Vacuum compatible large uniform-radiance source for ground calibration of satellite cameras inside a thermal vacuum environment

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ABSTRACT

A vacuum compatible integrating sphere was built to operate inside a thermal vacuum chamber. This paper presents the design and test results for a 1.65 meter diameter vacuum compatible integrating sphere with a 1.0 meter diameter exit port and approximately 10kW of internal tungsten lamps. Liquid nitrogen is used as cooling medium to remove the heat generated by these lamps. There are no moving parts inside the vacuum chamber.

The radiance is monitored with two filter-wheel detectors, one TE-cooled silicon and one TE-cooled germanium, as well as a TE-cooled silicon array spectrometer. All three detectors are located outside the thermal vacuum chamber and view the sphere radiance through fiber optic cables.

The system was tested inside a thermal vacuum chamber at NASA Goddard Space Flight Center before commissioning in the 5.5 meter thermal vacuum chamber at Space Applications Centre in Ahmedabad, India. Results of tests of radiance uniformity, radiance levels, and radiance stability are presented. Comparisons of the filter radiometers with the array spectrometer are also presented.

Keywords: integrating sphere, flat-fielding, vacuum chamber, uniform source, thermal vacuum

1. INTRODUCTION

Integrating sphere uniform sources are routinely used for ground calibration of earth-sensing satellite cameras. These sources provide a flat field for spatial and angular corrections of image nonuniformities as well as adjustable levels of radiance for radiometric calibration. Traditionally, these sources are built to operate at ambient temperature and pressure. This requires the cameras, which will be operated in a vacuum, to be tested at ambient temperature and atmospheric pressure in a laboratory. Or, for smaller aperture cameras, a window may be used between the thermal vacuum chamber containing the camera and the uniform source outside the chamber. An integrating sphere that operates inside a vacuum chamber would permit testing of the camera at the thermal-vacuum environment in which it will be used.

Space Applications Centre (SAC), a unit of Indian Space Research Organisation (ISRO), is engaged in the development of satellite-borne electro-optical (EO) sensors for remote sensing of earth's natural resources and meteorology. Integrating spheres are used in the laboratory environment as stable and uniform sources of illumination in 350-2500nm spectral range for carrying out pre-launch radiometric characterization and calibration of these sensors.

During their operations in the orbit, sensor optics or electronics may encounter extreme temperatures. In order to evaluate radiometric performance of EO sensors under different temperatures during development a vacuum compatible integrating sphere is built to ISRO specifications by SphereOptics, LLC. Liquid nitrogen is used to cool its walls from heat of high wattage tungsten halogen lamps used as internal illuminators. A reference source characterized at NIST is used to calibrate radiometers. The main source is tested at the factory and at NASA GSFC facilities before commissioning in a 5.5m diameter thermal vacuum chamber at SAC.

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The salient features of the integrating sphere include radiance scale traceable to NIST, user selectable variable spectral radiance levels without change in spectral profile of the output, real-time monitoring of spectral radiance and its spectral profile, excellent radiance stability, uniformity, and thermal behavior.

This paper reports on the design and testing of a large aperture uniform source that operates inside a thermal vacuum chamber. The aperture of the sphere is 1.0 meter (39.4 inches). Typically, the sphere diameter is at least three times the port diameter for best uniformity, so a 1.0 meter port is large for the 1650mm diameter (65 inch) sphere, but it is a reasonable tradeoff between cost and optical performance.

2. DESIGN

2.1 Lamps

In order to meet the radiance levels required, especially at 550nm, nearly 10kW of quartz tungsten halogen (QTH) lamps (electrical input power to the lamps) are required. This is accomplished by using thirteen nominal 600W lamps, several smaller lamps of various sizes to provide adjustability, and one lamp with a variable aperture for fine adjustment. All the lamps except the variable-input lamp are mounted inside the sphere. Specifically, the internal lamp configuration is:

Rated power (W)	Approx. actual power (W)	Number of lamps
600	685	13
300	290	2
150	160	1
75	85	1
50	50	1
20	20	1
10	10	1
8705	9810	all 20

The variable-input lamp is mounted outside the vacuum chamber with the light fed to the sphere via a fiber bundle. The light from this 150W QTH lamp, fed into the vacuum chamber with a fiber bundle, provided from zero up to the equivalent of a 10W internal lamp.

