

A vacuum-compatible, spectrally tunable, flat panel uniform source for testing large aperture earth observation systems

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ABSTRACT

Labsphere, Inc. in conjunction with NASA GSFC and Genesis Engineering Solutions Inc., has developed an innovative, vacuum compatible, calibration spectro-radiometric illumination source with a highly uniform large-area rectangular flat panel active area. This device features a uniquely shaped diffuse integration geometry to achieve high uniformity over a large active output area while maintaining a smaller and more robust overall form-factor when compared to previous designs or integrating spheres. A new liquid-cooled hybrid quartz-tungsten (QT) and light emitting diode (LED) source module has been engineered to provide direct-in-vacuum reference illumination over the full dynamic range and spectrum of the VIIRS instrument's optical bands during pre-launch testing. The first unit has been demonstrated to meet its requirements using ambient technology and a fully-vacuum-compatible second unit is planned to allow testing in thermal vacuum (TVAC) campaigns. This technology is flexible and capable of meeting the needs of many other instruments/missions requiring this type of test/calibration capability.

Keywords: Calibration, Remote Sensing, Vacuum, Tunable, Radiometry, Broad Band, Uniformity, Satellite

1. INTRODUCTION

A new and innovative vacuum compatible, flat panel illumination system (FPI II) design has been developed to facilitate in-situ spectro-radiometric characterization and performance trending of the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument during ambient laboratory and thermal vacuum testing. The new FPI II system will replace the FPI I system that has been in use since 2009 [1].

NPOESS/JPSS and VIIRS instrument background

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a calibrated scanning radiometer that collects visible and infrared imagery and radiometric measurements of the Earth's surface was originally developed for the National Polar-Orbiting Environmental Satellite System (NPOESS) program. VIIRS merges and enhances the capabilities of older generation operational weather satellites, such as the NOAA's Polar-orbiting Operational Environmental Satellite (POES) and the US Department of Defense (DoD)'s Defense Meteorological Satellite Program (DMSP) [1]. The NPOESS program was subsequently phased out and transitioned to the Joint Polar Satellite System (JPSS) program operated by NOAA, with NASA being responsible for procuring all flight instruments [2]. Currently, there are three VIIRS instruments operating in space, one onboard the S-NPP satellite launched in October 2011 a second on the NOAA-20 satellite (formerly known as the JPSS-1) launched in November 2017 and the third on the NOAA-21 satellite (formerly JPSS-2) launched in November 2022 [3]. Two additional JPSS satellites, JPSS-3 and JPSS-4, are presently being produced, with both well along in their manufacturing and testing phases. JPSS-4 is scheduled for launch in 2027 and JPSS-3 is scheduled for launch in 2032. Due to the multi-year timeline between completion and launch, both satellites will go into storage and undergo annual performance testing to ensure their flight readiness until their launch dates [4].

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Development of the FPI I

A need for spacecraft level spectro-radiometric characterization and performance trending of the VIIRS instrument was identified well before the first VIIRS instrument was completed. This testing was needed for spacecraft post-integration testing, thermal vacuum performance testing, and annual performance testing during periods of extended storage. In response to that need, a thermal vacuum (TVAC) compatible Flat Plate Illuminator (FPI) was developed as a quality control tool for the instrument's radiometric stability. The FPI I utilizes Xenon Arc lamps in conjunction with a supercontinuum laser source whose outputs are transmitted through a low OH fused silica fiber cable bundle to an array of low OH fused silica fibers bonded into a flat plate. This array of fibers illuminates an engineered diffuser plate which serves as the broadband spatially uniform spectro-radiant energy that the VIIRS instrument views [5].

The FPI was first used during the National Polar Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) at the spacecraft level for radiometric performance trending of the NPP VIIRS Flight 1 Sensor baseline acceptance testing and Spacecraft TVAC testing [6].

Subsequent to the NPP VIIRS testing, areas of improvement in the FPI source were identified and incorporated into an upgraded version of the FPI. The improved version of the FPI has been utilized for the Joint Polar Satellite System (JPSS) -1, -2 and -3 VIIRS instruments from 2010 through 2024 [7][8][9].

An assessment of the FPI system in late 2022, following testing with the JPSS-2 VIIRS, resulted in the recognition that some of the 15-year-old subsystems were needing replacement and would not meet program testing needs which extended out 10 more years to 2032. In addition, improvements in LED technology offered an opportunity to move away from the Xenon Arc lamps which continuously degrade during use and have a short usable life of only 200 – 300 hours. LEDs have better radiometric stability and much longer life (on the order of 10,000 hours).

Development of the FPI II

The FPI II project was initiated to develop, test, and deploy the next-generation pre-launch calibration source for the JPSS-3 and subsequent VIIRS program using updated technologies and new system architecture to improve key performance metrics for FPI such as uniformity, spectral radiance, stability, usability, and lifetime. The FPI II development program was structured into three core phases: (1) technology discovery and selection, (2) design, manufacture, and characterize a limited-performance demonstration system, and (3) engineer, manufacture, test, and deliver a full performance system. A summary of the technical requirements for the full performance system are shown in Table 1 (note: Table 1 was generated for instructive purposes and is not inclusive/representative of full program definition and requirements).

During the FPI II technology discovery phase, the Labsphere and Genesis teams made two significant architectural pivots away from the FPI I design to meet the updated system requirements. The first system decision was to change the light sources from Xenon Arc lamps and supercontinuum lasers to LEDs and Quartz-Tungsten (QT) lamps. This decision has significant benefits in radiometric control, but sources had to be carefully vetted to be acceptable within the vacuum environment. The second system-level change was to bring the light sources into the vacuum chamber. This eliminated the need to transmit light from outside of the vacuum chamber to the internal light assembly via fiber optics and thus the robustness and consistency of the light head is greatly enhanced, with the tradeoffs being the introduction of nontrivial thermal loads and the need to optically distribute the multitude of spectrally unique light sources across the exit aperture. Labsphere solved the spectral distribution problem through the development of a unique integration chamber which provides the necessary uniform illumination while occupying only 45% of the allowed volume. The team code-named the radiometric source assembly “LVIS” (pronounced “Elvis”) to reflect an implementation of a “Low Volume Integrating Source”. The in-vacuum thermal loads have been addressed by engineering liquid cooled copper cold sinks into the core light source assemblies.

The second phase of the project concluded in June 2024 with the delivery of a “demonstration unit” designed to achieve full program requirements for radiometric performance, including uniformity, but did not require full TVAC compatibility in all selected components. The demonstration unit was tested in ambient environmental conditions at Labsphere, Inc. as well as GSFC. The results reported here are exclusively from this demonstration unit.

The final, third, phase of the project takes the learning from the demonstration completes the work with the design and build of a fully TVAC-compatible system targeted for delivery in September 2024.

