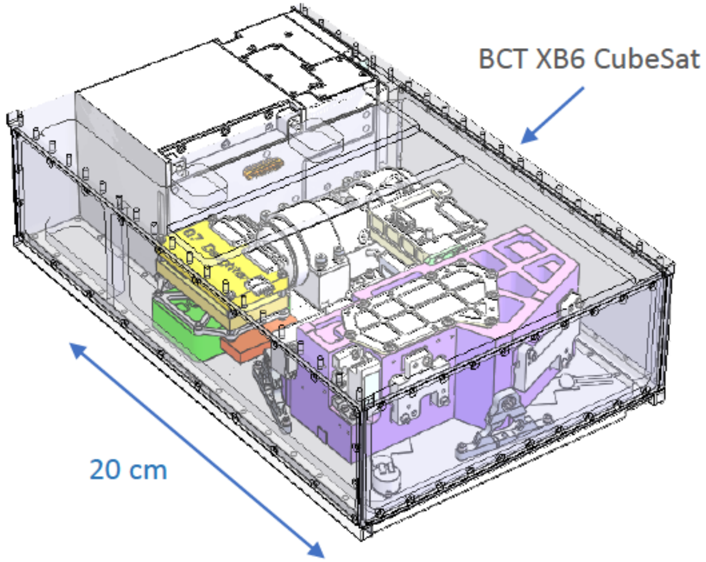
Key Technologies to Enable the Concept:

- Approach to orbital calibration via referencing Sun (TSIS/SIM measurements): Demonstration of lunar and solar measurements with *the same optical path using integration time to reduce solar signal (demonstrated in January 2021)*
- Pointing ability of spacecraft now permits obtaining required measurements *with instrument integrated into spacecraft*

ARCSTONE Status:

- Design Complete
- Fabrication complete
- Assembly and characterization in progress, TRL5 in July 2021.





Recent Publications & Contacts:

Please contact for additional information on ARCSTONE:
Dr. Constantine Lukashin: constantine.lukashin-1@nasa.gov

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

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

2. 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

3. NESC Academy Webcast on ARCSTONE (C. Lukashin & Team) available online at

https://mediaex-server.larc.nasa.gov/Academy/Play/ed1d00768a15486096edf4dac6d8cc7b1d

