FIRST RESULTS FROM LASER-BASED SPECTRAL CHARACTERIZATION OF LANDSAT 9 OPERATIONAL LAND IMAGER-2

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ABSTRACT

Landsat 9 will continue the Landsat data record into its fifth decade with launch scheduled for December 2020. The two instruments on Landsat 9 are Thermal Infrared Sensor-2 (TIRS-2) and Operational Land Imager-2 (OLI-2). OLI-2 is a nine-channel pushbroom imager with a 15-degree field of view that will have a 16-day measurement cadence from its nominal 705-km orbit altitude. A key aspect of the data that will be produced by OLI-2 is its spectral fidelity which enables countless science applications. The prelaunch test campaign for spectral characterization of OLI-2 was substantially improved relative to the methodology used for OLI: the full spectral response of every detector was characterized with greater accuracy, sampling, and precision. This paper will describe how this was accomplished with a tunable laser-based light source called Goddard Laser for Absolute Measurement of Radiance (GLAMR).

***Index Terms*—** Landsat 9, OLI-2, prelaunch characterization, calibration, tunable laser, GLAMR

1. INTRODUCTION

Landsat 9 will extend the Landsat data record into its fifth decade once it is launched in December 2020 to the orbit that is now occupied by Landsat 7 and will host two instruments: Thermal Infrared Sensor-2 and Operational Land Imager-2 [1]. OLI-2 and TIRS-2 have much in common with OLI and TIRS that are hosted on Landsat 8 which launched in February 2013; OLI-2 is near identical rebuild of OLI and TIRS-2 shares much of TIRS design, but has added redundancy for higher reliability and modified optical system for reduced stray light.

OLI-2 will produce radiometrically-traceable, geo-located imagery of the Earth with the same parameters as Landsat 8 OLI: 16-day repeat, 30-m spatial sampling, nine spectral channels, and 185-km swath width. Table 1 provides key sensor requirements. Sensor design and performance are available for the Landsat 8 OLI [2].

Table 1. OLI-2 key instrument requirements

Requirement	Landsat 9 OLI-2 requirement
Cross-track field of view	>185 km
Absolute geodetic accuracy (no ground control points)	<65 m
Relative geodetic accuracy (no ground control points)	<25 m
Geometric accuracy (w/ ground control points)	<12 m
Absolute radiometric uncertainty, 1-sigma	<5%
Top-of-atmosphere reflectance uncertainty, 1-sigma	<3%
16-day radiometric stability, Channels 1-8, 2-sigma	<1%
16-day radiometric stability, Channel 9, 2-sigma	<5%
Polarization sensitivity	<0.05%
Pixel-to-pixel uniformity	<0.5%
Adjacent pixel uniformity, 'streaking'	<0.005

OLI-2 has a pushbroom design with approximately 15-degree cross-track field of view that is implemented with 14 focal plane modules (FPM). Each FPM is staggered in the along-track direction and overlaps slightly in the across-track direction combining to form about 6900 effective across-track pixels for each spectral channel.

The next section details OLI-2 spectral channel specifications and associated characterization requirements. Section 3 describes the spectral test facility called GLAMR used to characterize OLI-2 spectral response. Sections 4 and 5 detail the test with OLI-2 and the subsequent spectral response calculation.

2. OLI-2 SPECTRAL CHANNELS AND CHARACTERIZATION REQUIREMENTS

The OLI-2 spectral channels are defined in Table 2. While spectral measurements were made of individual components and assembled detector modules, this laser-based test was designed to measure the full spectral response of the whole

OLI-2 instrument [3]. The requirements were designed to ensure a successful campaign to capture both the in-band relative spectral response (RSR), as well as the out-of-band RSR. The in-band regions were nominally sampled at 1-nm intervals for the visible/near-infrared and panchromatic channels and 2-nm for the shortwave infrared channels. The spectral ranges that are not within 0.1 percent of maximum response of any OLI-2 channels (out-of-band spectral regions) were sampled at 10 nm intervals below 1000 nm and 20-nm intervals above 1000 nm. Maximum radiance levels were set to prevent saturation and minimum radiance levels were set to ensure sufficient signal-to-noise ratio for every spectral sample.

