# Design and characterization of a large area uniform radiance source for calibration of a remote sensing imaging system

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## ABSTRACT

An application-specific contracted integrating sphere source of uniform spectral radiance is described. The source is used for pre-launch test and calibration of imaging radiometers which will be used as satellite borne earth remote sensors. The calibration source is primarily intended to serve as a transfer standard of radiance.

Design criteria for the uniform radiance source are presented. Included is a summary of the end-user specifications in regards to spectral radiance, radiance levels of attenuation, radiance stability, and aperture uniformity. Radiometric theory used to predict the source radiance for a specific spectral flux input is reviewed. Reasoning for the use of an integrating sphere platform for this application and characteristic features of the source are discussed.

Calibration methods and instrumentation are described. The resultant data presented include the modeled data compared with the measured performance. Methods of data reduction and uncertainty are addressed where applicable.

**Keywords**: ISRO, Labsphere, uniform source, integrating sphere, spectral radiance, luminance uniformity, calibration

## 1. INTRODUCTION

Three integrating sphere sources of uniform radiance of 76-inch (1.9 m) diameter, two of 850 mm exit aperture (with variable aperture plates) and one of 1200 mm exit aperture have been built by Labsphere Inc. to the Indian Space Research Organization (ISRO) specifications and cover increasing optics size and saturation radiance requirements of different electro-optical sensors in narrow and broad spectral band applications. These large aperture Lambertian sources are used to illuminate the entrance pupil of optics at equi-spaced radiance levels covering the desired dynamic range of the instrument during pre-flight radiometric calibration exercise of the electro-optical (E-O) Sensors in 350-2400 nm spectral range. These imaging sensors are placed aboard Indian Remote Sensing Satellites (IRS) and use linear array charge coupled devises (CCD) as detectors in each spectral band.

The pre-flight radiometric calibration generates a transfer function for each detector element in an array of linear charge coupled devices or elemental devices. During this exercise an entire array of detectors in a spectral band is illuminated by a sequence of radiance levels in decreasing order from near saturation radiance to dark. By applying linear regression to the digital counts and corresponding input radiance, calibration coefficients are derived that can predict the actual scene radiance within known uncertainties during orbital passes from digital counts of that channel. This requires the uniform source to provide known radiance levels with absolute accuracy traceable to the National Institute of Standards and Technologies (NIST) or equivalent primary standards of radiance scale. The uniform source should provide high-spatial and angular uniformity of better than at least 95% and stability better than 99.9% for about a 30-second duration after stabilization. The source must also provide spectral stability through about 25-30 levels in the dynamic range of interest in each spectral band. The discussion that follows is based on the 120 cm exit aperture source, the most recent near-Lambertian source delivered to ISRO for calibration of the E-O sensors.

## 2. SOURCE REQUIREMENTS

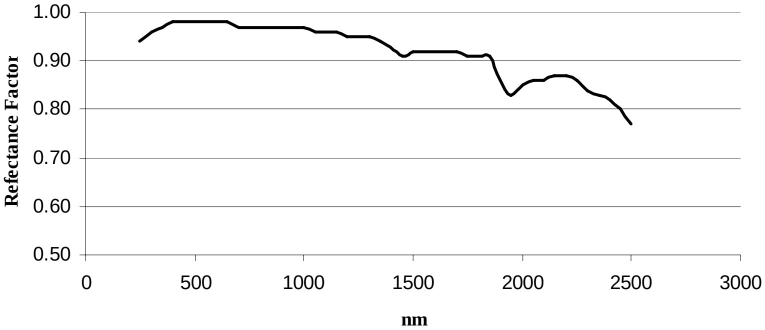

Figure 1. Published spectral reflectance of Spectraflect

The source aperture diameter and output radiance determine the optimal sphere diameter and lamp specifications. A general rule of thumb requires an integrating sphere diameter that is three times larger than the exit aperture diameter. For practical reasons an integrating sphere of 1.9 m or only 1.6 times larger than the exit aperture added a design challenge to produce a highly uniform source of spectral radiance. The field-of-view (FOV) of E-O sensors built at ISRO requires an aperture of 100 cm or larger. Labsphere's Spectraflect (Figure 1) high-reflective, diffuse white coating was requested to achieve high uniformity over the 120 cm diameter aperture at multiple levels of radiance.