Table 1: FPI II System Requirements

	Requirement	Radiometric Source (LVIS head assembly) Shall:
System Design	Volume envelope	Not exceed given design envelope (approx. 25x25x32 inches)
	Mass	Weigh less than 75 lbs.
	Source Area	Provide a viewable area measuring 10.5in x 14in or larger
	Operational Environment	Capable of operating in an ambient as well as a TVAC thermal environment of -170C to 30C.
	Redundancy	No single LED or other optical source string failure can affect more than 25% of covering a given wavelength
	Vacuum Compatibility	Designed for operation in thermal vacuum with vacuum-compatible design and materials per NASA guidelines
Radiometric Performance	Band Radiance	Provide band-averaged radiance values greater than 0.3 L_{max} across VIIRS spectral bands M1-11, I1-3
	Radiance Levels	Provide 6 band-averaged radiance levels below L_{max} and above 0.05 L_{max} including levels within 10% of L_{typ}
	Real Time Monitoring	Provide real time knowledge of output radiance covering the spectrum for VIIRS spectral bands M1-M10, I1-3 with respect to VIIRS FOV with 5% absolute uncertainty and 10% ($k=1$) absolute uncertainty in band M11
	Stability	Maintain radiance output over all wavelengths within 1% over a 20-minute period
	Spatial Uniformity	Maintain radiometric uniformity across any 7.5in diameter area within the FPI aperture >95% in any VIIRS spectral band when measured at any angle within +/- 2 degrees of normal

2. GENERAL JPSS FPI II DESCRIPTION

The FPI II system comprises LVIS and its critical support subsystems, which are engineered to provide in-vacuum reference illumination over all optical bands of VIIRS, including M1-M11 (412nm – 2250nm) and I1-I3 (640 – 1610nm).

LVIS consists of two highly engineered hybrid LED-QT source modules coupled to a Spectraflex[®] coated integration volume with a rectangular exit aperture of 400mm by 300mm. The source modules integrate 56 QT sources, 108 LEDs, and 8 Peltier devices into liquid-cooled copper cold sinks to provide precision light output and thermal control. The diffuse integration volume evenly distributes the full spectrum across the exit diffuser while simultaneously serving as a significant portion of the system structure. The structure protects electronic cabling on the system, anchors the stainless-steel plumbing, houses the monitor fiber optic bundle, provides machined-in handles and feet, incorporates optical and mechanical alignment features, and has four distinct mounting surfaces to serve a multitude of use cases for both ambient and TVAC use.

The four critical support subsystems for LVIS include (1) the Source Electronics Enclosure, (2) the Galden-compatible recirculating chiller, (3) the vacuum chamber bulkheads, and (4) the real-time optical monitor. The Source Electronics Enclosure includes all the power electronics necessary to interface and output precision current control to the source modules and thermal control to the Peltier devices. The recirculating chiller and associated plumbing provides ample margin for the designed thermal loads to achieve rapid response heating and cooling as the system undergoes different phases of operation. The vacuum chamber bulkheads bridge the TVAC envelope for the liquid cooling plumbing, electrical power, and fiber optic monitor. The real-time optical monitor consists of an 8-meter vacuum fiber bundle, a 12-meter bifurcated clean room fiber bundle, and two ASD FieldSpec4 monitor spectrometers. These spectrometers can be calibrated for spectral radiance using LVIS-integrated QT calibration lamps. The ASDs also interface with Labsphere's custom control software where data are easily monitored, and spectral output may be adjusted as needed.

The above description applies to the full-performance system. A truncated list of the deviations in the demonstration unit includes a water-glycol based chiller, no vacuum bulkheads, no long fiber optics for monitor feedback, and some structural differences on LVIS to accommodate more mounting options.

The full-performance system is graphically portrayed in Figure 1 and the demonstration unit is shown in Figure 2, below.

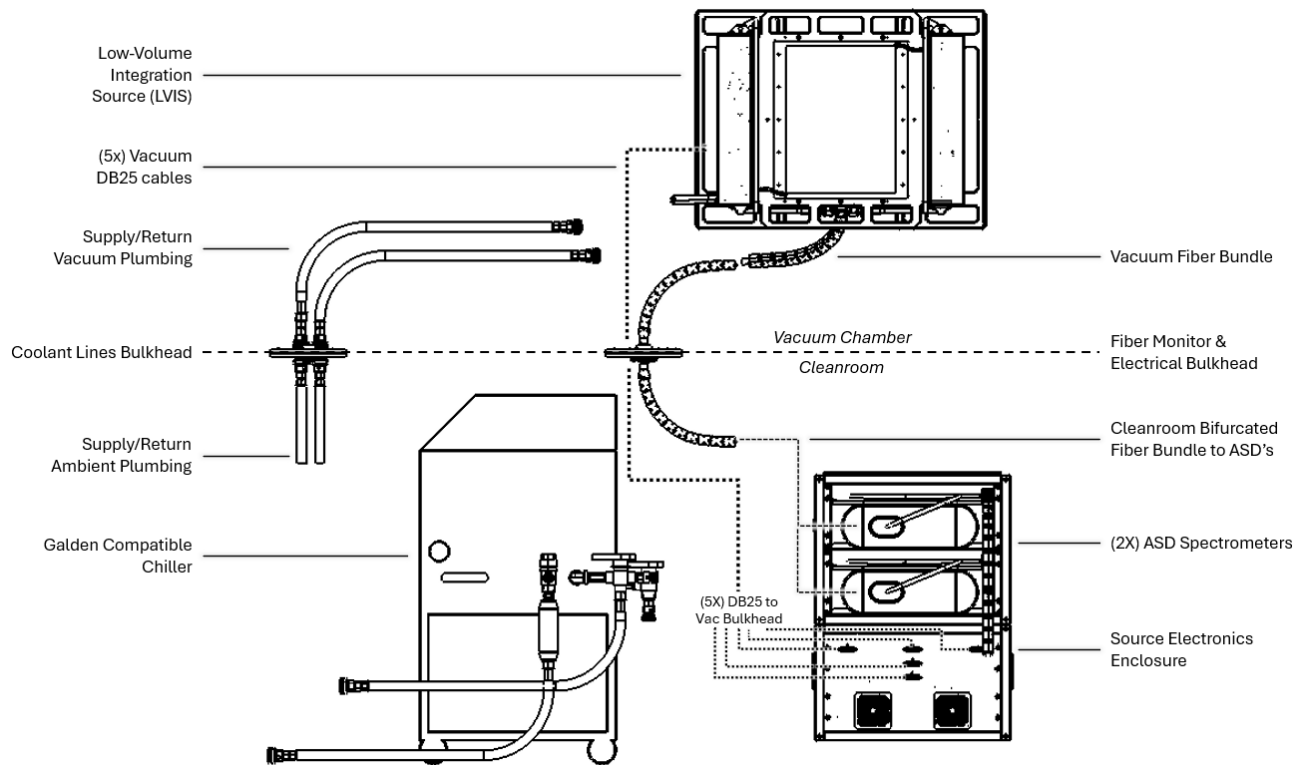


Figure 1: FPI II System Overview



Figure 2: FPI II Demonstration Unit; including demo chiller (top left), source electronics module, and LVIS

3. JPSS FPI II DEMO UNIT RADIOMETRIC PERFORMANCE

The spectral radiance of the LVIS Demo Unit was evaluated at Labsphere using a Spectral Evolution SR-4500 spectrometer with a 1° fore optic calibrated for absolute radiance traceable to NIST. The spectrometer FOV sampled the center of the LVIS diffuser plate over a three-inch diameter spot. Figure 3 shows the measured LVIS Demo Unit spectral radiance of the QT and LED sources, the required band-averaged radiance for the VIIRS bands at the 0.3L_{max} target, and FPI I spectral radiance at 0.3L_{max}. The measured spectral radiance of LVIS, $L_{LVIS}(\lambda)$ (W/m²/sr/μm), was converted to band-averaged radiance, $\overline{L_{LVIS}}$ (W/m²/sr/μm), using Equation 1, where $RSR_i(\lambda)$ is the VIIRS relative spectral response (unitless) for each of the 14 bands [10]. Table 2 shows $\overline{L_{LVIS}}$ as a percent of the required VIIRS band averaged radiance for three radiance levels, 0.7L_{typ}, L_{typ}, and 0.3L_{max}.

