FRM4SOC Laboratory Calibration Exercise 1 (LCE-1): Verification of Reference Irradiance and Radiance Sources

D-80b: **Protocols and Procedures to Verify the Performance of Reference Radiance Sources used by Fiducial Reference Measurement Ocean Colour Radiometers for Satellite Validation** (TR-3b)

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NPL Environment Division

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APPLICABLE DOCUMENTS

Ref. No.	Version / Issue	Document Title
1-8500 SoW	1	Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) Statement of Work (SOW)

ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
ANSI	American National Standards Institute
CCPR	Consultative Committee for Photometry and Radiometry
CEOS	Committee on Earth Observation Satellites
ESA	European Space Agency
FEL	Not an acronym. The lamp type designation.
FRM	Fiducial Reference Measurements
FRM4SOC	Fiducial Reference Measurements for Satellite Ocean Colour
FWHM	Full Width at Half Maximum
IR	Infra-Red
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCE	Laboratory Calibration Exercise
NMI	National Metrology Institute
NPL	National Physical Laboratory
NRR	National Reference Reflectometer
OCR	Ocean Colour Radiometry
RefSpec	Reference Spectroradiometer System
SI	Système Internationale
SRIPS	Spectral Radiance and Irradiance Primary Scales facility
TO	Tartu Observatory
TR	Technical Report
UK	United Kingdom
V	Volts
W	Watt
WGCV	Working Group for Calibration and Validation

1. INTRODUCTION

The FRM4SOC project, with funding from ESA, has been structured to provide support for evaluating and improving the state of the art in satellite ocean colour validation through a series of comparisons under the auspices of the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration & Validation and in support of the CEOS ocean colour virtual constellation. FRM4SOC also strives to help fulfil the International Ocean Colour Coordinating Group (IOCCG) in situ ocean colour radiometry white paper objectives and contribute to the relevant IOCCG working groups and task forces (e.g. the working group on uncertainties in ocean colour remote sensing and the ocean colour satellite sensor calibration task force).

The project makes a fundamental contribution to the European system for monitoring the Earth (Copernicus) through its core role of working to ensure that ground-based measurements of ocean colour parameters are traceable to SI standards. This is in support of ensuring high quality and accurate Copernicus satellite mission data, in particular Sentinel-2 MSI and Sentinel-3 OLCI ocean colour products. The FRM4SOC project also contributes directly to the work of ESA and EUMETSAT to ensure that these instruments are validated in orbit.

The main aim of FRM4SOC is to establish and maintain SI traceability of ground-based Fiducial Reference Measurements (FRM) for satellite ocean colour radiometry (OCR). Specifically the project will develop, document, implement and report OCR measurement procedures and protocols. It will design, document and implement both laboratory and field inter-comparison experiments for FRM OCR radiometers to verify their FRM status. Furthermore, FRM4SOC will undertake international coordination activities to define the next generation of Ocean Colour vicarious calibration/adjustment infrastructure.

The Laboratory Calibration Exercise 1: Reference Irradiance and Radiance Sources (LCE-1) is aimed at verifying the performance of irradiance and radiance sources used to calibrate ocean colour radiometers. It therefore acts as a check/validation of the SI-traceability for all FRM4SOC activities. This document is part two of the two part protocols reference document for LCE-1 and FRM4SOC. It establishes and documents protocols for the comparisons between radiance sources used for calibrating ocean colour radiometers.

2. ORGANIZATION

2.1 PILOT

LCE-1 will be implemented as a laboratory comparison of the irradiance sources, and through a round-robin inter-comparison of each participant's radiance sources using ocean colour transfer radiometers. NPL, the UK national metrology institute (NMI), will serve as pilot for these comparisons supported by Tartu, the coordinator of FRM4SOC. NPL, the pilot, will be responsible for inviting participants, circulating the transfer radiometers and for the analysis of data, following appropriate processing by individual participants. NPL, as pilot, will be the only organisation to have access and to view all data from all participants. This data will remain confidential to the participant and NPL at all times, until the publication of the report showing results of the comparison to all participants.

2.2 PARTICIPANTS

The draft list of participants in LCE-1 of FRM4SOC is shown in the table below and will be repeated in the final report on the outcomes of the comparisons as a final list. Dates for the comparison activities are provided in Section 3.6. All participants should be able to document their traceability to SI for both irradiance and radiance measurements via appropriate calibration certificates.

By their declared intention to participate in this comparison, the participants accept the general instructions and the technical protocols provided by this document, D80a and D90, the implementation plan for LCE-1, and commit themselves to follow the procedures strictly.

Once the protocols (described here) and list of participants have been reviewed and agreed, no change to the protocols may be made without prior agreement of all participants. Furthermore, only the final approved version shall be used for measurements.

2.3 PARTICIPANTS' DETAILS

Table 1. Participants' Contact Details

Contact Person	Short Version	Institute	Contact Details
Andrew Banks	NPL (Pilot)	National Physical Laboratory, UK	andrew.banks@npl.co.uk;
Joel Kuusk	TO	Tartu Observatory, Estonia	joel.kuusk@to.ee
Giuseppe Zibordi [1]	JRC	European Commission – DG Joint Research Centre	giuseppe.zibordi@jrc.ec.europa.eu
Vincenzo Vellucci	LOV	Laboratoire d'Océanographie de Villefranche, France	enzo@obs-vlfr.fr
Ronnie Van Dommelen	Satlantic	Satlantic, Canada Sea Bird Scientific	ronnie@satlantic.com
Stéphane Victori [4]	Cimel	Cimel Electronique S.A.S., France	s-victori@cimel.fr
Wojciech Klonowski	In-situ Marine Optics	In-situ Marine Optics, Australia	wojciech@insitumarineoptics.com
Ian Lau	CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia	ian.lau@csiro.au
Sabine Marty [2]	NIVA	Norsk Institutt for Vannforskning, Norway	sabine.marty@niva.no
Christopher MacLellan	NERC-FSF	Natural Environment Research Council's Field Spectroscopy Facility, UK	chris.maclellan@ed.ac.uk
Michael Ondrusek [1]	NOAA	National Oceanic and Atmospheric Administration, USA	michael.ondrusek@noaa.gov
Johannes Brachmann [3]	DLR-IMF	Remote Sensing Technology Institute, Deutsches Zentrum für Luft und Raumfahrt, Germany	johannes.brachmann@dlr.de

[1] Not in attendance during irradiance comparisons of LCE-1 at NPL (03-07 April 2017) but participating in both comparisons.
[2] Only participating in radiance comparisons of LCE-1 via transfer radiometer round robin.
[3] Only participating in radiance comparisons of LCE-1 via transfer radiometer round robin but attending LCE-1 at NPL (03-07 April 2017).
[4] Not participating in either comparison but attending LCE-1 at NPL (03-07 April 2017).

2.4 FORM OF COMPARISON

As stated above, LCE-1 covers the two comparisons of irradiance and radiance sources for ocean colour radiometry calibrations. Protocols for the irradiance source comparisons are provided in a separate document: D80a - Protocols and Procedures to Verify the Performance of Reference Irradiance Sources used by FRM OCRs for Satellite Validation (TR-3a).

The participant radiance source comparison will be conducted by NPL as pilot through the round-robin circulation of two ocean colour transfer radiometers (these are detailed in Section 3). The most commonly used radiance source for ocean colour radiometer calibration will be used for these comparisons. This is an FEL lamp and reflectance panel combination. The FEL lamps should be the same ones included in the irradiance comparison of LCE-1. It is mandatory that all participants' artefacts used in the comparisons are accompanied by SI traceable certificates detailing their last calibration.

