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SeaWiFS Technical Report Series

Stanford B. Hooker, Elaine R. Firestone, and James G. Acker, Editors

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Abstract

This report presents results of the third Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Intercalibration Round-Robin Experiment (SIRREX-3), which was held at the San Diego State University (SDSU) Center for Hydro-Optics and Remote Sensing (CHORS) on 19–30 September 1994. Spectral irradiances of FEL lamps belonging to each participant were intercompared by reference to the National Institute of Standards and Technology (NIST) scale of spectral irradiance using secondary standard lamps F268, F269, and F182, with a Type A relative standard uncertainty between 1.1–1.5%. This level of uncertainty was achieved despite difficulties with lamp F269. The average spectral irradiances of FEL lamps, compared in both SIRREX-2 and SIRREX-3, differed between the two experiments by 1.5%, which probably indicates that the values assigned to the secondary standard lamp at the time of SIRREX-2 were in error. With two exceptions, spectral radiance values of integrating sphere sources were measured during SIRREX-3 with relative standard uncertainties due to temporal stability of less than 0.3% and overall relative standard uncertainties of 1.5–2%. This is a significant improvement over similar intercomparisons in SIRREX-1 and SIRREX-2. Plaque reflectances were intercompared with a relative standard uncertainty of about 1–2%, but the overall uncertainty is undetermined. Although this is an improvement over results of previous SIRREXs, the sources and magnitude of uncertainty associated with transfers of spectral radiance using plaques requires further evaluation in future experiments.

1. INTRODUCTION

The Sea-viewing Wide Field-of-View Sensor (SeaWiFS) ocean color radiometer is now rescheduled to be launched in late 1995 and operated in a sun-synchronous orbit for five years. The National Aeronautics and Space Administration (NASA) will carry out a program to acquire the global SeaWiFS data set, validate and monitor its accuracy and quality, process the radiometric data into geophysical units, and distribute it to the scientific community.

The SeaWiFS Project has set two important goals regarding the use of SeaWiFS radiance measurements. The first goal is the determination of normalized water-leaving radiance with an uncertainty† of 5%; the second is the determination of chlorophyll *a* concentration with an uncertainty of 35%. (All uncertainties are expressed as one standard deviation, 1σ, unless otherwise noted.) These goals are very ambitious. They can only be achieved by augmenting the SeaWiFS imagery with *in situ* measurements. The measurements will be used to:

1) Verify the radiometric uncertainty and long-term stability of the SeaWiFS instrument's radiance responsivities; and
2) Validate the atmospheric correction models and algorithms used to convert SeaWiFS radiances to normalized water-leaving radiances.

One of the principal approaches to this critical aspect of validation will be frequent direct comparisons between SeaWiFS estimates and *in situ* measurements of water-leaving radiance. Because the primary goal is to demonstrate that normalized water-leaving radiances derived from SeaWiFS data have uncertainties of less than 5%, the comparative *in situ* radiometric measurements must be calibrated to an uncertainty of less than 5%. The 5% uncertainty goal for SeaWiFS water-leaving radiance determinations was recommended by the SeaWiFS Prelaunch Science Working Group, based in part on Gordon (1990).

The goal of the SeaWiFS Intercalibration Round-Robin Experiments (SIRREXs) is to reduce the uncertainty in the calibration of the instruments to a level that is negligible relative to the uncertainties associated with radiometric measurements in the field, such as the effects of wave focusing, stratification in the water column, etc. Overall uncertainties on the order of 1% for the spectroradiometric values of the calibration sources (standard irradiance lamps, integrating sphere sources, and illuminated plaques) and well-characterized, stable, oceanographic instruments are necessary to meet this goal. Progress is being made to meet this goal, but there is still work to be done.

The only economic approach to acquiring a large and globally distributed sample of *in situ* radiometric measurements for SeaWiFS validation is to solicit contributions of data from the oceanographic community at large. This aggregate data set must be of uniform quality and have uncertainties of less than 5%. The SeaWiFS Project at NASA's Goddard Space Flight Center (GSFC) is addressing this problem through the SeaWiFS Calibration and Validation Program (McClain et al. 1992). At the outset, the Project sponsored a workshop to draft protocols for ocean optics measurements to support SeaWiFS validation (Mueller and Austin 1995). The protocols include instrument performance specifications, and requirements for instrument characterization and calibration.

† In this publication, the term *uncertainty* used by itself, always means *relative standard uncertainty*.

Of the oceanographers and institutions who are expected to contribute ocean radiometric measurements to the SeaWiFS validation database, only a few are equipped to calibrate and characterize radiometric instruments. Personnel at the following laboratories are currently engaged in at least some aspects of the characterization and calibration of oceanographic radiometers:

1) GSFC;
2) Center for Hydro-Optics and Remote Sensing (CHORS) at San Diego State University (SDSU);
3) University of Miami (UM);
4) University of California at Santa Barbara (UCSB);
5) University of Arizona (UA);
6) Moss Landing Marine Laboratory (MLML), in collaboration with Dennis Clark of the National Oceanic and Atmospheric Administration (NOAA); and
7) The manufacturers of various instruments, including Biospherical Instruments, Inc. (BSI) and EG&G Gamma Scientific† both in San Diego, California.

The SeaWiFS instrument was characterized and calibrated by its manufacturer, the Santa Barbara Research Center (SBRC).

The strategy adopted for SeaWiFS validation is to calibrate all involved instruments within the network that consists of these (and possibly a few additional) laboratories. In recognition of the need to maintain consistency between calibrations of *in situ* instruments and that of the SeaWiFS instrument itself, the SeaWiFS Project, under the Calibration and Validation Program, has implemented an ongoing series of SIRREXs. The purpose of this program is to provide quality assurance and uncertainties for transfers of the National Institute of Standards and Technology (NIST) scales of spectral irradiance and radiance, through GSFC, to all participating laboratories in the SeaWiFS community.

The original objectives of the SIRREX series are to:

a) Intercompare working standard lamps of spectral irradiance (1000 W type FEL lamps) used at the participating laboratories, and to reference each to the NIST scale of spectral irradiance via a secondary standard to be maintained at GSFC;
b) Intercompare integrating sphere sources of spectral radiance used at the various laboratories;
c) Intercompare plaques used to transfer the scale of spectral irradiance from an FEL lamp to a scale of spectral radiance; and
d) Intercompare transfer radiometers and other types of support electronics, most critically shunts and voltmeters, used to support radiometric calibrations at each laboratory.

† Up to and including the period when SIRREX-3 took place, the company's name was EG&G Gamma Scientific. Subsequent to SIRREX-3, the EG&G prefix was dropped and the name was changed to Gamma Scientific; however, for the purpose of clarity, the company will be referred to EG&G throughout this document.

The first three intercomparison experiments were held at SDSU CHORS in San Diego. SIRREX-1 was held on 27–31 July 1992 (Mueller 1993), SIRREX-2 was held on 14–25 June 1993 (Mueller et al. 1994), and SIRREX-3 was held on 19–30 September 1994.

This report documents SIRREX-3 results for lamps, spheres, plaques, voltmeters, and shunts.

i. *Lamps:* The report covers the transfer and intercomparisons of the NIST August 1994 (8/94) spectral irradiance values of FEL lamps F269 and F268 to lamps that belong to the participating laboratories, using an Optronic Laboratories, Inc. (OL)‡ 746 spectroradiometer with an integrating sphere irradiance collector (the 746/ISIC).
ii. *Spheres:* The report also discusses the transfers and intercomparisons of radiance values between integrating sphere sources belonging to GSFC, BSI, CHORS, UCSB, UA, and MLML. The spectral irradiance values (from 8/94) of lamps F268 and F269 were used as the basis for calibrating several of the spheres using the 746/ISIC. The SeaWiFS transfer radiometer (SXR) was independently calibrated at NIST as a basis for transfers of spectral radiance at specific wavelengths. Radiance measurements of each sphere were also made with the UA transfer radiometer (UAXR) and the CHORS transfer radiometer (CXR), based on the calibrations of these instruments using the GSFC sphere.
iii. *Plaques:* Approximate (0°,45°) reflectance measurements were made using the SXR and CXR for several Spectralon™ plaques§ that were used to convert a lamp's spectral irradiance to diffuse spectral radiance.
iv. *Voltmeters and shunts:* Finally, this report also discusses the intercomparison of several voltmeters and shunts.

Conventions used for names, formats, and headers in the data files comprising the SIRREX-3 data set are given in Hooker et al. (1994). The organizations and individuals who participated in SIRREX-3, along with their respective instruments, are listed in Appendices A and C.

2. LAMP STANDARDS

All of the participating laboratories base absolute calibrations of instrument responsivities (except for the SXR)

‡ Certain commercial equipment, instruments, or materials are identified in this paper for clarity. Such identification does not imply recommendation or endorsement by NIST, NASA, CHORS, the UA, or any other institution mentioned in this paper. Furthermore, it also does not imply that the materials or equipment identified are necessarily the best available for the described purpose.

§ *Spectralon* is a registered trademark of Labsphere, Inc., P.O. Box 70, North Sutton, NH 03260.

for irradiance on the NIST scale of spectral irradiance, which is usually transferred to the scientific and engineering community in the US via calibrated tungsten-halogen lamps, usually FEL lamps, and less frequently DXW lamps (Walker et al. 1987a). Some laboratories acquire a calibrated FEL lamp secondary standard of spectral irradiance directly from NIST, but more typically, a laboratory will base its irradiance scale on a working standard lamp that has been calibrated and certified as traceable to the NIST scale by a commercial standardizing laboratory. In all cases, a laboratory will purchase additional lamps that are seasoned, but uncalibrated. Using a transfer radiometer, the spectral irradiance of their local standard reference lamp will be transferred to these less expensive lamps. These tertiary standards are then used for ordinary calibration experiments to avoid building up hours on, and expending the useful working life of, the local standard reference lamp.

A laboratory will periodically intercompare all of their working standard lamps and their standard reference lamps to maintain an internally consistent scale of spectral irradiance. Intercomparison also serves to detect cases when a lamp either starts becoming unstable, or to otherwise fail in a subtle way, because a lamp usually becomes an unreliable source of spectral irradiance long before it burns out. The first objective of the SIRREX program, i.e., intercomparison of irradiance lamps, extends this maintenance of internal consistency throughout the several laboratories participating in the calibration of the instruments for SeaWiFS validation. If a problem is observed and attributed to the assigned value for the lamp (as opposed to the transfer at the SIRREX), then the laboratory is responsible for examining their irradiance scale and for implementing the necessary solution.

2.1 Methods

Transfer of the F269 and F268 values of spectral irradiance to other lamps in SIRREX-3 follows the procedures for spectral irradiance calibrations described in Walker et al. (1987a). A small ISIC is attached, at its exit port, to the entrance slit of an OL 746 spectroradiometer (a single-monochromator based radiometer system with a silicon detector). This spectroradiometer is equipped with an internal chopper, so that background (or *dark*) signals are removed. For both SIRREX-2 and -3, the 746/ISIC was configured with a blazed grating yielding a usable spectral range of measurements extending from 350–1000 nm (in SIRREX-1, a different grating limited measurements to wavelengths greater than 400 nm).

During and after SIRREX-1, it was discovered that the spectral responsivity of the 746/ISIC drifted over time, and that the rate of drift was especially rapid and erratic during the first 2 hours of operation (Mueller 1993). For SIRREX-2 and -3 measurements, therefore, the 746/ISIC system was powered on the previous evening, when possible, which allowed it to stabilize overnight prior to its use in irradiance measurements. Furthermore, system responsivity was recalibrated at intervals of 2 hours or less during experiments. For some of the measurements of the integrating sphere sources (Section 3), the warm-up interval for the 746/ISIC may have been less than 12 hours.

The process of transferring the NIST irradiance scale from the secondary standard lamp, F269 or F268, to an unknown lamp began by mounting one of these lamps to illuminate the entrance aperture of the 746/ISIC. The instrument was placed normal to the center of the lamp filament at a distance of 50 cm, measured by convention to the front surface of the lamp's electrical connection posts. The lamp was powered on and allowed to warm up for approximately 20 minutes. The irradiance responsivity of the 746/ISIC was determined by measuring the known spectral irradiance output from lamp F269 (or F268). The calibrated responsivity of the 746/ISIC was then used to measure the spectral irradiance of a set of lamps. The first measurement was always made immediately on the secondary standard lamp (i.e., F269, F268, or F182) to provide an initial measure of the transfer uncertainty. Each lamp was then powered down and replaced by the next lamp to be calibrated, which was then allowed to warm up for approximately 15 minutes before its spectral irradiance output was measured with the 746/ISIC. This procedure was repeated until all lamps were calibrated (see Table 1).

At approximately 2-hour intervals, and near the end of each transfer session, the secondary standard lamp was measured again to estimate the rate of drift of the radiometer's responsivity through the duration of the entire procedure. In the analysis of the 746/ISIC lamp transfer data for SIRREX-3, the spectral responsivity of the 746/ISIC was adjusted (by linear interpolation between bracketing secondary standard lamp measurements) to provide the corresponding spectral responsivity at the start time of each lamp transfer. The stability of the secondary standard lamps were tested by intercomparing them to each other using data taken near the beginning and end of the entire sequence. The typical correction for drift was between 1% and 5%.

During SIRREX-3, the spectral irradiance values of GSFC's FEL lamps F269 and F268 were transferred to other FEL lamps belonging to the various participating laboratories. The irradiances of F269, F268, and F182 were recalibrated by NIST in August 1994 (the 8/94 values), to provide a recent NIST-traceable set of secondary standards as the basis for source intercalibration during SIRREX-3. The lamp irradiance measurement transfers were carried out, using F269 as the reference standard lamp, on 20 and 21 September 1994. Unfortunately, the irradiance of F269 decreased abruptly at some time during the series of measurements on 21 September (see below). To salvage the bulk of these transfers, on 28 September 1994 the NIST (8/94) values for F268 were transferred to

Table 1. Schedule of FEL lamp transfers during SIRREX-3. The dates are for September 1995.

Date	*Time* [PDT]	*Lamp ID*	*Current* [A]	*Owner*
20	0918	F269	8.0007	GSFC
20	0958	F268	8.0007	GSFC
20	1038	F315	8.0006	GSFC
20	1111	F297	8.0006	UA
20	1140	F296	8.0008	UA
20	1209	F269	8.0006	GSFC
20	1240	H91795	8.0008	UM
20	1310	F12G	7.9063	UM
20	1352	H91537	7.9011	BSI
20	1421	F269	8.0008	GSFC
20	1450	F321	7.9001	BSI
20	1517	F305	8.0009	UCSB
20	1548	F304	8.0007	UCSB
20	1615	F269	8.0009	GSFC
20	1650	F182	7.9003	GSFC
20	1718	F123	7.9002	NRIFSF
20	1748	F269	8.0009	GSFC
21	0859	F269	8.0000	GSFC
21	0927	F303	8.0000	UCSB
21	0955	H91534	8.0006	CHORS
21	1024	H91738	8.0007	CHORS
21	1054	F269	8.0008	GSFC
21	1123	H91739	8.0008	CHORS
21	1155	H90573	8.0009	CHORS
21	1225	F307	8.0009	NOAA
21	1258	F269	8.0007	GSFC
21	1326	F308	8.0011	NOAA
21	1358	H90572	7.1080	CHORS
21	1434	GS922	8.0009	NOAA
21	1506	F269	8.0008	GSFC
21	1536	H91348	7.6562	CHORS
21	1611	H91349	7.6563	CHORS
21	1640	F268	8.0010	GSFC
21	1710	F269	8.0010	GSFC
26	1150	F269	8.0001	GSFC
26	1226	F268	8.0001	GSFC
26	1300	F182	7.9000	GSFC
26	1334	F269	8.0001	GSFC
28	1412	F268	8.0001	GSFC
28	1441	H91534	8.0001	CHORS
28	1513	H90573	8.0003	CHORS
28	1543	F308	8.0003	NOAA
28	1611	H91349	7.6564	CHORS
28	1641	F268	8.0001	GSFC
28	1711	F269	8.0003	GSFC

four of the lamps which were distributed at 1–2 hour intervals during the 21 September transfer series. These four lamps were then used, together with F268, to transfer the NIST scale of spectral irradiance (8/94 F268 values) to the other seven lamps measured on 21 September.

2.2 Results

Lamps F269, F268, and F182 (all belonging to GSFC) were recalibrated by NIST in August 1994. The NIST values of F269 from October 1992 (the 10/92 F269 values) and August 1994 are compared in Fig. 1. The deviations (or relative changes) that are plotted in the figures are calculated according to the expression $(v-r)/r$, where r represents the reference data and v (for value) represents the data that is being compared to the reference data. In some cases, the factor 1 has been added to the deviation and is plotted; in still other cases the deviation is expressed in percent. The spectral irradiance at an arbitrary wavelength was determined by fitting the NIST calibration data intervals using the method of Saunders and Shumaker (1977) to produce tables of spectral irradiance ($\mu\,\mathrm{W\,cm^{-2}\,nm^{-1}}$) at wavelength intervals of 5 nm. For convenience in interpolating the 5 nm spectral irradiance tables to intermediate wavelengths, the tabulated values were fit to cubic polynomials over 50 nm intervals using a least-squares technique. This secondary fit was needed because the coefficients of the original fitted functions (in the form introduced by Saunders and Shumaker 1977) were not available during the data analysis.

During the FEL lamp irradiance transfers from F269 on 21 Sept 1994 (at SIRREX-3), F269 experienced a sudden downward shift of approximately −1.5 to +2% in spectral irradiance output (see below). These shifted F269 spectral irradiance data, which were illustrated in Fig. 1, were determined from a transfer using F268, F182, and four other FEL lamps. By coincidence, the shift coincides with the NIST (10/92) values to within 0.5%.

The 746/ISIC was used to transfer the NIST scale (8/94 F269 values) to 12 FEL lamps on 20 Sept 1994. The irradiance values of these lamps are itemized in Tables 2 and 3. The F269 transfers to F268 and F182 are shown, in comparison with their respective NIST (8/94) values, in Figs. 2 and 3. Also shown in Fig. 2 is the change in F268 as measured by NIST in October 1992 and August 1994. Since no hours were placed on the lamps between the August 1994 NIST calibration and SIRREX-3, the SIRREX-3 measurements of F268 and F182, using F269 as the reference, should be consistent with the NIST (8/94) values. The agreement is about 0.8% for F268, with the 746/ISIC values smaller than the NIST values, and about 0.2% for F182, with the 746/ISIC values higher than the NIST values. Therefore, the combined uncertainty of the transfer procedure using the 746/ISIC and the reference standard (F269) is about 1%, which is the typical transfer uncertainty for a repeated set of measurements of the same lamp using the 746/ISIC. These data support the conclusion that F269 did not experience the shift anomaly on 20 September. Figure 4 illustrates the relative variation with time of the spectral irradiance responsivity of the 746/ISIC during the transfer process.

On 21 Sept 1994, the 746/ISIC was used to transfer the NIST scale (8/94 F269 values) to another 12 FEL lamps. On this occasion, however, the measurement of F268 at the end of the day (intended as a check of the process, as well as the values of F269) showed a −2% discrepancy relative to the F268 values. By itself, this result indicated that one of these two lamps had shifted, but the measurement provided no independent information as to which lamp was responsible. If the spectral irradiance responsivity of the 746/ISIC was stable with time, then it would have been obvious which lamp was involved. Since the drift for 1 hour approaches the magnitude of the observed discrepancy, however, it was necessary first to determine which lamp had changed and then correct the data acquired on 21 September. F269, F268, and F182 were intercompared on 26 Sept 1994. Lamps F268 and F182 agreed with each other relative to their respective NIST (8/94) irradiance values with an uncertainty of less than 1%, while lamp F269 showed an apparent 1.5–2% decrease in output relative to its NIST (8/94) values (when measured using F268 or F182 to calibrate the 746/ISIC). Further evidence that lamp F269, and not lamp F268 or F182, had changed was the observation that the voltage across F269 differed by 0.79 V compared to the voltage measured across the lamp when it was calibrated at NIST in August 1994. Therefore, on 28 Sept 1994, the NIST (8/94) irradiance of F268 was transferred to four of the FEL lamps from the 21 September transfer series. The NIST (8/94) F268 values, as transferred to lamps H91534, H90573, F308, H91349, and F268 itself, were then used to recalculate the responsivity of the 746/ISIC as a basis for determining the values of the remaining eight lamps (including F269) measured on 21 September.

Figure 5 shows the results of repeated transfers of the F268 irradiance to F269 on 21, 26, and 28 September. The first three measurements on 21 September agree with the NIST (8/94) values within approximately 1%, based on a comparison of Figs. 1 and 5. Between 12:58 and 15:06 Pacific Daylight Time (PDT) on 21 September, the F269 irradiance decreased by approximately 2% at all wavelengths and remained at that level through the remainder of the period (Fig. 5).

The average of the five post-shift F268 and F182 comparisons to F269 is illustrated in Fig. 1. The standard deviations of the post-anomaly F269 irradiance values are typically less than 1%. These derived values for F269 were used in the analysis of the 21 September lamp data, as well as any 746/ISIC measurements of sphere sources using F269 as the reference lamp on 22 September or thereafter. Similar results would have been obtained using the 26 September F268 and F182 data to determine the new values for F269. This was not done because the results appeared to be satisfactory using the four lamps as described below.

For the transfers on 21 Sept 1994, the initial calibration of the 746/ISIC responsivity was recalculated with lamp H91534 at 09:55 PDT, using the spectral irradiance of this lamp transferred from F268 on 28 Sept 1994. The 746/ISIC responsivity was recalibrated at approximately 1–2 hour intervals using H90573, F308, and H91349, with data from F268 on 28 September, and finally using F268

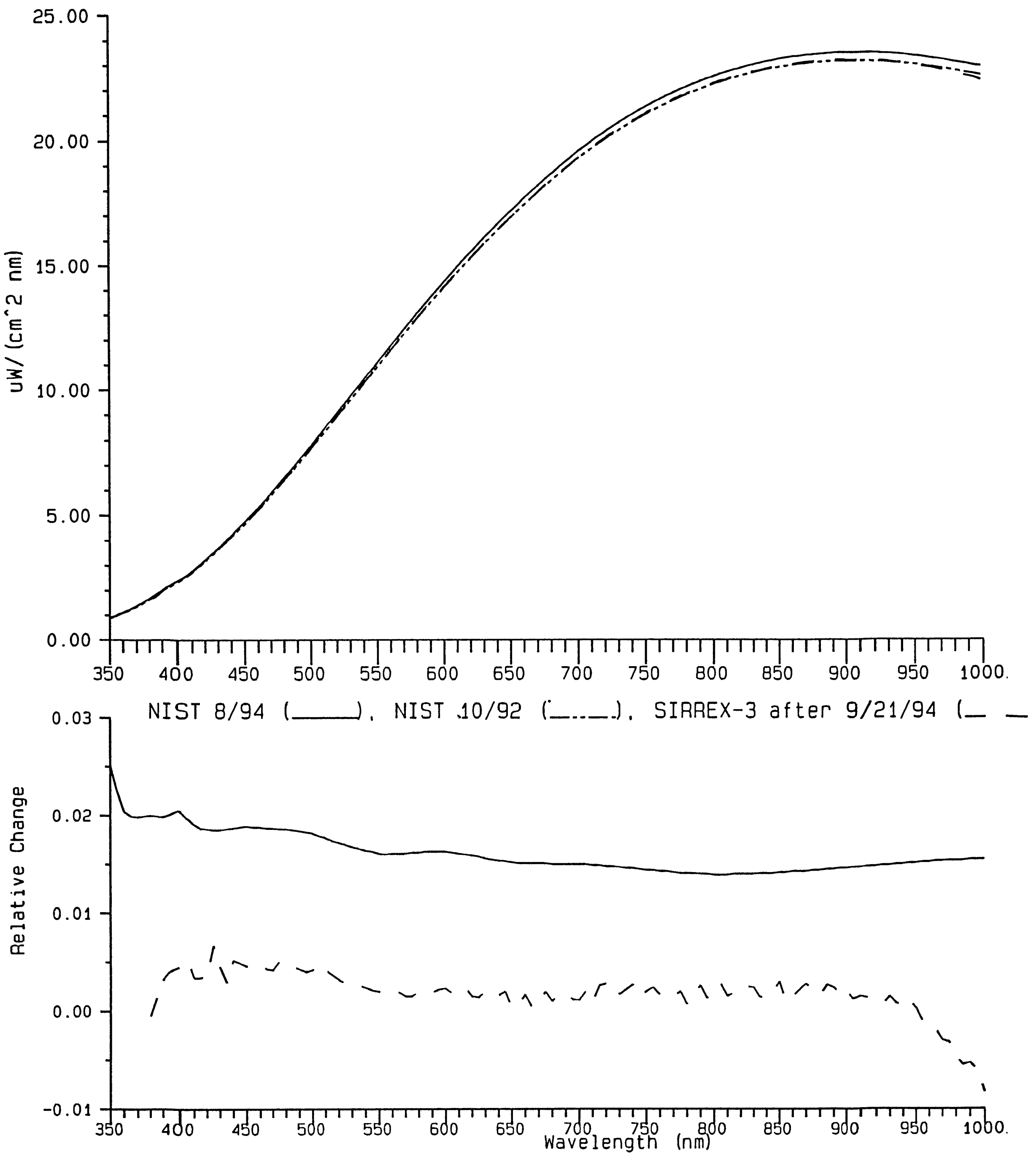


Fig. 1. NIST August 1994 calibration of the spectral irradiance (upper panel) of FEL lamp F269 (solid line) compared to the NIST October 1992 calibration, and to the new values derived using lamps F268 and F182, after the change in F269 between 12:58 and 15:06 PDT on 21 Sept 1994 (Fig. 2). The lower panel illustrates the relative changes with respect to the 1992 values. The quantity plotted using the solid line is the new *measured* value, or value being compared (NIST August 1994 data) minus the *reference* value (NIST October 1992 data), normalized to the NIST October 1992 data. The dashed line similarly shows the SIRREX-3 data compared to the NIST 1992 data.

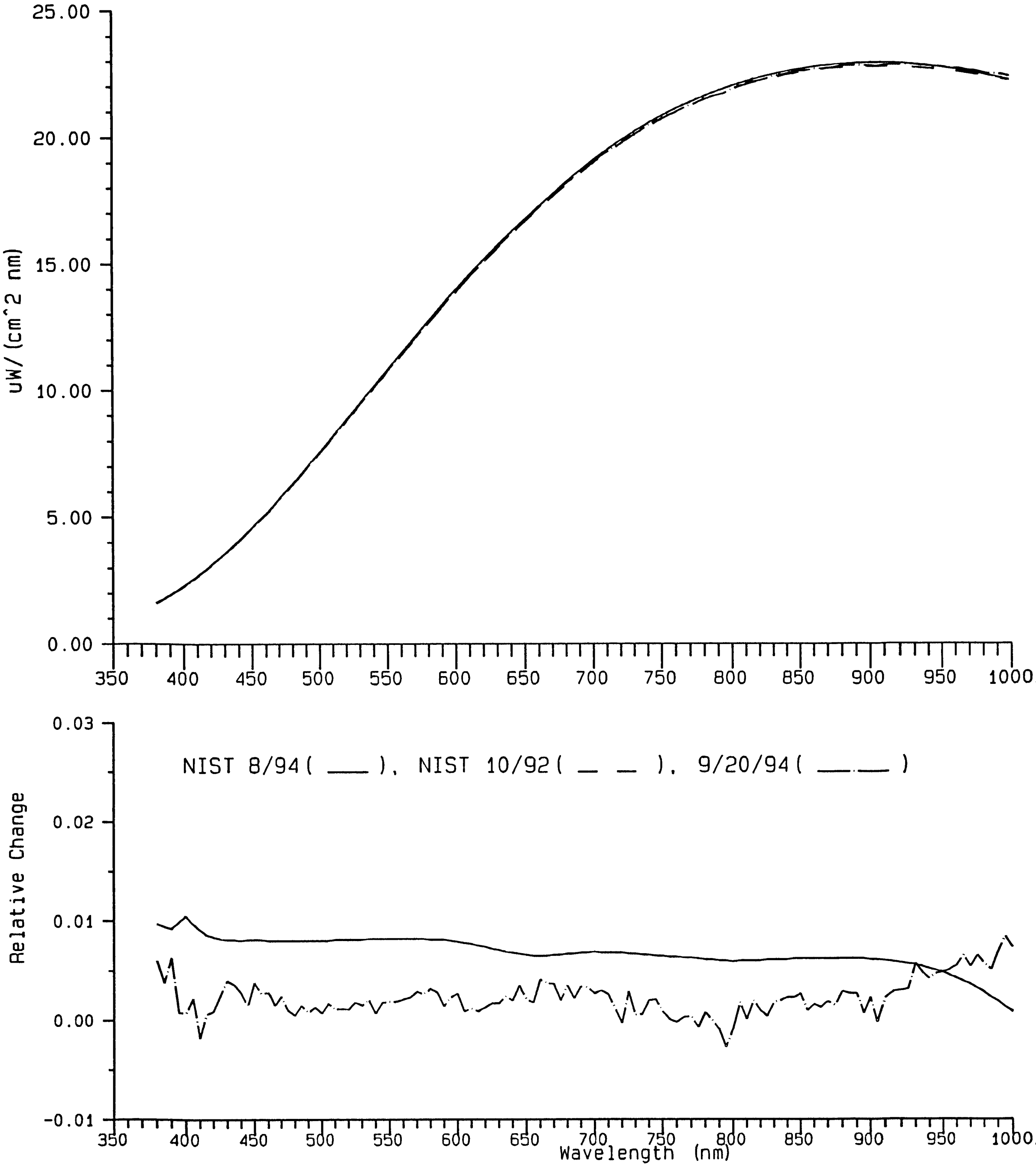


Fig. 2. Spectral irradiance of FEL lamp F268 measured using F269 (NIST August 1994 values) on 20 Sept 1994, compared with spectral irradiance values of F268 as calibrated by NIST in October 1992 and August 1994 (see legend above). The upper panel shows the spectral irradiance for F268 and the lower panel shows the changes with respect to the 1992 data. The quantity plotted is the new *measured* value (or value being compared from NIST August 1994) minus the *reference* value (NIST October 1992 data for F268), normalized to the NIST October 1992 data. The dash-dot-dash line shows the SIRREX-3 measurements for F268 compared to the NIST 1992 data.

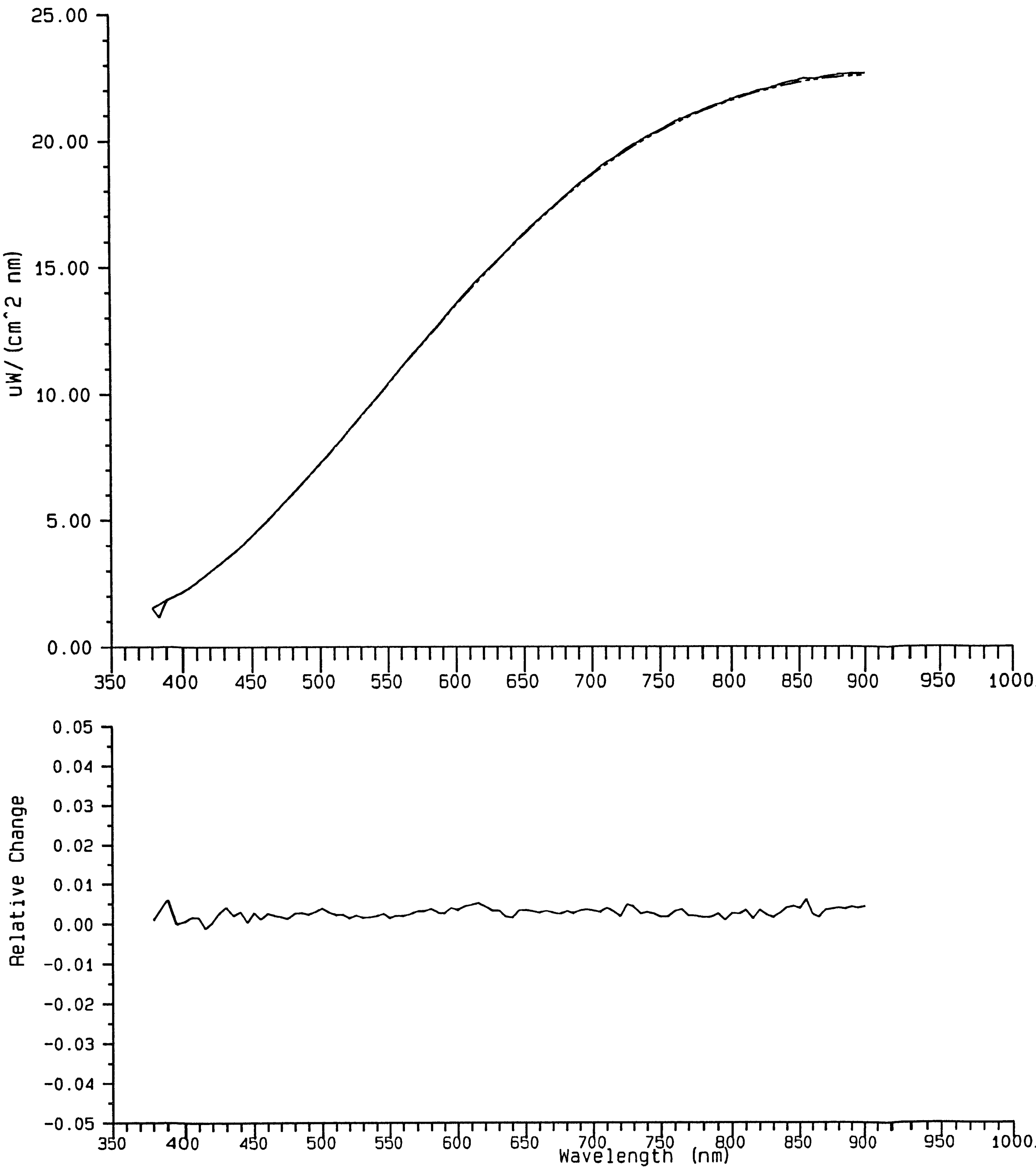


Fig. 3. Spectral irradiance of FEL lamp F182 measured using F269 (NIST August 1994 values) on 20 Sept 1994 (solid line) compared with the spectral irradiance of F182 as calibrated by NIST in August 1994 (dashed line). The upper panel shows the values for the spectral irradiance for F182 and the lower panel illustrates the relative changes with respect to the August 1994 NIST values for F182. The quantity plotted is the SIRREX-3 value minus the NIST August 1994 value, normalized to the NIST August 1994 value.

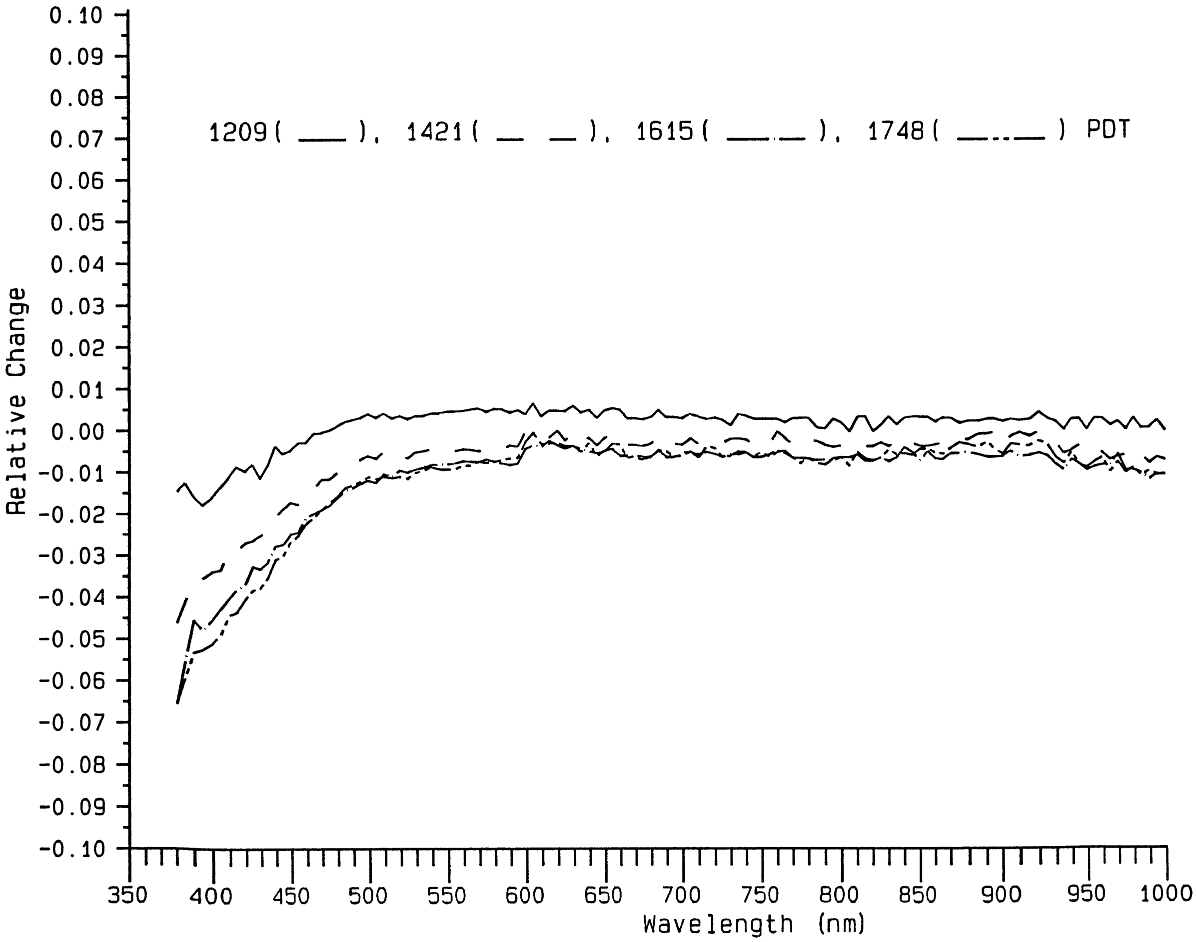


Fig. 4. The change in the spectral irradiance responsivity is shown here as a function of time of the 746/ISIC on 20 Sept 1994, during transfers of the NIST (August 1994 values) spectral irradiance of F269 to 12 other FEL lamps. The quantity plotted is the measured inverse responsivity of the 746/ISIC during the day (see legend for the time of measurement) minus the inverse responsivity of this instrument determined at 09:18 PDT, normalized to the inverse responsivity determined at 09:18 PDT.

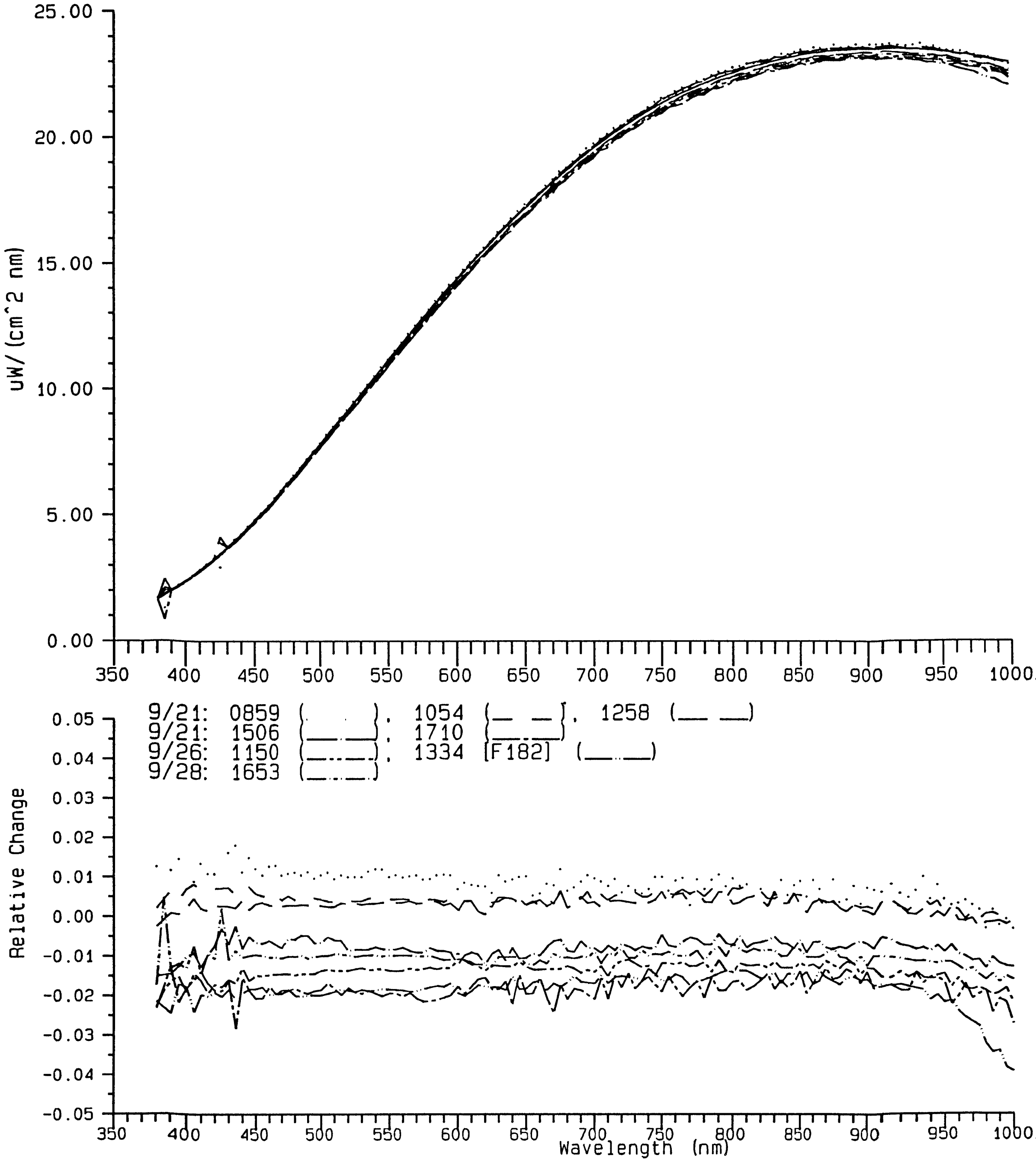


Fig. 5. The lower panel illustrates the relative changes with respect to the NIST October 1992 values for F269. The quantity plotted is the spectral irradiance for F269 which was determined at SIRREX-3 (using lamps F268 or F182) minus the NIST October 1992 values for F269, normalized to the NIST October 1992 values. The dates and times in the legends correspond to the measurements of F269 using the 746/ISIC. On 21 Sept 1994, the NIST August 1994 values of F268, transferred using other lamps at SIRREX-3 from the 28 Sept 1994 measurements, were used to determine the spectral irradiance of F269 (see text). On the other two days, the NIST August 1994 values of F268 (26 and 28 September) or F182 (26 September) were used as the reference lamp.

near the end of the day (see Fig. 6). Table 4 lists the irradiances of seven lamps transferred by this procedure from the F268 NIST (8/94) values on 21 September. The derived irradiance values of F269, as transferred twice on 21 and 26 September and once on 28 September, are itemized in Table 5 (see also Figs. 1 and 5).

