FINAL PUBLISHABLE REPORT

Grant Agreement number	16ENV03
Project short name	MetEOC3
Project full title	Further metrology for Earth Observation and Climate

Project start date and duration:	01 September 2017 (42 Months)	
Coordinator: Dr Nigel Fox, NPL Project website address: http://www.meteoc.org/	Tel: 020 8943 6825	E-mail: nigel.fox@npl.co.uk
Internal Funded Partners: 1. NPL, United Kingdom 2. Aalto, Finland 3. PTB, Germany 4. VSL, Netherlands	External Funded Partners: 5. BUW, Germany 6. JRC, Europe 7. NLS, Finland 8. Rayference, Belgium 9. STFC, United Kingdom 10. TNO, Netherlands 11. UT, Estonia, 12. UoR, United Kingdom	Unfunded Partners: 13. FZ-Juelich, Germany 14. KIT, Germany 15. SFI Davos, Switzerland 16. UZH, Switzerland
RMG: -		

TABLE OF CONTENTS

1 Overview

The Earth's climate is changing although the scale of impact to society remains uncertain and with-it government's ability to confidently take necessary mitigation/adaptation in a timely manner. A key limitation is the performance of forecast models and the quality of the data that drive them. Remote sensing from space, is the major means of obtaining the global data needed. The harshness of launch and environment of space severely limits accuracy and traceability. This project has improved pre-and post-launch calibration/validation (Cal/Val) of observations (land, ocean and atmosphere) and enabled more trustable information on the state-of-the-planet to be delivered to policy makers.

2 Need

Two thirds of the Essential Climate Variables (ECV) of the Global Climate Observing System (GCOS) rely on optical measurements. More than half must be measured from space. Improving traceability and accuracy of these data is at the top-of-the-agenda of space agencies. In many cases a factor of 10 improvement in measurement accuracy is required to optimally minimise the time to detect trends from natural variability. Climate forecast is based on models using empirical ground and space-based data. Ground based is mainly local data whereas space observations deliver a global picture. The uncertainty of the empirical data determines the trustworthiness of the climate forecast. Reducing the uncertainty of this data is therefore considered mandatory. Achieving this reduction in uncertainty, places an urgency to address the following challenges:

- Maximal use of satellite observational capacity to globally detect small signals without driving cost. This requires improved (efficiency and accuracy) of pre-flight calibration and validation methods that are rigorously traceable to the SI.
- Improved confidence in multi-decadal time-series of observations and 'on demand' delivery of data requires post-launch interoperability between different sensors. Since the performance of most sensors change in-orbit this requires improved SI traceable post-launch calibration, validation and harmonisation methods including networks of 'ideally' autonomous test sites of a range of parameters.
- Policy makers and commercial users require trustable long time-base climate information i.e.-, metrologically based quality metrics assigned to bio-geophysical parameters.
- Some climate parameters cannot be measured from space. Global representation requires networks of sensors tied to common international standards. Historical artefact-based standards need to be replaced/enhanced through improved linkage to SI to ensure long-term reliability.

Improvement necessitates evolution of laboratory-based metrology transferred to field (and space) situations.

Although work had been successfully completed in two previous EMRP projects the challenge remains vast and global and the MetEOC series of projects continues to address the overriding traceability issue through undertaking new case studies as well as extending previous activities. Many space related projects can take a decade or more from conception to realisation, and this is similarly reflected in the timelines needed to prove and implement technological changes, where the innovation first needs to be proven in the laboratory before adaptation and migration to the field. For MetEOC, laboratory techniques have now been proven and are now in adaption mode. In many cases the development of post-launch validation test sites, often in remote locations, requires, seasonally variant measurements to allow full characterisation and representation and thus long duration programs.

3 Objectives

The overall aim of the project was to contribute to the establishment of the necessary metrology infrastructure, tailored to climate needs in readiness for its use in climate observing systems. This was done through the following scientific and technical objectives:

1. To improve the accuracy, accessibility, and usability of SI traceable standards in pre-flight and post-launch calibration and validation and enable interoperability and harmonisation of 'at sensor' remote sensed 'level 1' (e.g. radiance, reflectance, irradiance) products. This focused on transportability and the needs of small satellites (mass/size) through development of spectrally tuneable laser-based sources with an uncertainty of 0.5 – 2 % for pre-flight calibration. Post-launch mathematical methods to enable bias removal and sensor

to sensor interoperability including further prototyping to increase the readiness and early implementation of an SI traceable reference satellite such as TRUTHS/CLARREO was also undertaken.

2. To further enhance the capabilities of autonomous 'SI traceable' networks of test-sites for the post-launch calibration and validation of sensors and their derived bio-geophysical products. This included uncertainty analysis, accounting for the "non-representativeness" of sampling, scaling and propagation to the sensor at Top of Atmosphere. It primarily focused on the uncertainty needs of Copernicus Sentinels S2 and S3 and their applications e.g. Ocean colour (Uncertainty <3 %) and vegetation Essential Climate Variables (ECVs) e.g. Leaf Area Index (LA) (accuracy <20 %).
3. To establish a method for assigning aggregated quality metrics to a broad range of bio-geophysical ECVs, long term climate data records (CDRs) and the monitoring of mitigation strategies, through 'end to end' analysis. This involved identifying gaps and weaknesses in retrieval algorithms, validation processes and use of historic data from extinct and not comprehensively characterised sensors such as the ATSR series.
4. To develop methods for enhancing the SI traceability of ground-based networks used for climate monitoring e.g. Broad band Solar Radiation Network (BSRN) of WMO and Network for Detection of Mesopause Change (NDMC). Emphasis was given to address community-based scales (e.g. World Infrared Standard Group (WISG) and World Radiometric Reference (WRR).
5. To facilitate the take up of the technology and measurement infrastructure developed in this and previous projects by the standards developing organisations, measurement supply chain (accredited laboratories, instrument manufacturers) and end users (environmental monitoring and regulation bodies such as the WMO and Group of Earth Observations (GEO)).