The two ocean colour transfer radiometers will be sent to each participant in order for them to take at least two sets of radiance measurements of their in-house radiance source (lamp-panel combination) according to these accompanying protocols. Measurement instructions can be found in Section 3 and the recommended setup and measurement procedure can be found in Appendix B.

The transfer radiometers will be calibrated by the pilot (NPL) before and after each round of measurements by the participants, in order to ascertain if there has been any change in their responsivity during the comparison. The pilot's measurements will be directly traceable to the NPL primary reference standards, using well-characterised facilities, and will be supported by full uncertainty budgets. This direct link to SI will not only provide a stringent test of the reliability of the various traceability routes used by the participants, but also allow the uncertainties associated with the comparison to be evaluated. As in the irradiance comparison, use of the calibration certificates of each participant's lamp and panel is also essential because they are a critical part of the uncertainty evaluation of each participant's radiance measurements.

Each participant will need to evaluate uncertainties associated with their radiance source operating in their own laboratory for these measurements. This includes all the additional uncertainty components related to the alignment of the lamp, panel and radiometer, distance measurements, and other relevant laboratory specific factors such as power supply stability and accuracy. All these aspects the pilot will discuss with participants to facilitate the correct compiling and reporting back of this uncertainty budget evaluation using the templates shown in Appendix C and previously provided by the pilot as Excel files.

The quantitative results of the comparison will be presented in terms of differences between each participants measurements and the mean value of all of them. Information will also be presented (using the pilot's measurements) relating to the level of agreement with SI for each participant and the degree to which the radiance values and uncertainty budgets are supported by the comparison results. The comparison measurand is the calibration factor determined for the transfer radiometer using each participant's own spectral radiance reference (i.e. a lamp-panel combination in a 0°:45° r arrangement with the lamp set at a known distance from the panel).For each participant a separate calibration factor will be determined for each of seven specified wavebands of the transfer radiometers (see Section 3) and each waveband will be treated independently for the purposes of the analysis.

An example description of the reflectance panels and FEL lamps that in combination will be the radiance sources used in this comparison is also given in Section 3 of this protocol. The type of FEL lamp that NPL recommends for this type of comparison is included for information, but participants should use the same lamps that were used for the irradiance comparisons. It is recognised that participants may be using different types of reflectance panels to the 45.72 cm (18 inch) Spectralon panel used by NPL and thus it is essential that they supply the pilot with the technical details and history of the artefacts along with SI-traceable calibration certificates, the uncertainty evaluation according to the format shown in Appendix C, and as much additional information on their laboratory conditions as possible in order to aid the pilot in carrying out this comparison.

2.5 TIMETABLE

There are three main phases to the comparison activity, shown in Table 2. The first phase prepares for the measurements; the second phase is the measurements themselves and the third phase the analysis and report writing.

Table 2. Comparison activity- Phases

PHASE 1: PREPARATION	
Release of international invitation to participate	September, 2016
Preparation and formal agreement of protocol	September, 2016 to February, 2017
Participants send details of their irradiance sources and radiance measurement setup in their calibration labs to pilot	January to March, 2017
Receipt of transfer radiometers at NPL and their preparation for use in LCE-1	December, 2016 to March, 2017
PHASE 2: MEASUREMENTS & TRAINING	
Comparison of participant's irradiance sources & LCE-1 training	April 03-07, 2017
Circulation of transfer radiometers and comparison of participants' radiance sources	April to December, 2017
PHASE 3: ANALYSIS AND REPORTS	
Pilot quality checks irradiance calibration data and uncertainties with participants and begins process of data base compilation and inter-comparison analysis	May, 2017
Participants send preliminary report of radiance measurements and uncertainty to pilot	June, 2017 to February, 2018
Draft A (results circulated to participants)	May, 2018
Final draft report circulated to participants	June, 2018
Draft B submitted to CEOS WGCV	July, 2018
Final Report published	August, 2018

Table 3 below shows the top-level plan for the comparison activity. Below this in Table 4 the more detailed timetable for the transfer radiometer round robin can be seen.

Table 3. Comparison Activity- Plan

Activity No.	Start Date	End Date	Experiment/Training	Venue
1a	03 April 2017	07 April 2017	LCE-1 Intercomparison of OCR Irradiance Sources	NPL
1b	04 April 2017	04 April 2017	Uncertainty in measurement lectures and training	NPL
1c	03 April 2017	06 April 2017	Absolute radiometric calibration with uncertainty training	NPL
1d	07 April 2017	07 April 2017	Cryogenic Radiometer, NRR & SRIPS/RefSpec Lab Tour	NPL
2	01 June 2017	28 February 2018	Circulation of transfer radiometers and LCE-1 round-robin intercomparison of participant's radiance sources (see companion document)	LCE-1 Participants' Laboratories

Table 4. Transfer Radiometer Round Robin Timetable

Month	Location	Round Robin Leg
May 2017	NPL calibration	NPL calibration
June 2017	TO, Estonia	European Leg
July 2017	DLR, Germany	
August 2017	NERC, UK	
September 2017	NIVA, Norway	
October 2017	LOV, France	
NPL check/recalibration	NPL check/recalibration	NPL check/recalibration
November 2017	NOAA, USA	N. American Leg
December 2017	Satlantic, USA/Canada	
NPL check/recalibration	NPL check/recalibration	NPL check/recalibration
January 2018	CSIRO (Perth)	Australian Leg
NPL check/recalibration	NPL check/recalibration	NPL check/recalibration
February 2018	JRC, Italy	Final Leg

2.6 HANDLING OF ARTEFACTS

Handling of FEL lamps was covered in the irradiance protocols document D80a - Protocols and Procedures to Verify the Performance of Reference Irradiance Sources used by FRM OCRs for Satellite Validation (TR-3a). For reflectance panels it is important that the front is not touched if at all avoidable. If there is the situation where it is absolutely necessary, for example where the depth of the panel is being measured, the corners should be used. For removing dust this can be carried out using air blowing using a suitable apparatus that will not leave a residue. Finally, the panel should be kept in a lidded box when not in use to avoid dust and exposure.

2.7 TRANSPORTATION OF ARTEFACTS

The contact person at the pilot is:

Dr. Andrew Clive Banks
Room F4-A10
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Hampton Road
Teddington
Middlesex
UK
TW11 0LW

Any queries can be directed to Andrew on andrew.banks@npl.co.uk or by phone on +44 (0)20 8943 6081.

2.8 RECORDING ARTEFACT USE

In the same way the pilot recorded FEL lamp usage for the irradiance comparison, for the radiance comparison each participant will record the number of on-off cycles for each lamp and the total burn hours for each lamp during the radiance measurements. In addition the current and voltage for each lamp should be recorded by each participant according to the form shown in Appendix D.

3. DESCRIPTION OF THE ARTEFACTS

3.1 THE TRANSFER RADIOMETERS

The transfer radiometers used in this comparison of radiance are two Satlantic ocean colour radiometers (OCR-200) on loan to the pilot from the Joint Research Centre of the European Commission. The general technical characteristics of these type of radiometers can be seen in the table below, although the two particular instruments used for FRM4SOC have been customized by Satlantic for JRC in terms of their spatial characteristics to provide a narrower (~3 °) field of view. Initial characterisation measurements to confirm this FOV have been carried out by NPL in air, and found to be 2.5° ± 0.3° at FWHM, with a close to Gaussian profile (see graph below).

