Wednesday, September 14, 2022 | 2:30 p.m.

Calibration Methods Using Celestial Objects

Presentation of radiometric measurements and calibration methods using the Sun, Moon, stars, and other celestial objects in the ultra-violet, visible, and infrared wavelengths

Celestial Object Calibration Possibilities with GOES-R ABI

Jon Fulbright – Arctic Slope Regional Corporation Federal (ASRC Federal); David Pogorzala – KBR; Elizabeth Kline – National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS)/GOES-R

ABSTRACT: The nominal full disk scanning scene utilizes by the ABI instrument on the GOES-R series satellites scans a sizable area of deep space. Some of this scan area is used in the two-point radiometric calibration, but the off-Earth pixel data is discarded before the L1b products are generated and distributed. However, these deep space regions contain other potentially useful observations. Taniguchi et al. (2022) used the deep space data from the Japanese AHI instrument (nearly identical to ABI) to characterize the “Great Dimming of Betelgeuse” in 2020 with enough precision to differentiate between the proposed physical mechanism for the dimming. Inspired by this work, we have endeavored to reprocess ABI data to extract these off-Earth pixels for a subset of celestial objects bright enough for ABI to record, including several bright stars, planets, and serendipitous observations of the Moon. In this talk, we present the present status of this work and early results in determining whether these objects could be developed into practical calibration targets for geostationary instruments.

Addressing Needs to Achieve High-accuracy Lunar Calibration

Tom Stone – U.S. Geological Survey

ABSTRACT: Established techniques that use the reflected light from the Moon for sensor radiometric calibration typically utilize the spatially integrated quantity of lunar spectral irradiance. The USGS ROLO model (and its replicated variants) has seen widespread use as the reference for lunar calibration since its development in the early 2000s. Although absolute scale uncertainties persist in the current ROLO model version, a predictive model for lunar spectral irradiance potentially can achieve tenths-percent uncertainty or better, with SI traceability. This would enable a number of important capabilities for on-orbit calibration of Earth observing sensors. To advance development toward a high-accuracy lunar calibration reference requires obtaining new characterization measurements of the Moon that have verified uncertainties and traceability to primary radiometric standards.

But to reach the levels of accuracy potentially achievable for lunar calibration also requires increased attention to and improvement in techniques for deriving irradiance measurements from Moon observations acquired by imaging sensors. For example, properly evaluating the oversampling of the Moon disk can present a considerable challenge for line-scanning imagers. The Operational Land Imager (OLI) on Landsats 8 and 9 provides a superb test bed for developing techniques for high-precision measurements of lunar irradiance from line-scanned Moon images. Both OLI instruments observe the Moon monthly at about 7 degrees phase angle, scanning the disk with all 14 Focal Plane Modules over two orbits. The 30-meter ground resolution produces Moon images with disk diameters of about 250 pixels, and the scans oversample the Moon by factors of about 8. The lunar disk can be framed using line-of-sight analysis derived from the Landsat ancillary data feed.

This paper will discuss how newly available, high-accuracy lunar irradiance measurements can inform the absolute scale for redeveloping the lunar calibration reference, and will overview the advanced techniques being developed for processing the line-scanned images of the Moon acquired by OLI.

ARCSTONE InVEST: Calibration of Lunar Spectral Reflectance from Space

Constantine Lukashin, Trevor Jackson, Cindy Young – NASA Langley Research Center; Greg Kopp – Laboratory for Atmospheric and Space Physics (LASP)/University of Colorado; Rand Swanson – Rasonon, Inc.; Christine Buleri – Quartus Engineering; Thomas Stone – U.S. Geological Survey; Mark Gorman – Blue Canyon Technologies