$$\overline{L_{LVIS}} = \frac{\int_{-1\%}^{+1\%} RSR_i(\lambda) \cdot L_{LVIS}(\lambda) \cdot d\lambda}{\int_{-1\%}^{+1\%} RSR_i(\lambda) \cdot d\lambda} \quad 1$$

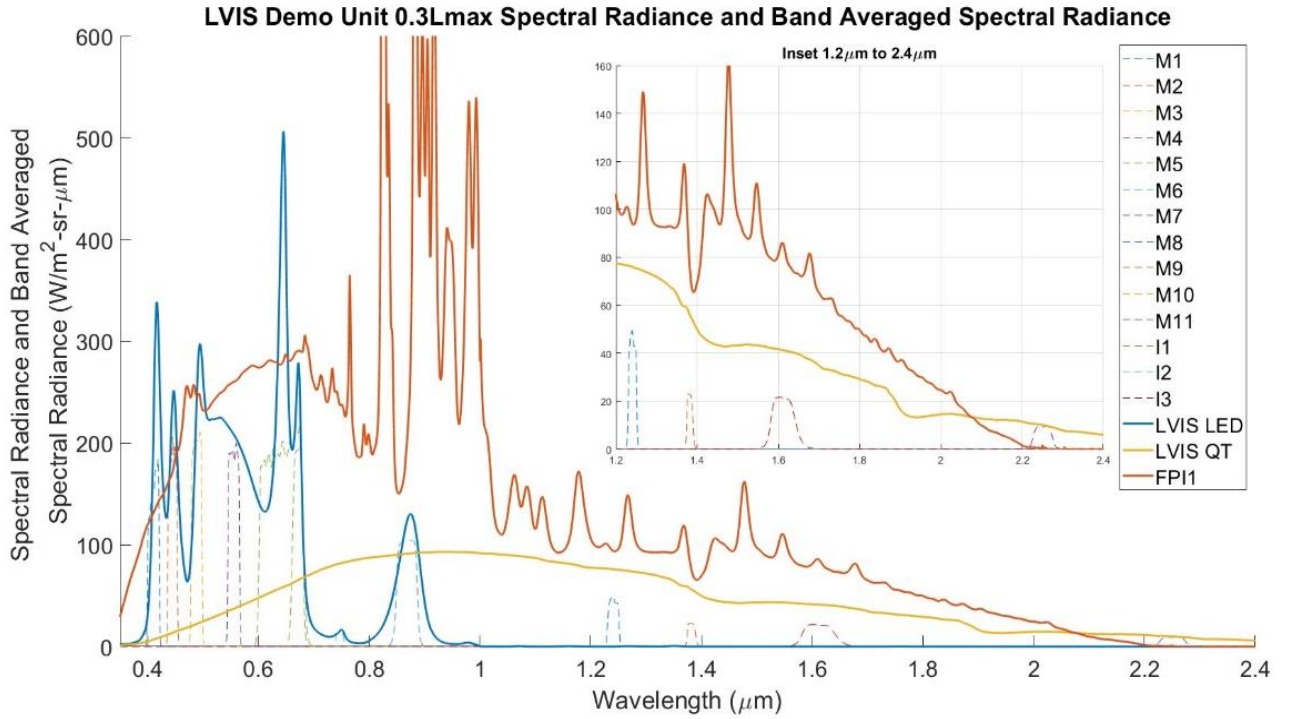


Figure 3: LVIS Demo Unit and FPI I spectral radiance for 0.3L_{max} (QT and LED) and required band averaged radiance at 0.3L_{max} for all VIIRS bands

Table 2: $\overline{L_{LVIS}}$ as a percent of the Specification

Band (λ_{nm})	$\overline{L_{LVIS}}$ as Percent of Specification		
	0.7L _{typ}	L _{typ}	0.3L _{max}
M1 (412)	94%	100%	114%
M2 (445)	101%	105%	102%
M3 (488)	99%	101%	105%
M4 (555)	108%	108%	104%
I1 (640)	93%	95%	110%
M5 (672)	94%	92%	105%
M6 (746)	89%	93%	117%
M7 (865)	103%	101%	103%
I2 (865)	109%	96%	102%
M8 (1240)	95%	91%	154%
M9 (1378)	93%	91%	242%
M10 (1610)	111%	106%	192%
I3 (1610)	111%	106%	189%
M11 (2250)	99%	106%	104%
Acceptance Bounds	86% to 114%	90% to 110%	>100%

Note the specification acceptance bounds in the final row of Table 2.

The band-averaged radiance stability of the Demo Unit was evaluated over a 20-minute period at 1-minute intervals using an ASD FieldSpec4 spectrometer with a 1° fore optic placed at a distance to provide a ~60mm spot at the diffuser plane. The spectral radiance was collected for the 0.3L_{max} setting for QT and LEDs sources individually. The spectral radiance was converted to band-averaged radiance using Equation 1. A one-minute warm up period was allowed for the light sources before the measurements began. Figure 4 shows the percent change in band-average radiance from t_{1min} for twelve VIIRS bands over a 20-minute period. Note that bands I2 and I3 were excluded from the analysis as they cover similar spectral regions to M7 and M10.

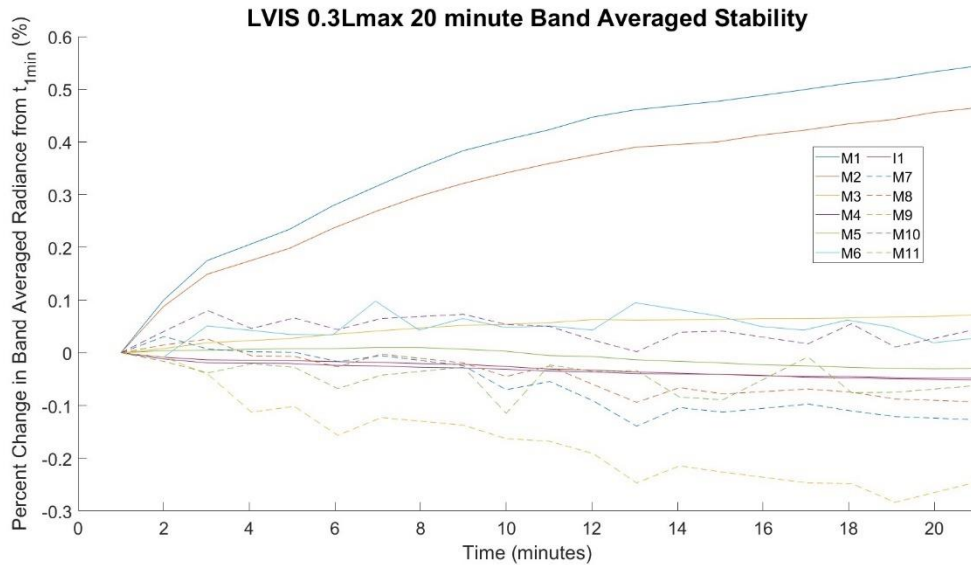


Figure 4: 20-minute band average radiance stability. Dashed lines indicate QT-only bands. Solid lines indicate LED-only bands.