2.2 Sphere coating

A sprayed barium sulfate coating was used on the sphere wall. This coating has the following outgassing properties, making it suitable for use in vacuum:

TML = 0.20%	CVCM = 0.02%	WVR = 0.03%

2.3 Cooling

To remove the 10kW of power inserted in the sphere, the aluminum sphere wall was fitted with stainless steel tubes carrying LN_2 as a coolant. The sphere operator required that only pure nitrogen could be used as a cooling medium. A cooling system using gaseous nitrogen in reasonable quantities and at reasonable flow rates would not provide sufficient capacity to remove 10kW of heat. So, LN_2 was the default choice. As a result, the sphere was cooled to much lower temperatures than necessary to prevent damage from overheating the coating, but successful operation nevertheless. If required, the user may close flow of LN_2 to the rear hemisphere thus avoiding low temperature on that part of the sphere.

For safety and serviceability, the cooling system is designed with no moving components inside the vacuum chamber. Other than two LN_2 level sensors (temperature based), all active cooling control is outside the chamber. Inside the chamber, the cooling system is purely passive and gravity operated. There is a reservoir located above the highest level of the sphere which provides LN_2, by gravity feed to a manifold at the bottom of the sphere. The LN_2 in the tubes around the sphere boils as it removes heat, venting gaseous nitrogen to the top of the reservoir. This gas is further vented to the atmosphere outside the chamber and outside the building. There are a “keep full” pair of level sensors inside the reservoir that operate a control solenoid that is outside the vacuum. This is the only active part of the cooling system, keeping the LN2 in the reservoir at an appropriate level so that passive gravity cooling can operate inside the chamber.

2.4 Monitoring

The radiance of the source is monitored by two broadband photovoltaic detectors, each behind an automated filter wheel, so that the spectral radiance of the source can be monitored at each of the filter wavelengths as follows:

center wavelength (nm)	bandwidth (nm)	detector (TE-cooled)
410	10	Silicon
440	10	Silicon
490	10	Silicon
510	10	Silicon
550	10	Silicon
550	70	Silicon
650	75	Silicon
650	200	Silicon
670	10	Silicon
675	350	Silicon
750	40	Silicon
815	90	Silicon
870	40	Germanium
1625	65	Germanium
1625	150	Germanium

In addition to the filtered detector, a TE-cooled fiberoptic array spectrometer monitors the spectral radiance from 300nm to 1000nm, with a bandwidth of approximately 1nm.

2.5 Mechanical

For several reasons, including serviceability, no moving parts are inside the vacuum chamber. A source such as this would, if outside a vacuum chamber, have several moving parts attached, specifically:

- filter wheel for the Si detector
- filter wheel for the Ge detector
- variable aperture for the external lamp

In addition, the three TE-cooled detectors (Si, Ge, and array) are also outside the vacuum chamber. This allows air-cooled heat sinks and the use of commercial, non-vacuum-compatible hardware.

2.6 Fibers

Fiberoptic cables are used to allow the moving parts and the TE-cooled components to be outside the vacuum chamber while providing light into the chamber and monitoring the radiance of the source that is inside the chamber. The following fiber bundles are used for operating the source:

Fiber use	Number of fibers	Bundle diameter (mm)	Fiber diameter (μm)	length (m)	fiber material
Light in from VA	~80,000	~16	50	8	borosilicate glass
Light out to VIS detector	~5,000	~4	50	8	borosilicate glass
Light out to IR detector	180	~4	220	8	quartz (LOH)
Array spectrometer	1	n/a	600	8	quartz

2.7 Electrical

The primary electrical load, the 21 power supplies, one for each lamp, is balanced across three phases. Each power supply has individual power factor correction, so operation on three-phase input can be accomplished without overloading the neutral or applying any external power factor correction scheme.

3. CALIBRATION

3.1 Radiometric

The filter radiometers (filter-wheels and detectors) and the array spectrometer were calibrated outside the vacuum chamber with an Oriel model 77715, double MS257, ¼-meter scanning monochromator. The spectral radiance of the sphere was measured with the double monochromator while simultaneously recording the signals on the detectors, which were being fed through their fibers.

3.2 Operation outside the vacuum chamber

During this calibration, the sphere was cooled by water that was forced through the tubes that would carry LN2 during vacuum operation. LN_2 cannot be used outside the vacuum chamber due to the inevitable frost ruining the water-soluble barium sulfate coating.

3.3 NIST-calibrated radiance source

The scanning double monochromator was calibrated directly from a 150mm Zenith® (sintered PTFE) integrating sphere that was measured for spectral radiance along with its single lamp, power supply, and monitor detector at NIST.