The uniform source is required to produce minimum and maximum spectral radiance levels at the 12 wavelengths shown in Table 1. Spectral radiance adjustability for a minimum of thirty levels incremented equally at each wavelength and maintaining spatial uniformity 95% or better and angular uniformity of 97% at ±10° and 94% at ± 45° with minimal color temperature shift is required.

Other features include filter-based temperature-controlled spectral radiance monitors with variable FOVs from 1° to 50° in five steps, two additional single filtered temperature controlled monitors with fixed FOV of 15°, two thermally electric controlled array spectrometers for monitoring spectral radiance from 300 to 2400 nm, temperature sensors for monitoring the internal temperature of the sphere not to exceed 50°C, and computer-controlled, lamp power supplies with 0.1% current stability and ramp up and ramp-down feature for maintaining lamp performance. Software is required to control the system and includes features such as user selectable actuation of lamps, light attenuators, filter wheels and radiometers, real-time tables and spectral plots, storage and labeling of data files, performance tolerances with audio alarms and more. Mechanical requirements include exit aperture center height adjustability from 150 cm to 200 cm from the floor, exit aperture cover for interior protection when not in use, and a sturdy frame with locking casters for mobility, and eye bolts for lifting.

| Wavelength nm | Max. Spectral Radiance mW/cm$^2$-sr-μm | Min. Spectral Radiance mW/cm$^2$-sr-μm |
|---|---|---|
| 400 | 10 | 0.300 |
| 450 | 20 | 0.600 |
| 500 | 35 | 1.050 |
| 550 | 62 | 0.620 |
| 600 | 58 | 0.580 |
| 650 | 52 | 0.520 |
| 700 | 46 | 0.460 |
| 800 | 36 | 0.360 |
| 900 | 29 | 0.290 |
| 1000 | 24 | 0.240 |
| 1500 | 10 | 0.100 |
| 1700 | 8 | 0.080 |

*Table 1*
*Spectral Radiance Requirements at Exit Aperture*

## 3. SPECTRAL RADIANCE PERFORMANCE MODELING

The spectral radiance produced by an integrating sphere from the spectral flux input is dependent on the sphere diameter, number of apertures in the sphere or coined aperture fraction area, and the spectral reflectance of the interior coating.[1]

$$L_\lambda = \frac{\phi_\lambda}{\pi A_s} \frac{\rho_\lambda}{\left(1-\left(\rho_\lambda\left(1-f\right)\right)\right)} \qquad (mW/cm^2\ sr\ \mu m) \tag{1}$$

Where $L_\lambda$ is the sphere wall spectral radiance, ρ is the sphere wall reflectance, $A_s$ is the sphere surface area and a $f$ is the port fractional area of the integrating sphere. Blackbody theory is applied for tungsten halogen lamp input. The total spectral flux of a tungsten filament lamp is expressed in the in terms of its spectral radiant exitance, emissivity and total surface:

$$\phi_\lambda = M_\lambda \varepsilon A \qquad (W/\mu m) \tag{2}$$

Planck's law describes the spectral exitance as a function of the wavelength and the surface temperature of the filament:

$$M_\lambda = \frac{c_1}{\lambda^5} \frac{1}{e^{c_2/\lambda T} - 1} \qquad (W/m^2 \mu m) \tag{3}$$

Applying the Stefan_Boltzmann law εA can be approximated by equating the electrical power to its total radiant power

$$\varphi = \varepsilon A \sigma T^4 \qquad (W) \tag{4}$$

Expressed in εA the equation becomes

$$\varepsilon A = \frac{\varphi}{\sigma T^4} \qquad (\mu m^2) \tag{5}$$

Substitute for M and εA the total spectral flux is expressed as:

$$\phi_\lambda = \frac{c_1}{\lambda^5} \frac{1}{e^{c_2/\lambda T} - 1} \frac{\varphi}{\sigma T^4} \qquad (W/\mu m) \tag{6}$$

Where $\phi_\lambda$ equals radiant flux, $c_2$ equals 3.7413E-4 W/$\mu m^2$, λ equals the wavelength in micron, $c_2$ equals 1.4388E4 μm-K, T is the filament temperature in Kelvin, φ is the lamp rate power and σ equals 5.6686 E-20 W/$\mu m^2 K^4$. This expression of spectral flux does not take into consideration the spectrally independent emissivity for tungsten at all temperatures, water band absorbance and the like, but it is adequate for integrating sphere spectral radiance approximation.

