Fiducial Reference Measurements for Satellite Ocean Colour Phase-2

Strategy plan for the secondary laboratory cal/char inter-comparison exercise and the definition and harmonization of laboratory guidelines

(FRM4SOC2-D11)

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Prepared By	Approved by
Name: Agnieszka Bialek	Name: Juan Ignacio Gossn
Organisation: NPL	Organisation: EUMETSAT
Position: Senior Research Scientist	Position: Project Technical Officer
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Acronyms and Abbreviations

Acronym	**Description**
AAOT	Acqua Alta Oceanographic Tower
AERONET-OC	The Ocean Color component of the Aerosol Robotic Network
AMT	Atlantic Meridional Transect
ARC	Assessment of In Situ Radiometric Capabilities for Coastal Water Remote Sensing Applications
BRDF	Bidirectional reflectance distribution function
Cal	Calibration
CCPR	Consultative Committee for Photometry and Radiometry
CEOS	Committee on Earth Observation Satellites
Char	Characterization
CIPM	Comité International des Poids et Mesures (International Committee for Weights and Measures)
CIMP MRA	CIPM Mutual Recognition Arrangement
EO	Earth Observation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FICE	Fiducial Inter-Comparison Experiment
FOV	Field of view
FRM	Fiducial Reference Measurements
FRMOCnet	Copernicus FRM-certified OC instrument network
FRM4SOC	Fiducial Reference Measurements for Satellite Ocean Colour
FWHM	Full Width at Half Maximum
GEO	Group on Earth Observations
ILAC	International Laboratory Accreditation Cooperation
IOCCG	International Ocean-Colour Coordinating Group
LUT	Look Up Table
MERIS	Medium Resolution Imaging Spectrometer
MVT	MERIS Validation Team
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NMI	National Metrology Institute
NPL	National Physical Laboratory
OC	Ocean Colour
OCDB	Ocean Colour Database
OCR	Ocean Colour Radiometer
QA	Quality Assurance
QA4EO	Quality Assurance framework for Earth Observation
QC	Quality Control
QTH	Quartz tungsten halogen
ROI	Return On Investment
RSP	Remote Sensing and Products Division
RD	Reference Document
S3	Sentinel-3
S3VT-OC	Sentinel-3 Validation Team – Ocean Colour group
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SIRREX	SeaWiFS Intercalibration Round Robin Experiments
SI	International System of Units
SOW	Statement of Work
SST	Sea Surface Temperature
TO	Tartu Observatory, University of Tartu
TR	Technical Report
UT	University of Tartu
VAL	Validation
VIM	Vocabulaire International de Métrologie (International Vocabulary in Metrology)

Contents

1 Scope

The current document is the Strategy plan for the secondary laboratory cal/char inter-comparison exercise (D-13) and the definition and harmonization of laboratory guidelines (D-12) as required by the terms of the Invitation To Tender (ITT) No. 20/220036 "Copernicus – Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC phase-2) issued by EUMETSAT. This document forms deliverable D-11 of the FRM4SOC phase-2 project.

The main aim of this deliverable is to develop guidelines, under the direction of the National Physical Laboratory (NPL) as an National Metrology Institute (NMI), for secondary cal/char laboratories to ensure full adoption of radiance/irradiance source calibration traceability, lab set-up, results and uncertainties and to establish a shared and common standard, to be applied at the cal/char laboratory level. These guidelines are based on the lessons learned from previous inter-comparison exercises, especially most recent FRM4SOC -1. We change the form of inter-comparison to round-robin for irradiance and radiance calibration. Thus, we will verify each secondary lab performance during the measurements rather than the standards in the pilot laboratory setting, as it was done for irradiance sources in FRM4SOC-1. The radiance calibration tends to be more challenging due to the higher number of uncertainty contributors and variability of possible set-ups and methods, thus we define a standard method as a principle to follow.

This document also outlines a plan for cal/char inter-comparison exercise of hyperspectral instruments for those labs to:

- verify the performance of secondary standards transferred from reference NMI SI traceable radiance sources and of lab protocol application, used by labs to perform the calibration of their FRM Ocean Colour Radiometer (OCR) instruments, this will be achieved by verification of the consistency of labs in using their reference standards during FRM4SOC standard cal/char procedures

- establish common processes to be followed in cal/char laboratories, vet them and gather consensus, if possible, involving multiple actors, including international coordination, either through the review process or direct participation.

The cal/char inter-comparison exercises will be performed with a number of participating laboratories. The timing of the FRM4SOC-2 activity necessitates that

- the inter-comparison exercises with the first participating labs will be used as input and lessons-learned in the development of D-12 Harmonized cal/char lab guidelines,
- the inter-comparison exercises with the final participating labs will be used to test in practice, review, and fine-tune D-12 Harmonized cal/char lab guidelines.

This Strategy plan for the secondary laboratory cal/char inter-comparison exercise and the definition and harmonization of laboratory guidelines is the guidance document that sets the principles for defining, organising, inter-comparison activities within the FRM4SOC phase-2 project and beyond for future FRM4SOC activities.

2 Compatibility

Table 2-1. Compatibility

No.	Requirement	
1.	SOW-REQ-36: A strategy for the inter-comparison and harmonization of secondary cal/char labs shall be defined by the Contractor as deliverable D-11 and it shall include a targeted lab inter-comparison exercise. A major part of the strategy shall address the lab cal/char harmonization guidelines for the most common OCR instruments in use in FRMOCnet. If feasible, in order to conserve time and resources, the strategy shall plan to combine the lab inter-comparison exercise with the full cal/char of the FRMOCnet OCR models from Task 4,	

3 Introduction

Metrological traceability to a measurement unit of the International System of Units (JCGM200:2012, 2012) is the concept that links all metrological measurements to the SI through a series of calibrations or comparisons. Each step in this traceability chain has rigorous uncertainty analysis, usually peer reviewed or audited and always documented. Comparisons (CIPM, 1999) are the process of validating an uncertainty analysis by comparing the measurement of artefacts by different laboratories. National Measurements Institutes (NMIs) must participate in regular (usually every 10 years) formal comparisons. Each technical discipline defines a limited number of “key comparisons” and these provide evidence to support uncertainty analysis for a certain number of related quantities in a “Calibration and Measurement Capability Database”. So, for example, the Consultative Committee for Photometry and Radiometry (CCPR) has defined a key comparison for six key measurands (spectral irradiance, spectral responsivity, luminous intensity, luminous flux, spectral diffuse transmittance and spectral regular reflectance). There is no key comparison for spectral radiance, as it is assumed that reliable results (results that are consistent with declared uncertainties) in the spectral irradiance comparison together with results for the comparison of reflectance provide sufficient evidence for spectral radiance measurements as well.