The GLAMR test set provided significant improvement on the Landsat-8 OLI instrument-level test [4]. The double monochromator illuminated only a small number of detectors on the OLI pushbroom focal plane; it provided a relatively dim signal which required non-flight-like changes in integration time to acquire enough signal to determine the RSR of some of the visible/near-infrared channels; and it was only intended to measure the in-band spectral response. In the end, the final OLI RSRs were derived from a sample of about 10 percent of the detectors from each channel.

Table 2. OLI-2 spectral channel specification

Spectral channel	Center wavelength (nm)	Bandwidth (nm)	GSD (m)	SNR
Coastal/Aerosol	443	20	30	130
Blue	482	65	30	130
Green	562	75	30	100
Red	655	50	30	90
Near infrared	865	40	30	90
SWIR-1	1610	100	30	100
SWIR-2	2200	200	30	100
Panchromatic	590	180	15	80
Cirrus	1375	30	30	50

3. GLAMR

GLAMR is a transportable calibration facility that is based on NIST's Spectral Irradiance and Radiance Calibrations using Uniform Sources (SIRCUS) facility [4] and was developed with guidance from NIST scientists. It consists of several tunable lasers that together are capable of tuning throughout the solar reflective spectrum (350-2500 nm) with no spectral gaps larger than 1 nm. The 350-1950 nm spectral range is covered with in-house developed optical parametric oscillators (OPO) and the 1950-2500 nm range is covered with commercial laser systems. Power output varies from several hundred milliWatts to several Watts depending on spectral position.

To be useful for characterizing spectral response of large field-of-view instruments, these lasers are coupled to an integrating sphere which homogenizes the light and creates a uniform disk of radiance at the sphere's exit port. The GLAMR sphere was configured with a 12-inch diameter port for its measurements with OLI-2.

GLAMR output radiance level is continuously monitored and traceable to NIST with accuracies in the 0.8-5% level depending on spectral region. Radiance monitoring is accomplished by three radiometers, called *sphere monitors*, that are permanently attached to the GLAMR integrating sphere. They stare at the rear of the sphere, the same location that OLI-2 measures during testing. Sphere monitors are unfiltered radiometers since spectral selection is inherent property of the GLAMR light source.

Radiometric traceability is achieved by relating the signal from the sphere monitors to another set of radiometers, called *transfer radiometers*, that are regularly characterized by NIST. Before and after testing with OLI-2, spectral scans with a set of portable transfer radiometers that hold NIST radiance scales are used to assign radiometric response to the sphere monitors. This experimental set up is shown in Fig 1. Spectral traceability is achieved with continuous measurement of GLAMR output wavelength by laser spectrum analyzers and wavemeters that have accuracy of 0.01 to 1 Angstrom depending on spectral region.