4 Results

The results of this project, aligned to the above objectives, are summarised below with simplified titles to represent objective goals.

4.1 Objective 1: To improve the accuracy, SI traceability and useability of 'Level 1' remote sensed data through improved standards, methods and facilities applied to the pre- and post- deployment calibration and validation of sensors.

4.1.1 Introduction.

Although the ultimate challenge related to this objective is the operational 'in-flight' performance and SI-Traceability of a sensor and its delivered data, the process has to begin with pre-flight calibration and characterisation. In this project, we have explored and developed novel facilities for the pre-flight calibration of a number of satellite and airborne sensors, in some cases optimising the performance of relatively classical methods (such as blackbodies for thermal infrared radiometers) as well as exploiting state of the art tuneable lasers to undertake new approaches.

In addressing this objective we also considered that it was very common for correction coefficients derived from the pre-flight calibration to change on transference to orbit, in the case of space flight, and also change during operation due to environmental effects (space and airborne). Our project thus also undertook research on standards and methods that can be used and deployed during useage, both on the same observing platform and also remotely using vicarious methods like test-sites, primarily discussed in objective 2.

4.1.2 Thermal infrared – on-board

In the thermal infrared, PTB together with BUW and supported by FZJ and KIT continued work initiated in previous MetEOC projects (1& 2) to improve the in-flight performance and traceability of limb-sounding imaging spectrometers through on-board reference standards. Limb-sounders in this spectral region are critical to determining the molecular composition and state of the atmosphere but the spectrometer and its detectors are prone to signal drift due to background and temperature effects etc. Thus regular 'flat fielding' with a source of know spectral radiance/Temperature is an essential part of the measurement and retrieval process. In this project the airborne sensor GLORIA was supported by calibration of Large Aperture Radiance Sources (LARS), flown on-board the aircraft calibrated against SI references at the new upgraded Reduced Background Calibration Facility (RBCF 2) of PTB to an uncertainty of < 100 mK, see Fig.1.

Although the LARS have been designed to be as homogenous, in terms of temperature, as possible there remains some residual non-uniformity, see fig 2, which increases the uncertainty that can ultimately be achieved. To help address this, PTB developed a novel correction algorithm which can help to reduce the impact of non-homogeneity. Whilst this method was shown to be successful and likely to have positive impact in other applications, residual temporal responsivity drifts in the GLORIA detector means that this method cannot be applied to this sensor.

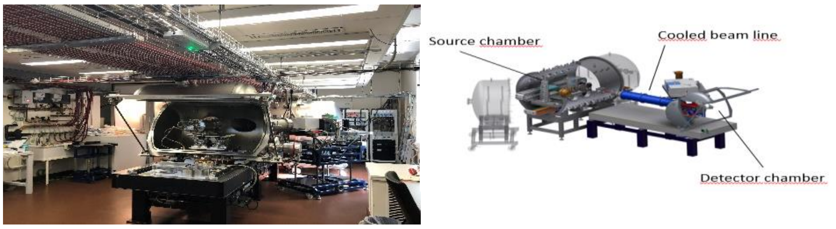


Figure 1: The new Reduced Background Calibration Facility -2)

However, a full end to end analysis of the uncertainty budget from the calibrated sensor through to retrieved level 2 atmospheric composition, resulting from this temperature non-uniformity was completed, see fig 3, and is the subject of a publication. This latter step was further extended and is described as an outcome under objective 3.

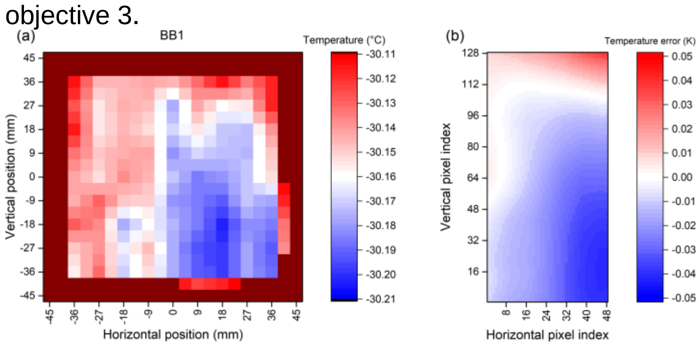


Figure 2: Temperature uniformity map of the LARS black body

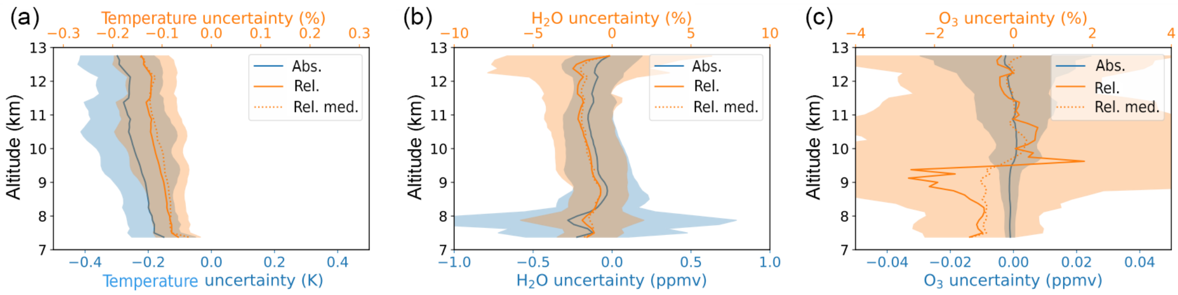


Figure 3: Resultant uncertainty of GLORIA observed parameters due to residual non-uniformity of temperature of the LARS blackbody.