On 28 Sept 1994, the 746/ISIC system was initially calibrated using F268 at 14:12 PDT and again at the end of the transfers to other FEL lamps at 16:41 PDT. The change in 746/ISIC responsivity during the course of the transfer on 28 September is illustrated in Fig. 7. The values for lamps H91534, H90573, F308, and H91349, as transferred from F268 on 28 September, are listed in Table 6.

The spectral irradiance of many of these lamps was previously transferred during SIRREX-2 (Mueller et al. 1994), or was calibrated by either NIST or the lamp manufacturer. Figures 8–14 compare the SIRREX-3 values for spectral irradiance with the SIRREX-2 values, and/or the independent calibrations of either the lamp's manufacturer or NIST. Figures 8–14 show that the SIRREX-3 values for spectral irradiance are systematically greater than the values determined at SIRREX-2 by 1–2%. The average apparent change in the spectral irradiance for these six lamps as measured at SIRREX-2 and SIRREX-3 is shown in Fig. 15; the results presented in this way facilitate assessment of the SIRREX data (see below).

2.3 Discussion

During the planning and preparation for SIRREX-3, it was anticipated that the FEL lamp transfers from the NIST-calibrated lamp F269 would be a straightforward replication of the results of SIRREX-2 (Mueller et al. 1994), and that this aspect of SIRREX-3 would be the most routine and simple aspect of the exercise. Two events changed that perception.

The first event is the consistent discrepancy between the SIRREX-2 and SIRREX-3 measurements. In both cases, the irradiance is traceable to NIST through the calibrations of F269 and F268 in October 1992 and August 1994, and it is unlikely that all six lamps for which these data exist (F321, F308, F123, F12G, F303, and F307) changed with similar magnitude and direction between the two SIRREXs. It is possible that the NIST scale was not reproducible between October 1992 and August 1994, but it is more likely that the measurements by NIST of F268 and F269 in 1992 and 1994 are reliable, since the observed difference is greater than the combined uncertainty reported by NIST. The authors of this report assume, therefore, that the approximately 2% and 1.5% increases in the irradiance of F269 and F268, respectively, are real.

If the irradiance of these secondary standard lamps did not change between the October 1992 NIST calibration and SIRREX-2, and the August 1994 NIST calibration and SIRREX-3, the SIRREX-2 data for the six lamps mentioned above should agree with the SIRREX-3 results. As Fig. 15 indicates, however, on average the irradiance of these lamps also increased by about 1.5%. One month elapsed between the NIST August 1994 calibration and SIRREX-3, but there were eight months between the October 1992 NIST calibration and SIRREX-2. Given the agreement between the changes observed by NIST in F269 and F268 and the disparity of the measurements of the six lamps employed at SIRREX-3, it would appear that F269 and F268 experienced the most drift between the 1992 calibration and SIRREX-2. GSFC did not maintain proper logs of the cumulative operating hours for either of these NIST secondary standard lamps, but the lamps were used regularly as reference standards.

Drift rates of FEL lamps vary, and NIST recommends recalibration every 50 burning hours, whereas the GSFC staff acknowledge that the usage between the October 1992 and August 1994 calibration could have exceeded this time limit. This situation posed the dilemma that there was no reliable way to determine when, or at what rate, either F269 or F268 had changed, and brings into question whether the SIRREX-2 measurements are valid. Therefore, the authors recommend that an additional 1.5–2% uncertainty component must be included for the spectral irradiance assigned to FEL working standards in SIRREX-2 (Mueller et al. 1994).

The second event, which more seriously complicated the execution and analysis of the SIRREX-3 measurements, was the shift anomaly in F269; this occurred on 21 September (Fig. 5). The lack of a complete record of operating hours for this lamp, with a history of both operating currents and voltages measured across the lamp terminals, greatly complicated both the initial detection of the anomaly and determination of the time at which it occurred on 21 September. The uncertainties associated with the shift affected not only the lamp results, but also the sphere radiance results, since F269 was extensively used as the working standard for calibrations of the 746/ISIC in many of the measurements of sphere radiance with that instrument (see Section 3). As was explained above, the NIST (8/94) spectral irradiance of the F268 secondary standard was then adopted as the primary reference for all SIRREX-3 measurements on and after 21 September.

Using other lamps with irradiances transferred from F268 on 28 Sept 1994 (Table 6), the lamps measured on 21 September were indirectly transferred from F268 (Table 4). A revised mean spectral irradiance for F269 was also transferred in this way from F268, for use as a reference in the analysis of the 746/ISIC sphere radiance measurements, which used that lamp after 21 September (Table 6 and Fig. 1). The Type A uncertainty of the F268-based irradiance of F269 is approximately 1% (Table 5).

The combined uncertainty for the spectral irradiance of the various lamps measured at SIRREX-3 derives from several sources. First, there is the uncertainty in the irradiance of the secondary standard as assigned by NIST to F269, F268, or F182 (depending on which lamp was used

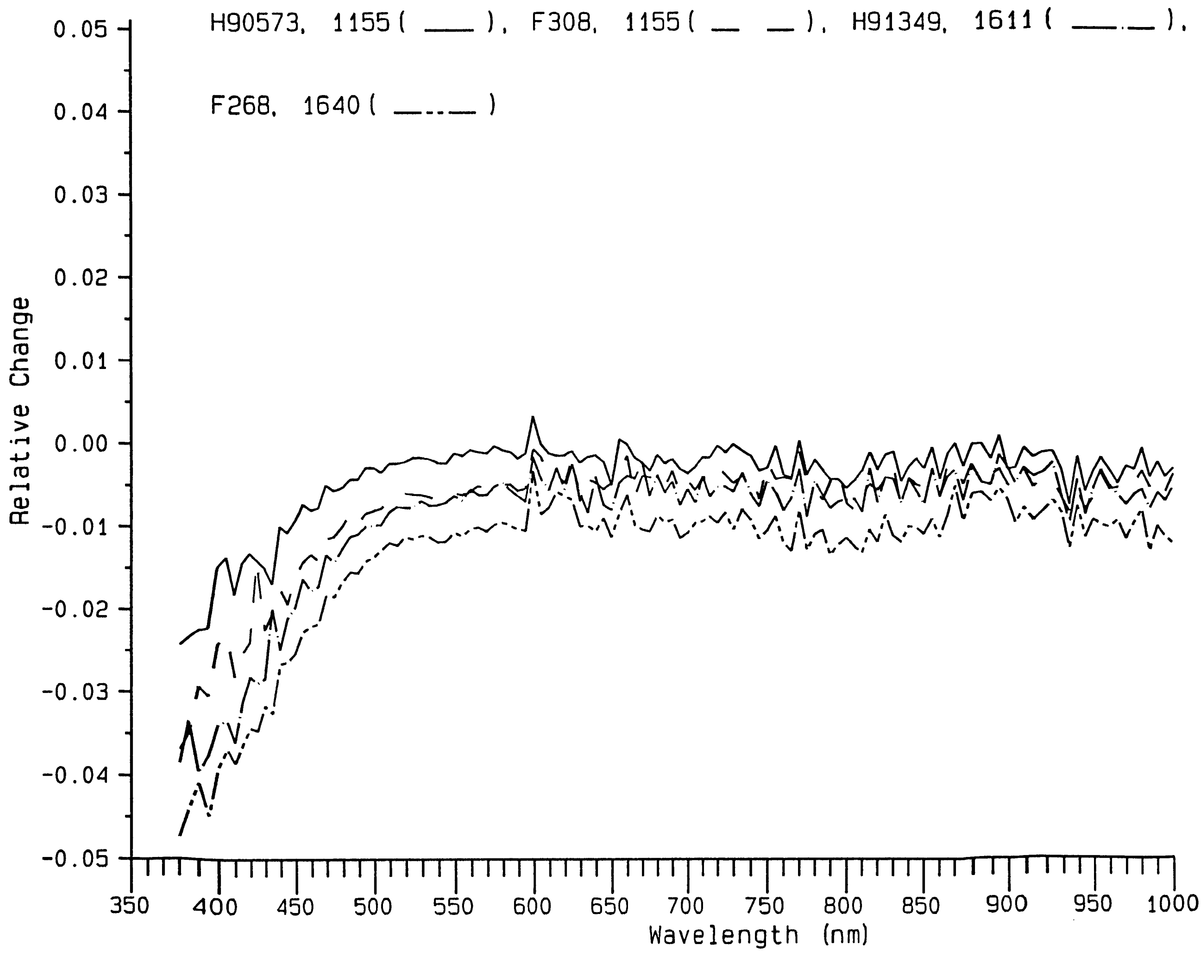


Fig. 6. The change in the spectral irradiance responsivity is shown as a function of time for the 746/ISIC on 21 Sept 1994 during transfers of the NIST August 1994 spectral irradiance of F268 to seven other FEL lamps. The responsivity of the 746/ISIC was determined using the lamps indicated; the assignments for these lamps were determined using the F268 measurements on 28 Sept 1994. The quantity plotted is the measured inverse responsivity of the 746/ISIC during the day (see legend for the time of measurement) minus the inverse responsivity of this instrument determined at 09:55 PDT (using H91534), normalized to the inverse responsivity determined at 09:55 PDT.

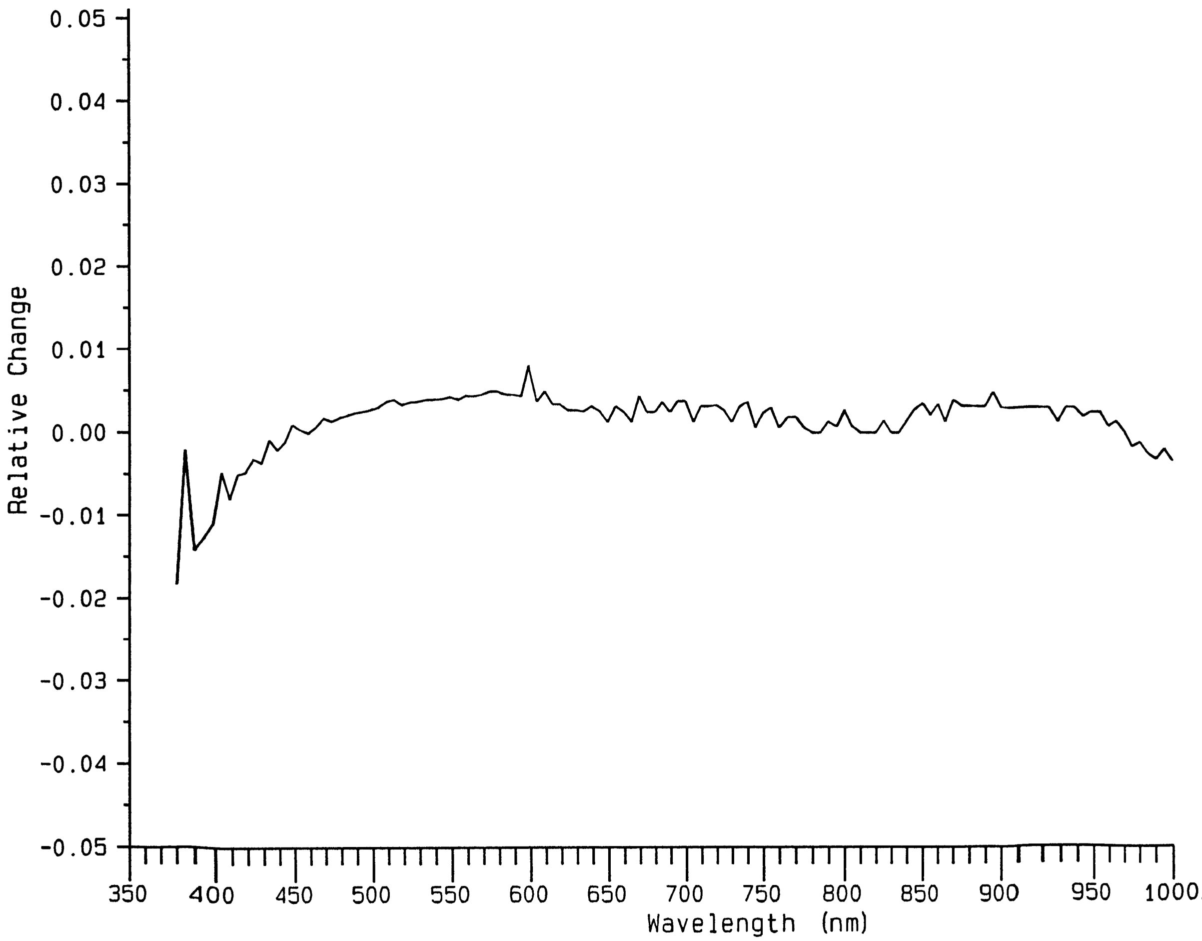


Fig. 7. The change in the spectral irradiance responsivity is shown as a function of time for the 746/ISIC on 28 Sept 1994 during transfers of the NIST August 1994 spectral irradiance of F268 to five other FEL lamps. The responsivity of the 746/ISIC was determined at 14:12 PDT and 16:41 PDT using F268. The quantity plotted is the measured inverse responsivity of the 746/ISIC at 14:12 PDT minus the inverse responsivity of this instrument determined at 16:41 PDT, normalized to the inverse responsivity determined at 16:41 PDT.

Table 2. Spectral irradiance measurements of FEL lamps transferred from the F269 (NIST 8/94 values) on 20 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.1%.

	Lamp Number					
λ (nm)	F123	F12G	F182	F268	F296	F297
380	1.4582	1.4775	1.5253	1.6150	1.8007	1.6536
385	1.1945	1.4984	1.1585	1.7673	2.4623	1.8154
390	1.7576	1.7729	1.8409	1.9364	2.1647	2.0032
395	1.9078	1.9251	1.9964	2.0980	2.3447	2.1622
400	2.0773	2.0858	2.1734	2.2787	2.5539	2.3492
405	2.2584	2.2686	2.3602	2.4755	2.7620	2.5515
410	2.4446	2.4578	2.5525	2.6669	2.9856	2.7564
415	2.6346	2.6546	2.7466	2.8830	3.2256	2.9694
420	2.8390	2.8505	2.9593	3.1015	3.4574	3.1925
425	3.0556	3.0627	3.1833	3.3323	3.7142	3.4273
430	3.2626	3.2690	3.4139	3.5709	3.9608	3.6601
435	3.5068	3.5082	3.6387	3.8101	4.2333	3.9091
440	3.7390	3.7412	3.8817	4.0549	4.5008	4.1655
445	3.9764	3.9747	4.1172	4.3037	4.7761	4.4242
450	4.2260	4.2204	4.3801	4.5751	5.0592	4.6972
455	4.4824	4.4754	4.6345	4.8406	5.3587	4.9694
460	4.7541	4.7369	4.9087	5.1174	5.6468	5.2462
465	5.0141	5.0049	5.1802	5.3925	5.9582	5.5300
470	5.2909	5.2834	5.4572	5.6846	6.2774	5.8235
475	5.5783	5.5518	5.7384	5.9688	6.5922	6.1265
480	5.8624	5.8391	6.0350	6.2619	6.9117	6.4300
485	6.1544	6.1216	6.3288	6.5695	7.2420	6.7350
490	6.4482	6.4165	6.6236	6.8697	7.5790	7.0481
495	6.7416	6.7117	6.9289	7.1813	7.9051	7.3563
500	7.0488	7.0008	7.2391	7.4880	8.2427	7.6828
505	7.3518	7.2933	7.5391	7.8094	8.5777	7.9982
510	7.6488	7.5893	7.8439	8.1210	8.9140	8.3187
515	7.9580	7.8902	8.1567	8.4402	9.2511	8.6497
520	8.2655	8.1910	8.4631	8.7589	9.5939	8.9679
525	8.5697	8.4976	8.7840	9.0873	9.9408	9.3017
530	8.8902	8.8064	9.0949	9.4074	10.2876	9.6317
535	9.2087	9.1146	9.4141	9.7362	10.6240	9.9554
540	9.5238	9.4269	9.7345	10.0465	10.9691	10.2861
545	9.8435	9.7414	10.0596	10.3818	11.3200	10.6231
550	10.1613	10.0498	10.3664	10.7075	11.6737	10.9545
555	10.4709	10.3566	10.6923	11.0304	12.0150	11.2790
560	10.7992	10.6660	11.0075	11.3556	12.3530	11.6058
565	11.1155	10.9790	11.3287	11.6792	12.7060	11.9404
570	11.4418	11.2891	11.6524	12.0064	13.0522	12.2718
575	11.7559	11.5941	11.9663	12.3210	13.3796	12.5923
580	12.0716	11.9037	12.2849	12.6442	13.7197	12.9225
585	12.3810	12.2047	12.5837	12.9537	14.0568	13.2378
590	12.6920	12.4997	12.8888	13.2463	14.3688	13.5520
595	13.0071	12.8058	13.2108	13.5672	14.7026	13.8703
600	13.3342	13.1175	13.5060	13.8778	14.9909	14.1541
605	13.6117	13.4376	13.8142	14.1503	15.3486	14.4762
610	13.9029	13.6816	14.1101	14.4488	15.6171	14.7723

Table 2. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F269 (NIST 8/94 values) on 20 Sept 1994. All units are in $\mu\mathrm{W\,cm^{-2}\,nm^{-1}}$ unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.1%.

	Lamp Number					
λ (nm)	F123	F12G	F182	F268	F296	F297
615	14.2175	13.9764	14.4068	14.7339	15.9364	15.0743
620	14.5058	14.2813	14.6775	15.0257	16.2598	15.3774
625	14.7720	14.5217	14.9437	15.3155	16.5162	15.6774
630	15.0571	14.8170	15.2214	15.5925	16.8427	15.9315
635	15.3355	15.0533	15.4707	15.8774	17.1189	16.2409
640	15.6000	15.3196	15.7346	16.1409	17.4081	16.5114
645	15.8346	15.5822	16.0272	16.4314	17.6552	16.7467
650	16.1218	15.8362	16.2903	16.6700	17.9678	17.0462
655	16.3887	16.0863	16.5410	16.9209	18.2347	17.3038
660	16.6632	16.3502	16.7876	17.2122	18.4784	17.5506
665	16.8680	16.5709	17.0446	17.4519	18.7097	17.8139
670	17.1202	16.8045	17.2803	17.6947	18.9775	18.0723
675	17.3522	17.0334	17.5140	17.9010	19.2174	18.2802
680	17.6163	17.2892	17.7596	18.1595	19.4633	18.5363
685	17.8357	17.5046	17.9808	18.3631	19.7004	18.7692
690	18.0780	17.6781	18.2180	18.6071	19.9304	18.9930
695	18.3179	17.9282	18.4421	18.8211	20.1765	19.2251
700	18.5223	18.1365	18.6520	19.0212	20.3675	19.4414
705	18.7190	18.3104	18.8471	19.2285	20.5950	19.6248
710	18.9040	18.4912	19.0641	19.4147	20.7840	19.8254
715	19.1262	18.6869	19.2384	19.5784	20.9677	20.0190
720	19.3269	18.8755	19.4011	19.7308	21.1189	20.1855
725	19.4985	19.0711	19.6393	19.9723	21.3399	20.3649
730	19.6871	19.2434	19.8012	20.0958	21.4861	20.5244
735	19.8730	19.3955	19.9363	20.2632	21.6684	20.7057
740	20.0009	19.5526	20.1069	20.4531	21.8350	20.8600
745	20.1765	19.7240	20.2556	20.6094	22.0041	21.0224
750	20.3307	19.8474	20.3891	20.7336	22.1561	21.1735
755	20.4695	19.9961	20.5397	20.8616	22.2669	21.2911
760	20.6083	20.1456	20.7065	20.9933	22.3894	21.4282
765	20.8155	20.3101	20.8525	21.1347	22.5367	21.5804
770	20.8809	20.3923	20.9500	21.2659	22.6736	21.7131
775	21.0233	20.5017	21.0737	21.3631	22.8112	21.8470
780	21.1557	20.6471	21.1844	21.5121	22.9436	21.9616
785	21.2827	20.7659	21.3015	21.6072	23.0062	22.0734
790	21.3911	20.8234	21.4295	21.6927	23.0690	22.1647
795	21.4747	20.9436	21.5008	21.7553	23.2224	22.3056
800	21.6050	21.0128	21.6359	21.8899	23.2584	22.3770
805	21.7278	21.1004	21.7257	22.0381	23.3858	22.4345
810	21.8263	21.2214	21.8377	22.0863	23.4880	22.5711
815	21.8967	21.2980	21.8758	22.2080	23.5973	22.7162
820	22.0191	21.3342	22.0027	22.2599	23.6120	22.7546
825	22.0692	21.4376	22.0527	22.3165	23.6668	22.8301
830	22.1445	21.4846	22.1088	22.4132	23.7976	22.8984
835	22.2233	21.5849	22.2019	22.4778	23.7848	22.9439
840	22.2830	21.6334	22.2926	22.5412	23.9193	23.0396
845	22.3699	21.7115	22.3583	22.5937	23.9688	23.1255

Table 2. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F269 (NIST 8/94 values) on 20 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (the spectral range from 400–1000 nm) is 1.1%.

	Lamp Number					
λ (nm)	F123	F12G	F182	F268	F296	F297
850	22.4330	21.7507	22.3978	22.6489	24.0123	23.1268
855	22.4711	21.7981	22.4987	22.6530	24.0488	23.1577
860	22.5026	21.8411	22.4615	22.7058	24.0524	23.2254
865	22.5054	21.9239	22.4806	22.7332	24.1068	23.2241
870	22.5966	21.9301	22.5567	22.7758	24.1285	23.2593
875	22.6281	21.9305	22.5952	22.7927	24.1499	23.2398
880	22.6710	22.0173	22.6280	22.8463	24.1607	23.3076
885	22.7042	22.0137	22.6472	22.8615	24.1852	23.3157
890	22.7177	22.0740	22.6779	22.8760	24.2184	23.3589
895	22.7136	22.0276	22.6869	22.8403	24.2203	23.3735
900	22.7272	22.0301	22.7090	22.8820	24.1943	23.3602
905	22.7587	22.0649	22.7186	22.8273	24.2006	23.3471
910	22.7716	22.0638	22.6826	22.8817	24.1814	23.3932
915	22.7795	22.0615	22.7499	22.8919	24.1982	23.3470
920	22.7873	22.0725	22.7269	22.8861	24.2335	23.3409
925	22.7813	22.0781	22.7079	22.8784	24.2097	23.3293
930	22.7492	22.0368	22.6971	22.9185	24.1722	23.3483
935	22.7423	22.0362	22.7035	22.8795	24.1643	23.2912
940	22.7528	22.0476	22.6606	22.8446	24.1416	23.2647
945	22.7127	22.0281	22.6589	22.8306	24.1202	23.2663
950	22.6648	21.9630	22.5934	22.8061	24.0770	23.2178
955	22.6657	21.9388	22.5900	22.7801	24.0679	23.2335
960	22.6626	21.8944	22.5686	22.7557	23.9977	23.1986
965	22.5767	21.8841	22.5335	22.7411	23.9462	23.1171
970	22.5819	21.8534	22.5240	22.6778	23.9113	23.1242
975	22.5048	21.8116	22.4520	22.6599	23.8441	23.0226
980	22.4513	21.7982	22.4036	22.5978	23.8436	23.0096
985	22.3970	21.7345	22.3421	22.5372	23.7444	22.9329
990	22.4130	21.6874	22.3084	22.5289	23.7094	22.9368
995	22.3230	21.6684	22.2603	22.5092	23.6695	22.8503
1000	22.2737	21.6038	22.2412	22.4302	23.6125	22.8243

Table 3. Spectral irradiance measurements of FEL lamps transferred from the F269 (NIST 8/94 values) on 20 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.1%.

	Lamp Number					
λ (nm)	F304	F305	F315	F321	H91537	H91795
380	1.6237	1.4830	1.3739	1.4608	1.3714	1.2183
385	1.2059	1.1996	1.4990	1.2677	1.3280	1.2856
390	1.9678	1.7877	1.6568	1.7505	1.6574	2.4352
395	2.1219	1.9455	1.8023	1.8992	1.8008	1.5909
400	2.3151	2.1156	1.9590	2.0669	1.9584	1.7325
405	2.5062	2.2902	2.1191	2.2388	2.1276	1.8894
410	2.7075	2.4846	2.2983	2.4256	2.3100	2.0459

Table 3. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F269 (NIST 8/94 values) on 20 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.1%.

	Lamp Number					
λ (nm)	F304	F305	F315	F321	H91537	H91795
415	2.9232	2.6755	2.4820	2.6170	2.4920	2.2208
420	3.1419	2.8818	2.6751	2.8213	2.6860	2.3935
425	3.3763	3.0977	2.8744	3.0276	2.8881	2.5828
430	3.6100	3.3184	3.0651	3.2341	3.0891	2.7585
435	3.8603	3.5460	3.2959	3.4711	3.3199	2.9619
440	4.1068	3.7817	3.5124	3.6970	3.5371	3.1790
445	4.3566	4.0228	3.7288	3.9318	3.7685	3.3863
450	4.6244	4.2752	3.9642	4.1784	4.0094	3.6055
455	4.8935	4.5230	4.2105	4.4271	4.2463	3.8310
460	5.1807	4.7887	4.4548	4.6840	4.4983	4.0576
465	5.4653	5.0550	4.7067	4.9515	4.7570	4.3015
470	5.7560	5.3367	4.9711	5.2304	5.0227	4.5413
475	6.0494	5.6102	5.2323	5.4970	5.2846	4.7931
480	6.3655	5.8996	5.5003	5.7829	5.5626	5.0461
485	6.6639	6.1954	5.7671	6.0706	5.8418	5.3064
490	6.9733	6.4842	6.0438	6.3550	6.1276	5.5691
495	7.2839	6.7812	6.3264	6.6450	6.4035	5.8435
500	7.6077	7.0754	6.6132	6.9405	6.6919	6.1075
505	7.9188	7.3763	6.8895	7.2350	6.9848	6.3841
510	8.2479	7.6833	7.1728	7.5331	7.2718	6.6606
515	8.5851	7.9977	7.4658	7.8365	7.5646	6.9365
520	8.9059	8.3056	7.7604	8.1348	7.8611	7.2137
525	9.2306	8.6144	8.0608	8.4456	8.1649	7.4991
530	9.5440	8.9290	8.3533	8.7545	8.4717	7.7876
535	9.8766	9.2476	8.6495	9.0627	8.7756	8.0737
540	10.2131	9.5613	8.9368	9.3639	9.0808	8.3661
545	10.5427	9.8834	9.2329	9.6707	9.3774	8.6552
550	10.8692	10.2025	9.5290	9.9844	9.6876	8.9496
555	11.1995	10.5216	9.8283	10.3010	9.9891	9.2379
560	11.5231	10.8368	10.1269	10.6062	10.2948	9.5310
565	11.8522	11.1524	10.4268	10.9222	10.6018	9.8271
570	12.1786	11.4631	10.7269	11.2366	10.9026	10.1200
575	12.5040	11.7746	11.0290	11.5562	11.2031	10.4046
580	12.8242	12.0871	11.3316	11.8576	11.5125	10.7026
585	13.1415	12.3819	11.6258	12.1554	11.8139	10.9910
590	13.4631	12.7031	11.9065	12.4768	12.1154	11.2815
595	13.7724	12.9925	12.2001	12.7764	12.4090	11.5622
600	14.1061	13.2759	12.5035	13.0623	12.7415	11.8841
605	14.4307	13.5933	12.7611	13.3765	13.0214	12.1473
610	14.7250	13.8726	13.0709	13.6939	13.3178	12.4150
615	15.0598	14.1858	13.3202	13.9250	13.5631	12.6745
620	15.3524	14.4812	13.6162	14.2306	13.8749	12.9776
625	15.6137	14.7260	13.8931	14.4926	14.1389	13.2023
630	15.8912	15.0174	14.1604	14.7661	14.4138	13.4687
635	16.1867	15.2812	14.3991	15.0460	14.6785	13.7461
640	16.4550	15.5389	14.6559	15.3182	14.9535	14.0039
645	16.7302	15.8129	14.9289	15.5747	15.2138	14.2584

Table 3. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F269 (NIST 8/94 values) on 20 Sept 1994. All units are in $\mu\mathrm{W\,cm^{-2}\,nm^{-1}}$ unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.1%.

	Lamp Number					
λ (nm)	F304	F305	F315	F321	H91537	H91795
650	16.9776	16.0587	15.1737	15.8233	15.4644	14.5571
655	17.2601	16.3447	15.4027	16.0733	15.7113	14.7391
660	17.5022	16.5529	15.6771	16.3225	15.9388	14.9973
665	17.7762	16.8396	15.9398	16.5719	16.1887	15.2560
670	18.0253	17.0706	16.1432	16.8495	16.4182	15.4757
675	18.2311	17.3022	16.3918	17.0316	16.6432	15.6912
680	18.5261	17.5493	16.6099	17.2993	16.8819	15.9539
685	18.7568	17.8042	16.8024	17.5268	17.1286	16.1892
690	18.9456	18.0060	17.0192	17.7253	17.3345	16.3838
695	19.1894	18.2235	17.2721	17.9759	17.5420	16.6022
700	19.4349	18.4350	17.4609	18.1908	17.7447	16.8295
705	19.6181	18.6215	17.6608	18.4303	17.9803	17.0049
710	19.8240	18.8331	17.8555	18.5836	18.1386	17.2054
715	19.9835	19.0485	18.0120	18.7642	18.3577	17.3861
720	20.1410	19.1991	18.1662	18.9515	18.4966	17.5406
725	20.3316	19.3916	18.3683	19.1533	18.7124	17.7331
730	20.5386	19.5914	18.5373	19.3307	18.8773	17.9418
735	20.6751	19.7017	18.7011	19.5178	19.0224	18.0678
740	20.8775	19.8871	18.8576	19.6497	19.2244	18.2567
745	21.0354	20.0633	19.0176	19.8139	19.3538	18.4104
750	21.1470	20.2135	19.1404	19.9242	19.5035	18.5460
755	21.3411	20.3442	19.2843	20.1032	19.6765	18.6992
760	21.5152	20.5279	19.4500	20.2652	19.8276	18.8440
765	21.6582	20.6415	19.5665	20.4000	19.9430	18.9678
770	21.6992	20.7483	19.7207	20.5004	20.0733	19.0975
775	21.8468	20.8783	19.8318	20.6401	20.1767	19.2395
780	21.9682	21.0178	19.9525	20.7814	20.3099	19.3841
785	22.0919	21.1515	20.0790	20.9103	20.4498	19.4697
790	22.2038	21.2226	20.1786	21.0151	20.5271	19.5961
795	22.2727	21.3041	20.3004	21.0927	20.6082	19.6889
800	22.3779	21.4647	20.3729	21.1995	20.7429	19.7768
805	22.4981	21.5684	20.5161	21.3143	20.8239	19.8814
810	22.5950	21.6152	20.5418	21.3858	20.9169	19.9824
815	22.6829	21.7148	20.6740	21.4570	21.0054	20.1066
820	22.7751	21.8132	20.6935	21.5855	21.1289	20.1654
825	22.8633	21.8784	20.7647	21.6492	21.1928	20.2471
830	22.8482	21.9431	20.8477	21.7132	21.2691	20.2854
835	22.9813	22.0455	20.9350	21.7854	21.3271	20.3515
840	23.0205	22.1139	21.0104	21.8692	21.4064	20.4828
845	23.0670	22.1743	21.1051	21.9217	21.4691	20.5499
850	23.0610	22.1858	21.1071	21.9593	21.5219	20.5861
855	23.1615	22.2667	21.1785	22.0319	21.5559	20.6313
860	23.1842	22.2979	21.1802	22.0768	21.6434	20.6668
865	23.2117	22.3271	21.2354	22.0814	21.6455	20.7063
870	23.2623	22.4363	21.3009	22.1786	21.7115	20.7863
875	23.3506	22.4431	21.3206	22.2167	21.7355	20.7882
880	23.3617	22.4539	21.3259	22.2461	21.7608	20.8361

Table 3. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F269 (NIST 8/94 values) on 20 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.1%.

	Lamp Number					
λ (nm)	F304	F305	F315	F321	H91537	H91795
885	23.3943	22.4974	21.3500	22.2880	21.8142	20.8888
890	23.4156	22.5072	21.3898	22.3042	21.8293	20.9391
895	23.4042	22.5413	21.4191	22.2871	21.8482	20.9350
900	23.4256	22.5550	21.4320	22.3166	21.8646	20.9494
905	23.4336	22.5771	21.4418	22.3168	21.8818	20.9640
910	23.4064	22.5873	21.4387	22.3420	21.9045	20.9677
915	23.4111	22.5786	21.4501	22.3295	21.8955	20.9813
915	23.4111	22.5786	21.4501	22.3295	21.8955	20.9813
920	23.4215	22.5995	21.4790	22.3555	21.9310	21.0306
925	23.3978	22.5948	21.4592	22.3389	21.9145	21.0137
930	23.3833	22.5803	21.4790	22.3379	21.9192	21.0044
935	23.3585	22.5731	21.4511	22.3241	21.9007	21.0176
940	23.3420	22.5516	21.4413	22.2820	21.8608	21.0044
945	23.3567	22.5638	21.4479	22.2645	21.8618	20.9874
950	23.3121	22.5404	21.4326	22.2508	21.8276	20.9447
955	23.2231	22.4843	21.4395	22.2310	21.8136	20.9662
960	23.1712	22.4504	21.3637	22.1783	21.7820	20.9559
965	23.1914	22.4237	21.3527	22.1531	21.7150	20.8941
970	23.1820	22.4201	21.3469	22.1783	21.7242	20.9066
975	23.0901	22.3994	21.2947	22.1189	21.6971	20.8507
980	23.0491	22.3393	21.3247	22.1039	21.6728	20.8831
985	23.0092	22.2947	21.2676	22.0805	21.6154	20.7940
990	22.9668	22.3063	21.2720	21.9919	21.5515	20.7625
995	22.9096	22.2125	21.2375	21.9509	21.5281	20.7614
1000	22.8615	22.2162	21.1823	21.9253	21.4896	20.7044

Table 4. Spectral irradiance measurements of FEL lamps transferred from the F268 (NIST 8/94 values) on 21 Sept 1994, also using working standards recalibrated on 28 Sept 1994 to monitor the responsivity drift of the 746/ISIC. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

	Lamp Number						
λ (nm)	F303	F307	GS-922	H90572	H91348	H91738	H91739
380	1.7025	1.6439	1.2544	0.5493	1.2545	1.6672	1.4730
385	2.8898	1.6827	1.1032	0.4696	1.0823	1.5432	1.4894
390	2.0392	1.9668	1.4381	0.5165	1.4779	2.0113	1.7762
395	2.2228	2.1400	1.6689	0.5673	1.6177	2.2005	1.9359
400	2.4126	2.3421	1.8030	0.6234	1.7622	2.3764	2.1039
405	2.6130	2.5362	1.9660	0.8555	1.9196	2.5801	2.2868
410	2.8297	2.7299	2.1256	0.9285	2.0719	2.7894	2.4687
415	3.0416	2.9470	2.2970	1.0127	2.2484	2.9984	2.6664
420	3.2711	3.1687	2.4781	1.1025	2.4308	3.2247	2.8678
425	3.2186	4.2607	2.6835	1.2034	2.6164	3.7719	3.7682
430	3.7673	3.6312	2.8382	1.2831	2.7812	3.7062	3.2952
435	4.0182	3.8690	3.0697	1.3873	3.0215	3.9489	3.5165

Table 4. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F268 (NIST 8/94 values) on 21 Sept 1994, also using working standards recalibrated on 28 Sept 1994 to monitor the responsivity drift of the 746/ISIC. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

	Lamp Number						
λ (nm)	F303	F307	GS-922	H90572	H91348	H91738	H91739
440	4.2654	4.1273	3.267	1.4900	3.1946	4.2058	3.7534
445	4.5383	4.3890	3.4802	1.5997	3.4143	4.4688	3.9942
450	4.8005	4.6560	3.7023	1.7169	3.6342	4.7324	4.2428
455	5.0780	4.9326	3.9348	1.8369	3.8607	5.0061	4.4898
460	5.3746	5.2108	4.1681	1.9754	4.0881	5.2948	4.7551
465	5.6686	5.5017	4.4035	2.1020	4.3238	5.5842	5.0168
470	5.9578	5.7929	4.6519	2.2340	4.5710	5.8727	5.2870
475	6.2661	6.0858	4.9009	2.3760	4.8183	6.1767	5.5652
480	6.5682	6.3916	5.1553	2.5165	5.0661	6.4787	5.8416
485	6.8794	6.6987	5.4200	2.6657	5.3291	6.7862	6.1276
490	7.2017	7.0076	5.6805	2.8134	5.5832	7.1030	6.4222
495	7.5200	7.3240	5.9482	2.9698	5.8497	7.4176	6.7120
500	7.8384	7.6394	6.2147	3.1240	6.1176	7.7342	7.0080
505	8.1691	7.9564	6.4910	3.2858	6.3846	8.0550	7.3029
510	8.4876	8.2794	6.7607	3.4472	6.6605	8.3777	7.6049
515	8.8241	8.6093	7.0475	3.6143	6.9388	8.7063	7.9112
520	9.1554	8.9326	7.3320	3.7824	7.2137	9.0307	8.2178
525	9.4923	9.2643	7.6115	3.9510	7.4948	9.3604	8.5284
530	9.8242	9.5945	7.8927	4.1262	7.7763	9.6886	8.8368
535	10.1653	9.9223	8.1825	4.3011	8.0580	10.0307	9.1513
540	10.5087	10.2566	8.4672	4.4801	8.3504	10.3633	9.4655
545	10.8454	10.5850	8.7560	4.6594	8.6374	10.6932	9.7733
550	11.1666	10.9149	9.0458	4.8383	8.9212	11.0248	10.0842
555	11.5048	11.2458	9.3317	5.0236	9.2031	11.3600	10.4016
560	11.8312	11.5753	9.6226	5.2100	9.4964	11.6862	10.7095
565	12.1681	11.9029	9.9089	5.3968	9.7782	12.0125	11.0192
570	12.4973	12.2294	10.1917	5.5807	10.0612	12.3401	11.3291
575	12.8180	12.5601	10.4787	5.7673	10.3462	12.6564	11.6379
580	13.1536	12.8808	10.7677	5.9454	10.6353	12.9840	11.9438
585	13.4778	13.2052	11.0539	6.1360	10.9159	13.3043	12.2480
590	13.8062	13.5113	11.3284	6.3245	11.1905	13.6200	12.5453
595	14.1264	13.8349	11.6094	6.5118	11.4684	13.9460	12.8522
600	14.3954	14.1070	11.8906	6.6880	11.7574	14.1833	13.1282
605	14.7610	14.4401	12.1705	6.8954	12.0241	14.5367	13.4143
610	15.0407	14.7340	12.4352	7.0652	12.2844	14.8683	13.7109
615	15.3008	15.0147	12.7057	7.2515	12.5465	15.1278	13.9820
620	15.5955	15.3149	12.9186	7.4260	12.8078	15.4124	14.2699
625	15.9056	15.6048	13.2356	7.6304	13.0697	15.6941	14.5536
630	16.2455	15.9151	13.4883	7.8072	13.3421	16.0758	14.8651
635	16.4740	16.2107	13.7173	7.9916	13.5770	16.3093	15.1417
640	16.7810	16.4615	13.9859	8.1733	13.8690	16.5615	15.3768
645	17.0394	16.7117	14.2153	8.3431	14.0950	16.8452	15.6255
650	17.3336	16.9636	14.4434	8.5244	14.3146	17.1371	15.8589
655	17.5454	17.2555	14.6917	8.6955	14.5609	17.3704	16.1476
660	17.7674	17.5209	14.9404	8.8772	14.8028	17.5972	16.3378
665	18.0693	17.7530	15.1761	9.0429	15.0518	17.9176	16.6445

Table 4. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F268 (NIST 8/94 values) on 21 Sept 1994, also using working standards recalibrated on 28 Sept 1994 to monitor the responsivity drift of the 746/ISIC. All units are in $\mu\mathrm{W\,cm^{-2}\,nm^{-1}}$ unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