The comparison concept as a validation of various laboratory measurement capabilities has been successfully adapted in Ocean Colour Radiometry (OCR) starting from a dedicated program to support the quality of Sea-viewing Wide Field-of-view Sensor (SeaWIFS) (Hooker *et al.*, 1992) products. A series of dedicated laboratory comparison exercises were conducted in the frame of SeaWiFS Intercalibration Round-Robin Experiment (SIRREX 1-8) (Mueller, 1993; Mueller *et al.*, 1994, 1996; Johnson *et al.*, 1996, 1999; Riley and Bailey, 1998; Hooker *et al.*, 2002; Zibordi, G. *et al.*, 2003) and then Second Intercomparison and Merger for Interdisciplinary Ocean Studies (SIMBIOS) Radiometric Intercomparison (SIMRIC) -1 and -2 (Meister *et al.*, 2002, 2003) programmes. Then in support of Medium Resolution Imaging Spectrometer (MERIS) (Rast, Bezy and Bruzzi, 1999) as MERIS AATV Validation Team (MAVT) activities like PlymCal (Tilstone *et al.*, 2002) that were related to inter-calibration of several radiometers using one irradiance and radiance source in one laboratory were implemented. Similar activity was then performed before Assessment of In Situ Radiometric Capabilities for Coastal Water Remote Sensing Applications (ARC) in situ comparison activities, where all participating radiometers were calibrated in the one laboratory (Zibordi at all 2012). The most recently in support of Sentinel 3 (Donlon *et al.*, 2012) in the frame of Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) (Banks *et al.*, 2020) the laboratory comparisons were performed (Białek *et al.*, 2020).

Table 3-1 shows an overview of all previous comparison exercises. The focus in that table is on the absolute radiometric calibration comparison, however, several of the listed comparisons included other characterisation measurements as well.

There is a huge amount of lessons learnt and recommendations as the result of all these comparisons exercises that are summarised in the NASA protocol series (Hooker *et al.*, 2002; Mueller, Morel, *et al.*, 2003; Mueller, Pietras, *et al.*, 2003). For the absolute radiometric calibration the later SIRREX and SIMBIOS exercises showed that the level of measurement uncertainty can be maintained at the level of 2- 3% if the protocols are followed (Hooker, McClain and Mannino, 2007).

Recently updated IOCCG protocols (Zibordi *et al.*, 2019) specify a need for radiometric intercomparisons and set a more challenging uncertainty target :

“Instrument manufacturers and a few research laboratories are equipped and staffed to perform these calibrations for the ocean color research community. These facilities should perform frequent intercomparisons to ensure the maintenance of the radiometric traceability to NMI standards. An ambitious goal is to perform calibrations from 350 nm to 900 nm with 1% target uncertainty (k = 1) for irradiance and slightly higher for radiance.”

The most recent results from FRM4SOC irradiance comparison showed an agreement between all lamps included in the comparison of within ±1.5%. The comparison of radiance sources (calibrated source – reflectance plaque combination) was performed via a calibration of the transfer radiometers in each participant lab. Results presented higher than expected discrepancies at the level of ±4% and the results separated into two distinct and separate groups of 9 and 4 different radiance sources. Additional investigation showed that the reason for this difference was caused by a sensitivity to the size of the illuminated patch (instrument size-of-source effect) and partly because the instrument-effective FOV included non-uniform parts of the illumination for a shorter lamp-diffuser distance which affected the results of the smaller (4) of the two groups. If these effects could be corrected for or the measurements repeated at different settings, we would expect to see all measurements agreeing within ±2.5%, as this is the level of agreement in the results from the majority group.

Comparisons previous to FRM4SOC-2 used multispectral instruments and focused on the absolute radiometric calibration of irradiance and radiance sensors. For FRM4SOC-2 two hyperspectral instrument models were selected, given future missions and validation measurements will be likely hyperspectral. We will encounter new challenges related to the characteristics of hyperspectral instruments. Thus, we propose to include additional characterisation measurements such as detector linearity, spectral calibration, spectral stray light, thermal sensitivity, polarisation sensitivity, etc. We are fully aware that not all participating laboratories will have capabilities to perform these additional characterisation tests. However, if any laboratory does wish to conduct additional tests, the results will be compared with the comparison pilot.

Table 3-1. Overview of past comparion exersises performed in support of various OC missions.

Name		Date	Irradiance	Radiance	Comments	Ancillary instrumentation
SIRREX	1	July 1992	Transfer of irradiance scale from a reference lamp to 17 FEL lamps	Integrating spheres (various sizes), lamps + plaques	Based in one lab – aim to transfer a common spectral irradiance and radiance scale from GSFC to participating labs, plaque BRDF issues reported, require improvement of instrumentation to meet the mission goals.	Shunt resistors, voltmeters
	2	June 1993	Transfer of irradiance scale from a reference lamp to 26 FEL and 1 DWX lamp	Integrating spheres (various sizes), lamps + plaques	Based in one lab – aim to transfer the scale. Irradiance results satisfactory, radiance results unsatisfactory	Shunt resistors, voltmeters
	3	Sep 1994	FEL lamps comparison	Integrating spheres (various sizes), lamps + plaques	Based in one lab – irradiance results satisfactory radiance results improved, plaque still require further investigation.	Shunt resistors, voltmeters
	4	May 1995	N/A	N/A	Based at NIST training in a common protocol for calibration of radiometers, Conversion between R (8°/h) to R (0°/45°) geometry was applied,	
	5	July 1996	NIST calibrated participants irradiance radiometers	NIST calibrated participants radiance radiometers	Based at NIST focusing on training and standard measurements protocols implementations	Instruments intercomparison in field
	6	Aug-Sep 1997	2 transfer radiometers measured irradiance at each lab	2 transfer radiometers measured irradiance at each lab	Measurements conducted by NASA personnel traveling to each participating lab.	
	7	March 1999	FEL comparison	lamp + plaques	Based in one lab focused on uncertainty in a single lab, plus rotation and polarisation sensitivity	
	8	Sep-Dec 2001	N/A	N/A	Based in 3 labs, focused on immersion factors and cosine response	
SIMRIC	1	2001	N/A	Lamp plaque, integrating sphere	7 labs measure in-house radiance source with a reference radiometer,	
	2	2002	N/A	Lamp plaque, integrating sphere	10 labs measure in-house radiance source with a reference radiometer,	
FRM4SOC	1	2017-2018	FEL comparison 14 lamps	Radiance comparison in participant laboratories using lamp + plaque	Lamp comparison and training based at NPL; radiance comparison based at each participant own lab. Irradiance results within uncertainty. Radiance saw two distinctive groups of results.	

