fiducial reference measurements for satellite ocean colour

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

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

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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
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 one of the two part protocols reference document for LCE-1 and FRM4SOC. It establishes and documents protocols for the comparisons between irradiance sources used for calibrating ocean colour radiometers.

2. ORGANIZATION

2.1 PILOT

LCE-1 will be implemented at NPL 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 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 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 should 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 radiance source comparisons are provided in a separate document: D80b - Protocols and Procedures to Verify the Performance of Reference Radiance Sources used by FRM OCRs for Satellite Validation (TR-3b).

The participant irradiance source comparison will be conducted at NPL and by NPL as pilot. It is mandatory that all participants' artefacts used in the comparisons are accompanied by SI traceable certificates from their last calibration and information about burn time since that calibration. The FEL lamps that have been burnt for more than 50 hours will not be accepted.

At NPL the Spectral Radiance and Irradiance Primary Scales (SRIPS; Woolliams et al, 2006) facility is used to transfer the scale from the NPL primary reference standard, a high temperature blackbody, to lamp and integrating sphere sources. These sources are then used as secondary spectral radiance and irradiance standards further down the chain. The spectral radiance of the blackbody is derived from knowledge of its temperature and Planck's law. The temperature is measured by a filter radiometer that has been calibrated in terms of its spectral radiance responsivity using a trap detector (a photodiode based standard of spectral responsivity). The trap detector is itself calibrated against the overall primary standard, a cryogenic radiometer, which underpins the SI traceability of all of NPL's optical radiation measurements.

For the irradiance comparison each participant lamp will be measured against an NPL secondary standard lamp. As a result, irradiance values will be obtained from each lamp as measured under the carefully controlled conditions of SRIPS and Ref Spec at NPL and these will be compared with their certificate values after estimation of any lamp aging related effects. This is the first step in the irradiance source comparison exercise and is designed to ascertain if the measurements performed at NPL and the original FEL lamp calibration certificates are in agreement within the stated uncertainties for both. For the participants, the main aim of this part is to fully understand irradiance source calibration results and uncertainties in order to appropriately apply them at the next stage in their own laboratories.

The second part relies on the concept of equivalence of measurements, defined as agreement within stated uncertainties between two measurement results, and is related to the operation of each participants' irradiance sources in their own laboratory facilities. Here each participant will need to apply the knowledge they have gained about irradiance source calibrations in order to evaluate uncertainties associated with their irradiance standard operating in their own laboratory. This includes all the additional uncertainty components related to the new alignment of the standard, distance measurements, and power supply stability and accuracy. All these aspects will be discussed with participants and NPL, as the pilot, will provide templates for compiling and reporting back this uncertainty budget evaluation.

The quantitative results of the comparison will be presented in terms of differences between the original calibrated values of the lamps and the mean calibration value of all of them derived from the NPL measurements. Information will also be presented relating to the level of agreement with SI for each participant and the degree to which the irradiance values and uncertainty budgets are supported by the comparison results. These will be given to participants during the draft A phase and published in the Final Report. The comparison measurand is the spectral irradiance of the lamps at 500 mm from a defined plane as determined separately at a (sub)set of 19 wavelengths in the range 350 nm to 1000 nm. Each wavelength is treated independently for the purposes of the analysis.

A full description of the FEL lamps that will be the irradiance source used in this comparison is given in Section 3 of this protocol. Participants will supply their own lamps and alignment jigs accompanied with relevant calibration certificates and additional in house laboratory facilities information. The type of FEL lamp that NPL presently encourages the use of in this type of comparison is described in Section 3. However, it is recognised that participants may be using other types of FEL lamps and thus it is essential that they supply the pilot with the technical details and history of their lamps well in advance of the comparisons. These lamps will remain the property of the participant on conclusion of their sequence of measurements.

Comparisons at NPL are carried out to the highest possible SI-traceable standards with full uncertainty characterisation using the NPL state of the art radiometric laboratories. The FRM4SOC LCE-1 irradiance source comparison will primarily use the NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility & Reference Spectroradiometer System (RefSpec).

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	April, 2017 to December, 2017
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. The first week starting on Monday 3rd April 2017 has been allocated to laboratory measurements of the participants' irradiance sources on the NPL SRIPS and RefSpec facilities. These measurements are expected to last all of that week and may possibly need some of the following week. Furthermore, every effort will be made to finish the irradiance measurements by Friday 07 April 2017 to allow participants to be able to hand-carry their irradiance sources back to their respective laboratories.