4.1.3 Solar reflective – pre-flight

4.1.3.1 Introduction

Although, particularly in the solar reflective domain (UV,VIS,SWIR), the performance and calibration coefficients of sensors are likely to change following deployment in space or on an aircraft it is essential that as full as possible a characterisation is made in representative operational conditions before deployment. In this way the source of changes can be more easily identified, modelled and compliance to the original design specification confirmed. The challenges of climate change are increasing the demand for improved performance and quality in observations made and with this there is a commensurate demand for more accurate and comprehensive pre-flight characterisation. However, there remains the continued pressure to keep cost and associated time taken to undertake pre-flight calibration to a minimum. In addition to climate, there are requirements for interoperability and consistency between sensors of similar design to allow for harmonised data sets, to allow information on demand for applications such as agriculture, and creation of data time-series. The EU Copernicus program is a good example of a long-term commitment to an operational series of similar spacecraft with 'users' able to plan with confidence for a continuous supply of data. This type of program encourages the establishment of more comprehensive test facilities with the knowledge that they will have multiple useage.

In the solar reflective domain, there is significant information content in the spectral properties of the radiation, although until recently, many missions addressing land applications, have limited their observations to a few

spectral bands due to the increase in complexity of adding beyond three or four spectral bands. For these types of application radiometric (spectral radiance) calibration can be readily achieved using spectrally continuous sources such as incandescent lamp radiation diffusely reflected from Lambertian plate diffusers or illuminated integrating spheres. Although spectral shape of the bands remains important for some specific applications, for many, it is a second order effect where ratios of signals between bands is more relevant, than absolute values.
The richness of spectral information contained across the spectrum is now leading to a demand for more spectral detail and spectrometer like (hyperspectral) satellite missions for land applications. This demand is building from experiences of ground and airborne hyperspectral instruments.
There is a similar requirement to understand and quantify ocean biology. In this case performance is further complicated by the relatively small signal levels reaching the sensor due to reflectance of the ocean. This places a severe requirement on spectral radiometric accuracy, translating to an equivalent uncertainty of <0.5% at Top of the Atmosphere (ToA) to meet climate needs.
However, the most demanding requirement for spectral radiometric information stems from observations of the atmosphere, where spectroscopic resolutions of <<1 nm are required to identify and quantify molecular composition. A particular challenge is the new Green House Gas (GHG). sensors such as MicroCARB and EU CO2M missions planned to be launched in the next few years. For these, not only is there a requirement for high spectral resolution but also an emphasis placed on spatial resolution and consequently demands on signal levels.

4.1.3.2 Tuneable laser-based calibration facilities
In MetEOC 3 we have developed two new facilities to address the pre-flight calibration needs of all the above sensors. The two facilities both utilise radiation from spectrally tuneable lasers to enable spectral radiometric calibration of sensors, including those with narrow spectroscopic bands for atmospheric monitoring. In both facilities, tuneable laser radiation illuminates an integrating sphere to provide Lambertian radiation to overfill the entrance aperture of a sensor. By measuring the spectral radiance emitted by the laser illuminated source, wavelength by wavelength with a solid-state detector as the laser is spectrally tuned, the spectral response of the imager can be determined by integrating the results over the spectral bandwidths of interest. These can be at all spectral scales, << 1 nm or 10s nm. The advantages of using laser radiation is not only that it provides the means to determine a detailed spectral shape of the bandwidth of the sensor under test, but that it can do this at the same time as measuring the absolute radiometric value. It can also simultaneously assess spectral stray-light, saving measurement time and thus cost, overall.
In this type of measurement configuration, traceability to SI, is through the spectral responsivity of a solid-state detector such as Silicon. This route can be significantly more accurate than that of radiance from a lamp. The detector-based approach is typically at least one or two steps nearer the primary standard realisation from a cryogenic radiometer.
However, the two facilities differ in their details. VSL have built a facility based on an optical parametric oscillator (OPO) laser which is tuneable from 210 to 2600 nm delivering pulses of 3 to 6 ns length at ~1 kHz, this results in a spectral bandwidth of ~0.1 nm and the source has an emitting circular area of 50 mm diameter. In this project, the VSL facility was used with TNO. to provide a calibration of the breadboard of the Cubesat sensor, TROPOLITE, over the spectral region 370 to 480 nm, see Fig 5.

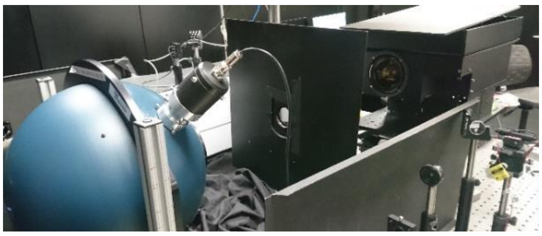


Figure 5: Calibration of TROPOLITE with the VSL laser source

The TROPOLITE mission is intended to be a forerunner of an atmospheric composition/air quality satellite constellation to be implemented in the near future, complementing Sentinel 4 and 5 and is thus a spectrometer-based sensor. The use of the facility was compared to a conventional measurement made using a lamp illuminated diffuser and the results shown to be consistent within their uncertainties, with the new laser based facility having an uncertainty of around 0.5 % k=1, half that of the lamp.
The NPL Spectroscopically Tuneable Absolute Radiance (STAR) facility, see fig 6, has been designed and built to be a comprehensive calibration and characterisation facility for satellite and other similar types of optical sensors, including those used terrestrially. Although able to perform the same task as the VSL facility, it differs in a number of ways. Firstly, it is based on a novel CW tuneable laser, capable of providing radiation with a spectral bandwidth of <0.1 pm and a tuning step of a few pm from 260 to 2600 nm. As a fully automated laser, dial up the wavelength and go, this is unique, although itself not developed for this project, its manufacturer, M-squared lasers, a Scottish SME, was an unfunded but integral member of the development and exploitation

