# Measurements of absolute, SI traceable lunar irradiance with the airborne Lunar Spectral Irradiance (air-LUSI) Mission

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**The air-LUSI instrument is developed around a spectrograph fiber-coupled to a telescope. The system is designed to make highly accurate SI-traceable measurements of the lunar spectral irradiance in the VNIR region from an aircraft at elevations from 60,000 feet to 70,000 feet. Five air-LUSI Demonstration Flights were conducted in November 2019 corresponding to lunar phase angles ranging from 10º to 60º. This presentation discusses the lunar irradiance measurements, the resultant uncertainty budgets, and the path forward to achieve uncertainties of 0.5 % or less in lunar irradiance.**

## INTRODUCTION

The Moon is an attractive exo-atmospheric calibration target for space-based sensors that observe the Earth because the lunar surface is photometrically stable, flux levels approximate those from the Earth, and no atmospheric corrections need to be applied for the calibration. While many sources of uncertainty that arise when vicariously calibrating sensors using land targets are eliminated, lunar measurements are complicated – though predictable – because the lunar irradiance is a function of the relative positions of the Sun, Moon, and Observer (spacecraft) among other variables. The United States Geological Survey (USGS) has developed the Robotic Lunar Observatory (ROLO) Model of Top-Of-the-Atmosphere (TOA) lunar reflectance/irradiance, which accounts for changes in lunar irradiance as a function of these variables. The USGS ROLO model - and the Global Space-based Inter-Calibration System (GSICS) Implementation of the ROLO model (the GIRO model) - represent the most precise knowledge of lunar spectral irradiance and are used frequently as a relative calibration standard by space-borne Earth-observing sensors. However, the current uncertainties in the ROLO Model are estimated to be between 5 % and 10 % in the Visible to Near InfraRed (VNIR) spectral region and are not traceable to the International System of Units (SI); consequently, the Moon is not used as an absolute standard.

The objective of the air-LUSI project is to make highly accurate (sub-0.5 % uncertainty), SI-traceable measurements of the lunar spectral irradiance in the VNIR region from an aircraft at altitudes from 60,000 feet to 70,000 feet. Air-LUSI measurements, corrected for residual atmospheric attenuation, are designed to provide a data set of low uncertainty TOA lunar irradiances at known lunar phase and libration angles to be compared and integrated with other lunar irradiance data sets.

## AIR-LUSI INSTRUMENT

A schematic diagram of air-LUSI is shown in Figure 1 as it is mounted in the aircraft. The instrument is mounted on one of two ER-2 wing pods. Each pod has three sections: an aft-body, a mid-body and a fore-body. The aft-body is open to the environment and during lunar measurements is at an atmospheric pressure ≈ *0.06 atm* and a temperature ≈ *-60 ºC*. The mid-body is kept at a pressure of *1/3 atm* and a temperature of *0 ºC*. The instrument enclosure is mounted in the mid-body and fiber-coupled through the bulkhead to the telescope mounted in the aft-body.

Heaters control the temperatures of the instrument enclosure, the fiber-optic bundles, the integrating

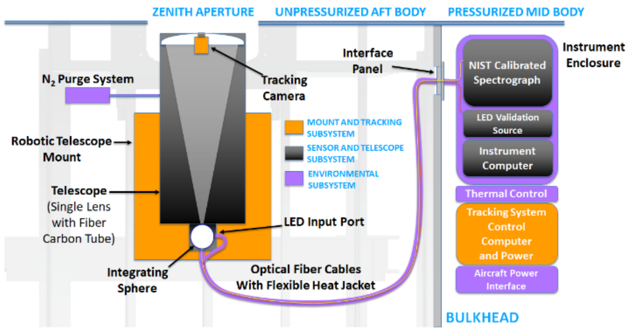


**Figure 1.** Schematic design of air-LUSI.

sphere detector on the telescope and the actuators that control pointing of the system.