Although not necessary, it is recommended that participants are present at the irradiance source comparisons. Not only does this give participants the chance to hand carry their lamps to the pilot but also the other days of the week of the irradiance source measurements have been allocated to training in uncertainty and absolute radiometric calibration (see full Agenda in Appendix F). Particular attention will be paid to training that ensures that each participant follows the same methodology according to the protocols in irradiance and radiance source measurement and evaluation of uncertainty at each stage of those processes, in preparation for receipt of the transfer radiometers from the pilot and the appropriate measurements at their home laboratories (see companion document D80b/TR-3b - Protocols and

Procedures to Verify the Performance of Reference Radiance Sources used by FRM OCRs for Satellite Validation).

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	17 April 2017	31 December 2017	Circulation of transfer radiometers and LCE-1 round-robin intercomparison of participant's radiance sources (see companion document)	LCE-1 Participants' Laboratories

2.6 HANDLING OF ARTEFACTS

Participants should ensure that the FEL lamps arrive in a suitable condition for measurement by the pilot laboratory. Transport of the lamps is detailed in the section below. The lamps should be examined immediately upon arrival at the pilot – by the participants and the pilot if hand carrying to LCE-1 or by the pilot if the lamps have been shipped from the participant. The condition of the lamps and associated packaging will be noted by the pilot according to the lamp inspection form (Appendix A).

The standard lamps should only be handled by authorised persons and stored in such a way as to prevent damage.

No cleaning of any lamp windows, jigs or envelopes should be attempted. No parts should be removed. If a standard lamp appears damaged the participant should contact the pilot immediately so that an appropriate decision can be made as regards replacement or partial use of results. However, appropriate insurance should be taken out by participating laboratories to cover the cost of such a replacement if the damage occurred in transit.

During operation of the standard lamps if there is any unusual occurrence, e.g. change of voltage or change in output etc., the pilot laboratory will note this immediately before making any decision to proceed.

After the measurements, the lamps should be re-packaged in their original transit cases. Ensure that the content of the package is complete before transporting. Always use the original packaging.

2.7 TRANSPORTATION OF ARTEFACTS

It is of utmost importance that the artefacts be transported in a manner in which they will not be lost, damaged or handled by un-authorised persons. Packaging for the artefacts should be suitably robust to protect the artefacts from being deformed or damaged during transit.

Artefacts should as a preference be carried by hand to and from the pilot, either by personal road transport, sea, or in an aircraft cabin. Participants are advised not to use commercial courier services, but each participant must decide the most appropriate means of transportation. They should under all circumstances be marked as 'Fragile'.

The artefacts should be accompanied by a suitable customs carnet (where appropriate) or documentation identifying the items uniquely. The packaging should be lockable e.g. by clasp, but also easy to open with minimum delay to allow customs inspections to take place.

Transportation is each participant's responsibility and cost. It is the responsibility of all participants to ensure that any instrumentation required by them is shipped with sufficient time to clear any customs requirements of the host country, in this case the UK. This includes transportation from any port of entry to the site of the comparison and any delay could result in them being excluded from the comparison. For this part of the comparison, participants should send their equipment to:

Dr. Andrew Clive Banks
Room F4-A10
National Physical Laboratory (NPL)
Hampton Road
Teddington
Middlesex
UK
TW11 0LW

