ARCSTONE:
Calibration of Lunar Spectral Reflectance from Space

Constantine Lukashin[1], Trevor Jackson[1], Rand Swanson[2], Michael Kehoe[2], Michael Stebbins[2], Hans Courrier[2], Greg Kopp[3], Paul Smith[3], Alan Hoskins[3] Michael Cooney[1], Warren Davis[1], Noah Ryan[1], David Taylor[1], Cindy Yong[1], Christine Buleri[4], Elise Minda[4], Alexander Halterman[4], Adam Phenis[5], Timothy Christianson[4], Thomas Stone[6]

[1]NASA Langley Research Center, Hampton, Virginia; [2]Resonon, Inc., Bozeman, Montana
[3]LASP Colorado University, Boulder, Colorado; [4]Quartus Engineering, Inc., San Diego, California;
[5]AMP Optics, LLC., Poway, California; [6]USGS, Flagstaff, Arizona.

Corresponding e-mail address: constantine.lukashin-1@nasa.gov

EXTENDED ABSTRACT

Improving scientific detection and understanding of long-term 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, but achieving sufficiently low uncertainties for these performance metrics, particularly for space-based instruments, poses a significant challenge. Such 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 observed as a calibration target by most spaceborne Earth-observing instruments. Since the lunar surface reflectance is effectively time-invariant, developing 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. The intensity of moonlight reaching a sensor changes with time, governed by the solar illumination of the Moon and the net lunar reflectance as a function of phase angle. To realize a radiometric calibration against the Moon, the Sun-Moon-observer geometry and the solar flux for a particular observation are combined with the lunar reflectance to predict the lunar brightness, for comparison with the sensor's response. This requires development of a lunar irradiance model that provides a continuous predictive capability.

Tools and a methodology for lunar calibration have been developed by the U.S. Geological Survey (USGS) in Flagstaff, AZ, under sponsorship from NASA's Earth Observing System program. The USGS lunar calibration system was built from a set of Moon images acquired by the ground-based Robotic Lunar Observatory (ROLO) over a period of more than 8 years. These measurements form the basis for an empirically-derived analytic model for the lunar disk-integrated reflectance [1], which can be queried for any geometry of Moon observations within the model's valid range. In operation, the disk reflectance spectrum is generated for a specified set of observation conditions, then interpolated and convolved with the solar spectral irradiance and the sensor's spectral response functions to produce spectral lunar irradiance values in a sensor's bandpasses corresponding to the time and location of its the observation. Utilizing lunar calibrations, top-of-atmosphere radiance measurements from SeaWiFS achieved long-term stability of 0.13% over the 13-year mission lifetime [2]. The USGS system is typically is not used for absolute calibration, however, due to limitations of the current ROLO model's accuracy, which is estimated at 5 – 10% (k=1).

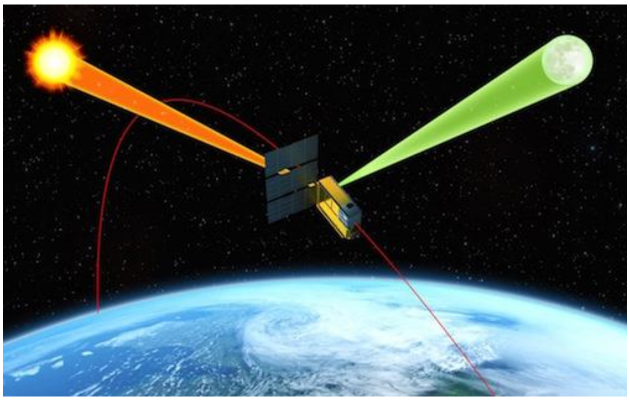

Figure 1: ARCSTONE conceptual mission to calibrate lunar spectral reflectance, flying on a 6U CubeSat (spacecraft bus image courtesy of Blue Canyon Technologies). Calibration of the ARCSTONE instrument itself is achieved on-orbit using the spectral solar irradiance as an absolute reference.