team. The narrow spectral bandwidth and tuning step allows the facility to perform detailed spectral calibration of very narrow spectroscopic instruments.
In STAR, this laser radiation can be presented to a sensor from an integrating sphere with exit apertures ranging up to 200 mm diameter. However, the STAR facility also allows radiation to be delivered by a collimator. In this latter case to allow spatially patterned targets to be inserted into the beam to characterise image quality of the sensor and out of field stray light. Both of the delivery routes of STAR are also equipped with lamp illumination to allow broad band calibration to be performed as well as linearity and other tests benefitting from an instantaneous broader spectral coverage. Both paths also have a polariser to allow full spectral polarimetric characterisation to be performed. In summary, STAR provides a comprehensive spectral calibration system.

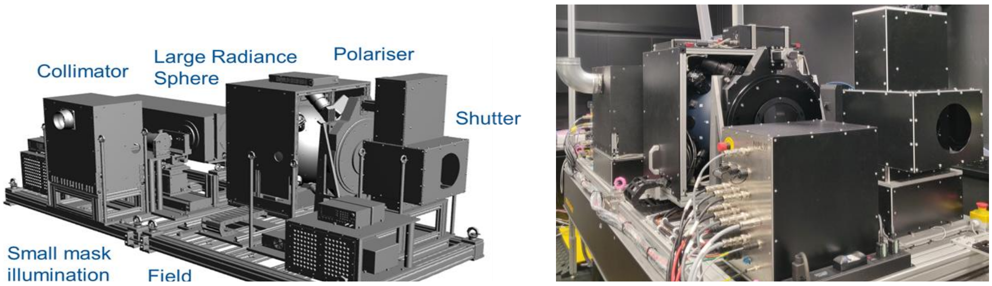


Figure 6: The NPL STAR facility, left schematic representation, right photograph of completed STAR facility under test

Designed to be transportable and operable in a clean room, absolute radiometric values of the radiance are measured by a detector system designed to operate inside the vacuum chamber, removing window transmittance from the uncertainty budget. Early in the MetEOC-3 project a first customer for STAR was secured and this became the focus for the first demonstration. This first STAR customer, Airbus Space and Defence, France is to enable the calibration and characterisation of the French/UK GHG mission MicroCARB. For this mission, the emphasis was on the more challenging NIR/SWIR part of the spectrum and the laser system was configured to operate from 700 to 2100 nm, and to provide an uncertainty of <0.5 %. The facility is currently (2020/21) in France delivering the calibration, with other customers already waiting to utilise it in the future.

4.1.3.3 Synthesised benefits of STAR

The STAR facility was originally planned to provide a calibration of the APEX airborne spectrometer as part of the project. However, due to COVID restrictions this was not possible, but instead a simulation of how it would help the performance was performed. This required a detailed analysis and subsequent software model of APEX to be built.
This software simulator has subsequently been used to assess the performance variation and uncertainty assessment for different scene and environmental conditions. The latter leading to further experimental laboratory based work using field spectrometers to assess effects of spectral slit shapes and bandwidth changes which might occur during flight – a direct benefit of detailed high resolution spectral calibration that can be obtained from a facility like STAR and also that of VSL, see fig 7.

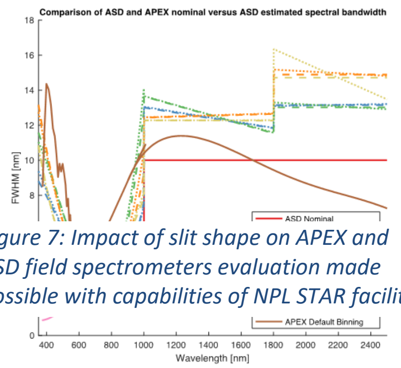


Figure 7: Impact of slit shape on APEX and ASD field spectrometers evaluation made possible with capabilities of NPL STAR facility.

4.1.4 Calibration of cubesat for Mesophere Temperature detection

The mesosphere is a part of the atmosphere which is very sensitive to climate change - skyglow emissions from temperature sensitive Oxygen A band transitions (Objective 4 addresses the same effect but from ground-based observations) are an indicator of warming. In space, a measurement of the radiance in a narrow spectral band around 762 nm with uncertainties < few % are required. In this project, BUW are using a spatial heterodyne spectrometer (essentially a Fourier transform spectrometer without moving parts) flown on a cubesat. In the early phase of this project, an opportunity arose for a prototype sensor (Atmoshine) to be flown on board a Chinese satellite. A facility was built to calibrate this sensor as a demonstrator. The mission was successful in demonstrating capability but as expected, only had a short lifetime, so little science was possible.

The main effort of this project was to learn the lessons of that prototype and with the support of PTB build an improved calibration facility and calibrate an optimised sensor tor flight on a dedicated cubesat called Atmocube A1. The major challenge to overcome was to build a calibration facility that could mimic the observation conditions of the sensor which was highly sensitive to homogeneity and wavefront flatness due to the nature of its design i.e. the calibration source needed to be spatially uniform and collimated. A design and system was built, see fig 8, but unfortunately due to covid this was not able to be fully characterised or used to calibrate the Atmocube sensor in the project lifetime.