ABSTRACT: Detecting and improving the scientific understanding of global trends in complex Earth systems, such as climate, increasingly depend on assimilating datasets from multiple instruments and platforms over decadal timescales. Calibration accuracy, stability, and inter-consistency among different instruments are key to developing reliable composite data records from sensors in low Earth and geostationary orbits, however, achieving sufficiently low uncertainties for these performance metrics poses a significant challenge. Space-borne instruments commonly carry on-board references for calibration at various wavelengths, but these increase mass and mission complexity and are subject to degradation in the space environment. The Moon can be considered a natural solar diffuser which can be utilized as an on-orbit calibration target by most space-borne Earth-observing instruments. Since the lunar surface reflectance is effectively time-invariant, establishing the Moon as a high-accuracy calibration reference enables broad inter-calibration opportunities even between temporally non-overlapping instruments and provides an exo-atmospheric absolute radiometric standard. This on-orbit radiometric spectral reference helps enable high-accuracy absolute calibrations and inter-calibrations of past, current, and future Earth-observing sensors, meteorological imagers, and long-term climate-monitoring satellite systems. The goal of the ARCSTONE In-Space Validation of Earth Science Technologies (InVEST) project, funded by NASA ESTO, is to demonstrate its novel lunar measurement approach from space and improve the Moon as a radiometric SI-traceable reference for high-accuracy on-orbit calibrations spanning the visible and near-infrared spectral regions. The ARCSTONE instrument is a compact spectrometer which will be accommodated on a 6U CubeSat intended for low Earth orbit with planned readiness for launch in about 2 years. It will measure the lunar spectral reflectance with combined standard uncertainty of 0.5% (k=1) across the 350 nm to 2300 nm spectral range. The ARCSTONE InVEST team will present the status of the project, the instrument design, calibration approach, concept of operations, and the planned path toward mission implementation.

ARCSTONE: Improving Radiometric Calibration Uncertainties of Lunar Spectral Measurements

Greg Kopp, Seth Cousin, Paul Smith – Colorado University/Laboratory for Atmospheric and Space Physics (LASP); Constantine Lukashin – NASA Langley Research Center

ABSTRACT: The ARCSTONE InVEST project will characterize the spectral lunar irradiance via high-accuracy < 0.5 % (k=1) average combined relative standard uncertainty reflectance measurements across the 350 to 2300 nm spectral range, helping benchmark the Moon as an on-orbit calibration reference for inter-calibrations with Earth-observing sensors, meteorological imagers, and long-term climate-monitoring satellite systems even between temporally non-overlapping instruments. This accuracy is enabled via the ARCSTONE's ratio technique comparing spectral solar- to lunar-signal measurements using the same optical path in the instrument's spatially integrating spectrometer. These relative signal ratios are used to convert spectral lunar reflectances to irradiances using known spectral solar irradiances provided daily by other on-orbit assets having ~ 0.2 % (k=1) uncertainties, providing SI traceability to the resulting ARCSTONE lunar irradiances. The solar-to-lunar ratio technique eliminates traditional effects of on-orbit degradation and aging that can cause long-term changes in optical efficiency, thus maintaining stable accuracy levels over the duration of the ARCSTONE mission.

To acquire both solar and lunar irradiances despite the six orders of magnitude difference in their signal levels while using the same optical path for both objects, the ARCSTONE relies on electronically clocked changes in integration time and known detector linearity. Under a NASA IIP project, a prototype instrument was built and characterized for uncertainties in obtaining those lunar-to-solar signal ratios, accounting for contributions from detector noise, non-linearities, background, polarization, dispersion shifts, and other effects. We present the results of those characterizations and their associated uncertainties to show the expectation of achieving the ARCSTONE's on-orbit spectral lunar-reflectance calibration uncertainties of < 0.5 % (k=1).

Extending the Spectral Range of the RObotic Lunar Observatory (ROLO) Model to Climate Science-relevant Wavelengths

Cindy Young – NASA Langley Research Center; Thomas Stone – U.S. Geological Survey; Janet Daniels – Science Systems and Applications, Inc.; Martin Snow – South African National Space Agency; Roger Clark – Planetary Science Institute; Jean-Pierre Williams – University of California, Los Angeles

ABSTRACT: A critical aspect of monitoring and understanding climate change is maintaining a continuous Earth Radiation Budget (ERB) record. The radiation budget is the balance between absorbed solar radiation and emitted thermal IR radiation by the Earth-atmosphere system, and ERB sensors require shortwave (SW) broadband measurements from 0.2 – 5 µm. Calibration accuracy, stability, and inter-consistency among different instruments are key to developing reliable composite long-term data records, but achieving sufficiently low uncertainties for these performance metrics poses a significant challenge. For this purpose, space-borne instruments commonly carry on-board references for calibration at various wavelengths, but these increase mass and mission complexity, and therefore cost, and are subject to degradation in the space environment. We present a new path towards accurate on-orbit calibration for SW broadband sensors.