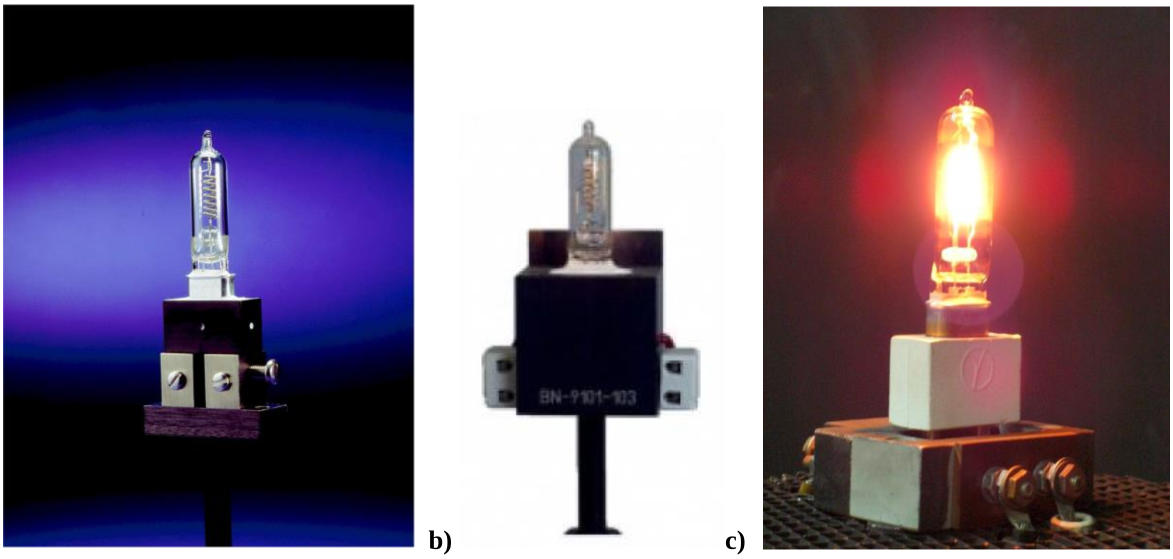
Any queries can be directed to Andrew on andrew.banks@npl.co.uk or by phone on +44 (0)20 8943 6081. As is stipulated on the application / expression of interest form for LCE-1, it is not obligatory for participants to be present at the comparisons.

Please note that the coordinator and host laboratory have no insurance for any loss or damage of the equipment during transportation or whilst in use during the comparison, however all reasonable efforts will be made to aid participants in any security issues. Following the initial inspection detailed above, equipment that has been sent to NPL will be stored until Monday 03 April 2017, when the pilot or their owners can unpack them, carry out a further inspection and assemble them for the lab comparisons. The inspection form (shown in Appendix A) should be used after every transportation or period of storage. Irradiance source power supplies are not needed as SRIPS and RefSpec have carefully controlled and monitored power supplies for the measurements.

2.8 RECORDING ARTEFACT USE

As part of the report for the irradiance comparison, the pilot will record the number of on-off cycles for each lamp and the total burn hours for each lamp. In addition the current and voltage for each lamp will be recorded according to the form shown in Appendix C.

3. DESCRIPTION OF THE ARTEFACTS



a) b) c)

Figure 1. 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 main types of lamp that are presently used as irradiance sources in calibration laboratories worldwide. The pilot's reference facilities are setup to be able to measure these types of lamps. There is the possibility that other types or variants of FEL lamps can be included in the comparison and participants should have informed the pilot using the irradiance source specifications form supplied to them well in advance of the laboratory comparison experiment in order to ensure that these lamps can be accommodated on the pilot's facilities. This form is also included here as Appendix D. Note that each type of lamp can have a slightly different alignment procedure and reference plane for the 500 mm distance. For consistency both the pilot and participants should follow what is specified on the calibration certificates for each lamp.

Table I 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

3.1 ELECTRICAL POWER

Before connecting to any electrical power supply, the lamps should be inspected for damage or contamination of either the window of the lamp (viewed through the front aperture), or its supporting mount. Any damage should be documented by photos or a drawing using the appropriate form in Appendix A and the pilot laboratory should be informed immediately.

Before switching on the current to any lamp, the lamp should be aligned and then all alignment jigs removed.

FEL lamps must always operate according to the marked polarity. Lamps will be operated at a constant DC current with the lamp voltage able to fluctuate to maintain the constant current. At NPL this current will be measured using a standard resistor and controlled using a feedback loop.

3.2 ALIGNING THE LAMPS

The lamps will be aligned according to the procedures described in Appendix B and according to what is specified on the calibration certificate for each lamp. Participants should supply the pilot with the alignment jig that they would normally use with each of their lamps. 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. At the end of the warm-up time, the operational parameters for each lamp (specified in the lamp operating procedure Appendix B) should be recorded.

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 for a further 30 minutes after switching off.

3.5 RECORDS

Before using any lamp, an appropriate time recording device and notebook should be established to allow the burn time for each lamp to be recorded. An example form that could be used has been attached as Appendix C. A summary sheet such as this should be completed for, and kept with, each lamp by the pilot laboratory.