4. JPSS FPI II DEMO UNIT UNIFORMITY-PERFORMANCE

A large portion of the LVIS demo unit design and testing phase was dedicated to understanding the system's spatial and angular uniformity. Optical modeling along with laboratory testing were used to predict and measure LVIS's uniformity. The uniformity tests were conducted at three spatial resolutions: high-resolution using a hyperspectral imager, medium-resolution using a spectrometer and raster mapping approach, and low-resolution using an off-axis-parabola with a similar FOV to VIIRS. The following sections describe the details of the optical modeling and test results.

Model-Derived Spatial Uniformity Results

A nonsequential optical model of LVIS was created in Fred MPC [11] software using a simplified version of the CAD model. A majority of the mechanical parts were represented as polygon objects and with a few others modeled as FRED objects. The model included coatings that represented the actual coatings as closely as possible (Spectrafect, glass, etc.). An analysis surface was placed on the diffuser to collect the rays exiting the surface.

Figure 5 illustrates the uniformity of LVIS at the diffuser plate with the FRED model, under the conditions mentioned above. Additional analysis was carried out on the data to generate a "VIIRS" perspective of the uniformity. This was accomplished by averaging the data over the projected field of view of the VIIRS instrument (footprint) on LVIS along the telescope boresight, Figure 6, demonstrating a uniformity of 2% across the centerline.

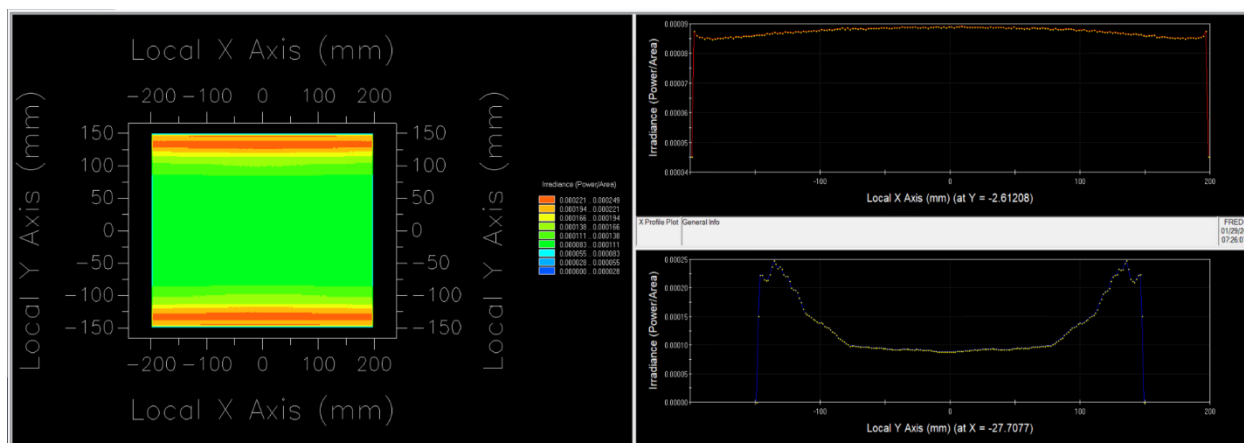


Figure 5: Raw data from FRED model of LVIS

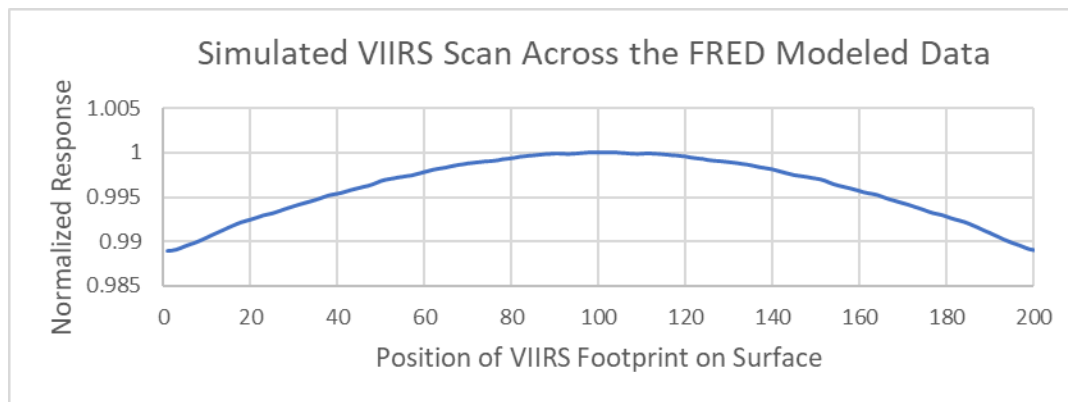


Figure 6: Cross section of normalized radiance from model processed as would be viewed by VIIRS

Medium-Resolution “Raster” Spatial Uniformity Evaluation Using Spectrograph

Demo Unit spectral uniformity data were acquired using a Spectral Evolution SR-4500 spectrometer with a square aperture Gershun tube fore optic. The fore optic provided a numerical aperture of approximately 0.22 and was mounted to a robotic arm positioned at a distance to provide a 2cm-by-2cm square spot at the Demo Unit diffuser plane. The spectrometer captured spectral radiance (350nm to 2400nm) at each 2cm-by-2cm square spot over the full diffuser clear aperture of 300mm x 400mm. The spectral radiance was converted to $\overline{L_{LVIS}}$ using Equation 1. $\overline{L_{LVIS}}$ uniformity was evaluated for the LED-only 0.3L_{max} and QT-only 0.3L_{max} conditions over the approximate VIIRS usable aperture of 26cm x 36cm. This is summarized in Figure 7 which shows M5 and M10 band uniformity as a fraction of the mean.

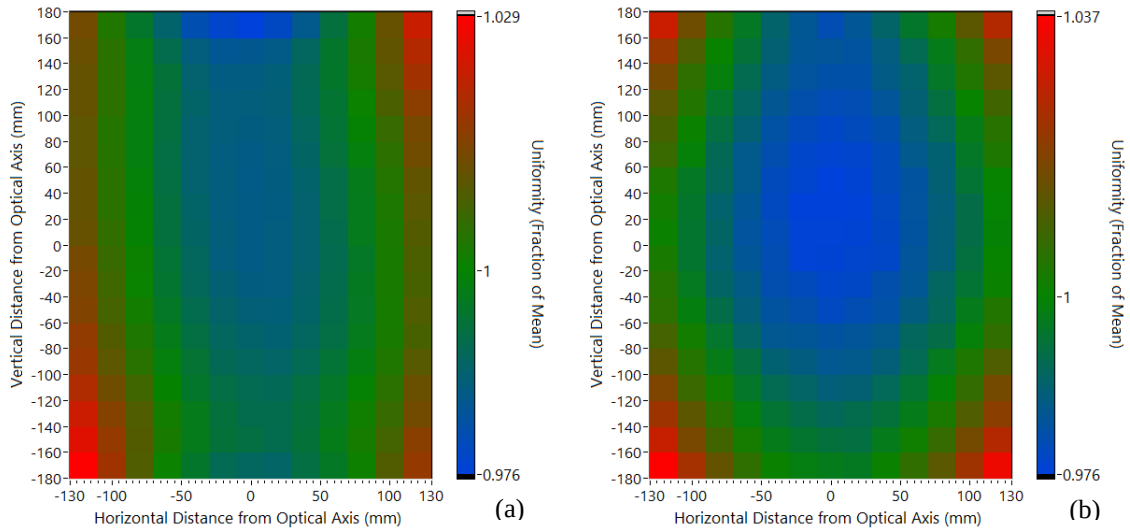


Figure 7. Uniformity Evaluation of 0.3L_{max} condition with Spectral Evolution: (a) LED-only condition evaluated at VIIRS band M5, (b) QT-only condition evaluated at VIIRS band M10. Maximum and minimum uniformity values indicated in color scale legend.

