

Title: VACUUM-COMPATIBLE STANDARD DIFFUSE SOURCE,
MANUFACTURE AND CALIBRATION

CONF-980731--

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Submitted to: SPIE '98
San Diego, CA
July 19-24, 1998

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Vacuum-compatible standard diffuse source, manufacture and calibration

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ABSTRACT

Los Alamos National Laboratories has completed the design, manufacture and calibration of a vacuum-compatible, tungsten lamp, integrating sphere. The light source has been calibrated at the National Institute of Standards and Technology (NIST) and is intended for use as a calibration standard for remote sensing instrumentation. Calibration 2σ uncertainty varied with wavelength from 1.21% at 400 nm and 0.73% at 900nm, to 3.95% at 2400nm.

The inner radius of the Spectralon-coated sphere is 21.2 cm with a 7.4 cm square exit aperture. A small satellite sphere is attached to the main sphere and its output coupled through a stepper motor driven aperture. The variable aperture allows a constant radiance without effecting the color temperature output from the main sphere. The sphere's output is transmitted into a vacuum test environment through a fused silica window that is an integral part of the outer housing of the vacuum shell assembly. The atmosphere within this outer housing is composed of 240°K nitrogen gas, provided by a custom LN₂ vaporizer unit. Use of the nitrogen gas maintains the internal temperature of the sphere at a nominal 300 °K \pm 10°.

The calibrated spectral range of the source is 0.4 μ m through 2.4 μ m. Three, color temperature matched, 20 W bulbs together with a 10 W bulb are within the main integrating sphere. Two 20 W bulbs, also color temperature matched, reside in the satellite integrating sphere. A Silicon and a Germanium broadband detector are situated within the inner surface of the main sphere. Their purpose is for the measurement of the internal broadband irradiance. A fiber-optic-coupled spectrometer measures the internal color temperature that is maintained by current control on the lamps. Each lamp is independently operated allowing for radiances with common color temperatures ranging from near 0.026 W/cm²/sr to about 0.1 W/cm²/sr at a wavelength of 0.9 μ m (the location of the peak spectral radiance).

Keywords: calibration, vacuum compatible visible integrating sphere, spectral radiance, uniform source, evaporator system, integrating sphere

1. INTRODUCTION

Los Alamos is developing a Radiometric Calibration Station (RCS) that will support state of the art calibration of moderate-aperture instrumentation having high spatial and thermal resolution. The spectral capability will range from 0.4 to 15 μ m. The configuration of the LANL RCS is shown in Figure 1. The RCS was designed to calibrate radiometers that are to be operated in a vacuum such as ones found onboard satellites. One of the radiometric sources included in this laboratory is a 0.4 μ m - 2.4 μ m (VIS/NIR) extended radiation source nicknamed the "whitebody". The whitebody has been designed to provide an extended diffuse source of 0.4 μ m - 2.4 μ m radiation that can be characterized directly at NIST and used as a secondary standard in a vacuum. The problems inherent with vacuum compatibility, i.e., heat removal and direct calibration difficulty have been largely overcome by this design. This paper addresses the design, manufacture, control system and the calibration of the unit.

2. DESIGN AND MANUFACTURE

The whitebody system is made up of four components, 1) the whitebody itself, 2) a liquid nitrogen (LN₂) vaporizer unit which supplies cool nitrogen gas to remove heat from the light source, 3) a computer control system to monitor and control the previous two items and 4) a vacuum calibration chamber, used only during calibration, that closely simulates the environment that the whitebody will experience when in use. The chamber allows the calibration and operational conditions to be somewhat similar.

2.1. Whitebody

The whitebody, shown in Figure 2, consists of a sphere within a sphere. The inner orb is a modified, commercial, integrating sphere. Purchased from Labsphere, the interior of the sphere is lined with Spectralon. The design goal for the

whitebody included seven discrete levels of calibrated radiance. To accomplish this, the integrating sphere has three 20 W and one 10 W color matched bulbs on the interior surface. There is also a satellite integrating sphere attached to the exterior of the inner sphere. It contains two 20 W bulbs and has a variable positioned stepper-motor-controlled shutter to allow fine adjustments to the whitebody output light level. The satellite sphere can add approximately +/- 1% to the output intensity of the whitebody. Silicon and germanium sensors are installed on the inner wall of the integrating sphere for the purpose of monitoring intensity. A fiber optic cable also penetrates the interior wall to allow sampling of the light by a spectrometer. Four RTD temperature sensors are mounted on the exterior of the inner sphere to monitor the temperature of the inner sphere. The outer sphere acts as a vacuum jacket. The gas pressures contained by the outer sphere are between one and two atmospheres. The inner sphere illumination exits from the 21 cm diameter integrating sphere through a 10.4 cm square fused silica window in the outer vacuum jacket. The heat from the lamps is dissipated convectively through controlled flow of cooled gaseous Nitrogen (GN_2) around and through the inner sphere (see Figure 3). This transfer of internal heat allows the unit to operate at a predefined temperature. The temperature is dependent upon the rate of gas flow, initial temperature of the gas, and the number of lamps being used. The gas flow is directed across the inside of the output window in order to force any heat-induced contaminants to exit through the gas flow port at the back of the sphere housing.

2.1.1. The output level of the white body is controlled by powering the bulbs in the main sphere independently. This coarse power regulation, coupled with the stepper-motor-controlled slide between the main and satellite spheres, allows for precise adjustment of luminance output of the unit up to about $0.1 \text{ W/cm}^2/\text{sr}$ at $0.9 \mu\text{m}$ wavelength (the location of the peak spectral radiance). Spectral monitoring of the internal luminance is accomplished by sending a small portion of the light within the inner sphere to a double linear array spectrometer, outside of the main vacuum chamber, via a fiber optic which has been calibrated for spectral losses. The color temperature of the bulbs can be adjusted by controlling the current to the bulbs. The correction of the internal integrated luminance level would then be accomplished by a small adjustment of the slide shutter between the main and satellite spheres. The integrated signal for this internal luminance would be detected within the integrating sphere using both Silicon and Germanium detectors, allowing for controlled use of this unit through the VIS and NIR wavelengths.