From the metrological point of view, it is important to repeat such comparison exercises at regular time frames; firstly, to achieve the measurement consistency, then to ensure that the consistency between the organisations is maintained long term and, finally, to enable new participants to verify their measurement capability. The key comparison between NMIs is repeated every 10 years, the previous NASA Ocean Colour comparison programmes tended to be run every year, which was a reasonable approach especially for the SIRREX as the protocols and methodologies had been developed at that same time. However, the regular NASA comparison projects were discontinued since early 2000. ESA in support of MERIS established a number comparison exercises, but they mainly focused on in situ comparison and a common inter-calibration of participating radiometers. The recent FRM4SOC-1 project ran the international comparison exercise that spanned from 2017 to 2018 and this project is about to set a next one in the frame of the ongoing FRM4SOC-2.

The frequency of the future comparisons hugely depends on the funding for such activities; however, as the protocols are already established, repeating such an exercise every three to five years seems to be acceptable. In the case of a new institute wanting to establish calibration and characterisation facility a dedicated bilateral comparison could be organised to verify this laboratory performance within the five-year period between the international comparison dates.

4 Definitions

This section contains the definitions of the terms used in metrology based on International Vocabulary in Metrology (VIM) followed by some FRM4SOC related terms.

4.1 Vocabulary in metrology

Metrological Traceability – property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Calibration – operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

Uncertainty – non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Metrological comparability – comparability of measurement results, for quantities of a given kind, that are metrologically traceable to the same reference.

In the context of FRM4SOC this means that the radiometric calibration results from different laboratories are metrologically comparable if all participating laboratories have radiometric calibration standards metrologically traceable to the same unit. This is $Wm^{-2}nm^{-1}$ for irradiance and $Wm^{-2}nm^{-1}sr^{-1}$ for radiance. Please note that it does not have to be the same physical standard i.e. one FEL lamp.

Metrological compatibility – property of a set of measurement results for a specified measurand, such that the absolute value of the difference of any pair of measured quantity values from two different measurement results is smaller than some chosen multiple of the standard measurement uncertainty of that difference.

NOTE 1 Metrological compatibility of measurement results replaces the traditional concept of ‘staying within the error’, as it represents the criterion for deciding whether two measurement results refer to the same measurand or not.

NOTE 2 Correlation between the measurements influences metrological compatibility of measurement results. If the measurements are completely uncorrelated, the standard measurement uncertainty of their difference is equal to the root mean square sum of their standard measurement uncertainties, while it is lower for positive covariance or higher for negative covariance.

Source: (JCGM200:2012, 2012)

The final note is about the word “*comparison*” that is commonly used in metrology terminology, however, other disciplines, and indeed Ocean Colour community, often use the word “*intercomparison*” or a version spelled as “*inter-comparison*”. The meaning of all three words is the same. In this document we chose to be consistent with metrological vocabulary.

4.2 FRM4SOC defined terms

Fiducial Reference Measurements (FRM) are a suite of independent, fully characterized, and traceable ground measurements that follow the guidelines outlined by the Group on Earth Observations (GEO)/CEOS Quality Assurance framework for Earth Observation (QA4EO). These FRM provide the maximum Return On Investment (ROI) for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission (*Fiducial Reference Measurements*, 2021)

The defining characteristics of FRM are:

- FRM have documented SI traceability (e.g. via calibration and/or round robin intercalibration of instruments) using metrology standards;
- FRM measurements are independent from the satellite geophysical retrieval process (noting the exception of L2 product vicarious adjustment that fundamentally depends on FRM ground based measurements);
- Uncertainty budgets for all FRM instruments and derived measurements are available and maintained, measurement results are[1] traceable where appropriate to SI ideally directly through an NMI;
- FRM measurement protocols and community-wide management practices (measurement, processing, archive, documents, etc.) are defined, published openly and adhered to by FRM instrument deployments;
- FRM measurements are openly and freely available for independent scrutiny.

Copernicus FRM-certified OC instrument network (FRMOCnet) this is a network that will be established and include of FRM-certified instruments and measurements.

FRM "certification" term will be defined during the study following discussion with the experts in the field and the community. Even though still not properly defined, FRM certification will certainly include several stages of the FRMOCnet:

- FRM compliant cal/char laboratories
- FRM Certification of OCR instrument models
- FRM certification of single individual OCR instrument
- FRM certified cal/char status
- FRM competence certified operators
- FRM certified measurement protocols
- Network of radiometric measurements with the FRM certification

In this document we mainly focus on FRM compliant cal/char laboratories. These should have an operational quality management system of ISO 17025 or equivalent plus compliance to specific requirements for FRM. There are several ways to make a proof of this.

- Participation in an international comparison such as FRM4SOC where results are to be compared with reference value with set uncertainties,
- International Laboratory Accreditation Cooperation (ILAC) recognised accreditation,
- NMIs under International Committee for Weights and Measures Mutual Recognition Arrangement (CIPM MRA),
- Establishing or designating a dedicated independent and authorised certification body outside the “ISO” system to make the audits and decisions on conformity

5 Absolute radiometric calibration comparison

Absolute radiometric calibration comparison is a first step necessary to obtain the FRMOCnet. The aim here is to ensure that all laboratories that calibrate and characterise radiometers that are used in situ for validation purposes reach metrological compatibility. This means that all instruments used for in situ FRM measurements are traceable to SI and the differences between calibration coefficients derived at different participating laboratories are fully explained by the measurement uncertainties. Comparisons allow the validation of each lab’s performance and reveal unknown issues that otherwise might not be detected. Quite often comparison exercises detect unexpected errors and allow these to be addressed and corrected, overall improving the quality of the measurements. In addition, the comparison exercises will verify the calibration procedures, allowing to further improve and clarify them.