LIME Overview

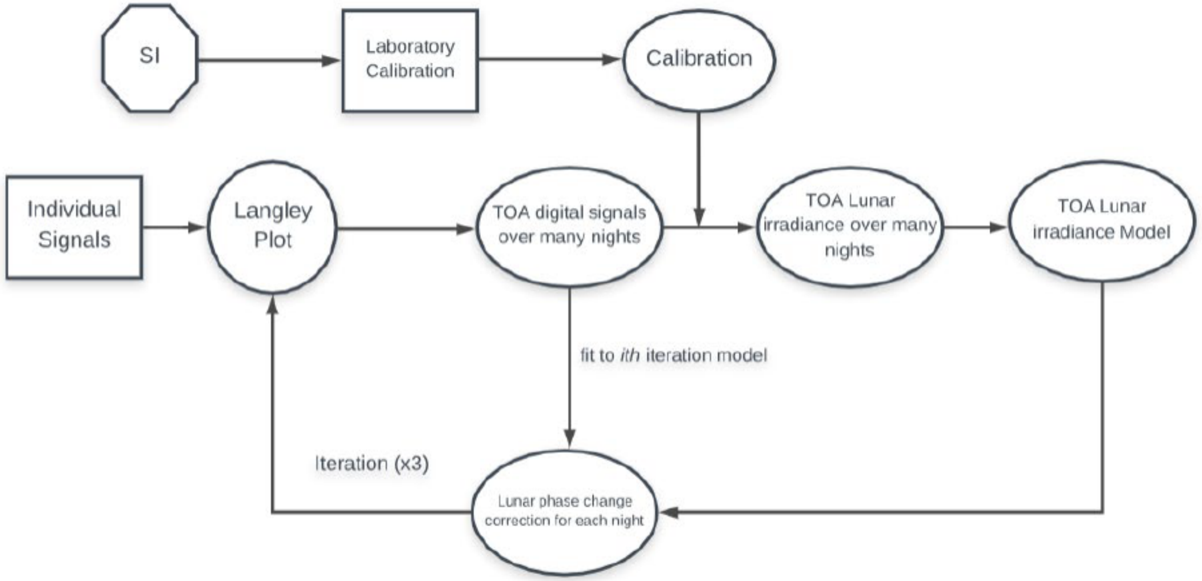
LIME
LUNAR IRRADIANCE MODEL OF ESA

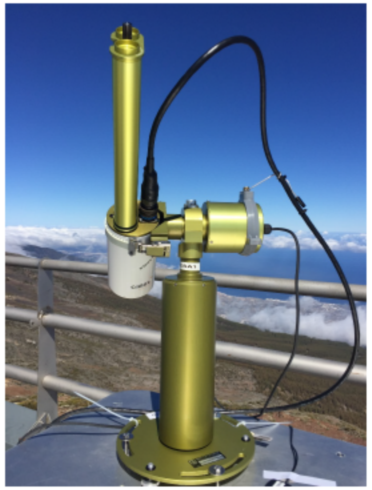
- Derived using SI-traceable ground-based measurements acquired with CIMEL 318-TP9 photometer from high altitude location at Teide Peak and Izaña Atmospheric Observatory in Tenerife

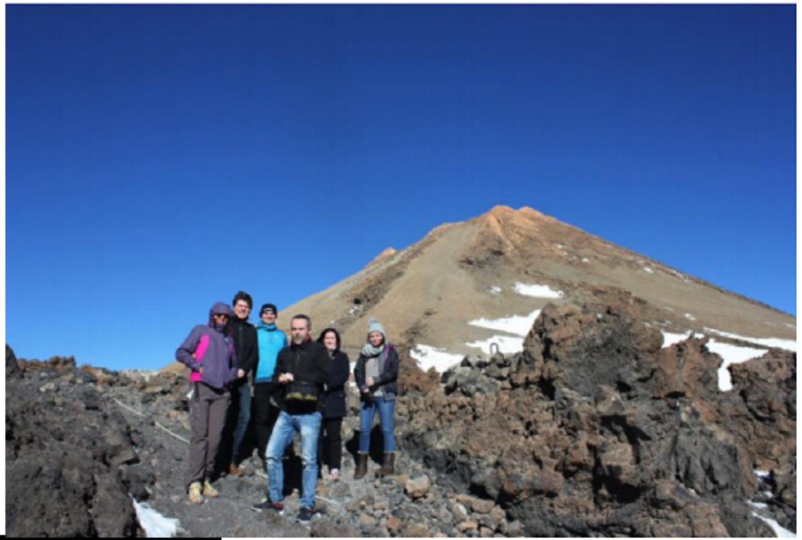
- Characterization and calibration at NPL and University of Valladolid

- Rigorous uncertainty analysis for calibration and individual observations

- Some modifications on original ROLO model and uncertainty estimated from Monte Carlo simulations.