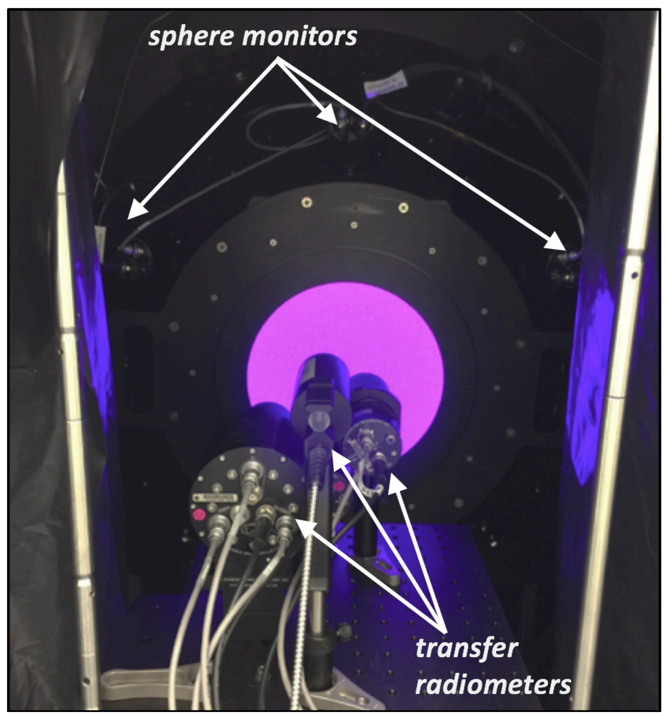

Fig 1. Photo showing the GLAMR integrating sphere with transfer radiometers in front. The transfer radiometers transfer NIST-traceable radiometric scale to the sphere monitors which report radiance during the test with OLI-2.

4. GLAMR SPECTRAL SCANS WITH OLI-2

The GLAMR sphere is placed in front of OLI-2 for spectral testing. OLI-2 is placed on a motorized rotation table inside a thermal vacuum chamber as shown in Figure 2. The 15-degree field of view of OLI-2 is too large to be illuminated by the 12-inch GLAMR so OLI-2 is rotated and tilted to 14 positions for each spectral sample. Each of these positions aligns the center of one FPM to the center of the integrating sphere. There is substantial margin in the illumination pattern over individual FPMs; Figure 3 shows the spatial coverage of the GLAMR sphere (black line) and spatial coverage of the monochromator (blue line) used for Landsat 8 OLI spectral testing.

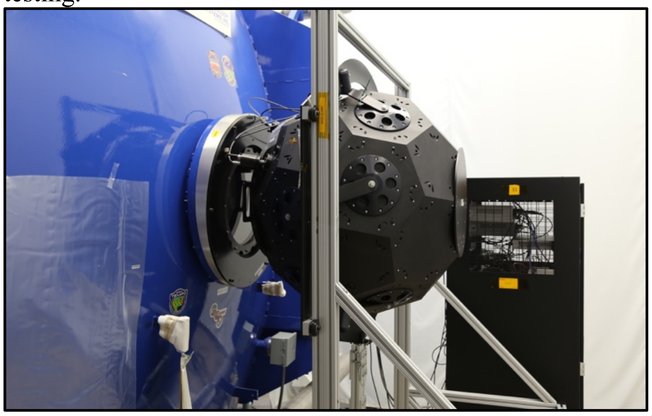

Fig 2. The thermal vacuum chamber and GLAMR integrating sphere. A light-tight shroud was constructed to block ambient light during spectral testing. The black tower on the right hold electronics that control and log data from the sphere monitors. The OLI-2 sits inside the chamber on a rotation table.

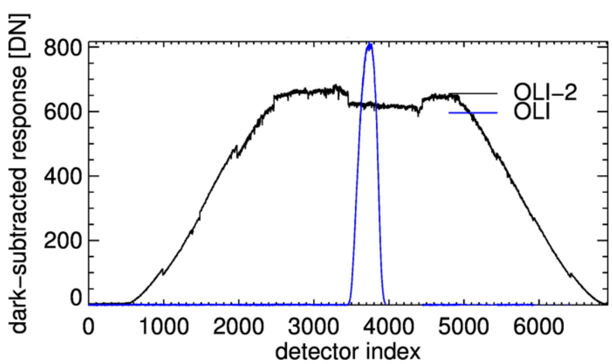

Fig 3. The GLAMR integrating sphere evenly illuminates approximately 5 of the 14 focal plane modules as shown with the black line. OLI-2 is rotated to center the field of view on each FPM. The blue line shows the smaller spatial coverage of the monochromator system used for OLI spectral characterization.