The operational conditions and alignment procedure for each lamp should be noted and followed according to the details described in the notes supplied with each lamp. The checklist presented in Appendix B should be followed, filled out and signed for each measurement. The checklist should be kept by the pilot and participants for documentation and quality assurance.

4. MEASUREMENT INSTRUCTIONS

4.1 TRACEABILITY

All participant sources 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 wavelength. The wavelengths for this comparison cover the ocean colour visible and NIR wavelength range and are as in Table II.

Table II Wavelengths for the comparison.

Wavelength Range	Wavelength steps	Wavelengths / nm
350 nm – 400 nm	10 nm	350, 360, 370, 380, 390, 400
450 nm – 1000 nm	50 nm + 555 nm	450, 500, 550, 555, 600, 650, 700, 750, 800, 850, 900, 950, 1000

4.3 MEASURAND

The measurand is the spectral irradiance of a lamp in a plane at 500 mm from the reference plane of the lamp aligned to the optical axis of the lamp system (see alignment procedures in Appendices). The spectral irradiance should be measured for the defined operating conditions for each lamp, defined by the associated power supply. 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.

The spectral irradiance of each lamp will be measured independently at least twice by the pilot. Each independent measurement will consist of the lamp being realigned in the measurement facility and there will be a break of at least 2 hours between each independent measurement for each lamp.

Any information obtained relating to the use or any results obtained by the pilot for each lamp during the course of the comparison shall be sent only to the participant laboratory who own that lamp. 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 lamp measurements performed during this comparison at NPL. A graphical representation of the SRIPS uncertainty budget when used in irradiance mode to calibrate an FEL lamp against the blackbody is shown in Appendix G. This figure gives a good idea of each of the uncertainty components for an FEL lamp calibration and their relative levels. However, it should be noted that the uncertainties shown are averaged values for the wavelength range 250 nm – 2500 nm and are given for example purposes only. Most of the uncertainties change with wavelength and for the calibrations and the measurements for the comparison of irradiance sources these will be evaluated at each distinct measurement wavelength.

The pilot will educate the participants on the methods to evaluate additional uncertainty components that will affect the irradiance standard during its use at their own laboratories. This will enable the pilot, in partnership with each participant, to include these uncertainties in a more complete uncertainty evaluation for each irradiance source, taking into account not only uncertainties from its absolute irradiance calibration 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.

List of essential additional information from each participant:

1. Power supply model and specification
2. Shunt resistor specification and calibration certificate
3. Frequency of lamp current and voltage monitoring during its operation
4. Distance measurement method and its uncertainty
5. In house lamp alignment repeatability

The pilot will lead the participants though the uncertainty evaluation process.

6. REPORTING OF RESULTS

On completion of the irradiance measurements by the pilot the provisional results of the comparison measurements, in terms of the difference to the mean comparison value, will be sent to each participant on an individual basis (i.e. results for their lamps only). During report drafting the pilot will reconfirm these values to the participant and ensure that the correct participant values are being used by the pilot and that no mix-up has occurred. The data receipt form (Appendix E) will be used via email in each instance of data communication.

Following this the pilot will provide a full comparison report which will include a full uncertainty analysis for the pilot's measurements as well as details of the measurement facilities 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 comparison results will be supplied in graphical format and as an Excel data file 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. The comparison value will be derived as a mean value of all participating lamps as measured at NPL. Then the difference between that comparison value and each individual lamp calibration value will be reported. The measurements will be equivalent when they all agree within stated comparison uncertainty value. This value will be calculated combining the original calibration certificate uncertainty, any lamp aging effects depending on the time since the last calibration, and the NPL system relative uncertainty for the comparison measurements.

ii. A further uncertainty analysis carried out by each participant, guided by the pilot, to evaluate the uncertainty budget related to each of their irradiance sources but 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 irradiance 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.

iii. Following the irradiance source comparison steps summarised above, a similar comparison analysis will have to be performed for each participant's radiance sources and calibration facilities. This is detailed in part 2 of these protocols although it is worth noting here that 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.