vito vision on technology

AEMet Agencia Estatal de Meteorología

Universidad de Valladolid

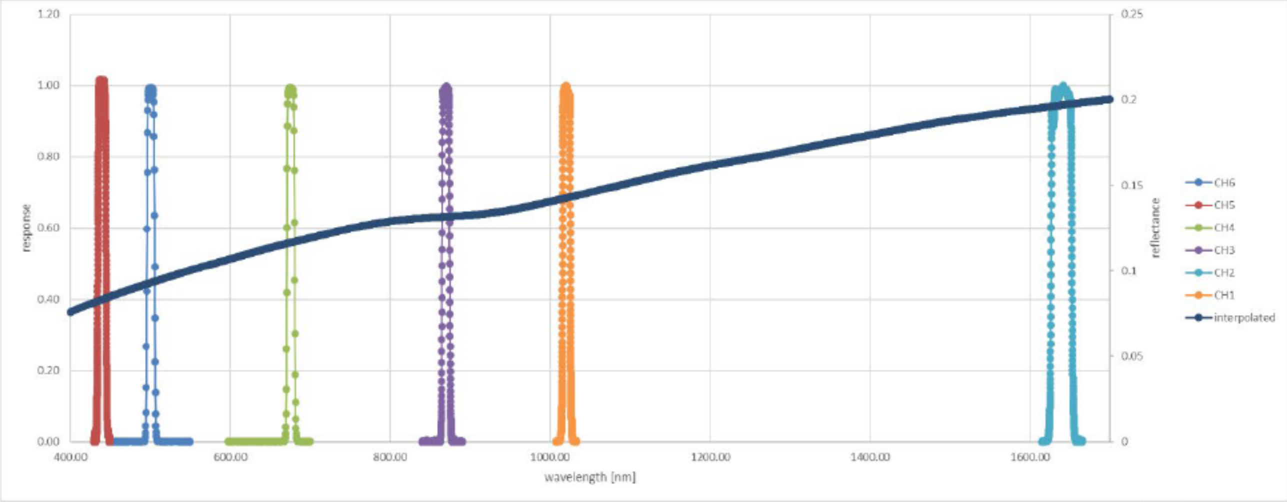
esa

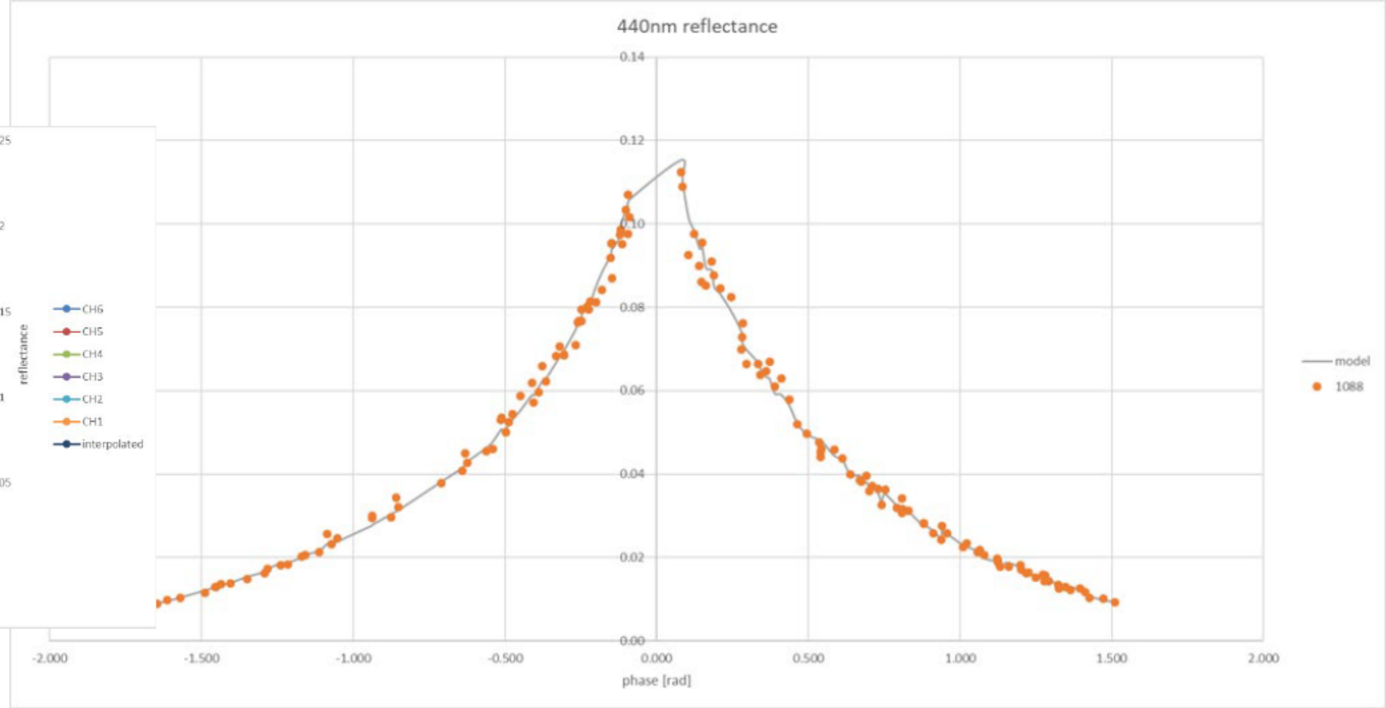
NPL National Physical Laboratory

LIME documentation and model coefficients are available on the CEOS Cal/Val portal
http://calvalportal.ceos.org/lime

Second version of the model released in December 2020 (2.5 years of irradiance data)

Lunar observations are scheduled to continue to 2024 with updates to the model expected each year, including improving the spectral model and uncertainty analysis