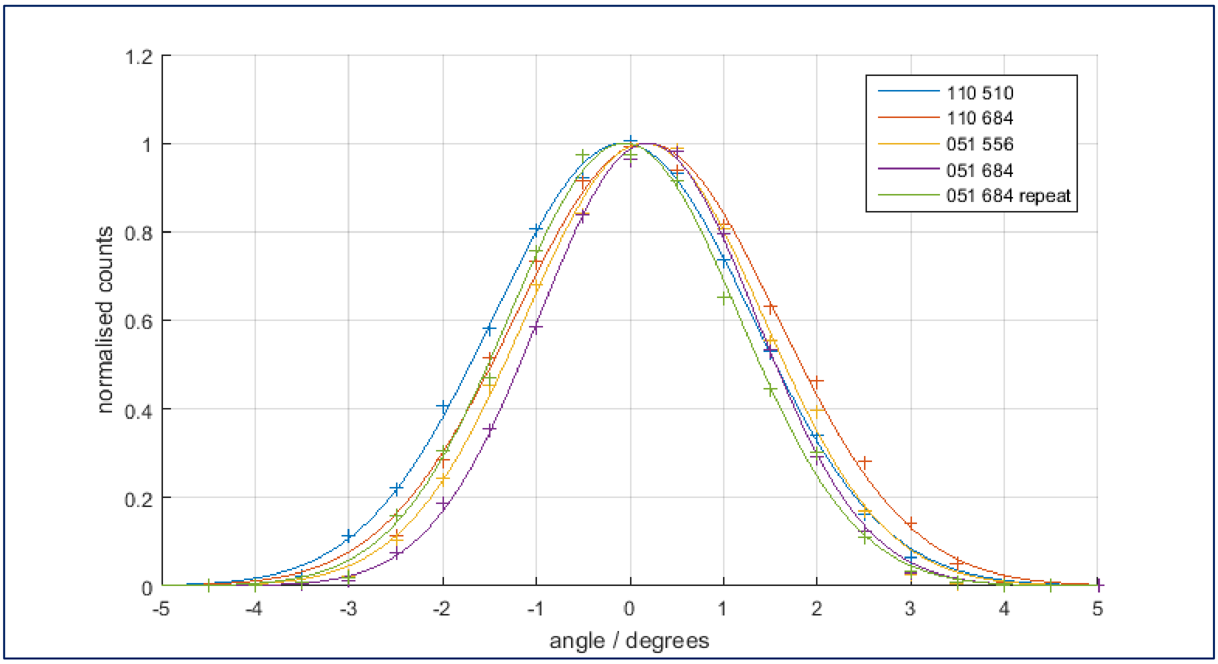


Figure 1. Measurement results to confirm the FOV of the transfer radiometers being used in the FRM4SOC LCE-1 radiance round robin

Upwelling Radiance Sensor Characteristics

Sensor Model : OCR-200

Spatial Characteristics:

- Field of view:	10° (0.100 steradians) in water 14° (0.200 steradians) in air
- Entrance aperture:	9.5 mm diameter
- Detectors:	custom 13 mm^2 silicon photodiodes

Spectral Characteristics:

- Bandwidth range:	400-700 nm
- Number of channels:	7
- Spectral bandwidth:	10 nm
- Filter Type:	custom low fluorescence interference
- Discrete wavelengths (centers):	412, 443, 490, 510, 560, 665, 683 nm

Optical Characteristics:

- Out of band rejection:	10^{-6}
- Out of field rejection:	$5x10^{-4}$
- Typical saturation:	$5\mu Wcm^{-2}nm^{-1}sr^{-1}$ (customizable)
- Typical NER:	$1x10^{-4}\mu Wcm^{-2}nm^{-1}sr^{-1}$

Temporal Characteristics:

- System time constant:	0.050 seconds
- -3dB frequency:	3 Hz

Physical Characteristics:

- size:	8.9cm diameter, 12cm long
- weight:	1.2kg (in air)
- depth rating:	400m
- interface	Subconn micro 12-pin for remote/stand alone application or inline interface with DATA-100
- analog output range:	0-5V (customizable)

Figure 2. General specifications of the Satlantic OCR-200 radiometers

3.2 DIFFUSE REFLECTANCE PANELS

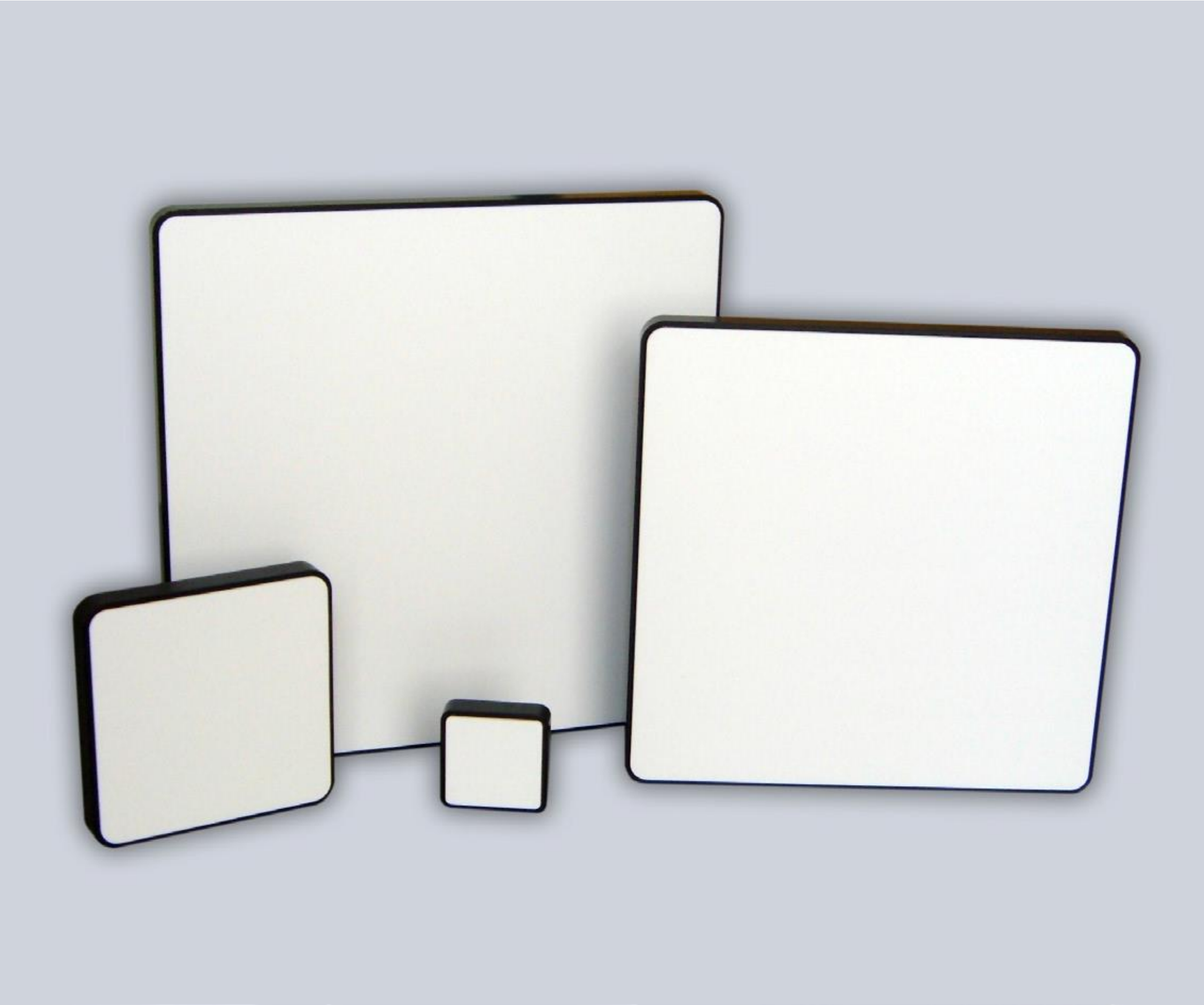


Figure 3. Spectralon panels (Source: Labsphere)

NPL (the pilot) is using 45.72 cm (18 inch) and 30.48 cm (12 inch) diffuse reflectance panels for the calibration of the transfer radiometers and to monitor any change against the NPL radiance scale during the round robin of FRM4SOC LCE-1. The choice of Spectralon for the calibration is because of its excellent uniformity and reflectance properties (see table below).