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[1] In red font a proposed updated phrase to align it with VIM SI metrological traceability definition

The absolute radiometric comparisons will be implemented through a round-robin comparison of each participant's irradiance and radiance calibration capability using ocean colour transfer radiometers. The transfer standards in targeted lab comparison exercise will be two TriOS-Ramses and two Satlantic-HyperOCR instruments. The measurand is the responsivity calibration factor determined for all transfer radiometers using each participant's own spectral irradiance and radiance reference standards, and FRM4SOC standard calibration procedures (briefly described in section 5.1 and 5.2, the full details will be available in D-12 Harmonized cal/char lab guidelines, including lab protocols for FRMOCnet OCR models). All participants must be able to document their traceability to SI for both irradiance and radiance measurements via appropriate calibration certificates and to evaluate their associated uncertainties. We recognise that for radiance calibration not all participants might be able to follow the FRM4SOC standard calibration procedure. Such laboratories can still participate in the comparison, but their measurements uncertainty budget will have to include components to correct for a different measurement set-up.

University of Tartu (UT) will act as a pilot lab. They will invite participants, prepare the time-schedule, will send transfer radiometers, will prepare draft comparison protocol, collect the comparison results, and prepare the report. All participants will be guided on the comparison protocol. The comparison report will also be discussed and agreed with all participants.

The transfer radiometers will be calibrated by the pilot (UT) 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 record of the detectors' stability will be described in the comparison report.

Each participant will need to evaluate uncertainties associated with their irradiance and radiance calibrations. This includes all the uncertainty components that are additional to those on the calibration certificates, e.g. those 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. To facilitate the correct compiling and reporting back of uncertainty budgets the pilot will discuss with participants all these additional uncertainty contributors.

The quantitative results of the comparison will be presented in terms of differences between each participant's measurement and the mean value of all of them. Although the measurements results will be available for all pixels some of the characterisation and correction coefficients like for example non-linearity correction might not be provided for the wavelengths below 400 nm (lower wavelengths have too low signal-to-noise-ratio on currently available facilities used for these test). The results of the comparison, for sake of clarity, might be presented convolved into satellite bands for example S3.

In the event of discrepancy in the results the pilot will work directly with the corresponding participant to investigate the source of that difference. It might be possible for the participant to repeat the measurements if the cause of error will be identified before the end of the comparison period. The pilot upon agreement with participants might decide to report the results of the comparison as a weighted mean or median to minimize the contribution of the outlier results on the final comparison value.

5.1 Irradiance calibration

In this comparison 1000 W quartz tungsten halogen (QTH) lamps, so-called FEL lamps (not acronym) according to ANSI (American National Standard Institute) designation, are considered as irradiance sources and are used at the standard calibration distance of 500 mm measured from their reference plane. All models from different manufactures are accepted. The sole condition for the participant to use a lamp is its calibration certificate and the burn time of less than 50 h since calibration. It is extremely important to use the lamp according to its manufacturer's specification. These apply to the alignment process, rump up time and the operational current. In addition, the lamp information from the calibration certificate should be carefully studied to obtain information about ambient temperature during calibration and full width at half maximum (FWHM) of the instrument used for that calibration.

For the lamps that are calibrated with their enclosure, that enclosure should be used during the comparison. Participants should monitor the lamp current and voltage across the lamp during the measurements and provide information about power supply accuracy, ideally including calibration certificate for a shunt resistor.

Each participant should use at least two lamps during this comparison to measure calibration coefficients for two transfer radiometers. The exact number of measurements per radiometer will be defined in the protocol.

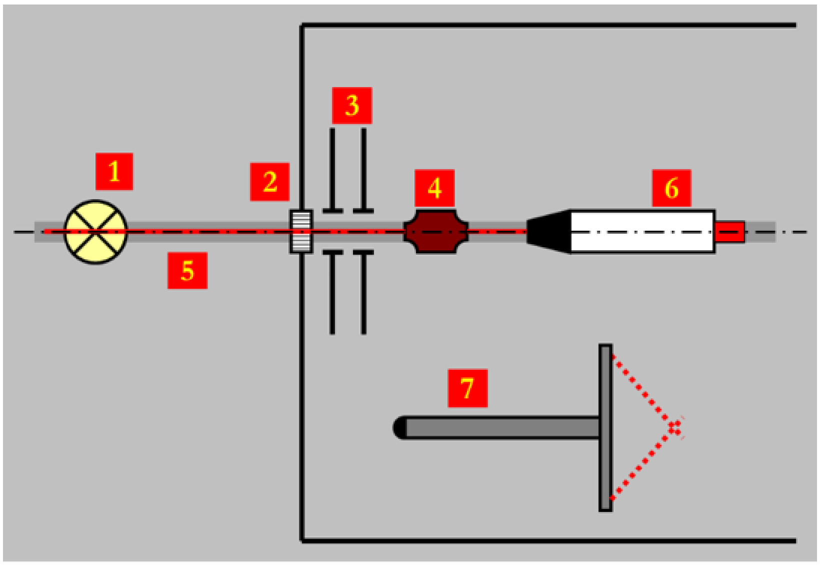

Figure 1.Pilot's (UT) irradiance calibration setup. 1 -FEL lamp; 2 – shutter; 3 – baffles; 4- -alignment laser; 5- optical rail; 6 – radiometer; 7 – contactless distance probe.

Figure 1 presents a schematic of irradiance calibration set-up at the pilot laboratory. Other participants might have slightly different solutions for the distance measurement, baffling, and power supply. But in principle the irradiance calibration is very standardised. The measurements are done at the nominal lamp calibration distance which is 500 mm. The distance is measured from the lamp reference plane defined by the manufacturer. Generally, in the past the irradiance comparisons were established relatively quickly and provided consistent results within the excepted uncertainty levels, providing that all lamps are properly handled and are within 50 h burning time from the recent calibration.