High-Resolution Spatial Uniformity Evaluation Using Hyperspectral Imager

Hyperspectral images (395-1013nm) were obtained from a Pika XC2 scanning hyperspectral camera observing the Demo Unit. The clear aperture was resolved to approximately 1485 by 1120 pixels, each with full spectral data, representing samples of approximately 0.27mm square. The hyperspectral imagery were corrected for integration time and converted to spectral radiance with a NIST-traceable calibration. The LVIS spectral radiance is calculated as the weighted average over the VIIRS band relative spectral response using Equation 1.

The resulting data provide per-band relative output of LVIS (weighted radiance) for each pixel in the observed measurement for each condition (illumination mode) tested. Note: the defined usable area of the LVIS clear aperture is 10.5 x 14 inches and represents about 90% of the illumination area. Example color-weighted images for M5 over four different illumination conditions are shown in **Error! Reference source not found.**

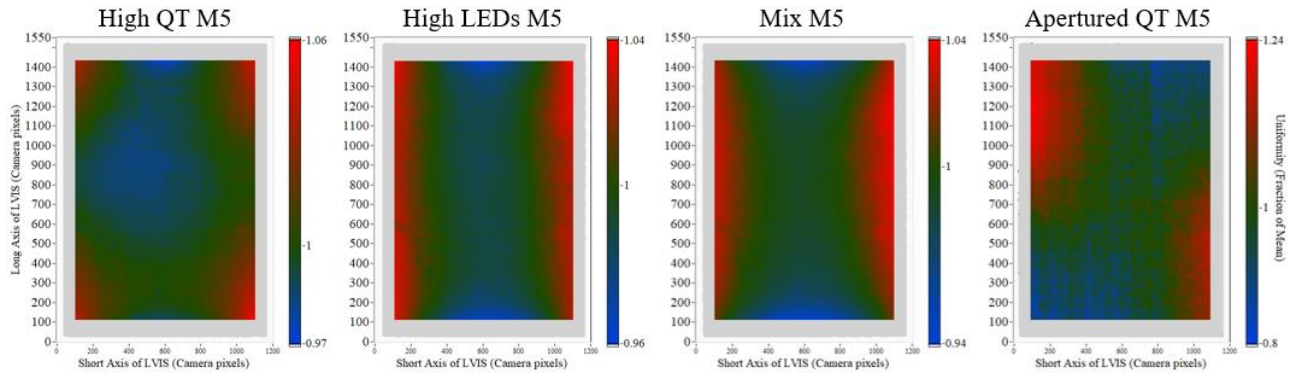


Figure 8: Example High-Resolution Uniformity Maps from Pika Camera Band-Weighted Data

LVIS illumination conditions evaluated by the Pika camera were selected to represent both LED-only and QT-only conditions as well high radiance output and a combined LED and QT condition. These conditions are provided in Table 3 as the source string settings for the electrical power (0.0 - 1.0).

The band-weighted radiance over usable area were evaluated for deviation from the mean providing a pixel map of normalized uniformity as well as minimum and maximum values of non-uniformity for a given band and illumination condition, see

Table 4.

Table 3: Source String Settings for Hyperspectral Measurements Test Conditions, where 1 represents full power for the given string.

Illum. Profile	415 nm	450 nm	490 nm	545 nm	645 nm	670 nm	750 nm	870 nm	QT High 1-3	QT Low 1-4	QT Low 20% Aper.	QT Low 10% Aper.
Lowest QT	0	0	0	0	0	0	0	0	0	0	0.92	0
High QT	0	0	0	0	0	0	0	0	1	1	0	0
High LED	0.5	0.45	0.85	0.75	0.5	0.3	0.075	0.75	0	0	0	0
Mix	0.5	0.43	0.6	0.43	0.2	0.04	0.075	0.3	0	0	1	1

Table 4: High-Resolution Hyperspectral (Band Averaged) Uniformity Results for Usable Source Area

Illumination Condition	Band	Average Radiance [W/m² sr um]	Deviation from Mean (lowest pixel)	Deviation from Mean (highest pixel)
High QT (many sources)	M1	5.649	-6.4%	3.5%
	M2	10.334	-4.0%	4.5%
	M3	17.448	-3.3%	5.0%
	M4	29.526	-2.8%	5.3%
	M5	52.297	-2.6%	5.5%
	M6	65.478	-2.5%	5.7%
	M7	73.278	-2.6%	5.8%
High LEDs (many sources)	M1	190.540	-4.5%	6.7%
	M2	203.781	-4.5%	4.5%
	M3	221.696	-4.8%	5.3%
	M4	206.603	-4.3%	4.0%
	M5	201.340	-4.0%	3.7%
	M6	15.887	-8.2%	6.2%
	M7	104.722	-4.2%	5.0%
Mix (LED and QT sources)	M1	184.368	-4.1%	6.9%
	M2	192.013	-4.2%	4.7%
	M3	159.974	-4.7%	5.3%
	M4	124.012	-4.2%	4.1%
	M5	30.107	-5.5%	3.9%
	M6	13.640	-6.9%	5.7%
	M7	43.960	-4.3%	4.8%
Low QT (apertured, one source on each side)	M1	0.002	-19.2%	19.3%
	M2	0.003	-22.8%	29.0%
	M3	0.006	-21.2%	28.3%
	M4	0.018	-19.8%	25.7%
	M5	0.054	-19.8%	24.4%
	M6	0.090	-19.9%	23.0%
	M7	0.186	-24.3%	17.4%

5. FPI II DEMO UNIT TEST PERFORMANCE

If the demo unit and the FPI-II light source were perfectly Lambertian, with spatially uniform and isotropic spectral radiance, the VIIRS instrument would see no radiance variation when scanning across FPI-II. However, as with all extended light sources, there will be some spectral radiance variation as a function of position and view angle. The intent of these measurements is to determine the magnitude of these variations with an optical system whose aperture and hence light-collecting footprint on the demo unit is comparable to VIIRS. To accomplish this, an off-axis parabola (OAP), on an optical bench with an 8" (203mm) aperture was used as shown in Figure 9. This is slightly larger than VIIRS 190mm

aperture, by 13% in area. The detector is a fiber at the focus connected to ASD spectrometer with a spectral range from 350 to 2500nm in 1nm steps. The expected VIIRS instruments response is determined by convolving the measured ASD spectral response with the VIIRS bandpass transmittance.