	Lamp Number						
λ (nm)	F303	F307	GS-922	H90572	H91348	H91738	H91739
670	18.3331	17.9952	15.4201	9.2281	15.3018	18.1279	16.8617
675	18.6109	18.2741	15.6613	9.4142	15.5195	18.4060	17.1401
680	18.7830	18.4531	15.8247	9.5512	15.7076	18.6055	17.2938
685	19.0522	18.6803	16.0106	9.7103	15.9473	18.8392	17.5279
690	19.2629	18.9556	16.2585	9.9000	16.1898	19.0514	17.7615
695	19.5377	19.1768	16.4620	10.0462	16.3918	19.3373	18.0085
700	19.7109	19.3577	16.6798	10.2158	16.5867	19.4780	18.2027
705	19.9203	19.5562	16.8617	10.3557	16.7514	19.7293	18.4004
710	20.0764	19.8140	17.0875	10.5152	16.9595	19.8929	18.6138
715	20.3179	19.9971	17.2464	10.6690	17.1265	20.1040	18.7970
720	20.4693	20.2026	17.4437	10.8100	17.3060	20.2772	18.9998
725	20.6380	20.3845	17.5926	10.9448	17.4718	20.4881	19.1524
730	20.8132	20.5627	17.7247	11.0797	17.6637	20.6630	19.3496
735	20.9899	20.7084	17.9318	11.2233	17.8282	20.7950	19.4688
740	21.1357	20.8878	18.0710	11.3505	17.9761	20.9510	19.6649
745	21.3479	21.0445	18.1986	11.4821	18.1532	21.1714	19.8109
750	21.5032	21.1982	18.4099	11.6490	18.3293	21.2779	19.9447
755	21.6003	21.3558	18.4711	11.7362	18.3943	21.4002	20.1307
760	21.7800	21.4640	18.6479	11.8785	18.5935	21.5940	20.2526
765	21.9414	21.6133	18.8042	12.0071	18.7468	21.7356	20.4015
770	21.9564	21.7513	18.9297	12.1108	18.8602	21.7954	20.4926
775	22.2019	21.9134	19.0547	12.2234	18.9692	22.0090	20.6756
780	22.2472	21.9555	19.1261	12.3147	19.1336	22.0699	20.7701
785	22.4192	22.0884	19.2718	12.4285	19.2328	22.2108	20.9039
790	22.5211	22.2542	19.3916	12.5685	19.3819	22.3270	21.0299
795	22.6150	22.3363	19.4665	12.6559	19.4393	22.4170	21.0967
800	22.7521	22.3754	19.5738	12.7349	19.5769	22.5406	21.2188
805	22.8243	22.5177	19.6666	12.8263	19.6767	22.6197	21.3294
810	22.9261	22.6536	19.7362	12.9297	19.7222	22.7317	21.4309
815	22.9385	22.7034	19.8649	13.0201	19.8792	22.7335	21.5469
820	23.0311	22.7629	19.8725	13.0992	19.8935	22.8344	21.5873
825	23.0375	22.8309	19.9626	13.1763	20.0124	22.8754	21.6351
830	23.1129	22.9755	20.0737	13.2885	20.1273	22.9875	21.7602
835	23.2449	22.9619	20.0966	13.3297	20.1492	23.0636	21.7575
840	23.2461	23.0278	20.1890	13.4122	20.2207	23.0851	21.8319
845	23.3296	23.0930	20.2207	13.4841	20.2643	23.1472	21.9069
850	23.3981	23.1341	20.2701	13.5448	20.3187	23.2034	21.9634
855	23.3810	23.1640	20.3162	13.5802	20.3900	23.2163	22.0122
860	23.4871	23.1913	20.3851	13.6705	20.4336	23.2823	22.0614
865	23.4856	23.2699	20.4520	13.7545	20.5189	23.3009	22.0906
870	23.4498	23.2776	20.4490	13.7764	20.5215	23.2972	22.0716
875	23.5997	23.2796	20.4905	13.8352	20.5351	23.3433	22.1437
880	23.5057	23.3398	20.5357	13.8807	20.5767	23.3123	22.1552
885	23.5145	23.3417	20.5128	14.0723	20.5747	23.3679	22.1845
890	23.6020	23.3441	20.5485	14.0560	20.6406	23.3936	22.1548
895	23.5525	23.3640	20.5623	14.0845	20.6464	23.3502	22.1815

Table 4. (cont.) Spectral irradiance measurements of FEL lamps transferred from the F268 (NIST 8/94 values) on 21 Sept 1994, also using working standards recalibrated on 28 Sept 1994 to monitor the responsivity drift of the 746/ISIC. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

	Lamp Number						
λ (nm)	F303	F307	GS-922	H90572	H91348	H91738	H91739
900	23.6347	23.3209	20.5888	14.1334	20.7171	23.3903	22.2034
905	23.6271	23.3543	20.5938	14.1863	20.6678	23.3858	22.2271
910	23.6440	23.4016	20.6310	14.2090	20.7279	23.4317	22.2622
915	23.6644	23.3950	20.6310	14.2280	20.7358	23.4000	22.2717
920	23.6034	23.3584	20.5964	14.2696	20.7216	23.4022	22.2363
925	23.5705	23.3104	20.5765	14.2915	20.7269	23.3577	22.2141
930	23.5842	23.3301	20.5523	14.2997	20.6865	23.3469	22.2505
935	23.6234	23.3190	20.5688	14.3625	20.7181	23.3914	22.2284
940	23.5050	23.2910	20.5257	14.3637	20.7215	23.2862	22.2080
945	23.5232	23.2552	20.5548	14.3707	20.6822	23.3096	22.1906
950	23.4399	23.2340	20.5016	14.4024	20.6832	23.2665	22.1388
955	23.4098	23.2222	20.5485	14.4456	20.7000	23.2282	22.1356
960	23.3602	23.1536	20.4851	14.4125	20.6239	23.1746	22.1163
965	23.3218	23.1081	20.4277	14.4184	20.5847	23.1299	21.9928
970	23.2649	23.0910	20.4010	14.4446	20.5691	23.1502	22.0288
975	23.2038	23.0286	20.3467	14.4169	20.5195	23.0272	21.9423
980	23.0768	22.9669	20.2830	14.3926	20.4663	22.9698	21.9015
985	23.1342	22.9647	20.2991	14.4637	20.4838	22.9717	21.8942
990	23.0166	22.8760	20.2308	14.4236	20.4435	22.9312	21.7969
995	22.9409	22.7965	20.1884	14.4016	20.3967	22.8809	21.7284
1000	22.8982	22.7421	20.1334	14.4430	20.3624	22.7845	21.6819

Table 5. Spectral irradiance values for F269 following the *shift anomaly* of 21 Sept 1994, as transferred from the NIST scale using F268 and F182 (8/94 values). The transfers of the F268 values to F269 on 21 Sept 1994 were, in part, accomplished indirectly through the use of other intermediate working standards. Times are in PDT. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

λ [nm]	F268 21 Sept 15:06	F268 21 Sept 17:10	F268 26 Sept 11:50	F182 26 Sept 13:34	F268 28 Sept 16:53	*Mean*	σ	σ [%]
380	1.6604	1.6467	1.6473	1.6497	1.6566	1.6521	0.0061	0.37
390	1.9896	1.9932	1.9856	1.9693	1.9926	1.9861	0.0098	0.50
395	2.1717	2.1516	2.1662	2.1618	2.1732	2.1649	0.0087	0.40
400	2.3647	2.3453	2.3436	2.3465	2.3578	2.3516	0.0092	0.39
405	2.5643	2.5471	2.5511	2.5256	2.5689	2.5514	0.0170	0.67
410	2.7606	2.7576	2.7509	2.7411	2.7551	2.7531	0.0076	0.28
415	2.9840	2.9621	2.9547	2.9519	2.9848	2.9675	0.0159	0.53
420	3.2148	3.1775	3.1827	3.1760	3.2040	3.1910	0.0174	0.55
425	3.4615	3.4066	3.4098	3.4014	3.4789	3.4316	0.0359	1.04
430	3.6871	3.6528	3.6540	3.6445	3.6728	3.6622	0.0173	0.47
435	3.9526	3.8500	3.8953	3.8802	3.9284	3.9013	0.0402	1.03
440	4.1847	4.1538	4.1639	4.1372	4.1752	4.1630	0.0185	0.44
445	4.4603	4.3989	4.4100	4.3999	4.4382	4.4215	0.0269	0.61
450	4.7216	4.6548	4.6827	4.6665	4.7072	4.6866	0.0277	0.59

Table 5. (cont.) Spectral irradiance values for F269 following the *shift anomaly* of 21 Sept 1994, as transferred from the NIST scale using F268 and F182 (8/94 values). The transfers of the F268 values to F269 on 21 Sept 1994 were, in part, accomplished indirectly through the use of other intermediate working standards. Times are in PDT. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

λ [nm]	F268 21 Sept 15:06	F268 21 Sept 17:10	F268 26 Sept 11:50	F182 26 Sept 13:34	F268 28 Sept 16:53	*Mean*	σ	σ [%]
455	4.9979	4.9283	4.9565	4.9418	4.9822	4.9613	0.0286	0.58
460	5.2850	5.2233	5.2392	5.2120	5.2623	5.2444	0.0295	0.56
465	5.5687	5.4992	5.5267	5.4977	5.5506	5.5286	0.0313	0.57
470	5.8582	5.7896	5.8194	5.7947	5.8428	5.8209	0.0297	0.51
475	6.1716	6.0906	6.1167	6.0916	6.1446	6.1230	0.0350	0.57
480	6.4746	6.3938	6.4165	6.3821	6.4470	6.4228	0.0381	0.59
485	6.7910	6.6938	6.7251	6.6857	6.7564	6.7304	0.0439	0.65
490	7.1031	6.9987	7.0344	6.9954	7.0625	7.0388	0.0453	0.64
495	7.4057	7.3155	7.3477	7.3074	7.3797	7.3512	0.0418	0.57
500	7.7254	7.6335	7.6706	7.6225	7.6997	7.6703	0.0434	0.57
505	8.0574	7.9640	7.9911	7.9423	8.0206	7.9951	0.0456	0.57
510	8.3755	8.2720	8.3096	8.2654	8.3458	8.3137	0.0473	0.57
515	8.6993	8.5793	8.6328	8.5920	8.6694	8.6346	0.0507	0.59
520	9.0039	8.9185	8.9586	8.9119	8.9935	8.9573	0.0420	0.47
525	9.3351	9.2332	9.2890	9.2329	9.3181	9.2817	0.0473	0.51
530	9.6626	9.5544	9.6177	9.5642	9.6486	9.6095	0.0487	0.51
535	9.9951	9.8884	9.9416	9.8876	9.9796	9.9385	0.0500	0.50
540	10.3304	10.2080	10.2722	10.2166	10.3091	10.2673	0.0544	0.53
545	10.6564	10.5279	10.6020	10.5459	10.6366	10.5938	0.0558	0.53
550	10.9841	10.8619	10.9250	10.8734	10.9691	10.9227	0.0549	0.50
555	11.3170	11.1872	11.2520	11.1994	11.2982	11.2508	0.0577	0.51
560	11.6503	11.5063	11.5822	11.5223	11.6287	11.5780	0.0634	0.55
565	11.9688	11.8401	11.9153	11.8435	11.9546	11.9045	0.0605	0.51
570	12.2894	12.1465	12.2363	12.1698	12.2782	12.2240	0.0639	0.52
575	12.6151	12.4572	12.5630	12.4981	12.6027	12.5472	0.0679	0.54
580	12.9528	12.7772	12.8884	12.8230	12.9263	12.8735	0.0727	0.56
585	13.2643	13.0986	13.2019	13.1448	13.2404	13.1900	0.0682	0.52
590	13.5814	13.4191	13.5226	13.4567	13.5493	13.5058	0.0667	0.49
595	13.8898	13.7394	13.8346	13.7797	13.8652	13.8217	0.0617	0.45
600	14.1558	14.0765	14.1773	14.0534	14.1978	14.1322	0.0637	0.45
605	14.4919	14.3507	14.4758	14.3429	14.4730	14.4269	0.0735	0.51
610	14.8010	14.6736	14.7645	14.6550	14.7559	14.7300	0.0627	0.43
615	15.0865	14.9920	15.0409	14.9693	15.0495	15.0276	0.0469	0.31
620	15.3389	15.2861	15.3148	15.2509	15.3348	15.3051	0.0368	0.24
625	15.6643	15.5231	15.6189	15.5307	15.6146	15.5903	0.0611	0.39
630	15.9618	15.8033	15.8973	15.8087	15.9348	15.8812	0.0724	0.46
635	16.1957	16.1080	16.1713	16.0719	16.2092	16.1512	0.0590	0.37
640	16.5201	16.2799	16.4418	16.4003	16.4822	16.4249	0.0926	0.56
645	16.7436	16.6750	16.7307	16.6118	16.7466	16.7015	0.0579	0.35
650	17.0102	16.8520	16.9705	16.8769	16.9832	16.9386	0.0697	0.41
655	17.2870	17.1116	17.2172	17.1608	17.2373	17.2028	0.0681	0.40
660	17.5356	17.4368	17.4720	17.4204	17.5121	17.4754	0.0487	0.28
665	17.8237	17.5921	17.7222	17.6278	17.7472	17.7026	0.0933	0.53
670	18.0977	17.7665	17.9681	17.9022	18.0384	17.9546	0.1283	0.71

Table 5. (cont.) Spectral irradiance values for F269 following the *shift anomaly* of 21 Sept 1994, as transferred from the NIST scale using F268 and F182 (8/94 values). The transfers of the F268 values to F269 on 21 Sept 1994 were, in part, accomplished indirectly through the use of other intermediate working standards. Times are in PDT. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

λ [nm]	F268 21 Sept 15:06	F268 21 Sept 17:10	F268 26 Sept 11:50	F182 26 Sept 13:34	F268 28 Sept 16:53	*Mean*	σ	σ [%]
675	18.3455	18.1354	18.2095	18.1239	18.2621	18.2153	0.0921	0.51
680	18.5297	18.3001	18.4576	18.3786	18.4988	18.4330	0.0934	0.51
685	18.7565	18.5773	18.6770	18.6403	18.7242	18.6751	0.0704	0.38
690	19.0321	18.7960	18.8789	18.8353	18.9585	18.9002	0.0953	0.50
695	19.2208	18.9900	19.1124	19.0497	19.1738	19.1093	0.0927	0.49
700	19.4334	19.1796	19.3160	19.2585	19.4150	19.3205	0.1065	0.55
705	19.6159	19.4888	19.5470	19.4997	19.5624	19.5428	0.0513	0.26
710	19.8479	19.5782	19.6942	19.6582	19.8080	19.7173	0.1103	0.56
715	20.0154	19.8861	19.9420	19.8773	19.9916	19.9425	0.0616	0.31
720	20.2331	20.0085	20.1465	20.0674	20.2095	20.1330	0.0947	0.47
725	20.4006	20.2598	20.3325	20.2395	20.3408	20.3146	0.0653	0.32
730	20.5524	20.3526	20.4838	20.4105	20.5141	20.4627	0.0806	0.39
735	20.7382	20.5566	20.6300	20.5620	20.7195	20.6413	0.0853	0.41
740	20.8918	20.7398	20.8004	20.7831	20.8527	20.8136	0.0596	0.29
745	21.0498	20.8496	20.9003	20.9092	21.0178	20.9453	0.0847	0.40
750	21.2705	20.9627	21.1167	21.0215	21.1628	21.1068	0.1205	0.57
755	21.3567	21.1901	21.2618	21.1726	21.3237	21.2610	0.0805	0.38
760	21.4880	21.2680	21.3900	21.3383	21.4427	21.3854	0.0864	0.40
765	21.6486	21.3487	21.5396	21.4548	21.5713	21.5126	0.1150	0.53
770	21.8016	21.5235	21.6426	21.5380	21.7029	21.6417	0.1162	0.54
775	21.9148	21.6815	21.7689	21.6750	21.8521	21.7785	0.1051	0.48
780	22.0030	21.7039	21.9047	21.8070	21.9165	21.8670	0.1146	0.52
785	22.1166	21.9288	21.9615	21.9340	22.0759	22.0034	0.0869	0.39
790	22.2806	21.9617	22.1329	22.0585	22.2090	22.1285	0.1249	0.56
795	22.3326	22.0644	22.1771	22.1758	22.2549	22.2010	0.1001	0.45
800	22.4158	22.2072	22.2610	22.2728	22.4258	22.3165	0.0984	0.44
805	22.5601	22.3055	22.4039	22.3635	22.4830	22.4232	0.1001	0.45
810	22.5813	22.3362	22.4774	22.4471	22.5554	22.4795	0.0971	0.43
815	22.6882	22.4408	22.5618	22.5085	22.6565	22.5712	0.1025	0.45
820	22.7696	22.5498	22.6405	22.5629	22.7202	22.6486	0.0961	0.42
825	22.8545	22.6617	22.6964	22.6432	22.8005	22.7313	0.0919	0.40
830	22.9436	22.6388	22.7977	22.7350	22.8620	22.7954	0.1168	0.51
835	22.9695	22.7526	22.8256	22.7336	22.8912	22.8345	0.0980	0.43
840	23.0211	22.7685	22.8821	22.8451	22.9542	22.8942	0.0975	0.43
845	23.0505	22.8473	22.9332	22.8988	23.0594	22.9578	0.0938	0.41
850	23.1495	22.9653	23.0128	22.9295	23.0914	23.0297	0.0903	0.39
855	23.1199	22.8789	23.0364	23.0039	23.0929	23.0264	0.0942	0.41
860	23.2214	22.9739	23.0887	22.9744	23.1342	23.0785	0.1065	0.46
865	23.2607	23.0261	23.1032	23.0873	23.1701	23.1295	0.0895	0.39
870	23.2588	23.1354	23.1779	23.0820	23.2228	23.1754	0.0699	0.30
875	23.2776	23.0956	23.1829	23.0866	23.2845	23.1854	0.0951	0.41
880	23.3152	23.1368	23.1850	23.0892	23.2564	23.1965	0.0907	0.39
885	23.3288	23.2038	23.2448	23.1491	23.2693	23.2392	0.0677	0.29
890	23.3685	23.1927	23.2537	23.1725	23.2497	23.2474	0.0763	0.33

Table 5. (cont.) Spectral irradiance values for F269 following the *shift anomaly* of 21 Sept 1994, as transferred from the NIST scale using F268 and F182 (8/94 values). The transfers of the F268 values to F269 on 21 Sept 1994 were, in part, accomplished indirectly through the use of other intermediate working standards. Times are in PDT. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.5%.

λ [nm]	F268 21 Sept 15:06	F268 21 Sept 17:10	F268 26 Sept 11:50	F182 26 Sept 13:34	F268 28 Sept 16:53	*Mean*	σ	σ [%]
895	23.3966	23.1470	23.2000	23.1624	23.3056	23.2423	0.1061	0.46
900	23.3902	23.2229	23.2469	23.1769	23.2573	23.2588	0.0797	0.34
905	23.3656	23.1279	23.2441	23.1441	23.3222	23.2408	0.1052	0.45
910	23.4326	23.1363	23.1951	23.1507	23.3158	23.2461	0.1259	0.54
915	23.4103	23.1407	23.1858	23.1393	23.3056	23.2363	0.1185	0.51
920	23.3730	23.1038	23.2152	23.1362	23.2915	23.2239	0.1107	0.48
925	23.3532	23.0885	23.1709	23.1147	23.2746	23.2004	0.1113	0.48
930	23.3199	23.1864	23.1802	23.0911	23.2478	23.2051	0.0851	0.37
935	23.3138	23.1359	23.1025	23.0636	23.2350	23.1702	0.1024	0.44
940	23.2729	23.1082	23.1170	22.9840	23.2067	23.1378	0.1095	0.47
945	23.2789	23.0916	23.1020	22.9878	23.1733	23.1267	0.1078	0.47
950	23.2141	23.0345	23.0838	22.9151	23.1571	23.0809	0.1153	0.50
955	23.2250	22.8756	22.9781	22.8951	23.1227	23.0193	0.1506	0.65
960	23.1374	22.8883	22.9965	22.7994	23.0636	22.9770	0.1351	0.59
965	23.0882	22.9255	22.8983	22.7268	22.9996	22.9277	0.1343	0.59
970	23.0222	22.7987	22.8538	22.6626	22.9787	22.8632	0.1441	0.63
975	22.9845	22.7851	22.8218	22.5953	22.8974	22.8168	0.1455	0.64
980	22.8926	22.7610	22.7578	22.4469	22.8245	22.7366	0.1711	0.75
985	22.9090	22.5855	22.6899	22.3518	22.8117	22.6696	0.2156	0.95
990	22.8219	22.6178	22.6511	22.3144	22.7127	22.6236	0.1895	0.84
995	22.7536	22.5418	22.6275	22.1634	22.6964	22.5565	0.2336	1.04
1000	22.6935	22.3630	22.4868	22.0864	22.6200	22.4499	0.2394	1.07

Table 6. Spectral irradiance values for five FEL lamps as transferred from the NIST scale using lamp F268 (8/94 values) on 28 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.%.

	Lamp Number				
λ (nm)	F269	F308	H90573	H91349	H91534
380	1.6566	1.6976	1.6519	1.1717	1.5256
385	1.8567	1.8777	1.8288	1.0257	1.3209
390	1.9926	2.0381	1.9792	1.4030	1.8289
395	2.1732	2.2224	2.1652	1.5394	1.9965
400	2.3578	2.4133	2.3517	1.6702	2.1694
405	2.5689	2.6198	2.5555	1.8262	2.3580
410	2.7551	2.8212	2.7532	1.9741	2.5510
415	2.9848	3.0435	2.9720	2.1411	2.7516
420	3.2040	3.2733	3.1969	2.3124	2.9625
425	3.4789	3.5409	4.6984	2.4867	3.1850
430	3.6728	3.7514	3.6607	2.6500	3.4120
435	3.9284	4.0060	3.9046	2.8635	3.6429
440	4.1752	4.2597	4.1658	3.0510	3.8780
445	4.4382	4.5288	4.4276	3.2602	4.1316

Table 6. (cont.) Spectral irradiance values for five FEL lamps as transferred from the NIST scale using lamp F268 (8/94 values) on 28 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.%.

	Lamp Number				
λ (nm)	F269	F308	H90573	H91349	H91534
450	4.7072	4.8001	4.6924	3.4639	4.3824
455	4.9822	5.0818	4.9702	3.6846	4.6405
460	5.2623	5.3727	5.2507	3.9041	4.9116
465	5.5506	5.6598	5.5422	4.1322	5.1873
470	5.8428	5.9589	5.8344	4.3655	5.4634
475	6.1446	6.2689	6.1347	4.6051	5.7521
480	6.4470	6.5759	6.4365	4.8492	6.0433
485	6.7564	6.8927	6.7468	5.0977	6.3364
490	7.0625	7.2048	7.0612	5.3487	6.6359
495	7.3797	7.5234	7.3790	5.6061	6.9377
500	7.6997	7.8505	7.6968	5.8635	7.2430
505	8.0206	8.1746	8.0145	6.1241	7.5553
510	8.3458	8.5031	8.3388	6.3906	7.8605
515	8.6694	8.8382	8.6672	6.6597	8.1795
520	8.9935	9.1696	8.9931	6.9273	8.4945
525	9.3181	9.5042	9.3270	7.2022	8.8120
530	9.6486	9.8370	9.6544	7.4766	9.1304
535	9.9796	10.1699	9.9872	7.7496	9.4527
540	10.3091	10.5065	10.3181	8.0303	9.7760
545	10.6366	10.8481	10.6536	8.3107	10.0979
550	10.9691	11.1801	10.9868	8.5894	10.4137
555	11.2982	11.5197	11.3205	8.8656	10.7369
560	11.6287	11.8515	11.6538	9.1491	11.0584
565	11.9546	12.1844	11.9815	9.4241	11.3790
570	12.2782	12.5152	12.3025	9.7044	11.6932
575	12.6027	12.8410	12.6322	9.9837	12.0056
580	12.9263	13.1719	12.9529	10.2674	12.3239
585	13.2404	13.4939	13.2742	10.5375	12.6350
590	13.5493	13.8146	13.5891	10.8058	12.9456
595	13.8652	14.1380	13.9131	11.0769	13.2554
600	14.1978	14.4337	14.2200	11.3442	13.5248
605	14.4730	14.7619	14.5370	11.6037	13.8631
610	14.7559	15.0367	14.8123	11.8647	14.1588
615	15.0495	15.3293	15.1115	12.1263	14.4279
620	15.3348	15.6141	15.3967	12.3648	14.7142
625	15.6146	15.9418	15.6849	12.6356	14.9934
630	15.9348	16.2219	16.0053	12.9007	15.3211
635	16.2092	16.5078	16.2800	13.1313	15.5929
640	16.4822	16.7871	16.5451	13.4105	15.8512
645	16.7466	17.0387	16.8184	13.6270	16.1219
650	16.9832	17.3222	17.0513	13.8611	16.3861
655	17.2373	17.5706	17.3446	14.0863	16.6030
660	17.5121	17.8554	17.5858	14.3432	16.8711
665	17.7472	18.0960	17.8612	14.5899	17.1548
670	18.0384	18.3580	18.1202	14.8206	17.3835
675	18.2621	18.6280	18.3607	15.0329	17.6558

Table 6. (cont.) Spectral irradiance values for five FEL lamps as transferred from the NIST scale using lamp F268 (8/94 values) on 28 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.%.

	Lamp Number				
λ (nm)	F269	F308	H90573	H91349	H91534
680	18.4988	18.8231	18.5870	15.2357	17.8408
685	18.7242	19.0620	18.8182	15.4556	18.0808
690	18.9585	19.3267	19.0492	15.6760	18.3291
695	19.1738	19.5447	19.2940	15.8713	18.5474
700	19.4150	19.7438	19.4891	16.0847	18.7547
705	19.5624	19.9495	19.6889	16.2531	18.9780
710	19.8080	20.1554	19.8946	16.4442	19.1626
715	19.9916	20.3591	20.0927	16.6318	19.3576
720	20.2095	20.5610	20.2873	16.7974	19.5453
725	20.3408	20.7109	20.4720	16.9794	19.7238
730	20.5141	20.9052	20.6636	17.1430	19.9102
735	20.7195	21.0653	20.8089	17.2979	20.0787
740	20.8527	21.2372	20.9688	17.4696	20.2075
745	21.0178	21.3877	21.1335	17.6154	20.4263
750	21.1628	21.5742	21.2988	17.7973	20.5693
755	21.3237	21.6669	21.4632	17.9283	20.6878
760	21.4427	21.8606	21.6000	18.0451	20.8751
765	21.5713	22.0049	21.7357	18.2240	21.0093
770	21.7029	22.1034	21.8566	18.3176	21.0926
775	21.8521	22.2498	21.9900	18.4647	21.2974
780	21.9165	22.3160	22.1093	18.5829	21.3655
785	22.0759	22.4417	22.2307	18.7131	21.5271
790	22.2090	22.6227	22.3295	18.8210	21.6198
795	22.2549	22.6852	22.4188	18.8970	21.7279
800	22.4258	22.7631	22.5269	19.0412	21.8429
805	22.4830	22.8535	22.6226	19.1356	21.9361
810	22.5554	22.9720	22.7560	19.2076	22.0309
815	22.6565	23.0476	22.8286	19.3237	22.0932
820	22.7202	23.1155	22.8625	19.3683	22.1985
825	22.8005	23.1797	22.9341	19.4411	22.2266
830	22.8620	23.2785	23.0542	19.5456	22.3493
835	22.8912	23.2913	23.0512	19.6096	22.4109
840	22.9542	23.3667	23.1203	19.6799	22.4424
845	23.0594	23.4346	23.1989	19.7406	22.5021
850	23.0914	23.4856	23.2329	19.8101	22.5703
855	23.0929	23.4701	23.2891	19.8778	22.5781
860	23.1342	23.5500	23.3033	19.9301	22.6716
865	23.1701	23.6074	23.3734	19.9688	22.6991
870	23.2228	23.6177	23.3750	20.0150	22.6838
875	23.2845	23.6670	23.4018	20.0459	22.7687
880	23.2564	23.6471	23.4153	20.0866	22.7639
885	23.2693	23.6542	23.4400	20.1035	22.7840
890	23.2497	23.6706	23.4318	20.1343	22.8282
895	23.3056	23.6545	23.4657	20.1730	22.7926
900	23.2573	23.6946	23.4757	20.2234	22.8469
905	23.3222	23.6867	23.4704	20.2022	22.8489

Table 6. (cont.) Spectral irradiance values for five FEL lamps as transferred from the NIST scale using lamp F268 (8/94 values) on 28 Sept 1994. All units are in μW cm^{-2} nm^{-1} unless otherwise indicated. The uncertainty in the spectral irradiances for these lamps (in the spectral range from 400–1000 nm) is 1.%.

	Lamp Number				
λ (nm)	F269	F308	H90573	H91349	H91534
910	23.3158	23.7173	23.4895	20.2503	22.8869
915	23.3056	23.7300	23.4909	20.2676	22.9070
920	23.2915	23.6594	23.4489	20.2416	22.8571
925	23.2746	23.6272	23.4310	20.2440	22.8300
930	23.2478	23.6237	23.4225	20.2215	22.8298
935	23.2350	23.6545	23.4052	20.2581	22.8410
940	23.2067	23.5583	23.3887	20.2371	22.7634
945	23.1733	23.5553	23.3379	20.2136	22.8065
950	23.1571	23.5325	23.3379	20.2207	22.7495
955	23.1227	23.5140	23.3180	20.2316	22.7122
960	23.0636	23.4554	23.2527	20.1525	22.7035
965	22.9996	23.3879	23.1801	20.1437	22.6353
970	22.9787	23.3617	23.1839	20.1064	22.6231
975	22.8974	23.2979	23.0979	20.0362	22.5502
980	22.8245	23.2529	23.0601	20.0135	22.4986
985	22.8117	23.2388	23.0329	20.0337	22.4932
990	22.7127	23.1452	22.9667	19.9562	22.4156
995	22.6964	23.0785	22.8877	19.9433	22.3582
1000	22.6200	23.0354	22.8442	19.8750	22.3179

to calibrate the 746/ISIC). This component of uncertainty is present in the measurement of all the lamps listed in Table 1, as reported in the data given in Tables 2–6. Second, there is the uncertainty component from the measurement of the unknown lamp using the 746/ISIC, which is about 1% (see Fig. 2 and 3). Third, in the case where the derived values of F269 were used, there is an additional uncertainty component of about 1%. In the spectral region, from 400–1000 nm, the overall standard uncertainty of the spectral irradiance of the secondary standard from NIST is typically between 0.4–0.5%. Therefore, the combined uncertainty in the spectral irradiance for the lamps measured at SIRREX-3 is between 1.1–1.5%, depending if the F268-based values for F269 applies.

Several independent spectral irradiance scales are compared to the SIRREX-3 measurements of seven FEL lamps in Figs. 8–14. For each lamp, the approximate deviations are:

1) F321, −0.5 to −1%, NIST (Fig. 8);
2) F308, −2.5%, NIST (Fig. 9);
3) F123, +0.5%, OL (Fig. 10);
4) F12G, −1.5% to −2%, UM (Fig. 11);
5) F303, −2% to −4.2%, OL (Fig. 12);
6) F307, −1% to −2.5%, OL (Fig. 13); and
7) GS-922, −4% to −5%, EG&G (Fig. 14).

Of these lamps, the most serious departures are for F303 and GS-922, and it is recommended that the spectral irradiance of these lamps be evaluated more closely using independent standards. It is probably advisable for F308 to be returned to NIST for recalibration to maintain its status as a NIST secondary standard. Furthermore, the idea of using the NIST-traceable secondary standard lamp to measure the drift of the 746/ISIC should be reconsidered. This procedure results in unnecessary hours on these standards, as some other lamp could be used for most of these measurements.

3. SPHERE SOURCES

Integrating spheres are used as sources of spectral radiance by several participating laboratories. Spheres for which radiance was measured during SIRREX-3 were:

1. *GSFC sphere.* This source is 107 cm in diameter and is illuminated by sixteen 45 W internal lamps. The exit aperture is 39.5 cm in diameter.
2. *CHORS sphere.* This source is 102 cm in diameter and is indirectly illuminated through four auxiliary spheres by four 200 W lamps. The exit aperture is 15.24 cm in diameter.
3. *BSI sphere.* This sphere is 50.8 cm in diameter and is indirectly illuminated using a 10.16 cm satellite

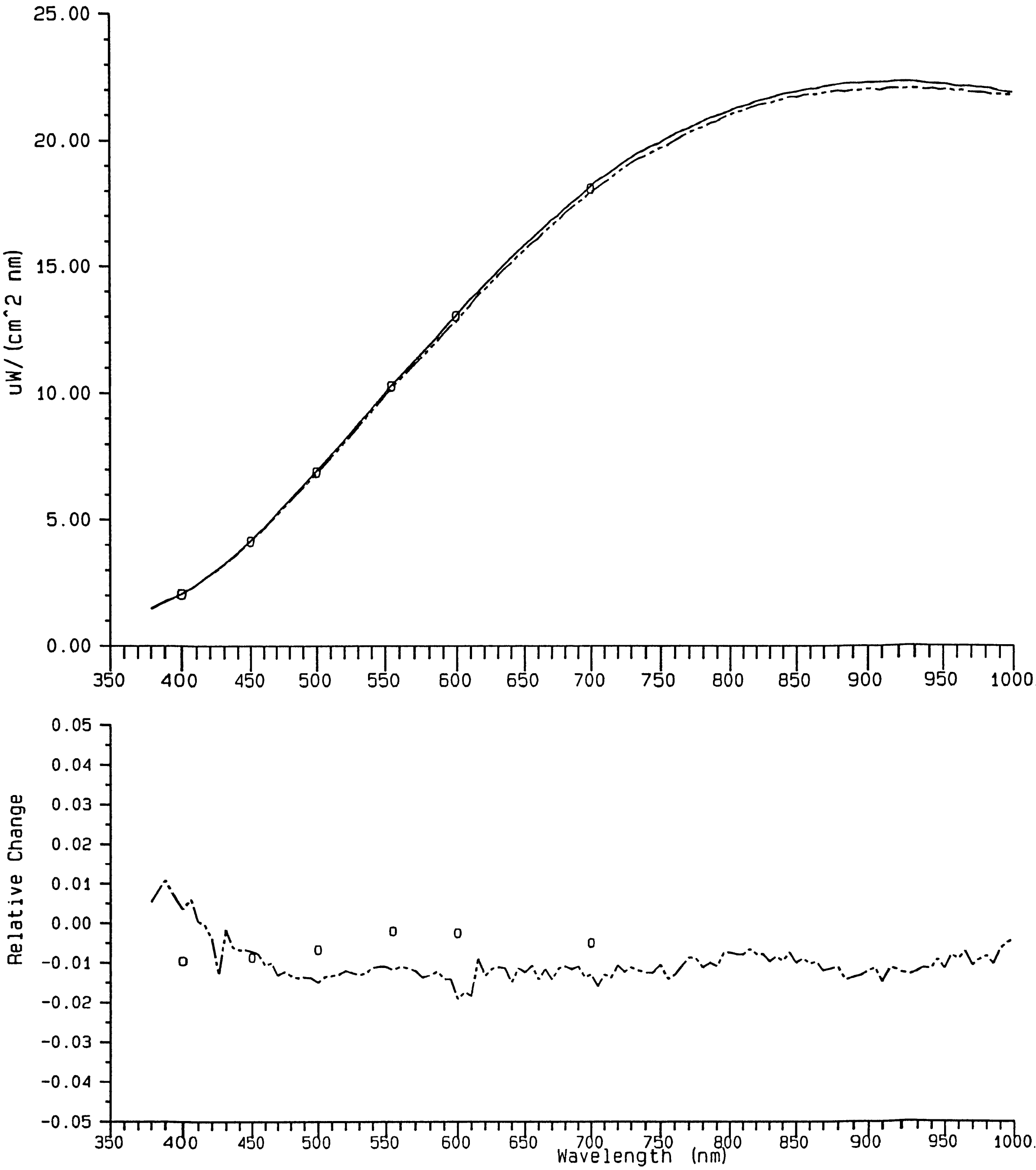


Fig. 8. Spectral irradiance of FEL lamp F321 determined using F269 on 20 Sept 1994 (solid line), compared to the SIRREX-2 values (dashed line) and the original calibration by NIST in February 1991 (o symbol). The spectral irradiance is plotted in the upper panel. The lower panel illustrates the relative changes with respect to the SIRREX-3 values. The quantity plotted using the dash-dot-dot line is the SIRREX-2 data minus the SIRREX-3 data, normalized to the SIRREX-3 data. The o symbol similarly shows the original calibration of F321 by NIST in February 1991.

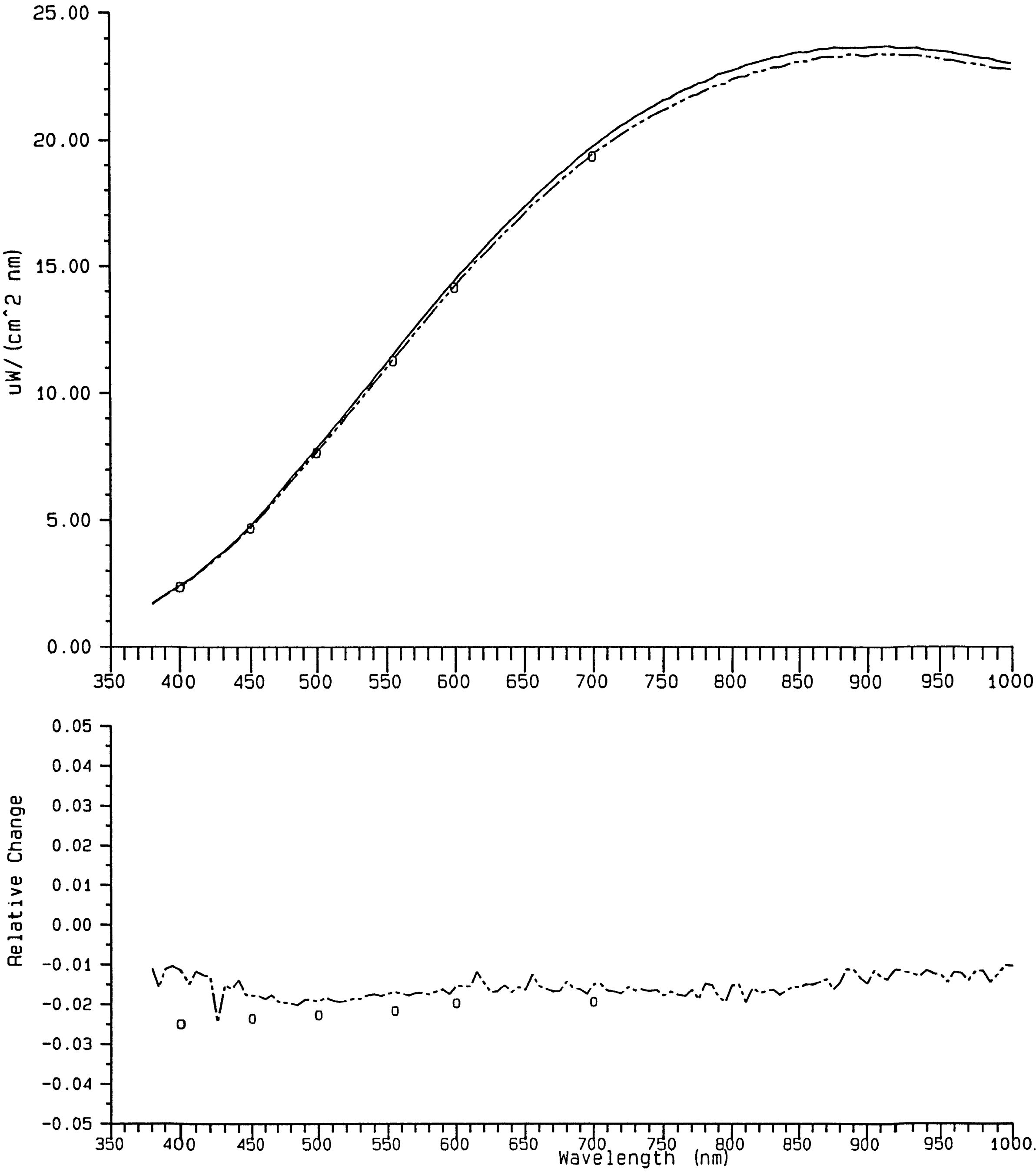


Fig. 9. Spectral irradiance of FEL lamp F308 determined using F268 on 28 September (solid line), compared to the SIRREX-2 values (dashed line) and the original calibration by NIST in October 1992 (o). The spectral irradiance is plotted in the upper panel. The lower panel illustrates the relative changes with respect to the SIRREX-3 values. The quantity plotted using the dash-dot-dot line is the SIRREX-2 data minus the SIRREX-3 data, normalized to the SIRREX-3 data. The o symbol similarly shows the calibration of F308 by NIST in October 1992.