CMA Lunar Measurement Campaign in Lijiang Observatory

Four Instruments: 3 Lunar spectrometer imagers, 1 Hyperspectral Lunar photometer

(1) VisNIR Ground-based Lunar Imaging Spectrometer (GLIS) （2015.12-2020.04-Now）

(2) ShortWave Infared Lunar Oberved Infared Spectrometer (LOIS) (2019.12--Now)

(3) VNIR LeSIRB - Lunar and Earth Spectral Imager Radiometry Benchmark (2019.12-Now)

(4) VNIR-SW Hyperspectral Lunar photometer (2021.03--)

Lunar Measurement Station in Lijiang

- LOIS（1000nm-2400nm）

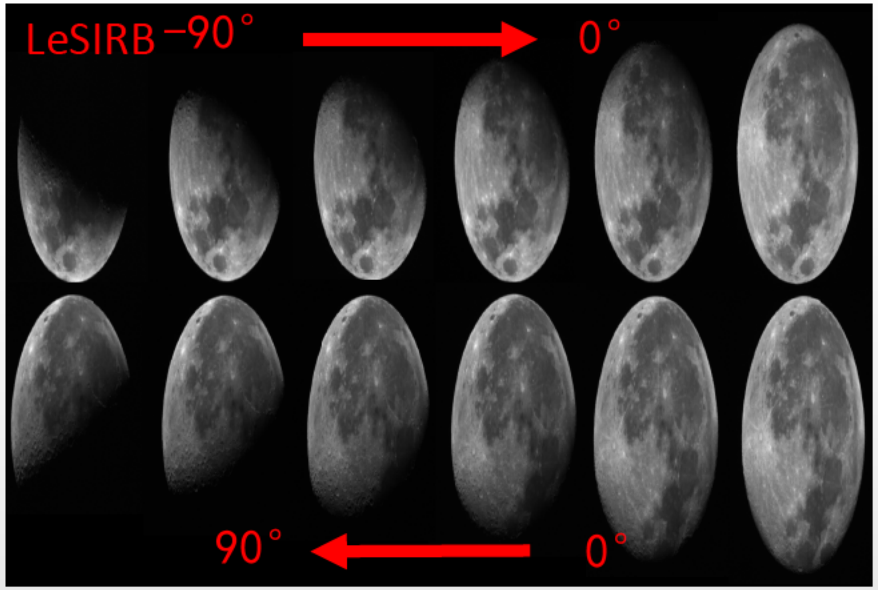
Hyperspectral Lunar Photometer(400-1700nm）