Other types of diffuse reflectance panel made from other materials are acceptable providing they have an SI traceable calibration certificate, including a statement of uncertainty, and provide uniform radiance within the field of view of the radiometers. Allowance must be made for the fact that the individual channels of the radiometer are centred at different points on the reflectance panel and therefore the minimum size panel recommended to be used by participants for these radiance measurements is 30.48 cm (12 inches) square (note that a smaller panel can be used if each radiometer channel is individually aligned to the centre of the reflectance panel, as recommended below). Even if the panel itself is perfectly uniform in terms of its reflectance, there will be some non-uniformity in the radiance viewed by the radiometer due to the non-uniform irradiance from the lamp. The effect of this non-uniformity must be allowed for in the uncertainty budget; one method for assessing the magnitude of the effect is to make a series of measurements with the detector rotated by 90° about its central axis between each measurement. Non-uniformity effects are minimised if each radiometer channel is individually aligned to the centre of the reflectance panel and it is therefore recommended that this is done if possible.

In addition to the calibration certificates all participants must also send the pilot supporting information regarding their panels using the form in Appendix F.

3.3 FEL LAMPS

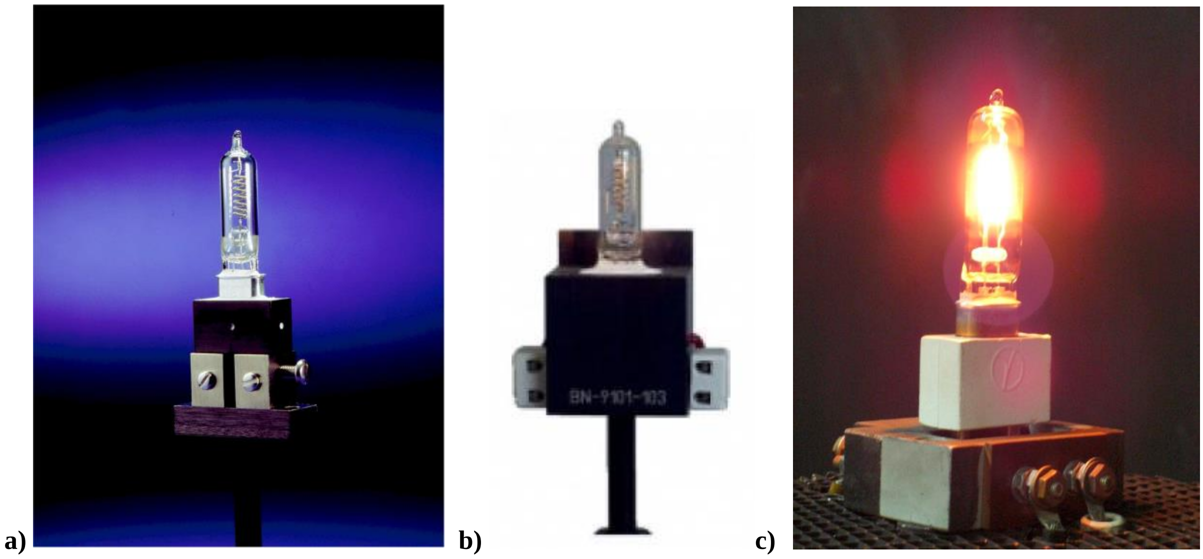


Figure 4. The three main types of FEL tungsten halogen lamps: a) Gooch and Housego OL FEL 1000 W, source Gooch and Housego; b) Gigahertz BN-9101 FEL 1000 W, source Gigahertz-Optik; c) Gamma Scientific Model 5000 FEL 1000 W, source Gamma Scientific.

The figure above shows the three types of FEL lamp that are used by participants in combination with their reflectance panels to form the radiance sources in these comparisons.

Table 5. Key operational parameters for the three types of lamp

	Gooch and Housego OL FEL 1000 W tungsten halogen lamp	Gigahertz BN-9101 FEL 1000 W tungsten halogen lamp	Gamma Scientific Model 5000 FEL 1000 W tungsten halogen lamp
Reliable wavelength range	250 nm – 2500 nm	250 nm – 2500 nm	250 nm – 2500 nm
Operating current	~8.0 A. DC. Maintain constant polarity	~8.0 A. DC. Maintain constant polarity	~8.0 A. DC. Maintain constant polarity
Operating voltage (approximate)	~ 105 V to 115 V	~ 105 V to 115 V	~ 105 V to 115 V
Alignment distance	500 mm to front plate	500 mm to front plate	500 mm to cross hairs on the alignment jig

In addition to the calibration certificates all participants who were not involved in the irradiance comparison should also send the pilot the information regarding their lamps using the form in Appendix E prior to being sent the transfer radiometers.

3.1 ELECTRICAL POWER

FEL lamps must always operate according to the marked polarity. Lamps should be operated at a constant DC current according to the lamp calibration certificate with the lamp voltage able to fluctuate to maintain the constant current. At NPL this current is measured using a standard resistor and controlled using a feedback loop. Running at a different current will produce a different irradiance and therefore not be useful for calibration. It may also damage the lamp if run significantly higher.

3.2 ALIGNING THE LAMPS, REFLECTANCE PANEL AND RADIOMETER

The lamp, panel, radiometer should be aligned together according to the procedures described in Appendix B. The pilot will clarify any questions from participants about alignment.

3.3 LAMP WARM-UP

Each lamp must be warmed up at the operational current for at least 30 minutes prior to the measurements being taken. Lamps should be ramped up slowly by increasing the electrical current over a 2 minute period to prevent sudden thermal shock.

3.4 LAMP COOL-DOWN

After operation the lamp should be ramped down slowly by decreasing the electrical current over a 2 minute period to prevent sudden thermal shock. The lamp should not be moved or covered for at least a further 30 minutes after switching off.

4. MEASUREMENT INSTRUCTIONS

4.1 TRACEABILITY

All participant sources (lamps and panels) should be independently traceable to SI units with documentary evidence (calibration certificates) of the route and associated uncertainty.

4.2 MEASUREMENT WAVELENGTHS

The comparison will be analysed as a set of separate comparisons for each waveband of the transfer radiometers covering the ocean colour visible and NIR wavelength range, as given in Table II. The reason these radiometers were designed to have these particular bands was because they were chosen to correspond with the wavelengths and bandwidths of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) that was a primary ocean colour satellite sensor between 1997 and 2010.

Table 6. Wavelengths for the radiance comparison.