The remaining parameters in the integrating sphere spectral radiance equations such as the surface area and aperture fractional area are easy to calculate and the spectral reflectance data are published[2] see Table 1.

## 4. DESIGN

### 4.1 Integrating sphere uniform source system

The integrating sphere assembly includes the 1.9 m main integrating sphere with a 120 cm exit aperture, has internal illuminators, an external illuminator, two motor-operated, filtered radiance monitoring units, two manually operated radiance monitoring units, two junction panels and two electronics racks. All of the components on the sphere assembly are supported by an extruded aluminum frame that is mounted on casters. Three lift eyebolts are installed along the frame perimeter of the sphere assembly. The integrating sphere is mounted on a motorized lift mechanism for adjusting the exit aperture center height between 150 cm to 200 cm from the floor.

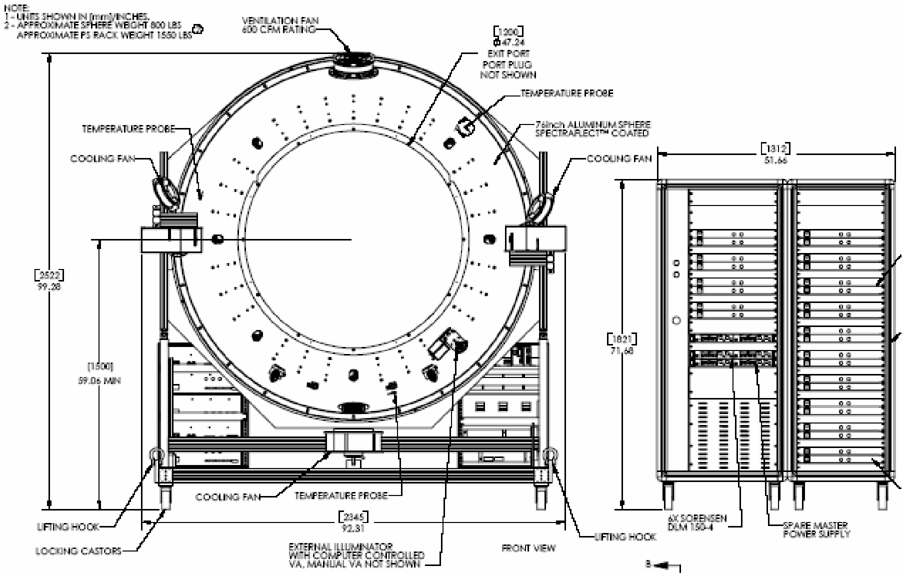

*Figure 2*
*1.9 m Integrating Sphere Uniform Source*

Applying the spectral radiance from equation (1), the integrating sphere and number of lamps are modeled to meet the spectral radiance requirements in Table 1. With near blackbody spectral distribution from the tungsten halogen sources, the 400 nm spectral radiance requirement set the goal for maximum spectral flux input. Once the maximum spectral radiance at 400 nm was met the remaining maximum radiance levels were exceeded. Having modeled the uniform source for maximum spectral flux input, the sphere can achieve practically any minimum and maximum desired range with a combination of an externally mounted projection lamp and internally mounted lamps. The external lamp projects light into the integrating sphere through a computer controlled, 256 step mechanical light attenuator. The input of this lamp is greater than the output of one internal lamp. The sum of the smallest internal lamp and variable external lamp is greater than the next largest internal lamp and so on. To achieve the spectral radiance levels with the complete output level controllability the 32 lamps presented in Table 2 are employed.