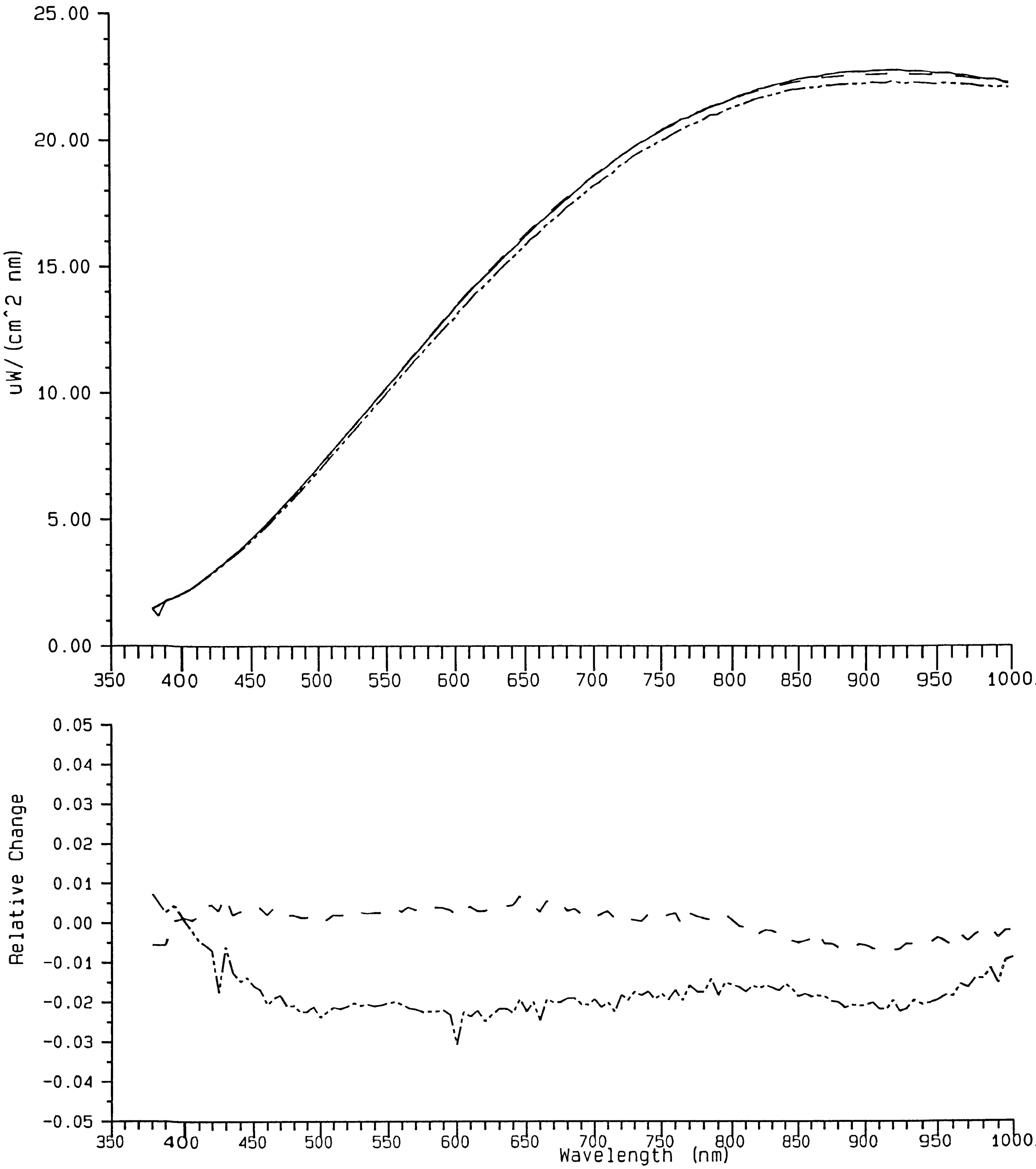


Fig. 10. Spectral irradiance of FEL lamp F123 determined by using F269 on 20 Sept 1994 (solid line), compared to the SIRREX-2 values (dash-dot-dot line) and the original calibration by OL in 1981 (dashed line). The spectral irradiance is plotted in the upper panel. The lower panel illustrates the relative changes with respect to the SIRREX-3 values. The quantity plotted using the dash-dot-dot line is the SIRREX-2 data minus the SIRREX-3 data, normalized to the SIRREX-3 data. The dashed line similarly shows the original calibration of F123 by OL in 1981.

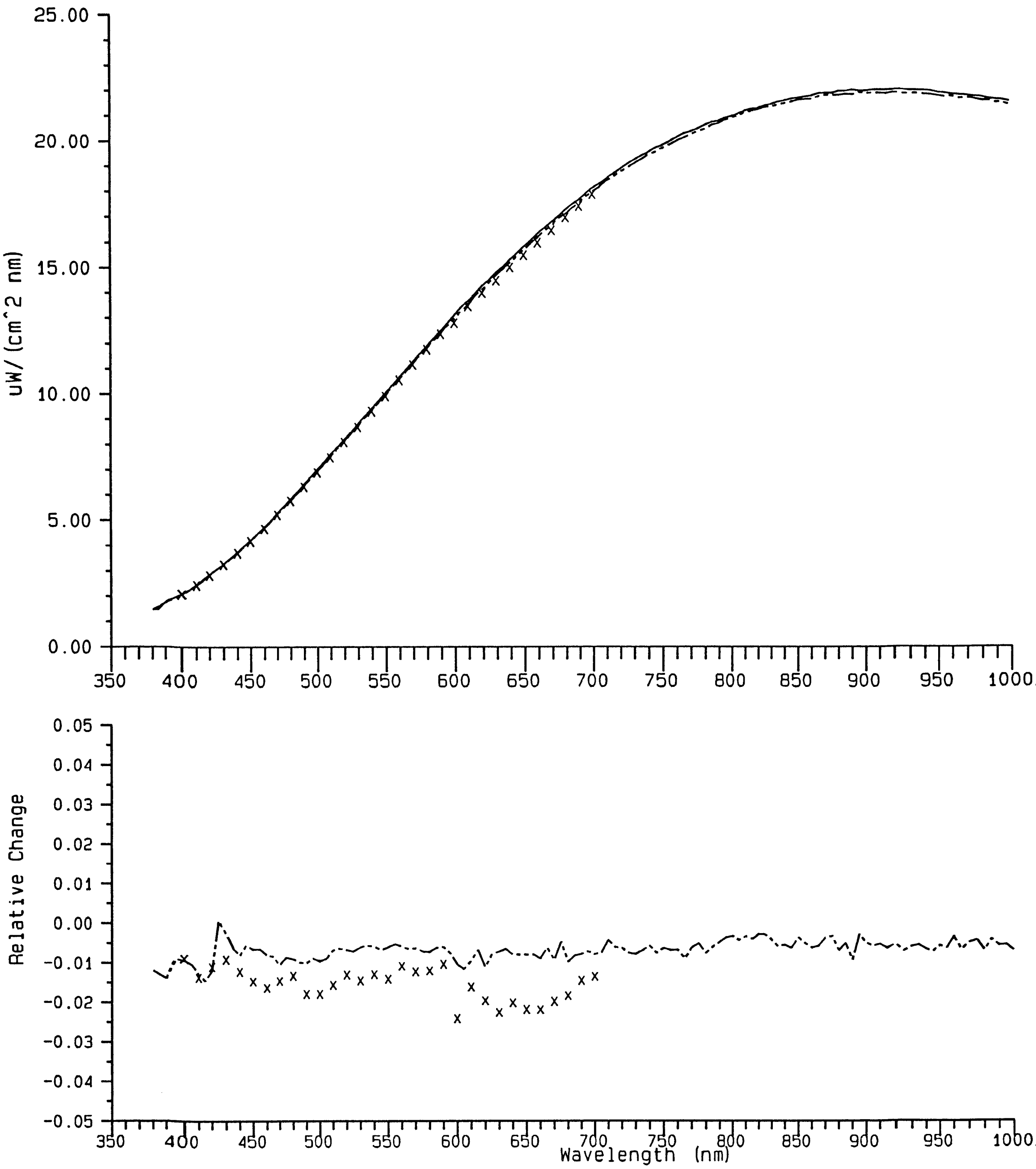


Fig. 11. Spectral irradiance of FEL lamp F12G determined using F269 on 20 Sept 1994 (solid line), compared to the SIRREX-2 values (dashed line) and the calibration by UM (× symbols). The spectral irradiance is plotted in the upper panel. The lower panel illustrates the relative changes with respect to the SIRREX-3 values. The quantity plotted using the dash-dot-dot line is the SIRREX-2 data minus the SIRREX-3 data, normalized to the SIRREX-3 data. The × symbol similarly shows the calibration of F12G by UM.

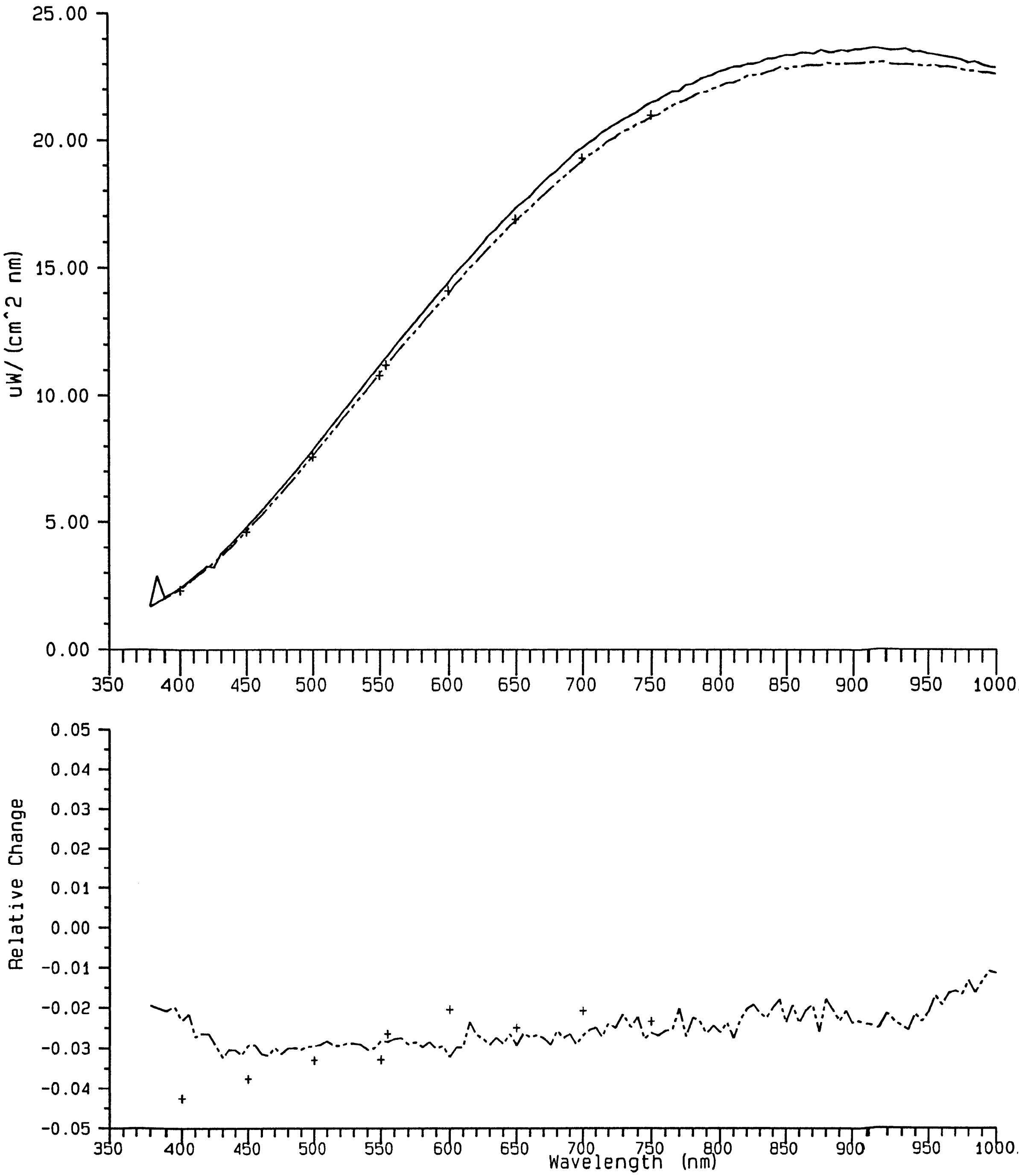


Fig. 12. Spectral irradiance of FEL lamp F303 determined using F268 on 21 Sept 1994 (solid line), compared to the SIRREX-2 values (dashed line) and the original calibration by OL (+). The spectral irradiance is plotted in the upper panel. The lower panel illustrates the relative changes with respect to the SIRREX-3 values. The quantity plotted using the dash-dot-dot line is the SIRREX-2 data minus the SIRREX-3 data, normalized to the SIRREX-3 data. The + symbol similarly shows the original calibration of F303 by OL.

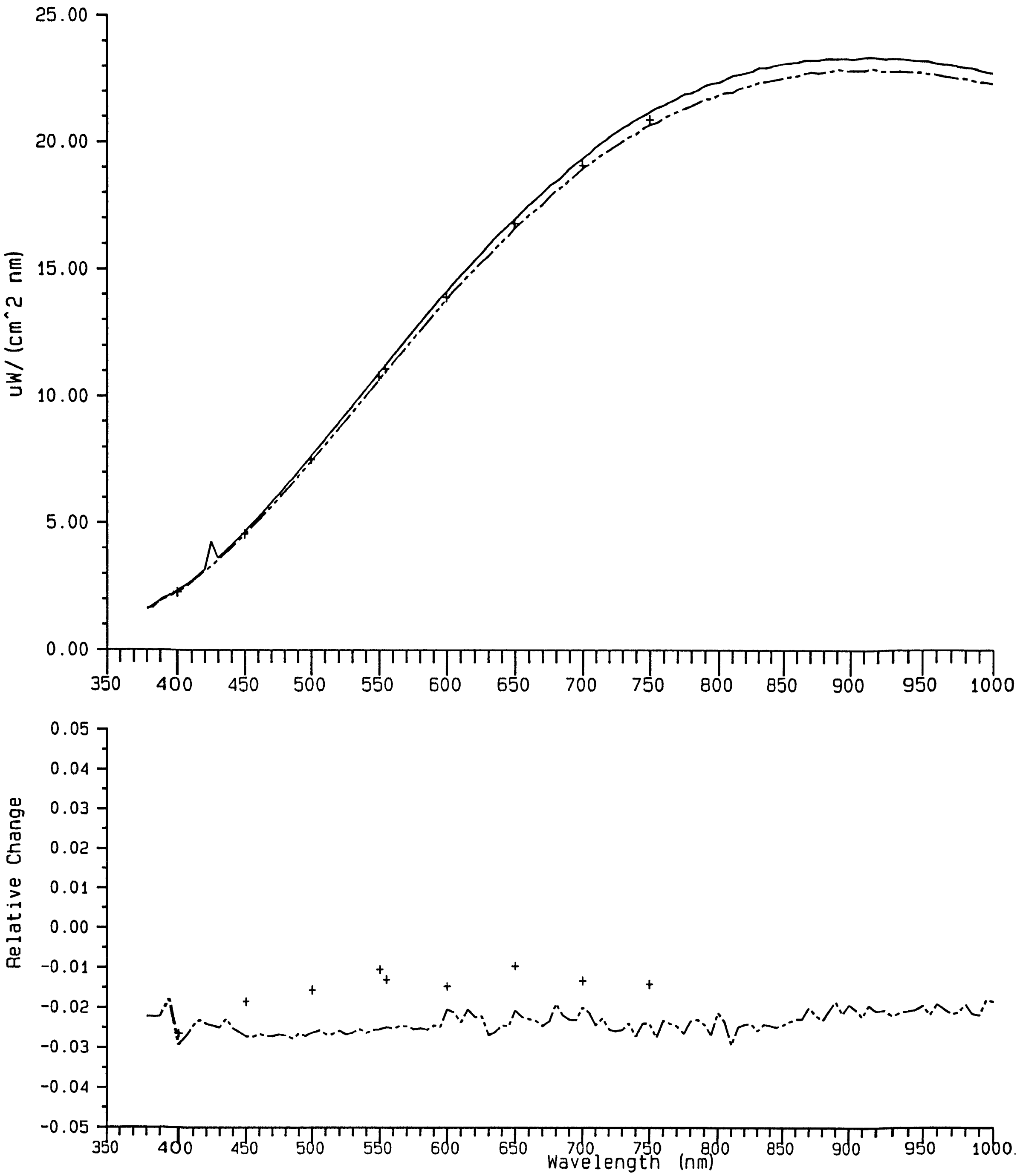


Fig. 13. Spectral irradiance of FEL lamp F307 determined using F268 on 21 Sept 1994 (solid line), compared to the SIRREX-2 values (dashed line) and the original calibration by OL (+). The spectral irradiance is plotted in the upper panel. The lower panel illustrates the relative changes with respect to the SIRREX-3 values. The quantity plotted using the dash-dot-dot line is the SIRREX-2 data minus the SIRREX-3 data, normalized to the SIRREX-3 data. The + symbol similarly shows the original calibration of F307 by OL.

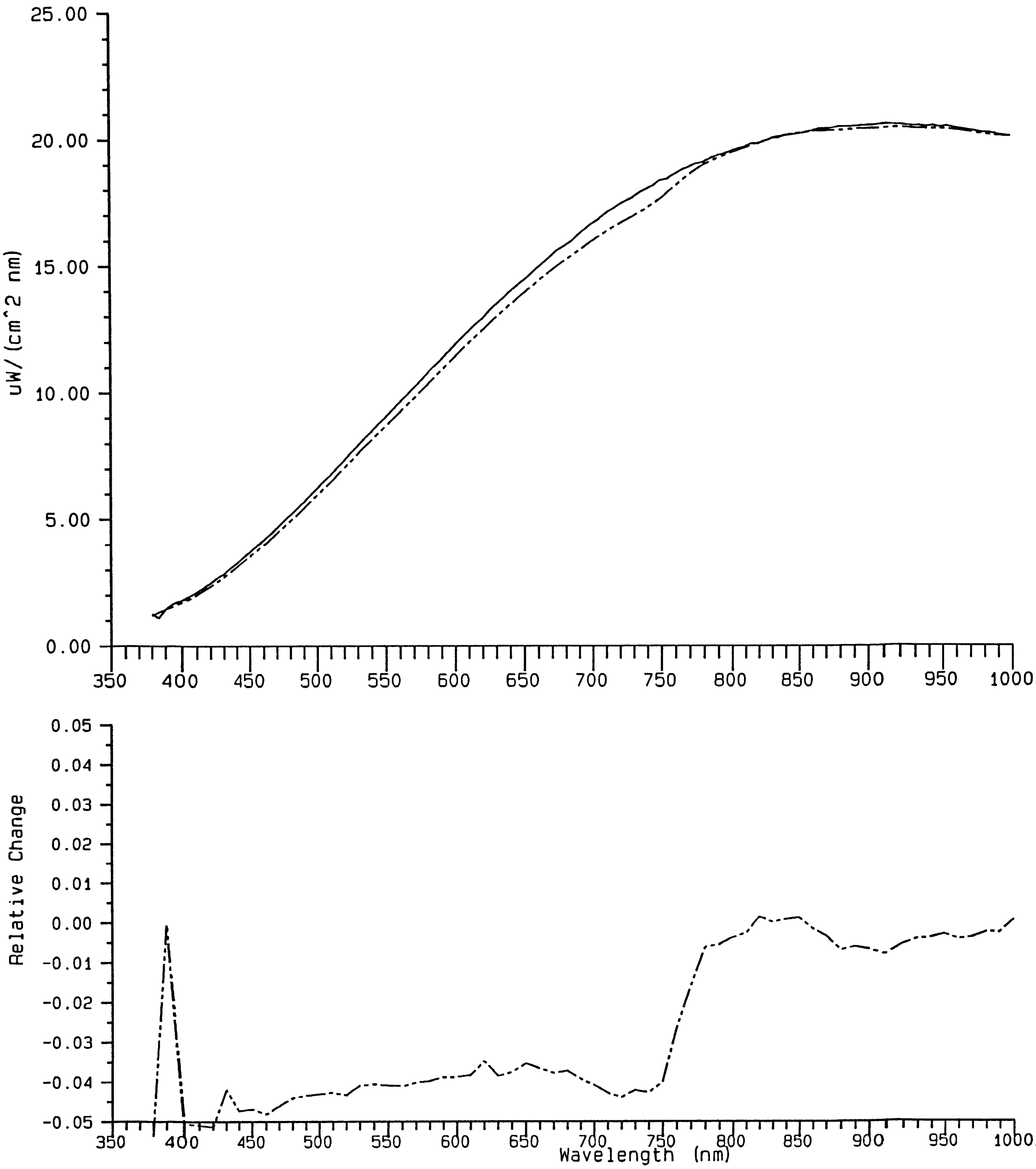


Fig. 14. Spectral irradiance of FEL lamp GS-922 determined using F268 on 21 Sept 1994 (solid line), compared to the original calibration by EG&G (dashed line). The spectral irradiance is plotted in the upper panel. The lower panel illustrates the relative changes with respect to the SIRREX-3 values. The quantity plotted using the dash-dot-dot line is the original calibration by EG&G minus the SIRREX-3 data, normalized to the SIRREX-3 data.

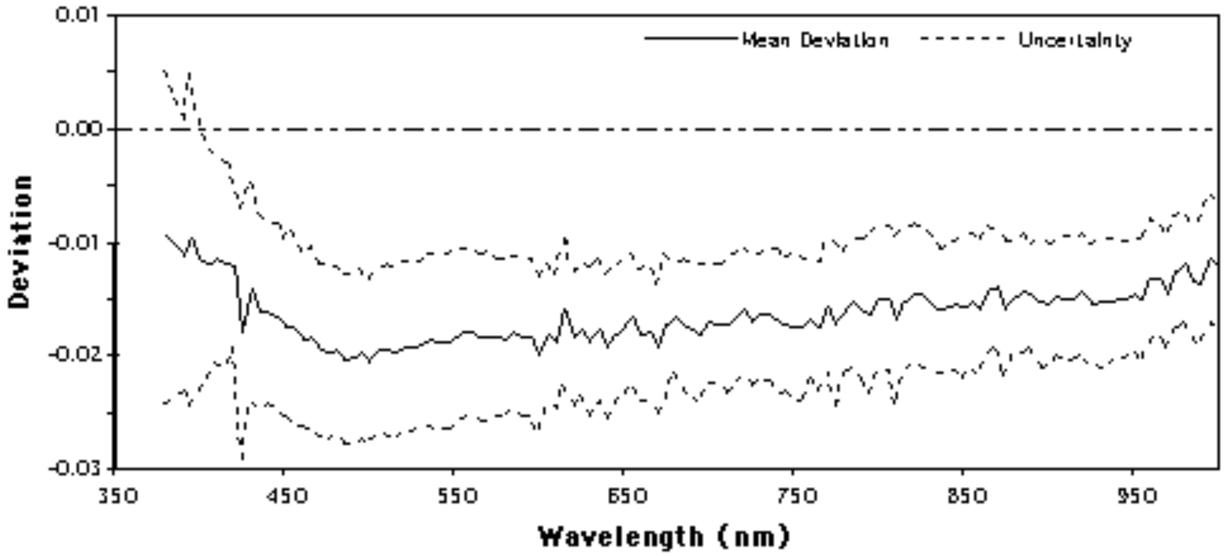


Fig. 15. The average change in the lamp irradiances measured at SIRREX-3 relative to those measured at SIRREX-2 for the six lamps (F321, F308, F123, F12G, F303, and F307) that were studied in both experiments. The quantity plotted using the solid line is the average of the relative changes, or deviations (i.e., the SIRREX-2 data minus the SIRREX-3 data) normalized to the SIRREX-3 data (see the lower panels of Figs. 8–13). The quantity plotted using the dashed line is the average deviation plus or minus the standard deviation of the relative changes for the six lamps.

sphere that has a single 30 W DZA type halogen lamp and an adjustable shutter between the two spheres. This sphere was manufactured by Labsphere and has a 12.7 cm exit aperture.

4. *UCSB sphere.* This source is also 50.8 cm in diameter and is illuminated with a calibrated FEL lamp at 50 cm through an entrance port. The entrance aperture diameter may be varied from 2.54–12.7 cm. The exit aperture is 15.24 cm in diameter.
5. *NOAA sphere.* The NOAA sphere is an OL420 sphere radiance source, illuminated externally, with lamp distance, shutter, and aperture controls to vary the radiance level. The exit aperture of this sphere has a glass window, and the exit aperture is 7.62 cm in diameter.
6. *UA sphere.* UA's Labsphere Spectralon Integrating Sphere (UA/SIS) is 15.24 cm in diameter. It is illuminated internally by a 30 W lamp and has an exit aperture 5.08 cm in diameter.
7. *NOAA system.* NOAA's GS-5000 spectral irradiance and radiance calibration system was manufactured by EG&G. The FEL lamp is mounted on an optical bar within a light containment enclosure. A port and light trap at the rear of the light enclosure are used to eliminate on-axis reflections, and a knife edge illumination aperture is aligned with the lamp and optical bar axis. A baffle tube extends along the bar from the illumination aperture to a kinematic mount, located exactly 50 cm from the lamp post holders. An integrating sphere (20.32 cm diameter) is attached to this mount for radiance calibrations, or a radiometer's irradiance collector may be attached to it for spectral irradiance calibrations.

In all cases, the purpose of using an integrating sphere is to create a diffuse source of spatially and angularly uniform radiance in an exit aperture with a diameter large enough to fill the entrance pupil of a radiometer to be calibrated. During SIRREX-3, extensive series of spectral radiance measurements were made on each of the spheres listed above. The SIRREX-3 spectral radiance determinations were compared where possible to independent scales that had been supplied by the manufacturer or the home laboratory. In the case of GSFC, this is the NIST-traceable double aperture method using a standard irradiance lamp and the 746/ISIC (see Appendix B in Mueller 1993). The NOAA OL420 had been calibrated by OL in June of 1994, also using the NIST-traceable double aperture technique and their spectroradiometer. The NOAA GS-5000 system with the sphere attachment was calibrated after SIRREX-3 by the manufacturer, EG&G, using a NIST-calibrated FEL lamp, a diffuse plaque made from pressed polytetrafluoroethylene (PTFE), and a transfer spectroradiometer. The UA/SIS was calibrated by the manufacturer, Labsphere, Inc., using a Spectralon plaque and a NIST-traceable standard irradiance lamp. Prior to SIRREX-3, the BSI sphere had been used for radiance calibrations in June of 1994. After SIRREX-3, spectral radiance transfers at BSI using a diffuse plaque illuminated with a standard irradiance lamp provided inconsistent results, and no spectral radiance results are available for comparison.

The following radiometers were used at SIRREX-3 for measurements on some, or all, of the spheres:

a. *746/ISIC.* The responsivity of this instrument was determined using FEL lamp F269 or F268, for each set of measurements.
b. *SXR.* The six-channel SXR was manufactured and independently characterized by NIST under contract for the NASA SeaWiFS Project and was calibrated using a small integrating sphere source. This source had previously been calibrated at the NIST Facility for Automated Spectroradiometric Calibrations.
c. *UAXR.* The UAXR is an eight channel filter radiometer with a detector employing three silicon photodiodes (p-on-n type) arranged in a light trapping configuration. It was built and independently characterized by UA. For SIRREX-3, the UAXR responsivity was calibrated using the GSFC sphere 746/ISIC (F268) radiance as measured on 29 Sept 1994.
d. *CXR.* The CXR, a 12-channel filter radiometer using a QED-200 detector, was built and characterized at SDSU CHORS. It was calibrated using the GSFC sphere 746/ISIC (F268) average spectral radiance. The CXR was operated without a bias voltage.

3.1 Methods

At SIRREX-3, transfer of the NIST scale of spectral irradiance from a secondary standard lamp to values of spectral radiance for a sphere was accomplished using the double aperture method and a second method that involved using the results of the first method, the UAXR or the CXR, and ancillary information on the spectral radiance responsivity functions for these two radiometers.

In the double aperture method, an FEL lamp of known spectral irradiance (see Appendix B in Mueller 1993), is first measured by the 746/ISIC, in a setup identical to that described in Section 2.1 for lamp transfers. The responsivity of the 746/ISIC to spectral irradiance is thus determined. The sphere's entrance aperture on the 746/ISIC is then positioned at a known distance from the exit aperture of the integrating sphere to be measured, which is illuminated by stable lamp sources. The apertures of the two spheres must be parallel and aligned on the mutual perpendicular joining their two centers. From the distance between the apertures of the two spheres and their respective areas, it is possible to calculate the average spectral radiance in the exit aperture of the integrating sphere radiance source from the irradiance determined from the lamp measurements. After this is done, one can then transfer spectral irradiance from a working standard lamp to establish the spectral radiance for the sphere.

Once this double aperture method was used to determine the spectral radiance of one reference sphere source (the GSFC sphere was used in this case), measurements of this sphere were made using the CXR and UAXR. Since the ancillary data on the relative spectral response for the filters and detectors in these instruments were available, the measurement wavelengths and bandwidths were known, and the spectral radiance of the GSFC sphere could be transferred to other spheres using these radiometers. The measurement wavelengths and bandwidths used for the three filter radiometers in analyzing the SIRREX-3 data are given in Table 7. For some of the spheres measured at SIRREX-3, the CXR data at 448.1 nm showed large standard deviations and these results are not included in this report. All three filter radiometers were used to measure integrating sphere sources at SIRREX-3. The SXR has a non-ideal point spread response function for some measurement wavelengths, which results in about a 1.6% overestimate of spectral radiance at 775 nm for the largest spheres—however, in this publication none of the SXR data have been corrected for this size-of-source effect.

Table 7. Measurement wavelength and spectral bandwidth of channels in the CXR, UAXR, and SXR.

Measurement λ [nm]	*Bandwidth* [nm]
CXR	
400.0	9.6
430.6	7.8
448.1	10.1
490.6	6.9
501.1	8.5
531.9	9.8
552.2	10.2
581.1	10.1
602.6	10.3
652.7	11.8
701.3	13.0
UAXR	
412.8	15.1
441.8	11.9
488.0	9.7
550.3	9.9
666.5	9.8
746.9	10.7
868.1	14.0
SXR	
411.5	10.8
441.6	10.3
487.1	10.6
548.0	10.4
661.8	9.6
774.8	11.6

The combined uncertainty for the measured spectral radiance of the integrating sphere depends on the experimental configuration. For measurements with the 746/ISIC, one component is the uncertainty in the secondary standard, which, for wavelengths between 400–1000 nm, is either about 0.5% (0.4% for wavelengths less than 600 nm) or 1.1%, depending if the NIST or the F268-derived values for F269 applies. Other components arise from the stability of the sphere source, the signal-to-noise ratio (SNR) for the measurements of the lamp and the sphere, and the transfer process (distance measurement, aperture area, alignment errors, scattered light, etc.). At SIRREX-3, these effects were quantitized, where possible, by independent measurements of the sphere source. For measurements of spheres other than the GSFC sphere using the UAXR or the CXR, the combined uncertainty includes:

1) The uncertainty of the spectral radiance of the GSFC sphere as determined with the 746/ISIC and the secondary standard lamps;
2) The uncertainty in the transfer process (alignment, stability of the transfer radiometer, etc.);
3) The SNR for the measurement of the sphere with the UAXR or the CXR; and
4) The stability of the sphere (which was also assessed where possible by repeat measurements).

The temporal stability and uncertainties of the radiance determined for each sphere were evaluated by repeated measurements with the four radiometers. More than one measurement was performed for every sphere with some or all of these radiometers within a single day; however, measurements of the GSFC, CHORS, and BSI spheres were repeated on several days. The CHORS sphere radiance was then continuously monitored overnight, for approximately 12 hours, by the SXR (at 10 minute sample intervals), CXR (at 2 minute sample intervals), and UAXR (at 30 second sample intervals).

Spatial and angular uniformity of spectral radiance in the exit ports of some spheres were also characterized during SIRREX-3. To test spatial (x, y) uniformity of radiance viewed normal to the plane of the exit aperture, the SXR was used to map the UCSB sphere. Prior to SIRREX-3, the SXR was used at GSFC to map the GSFC sphere, and the CXR was used at CHORS to map the CHORS sphere. For mapping the spheres, the radiometers were translated vertically and horizontally in fixed increments until the radiance emitted over the full (x, y) extent of the exit aperture was recorded. The UCSB sphere was scanned vertically in y at fixed x locations, at a grid spacing of 2.5 cm, using the SXR mounted on a camera tripod. The GSFC sphere was scanned horizontally in x at fixed y locations using the SXR mounted on a dual axis translation stage. The CHORS sphere was scanned horizontally at fixed y locations, using the CXR mounted on a single axis translation stage fixed at various heights.

A simple measurement was made of the Lambertian quality, i.e., angular uniformity, of radiance in the exit apertures of the GSFC and CHORS spheres. The GSFC sphere was characterized with the SXR, and the CHORS sphere was characterized with both the SXR and CXR. The radiometer was aligned to view the center of the exit aperture first along the normal axis, and then, still viewing the center of the sphere, at angles up to 15° left and right of the center normal axis. The height of the radiometer, (y), as well as the distance between the radiometer's aperture and the center of the exit aperture, were held fixed during each set of measurements.

3.2 Results

During SIRREX-3, seven integrating sphere sources of spectral radiance were intercompared using the 746/ISIC with two different working standard lamps, the SXR, the CXR, and the UAXR. One of these sources, the GS-5000, also operates in a spectral irradiance calibration mode, which was tested using the 746/ISIC and an immersible Marine Environmental Radiometer (MER-2040) manufactured by BSI.

The GSFC sphere, as calibrated by the 746/ISIC (F268 and F269) was used as the basis for calibrating both the CXR and UAXR for transfers of spectral radiance during SIRREX-3. The average spectral radiance of the GSFC sphere determined using the 746/ISIC at SIRREX-3 (twice on 23 Sept 1994 with F269, once on 26 Sept 1994 with F269, and twice on 29 Sept 1994 with F268), is illustrated in Fig. 16a as a solid line. The CXR data in Fig. 16 (squares) represent the average of four measurements of the GSFC sphere on three separate days, only two of which coincided with 746/ISIC calibrations of that sphere. Figure 16b illustrates both the uncertainties and the deviations relative to the sphere's mean 746/ISIC (F268) value of the average measurements presented in Fig. 16a. The mean CXR responses were used with the mean 746/ISIC (F268) radiance of the GSFC sphere to calibrate the CXR radiance responsivity. Therefore, the transferred means between these two instruments are not independent and agree exactly for this sphere (Fig. 16b).

In Fig. 16b, the uncertainties for the SXR are the standard deviations of the measured signals calculated from the repeat measurements of the GSFC sphere source. For the UAXR and the CXR, the uncertainties, referred to as the average uncertainty, correspond to the uncertainty in the mean of the standard deviations for all of the measurement wavelengths for that radiometer of the GSFC sphere source. This approach was also used to illustrate the uncertainties for the SXR, CXR, and UAXR for the other sphere sources. The two solid lines are the ±1 standard deviations of the 746/ISIC comparisons over three different days. Since all but two of the 746/ISIC radiance measurements were made using F269, rather than F268 directly, an additional 1% uncertainty should be combined in quadrature with the Type A uncertainties illustrated in Fig. 16b.

Conversely, the UAXR calibration was based on the average of two scans of the GSFC sphere on 29 Sept 1994, as calibrated with the 746/ISIC (F268) on that day. Consequently, the mean 746/ISIC radiance curve and UAXR radiances agree closely, but not exactly. The SXR radiances illustrated in Fig. 16 are based on an independent calibration of that instrument at NIST prior to SIRREX-3. The GSFC sphere radiance level is controlled by varying the number of lamps from 1–16, in a fixed sequence of lamp numbers (i.e., the 1-lamp configuration always uses the same lamp, and so forth). Spectral radiances of the GSFC sphere at selected lamp levels, as measured with the SXR on 21 Sept 1994, are shown in Fig. 16c. Figure 16d plots the color indices $L(\lambda)/L(411.5)$ of the sphere at selected lamp levels, normalized at each wavelength by the averages over the 16 levels of the color indices at that wavelength.

Figures 17a–d show the corresponding measurements of the CHORS sphere. The solid line 746/ISIC (Fig. 17a) is the average of the radiance measurements of the CHORS sphere using the 746/ISIC and lamps F269 (on 22 and 23 Sept 1994) and F268 (on 27 Sept 1994). Also shown in Fig. 17a is the blackbody function (in the Wien approximation) times a cubic polynomial model, i.e., the *greybody* model,

$$B_b(\lambda) = \lambda^{-5} e^{\frac{b}{\lambda}} (a_o + a_1\lambda + a_2\lambda^2 + a_3\lambda^3), \qquad (1)$$

which is fit by least squares regression to the combined SXR, CXR, and UAXR measurements (Saunders and Shumaker 1977). This model is not appropriate when any spectral features are present, and cannot be used to predict the spectral radiance of the CHORS sphere above approximately 850 nm because of the prominent feature at about 900 nm. $B_b(\lambda)$ coefficients [i.e., a_i and b in (1)] fit to the CHORS sphere radiances, and to data from the other spheres described below, are given in Table 8. Deviations from $B_b(\lambda)$ and standard deviations for the SXR (ranging from 1.7% at 411.5 nm to 0.4% at 774.8 nm, and averaging 1.2%) are illustrated in Fig. 17b. For the CXR, the average uncertainty of 2.7% is illustrated; the standard deviations ranged from 5.7% at 399.6 nm to 1.0% at 701.4 nm. The CXR and SXR radiance measurements agree with $B_b(\lambda)$, and with each other, within the average uncertainties. The UAXR was used to measure radiance of the CHORS sphere only once, and therefore, its uncertainty was not determined. The calibrated 746/ISIC radiance measurements also agree with $B_b(\lambda)$ and radiances from the other instruments at wavelengths between 500–800 nm, but deviate by more than 10% below 450 nm and by more than 5% above 900 nm (Fig. 17b).

The radiance levels of the CHORS sphere are varied using apertures of varying diameters between each of its four lamps and auxiliary spheres. These apertures affect the illumination of the main sphere. Figure 17c shows the variations of spectral radiance measured by the SXR and CXR at three of many possible aperture combinations, but which include as endpoints the largest and smallest possible combinations for which the sphere is equipped. At the largest aperture settings (maximum radiance), these individual SXR and CXR radiances are also compared to $B_b(\lambda)$ (Fig. 17c). Figure 17d illustrates the CHORS sphere's color indices relative to 411.5 nm, calculated as described above for the GSFC sphere (Fig. 16d).

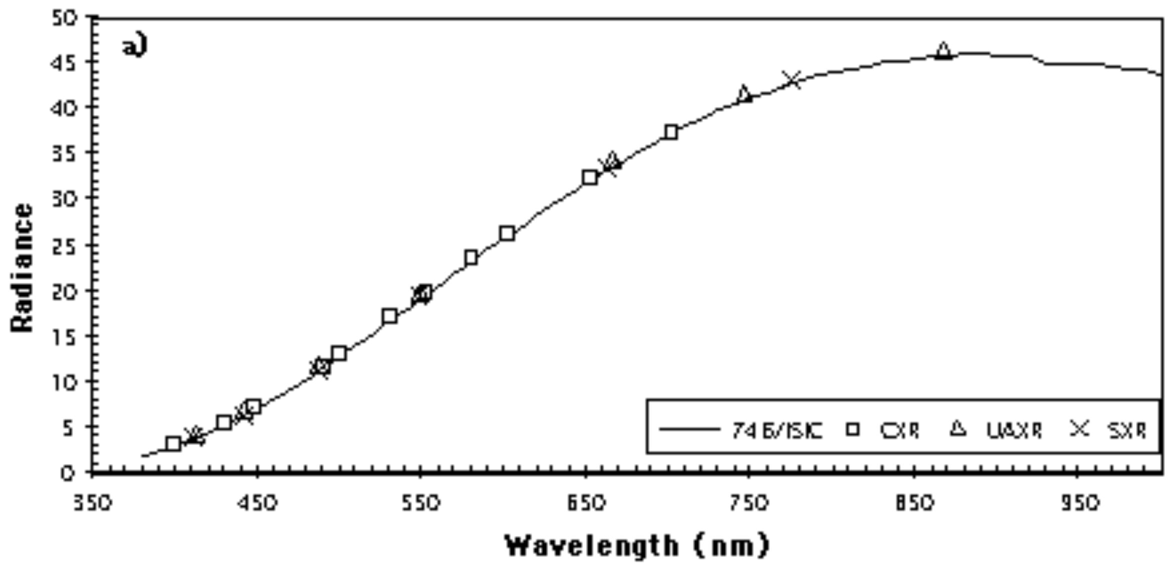
Figure 18 illustrates spectral radiance measurements of the UCSB sphere, which was illuminated externally with lamp F303 at 50 cm distance from the sphere entrance aperture. Using the 746/ISIC and lamp F269 on 22 Sept 1994, spectral radiances were measured using the standard curtains and baffles used by UCSB during routine calibrations (dashed curve in Fig. 18a). Then, an additional curtain for stray light blocking was placed over the setup, and the measurement was repeated (the solid curve in Fig. 18a). The CXR and SXR spectral radiance measurements of the UCSB sphere, and the $B_b(\lambda)$ model [(1) and Table 8] fit to these data, are compared to the 746/ISIC radiances in Fig. 18a. Deviations from $B_b(\lambda)$ of the measured radiances are illustrated in Fig. 18b. (The CXR was used only once with the UCSB sphere.) The SXR and CXR agree with $B_b(\lambda)$ within 1% and 3% respectively, while the 746/ISIC data agree at comparable levels only between 500–700 nm. The low sensitivity of the 746/ISIC results in deviations as large as 30% from the other instruments at shorter wavelengths.

The *unbaffled* 746/ISIC data are obviously affected by stray light at wavelengths greater than 750 nm. Note that $B_b(\lambda)$ is extrapolated at those wavelengths greater than 774.8 nm; therefore, no significance can be attached to the large apparent deviations of the *baffled* 746/ISIC radiances in this wavelength region.

The CXR, SXR, and the UAXR were used to measure the spectral radiance of the BSI sphere on 23 and 26 Sept 1994. The averages of these measurements, together with $B_b(\lambda)$ fit to the data [(1) and Table 8], are illustrated in Fig. 19a. Figure 19b shows deviations of the mean SXR, CXR, and UAXR radiances from $B_b(\lambda)$. The major contribution to the uncertainties was a monotonic increase in the spectral radiance of the BSI sphere over the measurement interval. The drift observed with the SXR at 411.5 nm, for example, was 6.7%. BSI attributes this drift to a thermal problem in the source.

Figure 20a illustrates CXR, SXR, and UAXR spectral radiance measurements, and the $B_b(\lambda)$ fit to these data [(1) and Table 8] of the UA/SIS, in comparison with the source's original calibration by Labsphere, Inc., its manufacturer. Deviations of the measured radiances from $B_b(\lambda)$ are approximately 2% or less, and the Labsphere calibration radiances deviate by 2–5% (Fig. 20b).