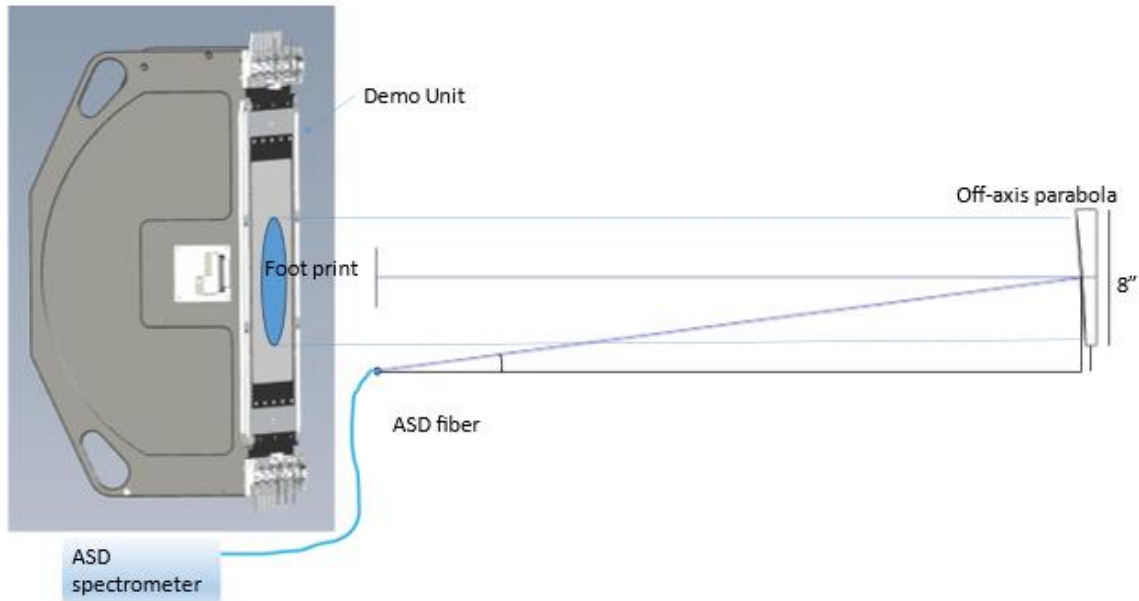


Figure 9: Sketch of LSF Test Configuration

Over the course of six days, in June of 2024, the measurements were performed at the Goddard Space Flight Center's PACE/OCI optical test facility. The demo unit was oriented such that 400mm by 300mm aperture was vertical and with the 400mm dimension being horizontal. After aligning the aperture normal (at the geometric center of the rectangular aperture) to be colinear with the OAP chief ray, the demo unit was moved horizontally, vertically, and tilted. Figure 10 shows the aim points and footprints of two (of many) horizontal and vertical scans.

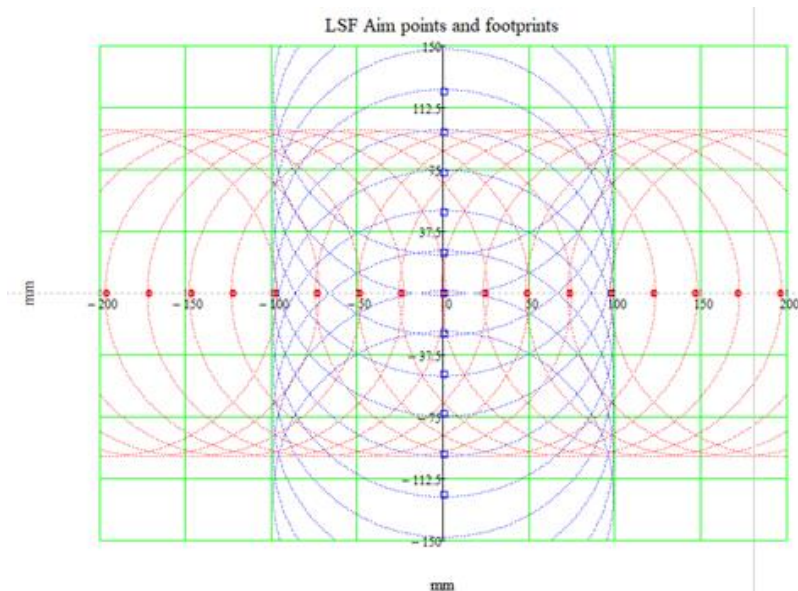


Figure 10: OAP Aim Points and Corresponding Footprints

The range of linear motion (horizontally -200mm to +200mm and vertically -150mm to +150mm) was chosen such that footprints went off the aperture to roughly the FWHM points of the plateau as shown below.

For the horizontal scan shown in Figure 10, with the demo unit’s “mode1” QT light sources turned on, Figure 11 shows, for VIIRS band M5, the FWHM points and a plateau as the footprint moved across the aperture; effectively simulating a cross-track scan of the VIIRS instrument.

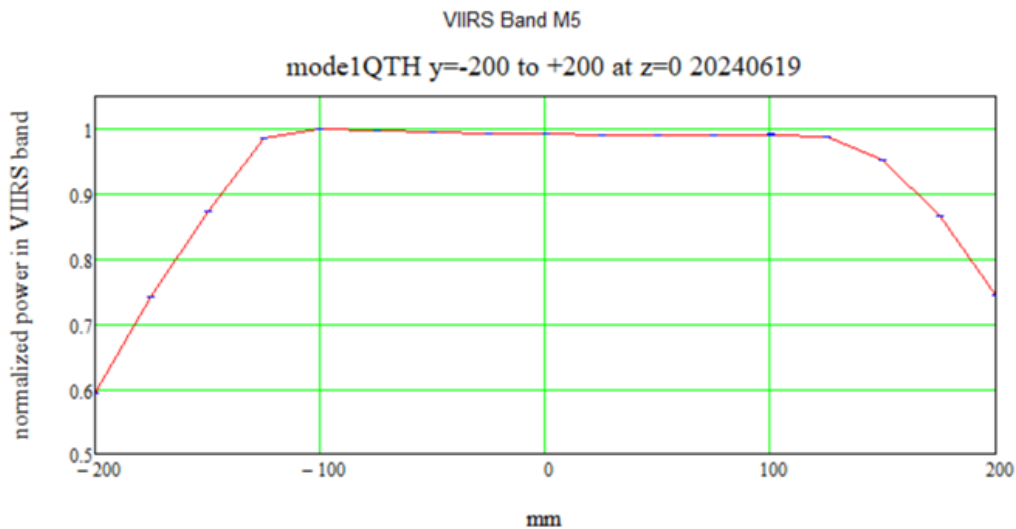


Figure 11: Scan Showing Relative Radiance Over Position of Footprint, VIIRS Band M5

The magnified view of the plateau portion of the measurement, Figure 12, shows a 0.776% (max-min)/mean variation.

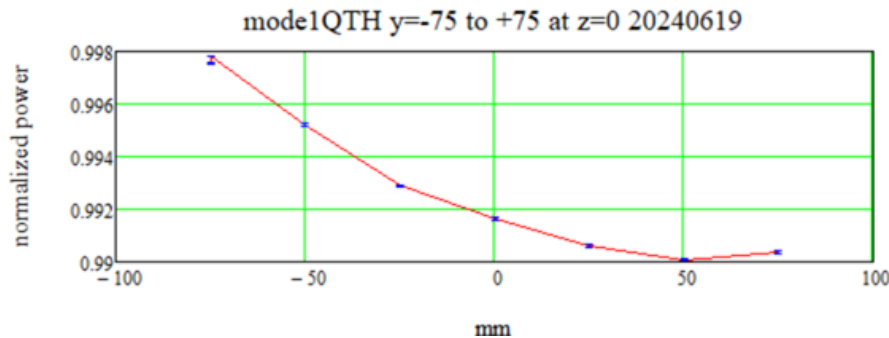


Figure 12: Plateau portion of scan

For the vertical scan shown in Figure 10 the figure below, Figure 13 shows lamp configuration and the plateau as the footprint moves vertically.