4. PERFORMANCE

4.1 Radiometric

The radiance exceeded the high-radiance specification at all wavelengths and has enough adjustability to meet the required low levels and provide a great deal of adjustability between the high and low levels. Figure 1 shows the maximum achievable spectral radiance, the minimum achievable spectral radiance (with internal lamps) as well as the required maximum and minimum.

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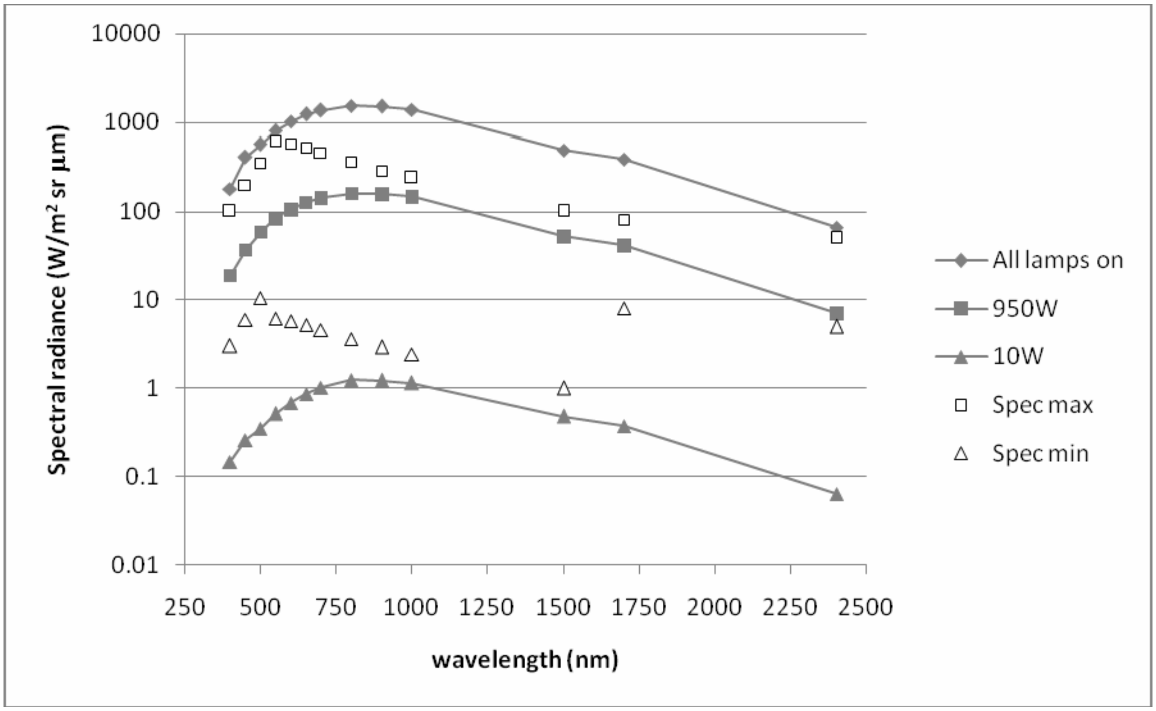

Figure 1: Spectral radiance at various input powers

4.2 Stability

The radiance stability is better with multiple lamps than with a single lamp. The following table shows the long term and short term rms radiance stability with one and four lamps.

Lamps	short term (30 seconds)	long term (10 minute)
single 10W lamp	0.0110%	0.0307%
four 600W lamps	0.0007%	0.0026%

4.3 Uniformity

The uniformity was measured outside the vacuum chamber by scanning the radiant port of the sphere with a luminance meter set at infinite conjugates (collimated viewing). 69 spatial readings and 37 angular readings were taken. Then, five spatial and 5 angular readings were taken with a static mapping station that was later used to verify that the in-vacuum uniformity was not significantly different from the out-of-vacuum uniformity. The details of that verification are not presented in this paper other than to state that there was no observable difference in uniformity between atmospheric and vacuum operation.

4.3.1 Spatial uniformity

The spatial uniformity on the 1.0 meter port in the 1.65 meter sphere with four approximately equally spaced 600W lamps operating was measured at 98.2 %.

4.3.2 Angular uniformity

The angular uniformity on the 1.0 meter port in the 1.65 meter sphere with four approximately equally spaced 600W lamps operating was measured at 98.9% from 0° to 10° and 96.8 from 0° to 45°.

4.4 Comparison of filter radiometer with array spectrometer

Figures 2 and 3 show the spectral radiance of the sphere, read via fiberoptics while the sphere was operating at vacuum inside the chamber.