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 LAMPS

Has the lamp 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 lamp or housing?…..☐Y / ☐N
If Yes please give details (e.g. scratches, dust, broken coil, alignment mask moved etc):

After warm-up is the lamp voltage and current within its specified range?….☐Y/ ☐N
If not what is the voltage and the current ? V, mA

Do you believe the lamp is functioning correctly ?…☐Y/ ☐N
If not please indicate your concerns

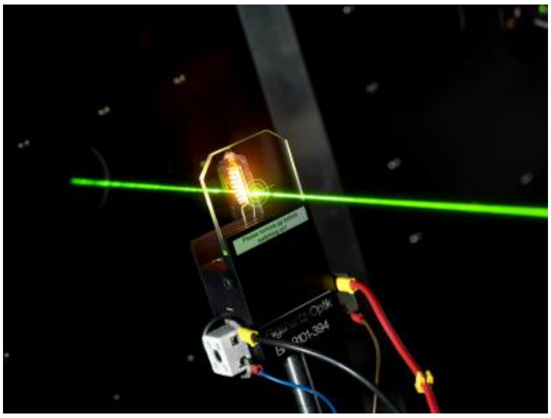
Operator:
Laboratory:

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

APPENDIX B: ALIGNING AND OPERATING FEL LAMPS

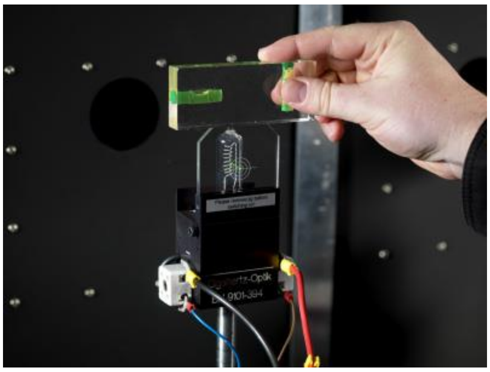
Example: FEL Lamp Type 1:
It is recommended that this description be used as a "tick sheet" in the laboratory

1. Position an alignment laser to define the optical axis of the spectral irradiance facility such that the laser points towards the facility entrance optics and the lamp will be placed between the laser and the facility
2. The lamp is fragile and the envelope should never be touched. It is recommended that gloves are worn when handling the lamp, since any finger marks will be burnt into the lamp envelope when it is run and will result in changes in output or possibly even lamp failure.
3. Place the lamp in a mount that provides 6 degrees of freedom (3 rotational and 3 positional).
4. Connect the electrical terminals – observing the marked polarity (+ / -) to a DC power supply operating at 8.1 A and ~110 V. **Do not switch on.**
5. Remove the protective housing and replace with the alignment jig. The etched side of the alignment jig should point towards the laser (away from the measurement facility)

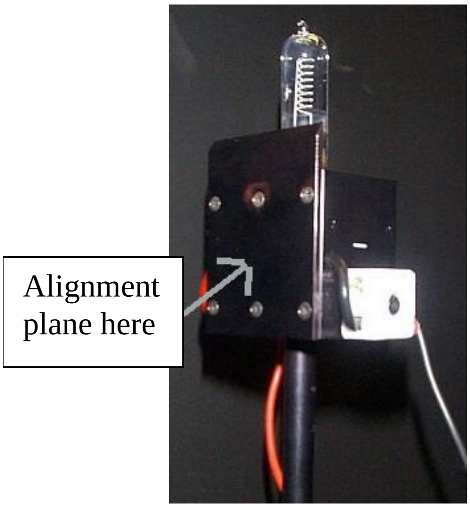


NB: Lamp on slightly in this photo to show filament – the lamp should not be on when the jig is still in place!

6. Rest a spirit level on the top of the alignment jig (taking care not to touch the lamp envelope) and rotate the lamp such that the top of the jig is level



7. Turn on the laser and move/rotate the lamp such that the laser hits the centre of the target and the laser beam is back-reflected back to the laser.
8. Move the lamp until the centre of the front plate is 500 mm from the entrance optics of the spectral irradiance facility.