2.1.2. During calibration the whitebody is mounted in a small vacuum chamber as shown in Figure 4. The vacuum chamber allows the whitebody to experience essentially the same thermal conditions that it will experience in RCS tank. One difference between this environment and the future environment in the RCS tank is the atmospheric pressure. In the RCS tank the whitebody will have a vacuum on the outside of the window whereas in the calibration configuration it sees normal atmospheric pressures. This extra pressure differential will cause some distortion to the window. This should have a negligible effect on the radiance calibration, but bench tests to verify this are planned.

2.2. LN_2 vaporizer

The LN_2 vaporizer provides the cooled nitrogen gas used to remove heat from the whitebody. Using LN_2 boil-off helps insure the gas cleanliness and at the same time provides controllable cooled nitrogen gas. An in-line filter is also included just in case impurities do make it into the gas. This arrangement is expected to allow for extended calibration lifetime of the whitebody unit. Figure 5 shows the block diagram for the vaporizer unit. The vaporizer can be seen in the photograph of Figure 7. Incoming LN_2 is fed to a 3 KW heater where it is vaporized. The temperature of the output gaseous nitrogen (GN_2) is measured at the output of the heater and fed to a commercial temperature controller module that controls the duty cycle of the power going to the 3 KW heater. By this method the output gas temperature can be controlled to within a few degrees Centigrade. During the calibration process, the goal was to maintain the temperature sensors on the integrating sphere at room temperature. To accomplish that goal, the set-point on the temperature controller is adjusted manually. The required set-point depended upon the number and type of lamps that were activated in the integrating sphere. The set-point ranged from -33°C , for the condition of all lamps turned on, to 0°C for one lamp. We now have the ability to communicate with the temperature controller so this loop can be closed automatically. The pressure and flow rate of the output gas is controlled by a continuously variable valve. The pressure is measured and sent to a commercial closed loop valve controller and the valve is adjusted to maintain the desired pressure. To prevent an over-pressure condition from rupturing the fused silica window, several over-pressure relief valves are also in the lines.

2.3. Control system

The computer control system block diagram is shown in Figure 6. The states of health of the vaporizer and the whitebody are constantly monitored and displayed. The control system includes a computer running LabView software, a VME based Input/Output Computer (IOC) linked to the computer via a network connection, and a Labsphere controller for the integrating sphere. The computer can be a Sun, Macintosh, or a PC as long as it can run LabView and has an Ethernet connection. The IOC monitors nine temperatures, two light detectors, three pressure sensors, one flow meter, and three valve positions. It also controls the satellite integrating sphere shutter position, the on/off state of six light bulbs, and open/close state of two valves. Each lamp has its own Labsphere precision power supply with manual current control capability.

The Sun host computer runs a LabView program that acts as the human interface for the control system. Our host computer was a Sun but it could just as well have been a PC or a Mac (any machine that can run LabView and make connections to a TCP/IP socket). The LabView program has a graphical user interface (GUI) and makes data and command requests to the network socket known to the IOC. It then plots the data and updates the system graphical display. Figure 8 shows the whitebody control panel. The IOC software is written in an object-oriented, C++, language. It is running on a VxWorks real-time operating system. The IOC software monitors the TCP/IP socket to receive commands from the LabView program. It then returns the data or results over the same socket connection.

2.4. Calibration vacuum chamber

The calibration vacuum chamber is also shown in Figure 7. The chamber is just large enough to encompass the whitebody and its associated cabling and tubing. There is a circular opening on the vacuum chamber where the window flange bolts to the whitebody. A circular o-ring lying between the vacuum chamber surface and the whitebody window flange, seals the opening. The chamber also has a signal port and a vacuum pump-down port.

3. NIST CALIBRATION

3.1. The primary calibration exercise took place at NIST in the Low Level Radiance Facility (LLR) in November 1996 and February 1997. The November calibration calibrated the whitebody at wavelengths between 400 and 900 nm. The February calibration calibrated the system at wavelengths between 800 and 2400 nm. Two calibrations were performed: 1) a spectral radiance measurement and 2) a spatial uniformity mapping across the exit port. Both calibrations were done for every combination of the 15 possible bulb states for each of two whitebodies. We experimented with stabilizing the light intensity by using the output of the silicon detector to make closed-loop adjustments to the satellite sphere shutter but we found that there seemed to be a correlation between the temperature of the shell and the light intensity as measured by the detector. We did not want to make the light intensity a function of the cooling gas temperature so we set the shutter at the midpoint and left it there. The low frequency light fluctuation was not large enough to give us concern and it seemed to be about the same magnitude with or without the closed loop control. Also, in all cases, lamp 5, one of the two lamps in the satellite sphere, was powered on continuously. In one case all of the lamps were on, including lamp 6 in the satellite sphere, so that a comparison to the initial Labsphere calibration could be made. All lamps were operated at the current specified for each individual lamp by the manufacturer. During the calibration exercise, the light leaving the exit port of the whitebody exited into normal atmospheric conditions. The nominal environmental condition of the laboratory was a temperature of approximately 23° C and a humidity of about 60%.

3.2. Spectral Radiance Calibration - The LLR monochromator is a 0.67 m (f4.7) scanning monochromator equipped with a prism predisperser and 600 groove per mm gratings. The monochromator has a wavelength repeatability and uncertainty of less than 0.05 nm from 200 nm to 2500 nm. The monochromator is equipped with a 500 nm blazed grating and a silicon detector in the 400 nm to 900 nm spectral region and with a 1000 nm blazed grating and a liquid nitrogen cooled indium antimonide detector with lock-in amplifier for the 1000 nm to 2400 nm spectral region. The calibration was performed for a rectangular target area 2 mm wide by 2 mm high located at the center of the exit port. The slit width of the spectroradiometer was 2mm for an approximate bandpass of 5 nm.⁴

3.3. Uniformity Mapping - Detailed mappings of the exit port spectral radiance were performed at a wavelength of 700 nm. The mapping included a 40 mm by 40 mm square grid about the center of the exit port. There was an 8 mm spacing between the sample points. For each point of the mapping, the signal from the silicon detector was recorded with the radiation from the exit port blocked from and then allowed through the monochromator. The center of the exit port was

measured after each scan in the horizontal direction. The repeated measurements on the center of the exit point give a measure for the stability and drift of the sphere source under test.⁴

3.4 Calibration Results - The results of the NIST calibration are found in the NIST final report.⁴ The sources of uncertainty, and their corresponding 2σ values (%), in the determination of the spectral radiance are given in Table 1. The resultant plots for the spectral radiance calibration for NIST are shown in Figure 9 for sphere 1 and Figure 10 for sphere 2. A representative uniformity plot is shown in Figure 11.