The ARCSTONE mission goal is to develop the Moon as a reliable reference for high-accuracy on-orbit calibration of reflected-solar instruments, including improvements to the absolute accuracy of the lunar spectral irradiance. The ARCSTONE instrument is a compact spectrometer, intended for a CubeSat platform in low Earth orbit. It will measure the lunar spectral reflectance with accuracy < 0.5% (k=1), sufficient to establish an SI-traceable absolute lunar calibration standard referenced to the spectral solar irradiance across the 350 to 2300 nm spectral range with 4 nm spectral sampling.

The ARCSTONE's on-orbit deployment strategy, illustrated in Figure 1, is to sample the Moon with frequency sufficient to adequately characterize the changes in lunar irradiance with time. To achieve the project goal of improving the current ROLO calibration reference, ARCSTONE observations must span both the range of lunar phases and the range of librations with sufficient coverage. The appearance of the Moon from the Earth's surface or low Earth orbit is constrained by its synchronized rotation rate and by the tilt of the lunar orbit. Consequently, at least three years of observations are required to fill out the libration parameter space, defining the duration of ARCSTONE on-orbit operations.

ARCSTONE mission operation requirement is to take lunar measurements every 12 hours when the phase angle (Sun-Moon-ARCSTONE angle) is in the range from zero to ±135 degrees, providing 3 weeks per month of usable calibration times, expanding the usable range of on-orbit lunar calibrations beyond the current limit of ±90 degrees phase, or two weeks per month. Lunar measurements will be taken at the highest latitudes of the ARCSTONE orbit, to view the largest range of lunar latitudes. Measurements of the Sun are planned to have at least a weekly cadence to account for solar and sensor variability.

Each lunar measurement sequence will last approximately 5 minutes, and consist of multiple acquisitions of 10 – 15 seconds integration time. Longer integration times are excluded due to orbital effects on the observed lunar irradiance. For a sensor in low Earth orbit, the lunar irradiance can vary up to 0.1% in about 16 seconds due to the changing Moon observer distance and the change in phase angle caused by the moving vantage point. Dark field measurements will be acquired before and after each lunar and solar measurement sequence. These will be obtained through a combination of a closed shutter on the instrument and by viewing deep space.

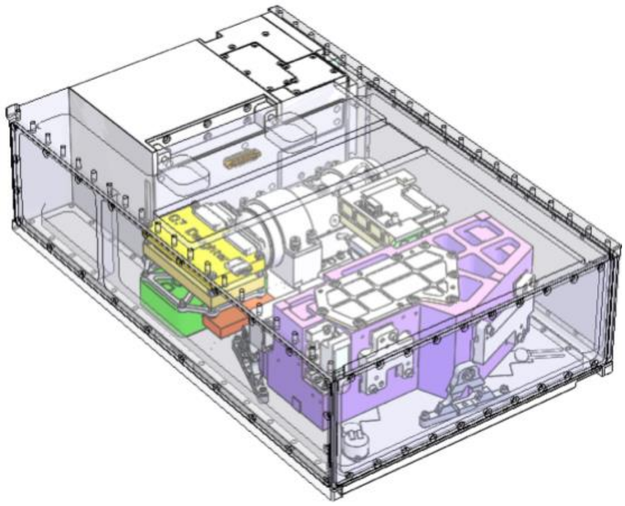

Figure 2: The ARCSTONE instrument integrated in a 6U CubeSat (spacecraft bus CAD courtesy Blue Canyon Technologies). The instrument components include: optical bench (blue), detector and cryocooler assembly (grey), and control electronics (yellow, green, and orange).

The ARCSTONE instrument's purpose is to accurately calibrate spectral lunar reflectance of the entire disc by taking the ratio of solar and lunar measurements. By utilizing identical optics for both solar and lunar measurements, potential impacts from long-term optical degradation are removed. Optical and mechanical designs of the instrument are advanced and a second-generation instrument is being fabricated. The instrument packaging into an intended 6U CubeSat bus is shown in Figure 2.

The ARCSTONE team will present the instrument design, development status, approach to calibration and characterization, and the planned path toward mission implementation.

REFERENCES

1. H.H. Kieffer and T. C. Stone, "The Spectral Irradiance of the Moon," Astron. J. 129, 2887-290, 2005.

2. R. E. Eplee Jr. et al., "On-orbit calibration of SeaWiFS," Applied Optics 51, 8702 - 8730, 2012.