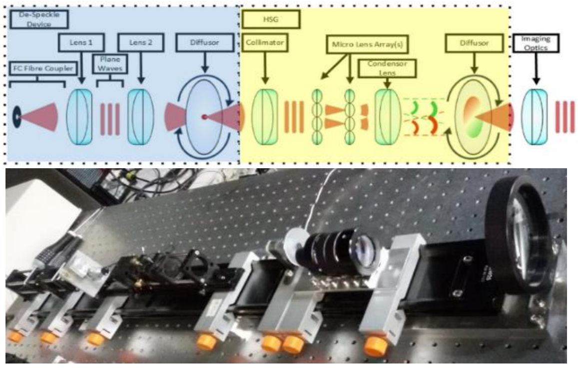


*Figure 8**Error! No text of specified style in document.**: Design of the calibration facility for the Atmocube sensor*

4.1.5: SI-Traceable satellite-based climate observing system

4.1.5.1 Introduction

The overarching goal of objective 1 is to progress towards establishing a framework to facilitate interoperability and climate quality uncertainty for the world's earth observing satellites. To achieve this ultimately requires satellites in orbit with sufficient means to establish or demonstrate adequate SI-traceability. The TRUTHS satellite mission is one designed explicitly to achieve this and, through cross-calibration to other satellites, upgrade their performance so that they too are traceable.

To realise this goal TRUTHS must be designed to calibrate the maximal number of sensors and effort made to build awareness in the global space community of the potential and benefits of such Si traceable satellites (SITSats).

4.1.5.2 Achievements

In conjunction with this project an international workshop was held at NPL (2019) under the auspices of CEOS and WMO-GSICS attended by >100 attendees. The workshop presented the scientific and socio-economic drivers for an SI-Traceable space-based climate observing system and the state of the art in remote sensing capabilities, in terms of meeting that need. In addition to being organiser and host, NPL also gave several presentations, derived in part from work in MetEOC. The workshop report (>200 pgs and 400 refs) will be published in 2021 and provides a number of recommendations on priorities and actions, many impacting the metrology community.

One of the conclusions of the workshop is the urgent demand for flights of SITSats such as TRUTHS. Fortunately, in November 2019, following proposals partly based on results from MetEOC, NPL succeeded in the TRUTHS mission being adopted into the ESA EarthWatch program with €32M funding to undertake phase A/B1 studies. This project has provided support through analysing the requirements on spectral bandwidth and wavelength accuracy needed to allow spectral matching with other sensors to a level that can facilitate uncertainty in calibration transfer of <0.3%.

4.1.6 Key outputs- objective 1

- New facilities to allow more time efficient and accurate (climate level) pre-flight calibration of optical sensors spectrally resolved in the UV-SWIR spectral region suitable for spectrometers.
- Upgraded facilities and methods to provide characterisation and calibration of black body targets used operationally together with a sensor to maintain traceability and performance.
- Novel calibration facility designed to meet demanding spatial homogeneity and wavefront requirements for a cubesat based interferometer.
- Progress towards the flight of a metrology focussed SI-Traceable satellite and the creation of space-based climate observing system

4.2 Objective 2: Enhance capabilities of 'test-sites' used for post-launch calibration and validation of satellite level 1 data and derived higher-level bio-geophysical parameters.

4.2.1 Introduction

Although every effort can be made to establish and assess performance of a satellite sensor through optimal design and on-board calibration systems, in practise there is always the need to utilise vicarious, generally natural targets as independent reference standards. Such references need to be well-calibrated by independent, ideally SI-traceable means and have characteristics that can be readily compared to those that would be observed by the sensor i.e. sufficient homogeneity at the scale of a pixel, to be representative. In general, the moon is an exception, measurements made on the ground must be corrected for atmospheric losses to allow comparison to the signals observed in space. Account must also be made for any differences in the view angle of the scene observed from space and that used for any ground characterisation, noting that the field of view of a satellite sensor can be large so that pixels in the centre may have a different view angle than those at the edges. If the test-site is not characterised simultaneously with that of the satellite view time, then differences for solar illumination angle must also be accounted for.

4.2.2 Level 1 radiometric gain: CEOS RadCalNet

Users of satellite data are primarily interested in information content derived from measurements of Level 1 physical quantities such as radiance, reflectance that has been transformed by an algorithm to a more interpretable bio-geophysical parameter such as amount of vegetation. Whilst this transformation process tends to dominate the resultant uncertainty it is essential as a starting to point to have reliability and consistency in the baseline level-1 measurements.

To help address this issue for medium to high resolution sensors, the Committee on Earth Observation Satellites (CEOS), the international coordination body of space agencies, has created a network of autonomous test-sites for the post-launch calibration of ToA reflectance. This network is now operational with more than 700 registered users of which half are active, not all using the data for satellite calibration. One of the unique features of this network is the emphasis on SI-Traceability and rigorous uncertainty evaluation. NPL has been involved in the development of this network supported in part by the Meteoc series of projects since its conception.

Figure 9: NPL staff measuring surface reflectance of Gobabeb test site.

In this project, NPL has undertaken field measurement campaigns at one of the sites, Gobabeb in Namibia, which NPL manage on behalf of ESA and CNES, using both surface-based spectrometers walked across the site, see fig 9, and a Drone mounted spectrometer. This activity combined with others led to the writing a protocol for site characterisation and the means to undertake site to site comparisons to ensure harmonisation of the network.

One of the conclusions of the measurement work was to determine the optimum spectral sampling resolution needed to ensure reliable representation for the bandwidths of typical satellite sensors like Sentinel 2. Fig 10, shows the result of this analysis and the improved consistency and uncertainty particularly for spectrally narrow bands (4,5 and 6) used for vegetation detection.