4. COMPARISONS WITH PREVIOUS CALIBRATIONS.

4.1. The inner spheres were initially calibrated for spectral radiance, angular uniformity, and correlated color temperature by the manufacturing vendor, Labsphere, prior to their insertion into the temperature controlled gaseous nitrogen environment vacuum jackets. The fused silica windows were provided to Labsphere to incorporate into their calibration exercises with the placement closely documented and replicated at all further stages of assembly. The spheres were operated at tabletop ambient conditions.

4.2. The color temperatures of the lamps were balanced independently of one another using a Labsphere calibrated diode array spectrometer referenced to a 1000 W FEL type tungsten spectral irradiance standard. A fifteen minute warm-up period is incorporated into these tests to allow for current settings for each lamp to result in a 2900K color temperature. The lamps for use in the spheres, as well as backup lamps, were each current calibrated for use at this color temperature.

4.3. The spectral radiance calibration for each of the two integrating spheres purchased from Labsphere was performed by a stationary detector (a scanning dispersive spectroradiometer) positioned at the center of the exit port aperture, tilted at 14 degrees to the plane of the port/window. This is the angle viewed along the chief ray of the RCS collimator optics. The readings were referenced against a diffuse Spectralon reflector (the same material coating the internal surface of the integrating sphere) irradiated by a tungsten halogen lamp standard. All integrating sphere lamps were on simultaneously for this test. The satellite sphere aperture was open to the halfway position. The total 3σ uncertainty predicted for these measurements varied only slightly through the visible/NIR region (0.3 to 1.1 microns wavelength) averaging about 2.4%, but rose significantly as the wavelength increased to 2.4 microns, peaking at 9%. The spectral radiance results for sphere 1 as compared to the NIST results are shown in Figure 12.

4.4 The angular uniformity mapping of each of the spheres was performed using a 0.4 degree FOV custom radiance meter translated in two axes in front of the exit port under test. The calibrations were performed at four angles relative to the normal to the exit port/window; 0, 4, 14, and 24 degrees. All integrating sphere lamps were on simultaneously for this test, with the satellite sphere aperture open halfway. The spectral sensitivity of the radiance measuring device follows that of a typical silicon detector. The uniformity measurements across the exit port from both Labsphere and NIST compared reasonably. A point by point comparison showed that the values were within a 1% of each other for both spheres.

5. CONCLUSIONS

5.1. We have been able to successfully design, assemble and calibrate two vacuum compatible diffuse source integrating spheres. When in a vacuum environment, the internal temperature of the spheres can be moderately controlled by means of cooled enclosed nitrogen gas that acts as the heat transfer medium. The sources have been calibrated at NIST both spectrally and spatially across its fused silica output window for each of the 15 combinations of its four lamps.

5.2. Data comparisons between the spectral radiance measurements taken initially at Labsphere and later at NIST show that the Labsphere measurements were consistently higher. The offset is somewhat constant over the full spectrum, leading one to suspect some systematic error between the two methodologies. The percentage error climbs dramatically in the low light level areas of the spectrum, causing concern over the sensitivities involved in collecting that data. The percentage errors shown in Figure 13, describe the most favorable comparison available between NIST and Labsphere data, using the lower end of the Labsphere uncertainty span with the high end of the NIST uncertainty span. Sphere 1 shows the

closest comparison in the high radiance region of the spectrum, with errors (negative values on the graph indicate possible overlap of the data) less than 2% from 700-2100 nm. The visible region discrepancies range from 2-22% higher than the NIST data, with the higher errors in the lower spectral regions, and the IR regions rise to as high as 4% discrepancy at 2400 nm. Sphere 2 is considerably worse when compared to the NIST spectral radiance measurements of that sphere, having 7% or less discrepancy between 600-1550 nm, 10% or less between 500-2000 nm, as high as 37% at 2400 nm, and 26% at 400 nm.

5.3. The cause of the calibration discrepancies is unknown at this time. The spheres, once encased within the vacuum jackets, as was done during the NIST calibrations, are kept at a constant temperature. When run outside of the jackets, as was done initially at Labsphere, the temperature inside the sphere may have been somewhat higher. The sphere 2 error plot would lead one to believe that this might have been the cause, but the sphere 1 data refutes that scenario. Pressure on the window was non-existent during the Labsphere calibrations, but may have risen to as much as a 1 atm delta across the window during the NIST calibrations due to the forced nitrogen flow. The effects of this bowing are considered to be small, but the experiment has yet to be performed to verify that. Currents to the lamps have been kept at the Labsphere prescribed values, and no disassembly of the unit has been performed. Investigations will continue to resolve these discrepancies.

6. ACKNOWLEDGEMENTS

We acknowledge E. Ambler Thompson and Edward A. Early of the National Institute of Standards and Technology for their work on the calibration and the analysis of the calibration data. Michael L Feind contributed by making the cryo system function properly. William T. Kornke and Terrence W. Lyons spent many hours solving electrical and mechanical problems. Allen Luetgen wrote the C interface software for the VME crate. Cynthia K. Little assisted in data analysis. The vaporizer was purchased from Cryogenic Experts, Inc. of Simi Valley, California and Cryofab of Kenilworth, NJ.

7. REFERENCES

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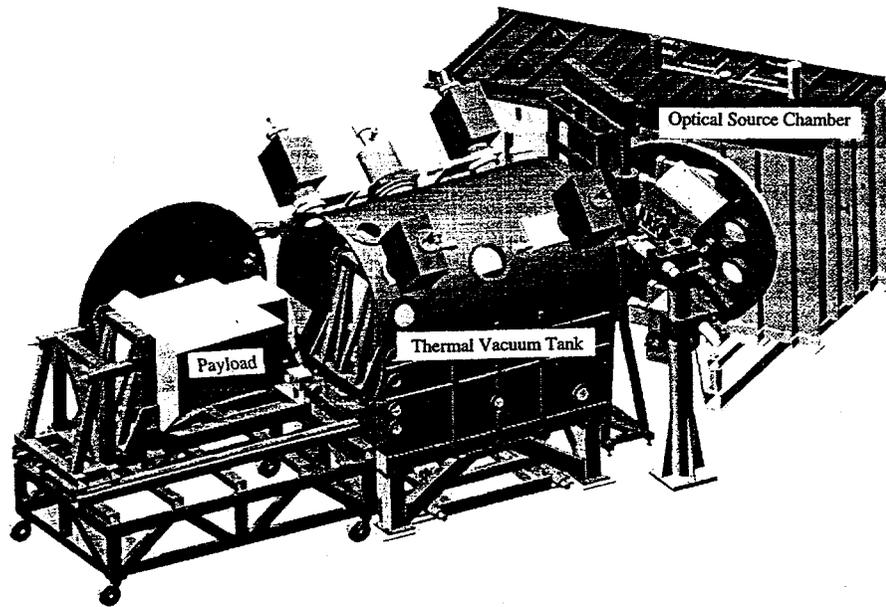