Wavelength Range	Discrete Wavelength Centres / nm
400 nm – 700 nm	412, 443, 490, 510, 560, 665, 683

4.3 MEASURAND

The measurand is the calibration factor determined for the transfer radiometer using each participant's own spectral radiance reference (a lamp-panel combination). Each participant should record the readings of the transfer radiometers when viewing their diffuse reflectance panel at 45° to the normal, with the panel illuminated at normal incidence using their irradiance lamp. Measurements should ideally be made with the lamp at a distance of exactly 500 mm from the panel (the distance at which the irradiance was calibrated), with the radiometer at a minimum distance of approximately 250 mm (see alignment procedures in Appendix B). Other distances may be used in addition and can be beneficial if non-uniformity effects are found to be significant (increasing the lamp-panel distance reduces the irradiance non-uniformity at the surface of the panel). Ideally each channel of the radiometer should be individually aligned to the centre of the reflectance panel, since this also reduces the influence of radiance non-uniformities on the measurement results. The measurements should be performed in suitable laboratory accommodation maintained at a temperature of 20 ºC to 25 ºC. The temperature of the laboratory during the time of the measurements should be reported.

At least 3 independent l measurements should be made using each radiometer by each participant. Each independent measurement should consist of a full realignment of the lamp-panel-radiometer configuration in the measurement facility and there should be a break of at least 2 hours between each independent measurement. The measurements that must be made and supplied to the pilot are: 1. The three transfer radiometer readings for each radiometer and each band obtained using the 0:45 setup described in Appendix B; 2. A table of spectral radiance as a function of wavelength from 400-700nm as determined from the lamp irradiance combined with the panel reflectance for the 0:45 geometry used.

Any information obtained relating to individual participant's measurement facilities or any results obtained by the pilot from each participant during the course of the comparison shall be shared only between the pilot and the participant laboratory who took those measurements. The pilot will be responsible for co-ordinating how the information should be disseminated to other participants. No communication whatsoever regarding any details of the comparison other than the general conditions described in this protocol shall occur between any of the participants or any party external to the comparison without the written consent of the pilot laboratory. The pilot laboratory will in turn seek permission of all the participants. This is to ensure that no bias from whatever accidental means can occur.

5. MEASUREMENT UNCERTAINTY

The uncertainty of measurement shall be estimated according to the Guide to the Expression of Uncertainty in Measurement (BIPM et al., 1995). The pilot will evaluate at the expanded uncertainty (k=2) for each of the radiance measurements performed during the round robin. Example components of a radiometer calibration uncertainty budget are shown in Appendix H.

The pilot has educated the participants on the methods used to evaluate additional uncertainty components that will affect the radiance measurements in their own laboratories and how to complete the uncertainty template shown in Appendix C. This will enable the pilot, in partnership with each participant, to include these uncertainties in a more complete uncertainty evaluation for each measurement, taking into account not only uncertainties from the absolute calibration of the lamps and panels but also each participants operational laboratory setup and environment as well.

Therefore, each participant, before the comparison, has to provide information about their own laboratory facilities that are relevant for uncertainty evaluation.

This information is in addition to the completion of the uncertainty budget template in Appendix C and is to aid the pilot in reviewing these uncertainty budgets from each participant. The pilot should be contacted if further guidance in completing the uncertainty budget for the radiance measurements is needed beyond the instructions given here and the template itself.

6. REPORTING OF RESULTS

On completion of the radiance measurements, each participant must send their results (radiometer readings and spectra radiance data) to the pilot – see Appendices H and I. The pilot will calculate radiometer calibration factors using these data. The calibration factors for each participant are related to that participant’s spectral radiance scale though the following equation:

$$C_{i,j} = \frac{\int r_i(\lambda) L_j(\lambda)\,\mathrm{d}\lambda}{R_{i,j}}$$

where

$C_{i,j}$ is the radiometer calibration factor for participant j and radiometer channel i

$r_i(\lambda)$ is the radiometer spectral response function for radiometer channel i

$L_j(\lambda)$ is the spectral radiance for participant j

$R_{i,j}$ is the radiometer reading for participant j and radiometer channel i

As the first stage in drafting the comparison report the pilot will reconfirm with each participant the data from which these calibration factors have been determined, in order to ensure that the correct participant values are being used by the pilot and that no mix-up has occurred. The data receipt form (Appendix G) will be used via email in each instance of data communication.

Following this the pilot will provide a draft of the full comparison report, which will include a full uncertainty analysis based on the data and uncertainties provided by each participant. This document will be sent to all participants as the pre-draft A report, maintaining anonymity between the participants. Participants will then comment on this and ask questions. The report will include the provisional results of the comparison measurements, expressed in terms of difference (for each individual waveband) between the radiometer calibration factors for each participant and the mean calibration factor of all the participants.

The comparison results will be supplied in graphical format and Excel worksheet format by the pilot laboratory and included in the draft and final measurement report which will be supplied in a Word format provided by the pilot. This will simplify the combination of edits and comments and the collation of a report by the pilot and reduce the possibility of transcription errors. Understanding that some participants are unlikely to have a native English speaker on their staff, the pilot will complete the final review and editing of the English of the report.

The comparison results and reports will be sent by e-mail to all participating laboratories. It would be appreciated if any edits or comments could be completed by computer and sent back electronically to the pilot. **Signed paper copies are not necessary.**

If, on examination of the complete set of provisional results, the pilot institute finds results that appear to be anomalous, the results will be checked for numerical errors by the pilot and corresponding participant to try and account for the apparent anomaly. If no numerical error is found the result stands and the complete set of final results is sent to all participants. Note that once all participants have been informed of the results, individual values and uncertainties may be changed or removed, or the complete comparison abandoned, only with the agreement of all participants and on the basis of a clear failure in the reference standard of the pilot or some other phenomenon that renders the comparison or part of it invalid.

Following receipt of all comments, additions and corrections from the participating laboratories, the pilot laboratory will prepare a final draft report on the comparison. This will be circulated to the participants for final approval before release as a publication.

7. COMPARISON ANALYSIS

Each comparison will be analysed by the pilot according to the procedures outlined in QA4EO-CEOSDQK-004 (Fox and Greening, 2010). The complete analysis process will be agreed by all participants at the pre-draft A stage and the detailed methodology will be included in the final report on the results of LCE-1. Nevertheless, it is worth mentioning in these protocols that the comparison analysis will need to be performed in several steps:

i. To maintain continuity in measurement and uncertainty evaluation in these comparison exercises, it is essential that for all comparisons it is the same irradiance standards that are used throughout, i.e. those that were involved in the irradiance comparison. Clearly this is not possible for those participants that are only taking part in the radiance round robin and for these participants the calibration certificates from the last calibration of the lamps used must be provided to the pilot prior to their receipt of the transfer radiometers.

ii. Each participant must provide an SI-traceable calibration certificate and the associated data (including calibration uncertainties) for the reflectance panel they use.

iii. Along with the actual radiance measurements, an uncertainty analysis will be carried out by each participant, guided by the pilot, to evaluate the uncertainty budget related to each of their radiance sources in operation at their own laboratories. This includes an analysis that accounts for all the additional effects particular to their own laboratory setup that will influence the radiance measurements. This data will be fed back to the pilot to be included in the full comparison analysis and end-to-end uncertainty evaluation for OCRs and FRM4SOC.

iv. The pilot will determine calibration factors for the two transfer radiometers for each participant at each waveband, based on the spectral radiance data and radiometer readings provided by that participant.

v. The pilot will perform a statistical analysis of the comparison of the calibration factors for the OCRs determined from measurements by each participant lab and the values obtained via measurements related to the NPL Spectral Radiance Scale.

vi. The pilot will investigate the degree of agreement between the participants, based on the comparison results and associated uncertainties. The results of this analysis will be presented to all participants in terms of differences between the radiometer calibration factors for each participant and the mean result using measurements from all participants.

vii. The pilot will also analyse the results in terms of the relationship to SI for each participant and the results of this analysis will be presented to all participants.