The Moon can be considered a natural solar diffuser that can be used as a calibration target by reflected-solar radiometer instruments and can be viewed by most Earth orbiting sensors. Using the Moon as a high accuracy on-orbit reference for ERB sensors will help reduce the time it takes to detect trends in climate variables to better inform public policy and societal actions, and may allow for more robust gap-tolerant observing systems in the future. The Moon has an exceptionally stable visible to SWIR reflectance, but its brightness is continually changing. Predicting this changing brightness requires an analytical model, the most reliable of which is the RObotic Lunar Observatory (ROLO) model, which has been established at the 0.35 – 2.45 µm spectral range. The lunar reflected UV radiation from 0.2 – 0.3 µm and reflected/emitted NIR radiation beyond 2.45 µm not accounted for by the ROLO model are small, but this additional uncertainty (on the order of a few percent) is enough to prevent using the Moon as an absolute calibration reference over the SW broadband range. We present a method for expanding the spectral range of the ROLO lunar calibration reference from the current 0.35 µm UV limit to 0.2 µm, and from the current 2.45 µm IR limit to 5.0 µm to fit the specific needs of the climate science community for absolute calibration. This expanded lunar reference will support past, present, and future ERB measurements in the SW broadband.

NOAA-20 VIIRS Day Night Band (DNB) Radiometric Calibration using Solar Diffuser and Lunar Observations

Taeyoung Choi – National Oceanic and Atmospheric Administration (NOAA)/Global Science and Technology, Inc. (GST); Changyong Cao – National Oceanic and Atmospheric Administration (NOAA); Xi Shao – National Oceanic and Atmospheric Administration (NOAA)/University of Maryland

ABSTRACT: On-board radiometric calibration of Day Night Band (DNB) on the National Oceanic and Atmospheric Administration (NOAA) 20 Visible Infrared Imaging Radiometer Suite (VIIRS) is based on the Solar Diffuser (SD) observations in the Low Gain Stage (LGS). DNB is a unique panchromatic band which has a broad spectral response covering a wavelength range roughly from 500 nm to 900 nm with over 7 orders of magnitude in radiometric dynamic range. To cover such a wide dynamic range, DNB has High Gain Stage (HGS), Middle Gain Stage (MGS), and LGS in the sensor design. The radiometric calibration of DNB MGS and HGS depends on the SD-based LGS gain estimation and then transferred to the MGS and HGS through gain ratios.

The on-orbit NOAA-20 DNB LGS gains have been derived daily from the on-board SD observations since its launch on November 18, 2017. Using the scheduled lunar observations of VIIRS as the independent radiometric calibration source, the lifetime SD-based DNB LGS gains can be independently validated. The NOAA-20 DNB lunar F-factors (or calibration coefficient) are derived through analyzing the lunar irradiance ratio between VIIRS lunar observations and the lunar irradiance model. i.e. the Global Space-based Inter-Calibration System (GSICS) Implementation of RObotic Lunar Observatory (ROLO) (GIRO). The primary on-orbit SD-based NOAA-20 DNB radiometric calibration is validated by the lunar F-factors. It is found that the difference between SD-based calibration coefficient and lunar-F factor for NOAA-20 DNB LGS is within two percent based on the analysis of 4 years of NOAA-20 VIIRS DNB measurements.