The OL420 radiance calibration sphere was previously calibrated at SIRREX-2 (June 1993) (Mueller et al. 1994), by NIST during experiments at the NOAA Marine Optical Buoy (MOBY) site in Honolulu, Hawaii (February



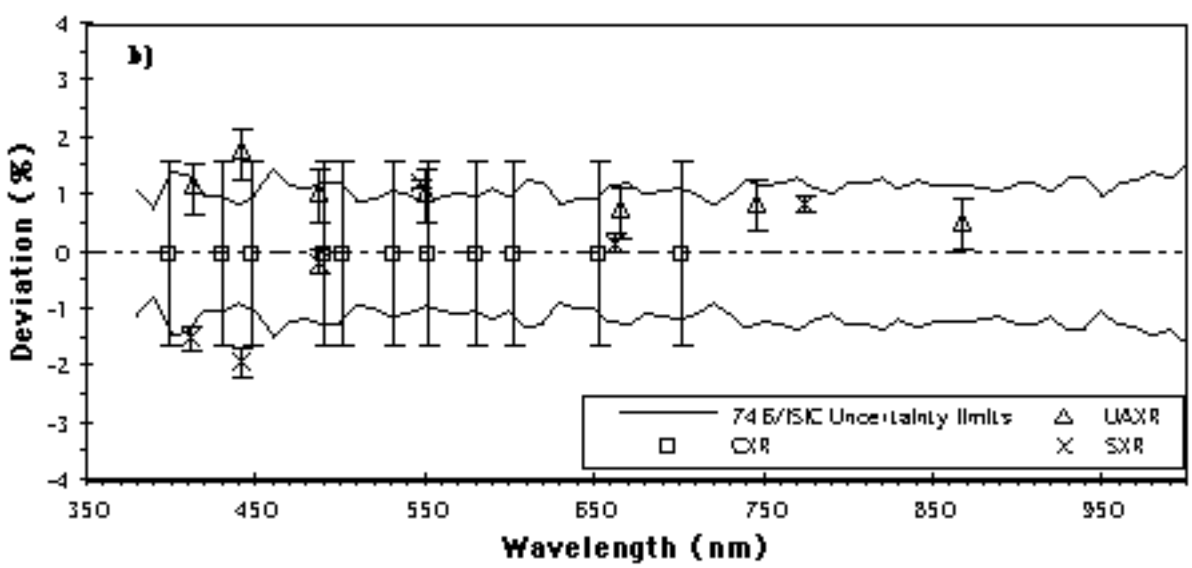
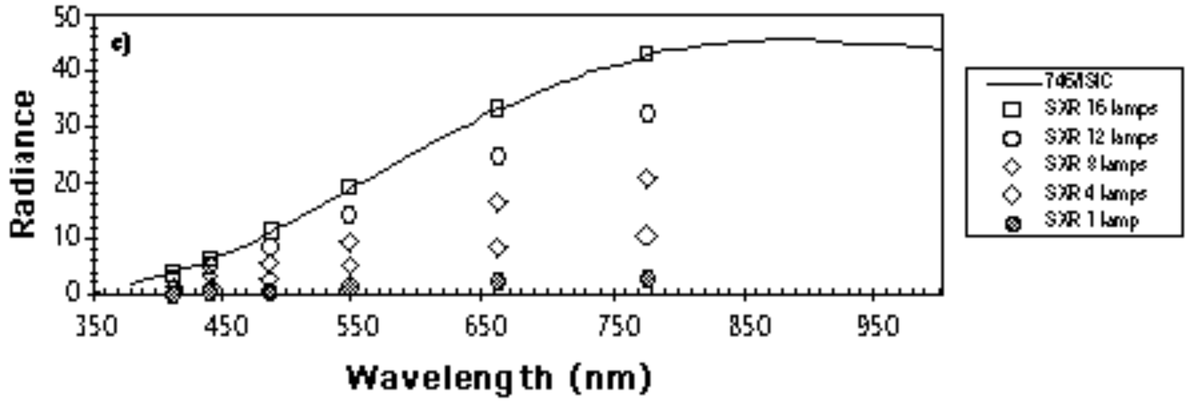


Fig. 16. a) Average spectral radiance in units of $\mu W/(cm^2\,sr\,nm)$ of the GSFC sphere (16 lamps) as measured with the 746/ISIC on three days using F268 or F269. The average spectral radiance of the two data sets using F268 on 29 Sept 1994 was used to calibrate the CXR and UAXR radiometers as explained in the text. **b)** Results from panel **a** with respect to the average of all of the 746/ISIC data for the GSFC sphere and the uncertainties, calculated using the standard deviation of the individual measurements. The quantity plotted using the symbol (see legend) is the average of the CXR, SXR, or UAXR data minus the average spectral radiance of the GSFC sphere as determined with the 746/ISIC, normalized to the average 746/ISIC values.



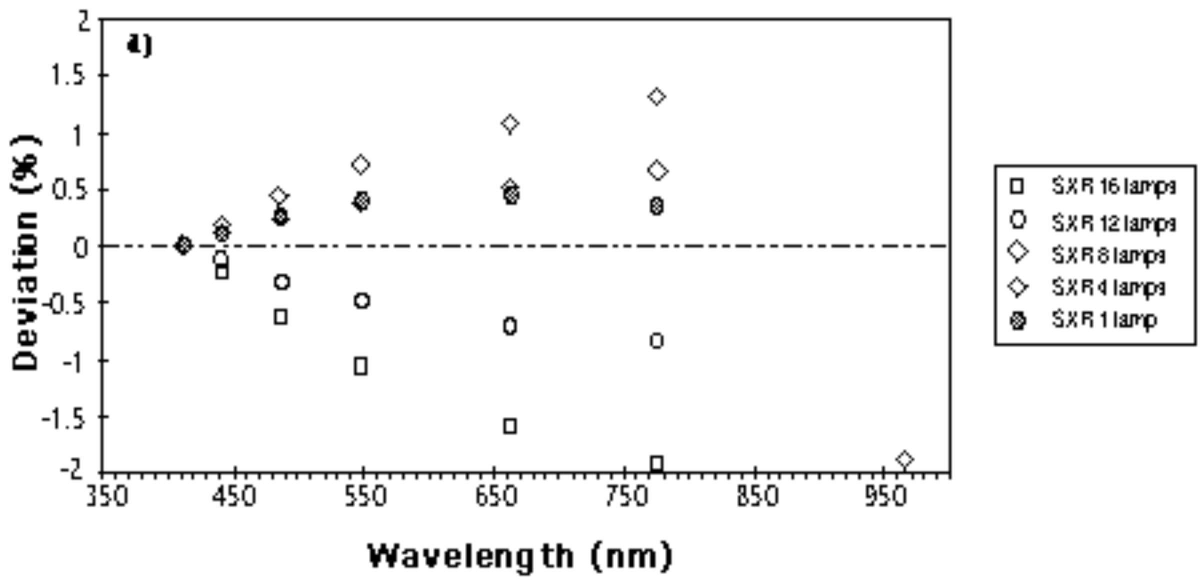


Fig. 16. (cont.) c) Spectral radiance in units of μW/(cm^2 sr nm) of the GSFC sphere when illuminated by 16, 12, 8, 4, or 1 lamps (other lamp levels were measured but for clarity are not show). **d)** The relative variability in the color indices measured with the SXR, $L(\lambda)/L(411.5)$. The quantity plotted is the color indices at the various lamp settings (see legend) at the six SXR measurement wavelengths minus the average color index for all lamp levels at the corresponding measurement wavelength, normalized to these average color indices.

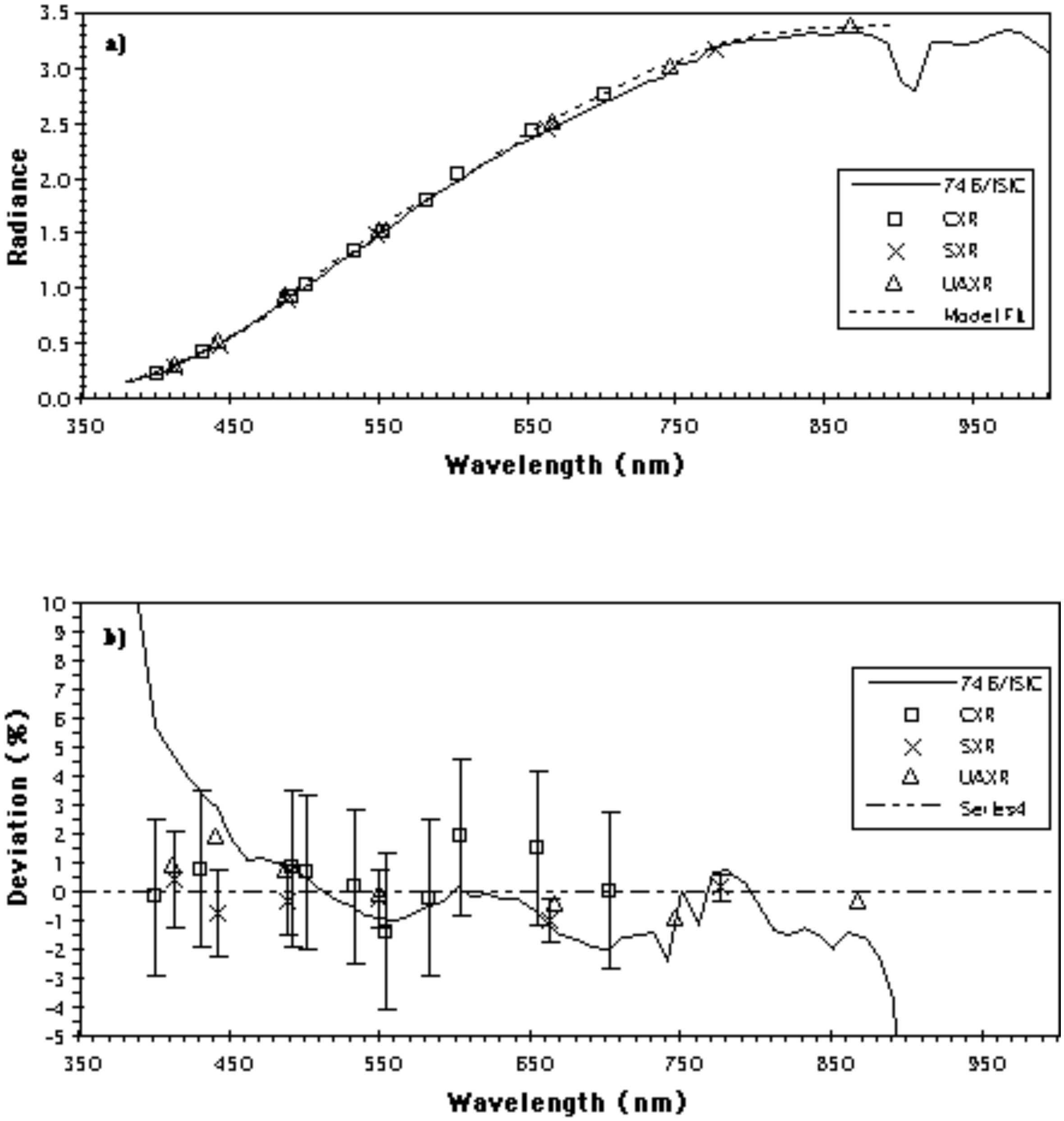
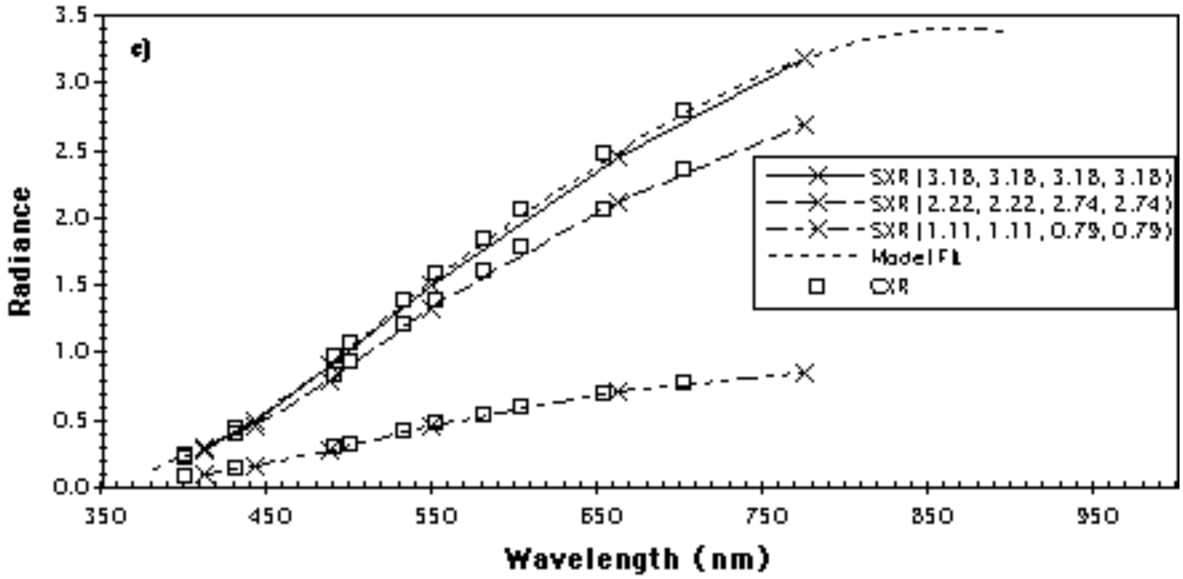


Fig. 17. **a)** Average spectral radiance in units of μW/(cm^2 sr nm) of the CHORS sphere as calibrated with the 746/ISIC (F269 and F268) and measured with the SXR, CXR, and UAXR. **b)** Results from panel **a** with respect to the greybody model for the CHORS sphere and uncertainties, calculated using the standard deviation of the individual measurements. The quantity plotted (see legend) is the average of the 746/ISIC, CXR, SXR, or UAXR data minus the greybody model, normalized to the greybody model.



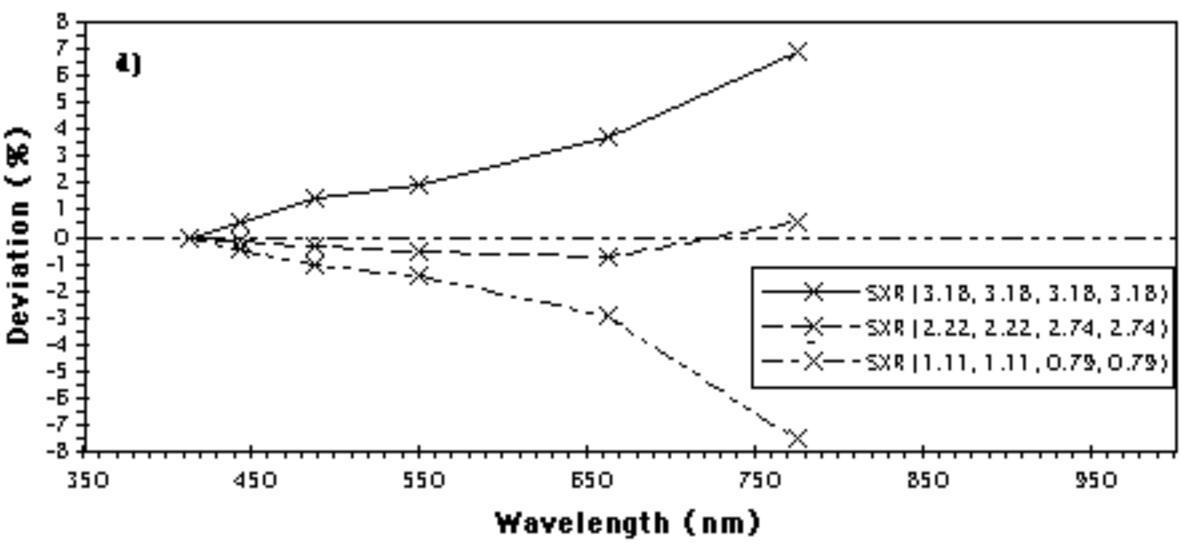
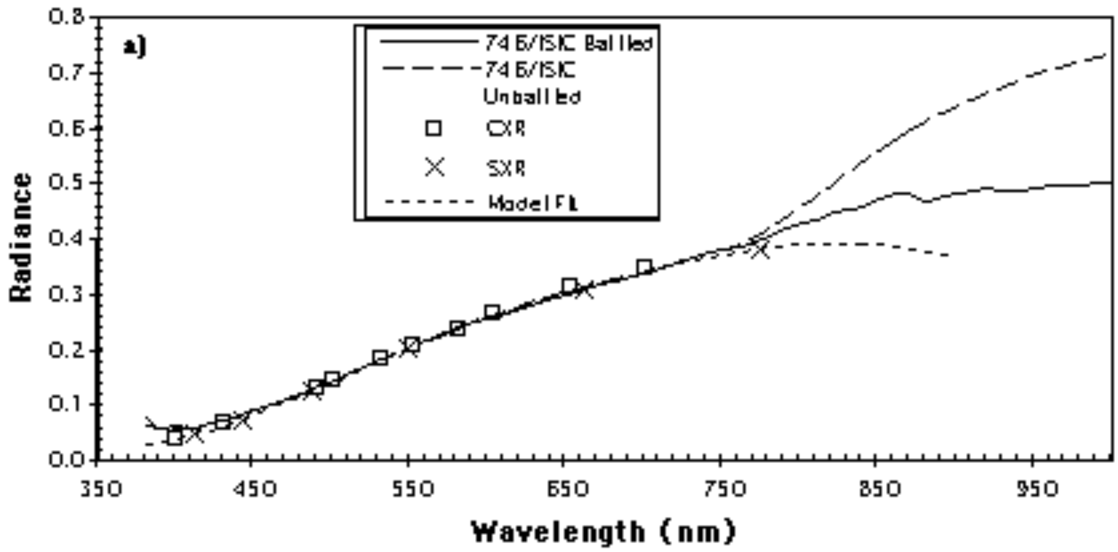


Fig. 17. (cont.) c) Spectral radiance in units of μW/(cm^2 sr nm) of the CHORS sphere at three lamp settings as measured with the SXR and the CXR (numbers in parentheses indicate the diameters, in centimeters, of the aperture on each of the sphere's four lamps). Also shown is the greybody model fit (panel a at setting 3.18, 3.18, 3.18, 3.18). **d)** The relative variability in the color indices measured with the SXR, $L(\lambda)/L(411.5)$. The quantity plotted is the color indices at the aperture settings (see legend) at the six SXR measurement wavelengths minus the average color index for all aperture settings at the corresponding measurement wavelength, normalized to these average color indices.



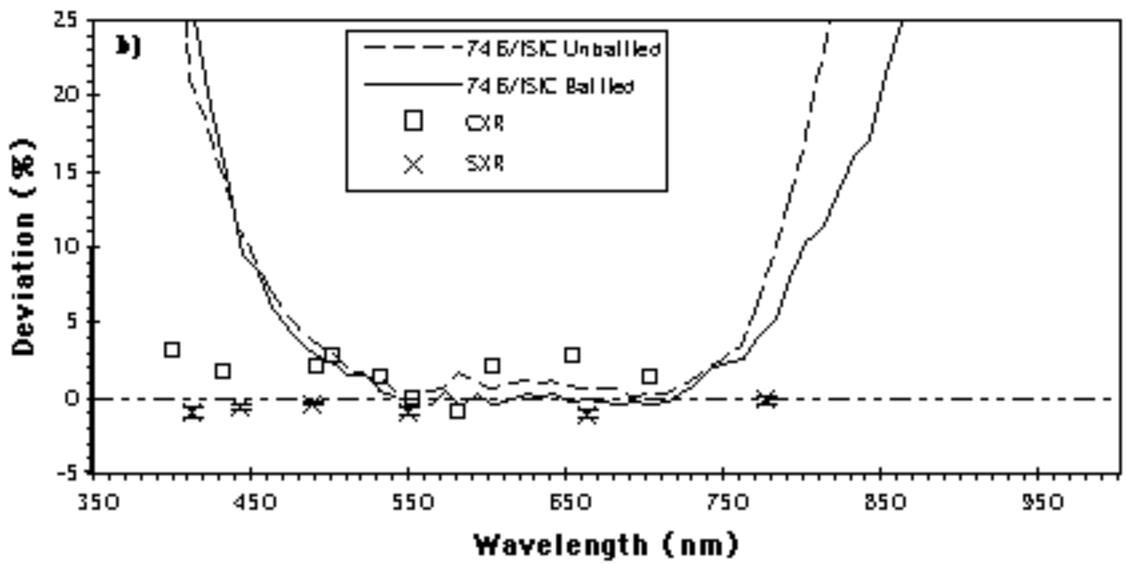


Fig. 18. **a)** Average spectral radiance in units of μW/(cm^2 sr nm) of the UCSB sphere as externally illuminated with lamp F303 at 50 cm and measured with the 746/ISIC (F269), the SXR, and the CXR. Also shown is the greymodel fit to the SXR and CXR data. **b)** Results from panel **a** with respect to the model fit and the uncertainties, calculated as described in the text. The quantity plotted (see legend) is the 746/ISIC, CXR, or SXR data minus the model fit, normalized to the model fit. One 746/ISIC measurement was performed with an extra curtain hung near the instrument to block stray light (solid line), and the other 746/ISIC measurement was made without the curtain (dashed line).

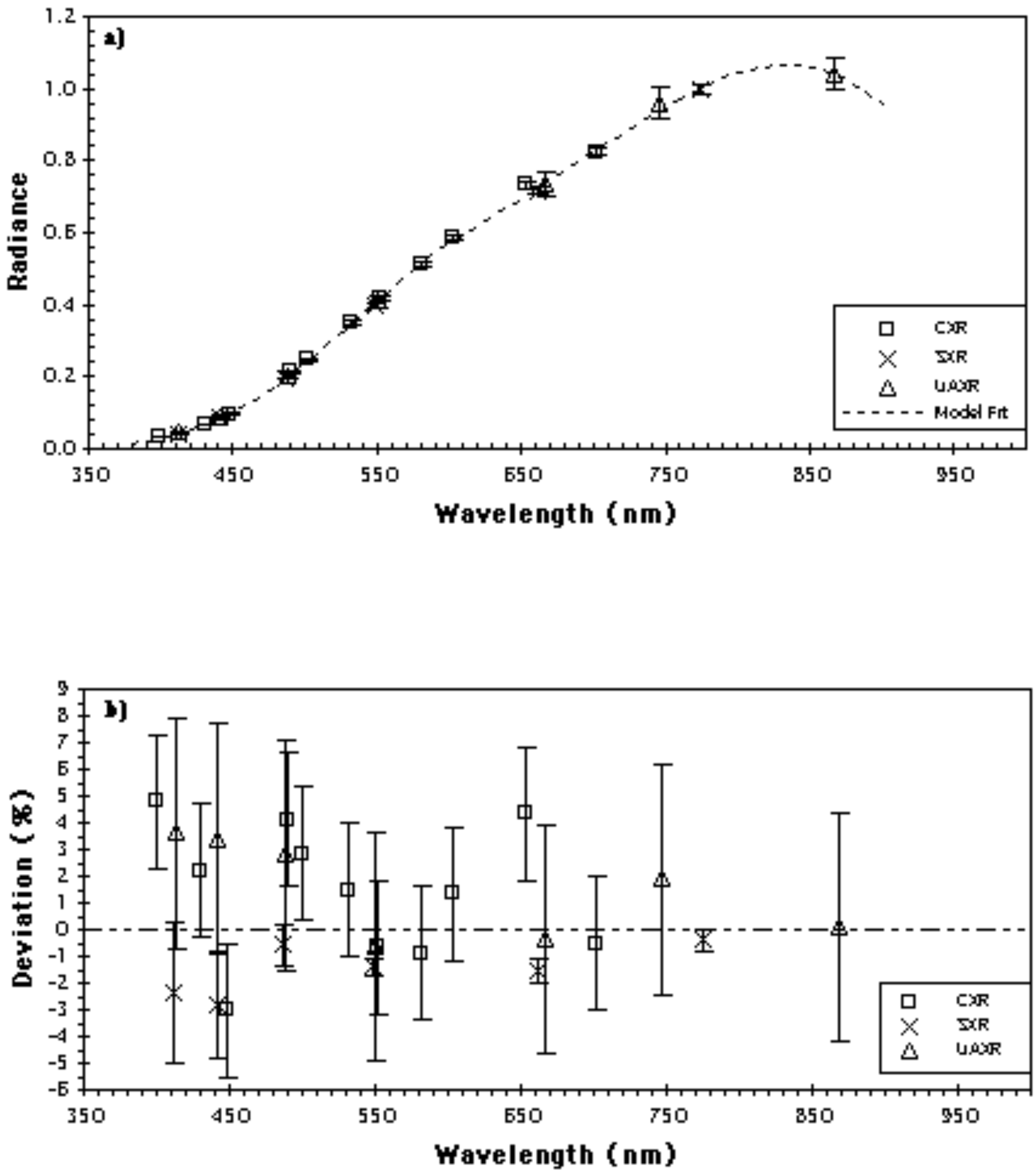


Fig. 19. **a)** Average spectral radiance in units of $\mu W/(cm^2 \, sr \, nm)$ of the BSI sphere as measured with the SXR, the UAXR, and the CXR, shown with the model fit to these data. **b)** Results from panel **a** with respect to the model fit and the uncertainties, calculated as described in the text. The quantity plotted (see legend) is the CXR, SXR, or UAXR data minus the model fit, normalized to the model fit.

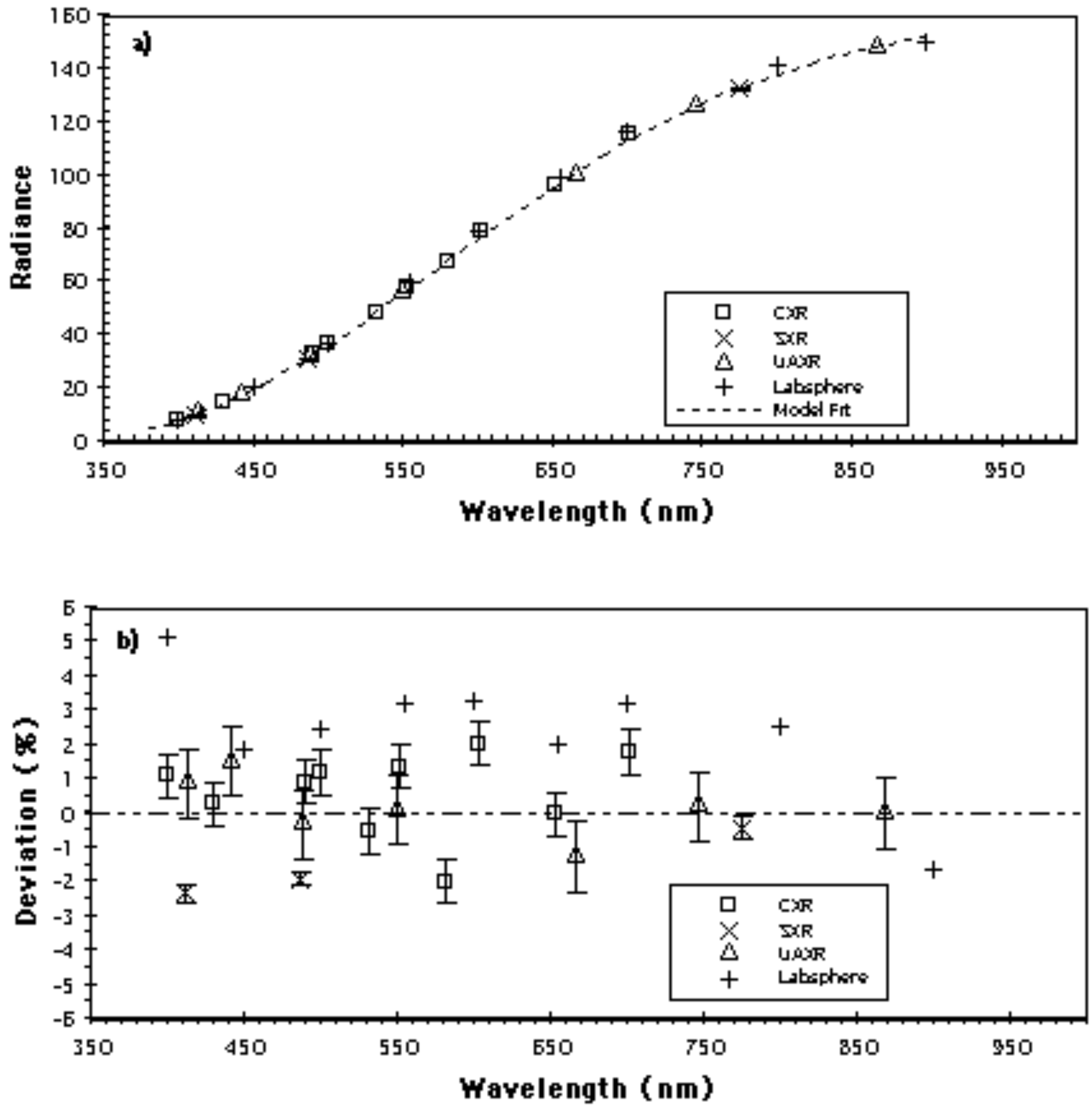


Fig. 20. a) Average spectral radiance in units of μW/(cm^2 sr nm) of the UA/SIS sphere as measured with the SXR, the UAXR, and the CXR, shown with the model fit to these data. Also shown are Labsphere calibration data for the sphere. **b)** Results from panel **a** with respect to the model fit and the uncertainties, calculated as described in the text. The quantity plotted (see legend) is the CXR, SXR, UAXR, or the Labsphere data minus the model fit, normalized to the model fit. The UA/SIS source saturated the SXR at 441.6 nm, 548.0 nm, and 661.8 nm, hence no values are reported.

Table 8. Greybody models of spectral radiance for several spheres measured during SIRREX-3. The coefficients correspond to the following model:

$$B_b(\lambda) = \lambda^{-5} e^{\frac{b}{\lambda}} (a_o + a_1\lambda + a_2\lambda^2 + a_3\lambda^3).$$

Coefficient	*Wavelength Range*	*CHORS Sphere*	*UCSB Sphere*	*BSI Sphere*	*UA/SIS Sphere*	*OL420 Sphere*
a_0	380–600 nm	-3.2525×10^{18}	1.2682×10^{12}	-1.5943×10^{18}	-7.7330×10^{19}	-2.2540×10^{17}
	600–900 nm	2.7125×10^{18}	3.4157×10^{17}	6.5756×10^{18}	1.3590×10^{19}	4.8438×10^{17}
a_1	380–600 nm	1.9596×10^{16}	1.5663×10^{13}	6.5196×10^{15}	5.4232×10^{17}	2.1910×10^{15}
	600–900 nm	-8.8699×10^{15}	-1.2468×10^{15}	-2.4544×10^{16}	5.5657×10^{16}	-7.2823×10^{14}
a_2	380–600 nm	-3.3443×10^{13}	2.5315×10^{11}	-2.8474×10^{12}	-9.5593×10^{14}	-3.0773×10^{12}
	600–900 nm	1.1734×10^{13}	1.7207×10^{12}	3.2617×10^{13}	-9.1392×10^{13}	7.3869×10^{11}
a_3	380–600 nm	1.8616×10^{10}	-3.3157×10^{08}	-3.9627×10^{09}	5.5534×10^{11}	1.2908×10^{09}
	600–900 nm	-5.2233×10^{09}	-7.9324×10^{08}	-1.4604×10^{10}	4.5351×10^{10}	-2.4610×10^{08}
b	380–600 nm	-4.8310×10^{03}	-4.5819×10^{03}	-5.5165×10^{03}	-4.9774×10^{03}	-4.9447×10^{03}
	600–900 nm	-4.8310×10^{03}	-4.5819×10^{03}	-5.5165×10^{03}	-4.9774×10^{03}	-4.9447×10^{03}

1994) (Appendix B), and by the manufacturer on 20 June 1994. Radiance levels of this source are varied using different apertures between the lamp and the sphere, as well as varying the distance from the lamp to the sphere. The aperture was left open for all of these measurements. An additional filter wheel is available, however, for filtered or shuttered measurements.

Two combinations of the aperture wheel and distance setting were measured at SIRREX-3 (Fig. 21a). Also shown in Fig. 21a are a recent (20 June 1994) calibration of this device by OL and the $B_b(\lambda)$ model fit [(1) and Table 8] to the combined SXR and UAXR data. Deviations from the $B_b(\lambda)$ model of SXR and UAXR radiances are illustrated in Fig. 21b. Figure 21c shows deviations from the SIRREX-3 SXR radiances of the SIRREX-2 (Mueller et al. 1994) and Honolulu (February 1994) SXR radiance measurements (Appendix B) of the OL420. It appears that on the W6D40S3 setting, the OL420 sphere has increased in spectral radiance since SIRREX-2, but the W5D100S3 setting has decreased or remained nearly constant. Both the OL420 and the SXR underwent repairs and recalibrations during the time interval illustrated in Fig. 21c.

The GS-5000 is a custom spectral radiance and irradiance calibration source manufactured for NOAA (Dennis Clark) by EG&G (San Diego, CA). This device combines an FEL working standard lamp, a light-tight lamp housing that traps excess radiant flux, a short optical bar, baffles, and a removable integrating sphere (20.32 cm diameter with a 5.08 cm diameter exit port). The lamp enclosure is configured with a black honeycomb material lining, a front exit port with a knife edge baffle aligned with the optical axis of the FEL lamp and optical bar, and a light trap to prevent on-axis reflections from the back surface of the enclosure. A specially designed mounting bracket is attached to the optical bar to allow either the integrating sphere entrance port, or a cosine collector, to be aligned on the lamp axis at a distance of 50 cm. A telescoping tube with internal knife edge baffles is provided to eliminate stray light reflections between the lamp housing and the irradiance collector bracket.

The knife edge port, rear light trap, and telescoping knife edge baffle tube were added to the GS-5000 after recommendation by NOAA and NIST, in order to eliminate stray light effects in the system's original design configuration. The amount of scattered radiation caused by the original configuration was measured using the SXR in February 1994 during experiments with the original GS-5000 system at the NOAA MOBY site in Honolulu, Hawaii (Appendix B). A fiducial level of spectral radiance was established using lamp F307, with both the light-tight housing and bellows removed and curtains placed to eliminate stray radiation from the lamp. The spectral radiance measured with lamp F307 enclosed by the housing and bellows is compared to this fiducial configuration in Fig. 22b.

With the sphere attached, the spectral radiance of the GS-5000 was measured during SIRREX-3 using the SXR and 746/ISIC with lamp F268 on 27 Sept 1994. These radiance measurements are compared with the manufacturer's radiance calibration of the system in Fig. 22a. Figure 22b shows deviations of the 746/ISIC radiances and the EG&G calibration from the SXR radiances. Fig. 22b also shows the original housing and bellows scattered radiant flux from the source into the sphere at the level of 5–8%.

The GS-5000 was also tested during SIRREX-3 for irradiance transfers using the 746/ISIC and a MER-2040 underwater radiometer manufactured by BSI. The measurement wavelengths of the MER-2040 are 440, 453, 487,

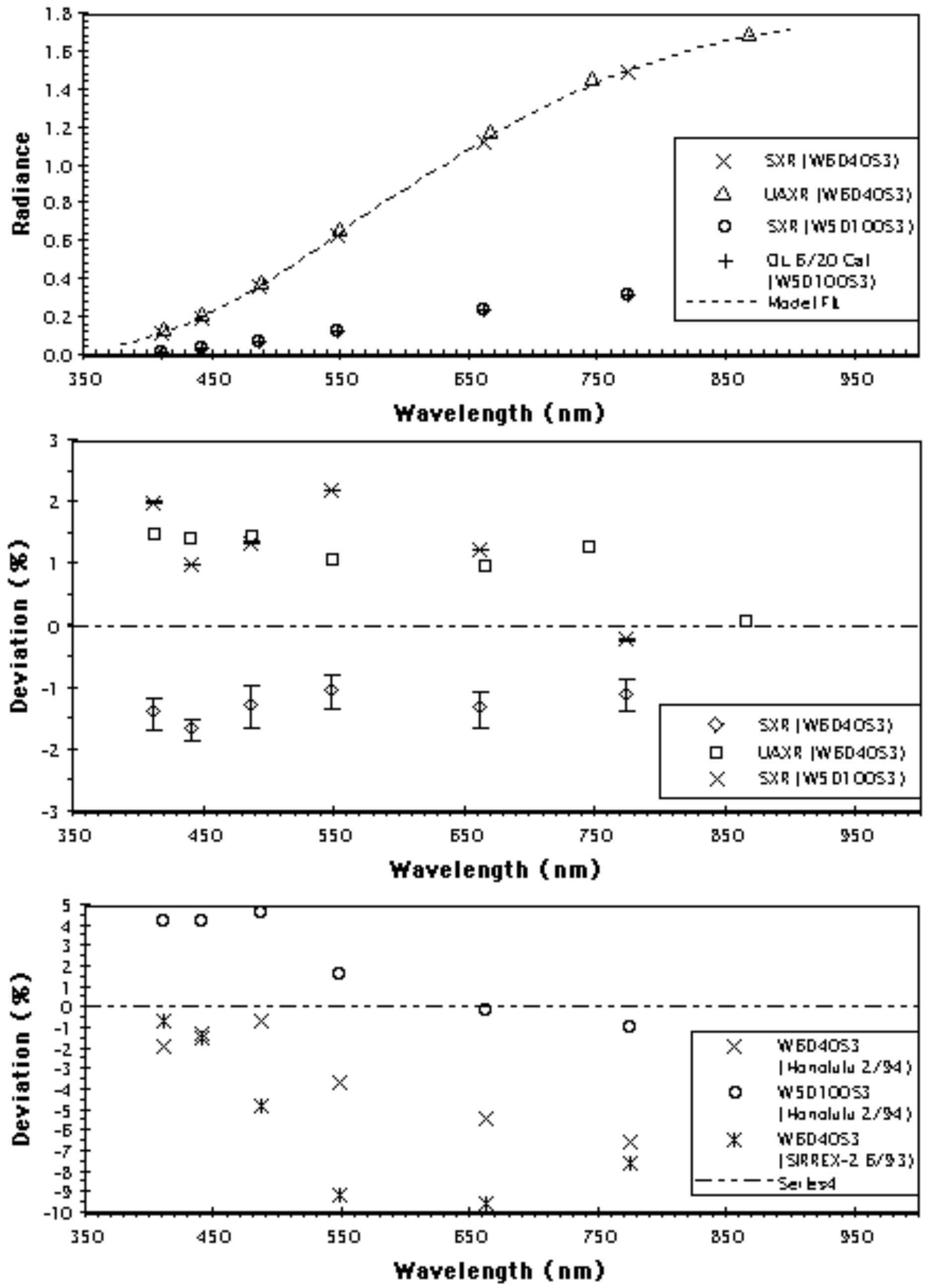
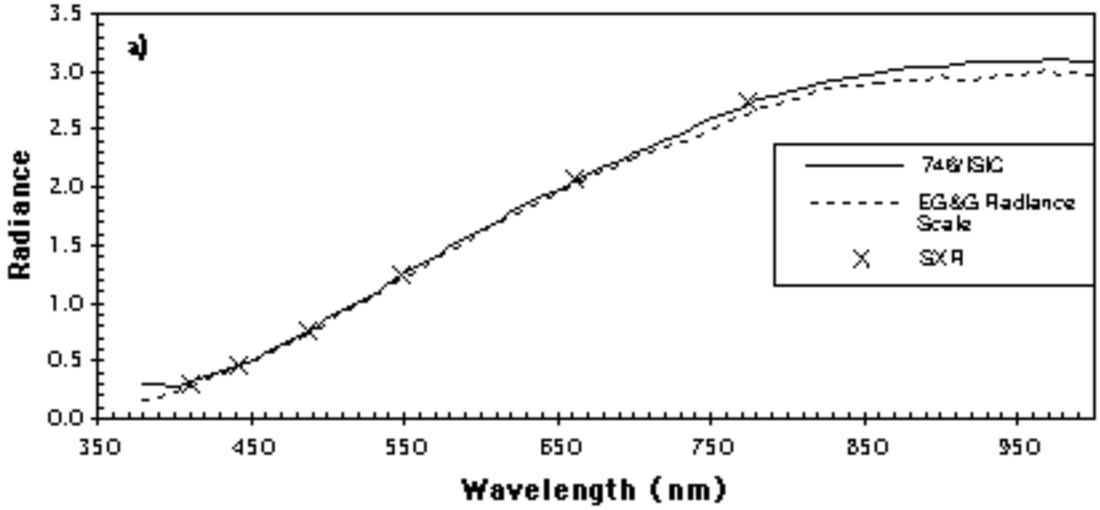


Fig. 21. **a)** Average spectral radiance in units of μW/(cm^2 sr nm) of the OL420 sphere as measured with the SXR and the UAXR, shown with the model fit to these data for the lamp distance and aperture setting designated W6D40S3. Also shown is the spectral radiance of the OL420 for the W5D100S3 configuration as measured by the SXR and as calibrated by OL in June 1994. **b)** Results from panel **a** with respect to the model fit and the uncertainties, calculated as described in the text. The quantity plotted for the W6D40S3 configuration (see legend) is the SXR or the UAXR data minus the model fit, normalized to the model fit. The quantity plotted for the W5D100S3 configuration is the SXR data minus the OL calibration, normalized to the OL calibration. The UAXR was used only once and no uncertainties are indicated. **c)** Comparison of SXR measurements at the MOBY facility in Honolulu and at SIRREX-2 to the results at SIRREX-3. The quantity plotted is average SXR data at Honolulu or SIRREX-2 (see legend) minus the average SXR SIRREX-3 data, normalized to the average SXR SIRREX-3 data. The sphere configuration is indicated in the legend.