9. Carefully remove the alignment jig with a smooth upward lift. It should be easy to remove, if it is not easy to remove, then the alignment process should be repeated.
10. Double check that the alignment jig has been removed before introducing any stray light shields on your system.
11. Triple check that the alignment jig has been removed before switching on the lamp to ramp up to 8.1 A over approximately 2 minutes.
12. Record lamp on-time on a record sheet
13. Wait for 30 minutes
14. Record lamp current and voltage and adjust current if necessary (and not automatic)
15. Record laboratory temperature
16. Take spectral irradiance measurements
17. Record lamp current and voltage and laboratory temperature
18. Ramp lamp current back to 0 over approximately 2 minutes
19. Record lamp off-time on a record sheet
20. Wait at least 30 minutes before moving the lamp

APPENDIX C: 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 pilot as a log during the intercomparison measurements and a copy will be given to the corresponding participant at the end.

Lamp reference number:

Operating current: e.g. 8.1 A

Measurement distance: e.g. 500 mm to front plate.

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

APPENDIX D: FORM FOR DESCRIPTION OF THE IRRADIANCE SOURCES

Lamp type and manufacturer:	*(e.g. 5000 FEL 1000W, Gamma Scientific)*
No. of lamps (3 recommended, 2 minimum):	*(e.g. 2)*
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:	
Hand carried (recommended) or shipped:	*(e.g. Hand carried)*
Photos:	*(e.g. as set up in participant's lab)*

APPENDIX E: DATA RECEIPT CONFIRMATION

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

To: (participating laboratory, please complete)

From: 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 Irradiance Sources used by FRM OCRs for Satellite Validation" on ....(date).

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

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

APPENDIX F: FRM4SOC LCE-1 PARTICIPANT'S SCHEDULE

Day 1 (Monday 03/04/2017)

The morning's activities are concerned with NPL induction and introductions, including health and safety as well as finding your way around briefings. The afternoon's activities are concerned with measurement training.

Time	Activity	Responsible Person
09:00	Arrive at security gate; you will be directed to Reception where you will hand over FEL lamps to members of the FRM4SOC NPL team; and then be collected by a member of the HR team for the NPL Induction in meeting room F4-LS1 (the FRM4SOC LCE-1 participants HQ for the week)	HR Team David Hemfrey Agnieszka Bialek & Will Servantes
09:30	Pass Induction in F4-LS1	HR Team
10:00	Break	
10:30	Welcome and Introduction to FRM4SOC Introduction to LCE-1	Andrew Banks Agnieszka Bialek
12:00	Lunch	See below

Lunch

A table for FRM4SOC LCE-1 participants is reserved in the NPL canteen (cash and card accepted). Andrew Banks/Agnieszka Bialek will accompany participants.

Time	Activity	Responsible Person
13:30	FEL lamp setup demo on the 8m bench	Barry Scott, Agnieszka Bialek & Claire Greenwell
15:30	Break	
	Hands on work on irradiance mode on the 8m bench Inverse square law, sensitivity to the position, current stability briefing	Barry Scott, Agnieszka Bialek & Claire Greenwell Barry Scott
17:00	Collection of belongings from F4-LS1 and end of day 1	Andrew Banks/David Hemfrey
18:00 (TBC)	Ice breaker drink @The Kings Head, Teddington	Andrew Banks

Day 2 (Tuesday 04/04/2017)

The morning and afternoon activities are concerned with theoretical metrology training and a chance for consultations with members of the NPL staff.

Time	Activity	Responsible Person
09:00	Arrive at NPL; Pass Security; Gather in F4-LS1 for informal discussions	Andrew Banks/Agnieszka Bialek/David Hemfrey
10:00	Lecture in F4-LS1: Introduction to Metrology and the Law of Propagation of Uncertainty	Emma Woolliams
12:00	Lunch	See below

Lunch

A table for FRM4SOC LCE-1 participants is reserved in the NPL canteen (cash and card accepted). Andrew Banks/Agnieszka Bialek will accompany participants.

Time	Activity	Responsible Person
13:30	Lecture in F4-LS1: Steps to an Uncertainty Budget	Paul Miller
14:30	Lecture in F4-LS1: The Measurement Equation	Agnieszka Bialek
15:15	Break	
15:30	Lecture in F4-LS1: Comparisons	Teresa Goodman
16:30	Informal consultations on FEL lamps / irradiance measurements	Will Servantes & Teresa Goodman
17:30	Collection of belongings from F4-LS1 and end of day 2	Andrew Banks/David Hemfrey

Day 3 (Wednesday 05/04/2017)

The morning's activities are concerned with theoretical metrology training and practical work in the lab. The afternoon's activities are a training workshop on completing your own uncertainty budget.