Airborne LUnar Spectral Irradiance (air-LUSI) Mission – First Operational Campaign

Kevin Turpie – University of Maryland, Baltimore County; John Woodward, Steven Brown, Steven Grantham, Thomas Larason, Stephen Maxwell – National Institute of Standards and Technology (NIST); Thomas Stone – U.S. Geological Survey; Andrew Gadsden, Andrew Newton – McMaster University

ABSTRACT: The objective of the airborne LUnar Spectral Irradiance (air-LUSI) mission is to make highly accurate, SI-traceable measurements of lunar spectral irradiance in the VNIR spectral region from NASA's high-altitude ER-2 aircraft, and these measurements are in turn expected to be used to improve our ability to use the Moon as an absolute calibration reference for Earth observing satellites. To that end, the air-LUSI system employs an autonomous, robotic telescope system that tracks the Moon in flight, and a stable spectrometer housed in an enclosure that provides a robustly controlled environment. During flight campaigns, these instrument subsystems are situated in a wing pod of the ER-2 aircraft where the telescope can observe the Moon through a small dorsal view port.

air-LUSI successfully conducted its first Operational Flight Campaign on the nights of 12, 14, 15 and 16 March 2022. The air-LUSI system observed the Moon each night at about or above 21 km altitude, above 95% of the Earth's atmosphere. Each observation measured the lunar spectral irradiance at wavelengths from about 380 to 1040 nm. The four flights corresponded to lunar phase angles of -60.3°, -37.0°, -25.0° and -12.9°. The measurement uncertainty is currently estimated to be about 0.8% or less through the mid-visible range. The accuracy was achieved in part using lessons learned and upgrades devised since the 2019 Demonstration Flight Campaign. This paper will summarize the air-LUSI objectives, review improvements done since the 2019 Demonstration campaign, and provide an overview of Operational Flight Campaign 01 and new lessons learned for the continued improvement of air-LUSI accuracy in future flights.

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Development of the Moon as an Absolute SI-traceable Celestial Calibration Target to Support Climate-quality Measurements by Earth Remote Sensing Instruments

Steven Brown, John Woodward – National Institute of Standards and Technology (NIST); Kevin Turpie – University of Maryland; Andrew Gadsden – McMaster University; Thomas Stone – U.S. Geological Survey

ABSTRACT: To support measurements relevant to climate observables, emphasis has been placed on the development of space-based Climate Observatories, e.g. CLARREO Pathfinder (CPF), that can maintain SI-traceability on-orbit with uncertainties that meet observation requirements. The transfer of radiometric scales from Climate Observatories to the suite of sensors on-orbit at any given time anticipates using Simultaneous Nadir Overpasses (SNOs) of terrestrial calibration targets, requiring a continuous train of Climate Observatories be maintained on-orbit. The cost and complexity of Climate Observatories warrants examination of alternate approaches to the in situ calibration of climate sensors.

The uncertainties in the transmittance through the atmosphere is one of the larger uncertainty components in terrestrial vicarious calibration. It makes sense, therefore, to consider exo-atmospheric calibration targets such as the sun, the moon, and stars. As a general calibration target for use by a wide range of sensors, the sun is too bright while stars are too dim, leaving the moon to evaluate as a possible calibration target supporting climate studies. The moon's radiometric properties in the reflected solar regime, while dependent on illumination and viewing geometries, are predictable to within one part in 103. Observations of the moon using the same geometry have been extremely valuable for trending the temporal response of on-orbit sensors.

Empirical models such as the USGS's RObotic Lunar Observatory (ROLO) model are used to predict the lunar spectral irradiance given an illumination and viewing geometry. The estimated uncertainties in current models are too large to support climate measurement requirements and, in most cases, are not traceable to the SI. Further development of the Moon as an absolute celestial calibration target for radiometric applications warrants a refinement of the ROLO model or replacement with a new empirical model. In either case, new measurements are required.

Air-LUSI is a program currently underway making low uncertainty, SI-traceable measurements of the lunar irradiance. To reduce the uncertainty in atmospheric transmittance, a dominant uncertainty component in ground-based measurements, air-LUSI makes

measurements of lunar irradiance from a NASA aircraft flying above 95% of the atmosphere. In this talk, implications of results from an air-LUSI Demonstration Flight campaign toward establishing the moon as an absolute SI-traceable calibration target are discussed.