Establishing metrological traceability for radiometric calibration of earth observation sensor in Malaysia

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Abstract. The space borne earth observation (EO) sensor provides a continuous large spatial coverage over the earth at relatively low cost (cost-effective) and can be practically accessible worldwide. The daily synoptic view offered by instrument in earth orbit is tremendously useful in various applications, particularly long term global monitoring that needs multi-disciplinary, multi-temporal and multi-sensor data. Due to the indirect measurement nature of the EO sensor, calibration and validation (cal/val) are essentially required to establish the linkage between the acquired raw data and the actual target of interest. Ultimately, EO sensor provider must strive to deliver “the right information, at the right time, to the right people”. This paper is authored with the main aim to report the process of establishing metrological traceability for radiometric calibration of EO sensor at Optical Calibration Laboratory (OCL), National Space Agency of Malaysia (ANGKASA). The paper is structured into six sections. The first section introduces the context of EO and background of radiometric calibration. The next section discusses the requirements for metrological traceability in radiometric calibration while the following third section outlines ANGKASA efforts in setting up the metrological traceability laboratory in radiometric calibration. Meanwhile, the uncertainty estimation results is reported in the fourth section and the fifth section explains some of the continuous efforts made in order to improve the current metrological traceability set up. Lastly, the summary of this paper is provided in the last section.

1. Introduction
According to [1], earth observation (EO) in narrow sense is the science of measurement of all aspects of the earth system, including its physical, chemical and biological processes by space borne sensor. Historically, EO data has been widely used in technical investigation and research by remote sensing community. The constant demand from both scientific and commercial sectors has led to continuous increment of both satellite available in orbit and satellite performance. In recent times, the use of EO data in supporting policy and regulatory decision making has gain tremendous popularity across the different countries and organisations. The ever increasing growth of EO data is also spurred by the open data policy recently adopted by United States Geological Survey (USGS) for its Landsat archive data, China-Brazil Earth Resources Satellite (CBERS) and European Union for Copernicus program, which includes constellation of Sentinel satellites [2].

However, data acquired by satellite-based remote sensing is indirect by nature, and calibration and validation (cal/val) are required to allow the retrieval of actual bio geophysical parameters of interest. In particular, quantitative analysis of EO data must take calibrated data as input to avoid “garbage in,
garbage out” output. Cal/val is crucial to ensure harmonisation and interoperability of data generated from multi-source, multi-resolution and multi-temporal input at various scales. Calibration establishes confidence in EO data by providing quality indicator that allows user to readily assess “fit for purpose” of the data and the derived products. Quality indicator provides user with metrological traceability and measurement uncertainty information that represents a convenient way of seeing the big picture by just looking at a small piece of it. Evaluation of EO data suitability and adequacy is only possible with the provision of quality indicator [3].

In general, the goal of cal/val is to characterise sensor response in five major domains: radiometric, spatial, spectral, temporal and polarisation properties. Radiometric calibration characterises sensor response to known radiometric input, including radiance and/or irradiance, response linearity, detector-to-detector response uniformity, etc [4]. One particular importance of the radiometric calibration in present-day operational use of EO data is global climate monitoring. The ultimate objective of global climate change study is to distinguish human effects from natural effects that are affecting the climate change. To do that, a trusted long termed data is required by scientists to simulate sophisticated global climate model. These data are usually a combination of EO data from multiple sensors, multiple dates, multiple resolutions and different measurement techniques. Therefore, uncertainty knowledge of each input data must be obtained to quantify relative biases between different sensor outputs and temporal drift of data from the same instrument [2-6].

2. Metrological traceability for radiometric calibration

By ISO International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM) definition, metrological traceability is the 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 [7]. In addition, VIM lists down eight corresponding notes to further explain the definition. Based on the definition and the eight additional notes, the elements required for metrological traceability are summed up in Table 1. One may refers to the VIM document for detailed definition of the terminology used in Table 1, including measurement unit, measurement procedure, measurement standard and calibration hierarchy.

| Requirements                      | Remarks                                                                                           |
|-----------------------------------|---------------------------------------------------------------------------------------------------|
| Reference                         | A measurement unit (e.g. radiance, Wm⁻²sr⁻¹) through its practical realisation. or               |
|                                   | A measurement procedure including the measurement unit for a non-ordinal quantity. or               |
|                                   | A measurement standard                                                                         |
| Calibration hierarchy             | Required                                                                                         |
| Reference information             | Include the time at which the reference was used in establishing calibration hierarchy             |
| More than one input quantity      | Each of the input quantity values should itself be metrological traceable and the calibration hierarchy involved may formed a branched structure or a network. |