Time	Activity	Responsible Person
09:00	Arrive at NPL; Pass Security; Gather in F4-LS1 for informal discussions	Andrew Banks/Agnieszka Bialek/David Hemfrey
09:30	Lecture in F4-LS1: Radiance calibration	Agnieszka Bialek
10:15	Break	
10:30	Hands on work on radiance mode on the 8m bench Uniformity of the panel, alignment etc.	Barry Scott, Agnieszka Bialek, & Claire Greenwell
12:30	Lunch	See below

Lunch

A table for FRM4SOC LCE-1 participants is reserved in the NPL canteen (cash and card accepted). Andrew Banks/Agnieszka Bialek will accompany participants.

Time	Activity	Responsible Person
14:00	Workshop format / discussion in F4-LS1 on: Preparing participants uncertainty budget: • Filling out uncertainty templates • Thinking through how to test real uncertainties back at their home labs	Agnieszka Bialek
15:30	Break	
15:30	Workshop format / discussion in F4-LS1 on: Preparing participants uncertainty budget: • Filling out uncertainty templates • Thinking through how to test real uncertainties back at their home labs	Agnieszka Bialek
17:00	Collection of belongings from F4-LS1 and end of day 3	Andrew Banks/David Hemfrey
18:30 (TBC)	FRM4SOC LCE-1 Participant's Dinner @Park Hotel, Teddington	Andrew Banks

Day 4 (Thursday 06/04/2017)

The morning and afternoon's activities are a chance to meet others at NPL and visit the other areas of metrological research being undertaken here. When this is not going on participants can work further on completing their own uncertainty budget as a follow-on from the previous days training.

Time	Activity	Responsible Person
09:00	Arrive at NPL; Pass Security; Gather in F4-LS1 for informal discussions	Andrew Banks/Agnieszka Bialek/David Hemfrey
09:30	Meeting others at NPL / other lab tours (and/or) continued uncertainty budget template work	Andrew Banks/David Hemfrey Agnieszka Bialek
10:30	Break	
10:45	Meeting others at NPL / other lab tours (and/or) continued uncertainty budget template work	Andrew Banks/David Hemfrey Agnieszka Bialek
12:30	Lunch	See below

Lunch

A table for FRM4SOC LCE-1 participants is reserved in the NPL canteen (cash and card accepted). Andrew Banks/Agnieszka Bialek will accompany participants.

Time	Activity	Responsible Person
14:00	Meeting others at NPL / other lab tours (and/or) continued uncertainty budget template work	Andrew Banks/David Hemfrey Agnieszka Bialek
15:30	Break	
15:30	Meeting others at NPL / other lab tours (and/or) continued uncertainty budget template work Repacking first set of participants' FEL lamps	Andrew Banks/David Hemfrey Agnieszka Bialek Will Servantes
17:00	Collection of belongings from F4-LS1 and end of day 4	Andrew Banks/David Hemfrey

Day 5 (Friday 06/04/2017)

The final morning's activities are a chance to tour the Earth Observation, Climate and Optical group's facilities used in FRM4SOC. The afternoon is an informal period when participants can collect their FEL lamps, arrange any other business and bid NPL and FRM4SOC LCE-1 goodbye.

Time	Activity	Responsible Person
09:00	Arrive at NPL; Pass Security; Gather in F4-LS1 for informal discussions	Andrew Banks/Agnieszka Bialek/David Hemfrey
09:30	Repacking second set of participants' FEL lamps NPL Earth Observation, Climate and Optical's lab tours in groups of 4 or 5 SRIPS tour NRR tour Cryogenic radiometer tour	Will Servantes Will Servantes Teresa Goodman Florian Graber
10:30	Break	
10:30	NPL Earth Observation, Climate and Optical's lab tours in groups of 4 or 5 (cont'd) SRIPS tour NRR tour Cryogenic radiometer tour Final round table discussion and completion of feedback forms	 Will Servantes Teresa Goodman Florian Graber Andrew Banks, Agnieszka Bialek, Teresa Goodman, Claire Greenwell, & Barry Scott
12:30	Lunch	See below