Note the increased input from the 35-watt lamp. The sphere is designed to minimize the color temperature shifts by operating all the lamps at 3000K +/- 50K. To achieve this, the 35-watt lamp is prorated from 2900K to 3000K or 35 watts to approximately 41 watts. The 100-watt external lamp assembly is configured with an elliptical rhodium reflector that concentrates the light through a 1-inch aperture on the sphere. The optical losses from the coupling to the integrating sphere are about 70% when used with the mechanical attenuator.

| Qty | Location | Lamp Wattage (W) | Nominal Wattage into Sphere (W) | Total Wattage into Sphere (W) |
|---|---|---|---|---|
| 24 | Internal | 500 | 500 | 12000 |
| 1 | Internal | 300 | 300 | 300 |
| 2 | Internal | 100 | 100 | 200 |
| 3 | Internal | 35 | 41 | 123 |
| 1 | Internal | 20 | 20 | 20 |
| 1 | External | 100 | 30 | 29 |

*Table 2*
*Integrating Sphere Uniform Source Lamps*

The lamps are spaced symmetrically around the circumference of the exit aperture, out of the FOV of the E-O sensors. Balancing the positioning of the lamps around the exit aperture increases the probability of higher uniformity at the lower radiance levels. Since the lamps are positioned around the optical center of the exit aperture it is critical that the selected lamps can operate in any orientation. The 500 and 300W tungsten halogen lamps are double-ended recessed contact lamps. These lamps are isolated from the integrating sphere interior wall with machined high reflective diffuse Spectralon® material. The lower wattage lamps are compact and rugged, coiled-coiled filament lamps. The external illuminator and variable attenuator located in the lower hemisphere of the integrating sphere are used to fine tune the integrating sphere radiance levels. All the lamps have rated lives of 500 to 2000 hours for prolonged radiance stability.

### 4.2 Radiance Monitoring

Precision spectral radiance monitoring can be done with a spectrometer or filtered photodiode detectors. The integrating sphere uniform source features four radiance monitoring units (RMU) to monitor the radiance through the integrating sphere exit aperture. The radiance monitoring units identified as RMU No. 1, RMU No. 2, RMU No. 3 and RMU No. 4 are positioned around the front base of the uniform source. The monitors are angled to collect sphere wall radiance emitting directly across from of the integrating sphere exit aperture. Monitoring units RMU No. 1 and No. 2 both incorporate motorized filter wheels and manually operated aperture wheels. The RMU No. 1 has an integrated Hamamatsu S2592-04 silicon (Si) photodiode. RMU No. 2 employs an Hamamatsu G5851-13 indium gallium arsenide (InGaAs) photodiode. The detectors are thermoelectrically (TE) cooled by Hamamatsu controllers. RMU No. 3 and RMU No. 4 use the same detectors and each are integrated with a single filter holder and aperture that produce a full angle FOV of 25°, equivalent to a numerical aperture of 0.22. The spectral radiance responsivity $R$ is derived in equation 7 as

$$R = A/L \quad (A/(W/cm^2\text{-}sr\text{-}\mu m)) \tag{7}$$

Where $A$ is the detector photocurrent and $L$ is the integrating sphere uniform source spectral radiance. The detector signals of RMU No.1 through RMU No. 4 are monitored with a single system control radiometer and detector multiplexer. The detector multiplexer is a switchbox controlled by the system control radiometer and control computer with system software.

Two spectrometers generate a profile of the uniform source spectral radiance. The spectrometer monitor units (SMU) communicate with the control computer via USB and are designated SMU No. 1 and SMU No. 2. SMU No. 1 is an S2000-TR spectrometer, responsive over the 350 - 1000 nm wavelength spectrum. SMU No. 2 is an InGaAs array with a wavelength capability of 900 to 2500 nm. Spectral control application software combines the scan data from both spectrometers and displays the data as continuous plots 350 to 2500 nm.

### 4.3 Power distribution

Current regulated programmable DC power supplies are required to ensure continuous radiance stability. Current regulation to the tungsten halogen lamps maintained short-term lamp flux stability. The current regulation through the source is ≤0.1%. To achieve this, each lamp operates with a dedicated power supply. All of the power supplies and auxiliary equipment are housed in two electronics racks. The system uses less than 25A per phase when all illuminators are operating. A delta-to-wye power transformer in the bottom of the power supply rack reduces the three-phase line voltage of 433 VAC on the supply to a 240 VAC single phase voltage inside the power supply rack. This voltage is distributed throughout the system. All components in the system are configured for single phase, 240 VAC.