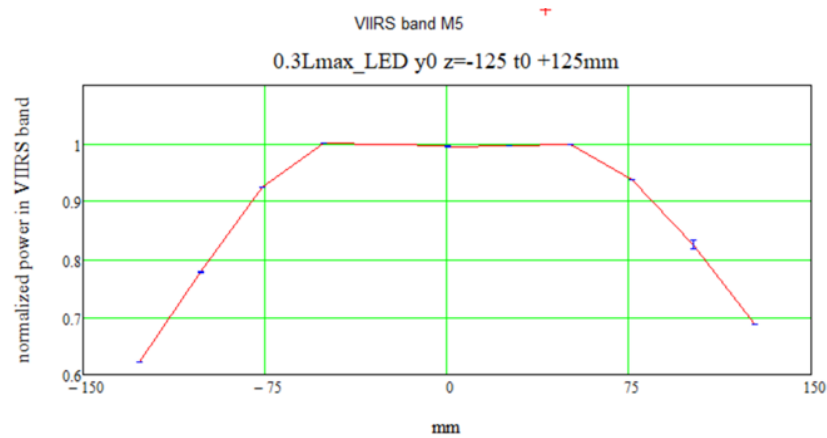


Figure 13: Vertical (short axis) Scan

The (max-min)/mean variation for the vertical scan in this case was 0.663% for the plateau portion.

The demo unit was “tilted” at a selection of angles with respect to the OAP axis to see how much the radiance changes when, with the footprint in the center of the rectangular aperture the demo unit is rotated, about the horizontal line. Figure 14 shows a 0.263% change in radiance for the indicated tilt angles.

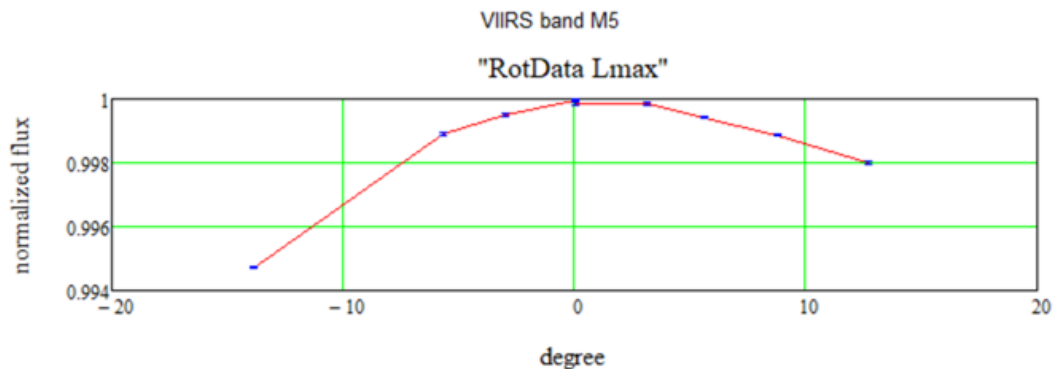


Figure 14: Radiance variation for tilt angles -13.9, -5.7, -3.0, 0.0, 0.0, 3.1, 5.6, 8.8, 12.7 degree

All of the measurements, of which the above discussed are representative samples, indicate that the demo unit is fairly Lambertian and that when VIIRS scans the FPI-II unit, the spatial variation will be less than 1% and angular variation will be about 0.5%.

Table 5 shows the percent plateau variation (noise indicating very low or no signal) for the above conditions of horizontal (Mode1 QT), vertical (0.3Lmax_LED) measurements and for the rotation about the horizontal axis (RotData Lmax) measurement for all the VIIRS bands.

Table 5: Percent Variation in Plateau Region of LSF Scan for All VIIRS Bands

High QT (Horizontal)			High LED (Vertical)			-13.9 to 12.7 Degree Angular	
Band	Variation (%)		Band	Variation (%)		Band	Variation (%)
M1	0.24		M1	0.85		M1	0.55
M2	0.32		M2	0.66		M2	0.61
M3	0.48		M3	0.57		M3	0.59
M4	0.66		M4	0.58		M4	0.58
M5	0.78		M5	0.66		M5	0.53
M6	0.76		M6	0.78		M6	0.21
M7	0.68		M7	noise		M7	0.32
M8	1.33		M8	noise		M8	noise
M9	0.50		M9	noise		M9	noise
M10	0.92		M10	noise		M10	noise
M11	0.17		M11	noise		M11	noise
I1	0.76		I1	0.74		I1	0.59
I2	0.67		I2	noise		I2	0.32
I3	0.90		I3	noise		I3	noise
DNBLGS	0.74		DNBLGS	0.75		DNBLGS	noise
DNBMGS	0.73		DNBMGS	0.73		DNBMGS	0.47

6. JPSS FPI II DEMO UNIT COMPARISON TO PREVIOUS AND ALTERNATE SYSTEMS

High-Resolution Spatial Uniformity Comparison

LVIS system performance may be compared to the previous version (FPI I) as well as to long-standing traditional technologies such as integrating spheres. To generate an “apples-to-apples” comparison, high-resolution uniformity data from FPI I, LVIS, and an example 65” sphere-based system were evaluated. Images comparing these can be viewed in Figure 15 (note: color scales are set to full range of given data for a specific system). An evaluation of overall uniformity deviation, as well as system and measurement device used, are shown in Table 6.

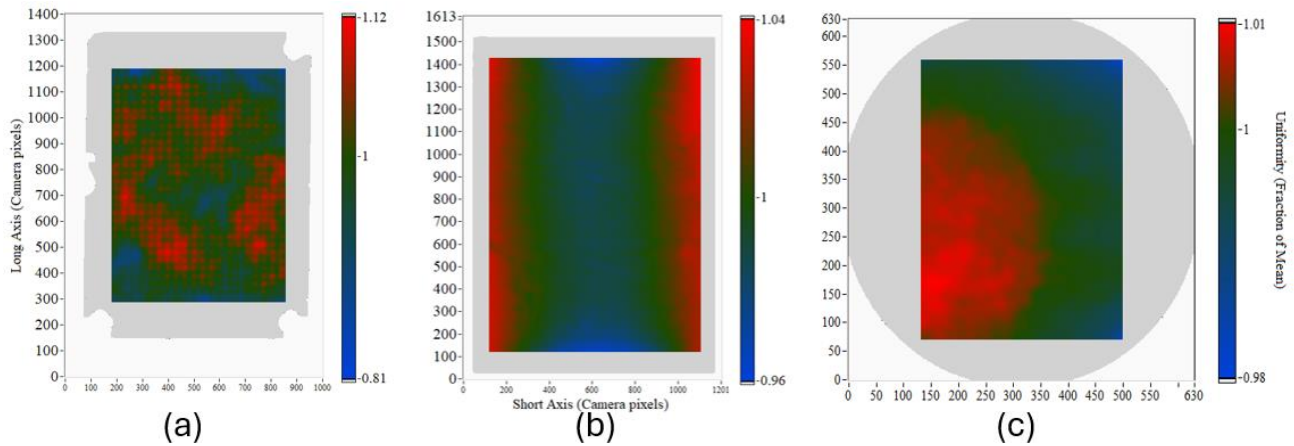


Figure 15: Uniformity comparison with (a) FPI I, (b) LVIS, and (c) a traditional sphere uniform source

Table 6: Uniformity deviation of comparison systems

Source	Measurement Instrument	Spectral Band	Evaluated Area (inches)	Min (Fraction of Mean)	Max (Fraction of Mean)	Uniformity (Max-Min)/Mean (%)
(a) FPI I	Pika	VIIRS M5	7.6 x 10.3	0.81	1.12	69%
(b) LVIS	Pika	VIIRS M5	10.5 x 14	0.96	1.04	92%
(c) 65" Sphere with 18" Dia Port	Westboro Luminance Camera	Luminance Filter	10.5 x 14	0.98	1.01	97%

Spectral Radiance Comparison

Radiometric system performance on LVIS demonstrates the results of the targeted source selection and increased capability of the LVIS solution as compared to that measured in the previous version, FPI I. Spectral radiance comparison can be found in Figure 3 and band-averaged results shown in Table 7 illustrating the performance of LVIS exceeding the required radiance levels.