Fig. 1. Radiometric Calibration Station Configuration

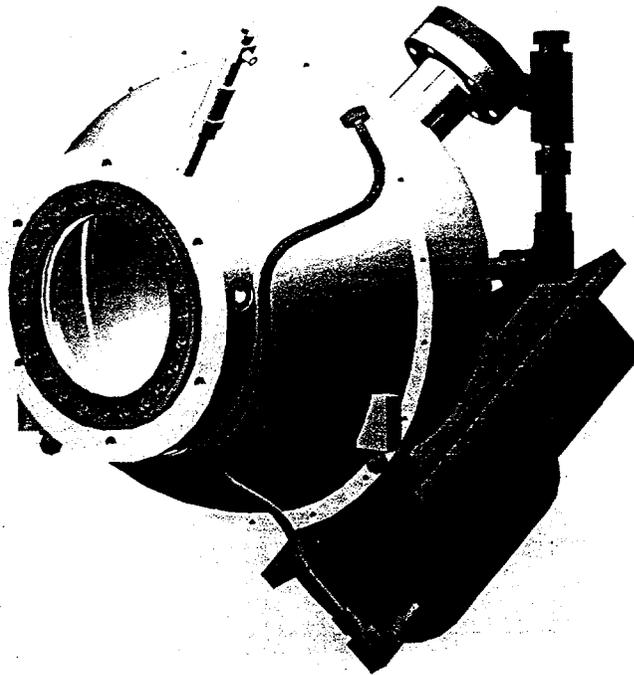


Fig. 2. Whitebody Hardware

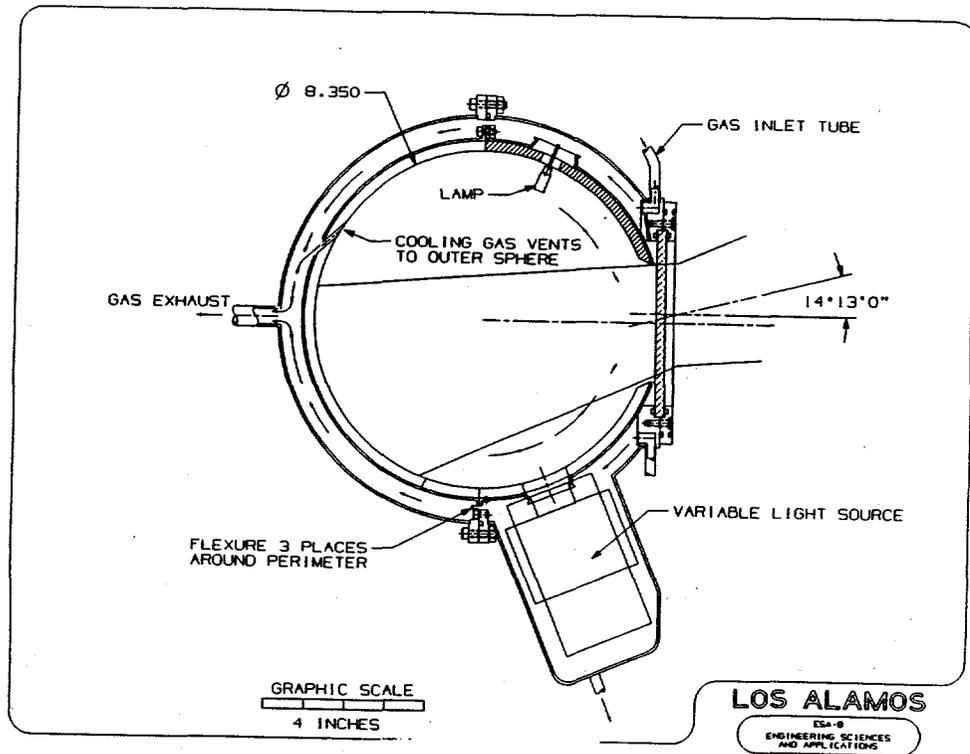


Fig. 3. View of Whitebody showing airflow

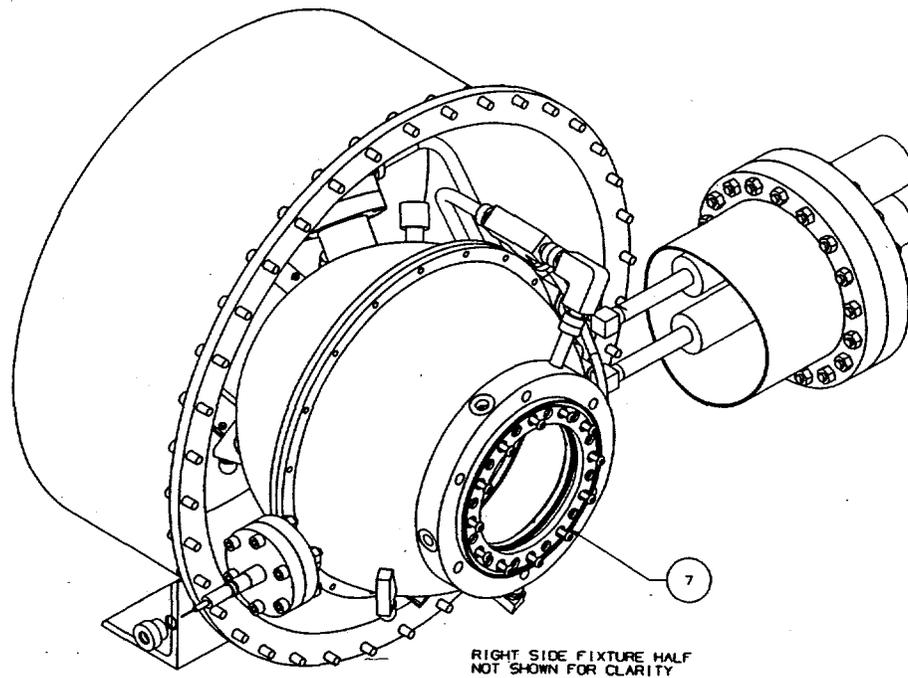


Fig. 4. View of Whitebody mounted in the Vacuum Chamber