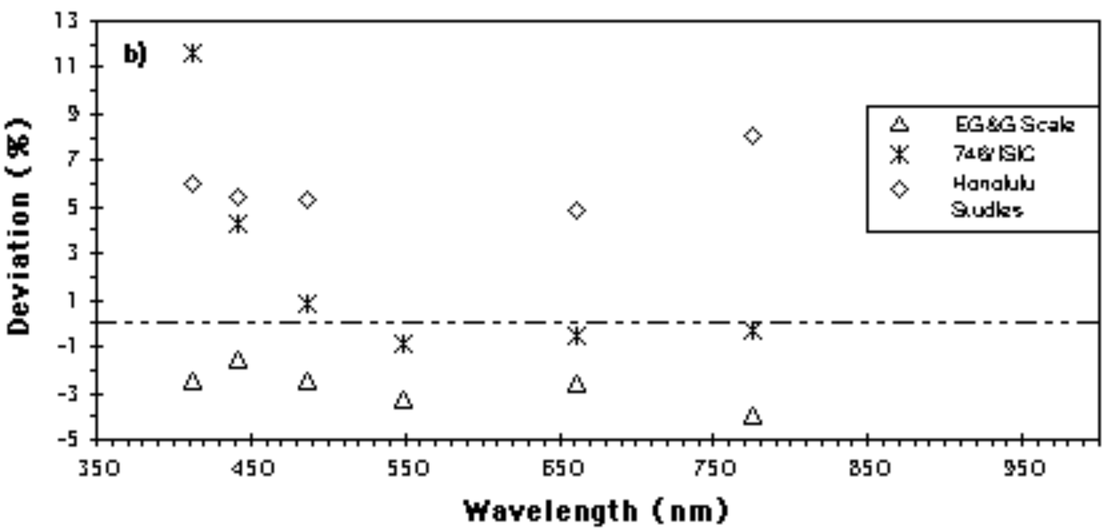


Fig. 22. **a)** Average spectral radiance in units of μW/(cm^2 sr nm) of the GS-5000 sphere, illuminated using FEL lamp GS-922 (values assigned from SIRREX-3 results) as measured with the 746/ISIC (and F268) and the SXR, shown with the radiance calibration of the system by its manufacturer, EG&G. **b)** Results from panel **a** with respect to the SXR. The quantity plotted using the $\triangle$ symbol is the EG&G data minus the SXR data, normalized to the SXR data. The $\ast$ symbol similarly shows the 746/ISIC data minus the SXR data, normalized to the SXR data. The $\diamond$ symbol shows the results of the SXR stray light tests of the GS-5000 lamp housing during the Honolulu measurements. Here the quantity plotted is the radiance measured with the original lamp housing in place minus the radiance measured with the lamp housing removed, normalized to the radiance measured with the lamp housing removed. In this latter configuration, large cloth screens were used to eliminate unwanted optical coupling between the integrating sphere and the external lamp, and served the same purpose as the EG&G lamp housing.

517, 530, 565, and 664 nm. The MER-2040 was calibrated on the CHORS optical bench, using standard procedures with lamp H91534 and its SIRREX-3 irradiance (Table 6). The 746/ISIC was calibrated for this test using F268. The GS-5000 was tested using lamp GS-922 (SIRREX-3 irradiance, Table 4). Figure 23a illustrates three 746/ISIC spectral irradiance measurements labeled A, B, and C. Test A was made with the light enclosure removed and no baffling in an open room. Test B was made by installing the light enclosure, but without the light trap, leaving a hole for light to escape into the open room. Test C was made with the fully assembled GS-5000, with the light trap attached.

In all of these measurements, it was necessary to position the 746/ISIC entrance aperture approximately 0.61 cm off axis and at an overall distance of 51.33 cm from the lamp. The translation of 0.61 cm decreases the irradiance by about 0.02% according to the expected distribution from a point source, and no correction was made for this effect. Neglecting the distance correction would result in a 5.4% error, so this correction was made (see below). Also shown in Fig. 23a are two spectral irradiance measurements using the MER-2040.

The MER-2040 was first used to measure irradiance with lamp GS-922 (SIRREX-3, Table 4) in the fully assembled GS-5000. The measurement was then repeated using lamp H91534 (SIRREX-3, Table 6) installed in the fully assembled GS-5000. Because the MER-2040 faceplate does not mate with the GS-5000 kinematic mount at 50 cm, the instrument was positioned on axis at 50.735 cm distance from the lamp in each measurement. All measured irradiances, illustrated in Fig. 23, were adjusted to a 50 cm lamp distance, assuming r^{-2} scaling. The dashed curve in Fig. 23a illustrates the independent spectral irradiance of GS-922 provided by the manufacturer (the SIRREX-3 and EG&G values of GS-922 are also compared in Fig. 14 above). Deviations of the 746/ISIC, MER-2040, and EG&G calibration radiance from the SIRREX-3 values of FEL GS-922 (or H91534, as appropriate) are illustrated in Fig. 23b.

Comparison of the A, B, and C tests in Fig. 23a shows that there was little difference when the on-axis light trap was added (these curves overlap in the figure), but that the irradiance measured with the entire housing removed (A) disagrees with the complete system (C) by about 2%, whereas these configurations should give identical results if stray light was managed properly in both measurements. The most likely explanation is that stray light contaminated the 746/ISIC measurements when the light enclosure was removed (A). Examination of Fig. 23b indicates that the MER-2040 faithfully realized spectral irradiance for this source, since the deviations among the measured irradiances are small. However, the 746/ISIC overestimated the spectral irradiance of GS-922, even with the light enclosure, baffling, and light trap attached (test C, where the discrepancies are shown as the solid line in Fig. 23b).

The uncertainties illustrated in Figs. 16–22 and discussed above, provide one measure of the day-to-day stability of the measured spectral radiances of the sphere sources and the radiometers. For the CHORS and BSI spheres, which have the largest Type A uncertainties, additional continuous time-series radiance measurements were monitored with the CXR, UAXR, or SXR to test for source stability.

The temporal stability of the CHORS sphere was tested by measuring overnight time series of radiance using the CXR (sampled at 1 minute intervals), the SXR (sampled at 10 minute intervals), and the UAXR (sampled at 30 second intervals). These experiments were conducted on two nights, with the results shown in Figs. 24a (26–27 September) and 24b (29–30 September). Perusal of these figures clearly indicates that the CHORS sphere varied significantly over a period of approximately 14 hours, with an approximate amplitude $\pm 1.5\%$ in the blue, decreasing slightly at longer wavelengths.

During the 29–30 September measurements, relative variations in shunt currents (Fig. 24c) and room temperature (Fig. 24d) were monitored concurrently with the CXR measurements at one minute sampling intervals. The four 200 W lamps in the CHORS sphere are operated by two separate power supplies, each system consisting of the power supply, a shunt resistor, and two lamps connected in series. Both shunts show current variations (drifts) of up to 2% over the first eight hours of the experiment, and then appeared to stabilize within the noise of the measurements (Fig. 24c). Room temperature was stable within less than 0.5%. Since the lamp currents and room temperature were not monitored during the first time series, it is not known if these parameters are the only factors responsible for the changes in the sphere radiance.

The spectral radiance $L(411.5)$ of the BSI sphere was monitored continuously with the SXR, at one minute intervals, for approximately one hour on 26 Sept 1994. This time series is presented in Fig. 25, with radiances plotted as percent deviations from the average spectral radiance for this sequence of measurements. During this period, the radiance of the BSI sphere (at 411.5 nm) increased at a linear rate of approximately 0.7% per hour.

The spatial uniformity of radiance of the GSFC sphere was scanned with the SXR on 9 Sept 1994, just prior to SIRREX-3, with the results illustrated in Figs. 26 and 27. Figure 26 shows a single horizontal scan through the center of the sphere's exit aperture at all six SXR wavelengths. The variability across the aperture is approximately 0.5% at all SXR wavelengths except 774.8 nm (SXR channel 6), where an apparent 1% range of variability was measured. The vignetted field of view (FOV) of SXR channel 6 is known to be relatively large, however, and the measurements in that channel include an uncorrected size-of-source effect which is estimated to be between 0.5–1.6% in magnitude. Figure 27 illustrates the two-dimensional (x, y) distribution of radiance in the GSFC sphere's exit aperture

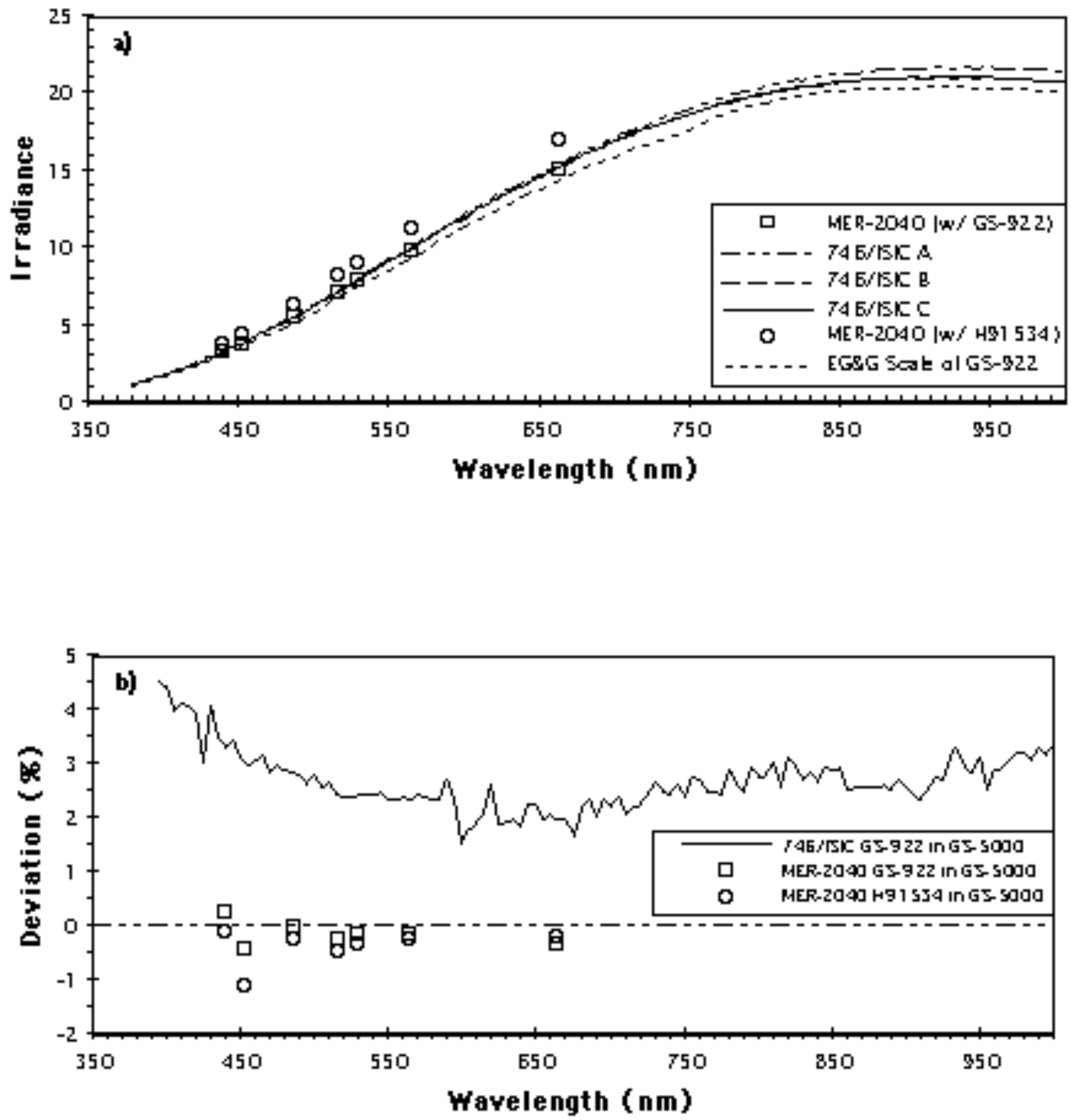
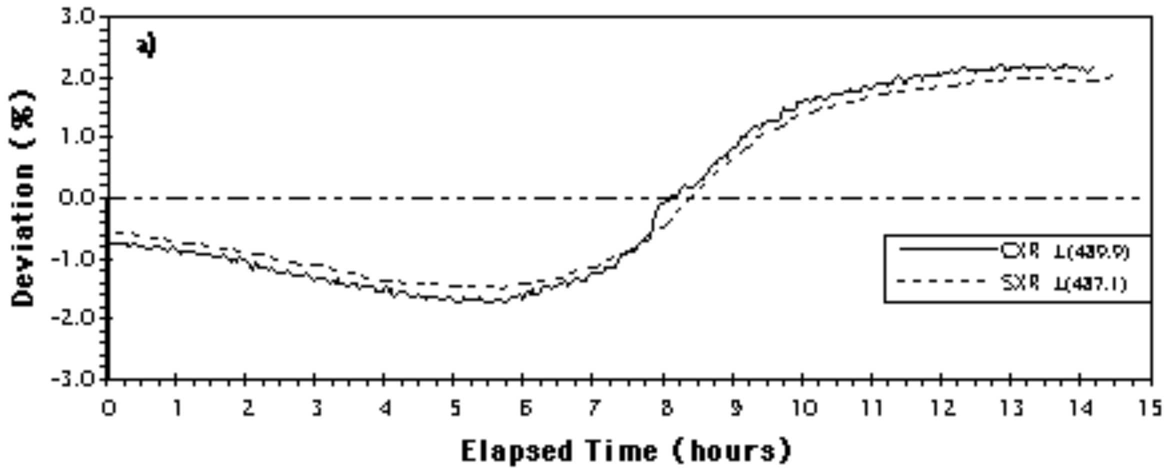


Fig. 23. a) Spectral irradiance in units of μW/(cm^2 sr nm) for the NOAA GS-5000 system (with lamps GS-922 and H91534, and the SIRREX-3 values) as measured by the MER-2040. Also shown is the spectral irradiance measured using the 746/ISIC (and F268) with GS-922 in the GS-5000 system for three configurations of the lamp housing (A, B, and C, see text). For comparison, the EG&G values of the GS-922 lamp are indicated. **b)** Results from panel **a** with respect to the SIRREX-3 lamp measurements. The quantity plotted using the solid line is the 746/ISIC (configuration C) data minus the SIRREX-3 data for GS-922, normalized to the SIRREX-3 data for GS-922. The □ symbol shows MER-2040 measurements of the GS-5000 illuminated with lamp GS-922 minus the SIRREX-3 data for GS-922, normalized to the GS-922 data for GS-922. The ○ symbol similarly shows the MER-2040 measurements of the GS-5000 using lamp H91534.



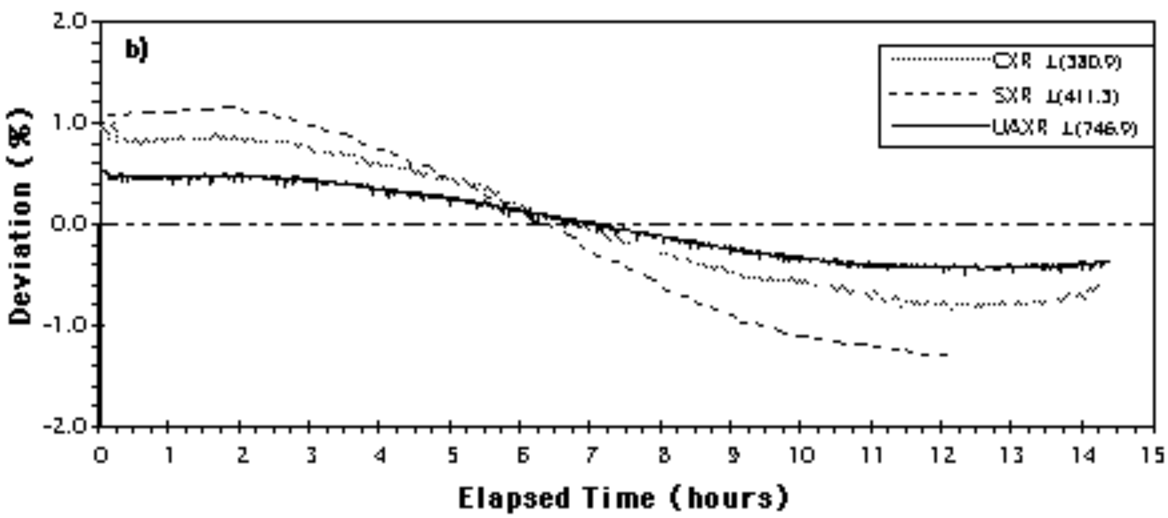
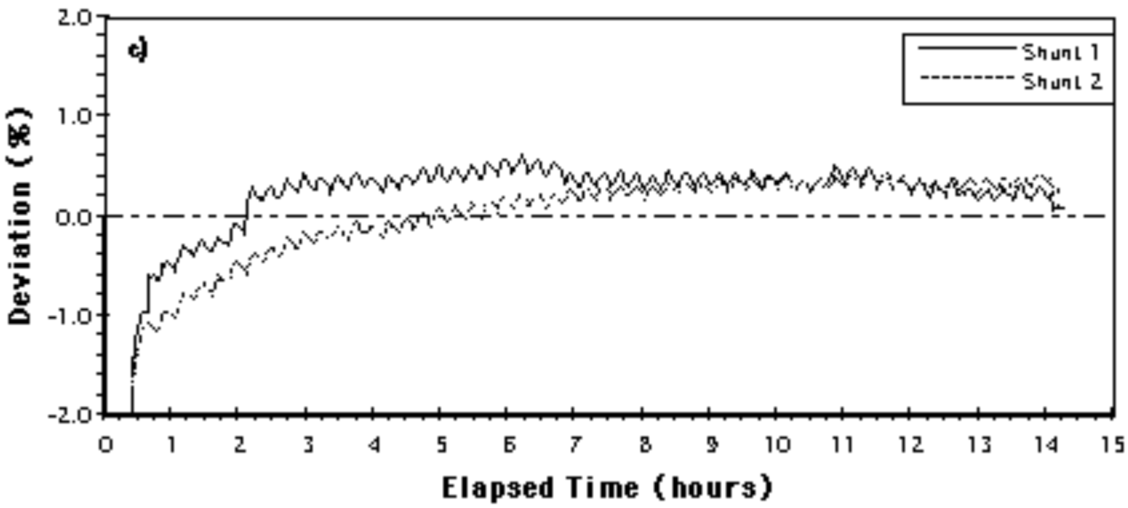


Fig. 24. a) Temporal stability of the spectral radiance of the CHORS sphere as measured with the CXR and the SXR on 26–27 Sept 1994. The quantity plotted (solid line) is the CXR data minus the average CXR data, normalized to the average CXR data. The dashed line similarly shows the SXR data acquired over the same time interval at a wavelength close to that measured using the CXR. **b)** Temporal stability of the spectral radiance of the CHORS sphere as measured with the CXR, the SXR, and the UAXR on 29–30 Sept 1994, shown as in panel **a** as deviations with respect to the averages. For this study, different wavelengths were chosen for observation and the greatest changes were observed at the shorter measurement wavelengths. In panels **a** and **b**, the measurement wavelength is indicated in the legend.



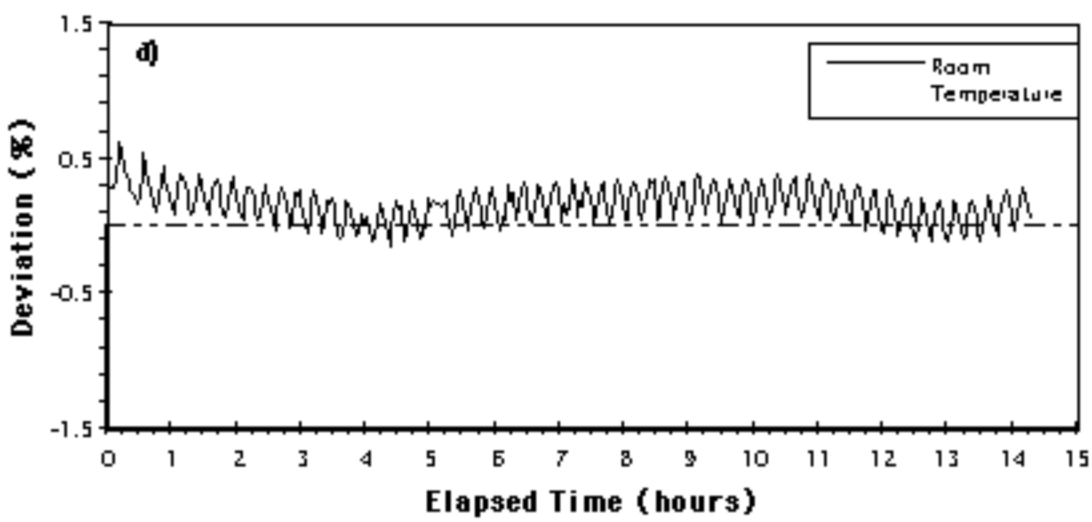


Fig. 24. (cont.) c) Temporal stability of the voltage measured across the two shunt resistors for the CHORS sphere during the 29–30 September tests, again plotted as deviations with respect to the average. **d)** Temporal stability of the room temperature during the 29–30 September tests of the CHORS sphere, again shown as deviations with respect to the mean temperature. A few outliers in panels **c** and **d** have been replaced with the average of temporally-adjacent data.

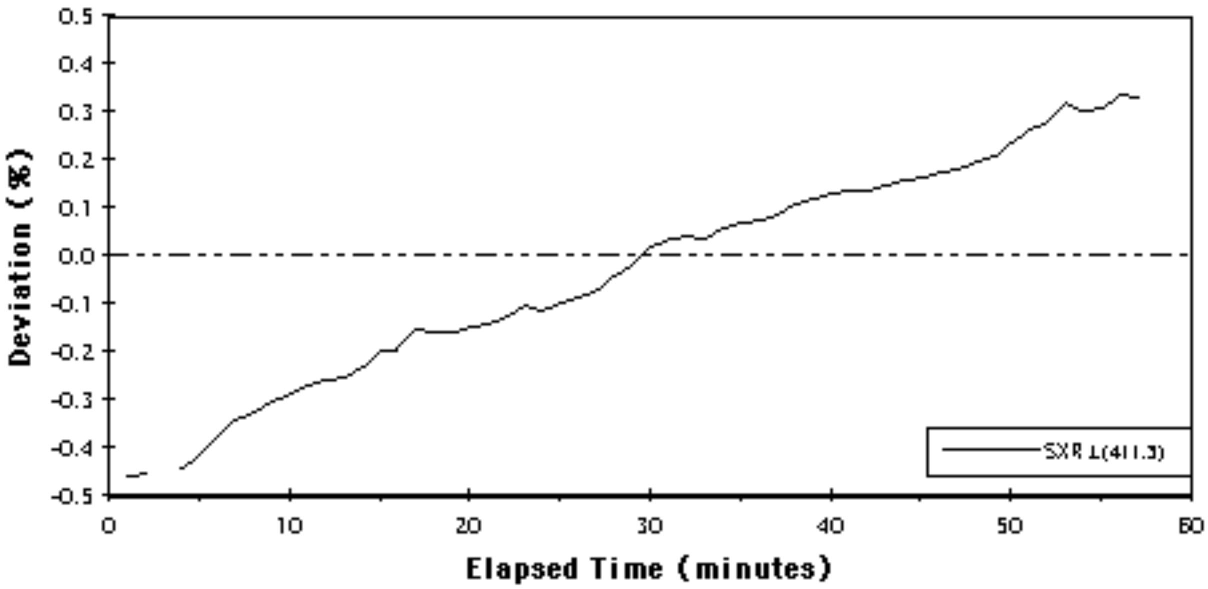


Fig. 25. Temporal stability of the spectral radiance of the BSI sphere as measured with the SXR on 26 Sept 1994, shown as the spectral radiance at 411.5 nm minus the average spectral radiance at this wavelength over the measurement interval, normalized to the average value.

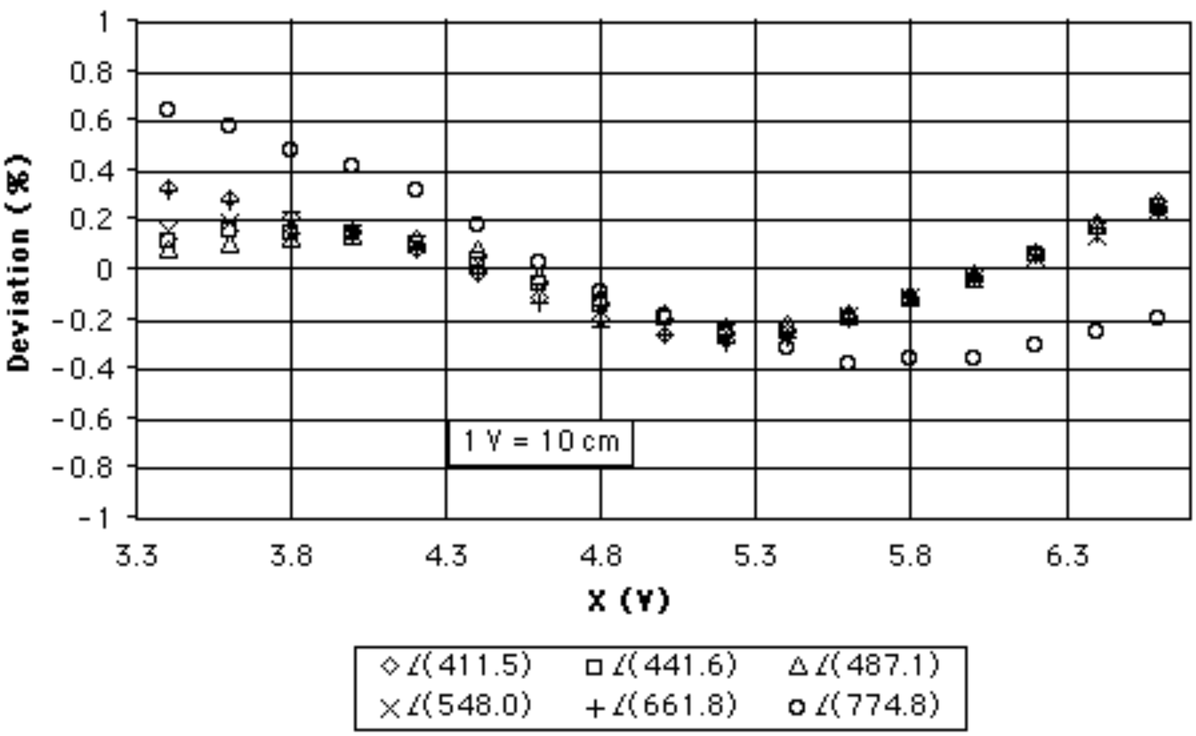


Fig. 26. Horizontal scans of the GSFC sphere radiance measured at all six wavelengths of the SXR on 9 Sept 1994, just prior to SIRREX-3 and after the GSFC sphere had been recoated. The SXR viewed a target area in the exit aperture of the sphere that was approximately 4 cm in diameter. The quantities plotted are the spectral radiance measured at a particular wavelength and horizontal position minus the average spectral radiance for all such measurements in the exit aperture of the sphere, normalized to this average value. The SXR was aligned to view the center of the exit aperture at the midpoint of the horizontal scan.

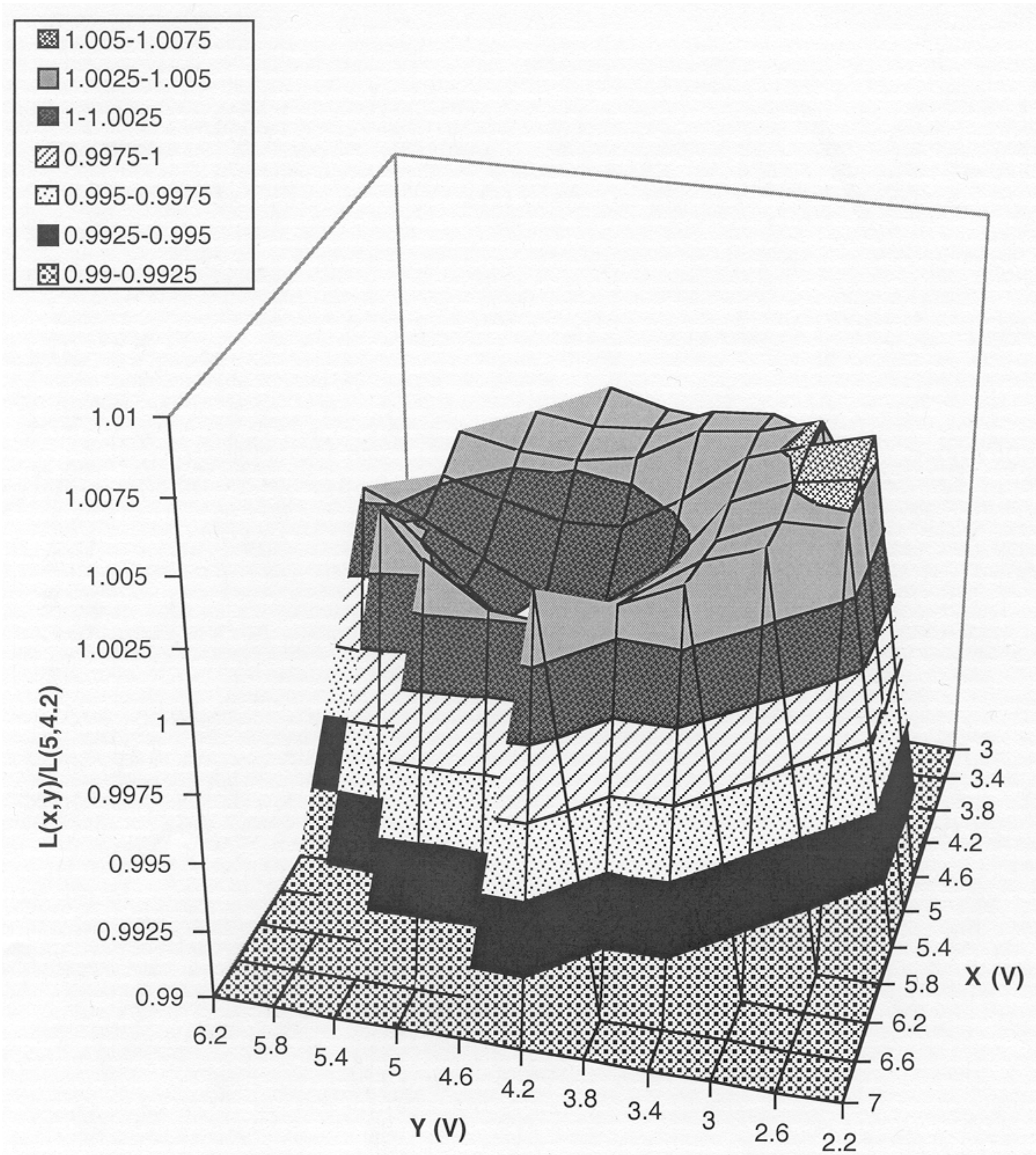


Fig. 27. Spatial variability of the spectral radiance $L(487.1)$ viewed normal to the plane of the exit aperture of the GSFC sphere, as measured with the SXR on 9 Sept 1994. The values are plotted relative to the radiance at the center of the exit aperture, i.e., at $(x,y) = (5.0\,\mathrm{V}, 4.2\,\mathrm{V})$. Variability of similar shapes and amplitudes was measured at 411.5 nm and 774.8 nm.

at 487.1 nm, obtained by combining 11 horizontal scans of the type illustrated in Fig. 26. The total range of variability is again seen to be approximately 0.5%, with a *dark* minimum area located slightly above the center of the exit aperture and a brighter maximum area across the bottom portion of the port. The two-dimensional patterns of spectral radiance are similar at 412 and 775 nm, the other two SXR channels used.

The spatial variability of radiance $L(532)$ in the exit aperture of the CHORS sphere was scanned with the CXR on 12 and 13 Sept 1994, in preparation for SIRREX-3. For this measurement, the CXR was mounted on a one dimensional machinist quality translation stage with a manual micrometer-head adjustment. The total x-direction range of travel was approximately 25 cm. The translation stage was attached to a plastic plate of 2.54 cm thickness, which was positioned on top of a stack of such plates. Two holes in the top plate were set over vertical rods to maintain the horizontal position of the stage as plates were added or removed, thus adjusting the vertical (y) dimension of the CXR in 2.54 cm increments. Pointing relative to the x, y position in the exit aperture of the sphere was determined using the CXR's internal aiming laser and a grid overlay on the exit aperture.

Figure 28 illustrates the two-dimensional variability of the radiance ratio $L(x, y)/L(0, 0)$, where $L(0, 0)$ is radiance measured at the point closest to the center of the sphere. The uppermost two horizontal scans illustrated in Fig. 28 ($y = 53.2$ mm and $y = 35.7$ mm) were measured on 12 September and the remaining scans were measured over a period of a few hours on 13 September; therefore, temporal variability on time ranges of day to day (Fig. 17) and several hours (Fig. 24) are also present in the data shown in Fig. 28. In the center area of the exit aperture, where the CXR's 4.8° vignetted FOV is clearly not overlapping the edge of the aperture, the total range of variability is less than 0.5%. This level of variability is well within the uncertainty introduced by temporal variations in the CHORS sphere's radiance level (Figs. 17 and 24).

The spatial variability of radiance of the UCSB sphere (externally illuminated with FEL lamp F305 at 50 cm) was measured at all six measurement wavelengths of the SXR on 21 September during SIRREX-3. Figure 29 illustrates the result at 487.1 nm. These data are shown as the ratio $L(x, y)/L(0, 0)$, where $L(0, 0)$ is the radiance measured in the center of the exit aperture. Radiance increases monotonically from the right side (−0.5% relative to the center) to the left side (+0.75% relative to the center) of the sphere's exit aperture. The entrance aperture for the lamp is located on the right side, suggesting that the area exposed to first-surface reflections of illumination from the FEL lamp is approximately 1.25% brighter than the portions of the sphere wall in the same hemisphere as the entrance aperture through which the sphere is illuminated.

For a Lambertian source, the radiance is independent of the viewing angle. The Lambertian quality (0–15° from normal) of the GSFC sphere, as measured with the SXR during SIRREX-3, is illustrated in Fig. 30. The radiance, viewed at angles away from the normal in this sphere, increases approximately linearly to a value 1.1% above the radiance measured at normal incidence. The Lambertian quality (at 0 and 15°) of the CHORS sphere, as measured with the SXR and CXR during SIRREX-3, is illustrated in Fig. 31. The off-normal radiance in this sphere decreases, relative to the normal radiance, to values ranging from 0.4–0.7% at −15° left of normal, and decreases by less than 0.1% at 15° right of normal (CXR only). These types of angular uniformity measurements were not made on the other spheres during SIRREX-3.

3.3 Discussion

In the interpretation of the sphere characteristics presented above and in Figs. 16–31, it is necessary to consider the relative contributions of the transfer radiometers and the sources of their calibrations, as well as those attributable to spheres alone.

When measuring sources with spectral radiance exceeding $5\,\mu\mathrm{W\,cm^{-2}\,nm^{-1}sr^{-1}}$ for $\lambda > 450$ nm (which applies to the GSFC sphere for lamp levels 12–16 and likely applies to the UA/SIS, although no 746/ISIC data were acquired at SIRREX-3), the 746/ISIC measurements have a relative standard deviation of about 1%, if measurements are made within an hour or so of the instrument's calibration using an FEL lamp. The instrument's sensitivity drops off, and the uncertainty increases to approximately 1.5% or more, at lower levels of spectral irradiance. These approximate uncertainties are deduced from measurements of lamp irradiance (and accompanying stability studies) below 500 nm (Figs. 4, 6, 7, and 15) and for spheres with high (Fig. 16b) and low (Figs. 17b and 18b) radiance levels in the blue. When the 746/ISIC has not been calibrated within one or two hours, the uncertainty in its responsivity may be larger.

The approach of measuring coaxial irradiance to derive mean radiance of a sphere's exit aperture is also especially susceptible to incomplete baffling of stray light within the laboratory, and uncertainties well over 10% may result in extreme cases (Fig. 18). In these particular data, an additional 1% uncertainty component in the transfer of the NIST (August 1994) spectral irradiance of F268 to F269 should be combined in quadrature with Type A uncertainties in 746/ISIC measurements based on F269. This affects the 746/ISIC overall uncertainty estimates of the GSFC, CHORS, and UCSB spheres.

The overall uncertainty in the NIST calibration of the radiance responsivity of the SXR is approximately 1.5%, and uncertainty in the repeatability of SXR radiance measurements is estimated to be less than 0.1%. The vignetted FOV of the SXR is approximately 2.5°; because of the asymmetric patterns of the SXR channels, channel 6 (774.8 nm) has a possible size-of-source uncertainty contribution for measurements of exit ports 5.7 cm in diameter

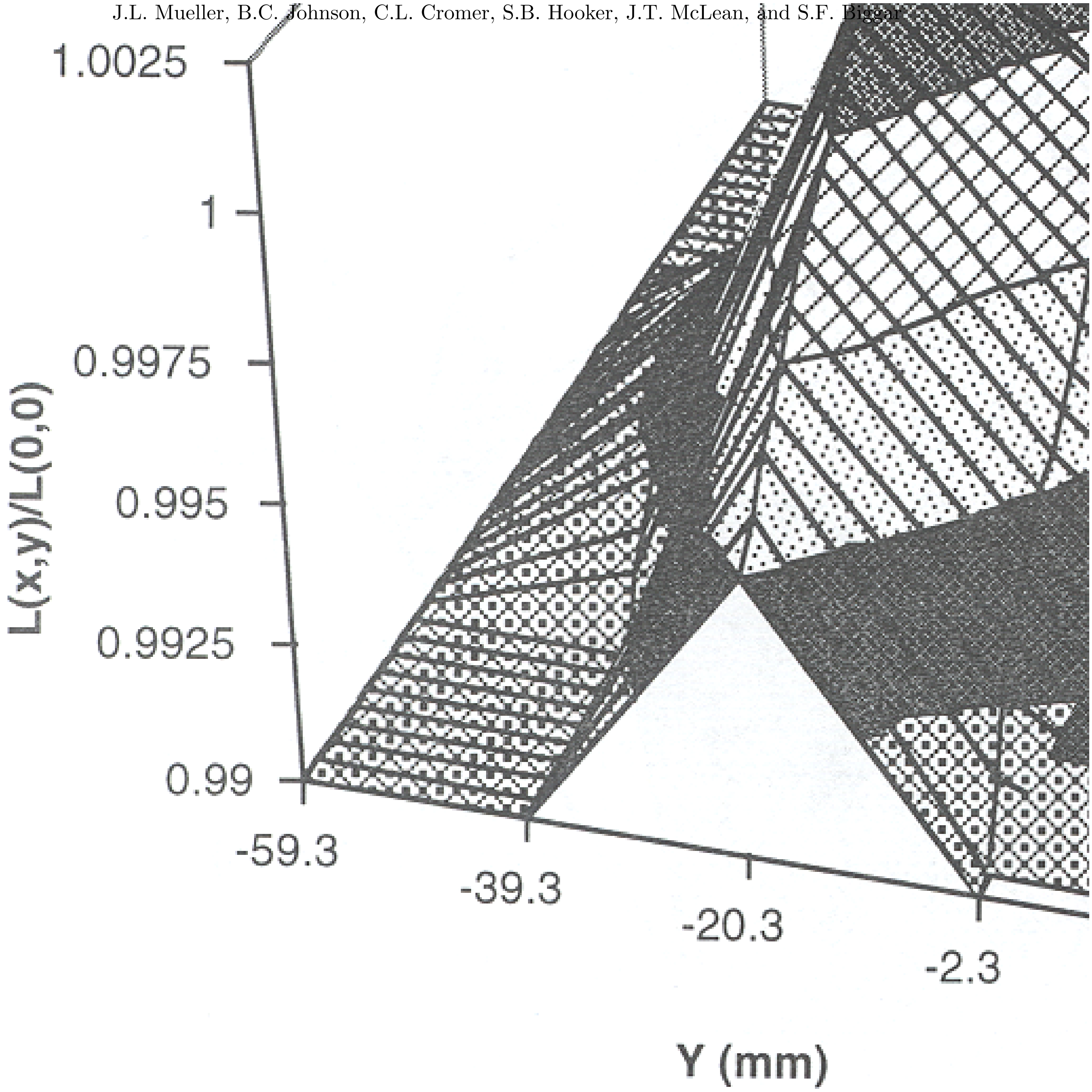


Fig. 28. Spatial variability of the spectral radiance $L(531.9)$, viewed normal to the plane of the exit aperture of the CHORS sphere, as measured with the CXR on 12 and 13 Sept 1994, just prior to SIRREX-3. The values are plotted relative to the radiance measured at the center of the exit aperture, i.e., at $(x, y) = (0\,\text{mm}, 0\,\text{mm})$.