8. REFERENCES

BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML, 1995. Guide to the Expression of Uncertainty in Measurement (Geneva, Switzerland: International Organisation for Standardisation).

CCPR-G4, *Guidelines for Preparing CCPR Key Comparisons*, 2013, available at http://www.bipm.org/utils/common/pdf/CC/CCPR/CCPR-G4.pdf

CIPM MRA-D-05, Measurement comparisons in the CIPM MRA, Version 1.3, available at http://www.bipm.org/utils/common/CIPM_MRA/CIPM_MRA-D-05.pdf

CCPR-G2, *Guidelines for CCPR Key Comparison Report Preparation*, *Rev. 3*, July 2013.

Fox, N. and Greening, M.C., 2010. A guide to comparisons – organisation, operation and analysis to establish measurement equivalence to underpin the Quality Assurance requirements of GEO, version-4, QA4EO-QAEO-GEN-DQK-004, available from http://qa4eo.org/docs/QA4EO-QAEO-GEN-DQK-004_v4.0.pdf

APPENDIX A: CHECK LIST FOR INSPECTION OF TRANSFER RADIOMETERS

Has the radiometer transportation package been opened during transit ?
e.g.Customs…☐Y /☐ N

If Yes please give details:

Is there any damage to the transportation package?……☐Y / ☐N.
If Yes please give details:

Are any of the enclosed strain gauges indicating any damage?…..☐Y / ☐N
If Yes give details:

Are there any visible signs of damage to the radiometers or associated equipment?…..☐Y / ☐N
If Yes please give details (e.g. scratches, dents, broken or cracked lenses etc):

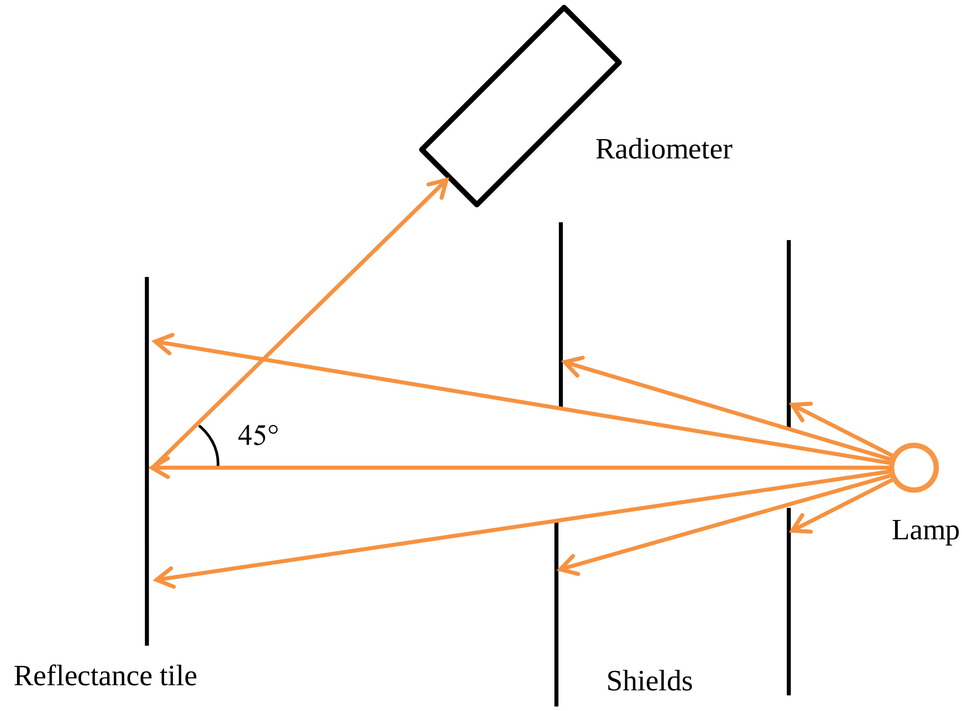
After connecting using the instructions in Appendix B, do you believe the radiometers are functioning correctly ?…☐Y/ ☐N
If not please indicate your concerns

Operator:
Laboratory:

Date:………………………………… Signature: ………………………………..

APPENDIX B: RADIANCE MEASUREMENT SETUP

It is recommended that this description be used as a "tick sheet" in the laboratory



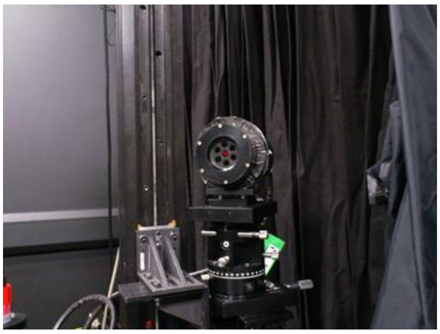
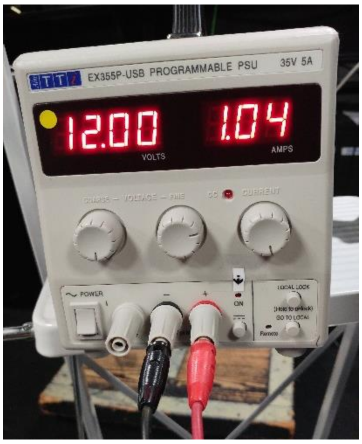


Figure 5: Radiance mode diagram of setup (top), multispectral radiometer (bottom).

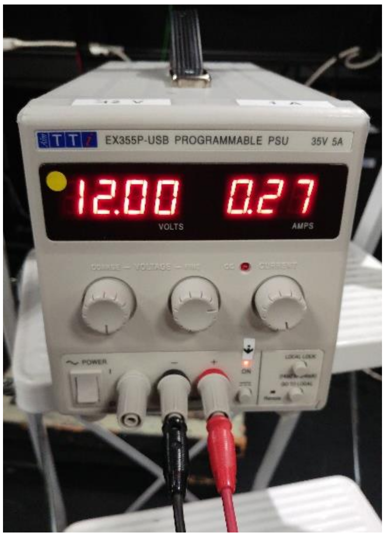
Step 0: Test radiometer function

1. Connect the data logger to the power supply

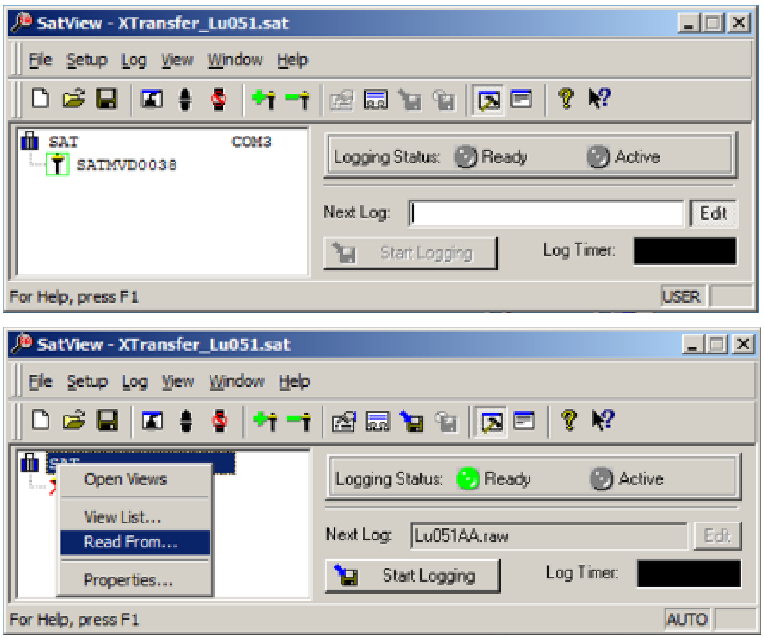
(left) data logger; (right) power supply after switching on but not powering up. The button to provide power to the radiometer is labelled with an arrow.