Integrating Sphere Atmospheric Flow Controller

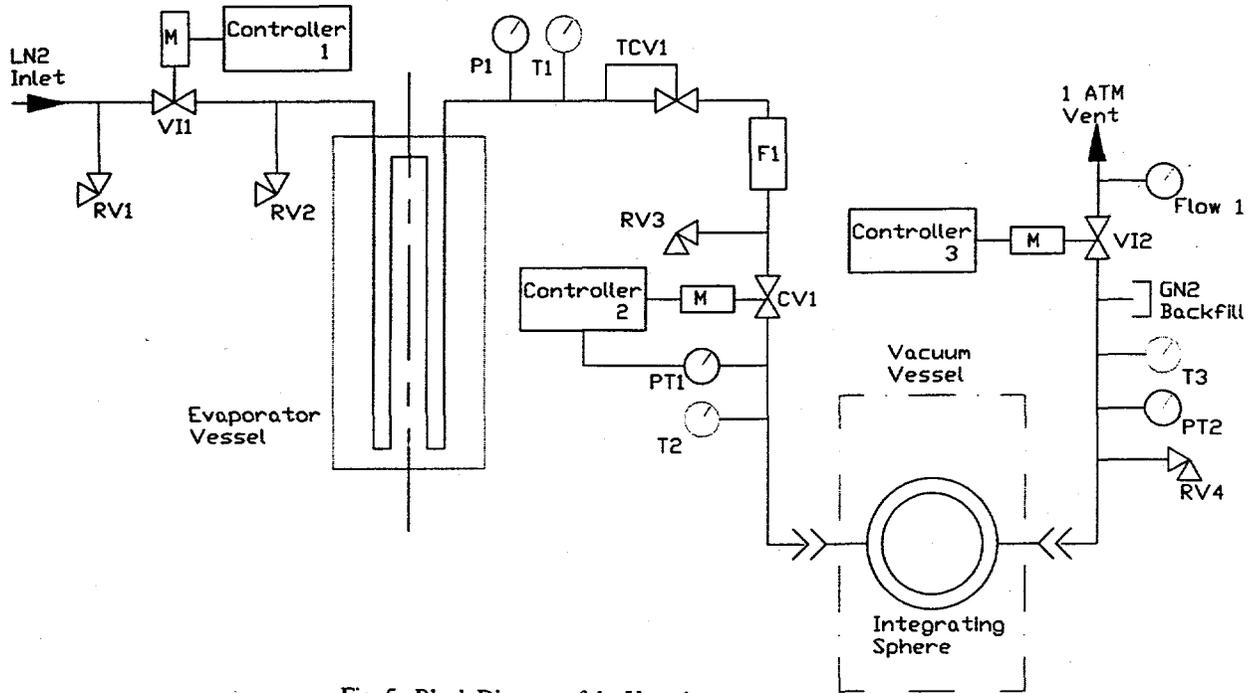


Fig. 5. Block Diagram of the Vaporizer

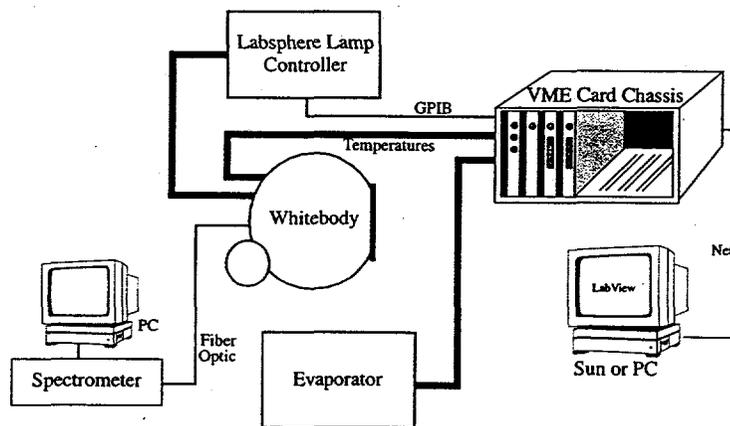
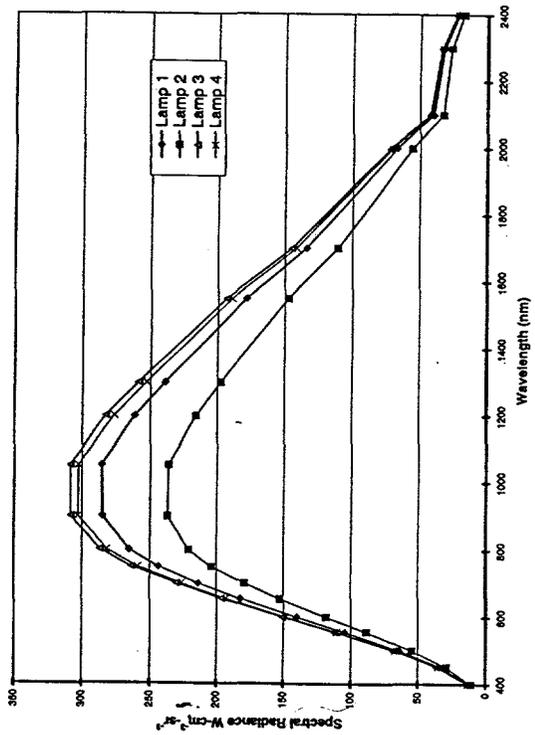
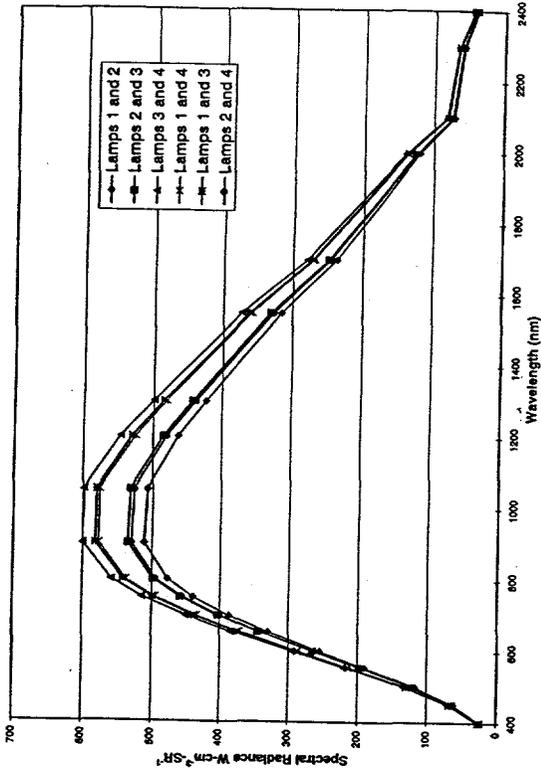