Table 7: Comparison of Band Averaged Radiance of FPI I and LVIS

	Percent of Band-Averaged Radiance Specification for 0.3L _{max} condition	
Band	FPI I	LVIS
M1	72%	114%
M2	85%	102%
M3	118%	105%
M4	130%	104%
I1	131%	110%
M5	148%	105%
M6	1957%	117%
M7	327%	103%
I2	324%	102%
M8	193%	154%
M9	341%	242%
M10	371%	192%
I3	364%	189%
M11	3%	104%
Acceptance Bounds	>100%	

Comparison of LVIS to traditional uniform source systems

Conventional uniform sources are used frequently in ambient and vacuum conditions to provide an instrument full aperture (full etendue) flat fielding radiometric calibration source. Figure 16 provides a juxtaposition of commonly used integrating spheres sizes for an 18” diameter exit port and the LVIS instrument. In an ambient laboratory environment, these large sphere sizes are quite manageable and can be wheeled away and safely stored when space is needed.

In a vacuum environment, volume, power, thermal control, and time are all costed at a premium due to the expensive nature of the vacuum chamber and its limited size. The primary purpose of vacuum testing is to get as close as possible to flight conditions with as much of the instrument as possible. The instrument must therefore fit inside the chamber, usually requiring a chamber of some size and capability (very expensive asset and time in chamber). Spheres can be used through windows (clear glass or quartz) into the chamber to save the valuable space that the sphere would demand, but the window limits uncertainty to about 2% absolute levels [12]. Implementation of a window may also prove logistically impractical or undesirable, as is the case for VIIRS, where an extremely large window would be required, and the instrument location makes this strategy unfeasible.

LVIS comes with some tradeoff in uniformity as shown in Table 8, but this same table also shows that LVIS can produce a full etendue solution with 172% less input flux and thermal load. Further, the illustration in Figure 16 clearly shows LVIS occupying a significantly reduced volume to that of other solutions. With reduced power (thermal) loading and reduced volume LVIS is a compelling system to consider for vacuum chamber applications.



Figure 16: Contrasting CAD Models Showing Relative Size of a 40'' Diameter Integrating Sphere, the LVIS System, and a 65'' Diameter Integrating Sphere

Labsphere typically evaluates spatial uniformity of integrating sphere systems over 90% of the aperture diameter. This evaluation is conducted over an evenly spaced 11 x 11 grid using one of two methods: either a raster mapping approach with a radiance spot meter or by averaging down high-resolution data to a smaller grid size from a calibrated imaging photometer. The sphere uniformity values displayed in Table 8 are consistent with this approach and are calculated as the maximum deviation, $U_{Max\ Deviation}$, defined in Equation 2, where L_{min} and L_{max} are the minimum and maximum radiance values of the 11 x 11 mapped points. The LVIS uniformity in Table 8 is derived from the data in Figure 7 (a).

$$U_{Max\ Deviation} = \frac{L_{min}}{L_{max}} \times 100 \quad 2$$

Table 8 Throughput and Uniformity assessment for 40'' and 65'' spheres compared with LVIS

System	Aperture	Relative Volume	Spatial Uniformity, Max Deviation	Relative Radiance/Flux Efficiency Avg. 400-2300nm	Flux Thruput Avg. 400-2300nm
LVIS	18'' Rectangle	17%	>95%	172%	56%
40'' Sphere	18'' Diameter	100%	>98%	100%	47%
65'' Sphere	18'' Diameter	430%	>99%	60%	28%

7. FUTURE WORK, FULL PERFORMANCE SYSTEM

While this paper focuses on the measured results of the Demonstration Unit, development of the full performance system is nearing completion. The full performance system will be fully vacuum compatible and has incorporated redundancy for the LED and QT source architectures. Presently, the full performance system is being manufactured and Labsphere expects to deliver the system in September of 2024.

Modeling work performed during this development suggests that the system's uniformity can be further improved through some strategic adjustments to coatings. The team has significant interest in testing these changes in a prototype unit, work that will be performed outside of the scope of the project reported here. Additionally, furthering this technology by improving the system's uniformity and looking for analogous applications to test scaled versions of the system.

8. SUMMARY, CONCLUSIONS, ETC.

In collaboration with NASA GSFC and Genesis Engineering Solutions Inc., Labsphere, Inc. has developed an innovative spectro-radiometric calibration source for satellite-based sensors. Key developments in the diffuse integration geometry and hybrid LED/QT source modules have enabled the performance described throughout this paper. This system's unique illumination architecture is extremely well-suited for the vacuum environment, being both power and space efficient, capable of producing the required radiance with 172% reduced power, and just 17% of the occupied volume when compared to a conventional uniform source (see Table 8). While the system does compromise marginally on uniformity, the nascency of the team's technological improvements can undoubtedly be further improved. The successful testing of the demonstration system instills confidence and enthusiasm within the team for the vacuum compatible units presently being produced for use in VIIRS TVAC campaigns.

Beyond VIIRS, this technology can serve the needs of other instruments and missions requiring prelaunch spectro-radiometric calibrations. The system's tunable light sources, radiance efficiency, and versatile mounting options make this a viable system for a wide range of visible-to-SWIR sensor suites used in volume-conscious applications. In summary, our collaborative effort has yielded a novel calibration system that addresses critical challenges in satellite radiometric testing. With this novel uniform source, we plan to illuminate not only VIIRS, but the path to a better understanding of our universe through more accurate space-based sensors.

9. ACKNOWLEDGMENTS

While this paper focuses on the measured radiometric performance of the LVIS illuminator and FPI II system, much of the team's excitement for implementation of the system are the small details that will make integration into test setups and the vacuum chamber simpler, faster, and more reliable. The team is indebted to the shared experiences and expertise from the implementation of prior generation Flat Plate Illuminators and thermal vacuum systems in general.

The team received significant support in making the system vacuum compatible from NASA's material experts Larissa Graziani and George Meadows, as well as Northrup Grumman's thermal engineer Billy Greenrock. Eric Johnson, of RTX, contributed critical inputs to the radiometric performance parameters. Emily Maheras and Mike Commons, both of Vertex Aerospace, have provided essential thermal analyses for the system in the TVAC chamber. Rachel Rashford, of Genesis, has contributed mechanical design expertise for key system elements. Finally, NASA's Joel McCorkel provided the technological and programmatic genesis of the FPI-2 effort and led the way to have the entire project funded.

*Identification of commercial equipment does not imply recommendation or endorsement by Labsphere Inc., Genesis Engineering Solutions Inc., or NASA.

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