5.1.1 FRM4SOC irradiance calibration guideline

The following guidelines set a point-by-point check list of what items are necessary for irradiance measurements, thus the participants can use it to verify their dark room laboratory equipment in advance of comparison. The comparison protocol and D12 Harmonized cal/char lab guidelines, including lab protocols for FRMOCnet OCR models documents, will specify in more details how to perform the measurements. In this report we show an example of step-by-step instructions for the irradiance measurements for one type of FEL lamp in Appendix A.

The checklist is split into three categories "Required", "Highly recommended" and "Preferable". To take part in comparison a participant must meet all required points. Lack of "Highly recommended" items increases the measurement uncertainty values. The "Preferable" category contains non-essential items that would be good to have to speed up or simplify the measurements, however it is possible to make measurements without them.

1. R – Optical rail or tale to set up the experiment
2. R – At least two radiometrically calibrated FEL lamps with a burning time less than 50 h since last calibration
3. R – Alignment laser to define the optical axis and align the lamps and the radiometers
4. R – Lamp, radiometer and laser posts. P – Six degrees of freedom lamp and laser mount (to facilitate the alignment)
5. R – Alignment procedure that strictly follows the lamp manufacturer instruction and the lamp calibration instruction (e.g. the reference point for distance measurements is different for every manufacturer of FEL lamp, and the distance setting must be done accordingly to the lamp type), an example of Gigahertz lamp alignment can be found in Appendix A.
6. R – Power supply, P – Power supply with a function of automatic rump up/down time
7. Hr – Standard resistor and independent voltmeter readings, P – automatic current and voltage readings with the file output, rather than an operator handwritten notes in a lab book.
8. R – Distance measurement devise, Hr – calibrated measurement stick, P – contactless distance probe
9. R – light shields
10. R – Lab temperature readings (section 7 Harmonisation of laboratory guidelines contain the explanation why this is required)

5.2 Radiance calibration

The aim of the comparison is to test the participants' calibration of the radiance responsivity of the transfer detector. The standard FRM4SOC radiance calibration is based on the so-called lamp-plaque technique, where an FEL lamp with known irradiance is used to illuminate a reflectance standard with known reflectance. An alternative method to obtain a source of radiance uses an integrating sphere. This method was not used during FRM4SOC -1 comparison but in SIRREX and SIMRIC exercises. Thus, in the future comparison participants with integrating spheres can joint FRM4SOC, however they will have to work closely with the pilot to determine all sources of uncertainty related to their system.

For the three sensors measurement configuration that is commonly used for measurement of the remote sensing reflectance using of a single FEL lamp standard and reflectance panel is preferable. Such system calibration accounts for mechanical alignments of lamps, plaques and sensors, faulty baffling, short time instability of lamp standard, and uncertainty of diffuse reflectance plaque. Consequently, the uncertainty of a lamp is cancelled out. For independent reference standards (lamp and integrating sphere) all uncertainties must be fully accounted for.

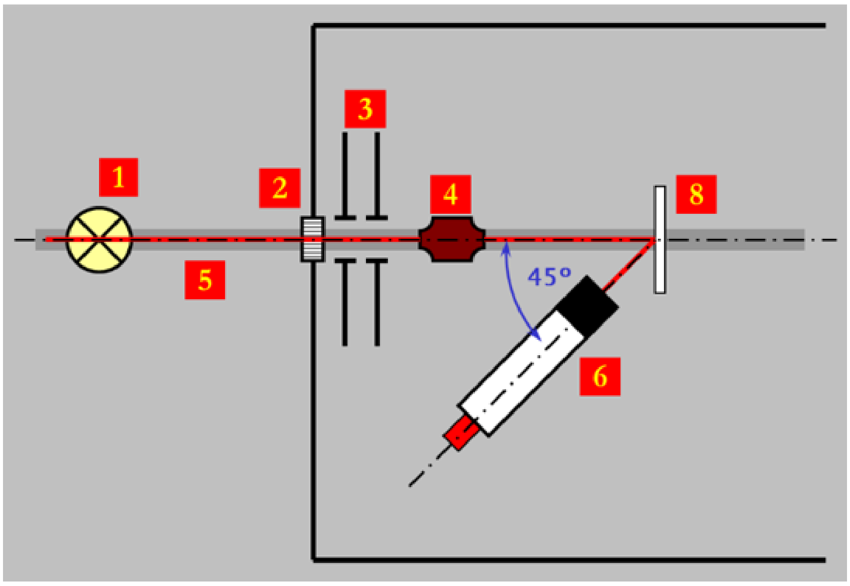

Figure 2. Pilot's (UT) radiance calibration setup. 1 -FEL lamp; 2 – shutter; 3 – baffles; 4- alignment laser; 5-optical rail; 6 – radiometer; 8 – reflectance panel.

A typical lamp-plaque radiance calibration set-up is presented in Figure 2. Although in principle the lamp-plaque radiance calibration set-up is standardised, as the reflectance panel is illuminated at normal incidence using the irradiance lamp and the transfer radiometers are set at 45° to the normal, in detail, there are several factors that can vary between laboratories and some of them cannot be easily changed, for example due to the size of the dark room.

Therefore, to unify the measurements set-ups we define the standard FRM4SOC radiance calibration protocol that all participants should follow. We do understand that for some participants this might not be possible. In this case, they will be still allowed to take part in comparison but will need to work very closely with the pilot to identify all differences in conditions during calibration as they may be a source for additional uncertainty.

For radiance calibration we request to use the same irradiance standards as were used for irradiance calibration under the same conditions described in section 5.1 Irradiance calibration. In order to avoid non-uniformity of the illumination patch within the field of view (FOV) of the radiometer, the distance between the lamp and the reflectance panel must be set to 1000 mm and the illumination patch size must be 3 times bigger than the FOV.

5.2.1 FRM4SOC radiance calibration guideline

The same three categories (R, Hr, P) are used for radiance calibration check list as for irradiance. To perform the lamp-plaque calibration all points listed in irradiance section must be meet plus the new listed here that are relevant to the radiance setting. The check list for radiance contains the equipment's list and processing steps necessary to correctly calculate radiance values.