3. Metrological traceability at Optical Calibration Laboratory

National metrology institutes (NMIs) are solely responsible for practical realization of International System of Unit (SI) quantity definition and disseminate them via primary standard. The calibration laboratory then uses the working standard, which has an unbroken record of traceability to primary standard issues by NMIs to calibrate user instrument. Unfortunately, the National Metrology Institute
of Malaysia does not maintain either spectral radiance or spectral irradiance standard. The Optical Calibration Laboratory (OCL) has to source from commercial vendor for 1kw FEL-type incandescent lamp that is traceable to US National Institute of Standard and Technology (NIST) primary standard as working spectral irradiance standard. It is a pre-treated lamp and has a vertical, double-coiled, helical filament with the filament supported only at the top and bottom [8]. The NIST has utilised electrical substitution radiometry (a.k.a detector based radiometry) in assigning the spectral irradiance scale to the primary standard lamp [9].

The incandescent lamp alone is not suitable for most instrument calibration, especially the large-aperture instrument. Instead, this spectral irradiance standard lamp is applied together with a good Lambertian diffuse reflectance target. A known radiance can be computed from the reflected light off the target if the Bidirectional Reflectance Distribution Function (BRDF) of the diffuser is known. The user instrument can then be positioned to measure the known radiance reflected from the target, or alternatively, an intermediate spectro radiometer is placed such that it can then transfer the standard to another light source [9-10]. For measurement in OCL, a 99% reflectance Spectralon® target with a known BRDF is obtained from commercial vendor and it is also traceable to NIST primary standard via vendor calibration transfer. Subsequently, both measurement standards used in OCL radiometric measurement are metrologically traceable with their own calibration hierarchy. The traceability chain of this lamp-plague method is depicted in Figure 1.

![Figure 1. Metrological traceability chain in OCL for lamp-plague method](image-url)
4. Uncertainty analysis

The uncertainty analysis is conducted in accordance with the Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement (GUM) [11]. The reflected radiance from the diffuser target is given by:

\[ L_s = \frac{E_{\text{lamp}} \beta_{\theta, \alpha}}{\pi} \]

where \( L_s \) is the source radiance \( (\text{W.m}^2 \text{sr}^{-1}) \), \( E_{\text{lamp}} \) is the lamp irradiance \( (\text{W.m}^2) \) and \( \beta_{\theta, \alpha} \) is the diffuser reflectance factor. Angle \( \theta \) and \( \alpha \) represents the light incidence angle and the instrument viewing angle, respectively.

Radiance and irradiance in Equation 1 are spectral quantities but the wavelength dependence is not specifically written in the equation. However, the equation is still valid for any specific wavelength. Reflectance factor is defined as the ratio of radiant power reflected by an elemental sample surface to that which would be reflected into the same reflected beam geometry with apex at the surface element by an ideal perfectly diffuse (Lambertian) surface irradiated in exactly the same way as the sample. One should further read on [12] to have comprehensive understanding on the subject of BRDF.

From Equation 1, one can immediately identify the uncertainties sources: (a) lamp irradiance; (b) diffuser reflectance factor; and (c) reproducibility. Reproducibility is measurement precision under reproducibility conditions of measurement, which includes different locations, operators, measuring systems and also replicate measurements on the same or similar objects [7]. It is almost impossible to provide an exhaustive list of all sources of uncertainty. Nonetheless, this study has considered as many as possible sources to obtain good assessment of uncertainties that are associated with the way the measurement is set up, the values indicated by the instruments and the residual uncertainties associated with the corrections applied. In addition to the three main sources mentioned earlier, these working lamp and diffuser target may be sensitive to environmental condition, e.g. temperature, humidity and pressure. Since the calibration activity is performed in laboratory environment where temperature and humidity are controlled, the environment effects are considered negligible and hence excluded in the uncertainty analysis. Effect of stray light is also considered negligible as the room is totally maintained in “black-out” condition during the calibration activity.

The main uncertainties associated with lamp irradiance are lamp-diffuser distance, lamp alignment, lamp current control, short and long term stability. Uncertainties due to lamp irradiance output are directly read off from calibration certificate at three specified wavelength: 350nm, 655nm and 900nm. The lamp irradiance is calibrated at fixed distance 50cm, and therefore lamp-diffuser target should be set up at the same distance or else there will be irradiance output variation according to the irradiance inverse square law. The uncertainties due to lamp-diffuser distance is estimated at 0.2%, based on the accuracy of laser distance meter, i.e. 1mm over 50cm distance. Lamp alignment uncertainty is caused by the difficulty in rotating and positioning the centre of the lamp (the filament) normal to the diffuser target. To estimate lamp alignment sensitivity, measurement experiment is set up to compare standard deviation of 20 measurements with lamp re-aligned between the measurements and with lamp is not aligned between the measurements. The working irradiance lamp is operated at constant current 8.2A since lamp current fluctuation will lead to different lamp output. Similar to lamp alignment sensitivity estimation, lamp current sensitivity is determined experimentally by varying the current at (8.2 ± 0.1)A. Long term stability for lamp is not considered in this paper as the lamp used in the study is below 10 hours of operation.