GLAMR incrementally scans the spectral ranges described in Section 2 for the specified in-band and out-of-band spectral sampling. For each spectral sample, GLAMR holds the wavelength and radiance steady while OLI-2 is rotated to align each of its FPMs to the center of the sphere. Each position is held for 2 seconds, then the rotation table increments to the next FPM position. Summing the measurement time, stage travel time, and dark measurements, the total time for each spectral channel is about two minutes. Accounting for repeated measurements for instances of unstable laser light levels, unstable laser wavelength, laser configuration changes, shift changes, etc., the experiment took ten days. The plots in Figure 4 show a summary of spectral sampling and performance of GLAMR during the test campaign.

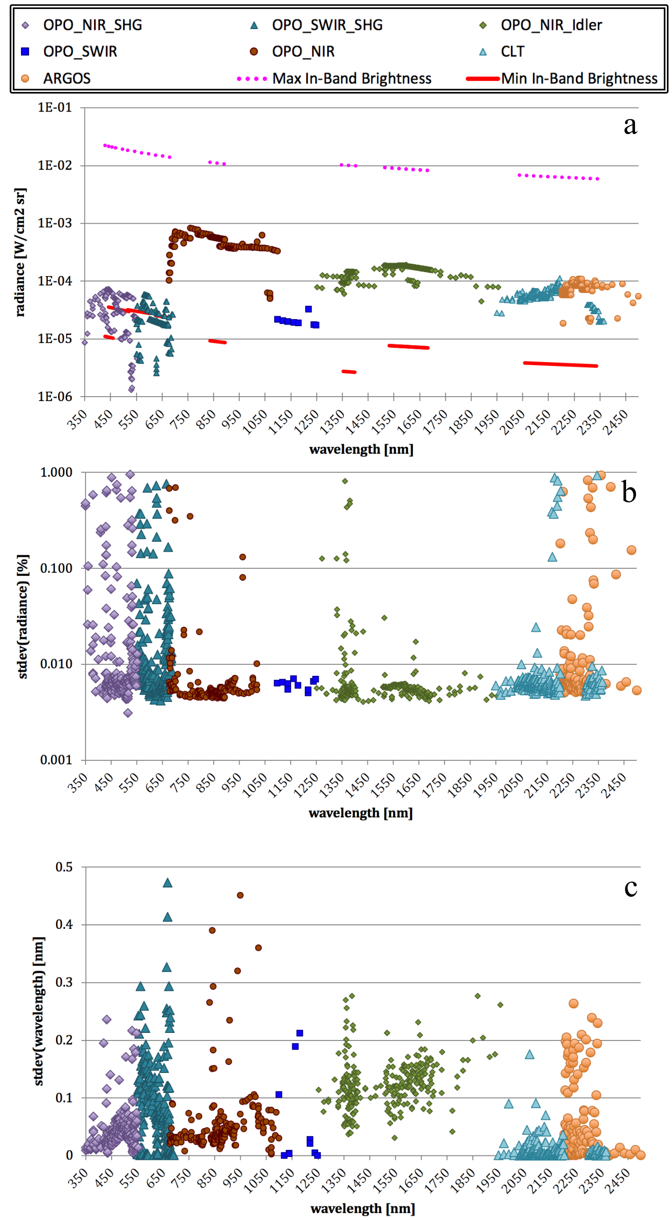

Fig 4. These plots summarize GLAMR performance during the Landsat 9 OLI-2 spectral testing. Plot a) shows radiance levels achieved for each spectral sample; b) shows the variability of the radiance of each sample; and c) shows the variability of wavelength during each sample. The various marker colors and shapes in the legend above plot a) indicate the laser or OPO configuration that was used for each spectral sample. The pink and red lines in a) show the maximum (saturation limit) and minimum (SNR threshold) radiance requirements for the spectral test.

5. SPECTRAL RESPONSE CALCULATION

OLI-2 and the sphere monitors measure the near-monochromatic radiance emitted by the GLAMR integrating sphere for each spectral location indicated in the plots in Figure 4. Since there are several devices recording these data and associated telemetry asynchronously, analysis software was developed to correlate samples from each device and calculate means, standard deviations, and other statistics of each spectral sample for each FPM. The primary values calculated for each spectral-FPM sample are mean radiance, mean wavelength, and mean dark-subtracted OLI-2 image response. These data are then used to calculate per-detector Absolute Spectral Response (ASR), $ASR(\lambda) = Q_\lambda / L(\lambda)$, where Q_λ is dark-subtracted image response, and $L(\lambda)$ is the GLAMR radiance derived from sphere monitor measurements [6].