1. R – Any clean and recently calibrated white pseudo-Lambertian reflectance standard with correction applied to convert the calibration value to 0°:45° geometry for calibration performed at most common and widely available 8°:hemispherical geometry (see text below), Hr – Calibrated Reflectance standard with reflectance factor calibration at 0°:45° geometry.
2. P – Mirror with 6 degrees of freedom mount to verify the 45 degrees optical axis
3. R – Lamp filament distance offset. For Gigahertz lamps, Hr – lamp filament offset for other lamp types. This is necessary to account for the difference in the plane of the distance setting and actual lamp filament position for measurements performed at any other distance than the default calibration 500 mm.

The reflectance standard should be calibrated for reflectance factor at 0°:45° geometry, however we do know that it is not always easy to find a measurement provider willing to do this type of calibration. The most common calibration is reflectance at 8°: hemispherical, which can be easily corrected for 0°:45° geometry for Spectralon™ reflectance targets. NPL will support the pilot to help derive a correct correction factor if any of the participants uses a reflectance standard that is not Spectralon™ and has only been calibrated for 8°: hemispherical. We strongly recommend using the standards that are clean upon a visual inspection and have been used only in the laboratory environment. It is well known that Spectralon™ can change its reflectance due to exposure to UV light, and get dirty while used in field environments (Moller, Nikolaus and Hope, 2003). If the surface of the reflectance standard is visibly dirty a participant must follow the reflectance standard manufacturer specific instruction to clean the surface such as for Spectralon™ (*User Guide: Spectralon Reflectance Standards Care & Handling Guide*, 2019). It is mandatory to recalibrate the standard after the cleaning procedure. We would encourage the participants to recalibrate their reflectance standards before the comparison.

5.2.2 Integrating spheres

For the participants that will have an integrating sphere, the size of the sphere and the size of the port, uniformity of that port and the sphere flux level might vary. Generally, the size of the entrance port will have to be big enough to full field the instrument field of view (R). An integrating sphere can be directly calibrated for radiance, then the calibration certificate will state the area of the entrance port that was measured during the calibration, if the radiometer under the test has the significantly larger FOV, a correction must be applied to account for that difference (Hr). The burn time since the last calibration should be monitored and it cannot extend 50 h for the sphere to be used in this comparison (R).

Some integrating spheres might not have a radiance calibration but a dedicated transfer radiometer that is used to calibrate the sphere. The stability of that radiometer, FOV, spectral characteristics need to be known to account for the difference between the transfer radiometer deriving the radiance calibration and the radiometers that will be used in this comparison. In this case SI traceability must be proved by the calibration certificate of the transfer radiometer (R). As the SI traceability for a standard detector is obtained via different route (standard detector is from detector scales rather than source scales used for the FEL lamps or the sphere directly calibrated for radiance), therefore the number of burned hours is not relevant as the condition for recalibration. Although there are no precise guidelines about frequency of the transfer radiometer calibration, we would expect that the recent calibration is not older than two years (Hr).

Currently we do not have participants using integrating sphere as a radiance source. If any participant with an integrating sphere will want to join the comparison, we will study the setups used in the comparison and draw further conclusions and recommendations on that basis.

6 Laboratory characterisation comparisons

We present a full list of characterisations and calibrations of FRM OCR instruments used to acquire field data for satellite ocean colour validation and doing above- and/or in-water measurements as specified in IOCGG protocols (Zibordi *et al.*, 2019) that includes a number of specific tests and measurements required for the uncertainty budget calculation:

1. Spectral radiometric responsivity calibration traceable to SI through NMI standards. It is fundamental basis for conversion measured Digital Numbers to the radiance or irradiance values in SI units, with specified uncertainties.
2. Wavelength calibration: relates a pixel number to the central wavelength of the pixel.
3. Spectral response (i.e. bandpass) functions of the various radiometer bands typical for filter radiometers, central wavelength and bandpass of each band.
4. Radiometric noise: signal to noise ratio for each band/pixel.
5. Spectral straylight and/or out-of-band response and perturbations: expressed as a straylight distribution function matrix.
6. Responsivity change with operating medium (i.e. immersion factor), relevant for instruments used in water.
7. Angular response, in air or in water, depending on the medium in which the radiometer operates.
8. Linearity of a detector response.
9. Integration time response[2].
10. Temperature Stability.
11. Polarization sensitivity.
12. Sensitivity decay: responsivity of radiometers may change over time implying regular responsivity checks. It is characterised as variability in relation with expanded uncertainty. If responsivity change is comparable (larger) than its uncertainty then SI traceability is lost, and therefore, recalibration is needed.
13. Dark signal.
14. Temporal response: response to stepwise changed input signal.

This is unlikely that any participating lab other than the pilot has capabilities to perform all the tests listed above apart from the point 1 which refers to absolute radiometric calibration described in more details in previous section. Some of these tests are time consuming thus running the full comparison including all tests would be highly challenging in terms of timeline management and funding. During the invitation phase of the comparison the pilot should verify if any participating laboratory is willing to perform any of these additional characterisation tests.

If any participant agrees to perform additional characterisation tests the details with regards to the supplementary timing and procedures to apply will be further coordinated with the pilot (UT) and described in D-12 Harmonized cal/char lab guidelines, including lab protocols for FRMOCnet OCR models document. UT will perform all these tests for several radiometers that will take part in in situ comparisons (FICE), therefore they will have their results ready for the comparison purposes. It is quite likely that we will have few bilateral companions for different characteristics, where bilateral means the comparison between two participants.

7 Harmonisation of laboratory guidelines

This is a first OCR international comparison where hyperspectral instruments are used as a transfer radiometer. The hyperspectral aspect might bring several new challenges that were not observed while using the multispectral instruments. To minimise unwanted discrepancies between measurements a set of harmonisation guidelines is presented in this section. This is important to note that not all characterisation tests are required for the radiometric calibration, and some of them are necessary to adapt to the changing conditions in situ. For analysis of different results of radiometric calibration comparison, thermal and nonlinearity coefficients are needed to minimize unwanted discrepancies between participants, as measurements in different laboratories are carried out at slightly different temperatures and by using different radiation sources. For correcting field measurements, characterizations for all conditions that differ during calibration and during later use, are needed. For example, the immersion coefficient will not have any impact on the results of radiometric calibration, similarly the cosine response of the diffuser, although extremely important for in situ observations, will not change the results of irradiance calibration.