Uniformity of diffuser and reflectance factor geometry are the two primary sources of uncertainties in diffuser reflectance factor. Uncertainties due to diffuser reflectance factor are directly read off from calibration certificate. The uncertainties due to diffuser uniformity arise because of the non-uniformity of diffuser surface within the instrument field-of-view and the geometry is the BRDF ambiguity as the result of uncertainty in setting up incident flux angle and instrument viewing angle. Both uncertainties are assumed to be at 0.5% and 1.45%, respectively, based on findings from literatures [13] and [14] as OCL does not have the measuring instrument to experimentally estimate the diffuser uniformity and BRDF. A list of uncertainty sources, their estimated values and their contribution to the total combined
uncertainty are tabulated in Table 2. The uncertainty budget are estimated at three wavelengths (i.e. 350, 655 and 900 nm) with 0° incident flux angle and 45° instrument viewing angle. Most of the uncertainties discussed in the paper are wavelength- and angle-dependent. Therefore, re-assessment is needed to analyse uncertainty budget for other wavelength and angle.

Table 2. Uncertainty budget for radiometric calibration at OCL

| Standard Uncertainty (%) | Sensitivity Coefficient | Wavelength (nm) |
|--------------------------|-------------------------|-----------------|
| Lamp irradiance          | 1                       | 2.1             |
|                          |                         | 1.7             |
|                          |                         | 1.7             |
| Lamp-diffuser distance   | 2                       | 0.4             |
|                          |                         | 0.4             |
|                          |                         | 0.4             |
| Alignment of lamp        | 1                       | 0.1             |
|                          |                         | 0.1             |
|                          |                         | 0.1             |
| Lamp current stability   | 1                       | 0.3             |
|                          |                         | 0.3             |
|                          |                         | 0.3             |
| Lamp short term stability| 1                       | 0.1             |
|                          |                         | 0.1             |
|                          |                         | 0.1             |
| Diffuser reflectance factor | 1                     | 0.25           |
|                          |                         | 0.3             |
|                          |                         | 0.3             |
| Reflectance factor geometry | 1                   | 1.45           |
|                          |                         | 1.45           |
|                          |                         | 1.45           |
| Uniformity of diffuser   | 1                       | 0.5             |
|                          |                         | 0.5             |
|                          |                         | 0.5             |

Expanded Uncertainty (%), k=2

| Irradiance | 4.33 | 3.56 | 3.56 |
| Radiance   | 5.33 | 4.73 | 4.73 |

5. Continuous improvement
As discussed in [8], despite its popular choice as main means of spectral irradiance scale dissemination, this 1kW FEL-type incandescent lamp suffers much higher degradation rate than previously reported. The coil in the lamp will collapse in between 140 to 250 hours burn time, or after 100 cycles of turning on and off cycle. Although the commercial vendor generally recommends hundreds of hours for lamp operation, internal quality assurance program will be created to assess regularly the calibration status of the working lamp. Among others, this includes setting up three calibrated working lamp standards for inter-comparison between these lamps. Meanwhile, periodical checking of diffuser target ageing rate is also required to assess the long term stability of the target reflectance factor.

The overall combined uncertainty for spectral irradiance and radiance measurement is in the order of 2% or more. Such uncertainty may not fit for some EO sensor metrological requirements, especially those involve in mission for climate change study. There are two stumbling blocks in reducing the measurement uncertainty: the lamp irradiance and the reflectance factor geometry. One way to reduce the uncertainty associated with lamp irradiance is to source primary standard lamp directly from NIST instead of using commercial vendor working lamp. Consequently, there will be additional cost and other non-monetary resources required to purchase, maintain and transfer this primary standard. On the other hand, the plan for facility upgrade in goniometry for the angular reflectance measurement of diffuse target is currently initiated in order to reduce uncertainty in reflectance factor geometry.

6. Conclusion
The establishment of metrological traceability for radiometric calibration at the OCL, National Space Centre is reported. A details uncertainty budget has been discussed for spectral irradiance and spectral radiance measurement at OCL. Currently, the combined uncertainty is estimated in the range of 3.6–5.3 %. There are some continuous efforts in place, both in planning and on-going phases, to reduce the overall uncertainty. The improvement efforts are a continuous process implemented in OCL in refining the operation and achieving better uncertainty goals.
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