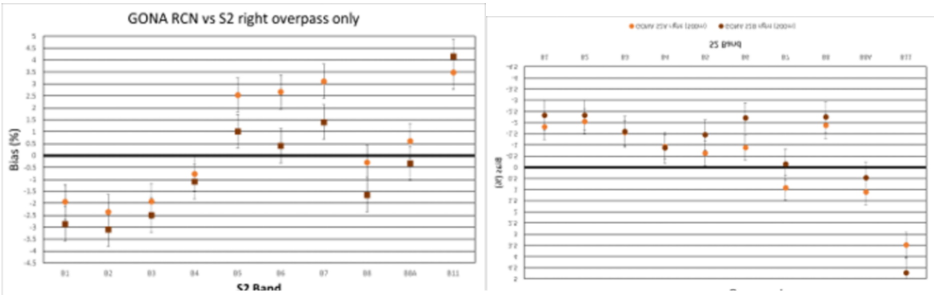


Figure 10: Comparison of RadCalNet and Satellite (sentinel 2) derived values when viewing Gobabeb, left before updated spectral resolution, right after correction.

As part of the field campaign representative spectral measurements of the site were made, geo-located and stored in an adaptation of the SPECCIO database by UZH as part of a community reference library. In addition, samples of sand were collected for laboratory analysis using a specially designed and built facility to characterise the angular reflectance of Sand.

4.2.3 Spectral and angular properties, Bidirectional Reflectance Distribution Factor (BRDF) of sand

One of the most significant sources of uncertainty in using surface sites for calibration of satellites is the ability to account for non-Lambertian reflection of the surface. Whilst for some sites it is possible to do some of this characterisation in the field, it is time-consuming and costly. In this project an effort was made to evaluate laboratory measurement capabilities for sand BRDF. AALTO like most NMIs usually measure BRDF of solid surfaces and as such, for convenience have facilities that lie in plane with the horizontal and the surface under test perpendicular to it. For sand this is clearly not viable.

Figure 11: Facility to measure BRDF of sand

For this project AALTO built a dedicated facility, see fig 11, to allow the sand to remain horizontal and BRDF measurements made perpendicular, mimicking reality of a desert and satellite observation.

Although the facility performs successfully, representativeness of collected sand measured in the laboratory and real in-situ measurements showed that there were significant differences in measured values possibly due to changes in composition uniformity (size of grains at the surface) and/or humidity. Further work to evaluate methods of maintaining representativeness of sand when transported to and measured in the laboratory will need to be undertaken for this to be a viable service. However, the built facility now has the capabilities to measure a broader range of materials such as powders that would have previously not been possible.

4.2.4 Propagating data from surface to satellite – A metrologically traceable radiative transfer (RT) code.

When using surface sites for calibration or validation of satellites and indeed to make full use of satellite observations for surface derived parameters, it is essential to make use of some form of radiative transfer (RT) code. This RT code not only needs to account for transmission through the atmosphere but also angular and structural effects of the scene being observed. There have and continue to be many different RT codes, each optimised for different applications. The degree of sophistication needed within each code tends to be a compromise to computer power and time to make the calculations. Efforts to evaluate potential differences between RT codes has been carried out on a number of occasions, through comparisons, but in all cases the result is a determination of variance as there is no defined 'reference' RT code or one which can claim to have rigorous metrology embedded within it and as part of its testing.

Through this project Ray, supported by NPL, has developed a user specification and outline software specification for an opensource European RT code to serve as a new reference code. This initial piloting phase raised significant attention within the international community such that ESA invested further resources to take this aspect of the project into development as an operational product. The ERADIATE project https://eradiate.eu and its development is now funded by ESA and this pilot activity can be considered a significant enabling success.

4.2.5 Ocean colour in-situ 'test sites'

4.2.5.1 introduction

The Oceans absorb a ¼ of emitted CO2 mostly through photosynthesis in phytoplankton, which is subsequently sequestrated through the food chain as a natural sink of carbon to combat the effect of CO2 on climate change. Measurement of the biological activity and scale of such phytoplankton is thus a key element for a net zero strategy. Although such microorganisms cannot be readily detected individually, existing as large clusters, they reflect sunlight spectrally differently to that of pure water and so a measure of this reflectance change, ocean colour, is readily correlated and can be detected from space.

However, the reflectance is small, approximately 10% of that back scattered from the atmosphere itself, so measurement is challenging. A measurement uncertainty of water leaving radiance of 5% (a target requirement of the Global Climate Observing System, GCOS) would correspond to a 0.5% requirement at ToA by the satellite.

Since satellites are not currently able to perform at this uncertainty level from their own inherent calibration systems, In-situ observations are used to compare and anchor satellite observations combined with its retrieval algorithm, largely the effect of atmosphere, in a process called system vicarious calibration (SVC). Making such measurements at well controlled sites allows the satellite to be 'tuned' to a ground truth value which can then be validated at other locations. In-situ observations and the sensors used to make them are thus particularly critical for satellite ocean colour observations.

4.2.5.2 Linearity testing

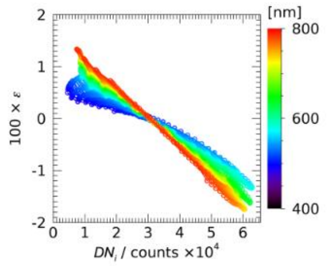
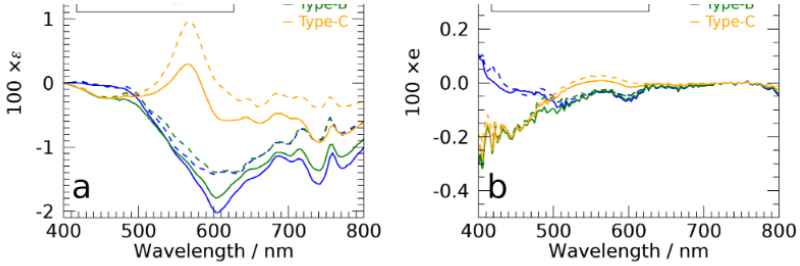


Figure 12: Measured non-linearity of typical in-situ hyperspectral ocean colour sensor, exhibiting an effect of 1.5%.