Figure 6 - Whitebody Computer Control System Block Diagram

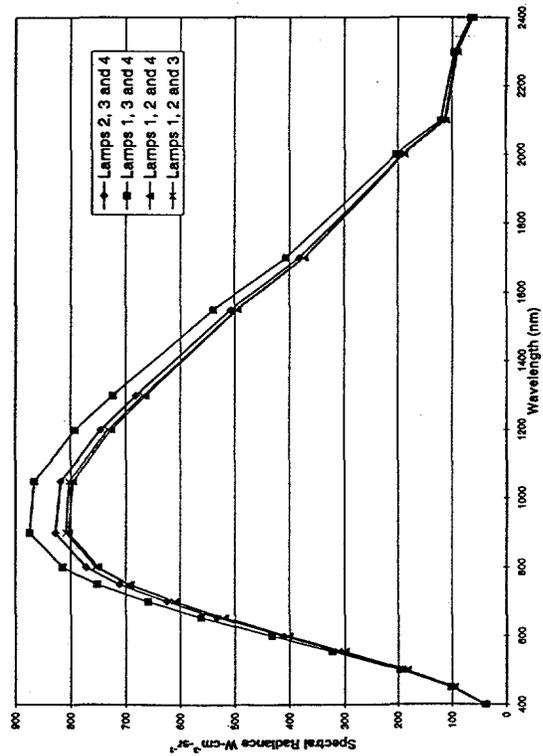
Whitebody Sphere#1 Spectral Radiance for Single Lamp Combinations



Whitebody Sphere #1 - Spectral Radiance for Two Lamp Combinations



Whitebody Sphere #1 Spectral Radiance for Three Lamp Combinations



Whitebody Sphere#1 Spectral Radiance for All Four Lamps

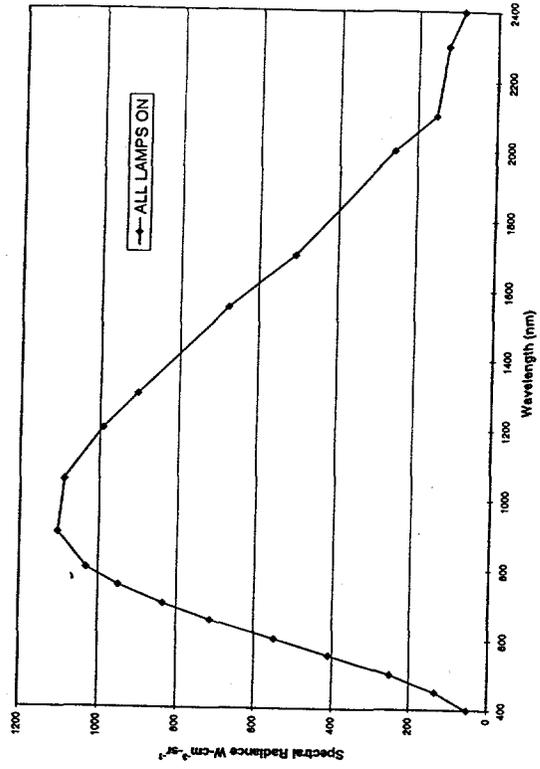
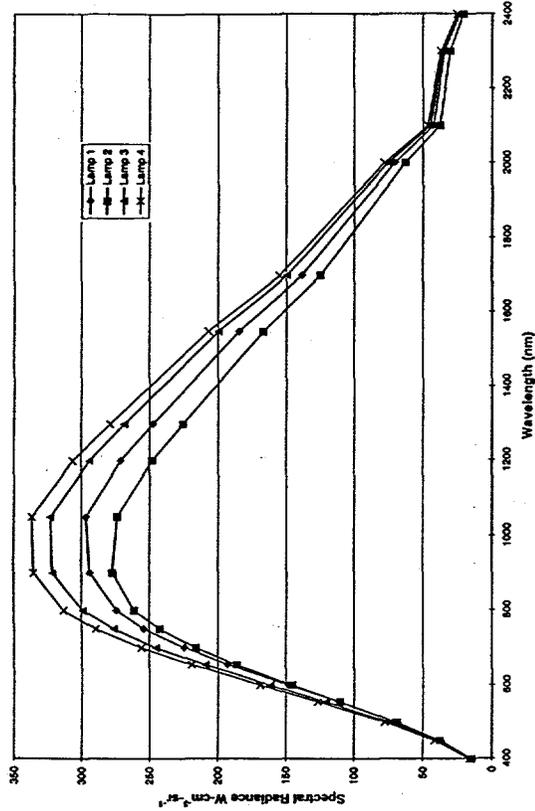
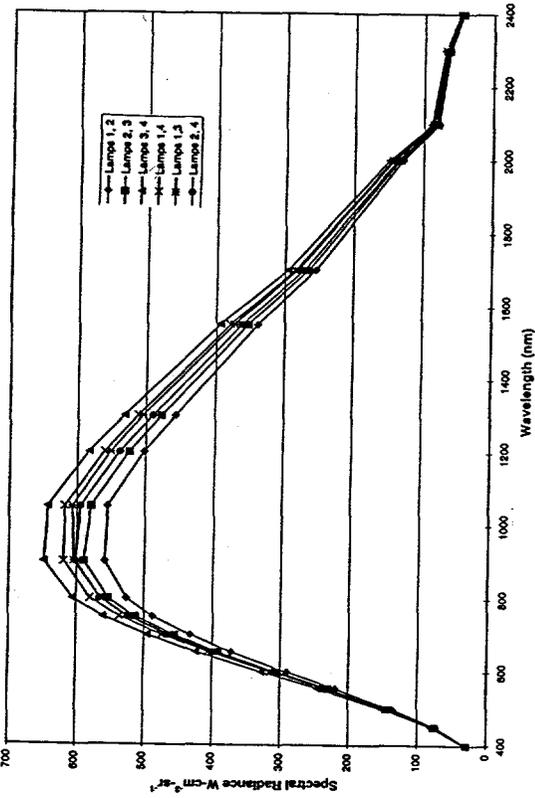