Example ASR results are shown in Figure 5 for the coastal/aerosol and SWIR1 channels. Each line in these plots represents the mean response of the channel for each FPM. The spread of the curves shows the difference in the combination of differing response of detectors and differing transmittance of filters among the FPM. These ASRs are normalized to calculate RSR which are used to assess OLI-2 spectral performance.

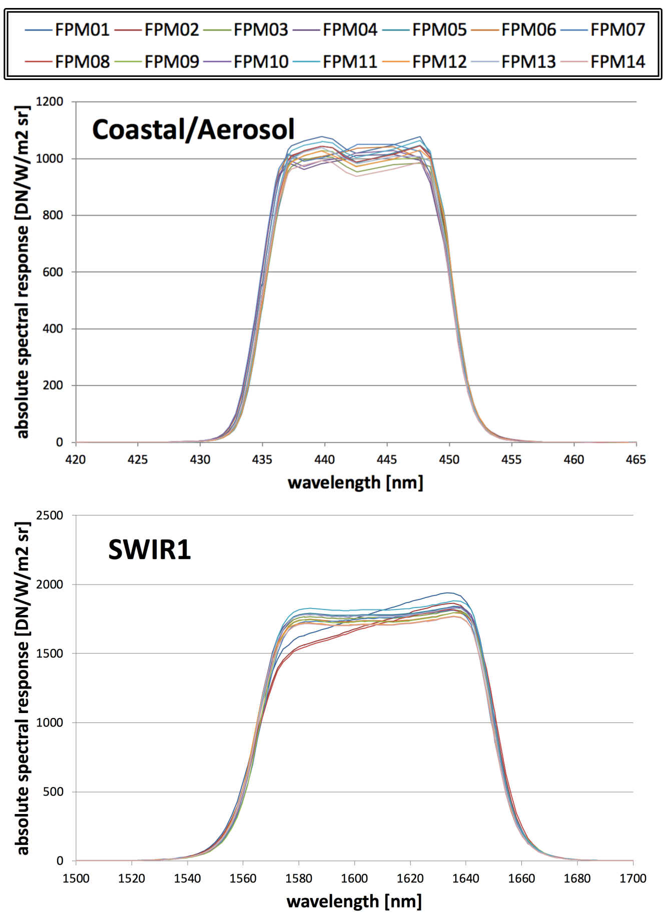

Fig 5. Absolute spectral response examples for the Coastal/Aerosol (top) and SWIR1 (bottom) channels are shown here. The averge response of each of the 14 FPMs is plotted.

6. CONCLUSION AND FUTURE WORK

This work described the first-ever laser-based spectral characterization of a spaceflight pushbroom sensor over the full solar reflective spectral region. GLAMR improved the spectral characterization for the Landsat-9 OLI-2 instrument in a number of significant ways:

- characterizing 100% of the imaging detectors at the instrument level
- covering the full spectral range, including the out-of-band wavelength regions, with a single system
- providing suitable radiance levels without special instrument configurations
- illuminating the OLI-2 aperture with nearly full-field light

While absolute calibration and linearity characterization were not requirements of the GLAMR test for OLI-2, GLAMR data can be used to verify the other methods used to generate the absolute calibration and linearity characterization. GLAMR data enabled the Landsat-9 team to identify several previously unknown features in the OLI-2 spectral filters and the measure of spectral uniformity across the focal plane will be based on instrument-level data, rather than component-level measurements made at earlier steps in the development process. The OLI-2 spectral responses that will be released will be the most complete spectral response data set for a Landsat instrument, which will have a positive impact on the understanding of the image data for the most demanding science communities.

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