In this project JRC have evaluated the linearity of a range of commercially available radiometers both multi- and hyper-spectral. The non-linearities observed, which can be 1.5% over typical radiance level variations, See Fig 12., and their impacts on the measurements made in the ocean were also evaluated see fig 13.

Figure 13: impact of non-linearity on the derivation of water leaving radiance (a) before applying linearity correction and (b) after applying correction.



4.2.5.3 Protype 'next generation' radiometer

Considering some of the performance challenges that current commercial sensors have TO supported by NPL have designed, built and tested a prototype, hyperspectral sensor. The new prototype was not only intended to improve performance but also extend the spectral range into the UV (340 nm) and have higher spectral resolution, < 2 nm to meet the needs of the future satellite mission. PACE.

Full radiometric characterisation of the new radiometer was carried out with the results showing that it was a significant improvement on existing radiometers. As an example, fig 14 shows the non-linearity of the new prototype on the right and that of an existing radiometer, on the left.

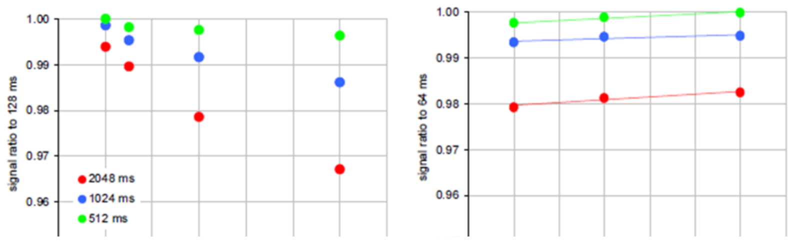


Figure 14: comparison of non-linearity of existing (left) and new design of radiometer (right).

4.2.6 Land product Validation test-site characterisation

4.2.6.1 introduction

Similar to ocean colour, 'land products' are derived from the spectral reflectance of the surface, in particular for many ECVs, vegetation. Since the other ¼ of CO2 not remaining in the atmosphere is absorbed in vegetation, again by photosynthesis, this is also an important natural carbon sink. However, in contrast to the oceans, whilst the observed signals for land products are higher, the scenes tend to be more complex and less homogenous with structures and species type making the spectral signal difficult to untangle and attribute, even within a single pixel.

Whilst in principle, each ECV product should be consistently defined to avoid ambiguities, this is unfortunately not as yet the case for many land products and thus a significant reason for relatively large variances between observations of nominally the same quantity and the same scene. In this project, we usef the virtual test site created for Wytham woods. using data collected in earlier Meteoc projects, to evaluate variances that occur due to differences in specifications and assumptions and how these might be reduced.

4.2.6.2 fAPAR – comparison between observed and 'true' values

fAPAR (fraction of absorbed photosynthetic active radiation) is a key ECV in the carbon cycle and has a GCOS measurement uncertainty requirement of <10%. Although seemingly large in metrological terms this value is highly challenging to achieve. In this project, we undertook studies to evaluate the effect of the location and characteristics of in-situ sensors placed in a woodland scene and their ability to accurately measure the fAPAR of a particular volume and also compared it to observations made by satellite.

The studies were performed within a monte-carlo ray tracing model where the scene was realistically created from Lidar point cloud measurements of the CEOS supersite, Wytham woods in Oxfordshire, UK. The true values were deemed, by definition, in this study to be those simulated by the model and thus to have no uncertainty.

Here we present the Sentinel 2 satellite results as an illustration, but similar conclusions can be drawn for the in-situ case. In Fig 15, we compare fAPAR calculated by the Sentinel 2 algorithm for the radiation that it would observe coming from the simulated scene with that of the nominal true value determined by the simulation. As can be seen there are large biases between the results, in all cases more than 35% rising to > 60%.

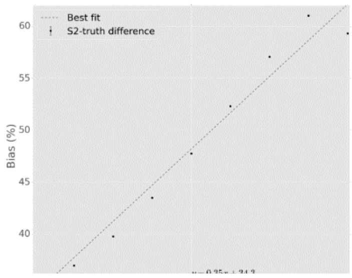


Figure 15: plot showing comparison of fAPAR calculated by Sentinel 2 algorithm compared with truth as defined by simulation.

However, if one creates a new model following the assumptions made in the sentinel 2 algorithm i.e. that it is a 1D canopy, there are only leaves and no woody material etc, then the consistency can improve dramatically (a factor of 10) as seen in fig 16,. What this demonstrates is the importance of definitions and in effect comparing apples with apples. Comparing or tying to combine products from different sensors using different assumptions in their retrieval algorithms will likely lead to large biases. Similarly, comparisons to real in-situ data needs careful assessment to ensure the assumptions made in each case regarding the nature and structure of the canopy do not result in significant biases.

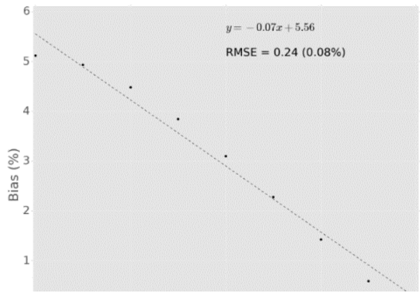


Figure16: Comparison of fAPAR from Sentinel 2 algorithm and that of the simulation using assumptions of the Sentinel 2 algorithm

Similar studies and results were performed for Leaf Area Index (LAI), although even following corrections in the model assumptions, differences remained and only a factor 2 gain was achieved with the residual bias remaining at a level twice the target GCOS requirement of <15%. There is clearly significant work to be done to understand the source of these discrepancies and indeed whether this is a general problem or a special case due to the complex nature of deciduous woodland.

4.2.6.3 Test-site characterisation optimisation

Work described in 4.2.6.2 and earlier Meteoc series projects have made use of a 3D software model reconstructing the Wytham woods CEOS supersite from Lidar data collected using, at the time, state of the art methods. In this project, we consider enhancements to that original strategy, some of which are evaluated experimentally.