2. Switch on the power supply (without activating the power to the radiometer) and check that the voltage and current are set (12V, 1A limit)
3. Connect the instrument to the power supply and power it up



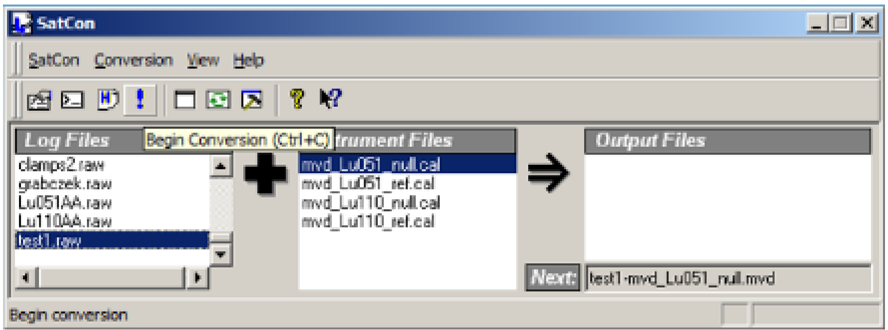
(left) radiometer connected with serial number visible; (right) power supply with radiometer powered up

4. Connect the RS232 to USB converter to the computer and check that it is installed correctly
5. Connect the data logger to the computer via the converter
6. Run Satview: on the desktop there should be a satview file with the instrument number (either 051 or 110: check the back e.g XTr_Lu051); a box will pop up asking to overwrite a log file – click no, and you'll rename the output file anyway
7. If connected properly, a green box should appear around the instrument symbol



(top) program appearance when the instrument is properly connected; (bottom) right click on SAT, then choose "read from" COM3

8. If not, the COM port may need to be changed: right click on the section and change communication to COM3
9. To set up logging click on "Log", then "Options". Change "File Naming Mode" to user defined and change the log duration to the length of time you want to record for and the log directory to where you want to store the data: a sub folder of the automatic folder for each participant would be helpful
10. To start logging from the main screen, first enter the filename by clicking edit and typing it into the "next log" box, then unclicking edit. The start logging button can then be pressed. It will record for your chosen log duration or until "Stop Logging" is pressed
11. This will produce ".raw" files. To convert these to text (".mvd") use the program "SatCon". Select the log file in the first box (multiple files can be selected), then the instrument file (using the number again e.g. mvd_Lu051_null.cal) in the second window. Press the exclamation mark "Begin Conversion" to convert files



SatCon layout for converting "test1.raw" files. Note the output file naming convention in the "next" box

12. Output will be in columns of digital counts for each channel. Date and time are also included

Step 1: Set up basic radiance measurement arrangement. Participants should use their standard radiance measurement set up wherever possible. Typically this will include the following elements:

a. Main rail: on which the lamp and reflectance panel are placed, with the lamp aligned perpendicular to, and centred on, the reflectance panel

b. 45° rail: on which the radiometer will be placed such that it views the centre of the reflectance panel at an angle of 45° to the normal..

c. Mounts:

   i. Stray light baffle mounts

   ii. Lamp mount: needs to provide all adjustments necessary to allow the alignment jig to be set perpendicular to, and centred on, the optical axis of the main rail and to allow the required distance to the reflectance panel to be set. NB The power cables must be long enough to move the lamp mount along the rail without pulling

   iii. Reflectance panel mount: needs to provide all adjustments necessary to allow the reflectance panel to be set perpendicular to, and centred on, the optical axis of the main rail and to allow the front of the reflectance panel to be set at the point of intersection between the optical axes of the main rail and the 45° rail.

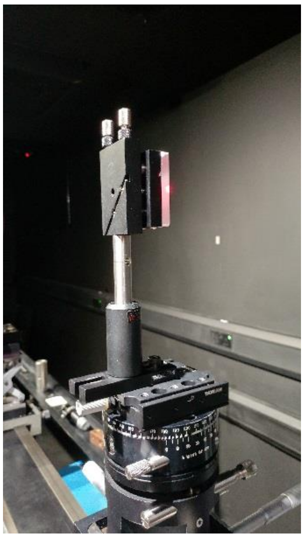
   iv. Any other mounts as required to facilitate correct alignment of lamp, reflectance panel and radiometer.

d. Alignment Laser: This is used as the reference for correct alignment of the lamp jig and the reflectance panel and must therefore be aligned along the optical axis of the main rail. Often a pinhole mounted on the main rail and translated along its length is used to check correct alignment of the laser, but other techniques may also be used, depending on each participant's normal practice. The uncertainty associated with correct alignment of the laser must be included in the uncertainty budget for the radiance measurements.

e. The laser is potentially being aligned over a very short distance, so some angular offset is likely. This can be calculated and added to the uncertainties.

Step 2: Alignment of Equipment

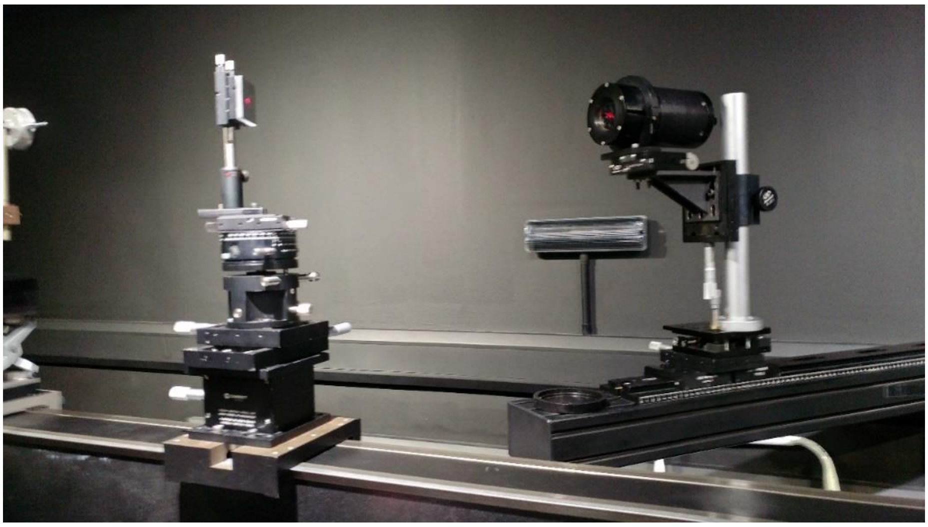
1. 45° rail: The optical axis of this rail must be set at an angle of 45° to the optical axis of the main rail, and the point of intersection of these two optical axes must be identified (this is the point at which the centre of the reflectance panel should be located). Correct alignment at the required angle is generally achieved by use of a mirror mounted on the main rail but other techniques may also be used, depending on each participant's normal practice. If a mirror is used, the typical method is to adjust this to be perpendicular to the optical axis of the main rail by back reflection of the alignment laser, and then to rotate the mirror by 22.5° so that it reflects the laser at 45°. This defines an optical axis at 45°, which can be used as the reference for alignment of the 45° rail. Note care must be taken to ensure that the point about which the mirror is rotated is coincident with the front surface of the mirror.