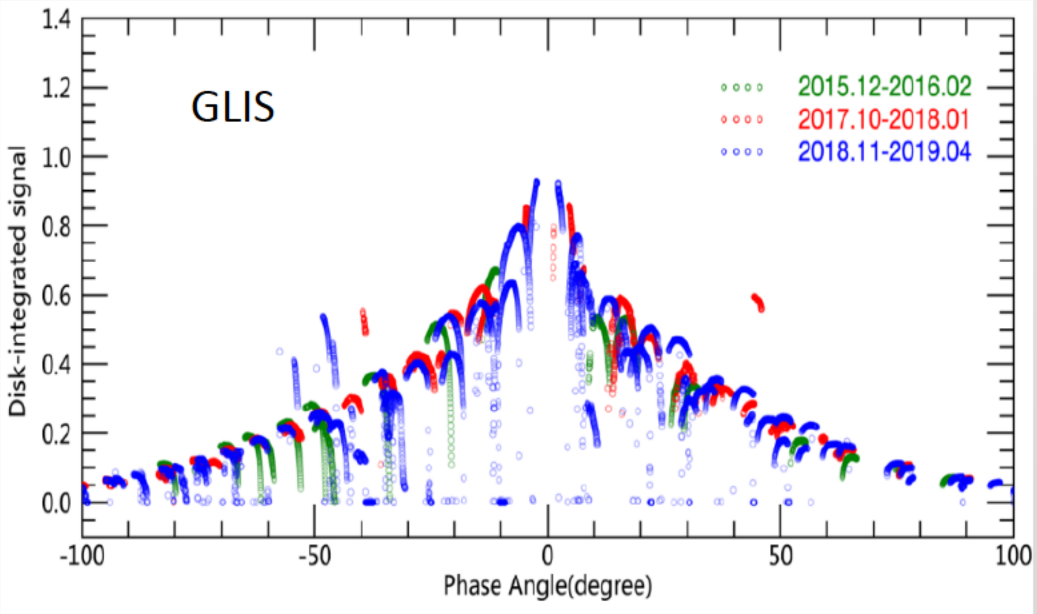
GLIS (400-1000nm)

CMA Ground-based Lunar observations ongoing since 2015 and More and more Lunar instruments were involved

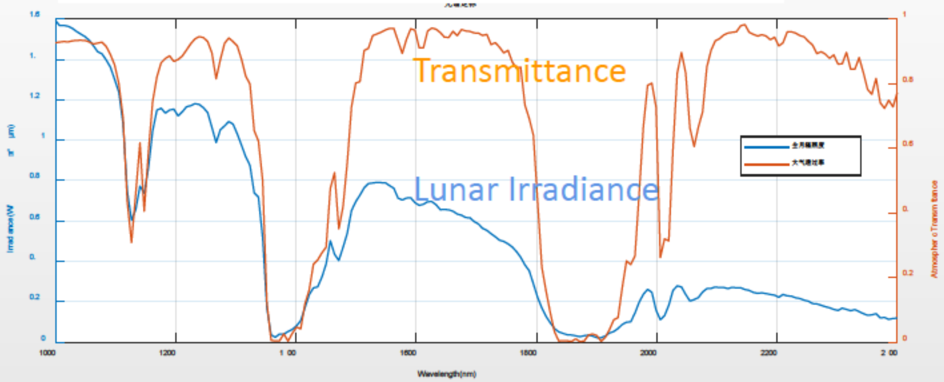
Lunar and Ancillary Observation--CMA

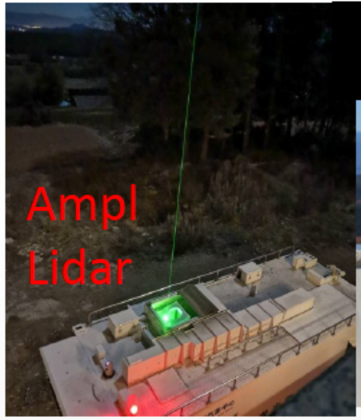
Instrument Calibration and Traceability--NIM