## 5. CALIBRATION

### 5.1 Spectral radiance

The spectral radiance measurements of the integrating sphere source of uniform radiance are performed by direct comparison of measurements carried out with equipment and methods traceable to the NIST. Measurement uncertainty is determined by best practices of expressions of uncertainties.

### 5.2 Spectroradiometer

The calibration is accomplished by referencing a FEL type tungsten halogen lamp standard of spectral irradiance that irradiates a Spectralon standard of diffuse reflectance. The standard becomes the reference source of spectral radiance as determined by

$$L_\lambda = \frac{E_\lambda \rho_\lambda}{\pi} \qquad (mW/cm^2\ sr\ \mu m) \tag{8}$$

Where $\rho$ is the spectral reflectance of the Spectralon target in 0/45 reflectance geometry. The measuring instrument used to perform the calibration is a scanning, dispersive spectroradiometer. The radiance of the Spectralon standard is transferred to the diffraction grating monochromator with a four mirror input optics system. Long pass order sorting filters are used at the entrance slit to reduce stray light. A mechanical chopper provides a modulated reference signal. The complete spectral measurement range requires two photo detectors and three diffraction gratings. In the spectral region from 300 nm to 375 nm, a 1200 grooves/mm holographic grating is used with a silicon detector. From 375 nm to 1100 nm, a 1200 grooves/mm, 500 nm blaze grating is used with a silicon detector. In the spectral region from 1100 nm to 2400 nm, a 600 grooves/mm, 1600 nm grating is used with a thermoelectrically cooled InGaAs detector.

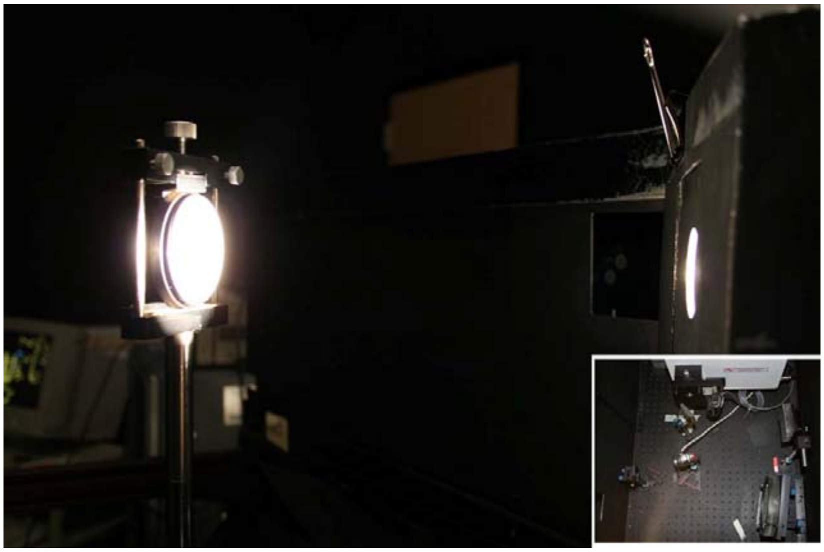
*Figure 3*
*Scanning Spectroradiometer*

Signal conditioning electronics include low-noise, high-impedance preamplifiers and a single-phase lock-in amplifier. The spectroradiometer calibration is performed by viewing the diffuse standard illuminated by the calibrated lamp of known spectral irradiance. After scanning the diffuse standard, it is replaced with the integrating sphere uniform sources and the measurement process is repeated. The measured FOV of the spectroradiometer is 10mm x 4mm with an aperture ratio of f/4. Spectral measurements are performed with this FOV positioned at the center of the plane of the diffuse standard.