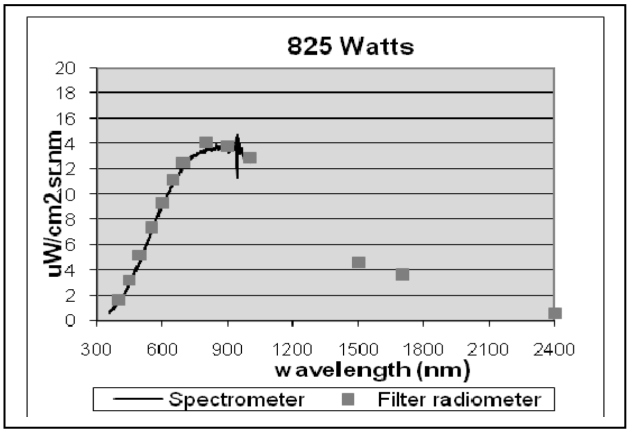

Figure 2: 825W nominal power

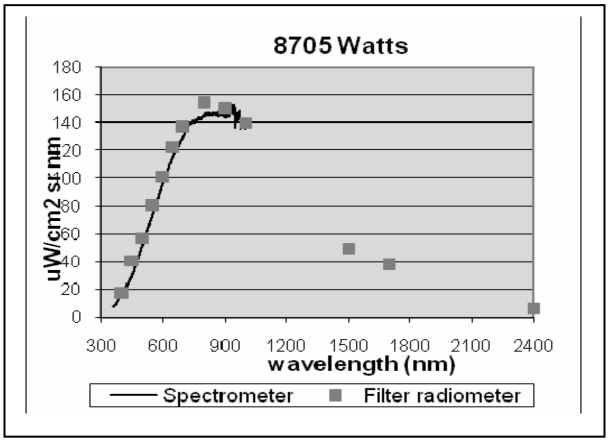

Figure 3: 8705W nominal power

4.5 Thermal

The sphere was fitted with four temperature probes at various locations on the sphere. The sensor T4 was near the lower LN_2 manifold and was the coldest; sensor T3 was closest to the lamps and the warmest. The sphere was brought to vacuum and then cooled until it reached equilibrium temperature of -160°C to -175°C. At that point, the lamps were turned on until they were all fully powered after ramp up and the sphere was again allowed to come to equilibrium temperature. With all lamps on, the warmest steady state temperature recorded was approximately -110°C (see Figure 4). This is 150 degrees colder than the goal high of +40°C. Barium sulfate coating should be kept below approximately 80°C to prevent degradation, so a goal of 40°C was established for this project.