Figure 9 - NIST Spectral Radiance Plots for Sphere #1

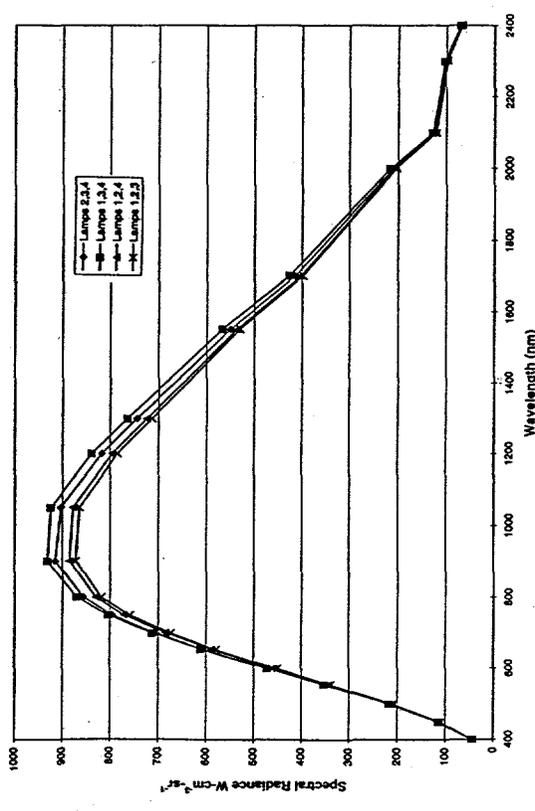
Whitebody Sphere#2 - Spectral Radiance for One Lamp Combinations