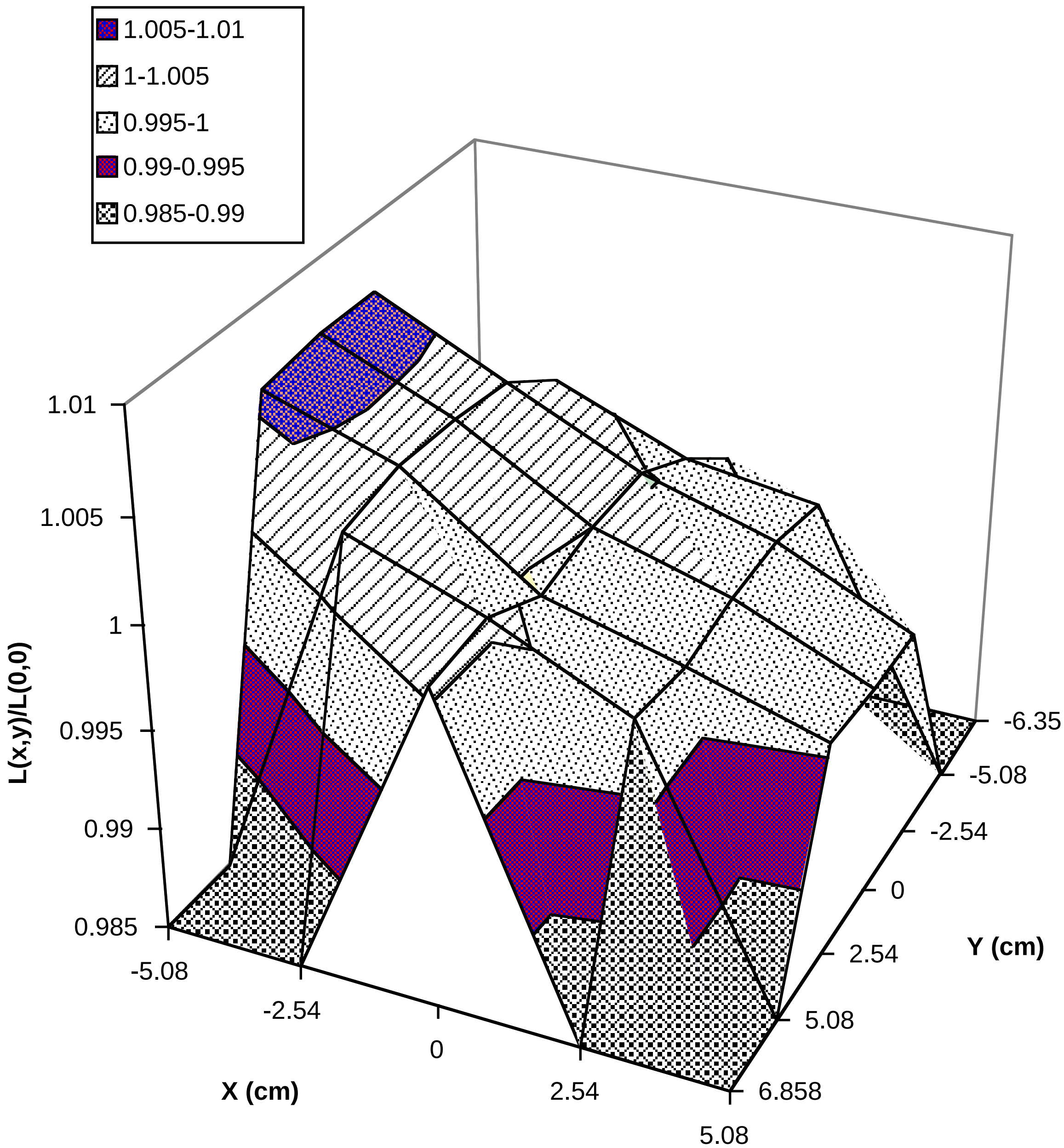


Fig. 29. Spatial variability of the spectral radiance $L(487.1)$, viewed normal to the plane of the exit aperture of the UCSB sphere, as measured with the SXR during SIRREX-3. The values are plotted relative to the radiance measured at the center of the exit aperture, i.e., at $(x, y) = (0\,\text{cm}, 0\,\text{cm})$. Note that unlike Figs. 27 and 28, the x and y axes have been plotted here in reverse orientation.

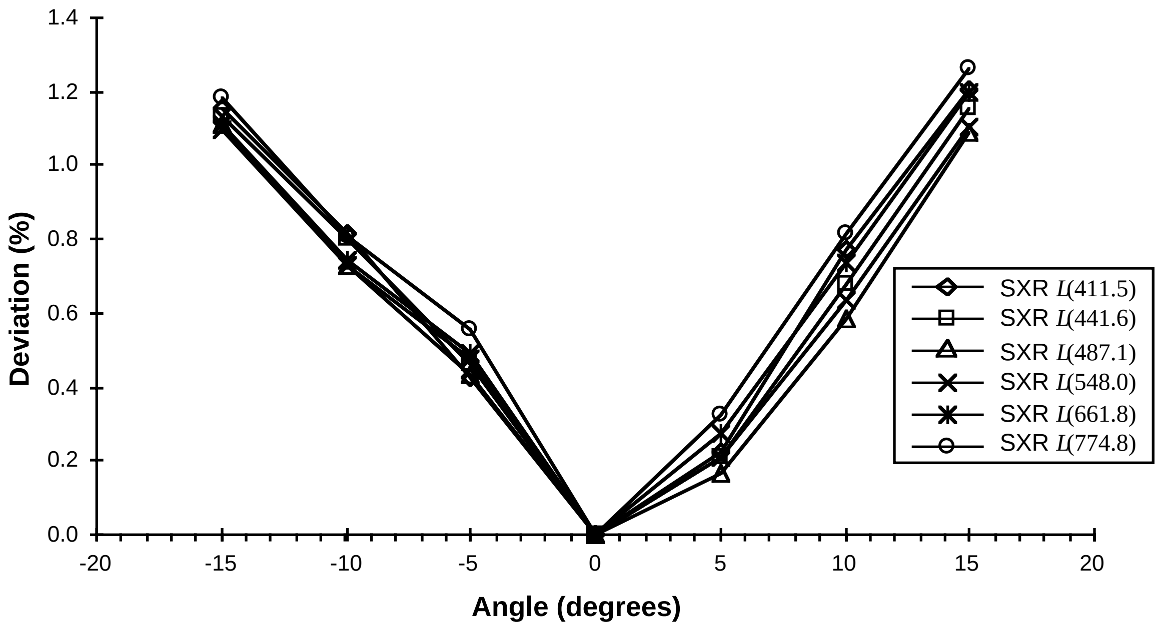


Fig. 30. Lambertian quality (angular uniformity of radiance) of the GSFC sphere, measured within 15° of the normal to the center of the plane of the exit aperture using the SXR. The quantity plotted is the spectral radiance at a particular viewing angle minus the spectral radiance at normal incidence, normalized to the normal incidence value, for the six measurement wavelengths of the SXR.

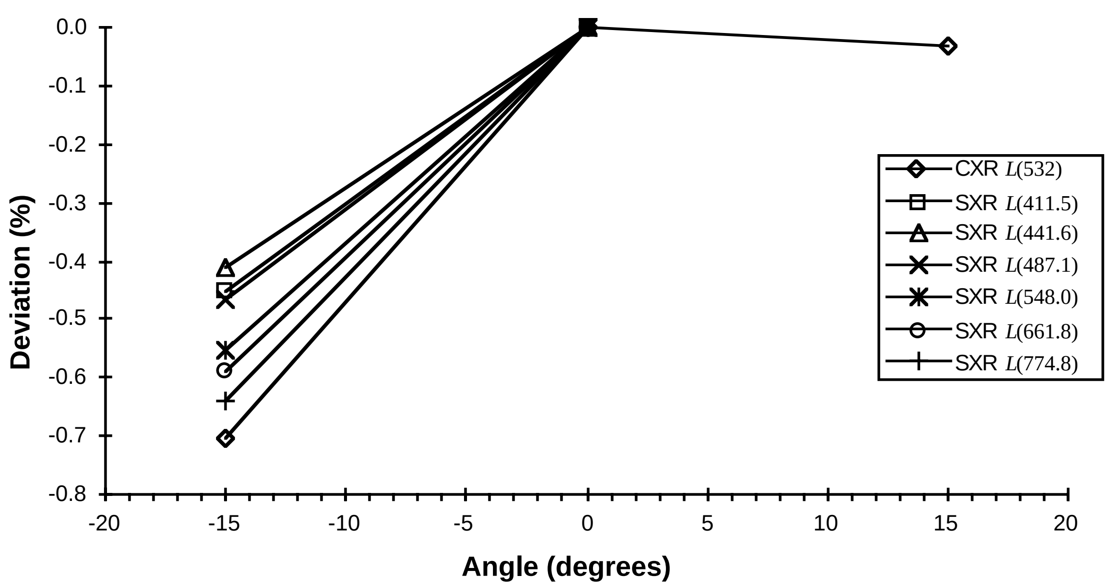


Fig. 31. Lambertian quality (angular uniformity of radiance) of the CHORS sphere, measured within 15° of the normal to the center of the plane of the exit aperture using the SXR (all wavelengths) and the CXR (531.9 nm only). The quantity plotted is the spectral radiance at a particular viewing angle minus the spectral radiance at normal incidence, normalized to the normal incidence value, for the indicated measurement wavelengths of the SXR and the CXR.

or larger. (This includes all spheres from SIRREX-3 except the EG&G GS-5000 with sphere assembly and the OL420.) This presence of a size-of-source effect on the order of 0.5% was confirmed at SIRREX-3 by comparing UAXR (746.2 nm) and SXR (774.8 nm) measurements of variability between three locations spaced across the GSFC exit aperture. The difference measured between the two near-edge locations by the UAXR was 0.4%, while the corresponding difference in SXR measurements was 0.8%. The SXR is pointed using an eyepiece aligned with the center of its optical axis, and there is negligible uncertainty in the pointing of the FOV. Measurements of the GSFC and CHORS spheres at different SXR rotational orientations about the optical axis of the SXR indicate a negligible uncertainty of less than 0.3%, which is well within the spatial and temporal uncertainty limits of these spheres.

Summarized in Fig. 32 are the measurements of the GSFC, CHORS, UCSB, and GS-5000 sphere sources with the 746/ISIC and the SXR. These data are from Fig. 16b for the GSFC sphere, and from Fig. 22b for the GS-5000 sphere system. (For the CHORS and UCSB spheres, the relevant data are illustrated in Figs. 17b and 18b, respectively, although there the deviations were calculated relative to the greybody model.) Cubic spline interpolation was used to calculate the spectral radiance measured by the 746/ISIC at the SXR wavelengths. Figure 32a illustrates the deviations (in percent) as a function of the measurement wavelength; Fig. 32b presents the same results as a function of the spectral radiance of the sphere source. The largest discrepancies (up to 30%) occur for wavelengths below 450 nm and/or spectral radiances below approximately 0.5 μW cm^{-2} nm^{-1}sr^{-1}. The average deviation for spectral radiances greater than 1 μW cm^{-2} nm^{-1} sr^{-1} is 0.007% with an uncertainty in this mean of 0.27%. If the range is extended to include spectral radiances of 0.1 μW cm^{-2} nm^{-1}sr^{-1}, but excluding the four points with deviations greater than 5%, the average deviation is 1.0% and the uncertainty in this mean is 0.4%. This average deviation is within the combined uncertainties of the 746/ISIC and the SXR, which is about 2.3% for wavelengths between 450–800 nm.

The spectral radiance responsivity of the CXR was calibrated using the mean 746/ISIC (F268/F269) derived spectral radiance of the GSFC sphere. Its overall uncertainty, therefore, is the 1.1% uncertainty associated with the calibration of the 746/ISIC, combined in quadrature by the 1.0% Type A transfer uncertainty of the GSFC sphere's repeat measurements using the 746/ISIC. The average Type A uncertainty for the CXR measurements of the GSFC sphere is 1.6%. Therefore, it is estimated that the uncertainty associated with the CXR radiance measurements (over the several days, and at radiance levels typical of the GSFC sphere) is approximately 2.2%. When observing sources with low radiance levels, the relatively low sensitivity of the CXR increases its uncertainty to approximately 5%. This signal-to-noise characteristic of the CXR is estimated by comparing the Type A uncertainties of CXR (5.6% at 399.6 nm) and SXR (1.7% at 411.5 nm) radiance measurements of the CHORS sphere. The vignetted FOV (full width) of the CXR is approximately 4.8°, and its shape is approximately circular. The instrument is pointed using an internal laser and removable mirror which directs the pointing laser beam into the optical axis. Characterization tests after SIRREX-3 show that the uncertainty (displacement) in the alignment of the pointing laser, relative to the centroid of the vignetted FOV, is approximately 1.5°.

Very few replicate sets of UAXR measurements were made on any of the spheres, and only then on a single day. The UAXR radiance responsivities used here were calibrated using the GSFC sphere, as calibrated with the 746/ISIC on the same day that the UAXR measurements were made. The overall uncertainty of the radiance of the GSFC sphere for the calibration of the UAXR is 1.2%. The uncertainty in two UAXR measurements of the GSFC sphere (made within an hour of one another) was approximately 0.5%, which is assumed to be the approximate uncertainty in short-term repeatability of UAXR radiances. Therefore, the uncertainty associated with the UAXR at radiance levels typical of the GSFC sphere is approximately 1.3%. The circular, vignetted FOV of the UAXR is approximately 5°. The UAXR is aligned by using the V-block that holds the cylindrical radiometer or a sight tube that is the same outside diameter as the UAXR. The contribution to the uncertainty from alignment errors is probably negligible.

The best estimate of day-to-day stability in the spectral radiance of the GSFC sphere is the approximate 0.3% Type A uncertainty computed from the SXR measurements of this sphere. The absolute radiance is, however, uncertain at approximately the 1.5% level associated with the irradiance responsivity calibrations of the 746/ISIC (F269/F268) and the standard deviation of the measurements. Because the spectral radiance responsivities of the CXR and UAXR were calibrated using the measurements of the GSFC sphere with those instruments, estimates of sphere radiance uncertainty cannot be derived from data on this sphere measured with those instruments.

Time series measurements, which would allow detection of possible drifts of the radiance over periods of several hours, were not attempted with this sphere. The SXR data, however, show that the sphere is stable to with ±0.3% from 21–29 Sept 1994. The radiance levels of the GSFC sphere were only varied once, so it is not possible to compute Type A uncertainties except for the 16-lamp maximum radiance configuration (Fig. 16c). The color ratios of the radiance spectrum of this sphere generally become more red as the number of lamps is decreased (Fig. 16d). Close scrutiny of Fig. 16d shows that this tendency is not monotonic and probably is a manifestation of the color temperatures of the different combinations of lamps. The most important consequence of this phenomenon is that

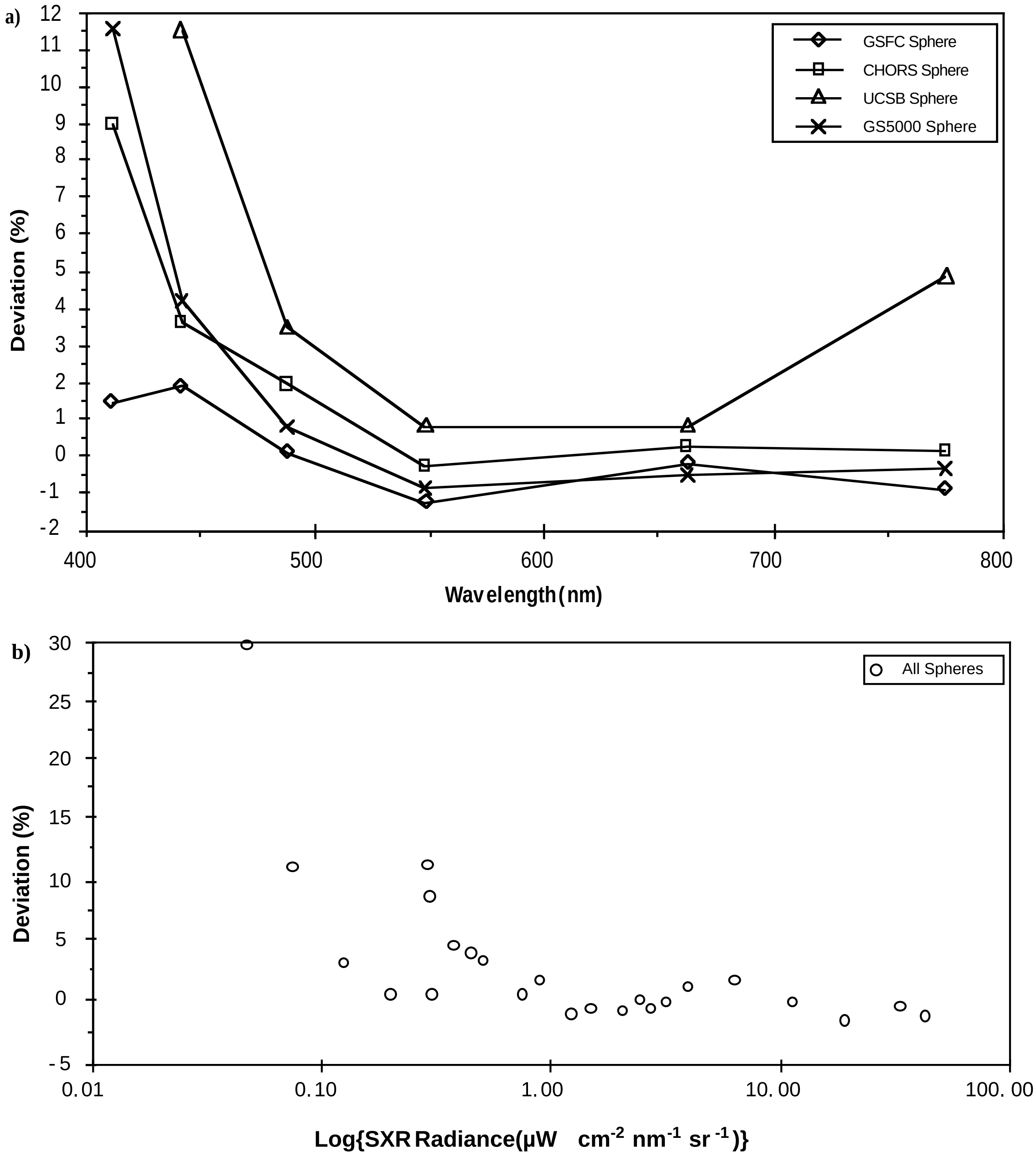


Fig. 32. a) Comparison of measurements of spectral radiance of the GSFC, CHORS, UCSB, and GS-5000 sphere sources using the 746/ISIC and the SXR. The quantity plotted for each sphere source (see legend) is the 746/ISIC result minus the SXR result, normalized to the SXR result. **b)** The same data as in panel **a**, except that the normalized deviations between the 746/ISIC and SXR measurements for these four sphere sources have been plotted as a function of the spectral radiance as measured by the SXR.

lamp combinations are not interchangeable and must always be combined in a fixed sequence to maintain a repeatable set of 16 levels of spectral radiance.

Spatial (x, y) variability of spectral radiance in the exit port of the GSFC sphere is approximately 0.5%, except for SXR channel 6 (774.8 nm) (Figs. 26 and 27). The greater apparent variability at 774.8 nm is probably a size-of-source effect near the edge of the port, due to the *side lobe* in the FOV of this SXR channel (see above). Lambertian quality (0–15° from normal) in the center of the GSFC exit aperture is approximately 1.1% (Fig. 30).

Based on the SXR radiance measurement set, the day-to-day uncertainty of the CHORS sphere's (maximum aperture settings) spectral radiance averages about 1.2% (Fig. 17), and varies with wavelength from approximately 1.7% at 411.5 nm to 0.4% at 774.8 nm. The CXR radiance Type A uncertainty for this sphere ranges from 5.6% in the blue (where the sphere radiance and CXR sensitivities are both low) to approximately 1% in the red, averaging 2.7% over the spectrum. The $B_b(\lambda)$ model fit of (1) to the combined SXR, CXR, and UAXR data set (Table 7) provides a robust estimate of the average maximum radiance ($\lambda < 900$ nm) for this sphere. Maximum deviations from $B_b(\lambda)$ are less than 2% for the CXR and UAXR, and less than 1% for the SXR mean spectral radiances (Fig. 16b). The internal agreement between the SXR, CXR, and UAXR spectral radiance values indicates that the method of calibrating the CXR and the UAXR was applied successfully to the measurements of the CHORS sphere. The mean 746/ISIC radiance also agrees with $B_b(\lambda)$ within 2% over the wavelength range $450 < \lambda < 850$ nm, where the radiance levels of this sphere are large enough to yield a good SNR.

The 746/ISIC mean spectrum provides a better measure of the radiance than $B_b(\lambda)$ in the region $\lambda > 800$ nm, where the radiance spectrum obviously departs severely from a greybody curve (Fig. 17a). The two overnight time series of the CHORS sphere show that radiance drifted by up to 3% at 490 nm, and 1.6% at 581 nm, over a period of 14 hours (Figs. 24a and 24b). Lamp current drifted concurrently by 2% during the period (Fig. 24c). Room temperature variations were less than 0.5% during the period (Fig. 24d) and seem unlikely to be a significant contributor to the observed drift. The probable source of this drift is inadequate current regulation in the two power supplies controlling the lamps in this source. The drift rate is slow enough for the sphere to be used as a radiance source if it is recalibrated before and after each use. A better (but initially more expensive) solution is to replace the power supplies and provide better lamp current regulation.

Variations of the CHORS sphere lamp aperture combinations were done only once to compare the maximum, minimum, and one intermediate radiance level (Fig. 17c). The color ratios for this sphere (Fig. 17d) show that the radiance spectrum becomes more blue as the radiance level is decreased. This observation possibly results from either color temperature differences between the four lamps, or some wavelength-selective properties of the parabolic reflector and lamp housing assembly, which vary geometrically. The range of color ratio variations is approximately 15%, and again, specific combinations of lamp aperture settings are not interchangeable. At its maximum aperture setting, the spatial uniformity of radiance in the CHORS sphere is less than 0.5% (Fig. 28) and its Lambertian quality (0–15° from normal) is less than 0.7% (Fig. 31).

The Type A uncertainty in the stability of the spectral radiance of the UCSB sphere, when illuminated with FEL F303, is approximately 0.3%. This estimate is based on four SXR measurements, distributed over three days, of the radiance of the sphere in this configuration. The $B_b(\lambda)$ fit to these SXR data and one CXR data set provide a robust fit to the radiance spectrum of this sphere at $\lambda < 700$ nm. Maximum deviations of SXR mean spectral radiances are 1% for the SXR, 3% for the CXR, and 3% for the 746/ISIC ($500 < \lambda < 700$ nm) (Figs. 18a and 18b).

Above 700 nm, the $B_b(\lambda)$ fit of (1) is dominated by the single SXR channel 6 radiance (Fig. 18a), which could be high by about 1.3% due to the size-of-source effect in the SXR discussed above; therefore, the *baffled* 746/ISIC measurements are the best indicator of the spectral radiance of this source for wavelengths above 775 nm. The 746/ISIC is obviously sensitive to red stray light in the room, as evidenced by comparison of the measurements with and without a curtain draped to shield the instrument from the room at large (Fig. 18a). The radiance in the USCB sphere, illuminated by F305 rather than F303, varies spatially, (x, y), by approximately 1.3% across the exit aperture (Fig. 29). The sphere is brighter on the left hemisphere (the side directly illuminated by the FEL lamp), and darker on the right hemisphere, which contains the sphere's entrance aperture. Since the CXR was only used once with this source, it is not possible to calculate a standard deviation, and therefore, it cannot be determined if the CXR and SXR values are mutually consistent within there absolute uncertainties. The maximum departure, however, is not more than 4%, again indicating the success of the CXR calibration method.

The individual Type A uncertainties of SXR and CXR measurements of radiance in the BSI sphere both range from approximately 2.5% in the blue to 0.4% in the red. The deviations from the $B_b(\lambda)$ model fit of (1) to the combined SXR, CXR, and UAXR measurements for this sphere, however, are up to 5% for the CXR and UAXR, and up to 2.5% for the SXR (Fig. 19). The uncertainty of radiance stability for this sphere is the largest observed during SIRREX-3; a short (one hour) time series of radiance at 411.5 nm showed a steady linear rate of increase of approximately 0.7% per hour over the period (Fig. 25). In the configuration studied during SIRREX-3, this sphere is probably not a useful source of spectral radiance. BSI was previously aware of the instability of this sphere and discontinued its use for radiance calibrations.

The Type A uncertainties of spectral radiance of the UA/SIS, measured on two days, were 0.3% for SXR radiances and 1% for UAXR radiances. The larger UAXR radiance uncertainty results suggests that the uncertainty in the repeatability of its radiance responsivity may be somewhat larger than the 0.5% estimated above, as compared to the 0.1% figure for the SXR. The maximum deviations from the $B_b(\lambda)$ model fit of (1) to the combined SXR, UAXR, and CXR data for this sphere are approximately ±2% for the three radiometers (Fig. 20).

At its brighter setting (W6D40S3), the Type A uncertainty of SXR measurements of spectral radiance of the OL420 sphere was approximately 0.3%, and the single set of UAXR radiances were consistently greater than the SXR mean by 3–5% (Figs. 29a and 29b). When compared to the $B_b(\lambda)$ model fit to the combined data, SXR and UAXR radiances disagree with the model 1% and 2%—low and high—respectively. This difference is unexpected as the measurement with the UAXR on 29 Sept 1994 followed those with the SXR. The observation probably indicates some source of systematic error that was not identified, since it is unlikely that either radiometer changed in spectral response.

At the darker setting (W5D100S3), the SXR Type A radiance uncertainty was less than 1%, based on only two measurements taken on the same day. At these settings, the recent calibration of this source by OL deviated from the SXR mean radiances by up to 2% (Figs. 21a and 21b). This deviation is within the mutual uncertainties of the SXR and the calibration by OL, since the uncertainties in the calibration report are ±3% at 350 nm and ±2% at 550 nm for the highest radiance level. The uncertainties increase as the sphere settings are adjusted for decreasing radiance until they are ±10% at 350 nm and ±8% at 550 nm for the lowest radiance level possible with this source.

Relative to the SIRREX-3 SXR results in Fig. 21c, the radiance of this sphere at the brighter setting was as much as 10% lower during SIRREX-2 (Mueller et al. 1994), and 6% lower during experiments in Honolulu, Hawaii in February 1994 (Fig. 21c and Appendix B). At the darker setting, the sphere radiance was approximately 5% brighter in the blue and unchanged in the red in February 1994 (Fig. 21c). The OL420 was reconfigured with a new lamp by the manufacturer in the interim between these earlier measurements and SIRREX-3. In addition, the SXR was modified and recalibrated between SIRREX-2 and the Honolulu measurements.

The Type A uncertainty in the SXR measurements of GS-5000 sphere radiances with FEL GS-922 (Fig. 22) was less than 0.1%, based on three measurements on the same day. Measurements of this sphere with the 746/ISIC exhibit deviations from SXR spectral radiances that are less than 1% at wavelengths of 500 nm and longer. The deviations increase to 12% in the blue, where the 746/ISIC does not have sufficient sensitivity to measure the low radiance level of this source (Fig. 22b). The manufacturer's calibration of this device, using lamp GS-922, was lower than the SIRREX-3 SXR radiance measurement by up to 4% (Fig. 22b), which is consistent with the 4–5% deviations of the EG&G spectral irradiance values for GS-922 from the SIRREX-3 measurements (Fig. 14). The design modifications to the unit's baffle tube and lamp housing aperture, and the addition of a light trap to the back of the lamp housing, have clearly been effective in significantly reducing stray light effects, which were measured with the original system design configuration by NIST in February 1992 (Fig. 22b and Appendix B).

Measurements of the spectral irradiance of the GS-5000, with its integrating sphere removed, were made using the 746/ISIC and a MER-2040 underwater radiometer (Fig. 23a). The MER-2040 spectral irradiance measurements, in particular, demonstrate the effectiveness of the stray light baffling improvements in this system's design (Fig. 23b). In tests using two FELs, GS-922 and H91534, the MER-2040 irradiances agree within less than 1% with the respective SIRREX-3 values for these lamps (Tables 4 and 6). The 2–4% deviations of the 746/ISIC irradiance measurements of this device may be related to the required alignment of the ISIC entrance aperture for these measurements, which is offset from the lamp axis by approximately 0.6 cm. These levels of deviation are not within the goniometric distribution of FEL lamps, which are generally less than 1% at the angle used, so perhaps interreflections affected the measurements. The deviation of the EG&G irradiance calibration of this device is explained by the differences in the independent values used for GS-922, compared to that measured during SIRREX-3 (Fig. 14).

4. PLAQUES

Many of the participating laboratories use Spectralon plaques (Table A-1) to convert the spectral irradiance of an FEL lamp to values of spectral radiance. In some cases, a plaque is used to directly calibrate a field instrument. A plaque is used in other cases to calibrate a laboratory transfer radiometer, which is used in turn to calibrate the radiance of an integrating sphere source.

Attempts were made during SIRREX-1 and -2 to characterize and compare the reflectance of Spectralon plaques (Mueller 1993 and Mueller et al. 1994). The results of these experiments were at best inconclusive. In SIRREX-1, the measurements were too fragmentary to estimate reflectances with any quantifiable uncertainty. In SIRREX-2, measurements of eight plaques were made using a Photo Research PR714 monochromator with a silicon diode array for the detectors. While the spectra of all plaques fell approximately within a 1% envelope, the reflectances of the plaques varied from approximately 0.94 in the blue to 1.05 at 725 nm. These reflectances were probably affected by changes in the spectral responsivity of the PR714. Based on sphere measurements during SIRREX-2, an uncertainty of a few percent was attributed to difficulties in determining the spectral radiance responsivity of the PR714.

The plaque measurements showed strong wavelength dependent features characteristic of the PR714's apparent responsivity spectrum, as calibrated with the GSFC sphere (Mueller et al. 1994). During SIRREX-3, radiance measurements were made with the SXR and CXR to estimate spectral (0°, 45°) reflectance factors for six plaques (Table A-1).

4.1 Methods

Each plaque was mounted on the CHORS optical bench using a mounting bracket. With the back of either a 25.4 cm or 43.2 cm square plaque mounted flush against the bracket, FEL lamp H91534 was positioned normal to the center of the plaque at a distance of 150.0 cm. The two 61 cm plaques were too large for the bracket; they were mounted using standoff blocks, reducing the distance to 148.0 cm between the lamp and plaque.

Spectral radiance, at a viewing angle of 45°, was measured simultaneously with the SXR and CXR from opposite sides of the optical bar. Assuming the plaque to be a Lambertian (diffuse) reflector, the (0°, 45°) reflectance factor $\rho(\lambda)$ at wavelength λ was calculated as

$$\rho(\lambda) = \frac{\pi L(\lambda) r^2}{50^2 E(\lambda, 50)}, \qquad (2)$$

where $L(\lambda)$ is the spectral radiance measured at wavelength λ with either the SXR or CXR, r is the lamp-to-plaque distance in cm, and $E(\lambda, 50)$ is the spectral irradiance of FEL lamp H91534 at 50 cm (Table 6).

4.2 Results

The spectral radiance of the illuminated plaques was measured once with each instrument, as described above, on 24 Sept 1994. On 30 Sept 1994, the CHORS and NIST plaques were measured again. The CHORS plaque was then cleaned with 400 grit waterproof emery cloth under a flow of deionized water (as recommended by Labsphere, Inc., the manufacturer). Subsequently, measurements of the CHORS plaque were repeated. The resulting (0°, 45°) reflectance factors $\rho(\lambda)$, as calculated for all plaques on both days with (2), are illustrated in Figs. 33a and 33b for the SXR and CXR measurements, respectively. The CXR and SXR measurements of the NIST and CHORS plaques are compared in Figs. 34a and 34b, respectively. In Figs. 33 and 34, the spectral reflectances of the CHORS plaque designated 9/30 A and 9/30 B are results from measurements before and after cleaning.

4.3 Discussion

Perusal of Figs. 33 and 34, together with consideration of the uncertainties in the SXR and CXR radiance responsivities (Section 3.3), suggests that the SXR measurements provide far better estimates of plaque reflectance. With notable exceptions discussed below, the CXR data are in general agreement with the SXR reflectance estimates, but its uncertainties are significantly higher than those of the SXR-derived reflectances.

The (0°,45°) reflectance factors $\rho(\lambda)$, calculated from the SXR data for most of the plaques (Fig. 33a), exceed unity. This indicates that $\rho(\lambda)$ does not represent a perfect (lossless) Lambertian diffuser. The major exception to this generalization is the spectral reflectance of the CHORS plaque, which was up to 3% lower that the others during the measurements on 24 Sept 1994 (Fig. 33a). As measured by the SXR, the reflectances of all of the plaques, except the CHORS plaque, exhibit a variability of approximately ±1% or less at all wavelengths. The reflectance spectra of these plaques are similar in shape and vary over wavelength with a range of approximately 2%, with a nominal range of 1.0–1.02 (Fig. 33a).

The SXR estimated reflectances of the CHORS plaque were 0.98 at 411.5 and 441.6 nm, and at longer wavelengths ranged between approximately 1.0 and 1.01 on 24 Sept 1994 (Fig. 34b). The reflectance spectrum on 24 September was similar in shape to those of the other plaques, but was approximately 2–3% lower in magnitude. This plaque has obviously been contaminated and its reflectance has degraded. Prior to the plaque being cleaned, its reflectance was measured again with the SXR (CHORS 9/30 A, Fig. 34b). At most wavelengths, the SXR measurements of reflectance were approximately 0.7% higher than those measured on 24 September. At 774.8 nm, however, the apparent reflectance measured with the SXR increased by approximately 3% relative to the 24 September measurement. After the plaque was cleaned, the reflectance at all wavelengths other than 774.8 nm was increased by approximately 1%, and ranged from 0.995–1.02 (CHORS 9/30 B, Fig. 34b). This is a clear improvement, but the reflectance of this plaque remains 2% lower than that of the newer NIST plaque (Fig. 34a). The increased reflectance anomaly at 774.8 nm, which was observed on 30 September relative to 24 September, showed no change after the plaque was cleaned. This anomaly may have resulted from some difference in either the stray light baffling or ambient light correction procedures used on the two different days.

There is an obvious problem with the CXR measurements at 400 nm (Fig. 33b); this data should be ignored. At the other wavelengths, the deviation between the CXR spectral reflectances of the 25.4 and 45.7 cm plaques is approximately 3%, compared to 1% for the SXR (Figs. 33a and 33b). In comparing the CXR and SXR measurements of the NIST plaque alone (Fig. 34a), the larger uncertainties of the CXR radiance measurements are clearly apparent; with two exceptions (at 400 and 660 nm), the agreement between the two instruments is approximately 2%. When comparing the SXR and CXR reflectances for the CHORS plaque alone (Fig. 34b), the SXR clearly shows the approximately 1% increase in reflectance after the plaque was cleaned, but this effect is not discernible in the CXR

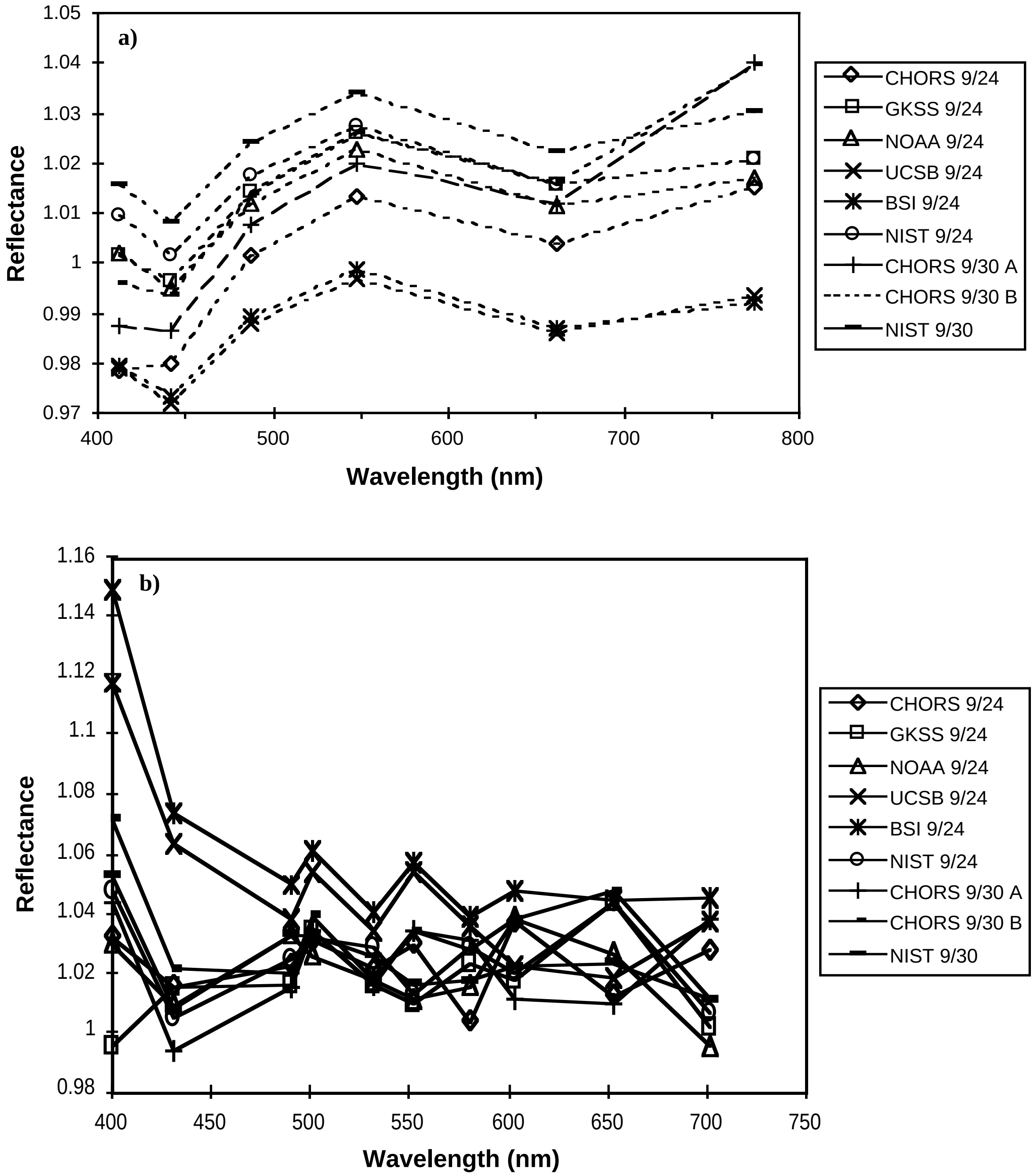
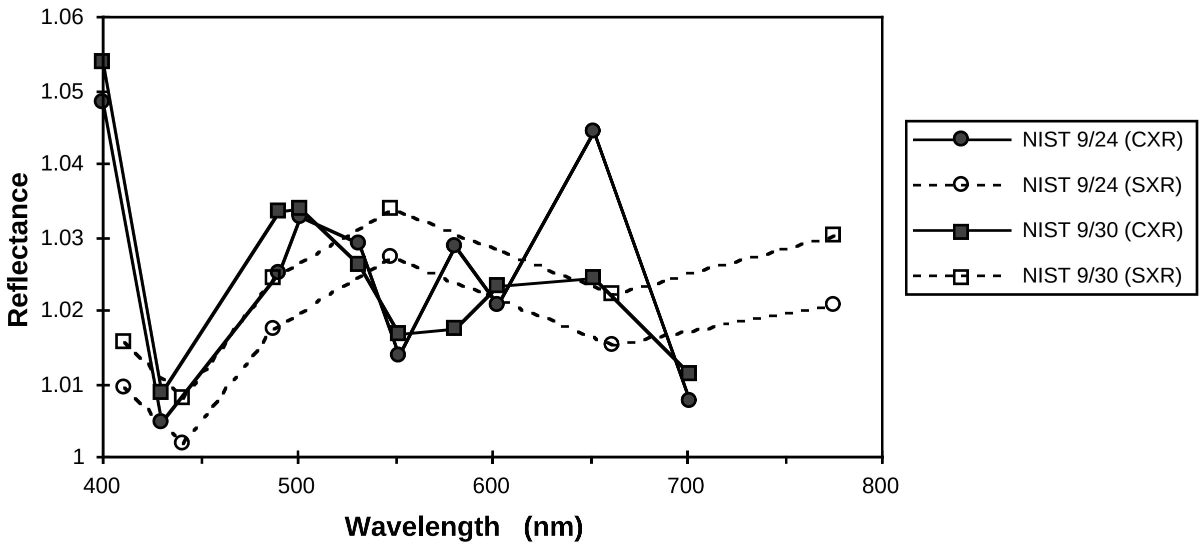


Fig. 33. Reflectance factors of all Spectralon plaques (Table A-1) estimated from radiance measurements by the SXR (panel **a**) and the CXR (panel **b**) at a viewing angle of 45°. The plaques were illuminated with FEL lamp H91534 at normal incidence at a distance of 150 cm (148 cm for the UCSB and the BSI plaques). The SIRREX-3 values for spectral irradiance for H91534 (Table 6) was used to calculate the irradiance at the surface of the plaque.