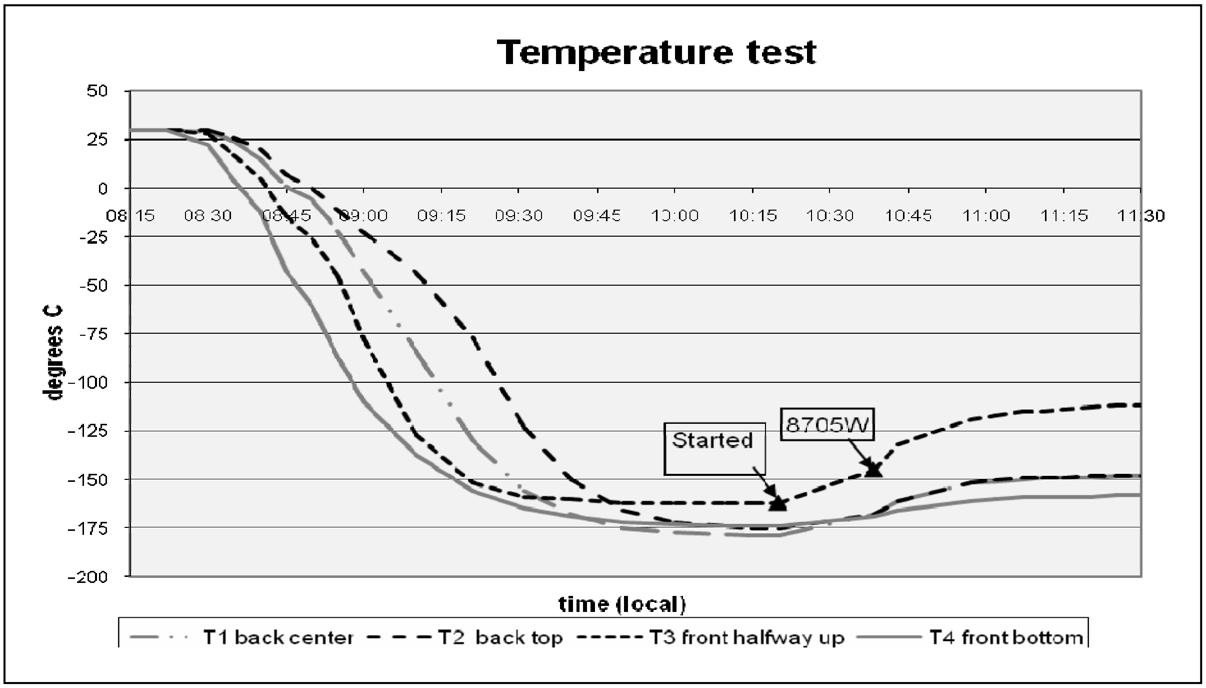

Figure 4: Thermal performance under vacuum conditions.

4.6 Vacuum

The pressure in the vacuum chamber during the temperature test was below 10^{-6} torr.

5. CONCLUSIONS

5.1 Overall

The main conclusion is that it is feasible and practical to provide a uniform source that operates in a thermal-vacuum chamber. In addition, two separate sets of conclusions can be drawn from this work (a) Operation in vacuum and (b) Operation at cryogenic temperatures. It is important that they be kept separate, since vacuum operation does not necessarily demand cryogenic operation.

5.2 Vacuum operation

The system handled the vacuum environment quite well, with several lessons learnt. Some are not entirely new, but will be listed here anyway.

- Spray coating of barium sulfate has no problem for operating in a vacuum.
- QTH lamps operate quite well in **vacuum.** The sockets presented a problem that is discussed below.
- Monitoring radiance over long (8 meter) optical fibers works well.
- Supplying light through a fiber bundle is extremely inefficient, delivering less than 7% of the input light in this case.
- Uniformity mapping of the integrating sphere is possible in a closed vacuum chamber through comparison against laboratory measurements.

5.3 Operating at cryogenic temperatures

Operation at cryogenic temperatures in this case was dictated by the requirement to use only nitrogen as the cooling fluid. Gaseous nitrogen was unable to do the job, so LN_2 was the only alternative. This provided cooling to very low temperature and presented several challenges that are detailed below.

- QTH lamps operate quite well in at cryogenic temperatures. The sockets presented a problem that is discussed below.
- The barium sulfate spray coating has a tendency to crack due to sudden cooling of the sphere aluminum. This happened once with this system at the bottom of the sphere, the first place to be hit with LN_2. After this was repaired, an initial cooling process was established in which the first feed of LN_2 to the reservoir was done manually and slowly so the sphere could be cooled more slowly.
- Cryogenic cooling cannot be used outside the vacuum because the inevitable frost would ruin the sphere coating. To operate the system in air required chilled water cooling. This worked quite well as far as cooling was concerned. In fact, it maintained the sphere temperature at a much more reasonable, yet cool, temperature. However, to switch from water to LN2 cooling required a thorough cleanout and drying of the cooling piping to prevent icing when LN2 is introduced.

5.4 Lamps and sockets

QTH lamps will operate quite well in a vacuum, even when started from cryogenic temperatures. However, conventional two-pin sockets do not work well under these conditions. Apparently, the spring clips that hold the lamp pins lose their grip and open their contact with the pins. The opening did not occur until after the lamps burned for a period of time, so it is not clear whether the cause was the low temperature due to cryogenic cooling or the high temperature due to lack of convection cooling of the sockets and poor conductive cooling to the sphere wall. This problem was overcome in this system by tinning the lamp pins, increasing their diameter.

6. RECOMMENDATIONS

Constraint on the use of only LN_2 as a coolant was the result of the operational needs at SAC chamber. However it was put to advantage in demonstrating stable performance for QTH lamps and internal high reflectance white coatings under low temperature environment through proper design of a reservoir, plumbing interfaces and flow mechanism.

In the laboratory, water cooling worked effectively. Where chamber operation allows, it is possible to cool the sphere wall to conventional temperature limits of 10º C and 65º C at full power during tests of flight hardware using inert refrigerants. Such a closed system, with chiller or condenser, would allow operation either in vacuum or in air with the same cooling system. It would also eliminate the need to provide piping from the chamber to the outside to exhaust the large quantities of gaseous nitrogen leaving the chamber.

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