(left) aligning the mirror so that the centre of rotation coincides with the laser

(right) aligning the mirror so it back reflects to the laser

2. Radiometer: The radiometer must be set so that it is perpendicular to, and centred on, the optical axis of the 45° rail (ideally each individual channel of the radiometer should be centred in turn on the optical axis of the 45° rail in order to minimise non-uniformity effects, as noted in Section 4.3). Correct alignment is generally achieved by use of a mirror mounted on the main rail and rotated by 22.5° to the optical axis of the main rail to define the optical axis of the 45° rail, as described above, but other techniques may also be used, depending on each participant's normal practice. If a laser is used, the radiometer can be set perpendicular to the optical axis of the 45° rail by back reflection from the glass at the front of the radiometer. The laser can also be used to align the centre of the aperture of the radiometer on the optical axis. It is important to make sure the radiometer is at an appropriate distance from the point at which the reflectance panel will be located – the field of view should be well within the illuminated area on the reflectance panel to avoid any edge effects. However it is also important not to move the radiometer so close that it obstructs any of the radiation from the lamp from reaching the panel; this means the minimum distance should be approximately 250 mm.



Aligning the transfer radiometer to the 45° laser using the mirror

3. Reflectance panel: This needs to be set so that it is perpendicular to, and centred on, the optical axis of the main rail. It also needs to be positioned along the main rail such that the centre of its front face is located at the point of intersection between the optical axis of the main rail and that of the 45° rail. This is generally achieved using the alignment laser and mirror arrangement described above, but other techniques may also be used, depending on each participant's normal practice. Since it is important not to touch the front surface of the reflectance panel, the rear surface is usually used for alignment purposes (the panel is then rotated by 180°), The correct location of the front surface at the point of intersection of the optical axes of the main rail and the 45° rail can be achieved by using a telescope set perpendicular to the optical axis of the main rail at this point, or by means of a pointer located at the correct position, or by other means depending on each participant's normal practice.

(left) aligning the panel so it is perpendicular to the laser

(right) setting the distance of the panel using a pointer

4. Lamp: This must be aligned (using the alignment jig) such that it is perpendicular to, and centred on, the optical axis of the main bench. The alignment laser is used for this purpose. It is important to always connect the wires to the lamp before alignment, since the lamp may move when these are connected, but do not power it up. The jig must be removed before the lamp is powered up.

Aligning the lamp using its alignment jig so that it is on the optical axis

5. Distance setting: The distance between the front face of the alignment jig and front face of the reflectance panel should be set to the correct calibration distance i.e. the distance for which the lamp irradiance has been calibrated. This will be stated on the calibration certificate and is usually 500 mm. The distance is generally be measured using a measuring stick or by means

of the length scale on the main rail (using a telescope set perpendicular to the optical axis as the datum); other techniques may also be used, however, depending on each participant's normal practice. Note other distances may be used in addition, provided that the irradiance at each distance used is known (it may be beneficial to make measurements at an increased lamp-panel separation in order to minimise the effects of irradiance non-uniformity).

6. Stray light shields: these should be positioned as required in order to minimise stray light effects.

A possible arrangement of the shields, including only those directly between the lamp and panel. Others should be added to the sides of the lamp.

Step 3: Take measurements using radiometer.

1. Power up lamp (remember to remove alignment jig first) and allow to stabilise.
2. Record radiometer readings for each radiometer waveband. Each reading should consist of multiple measurements of both light and dark, with measurement times of at least 30 seconds each (longer if possible). Dark measurements should be made with the direct light from the source blocked, rather than by blocking all light at the entrance to the radiometer, so that any residual stray light is still recorded by the radiometer.
3. Three sets of independent measurements should be taken using each radiometer. The measurement set up (lamp, reflectance panel and radiometer) must be completely realigned between each of these measurements.
4. Results must be submitted in Excel format, using the template in Appendix I. Spectral radiance data for the lamp-reflectance tile combination must also be provided in Excel format, using the template in Appendix J.

APPENDIX C: UNCERTAINTY BUDGET EVALUATION TEMPLATE

Parameter	Source of Uncertainty
Nominal signal	Short-term effect light readings
	Short-term effect dark readings
	Signal stability
	Room stray light
Lamp Irradiance	FEL calibration
	Filament offset distance
	Calibration distance
	Realignment (lamp , panel, instrument)
	Current
	Age
Radiance	Panel reflectance
	Panel reflectance conversion to 0:45
	Tile uniformity

APPENDIX D: RECORD SHEET FOR FEL LAMPS

This record is only for the intercomparison measurements and will start with the burn time to date for each lamp, information supplied by each participant prior to the intercomparisons. It will then be kept for each lamp by the participant owner of that lamp as a log during the intercomparison measurements and a copy sent to the pilot at the end.

Lamp reference number:

Operating current: e.g. 8.1 A

Date	Time on	After Warm-up		Before switch-off		Time off	Burn Time	Cumulative Burn Time
		Current	Voltage	Current	Voltage			

APPENDIX E: FORM FOR DESCRIPTION OF THE IRRADIANCE SOURCE

Lamp type and manufacturer:	*(e.g. 5000 FEL 1000W, Gamma Scientific)*
Reliable wavelength range:	*(e.g. 250-2500nm)*
Operating current:	*(e.g. 8.1 A DC)*
Operating voltage (approximate):	*(e.g. 115 V)*
Alignment:	*(e.g. front, back)*
Distance reference plane :	*(e.g. to front plate/back plate/lateral mark on alignment jig/centre of filament)*
In house distance measurements method and its uncertainty:	
Total burn time to date:	*(e.g. 53 hours)*
Burn time since last calibration:	*(e.g. 3 hours)*
Last calibration date:	*(e.g. 31/01/2017)*
First calibration date:	*(e.g. 31/01/2016)*
In house power supply model:	
In house power supply current accuracy:	
In house standard resistor calibration:	
Photos:	*(e.g. as set up in participant's lab)*

APPENDIX F: FORM FOR DESCRIPTION OF THE REFLECTANCE PANEL USED

Panel type and manufacturer:	*(e.g. Spectralon, Labsphere)*
Panel size:	*(e.g. 12 x 12 inch)*
Reliable wavelength range:	*(e.g. 250-2500nm)*
Alignment:	*(e.g. front, back)*
In house distance measurements method and its uncertainty:	
Last calibration date:	*(e.g. 31/01/2017)*
First calibration date:	*(e.g. 31/01/2016)*
Photos:	*(e.g. as set up in participant's lab)*

APPENDIX G: DATA RECEIPT CONFIRMATION

All data should be sent to the pilot NPL. The details of the contact person for this are:

From: (participating laboratory, please complete)

To: Dr Andrew Clive Banks

National Physical Laboratory

Hampton Road

Teddington

Middlesex

United Kingdom

TW11 0LW

Tel: ++44 20 8943 6081 e-mail: andrew.banks@npl.co.uk

We confirm that we have received the data listed below which resulted from the ESA FRM4SOC/CEOS comparison of "Reference Radiance Sources used by FRM OCRs for Satellite Validation" on ....(date).

....
....
....

Date:………………………………Signature:………………………….

APPENDIX H: RADIOMETER MEASUREMENT RESULTS

Radiometer reference number:

Radiometer channel number	Measurement 1		Measurement 2		Measurement 3		Mean reading (light – dark)
	Light	Dark	Light	Dark	Light	Dark	

APPENDIX I: SPECTRAL RADIANCE DATA

Lamp reference number:

Reflectance panel reference number:

Wavelength	Spectral radiance	Wavelength	Spectral radiance
400		560	
410		570	
420		580	
430		590	
440		600	
450		610	
460		620	
470		630	
480		640	
490		650	
500		660	
510		670	
520		680	
530		690	
540		700	
550			