## MEASUREMENTS OF LUNAR IRRADIANCE

The instrument was successfully integrated into a wing pod of an ER-2 research aircraft at NASA's Armstrong Flight Research Center and five Demonstration Flights were conducted in November 2019 covering lunar phase angles from ≈10° (Flight 1) to ≈60° (Flight 5).

The lunar irradiance averaged over the full lunar data sets from each night of measurements is shown in Figure 1. Estimated uncertainties in the measurements of lunar irradiance are shown in Figure 2. Only one uncertainty budget is shown because there is only a small difference in the uncertainty budget as the phase changes from 10° to 60°. The uncertainty is less than 1 % from 400 nm to 1000 nm.

## DISCUSSION

While the target uncertainties are less than 0.5 %, SI-traceable TOA lunar irradiances with higher uncertainties are very useful. An SI- traceable, TOA lunar irradiance data set with uncertainties less than 1% could meet many sensor calibration uncertainty requirements and include the ability to bring inter-consistently between contemporary missions and across series of missions by using a common, stable reference.

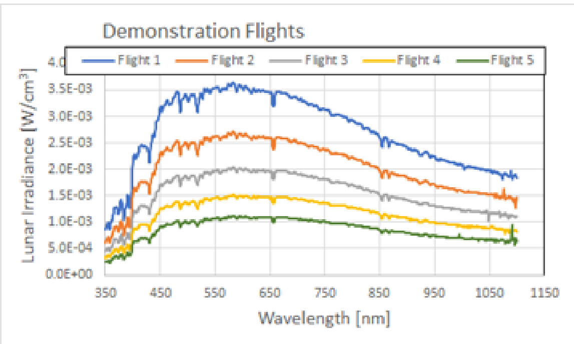


Figure 1. Mean lunar irradiances measured by air-LUSI during Demonstration Flights in November 2019.

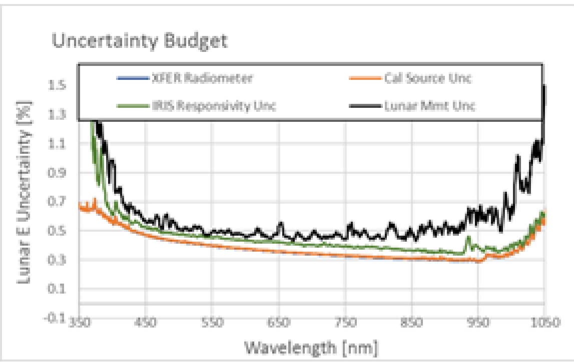


Figure 2. Lunar irradiance uncertainty budget.

The air-LUSI measurements may also resolve questions about the origin of differences between sensor measurements of the lunar irradiances and model predictions. Figure 3 shows the ratio of measurements by seven different instruments to the ROLO Model, 6 US instruments and 1 non-US instrument, shown in red in Figure 3. Instrument 6 is the only ground-based instrument in the comparison; it measured the lunar irradiance at two different phases, 6.9° and 16.9°.

This presentation discusses the results of the air-LUSI Demonstration Flights, focusing on the development of the uncertainty budget.

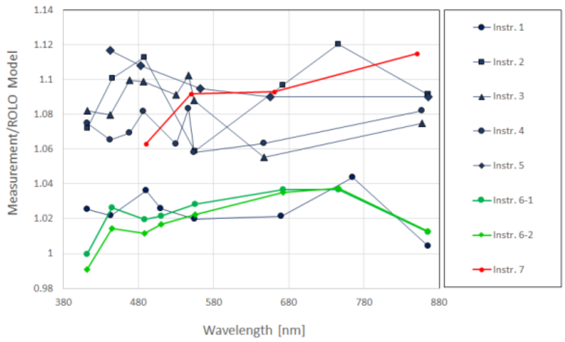


Figure 3. Ratio of measurements by different instruments to the ROLO Model.

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