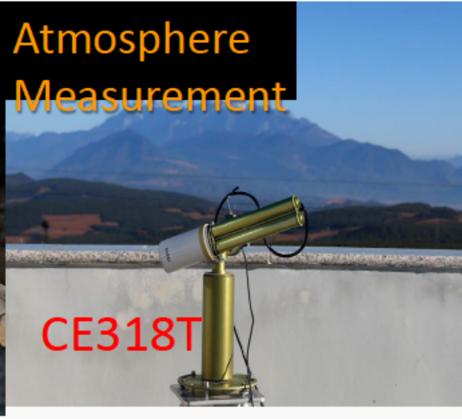




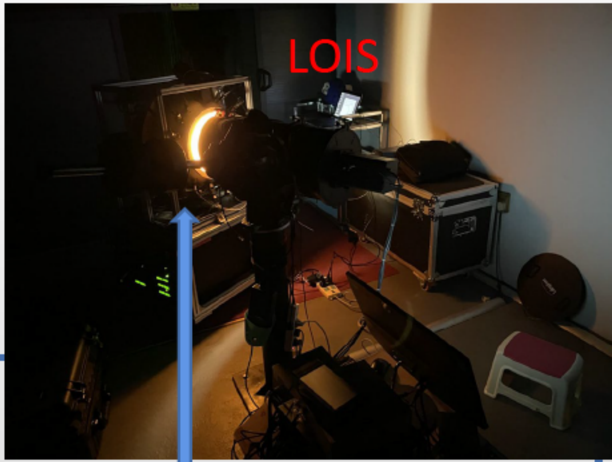
Shortwave Band Lunar Irradiance







Onsite Calibration



NIST

1） SR4500A spectrometer

Integrating sphere

2） Lunar imaging spectrometer

JiLin-1 Small Satellite -- Collaboration with CMA

Space-borne Lunar Imager

JILIN-01-09/B4 lunar image (559.61nm) June 2019

20190613_50.07° 20190614_37.52° 20190615_25.18° 20190616_12.26°

20190617_1.94° 20190618_11.65° 20190620_34.22° 20190621_45.25°

20190622_56.14° 20190623_67.67° 20190624_78.46°

Data_Phase Angle

JiLin-1 Lunar observation （17 months since April, 2019）

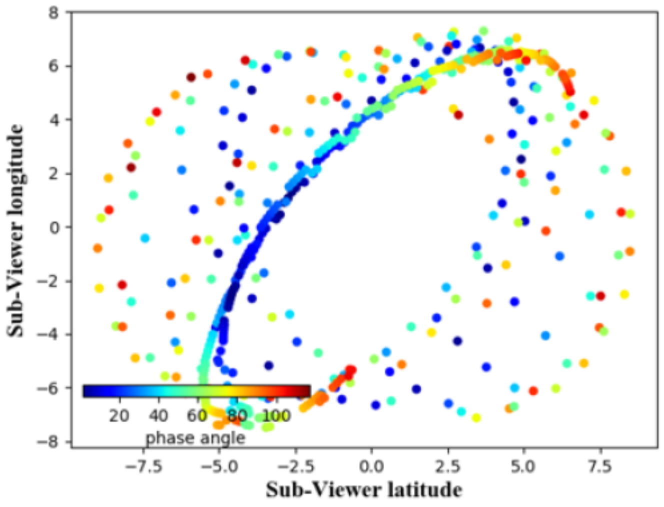


图 5 Sub-observer 201911-202101

Date	Number	PhaseAngle (°)
2019.04	1	5.79
2019.05	3	23.87~46.94
2019.06	10	-50.07~78.46
2019.07	14	-77.88~81.92
2019.08	12	-81.81~75.77
2019.11	16	-100.55~71.19
2019.12	16	-109.84~66.43
2020.01	13	-98.09~100.75
2020.02	17	-107.89~108.45
2020.03	17	-116.91~102.03
2020.04	18	-113.77~106.26
2020.05	18	-107.51~108.87
2020.06	15	-86.48~101.73
2020.07	18	-102.35~105.32