The guidelines are based on the knowledge obtained from the characteristics of both instrument classes. The pilot (UT) has already tested several models of each type, TriOS-Ramses and Satlantic-HyperOCR instruments. Thus in

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[2] Determination of the integration time response is often considered as the simplest method for non-linearity characterisation.

addition to the comparison requirements in terms of absolute standards, listed in sections 5.1 Irradiance calibration and 5.2 Radiance calibration, the following requirements must be considered.

1. Apply integration time correction (R)

Ramses instruments showed significant non-linearity in previous studies (Talone and Zibordi, 2018; Vabson *et al.*, 2019; Talone, Zibordi and Białek, 2020). Figure 3 left panel shows how the normalised to arbitrary radiometric unit pixel values change with integration time. The right panel shows the corrected spectrum using a nonlinearity coefficient.

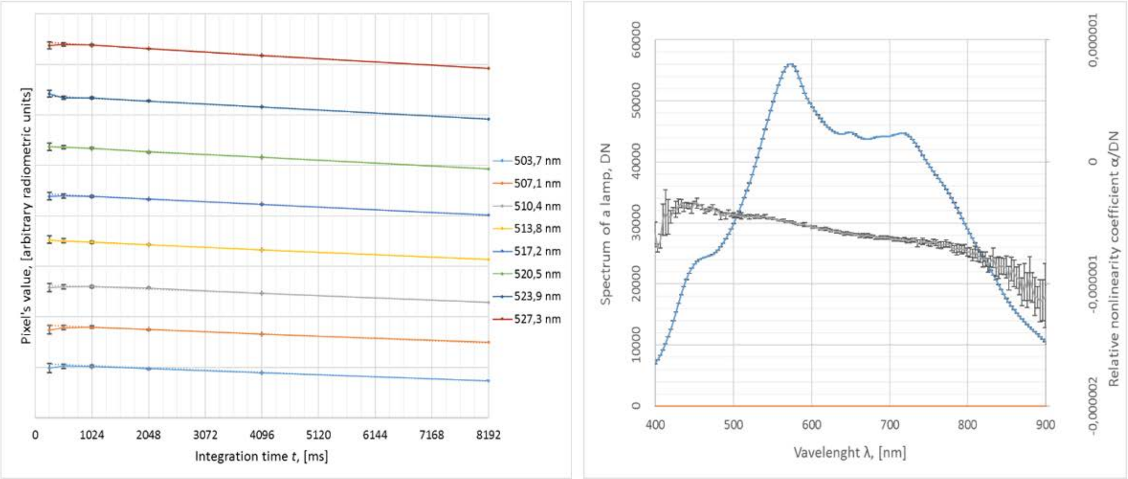

Figure 3. Pixel values normalised to arbitrary radiometric units as a function of integration time, left. Relative nonlinearity coefficient determined pixel by pixel with least square method from measurements with five integration times (black curve) and corrected spectrum (blue curve), right.

To derive this non-linearity correction incandescent lamps were used. They intensity values determine the range where correction of the nonlinearity effect is reasonable, for the spectrum shown in Figure 3 (blue curve) the correctable range is 450 nm to 800 nm, outside that rage the nonlinearity coefficient (black curve) has significantly higher errors, expressed as errors bars on the black curve. With higher intensity sources the useful range, likely, would be wider. To correct for possible difference in the radiance flux level at different participating laboratories a correction formula will be provided by the pilot. In the proposal stage the pilot suggested:

"As an example, a normalised signal amplitude in arbitrary radiometric units for five pixels as a function of integration time for TriOS RAMSES is shown in Figure 3. For all pixels, nearly linear dependence is evident with the smallest nonlinearity error at the zero-integration time. Thus, correcting the nonlinearity to zero bias of nonlinearity at zero-signal is well-defined and natural choice. Uncertainty and reproducibility of calibration results will be substantially improved. Otherwise, if some other reference signal level is aimed, due to different radiation sources used by different laboratories, some residual difference due to nonlinearity will stay present even after correcting."

2. Temperature in the laboratory during the measurements must be below 25°C (R)

UT has calculated the signal-to-noise ratios of radiometers during the measurements made for determination of thermal stability of sensors. For both types of sensors, the signal-to-noise-ratio has dropped below 1000:1 for temperatures just a little over 25 °C. Figure 4 presents the results for Ramses radiometers, where the 1000:1 signal-to-noise threshold is marked with a solid red line, and the measured signal-to-noise values for few integration times presented as data series. The temperature 45 °C was too noisy to be realized. To correct for systematic effects to 0.1% level, the 1000:1 requirement is vital. Thus, quite likely, correction of systematic effects for outside temperatures over 25 °C will not be possible if a suitably small uncertainty is aimed for. All measurements done at temperatures above 25 °C ambient temperature and with integration time longer than 512 ms will be subject to increased uncertainty due to rapid decrease of signal-to-noise ratio. This is possible to avoid this situation during the laboratory comparisons by following this guideline.

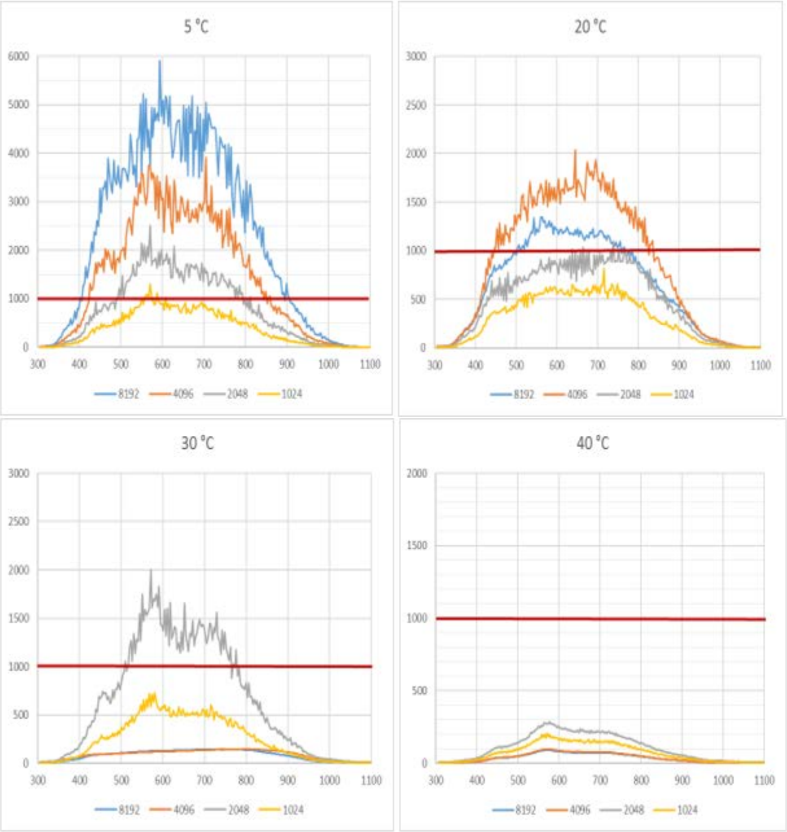

Figure 4. The set signal-to-noise-ratios of a Ramses radiometer measured at 5 °C, 20 °C, and 30 °C and 40 °C with integration times from 1024 ms to 8192 ms.