Whitebody Sphere#2 - Spectral Radiance for Two Lamp Combinations



Whitebody Sphere #2 - Spectral Radiance for Three Lamp Combinations



Whitebody Sphere #2 - Spectral Radiance for All Lamps

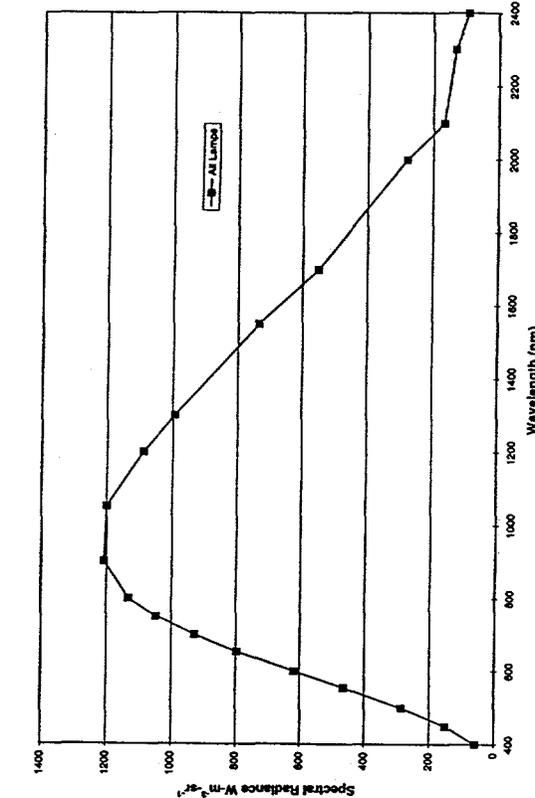


Figure 10 - NIST Spectral Radiance Plots for Sphere #2

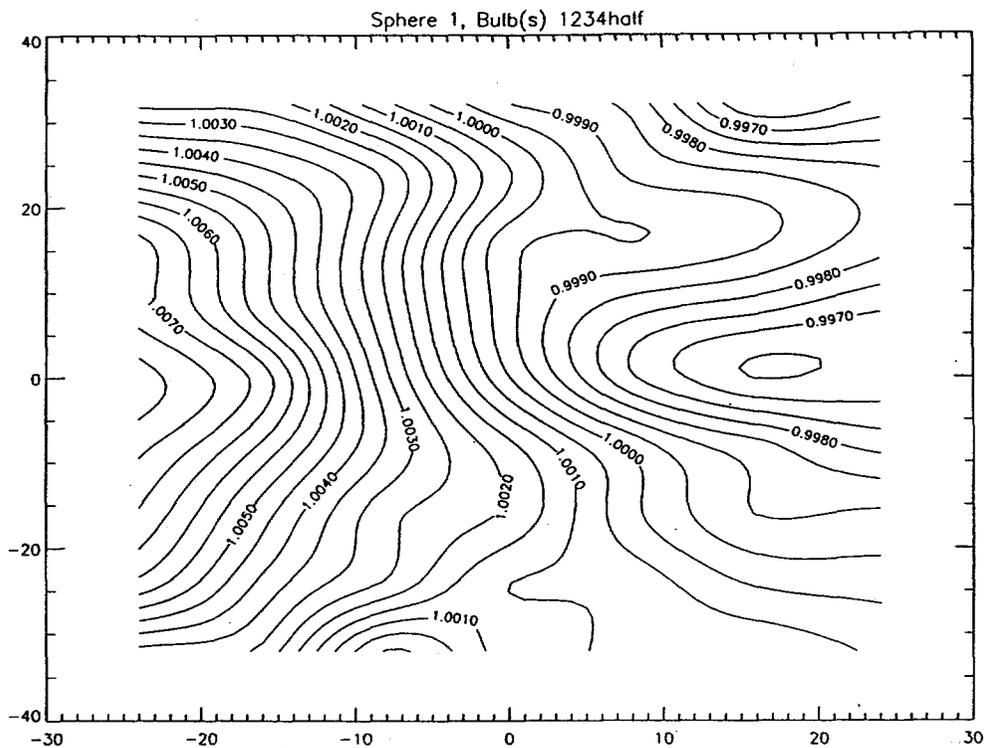


Figure 11 - Typical NIST Uniformity Measurement Plot

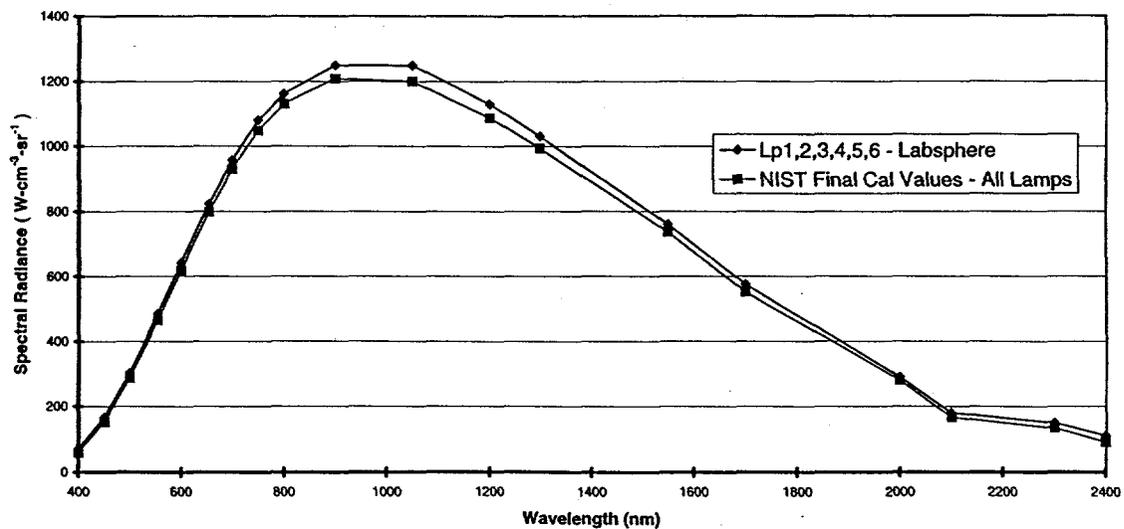


Fig. 12 - Spectral Radiance NIST vs Labsphere Comparison Plot (Sphere 2)

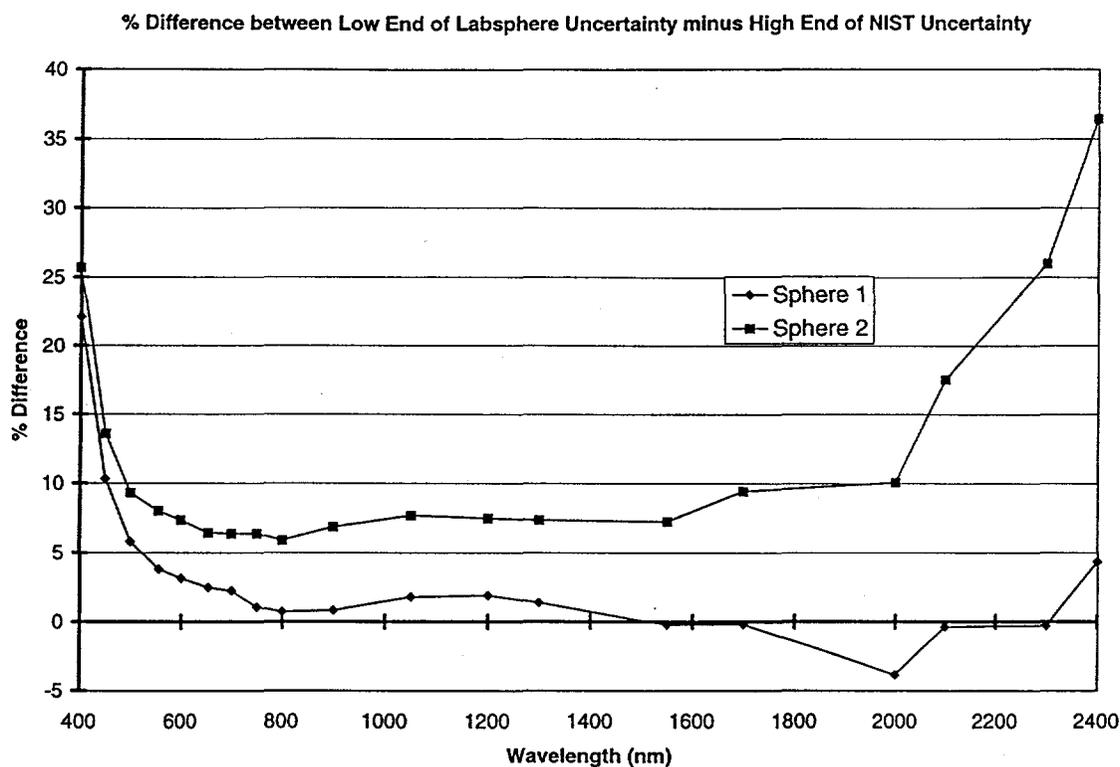


Figure 13 - NIST vs Labsphere Comparison % Difference Plot

Table 1 -NIST Spectral Radiance Calibration Relative Expanded Uncertainties

Source of Uncertainty	Type	Relative Expanded Uncertainties [%]				
		400 nm	654.6 nm	900 nm	1550 nm	2400 nm
1. Blackbody Quality	B	0.07	0.00	0.03	0.06	0.07
2. Calibration of the reference radiance temperature lamp relative to the 1990 NIST Radiance Temperature Scale	B	0.27	0.16	0.11	0.07	0.05
3. Temperature determination of blackbody and transfer of blackbody spectral radiance to secondary standard sphere source	A	1.02	0.71	0.64	0.52	3.8
4. Wavelength Measurement	B	0.10	0.05	0.04	0.02	0.01
5. 1990 NIST Radiance Temperature Scale	B	0.46	0.28	0.20	0.12	0.07
6. Spectral radiance transfer secondary standard sphere source to test sphere source	A	0.30	0.32	0.18	0.45	1.0
	B	0.2	0.2	0.2	0.46	0.46
Relative expanded uncertainty $U = ku_c(L_u)$, where $k = 2$		1.21	0.86	0.73	0.84	3.95