### 5.3 Spectral radiance uncertainty

The spectral radiance measurements uncertainty is a function of the systematic and random errors. The calibration of the integrating sphere source of uniform radiance is listed in Table 3 presented with an expression of uncertainty with a coverage factor of k=3.

| **Wavelength** | 0.350 µm | 0.6546 µm | 0.900 µm | 1.300 µm | 1.600 µm | 2.000 µm | 2.400 µm |
|---|---|---|---|---|---|---|---|
| **Systematic Errors** | | | | | | | |
| **Irradiance of Standard Lamp** | 1.22 | 1.13 | 1.47 | 1.57 | 2.01 | 3.37 | 6.55 |
| **Standard Reflectance** | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 6.0 |
| **Non-Linearity of Detectors/Amplifiers** | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| **Random Errors** | | | | | | | |
| **Lamp Current Setting** | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| **Lamp Current Drift** | 0.06 | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 |
| **Lamp Reference Distance** | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| **Monochromator Wavelength Setting** | 0.85 | 0.49 | 0.33 | 0.92 | 0.75 | 0.60 | 0.50 |
| **Total Precision** | 1.06 | 0.80 | 0.71 | 1.11 | 0.98 | 0.87 | 0.80 |
| **Total RSS Measurement Uncertainty** | 2.42 | 2.27 | 2.43 | 2.64 | 2.87 | 3.92 | 9.01 |

*Table 3*
*Spectral Radiance Uncertainty*

The maximum spectral radiance for the sphere is present in Figure 4. The measured results are compared to the modeled results using Equation (1). The measured spectral radiance is greater than the modeled spectral radiance. Having met the highest spectral radiance requirement at 450 nm all other lower spectral radiance requirements were met with the radiance adjustability feature.

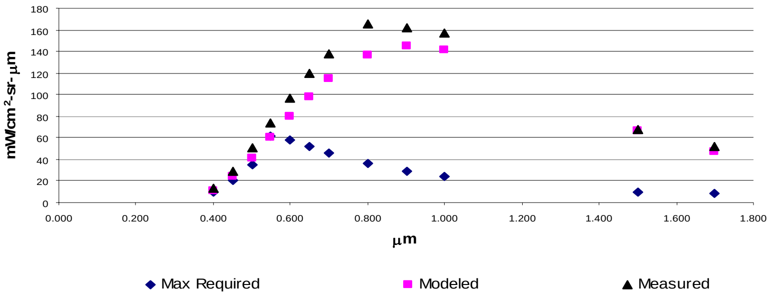

*Figure 4. Measured vs. Modeled Spectral Radiance*

### 5.4 Uniformity mapping

ISRO required the radiance uniformity be greater than or equal to 95% at 100%, 10% and 1% of maximum radiance. The requirements were exceeded with 98.3%, 97.7% and 96.9% respectively.

A luminance mapping is performed with a commercial Minolta luminance meter. The luminance meter is mounted on an XY translation station (Figure 5) at a reference distance of 678 mm from the uniform source sphere exit aperture plane. The luminance meter FOV is circular, with a cone full-angle of 1°. The area of view at the exit aperture plane is a circle of 9 mm diameter. Measurement points are defined in a 69-point raster array, centered on the exit aperture, with data point spacing of 12 cm or 0.1 times the diameter of the exit aperture aperture. For each data point recorded photocurrent from RMU No. 1 at 550 nm is monitored in order to detect any changes in sphere luminance due to back-reflection from the mapping apparatus.

*Figure 5*
*Mapping Stage*

Mappings are performed after the uniform source sphere has stabilized at a given power level for at least 30 minutes. The mapping is performed by recording the ratio of the luminance meter reading to the monitor detector reading for each measurement position. The data are normalized to the *maximum* reading recorded. The raster mapping at maximum radiance is presented in Table 4.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0.990 | 0.991 | 0.991 | 0.990 | 0.987 | | |
| | 0.994 | 0.996 | 0.995 | 0.994 | 0.994 | 0.993 | 0.984 | |
| 0.991 | 0.993 | 0.994 | 0.993 | 0.992 | 0.994 | 0.994 | 0.989 | 0.983 |
| 0.989 | 0.992 | 0.991 | 0.987 | 0.987 | 0.991 | 0.994 | 0.993 | 0.987 |
| 0.989 | 0.991 | 0.990 | 0.987 | 0.988 | 0.992 | 0.994 | 0.994 | 0.988 |
| 0.990 | 0.993 | 0.992 | 0.990 | 0.992 | 0.995 | 0.998 | 0.997 | 0.985 |
| 0.993 | 0.997 | 0.997 | 0.997 | 0.997 | 0.999 | 1.000 | 0.997 | 0.985 |
| | 0.995 | 0.996 | 0.997 | 0.998 | 0.999 | 1.000 | 0.994 | |
| | | 0.993 | 0.995 | 0.996 | 0.997 | 0.995 | | |