8 Summary

This document describes the strategy plan for the secondary laboratory cal/char comparison exercise and harmonization of laboratory guidelines, and it forms deliverable D-11 of the FRM4SOC phase-2 project.

We first presented past activities related to laboratory comparison exercises in support to various Ocean Colour missions. This mainly included absolute radiometric calibration of multispectral radiometers and a few exercises focused on other characterisation like polarisation sensitivity, immersion factor, and cosine response. Most of the past exercises finished in early 2000 with exception of FRM4SOC phase 1 that was conducted in 2017-2018. As the absolute calibration protocols were established, we could see the move in the comparison organisation toward round robin measurements at each participant's laboratory. This approach provides the full information about each laboratory's measurement capabilities, as distinct from a standards comparison only, including the setup, accuracy of the power supplies, baffling scheme, and the staff skills. Therefore, we highly recommend continuing this approach and perform future comparisons in-house at participants' laboratories.

Historically, radiance measurements always caused more issues than irradiance comparisons, as they are more complex and have more uncertainty contributors. At the same time radiance calibrations are less standardised leaving the room for variation in the measurements set-up thus variation in the measurements' errors. Therefore, we defined a standard FRM4SOC radiance calibration protocol that for a typical set up of three instruments used to derive remote sensing reflectance minimalize in situ uncertainty and should be followed. We aim to accommodate the set ups of all the participants in the comparison, but we will require the participants to apply corrections for conditions that deviated from the conditions during the standard FRM4SOC radiance calibration.

In the past especially during SIRREX 1-3 a radiometric scale was transferred from a one "primary" standard lamp of other working standards. With an aim to reduce the uncertainty in measurements for future absolute calibration we recommend using the standards calibrated at NMIs or secondary laboratories that do routine calibration such as Optronics. Every scale transfer increases the calibration uncertainties, therefore with the aim to reduce uncertainty we would recommend buying a new calibrated lamp - or re-calibrated lamp every 50 h burn time - in designated laboratories, rather than do it in-house.

We envisage some new challenges that will arise from the nature of hyperspectral instruments thus we set additional guidelines to ensure that the laboratory temperature is kept below 25 °C and the pilot will provide the correction formula for the detector non-linearity.

The comparisons in the frame of FRM will be publicly announced and open to any laboratory that holds SI traceable radiometric calibration standards. The provisional list of laboratories that already expressed interest in FRM4SOC-2 comparisons contains 8 international institutes. The transfer radiometers will be sent in turn to each participant for in house measurements. The exact timing and measurement protocol will be prepared by the pilot. The measurand on the comparison is the radiometric responsivity calibration factor for transfer radiometers (irradiance and radiance). The participants will be requested to provide uncertainty evaluation for their measurements. The pilot and NPL will be available during the whole time to support and train participants when necessary. 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.

Finally, we want to stress that there is no such thing as a bad result, any outliers that might occur should be treated as opportunities to investigate further, learn, and improve individual systems. We will aim to address any unexpected results via additional or repeated tests, but this might take longer than this project's timeline. The comparison should be organised regularly every couple of years firstly to achieve the measurements agreement, then to ensure that the consistency between the organisations is held stable and, finally, to enable new participants to verify their measurements capability.

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Appendix A 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

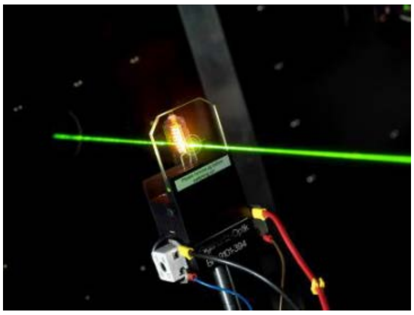
1. Position an alignment laser to define the optical axis of the spectral irradiance facility such that the laser points towards the facility entrance optics and the lamp will be placed between the laser and the facility

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).

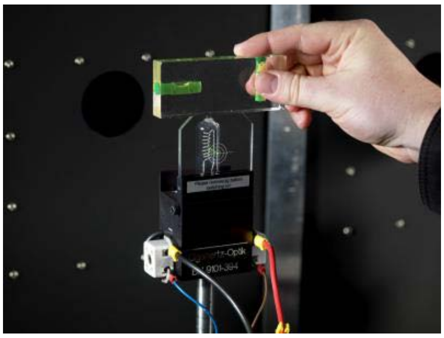
4. Connect the electrical terminals – observing the marked polarity (+ / -) to a DC power supply operating at 8.1 A and ~110 V. Do not switch on.

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)



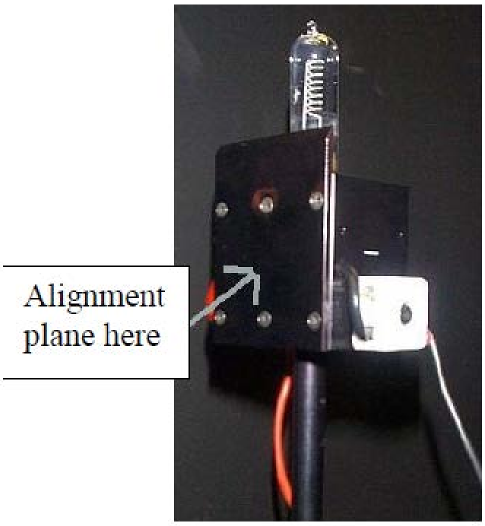
NB: Lamp on slightly in this photo to show filament –the lamp should not be on when the jig is still in place!

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