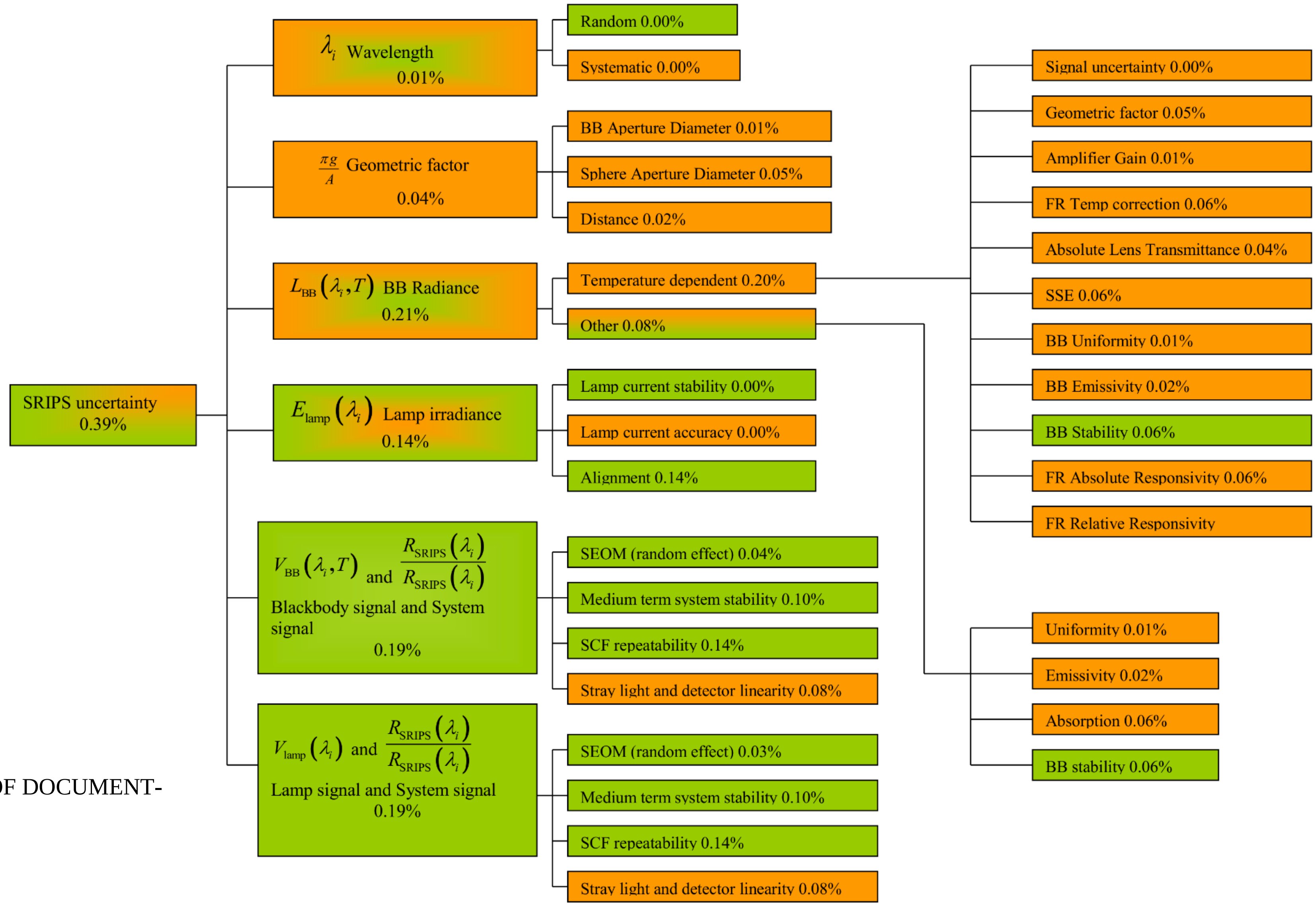
Lunch

A table for FRM4SOC LCE-1 participants is reserved in the NPL canteen (cash and card accepted). Andrew Banks/Agnieszka Bialek will accompany participants.

Time	Activity	Responsible Person
14:00-17:30	Collection of FEL lamps Farewell, travel arrangements and collection of belongings from F4-LS1	Will Servantes Andrew Banks/Agnieszka Bialek/David Hemfrey

APPENDIX G: SRIPS UNCERTAINTY BUDGET

Orange represents systematic and green random uncertainty. The colour mixture represents values composed of random and systematic uncertainties.



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