Uniformity = 98.3%

*Table 4*
*Luminance mapping at 100% Power*

ISRO required the angular uniformity be greater than or equal to 97% at +/- 10° and greater than or equal to 94% at +/-45°. The equipment used for the raster mapping is also used for the angular mapping. The requirements were exceeded with 99.6% and 98.3% respectively.

### 5.5 Radiance stability

ISRO required short-term radiance stability of 0.100% and long term stability of 1.000%. The requirements were exceeded with 0.010% and 0.012% respectively. The data are presented in Table 5.

| | **Short Term** | **Long Term** |
|---|---|---|
| **Duration** | 30 seconds | 10 minutes |
| **Mean Photocurrent (A)** | 4.913E-06 | 4.913E-06 |
| **Standard Deviation of Photocurrent (A)** | 4.716E-10 | 5.794E-10 |
| **Coefficient of Variation of Photocurrent** | 0.010% | 0.012% |

*Table 5*
*Short-Term and Long-Term Radiance Stability*

The radiance stability is performed with all 32 lamps operating. The photocurrent from RMU No. 1 was used to monitor the radiance of the sphere system. The photocurrent is monitored via the system control software. For the short-term stability test the photocurrent is recorded once every 0.5 second for 30 seconds to produce 60 data points. For the long-term stability test the photocurrent is recorded once every 0.5 second for 10 minutes to produce 1200 data points. For each of these data sets the mean, standard deviation and coefficient of variation are calculated and presented in Table 5.

## 6. CONCLUSION

The sensors placed on polar sun-synchronous orbit of about 700-900 km height cover two main application areas, specifically marine resources with eight narrow spectral bands of an instrument called Ocean Color Monitor; land resource monitoring with exclusive emphasis on crop production forecasting in multi-crop heterogeneous agri-climate regions, plant species identification in forest ecosystems and crop classification, mineral exploration, and environmental monitoring with instruments such as the Linear Imaging Self-Scanning Sensors LISS-3, LISS-4 and Advanced Wide-Field Sensors (AWiFS) placed aboard Resourcesat.

The meteorological data from imaging and atmospheric sounding instruments placed aboard geosynchronous orbit at 36,000 km above earth's surface provide a synoptic view of cloud coverage over the globe every 30 minutes and provide information on wind velocity through imaging in reflected electromagnetic radiation complemented by results from infrared spectral bands in emitting regions of the spectrum.

These instruments on the IRS System and Indian National Satellite System (INSAT) missions have optics of varying diameter, the FOV spans wide range from $\pm 0.1^{o}$ to $\pm 43^{o}$ and saturation radiance requirement vary from 62 $mW/cm^2$-sr-μm at 550 nm to 7 $mW/cm^2$-sr-μm at 1625 nm. The radiometric resolution ranges from 8 to 12 bits for different instruments based on application.

Currently data from existing operational payloads on IRS platforms are acquired through a network of worldwide ground stations in the Indian subcontinent including Weilham in Germany and Norman in the USA. The data is disseminated directly to the global earth observation community by the ISRO as well as through commercial ventures by private agencies.

Large aperture uniform radiance sources are needed for the pre-flight characterization and calibration of E-O sensors with FOVs approaching $\pm 45^{o}$. It is not always practical to proportionally increase the sphere diameter to maintain a 5% or less aperture fraction area to conserve the light mixing properties of an integrating sphere. This paper shows that the proper choice of sphere coating, lamps and lamp placement, auxiliary supplies, and years of empirical and theoretical experience we can stretch the limits of integrating sphere theory and still maintain performance integrity.

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We also like to thank the Labsphere team for their continued ingenuity and quality of workmanship.

## 8. REFERENCES

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