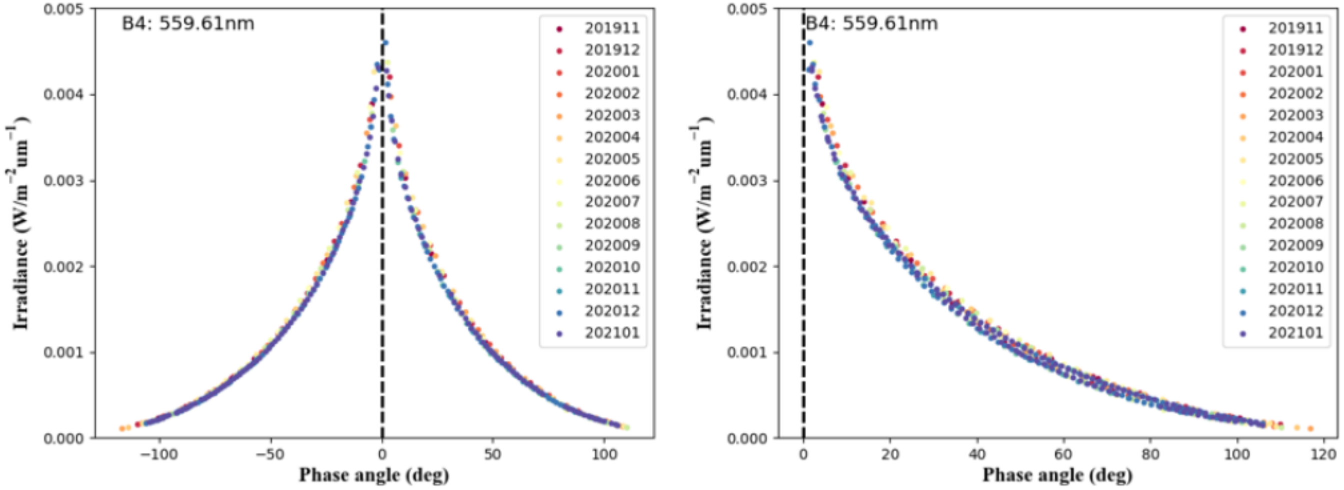


图 4 201911-202101(两个月加密数据)

Parameter	ARCSTONE (space)	Air-LUSI (airborne)	MLO-LUSI (ground)	LIME (ground)	Lijiang (ground)
Altitude	Measurements from LEO	Above 95% of atmosphere	Above 1/3 of atmosphere	Above 1/3 of atmosphere	Above 1/3 of atmosphere
Measurement	Lunar spectral irradiance	Lunar spectral irradiance	Lunar spectral irradiance (polarization planned)	Lunar spectral irradiance and polarization	Lunar spectral irradiance
Atmospheric correction	None	Modeling @ max 3% uncertainty	Langley approach + available data from MLO	Iterative Langley approach	Model + Lidar + sun photometer
Sampling Frequency	Every 12 hours	5 - 7 observations per campaign	Nightly observations (weather, phase)	Nightly observations (weather, phase)	
Duration	3+ years	20 flights over 2+ years	3+ years	5+ years (>300 nights so far)	Ongoing for foreseeable future. First meas 2015.
Spectral Range	VNIR-SWIR	VNIR (SWIR possible)	VNIR (SWIR planned)	4 VNIR, 2 SWIR bands	VNIR and SWIR
Accuracy Goals	< 0.5% (k=1)	< 0.5% (k=1)	< 0.5% (k=1)		
Calibration Approach	On-orbit to SSI (TSIS/SIM, 0.2%)	Stable spectrograph traceable to NIST FASCAL2	Stable spectrograph traceable to NIST FASCAL2	Pre-deployment characterization at NPL and solar langley	NIM Source. Lamp/Plaque
Role	New Lunar Reference (75% app**)	New Lunar Reference/Validation	New Lunar Reference (50% app**)	New lunar reference	New lunar reference
Readiness	Field validation of prototype June 2021	3 engineering flights, 5 demonstration flights completed	multiple campaigns completed with portable unit, long-term starting mid 2021	Operational	Operational
Agencies	NASA	NASA / NIST	NIST	VITO/ESA/NPL/AEmet/Univ. de Valladolid	CMA