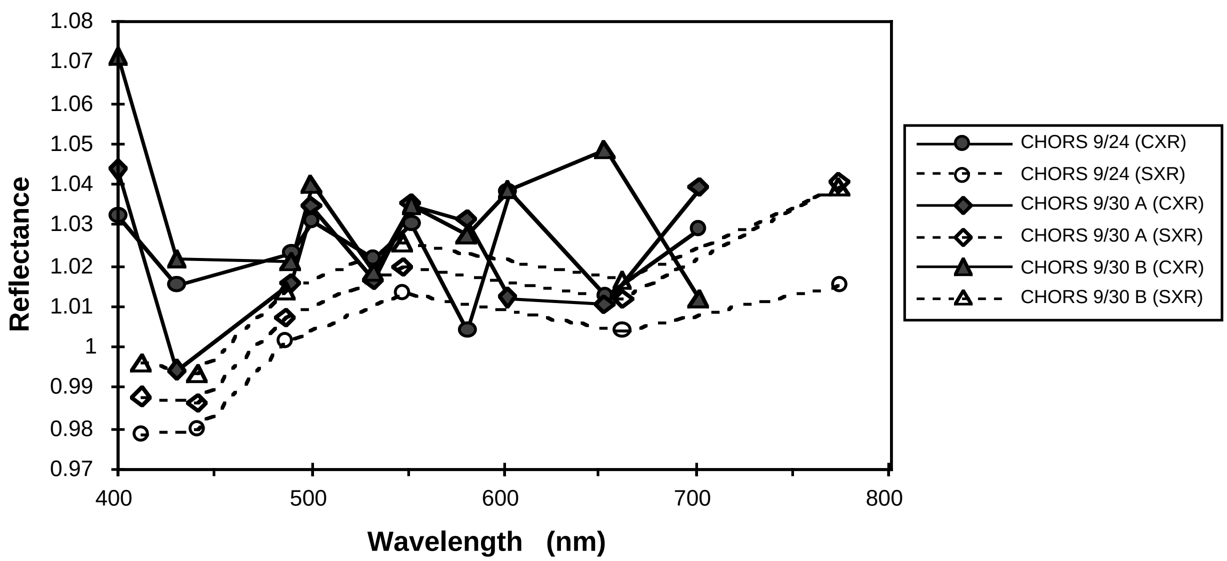


Fig. 34. Reflectance factors of the NIST (panel **a**) and the CHORS (panel **b**) plaque using the SXR (dashed lines and open symbols) and the CXR (solid lines and filled symbols) at a viewing angle of 45°. The plaques were illuminated with H91534 (SIRREX-3 data) at a distance of 150 cm. The CHORS plaque was cleaned between the A and B measurements on 30 Sept 1994.

data. It may be concluded from these results that the CXR signal-to-noise characteristics must be improved if this instrument is to be used with these relatively dark sources for radiance transfers with acceptable uncertainties.

The CXR reflectance estimates appear to be biased high relative to those derived from the SXR, although the bias is difficult to distinguish from the scatter in the CXR data. This effect is particularly strong in the reflectance measurements of the two 61 cm plaques (belonging to BSI and UCSB), as measured by both instruments on 24 Sept 1994 (Figs. 33a and 33b). In this case, the 4% observed differences are large enough to exceed the 3% uncertainty of the CXR radiance measurements. Part of the explanation for this major discrepancy may be explained by differences in stray light corrections between the SXR and CXR radiances. The SXR radiances were corrected using ambient background measurements, made using a baffle to block the direct path between the FEL lamp and the plaque. Only instrumental dark values were subtracted to calculate the CXR radiances, as the ambient background for each plaque was not measured with this instrument.

The presence of stray light contamination, which may be expected to increase with increasing plaque sizes, seems the most likely explanation for the discrepancies between the CXR and SXR reflectances (Fig. 33) for the larger plaques. The effectiveness, however, of the ambient measurement is itself uncertain. When the plaque is fully illuminated, light reflected from the plaque may be a source of stray light if there are secondary reflections of this light from other surfaces around the room. These secondary reflections will not be present when the lamp is blocked for the ambient measurement.

At this stage, the authors can only speculate on the magnitudes and sources of uncertainty associated with this technique. The proper determination of ambient stray light corrections is one procedural difficulty requiring further study and improvement. There are other unresolved contributions, as well, to absolute radiance determinations using this approach. Goniometric measurements at NIST of irradiance variations of FEL lamps show variations up to 10% at off-axis angles of 10°. The larger vignetted FOV (4.8°) and approximately 2° uncertainty in pointing alignment of the CXR are potential sources of variations in these particular comparisons. The CHORS alignment bracket could not hold the 61 cm plaques, and the temporary mounting solution also introduced an unquantified possible source of uncertainty in the alignment of those two plaques.

5. SHUNTS AND VOLTMETERS

Three voltmeters and four shunts were intercompared on 30 Sept 1994. The voltmeters belong to these participating organizations:

1) GSFC—Fluke model 8842A, Serial Number (S/N) 610278;
2) The National Research Institute for Far Seas Fisheries (NRIFSF)—HP34401A, S/N 3146A15981; and
3) UA—HP3458A, S/N 2823A10963.

The shunts belong to:

a) GSFC (Leeds and Northrup 4222-B, S/N 1921670);
b) NRIFSF (Yokogawa 10 mΩ, S/N 00343);
c) NOAA (Weston Catalog Number 0042210, 10 A/100 mV); and
d) CHORS (Leeds and Northrup model 4385, S/N 1630135).

The shunts were all connected in series with the GSFC OL power supply and FEL lamp 89162, which was operated at 117.8 V and 8.0005 A, as measured on the GSFC shunt with the GSFC voltmeter. The voltage drop across each of the shunts was then measured with each voltmeter.

Across each individual shunt, the UA voltmeter registered consistently higher than the GSFC voltmeter by less than 0.5 mV (corresponding to 0.5 mA). Conversely the NRIFSF voltmeter consistently measured lower voltage drops than the GSFC voltmeter by approximately 1 mV (corresponding to 1.0 mA). Variations about these offsets are less than 0.1 mV in each case.

The maximum ranges of variation between the four shunts were 0.5 mV for the UA voltmeter and 1 mV for the other two voltmeters. These levels of agreement are within the uncertainty limits specified for determining lamp currents in spectral irradiance calibrations using FEL lamps (Walker et al. 1987a). The error in spectral irradiance at a wavelength of 350 nm will be approximately 0.05% for an error of 0.5 mA in the current.

6. DISCUSSION & CONCLUSIONS

The spectral irradiances of the participants' FEL lamps were intercompared by transferring the NIST scale of spectral irradiance using F268, F269, and F182 (8/94 values), with a Type A uncertainty of about 1%. This 1% level of internal Type A uncertainty was also obtained during SIRREX-2 (Mueller et al. 1994). However, the SIRREX-2 and -3 measurements of lamps common to both experiments differ by an average of 1.5% (Fig. 15). This difference is consistent with the differences between the NIST 10/92 and 8/94 spectral irradiance measurements of F268 and F269, which suggests that the change in F269 had already occurred by the time it was used for the lamp transfer intercomparisons during SIRREX-2 in June 1993. The SIRREX-3 measurements (Tables 2–6) are more closely traceable to the NIST scale of spectral irradiance than are the SIRREX-2 values (Mueller et al. 1994). For future SIRREX lamp intercomparisons, the NIST secondary working standards of spectral irradiance (intended for use as the reference for lamp intercomparisons) should be recalibrated by NIST at intervals of no more than approximately 20 lamp hours.

The shift in the spectral irradiance of F269, which occurred on 21 Sept 1994 (Fig. 5), emphasizes the need to closely adhere to several extremely important protocols for usage and record keeping associated with FEL lamps in general, and with NIST secondary standards in particular. Lamp operating hours should be recorded religiously. The voltage across the lamp terminals, as well as the lamp operating current, should be measured and recorded during each use of a lamp. As a matter of routine practice, the NIST scale of secondary standard of spectral irradiance should be transferred to several additional FEL lamps using the secondary standard. This transfer is periodically verified for each of the tertiary standards at intervals of 20–30 lamp hours.

The local tertiary standards should be used as the reference in most laboratory experiments, including lamp transfer intercomparisons, with the NIST secondary standard usage limited to occasional verification of the tertiary standard lamp. This procedure will minimize the operating time accumulation on the NIST secondary standard. Lamp hours were not regularly logged for lamp F269, and lamp operating voltages were not recorded. Had the lamp's voltage history been maintained, the time at which the shift occurred on 21 Sept 1994 would have been more easily detected. Moreover, there is no firm determination of the number of operating hours accumulated on F269, although GSFC's estimate was something in excess of 200 hours. That number of hours following the lamp's calibration by NIST in 10/92 is an order of magnitude too large for this lamp to have been regarded as a reliable secondary working standard for SIRREX intercomparison experiments.

The 746/ISIC is a far from ideal transfer radiometer for these types of lamp and sphere intercomparison experiments. In the lamp transfers, the SNRs of this instrument are, at best, marginally adequate at wavelengths of 450–500 nm and are inadequate below this range. For measurements of the lower radiance level spheres, the 746/ISIC SNRs result in uncertainties greater than 5% at wavelengths below 500 nm. Furthermore, the responsivity drift of the 746/ISIC apparently approaches 1% per hour and it is necessary to recalibrate the instrument by viewing a reference FEL lamp at two-hour intervals during extended transfer intercomparisons. This requirement significantly increases the difficulty of transfer experiments and rapidly accumulates operating hours on the reference lamp.

The SXR has proven to be a reliable transfer radiometer, with an uncertainty component due to temporal stability and measurement repeatability less than 0.1%, and an estimated overall uncertainty of approximately 1.5% in radiance responsivity at all wavelengths. The *side lobes* in SXR channel 6 introduce a size-of-source correction on the order of 0.5–1.6% in measurements of spheres with larger exit apertures than the one used to calibrate the SXR; the data in this report have not been corrected for this effect.

The CXR, as configured for SIRREX-3, had a sensitivity that was too low to approach 1% uncertainties for measurements of sources (plaques and several spheres), which have low levels of radiance. At the higher radiance levels of the GSFC sphere, and for most spheres at wavelengths above 450 nm, the CXR responsivity uncertainty is estimated to be approximately 2.3%. This instrument's signal-to-noise characteristics and sensitivity must be significantly improved if it is to be used for radiance measurements at a 1% level of Type A uncertainty. The uncertainty in alignment of its pointing laser must also be improved to eliminate that geometric source of uncertainty in its data.

The uncertainties associated with sphere characterizations and sphere radiance transfers in SIRREX-3 represent a significant improvement over the 5–7% Type A uncertainty estimates in the sphere transfer results obtained during both SIRREX-1 (Mueller 1993) and SIRREX-2 (Mueller et al. 1994). The inability to positively identify and quantify specific sources of uncertainty in these earlier experiments was rectified by better characterizing the transfer radiometers (FOVs, relative spectral response functions, and stability of absolute responsivities) and spheres (spatial uniformity, Lambertian quality, and temporal stability).

The spatial nonuniformity in the spectral radiance of the GSFC sphere, identified as a major source of uncertainty in measurements of this sphere during SIRREX-2 (Mueller et al. 1994, Appendix C), was corrected by recoating the sphere. Immediately before and during SIRREX-3, the radiances of the GSFC and CHORS spheres were both verified to be spatially uniform within less than 0.5%. The spheres were angularly uniform up to 15° from normal within less than 1.2% and 0.7%, respectively. The spectral radiance of the UCSB sphere was shown to decrease by 1.3% from left to right across its exit port.

The SIRREX-3 estimates of the spectral radiance measurements of the GSFC sphere have uncertainties between 1.7% and 1.5%, as determined by the estimated calibration uncertainties of the radiance responsivities of the 746/ISIC and SXR, respectively. The calibrations of the CXR and UAXR radiance responsivities were derived using the spectral radiance of the GSFC sphere. Therefore, these radiance responsivities are not independent of the 746/ISIC (F268). The CHORS sphere was found to have an uncertainty of slightly more than 2% in the day-to-day stability of its spectral radiance. In time series measurements, the sphere's lamp shunt currents and spectral radiance were found to drift over a period of 14 hours with respective amplitudes of approximately 2% and 3% (at blue wavelengths, decreasing slightly at longer wavelengths). The CHORS sphere must be equipped with power supplies capable of better current regulation to reduce this level of temporal uncertainty in its radiance stability. The BSI sphere was also observed to have uncertainties in excess of 3%, and over a 1 hour period, its radiance drifted by 0.7% in the blue. This sphere would not be usable as a SeaWiFS calibration source in its SIRREX-3 configuration. (BSI was already aware of this prior to SIRREX-3, and this sphere was not in use.) The uncertainty in the day-to-day temporal stability of all of the other sphere sources was determined to fall between 0.2–0.3%.

In the progression from SIRREX-1 to -2 to -3, uncertainties in the NIST traceability of intercomparisons between the spectral irradiance of the lamps have improved from 8% to 2% to 1.1%, respectively. The intercomparisons of sphere radiance showed little improvement between SIRREX-1 and -2, with uncertainties as large as 7% in both experiments. In SIRREX-3, more rigorous characterization of both spheres and transfer radiometers reduced the uncertainties to approximately 1.5% in absolute spectral radiances and 0.3% in radiance stability for most spheres, and clearly identified inadequate lamp current regulation as the source of larger 2% uncertainty in the stability of radiance in the CHORS sphere.

With the SXR as a reference, some conclusions can be drawn regarding the GSFC/ISIC technique of realizing spectral radiance and the consistency of spectral radiances assigned to commercial equipment by secondary standards laboratories. The SXR and 746/ISIC technique agree within their mutual uncertainties for the GSFC sphere (Fig. 16b). For the other spheres measured with the 746/ISIC (CHORS, UCSB, BSI, and the GS-5000 system with the sphere attachment), the two techniques agree within their respective uncertainties for wavelengths greater than about 475 nm (Fig. 32). This agreement is encouraging, but does not meet the SeaWiFS requirement to realize spectral radiance between 400–475 nm.

The SXR and the original calibration of the UA/SIS from Labsphere disagree by between approximately 3–5%, depending on wavelength, with Labsphere's measuring high (Fig. 20b). The SXR and the June 1994 calibration on the OL420 by OL agree within the mutual uncertainties (Fig. 21b). The SXR and the post-SIRREX-3 calibration of the GS-5000 sphere source system by EG&G exhibit a consistent shift of about 3%, with EG&G measuring low (Fig. 22b); the lamp supplied with this system (GS-922) also measured low compared to F268 (Fig. 14). It is assumed that the UA/SIS source decreased in radiance as the sphere was used. The discrepancy with the EG&G system can be explained by the spectral irradiance values for the lamp. The lesson that may be illustrated here is that routine recalibration of these sources, and the underlying standards, is required in order to meet the accuracy requirements of the SeaWiFS Project. As with the lamps, it is essential for the sphere sources that operating hours and lamp currents and voltages be recorded.

The technique of performing absolute calibration of filter radiometers with known relative spectral response functions using the GSFC sphere as a reference appears to have been moderately successful. The CXR and the UAXR track the SXR for the measurements of the CHORS sphere (Fig. 17b), the UCSB sphere (Fig. 18b), the UA/SIS sphere (Fig. 20b), and most of the plaque measurements (Fig. 33), but not for the OL420 (Fig. 21b), and probably not for the BSI sphere, although comparison to the BSI sphere is difficult because the sphere was not stable during SIRREX-3 (Fig. 10b). The critical evaluation of this procedure is difficult because of the disparate sensitivities of the radiometers—the UAXR was designed for sources with high radiances and the CXR had inadequate sensitivity. The SXR was designed specifically for spectral radiance levels encountered in ocean color science, and hence, it is not surprising that the radiometer performs well for all spheres and plaques that were used at SIRREX-3.

Plaque reflectance measurements in SIRREX-3 represent a qualitative improvement over results obtained during the earlier SIRREXs, primarily due to the improved performance of the SXR. Significant improvements, however, are needed in this technique to resolve several poorly quantified uncertainties, including the development of proper methods for stray light baffling, goniometric corrections for FEL off-axis irradiances, and quantitative characterization of the bidirectional reflectance distribution function (BRDF), or reflectance factors, of Spectralon plaques. Intercomparisons between shunts and voltmeters have been done in all three SIRREXs, and in general, the equipment used by all participants met the specified levels of uncertainty for radiometric calibration measurements. In the first two SIRREXs, minor problems were identified with particular voltmeters which were either corrected or the instruments were taken out of service for this particular application.

For future SIRREXs, there should be an emphasis on training and work to foster and encourage uniform use of accepted protocols for laboratory calibration of radiometric instruments. These include not only laboratory procedures and equipment specifications, but should stress also the importance of thorough quality control and record keeping procedures. For lamp and sphere sources, further improvement and quality control can be obtained by following the characterization and measurement procedures utilized in SIRREX-3 within the individual laboratories, with occasional intercomparisons between calibrations of individual instruments performed at different laboratories. Improved procedures must be developed and tested if the uncertainties associated with realizations of spectral radiance using Spectralon plaques, are to be quantified and reduced; this should become a priority item in the agenda for future SIRREX laboratory experiments.

Acknowledgments

The authors would like to thank a number a people who were involved with SIRREX-3 by taking data and verifying measurements. These include: Joe Rice of NIST, John Cooper of GSFC, and Clay Titus of CHORS.

Appendix A

Table A-1. Organizations participating in the September 1994 SIRREX and their intercalibrated radiometric sources and radiometers.

Organization	*Contact*	*Radiometer*	*Lamps*	*Sphere*	*Plaque*
BSI	J. Ehramjiam		F310 F321 H91537	50.8 cm (20 in)	60.1 cm (24 in) (Large)
CHORS	J. Mueller Ross Austin C. Titus	CXR MER-2040	H90572 H90573 H91348 H91349 H91534 H91738 H91739	102 cm (40 in)	43.2 cm (17 in) (Large)
EG&G	Richard Austin		GS-922		
GSFC	J. McLean J. Cooper S. Hooker	746/ISIC SXR	F268 F269 F182 F315	107 cm (42 in)	
GKSS Forschungszentrum	H. Rinck				25.4 cm (10 in) (Small)
NIST	C. Johnson J. Rice				25.4 cm (10 in) (Small)
NOAA	D. Clark		F307 F308	OL420 GS-5000	25.4 cm (10 in) (Small)
NRIFSF	K. Kawasaki		F123		
UA	S. Biggar	UAXR	F296 F297		
UCSB	D. Menzies		F303 F304 F305	50.8 cm (20 in)	60.1 cm (24 in) (Large)
UM	K. Voss		F12G H91795		

Appendix B

This appendix, written by C.L. Cromer and B.C. Johnson of NIST for Dennis Clark of NOAA, is a report on the calibration of MOBY, which took place from 1–10 Feb 1994.

B1. INTRODUCTION

NIST participated in the predeployment calibration and attempted deployment of the prototype MOBY at the University of Hawaii/NOAA facility at Snug Harbor in Honolulu, Hawaii, from 1–10 February 1994. The MOBY is a tethered ocean optical instrument designed to measure spectral radiance and irradiance for upwelling and downwelling radiation at depths down to 15 m.

The MOBY optical system consists of four upward-looking irradiance (E_d) and four downward-looking radiance (L_u) receiver heads. All the optical receivers (except the bottom radiance head) were coupled to a spectrograph via 1 mm diameter fiber optics. The irradiance heads were equipped with a diffuser to provide a cosine angular response. The radiance heads consisted of a window and a lens which focused the incoming radiation onto the end of the fiber. The lens was nominally focused at infinity, and the FOV was approximately 5°.

B2. DESCRIPTION OF EQUIPMENT

The MOBY calibrations were performed using sources provided by NOAA. The SXR was used to verify the spectral radiance of the integrating sphere sources. Specific equipment available at the time of the calibration were:

1) GS-5000 calibration bench with integrating sphere attachment;
2) OL420 low level integrating sphere;
3) Two FEL-type standard lamps (F307 and GS-0910-L);
4) Optical rail and bipost mount for FEL standard lamps;
5) 30.5 cm × 30.5 cm Teflon diffuser;
6) Several power supplies for incandescent lamps;
7) SXR; and
8) An assortment of optical mounts and components.

The GS-5000 bench is intended to be the workhorse for calibrations of marine instruments for spectral irradiance and radiance. It consisted of an optical rail, a bipost mount for FEL lamps, a housing surrounding the lamp, a reference bracket, a black paper bellows (which connects to the lamp housing and the reference bracket), and a rotatable integrating sphere in the 90° configuration. The lamp housing was double walled and had metallic honeycomb inserts for convective cooling. The rail was supplied with indents for positioning of the major components.

Irradiance measurements (Fig. B-1) were performed by positioning the irradiance device under test (DUT) at the reference bracket, with the reference surface of the DUT flush against the reference surface of the bracket. This was somewhat difficult to achieve with the MOBY since the irradiance heads were fixed at the ends of the mounting booms. The alignment would be easier if the heads were detached from the boom during calibrations. The distance from the reference bracket to the lamp was set using a 50 cm measuring rod supplied by EG&G and the alignment jig for the bipost mount.

Radiance measurements (Fig. B-2) were performed using the integrating sphere accessory (ISA). The entrance aperture of the ISA was aligned with the reference bracket, and the DUT was aligned to view the exit aperture of the ISA. The ISA can also be used to intercompare irradiance standards. Lamps are positioned on either side of the ISA at equal distances. A detector (or spectrometer) is used to view the output aperture of the ISA while the sphere is rotated through 180°.

The OL420 spectral radiance source was also used for radiance calibrations. The OL420 consists of an integrating sphere, which is illuminated with an external lamp through an aperture wheel at the entrance to the sphere. The output radiance level of the OL420 can be set by adjusting the distance of the lamp to the sphere and by changing the aperture wheel setting. It is equipped with a removable 19 mm aperture at the exit port, which was not used during these measurements. The calibration of the OL420 by the manufacturer is valid only with the 19 mm aperture in place.

The SXR radiometer was also available for radiance measurements at the six channel wavelengths. The six SXR channel wavelengths are listed in Table B-1.

Table B-1. The six SXR channel wavelengths (CWL).

Channel	*CWL*	*Channel*	*CWL*
1	410.54	4	547.23
2	440.74	5	660.59
3	486.59	6	772.31

The FOV of the SXR is about 2.5°, corresponding to a target area of about 37 mm at the minimum focus distance (85 cm).

B3. SOURCE INTERCOMPARISONS

The SXR was used to compare the various radiance sources with the NIST calibration of the SXR. The sources used were the OL420, the GS-5000 bench with the integrating sphere attachment, and the Teflon plaque. The OL420 was compared to the SXR measurements using both the calibration from the manufacturer and the calibration from the last CHORS intercomparison with the GSFC integrating sphere. The OL420 was measured at two output levels (denoted as W6D40S3 and W5D100S3). The manufacturer gives calibration factors for converting the output radiance at different settings. The SXR measurements of the two

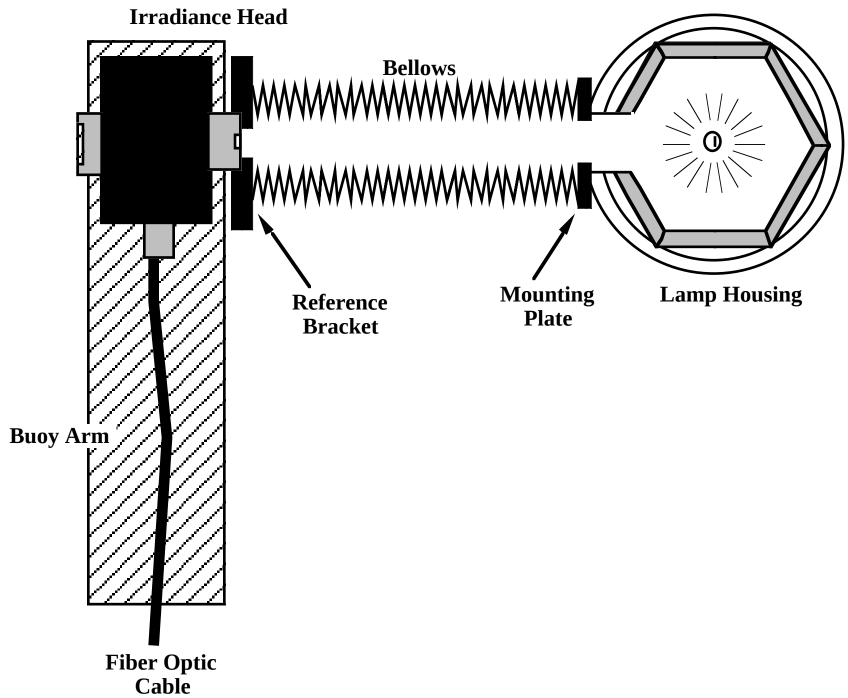


Fig. B-1. Irradiance measurements were performed by positioning the irradiance DUT at the reference bracket, with the reference surface of the DUT flush against the reference surface of the bracket.

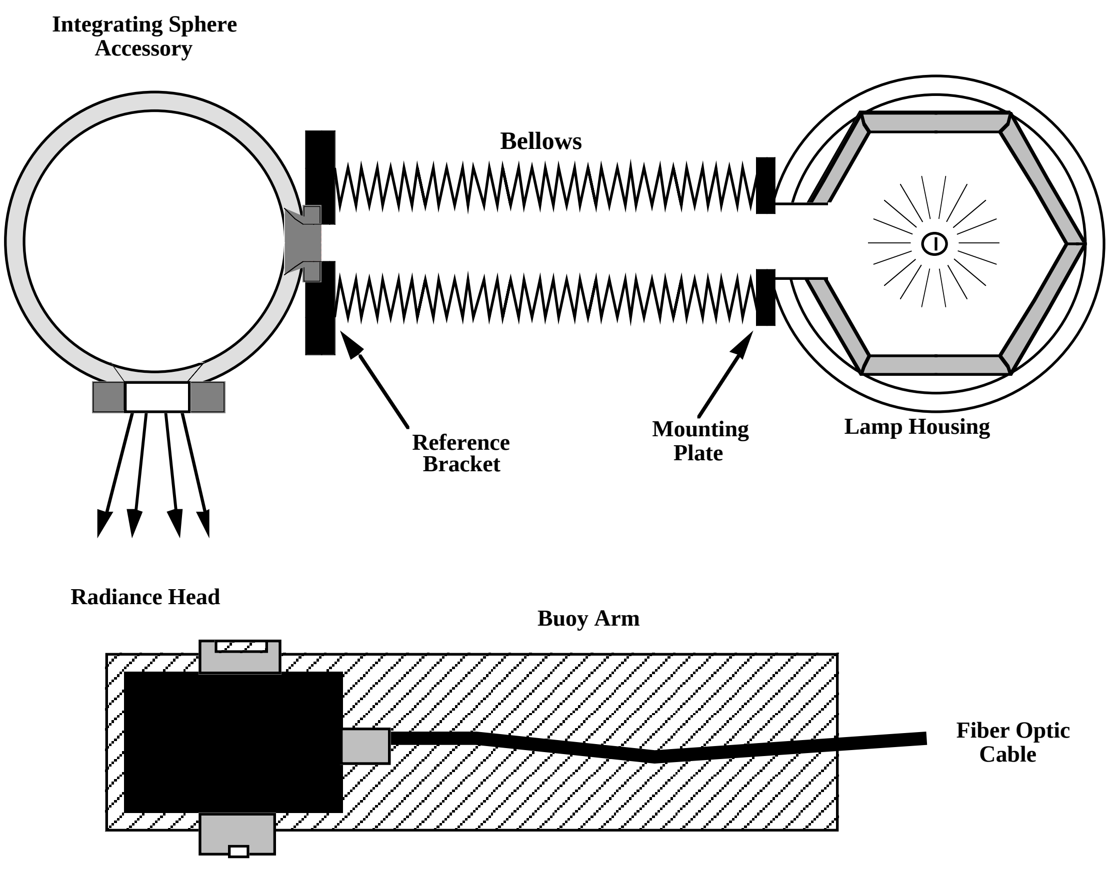


Fig. B-2. Radiance measurements were performed using the ISA. The entrance aperture of the ISA was aligned with the reference bracket, and the DUT was aligned to view the exit aperture of the ISA.

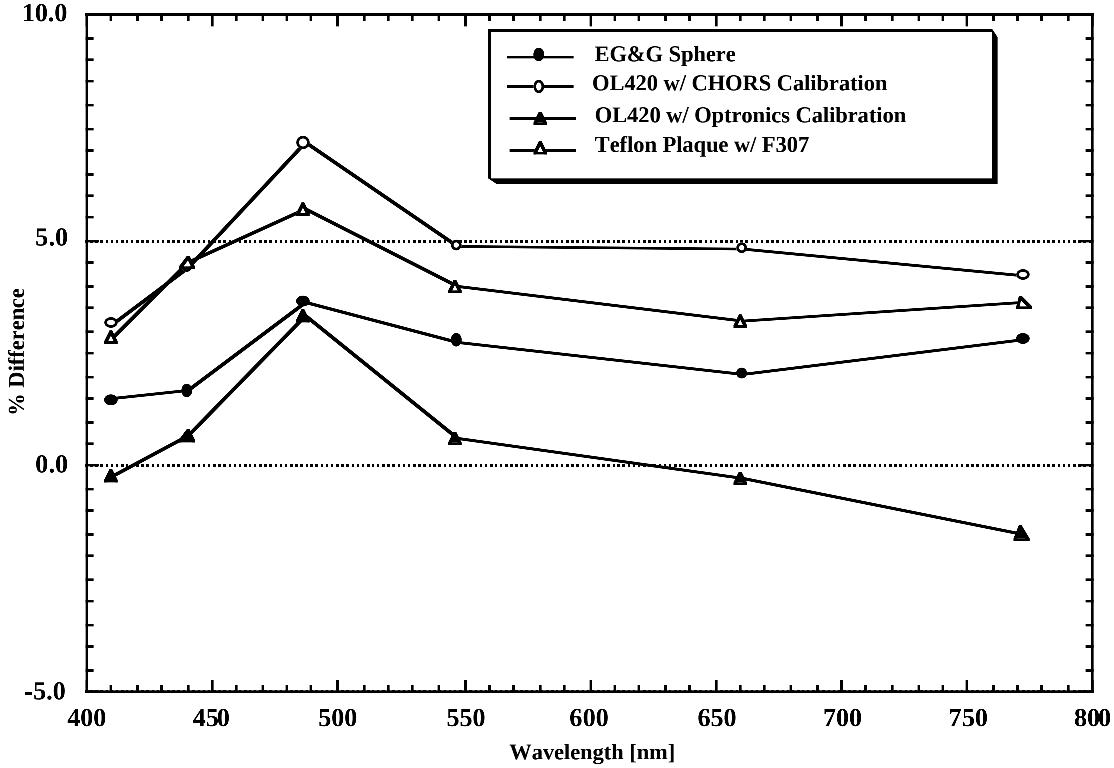


Fig. B-3. This figure shows the plot of the percent deviation of the SXR measurement from the presumed radiance of the sources at the six SXR channel wavelengths.

output levels confirmed the manufacturer's calibration factor of 4.365 to better that 1% (except for channel 6 which was 1.1%) Note that the OL calibrations were valid with the 19 mm aperture in place. All measurements described in this report were performed with the 19 mm aperture removed, which could alter the output level and the spectral shape of the output radiance.

The percent deviation of the SXR measurement from the presumed radiance of the sources at the six SXR channel wavelengths is plotted in Fig. B-3. The SXR was calibrated after returning to NIST using an integrating sphere calibrated for spectral radiance using FASCAL (Walker et al. 1987a and 1987b). The SXR measurements show reasonable agreement with the EG&G source and with the OL420 using the manufacturers calibration. Channel 3 of the SXR seems to still have some problem with channel crosstalk which may account for the larger discrepancy in the data. This will be corrected before delivery of the SXR. The fact that the OL420 sphere agrees with the EG&G sphere indicates that the removal of the 19 mm aperture did not significantly change the output of the OL420. The remaining discrepancies could be attributed to nonuniformity in the radiance of the output ports. The SXR measurements of the Teflon plaque are useful for relative comparisons of the channels, since the distance from the plaque to the lamp and the reflectance of the plaque were not accurately measured (a reflectance factor of 1.01 was assumed).

The EG&G sphere source was used to calibrate the radiance heads on the MOBY. Alignment was accomplished by positioning the exit aperture of the sphere in front of the input window of the radiance head, with the window parallel to, and centered in, the port. This alignment was somewhat difficult to achieve.

B4. LAMP HOUSING TESTS

The effectiveness of the EG&G lamp housing and baffles on the irradiance measurements at the reference bracket was studied, using the ISA and the SXR. The output radiance of the ISA was measured as the baffle tube, mounting plate, and honeycomb baffles (see Fig. B-1) were sequentially removed. These measurements were referenced to measurements made with the entire housing and baffle system removed, and NIST's best effort at baffling with black cloth and an aperture plate painted with flat black paint. The measurements were made inside a tent constructed with black sailcloth. It was verified that scattered light was not entering the sphere by blocking the direct path from the lamp to the ISA. The results are shown in Fig. B-4. A significant amount of scattered light is incident at the reference bracket with the housing and baffles in place. The mounting plate for the bellows is seen to have a large effect (approximately 2%), and the honeycomb baffles seem to improve the scattered light only for channel 6. It was also noted that the wiring from the bipost mount to the external connections on the bench are prone to shorting to the lamp housing and should be rerouted below the fixture.

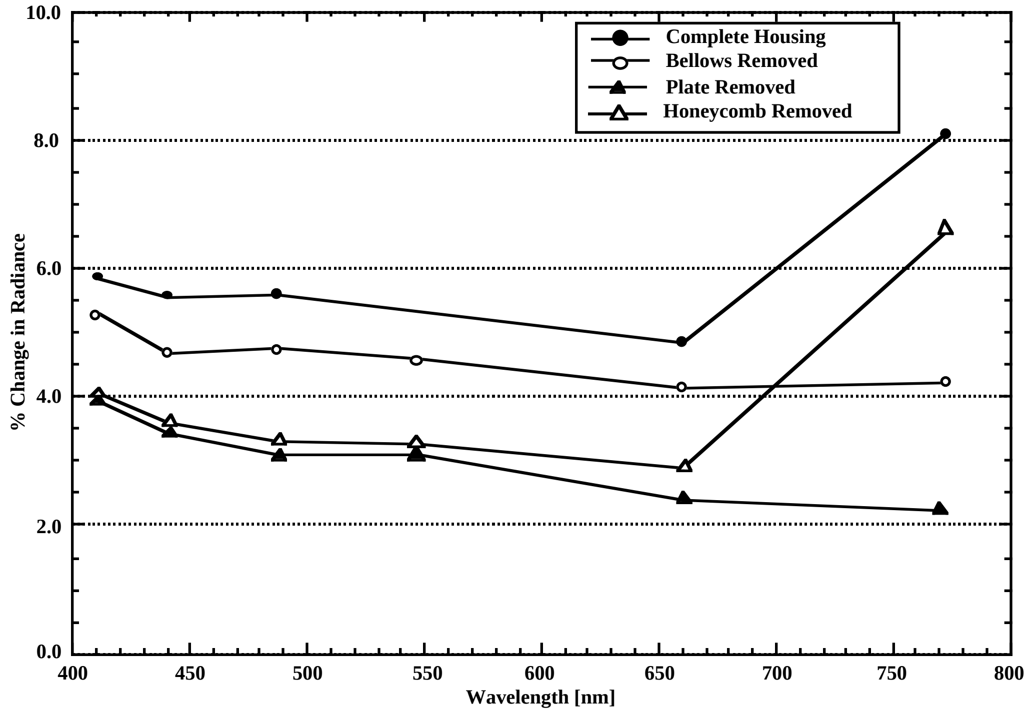


Fig. B-4. It was verified that scattered light was not entering the sphere by blocking the direct path from the lamp to the ISA. The results are shown in this figure.

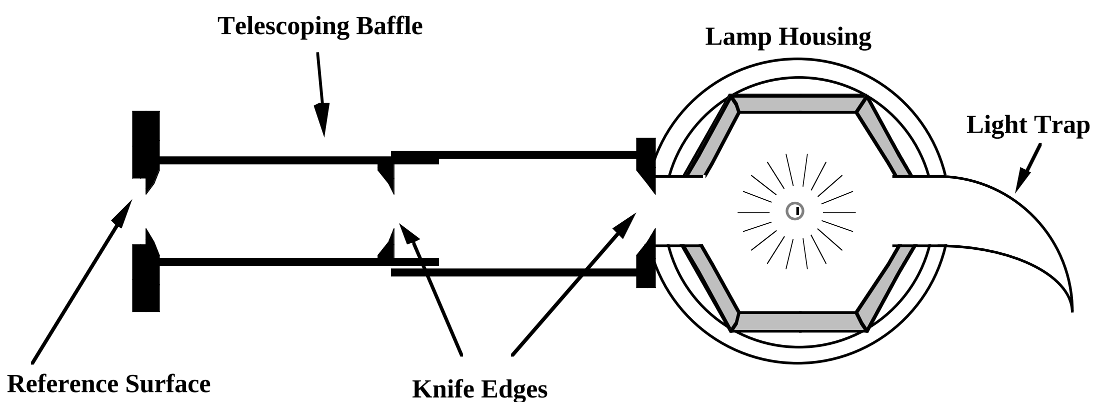


Fig. B-5. This figure shows specific improvements to be made to the baffling on the EG&G bench to assure accuracy during the irradiance calibrations.

B5. RECOMMENDATIONS

The baffling on the EG&G bench should be improved to assure accuracy during the irradiance calibrations. Specific improvements are (see Fig. B-5):

a. Replace the flexible baffle with a telescoping baffle tube with knife edge baffle plates.
b. Add a knife edge to exit hole in lamp housing.
c. Add a hole in the back of lamp housing, with a light trap to absorb all radiation within the field of view provided by the knife edge baffles.

If possible, the sensor heads at the ends of the fibers should be mounted in a way to allow for the heads to be decoupled and floating from the buoy mount during calibration. This would allow easier and quicker alignment to the reference bracket on the optical bench during calibrations. This will work as long as the throughput from the heads to the spectrometer does not change when the fibers are bent a small amount. This affect can be measured.

An improved method for alignment of the radiance heads is needed. The radiance head can be a few degrees from the normal to the exit port, and the distance from the exit aperture of ISA to the radiance head is not critical (but should not be so small as to influence the sphere). The critical alignment concern is that the entire field of view of the radiance head be overfilled by the source. Alignment would be easier if an alignment tool or *jig* were constructed to mount on the front of the radiance head. The tool should mount such that it is normal to the axis of the field of view of the radiance head and should indicate the location of the center of the field of view some distance in front of the radiance head window. The tool can be centered in the exit aperture of the ISA and then removed for calibration. An alternative method would be to illuminate the fiber from the end at the spectrometer. This would produce a beam projecting from the radiance head that would indicate the field of view. A piece of paper or target placed in the exit aperture of the ISA could be used for the alignment.

The NIST filter radiometers that are being constructed for NOAA will have a removable fore-optics with a viewer for radiance measurements. This will eliminate the need for a geometrical flux transfer measurement during sphere radiance measurements with the radiometers designed for irradiance measurements. During irradiance measurement, the NIST filter radiometers will also mate to the EG&G reference bracket, and can be used to check the bench during calibrations. The fore-optics will be removable and a diffuser assembly provided for conversion to irradiance measurements.

Appendix C

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Glossary

BSI Biospherical Instruments, Inc.
BRDF Bidirectional Reflectance Distribution Function

CHORS Center for Hydro-Optics and Remote Sensing
CWL Center Wavelength
CXR CHORS Transfer Radiometer

DUT Device Under Test
DXW Not an acronym, but a lamp designator.

EG&G Not an acronym, but a shortened form of EG&G-Gamma Scientific (now known simply as Gamma Scientific).

FEL Not an acronym, but a lamp designator.
FOV Field-of-view

GSFC Goddard Space Flight Center

ISA Integrating Sphere Accessory
ISIC Integrating Sphere Irradiance Collector

MER Marine Environmental Radiometer
MLML Moss Landing Marine Laboratory
MOBY Marine Optical Buoy

NASA National Aeronautics and Space Administration
NIST National Institute of Standards and Technology
NOAA National Oceanic and Atmospheric Administration

OL Optronics Laboratories

PDT Pacific Daylight Time
PTFE Polytetrafluoroethylene

QED Quantum Efficient Device

SBRC Santa Barbara Research Center
SDSU San Diego State University
SeaWiFS Sea-viewing Wide Field-of-view Sensor
SIRREX SeaWiFS Intercalibration Round-Robin Experiment
SIRREX-1 The First SIRREX (July 1992)
SIRREX-2 The Second SIRREX (June 1993)
SIRREX-3 The Third SIRREX (September 1994)
SIS Spectralon Integrating Sphere
S/N Serial Number
SNR Signal-to-Noise Ratio
SXR SeaWiFS Transfer Radiometer

UA University of Arizona
UAXR University of Arizona Transfer Radiometer
UCSB University of California at Santa Barbara
UM University of Miami

Symbols

a_i Cubic polynomial coefficients.

$B_b(\lambda)$ Greybody radiance model.

$E(\lambda, 50)$ Spectral irradiance measured 50 cm from a source.

$L(\lambda)$ Spectral radiance.
$L(411.5)$ Spectral radiance at 411.5 nm.
$L(532)$ Spectral radiance at 532 nm.
$L(0,0)$ Spectral radiance measured at the point closest to the center of the sphere.

r The lamp-to-plaque distance in cm.

x, y Spatial coordinates (horizontal and vertical).

$\rho(\lambda)$ A bidirectional reflectance factor.

σ Standard deviation.

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13. ABSTRACT *(Maximum 200 words)*

This report presents results of the third Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Intercalibration Round-Robin Experiment (SIRREX-3), which was held at the San Diego State University (SDSU) Center for Hydro-Optics and Remote Sensing (CHORS) on 19–30 September 1994. Spectral irradiances of FEL lamps belonging to each participant were intercompared by reference to the National Institute of Standards and Technology (NIST) scale of spectral irradiance using secondary standard lamps F268, F269, and F182, with a Type A uncertainty between 1.1–1.5%. This level of uncertainty was achieved despite difficulties with lamp F269. The average spectral irradiances of FEL lamps, compared in both SIRREX-2 and SIRREX-3, differed between the two experiments by 1.5%, which probably indicates that the values assigned to the secondary standard lamp at the time of SIRREX-2 were in error. With two exceptions, spectral radiance values of integrating sphere sources were measured during SIRREX-3 with uncertainties in temporal stability of less than 0.3% and absolute uncertainties of 1.5–2%. This is a significant improvement over similar intercomparisons in SIRREX-1 and SIRREX-2. Plaque reflectances were intercompared with an uncertainty of about 1–2%, but the absolute uncertainty is undefined. Although this is an improvement over results of previous SIRREXs, the sources and magnitude of uncertainty associated with transfers of spectral radiance using plaques requires further evaluation in future experiments.

14. SUBJECT TERMS
SeaWiFS, Oceanography, SIRREX-3, Lamps Standards, Sphere Sources, Plaque Reflectance,Voltmeters, Shunts, Spectral Radiance, Spectral Irradiance

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