The most direct approach to assess an ECV such as LAI, and subsequently, stored carbon, is to do direct destructive methods, harvesting of trees with traps to collect foliage etc. Alternative approaches with surface-based measuring instruments ranging to Terrestrial Lidar scanners are more routinely used (and the basis of the current Wytham woods model). However, these are costly and time-consuming to cover large areas.


Figure 17: Drone with lidar scanner

In this project we explore lidar on a small UAV/Drones, see fig 17, and compare results to that simulated by the Wytham software model derived from surface measurements made some 3 years earlier. Fig 18 presents the comparison of the two results, which, whilst in the main has good visual similarity, there are clearly anomalies. Further work is needed to evaluate these anomalies NLS extended the work using Drones to include forest sites in Finland and evaluated sampling strategies (flight paths) and calibration methods to optimise their useage.

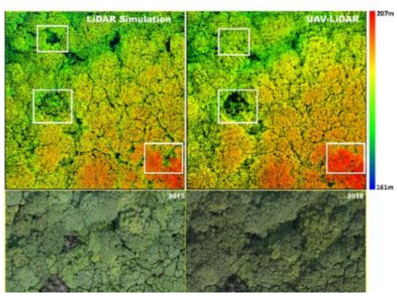


Figure 18: Reconstructed lidar images of Wytham woods derived from model based on data collected in 2015 (left) and that with drone lidar in 2018 (right).

4.2.7 Key Outputs – Objective 2

- A fully operational network of calibration test-sites that are SI-traceable with robust procedures for site characterisation including necessary spectral resolution enabled by field-site characterisation.
- A new facility to allow BRDF characterisation of sand and other powders

- Technical specification and prototyping of an SI-traceable community RT code to enable full external funding to become operational.
- Linearity characterisation and correction of current in-situ radiometers used for measuring ocean colour. Leading to the design and characterisation of a prototype next generation radiometer.
- Drone mounted LIDAR characterisation of woodland test-site and comparison of satellite derived measurements of vegetation-ECVs (fAPAR and LAI) of a CEOS test-site with those of software model built from ground truth observations. Results identify that observed significant differences are primarily due to differences in assumptions and definitions.

4.3 Objective 3: Develop methods to assign and make transparent, quality metrics to bio-geophysical ECVs, long time-base Climate Data Records (CDRs) through end to end assessment of traceability and uncertainty from observations (historic, current and future sensors) and through transformational algorithms.

4.3.1 Introduction

Signals of climate change are so small that they typically take many decades to build-up to values large enough that they can be reliably detected and attributed above the noise of natural variability. With the typical planned lifetime of a satellite sensor being 5-7 years this means that no single sensor will be able to observe long enough to detect a change, placing a strong requirement that any ‘starting point’ or benchmark dataset needs to be reliable and fully described so that any future observation looking for change can be certain that this is real and not differences in sensor performance or sampling strategies etc. Robust SI-traceability of not only the sensor but also the complete measurement process and any associated algorithms needs to be carried out and documented in a manner that cannot be ambiguous with all sources of potential error and uncertainty described.

At present this degree of rigour is not the norm. For sensors, often uncertainty budgets, where present, are incomplete, justifications and evidence of traceability not present or considered proprietary, have un-considered correlations and inconsistencies in how uncertainties combine. Uncertainty assessment of transformational algorithms is even less mature as are processes to harmonise data sets from one sensor to another to create temporally continuous long-time-series CDRs. The latter often needed to minimise potential anomalies due to natural variability of the earth system e.g. ENSO events, volcanoes etc.

This project sought to encourage metrological best-practise by developing methods tailored to the environmental/climate monitoring community. In particular, extending the application of a visualisation and documentation approach pioneered in an EU H2020 project called FIDUCEO by NPL and UoR which was originally targeted towards historic sensors. In this project we adapted and applied this approach and others, to a range of sensors and applications as case studies to illustrate the value and ease of use, to the stakeholder community. These efforts have been highly successful, with many new projects being established and funded by ESA and elsewhere in the world to implement these methods both for existing datasets and for new upcoming sensors. In many cases, NMIs are requested to support the activity and metrological analysis.

4.3.2 Sentinel 3 – metrological review.

4.3.2.1 Introduction: Sentinel 3 forms part of the Copernicus program, with currently two satellites (A & B) in operation and a further two planned as replacements over the next decade to maintain the series. In addition to an altimeter, each platform has two main sensors both operating in the optical domain, SLSTR primarily measuring water and land brightness temperature and OLCI measuring ocean and land ‘colour’ (biology). Both sensors are evolutions of previous ones and as such seek to continue a time series. Their measurands being ECVs means there is an increased emphasis on traceability and uncertainty. To help evaluate biases and harmonise data between the two sensors, ESA arranged for the B satellite to be launched into a special orbit during the commissioning phase of the mission that meant it would follow that of the A satellite with only a 30 second delay allowing direct, near simultaneous comparison of the same targets. Although this activity and analysis was carried out in an independent ESA project the results of this project were used to support this analysis and acknowledged in the subsequent publications.

In this project, NPL, UoR and STFC work with ESA and its sub-contractors to develop traceability models and uncertainty budgets for the sensors and products of Sentinel 3.

4.3.2.2 Analysis

For both sensors, the measurement equation for the sensor was created and expanded to identify and include all contributors to the process, for example, dark noise drift in the sensor and its sensitivity to temperature change. Fig 19 illustrates this for OLCI, and Fig 20 provides an example of an individual ‘effects table’ for one parameter, non-linearity and its associated values and impact on the overall measurement. Such effects tables were created for all parameters where possible and in many cases required significant detailed analysis to populate them from available calibration information.

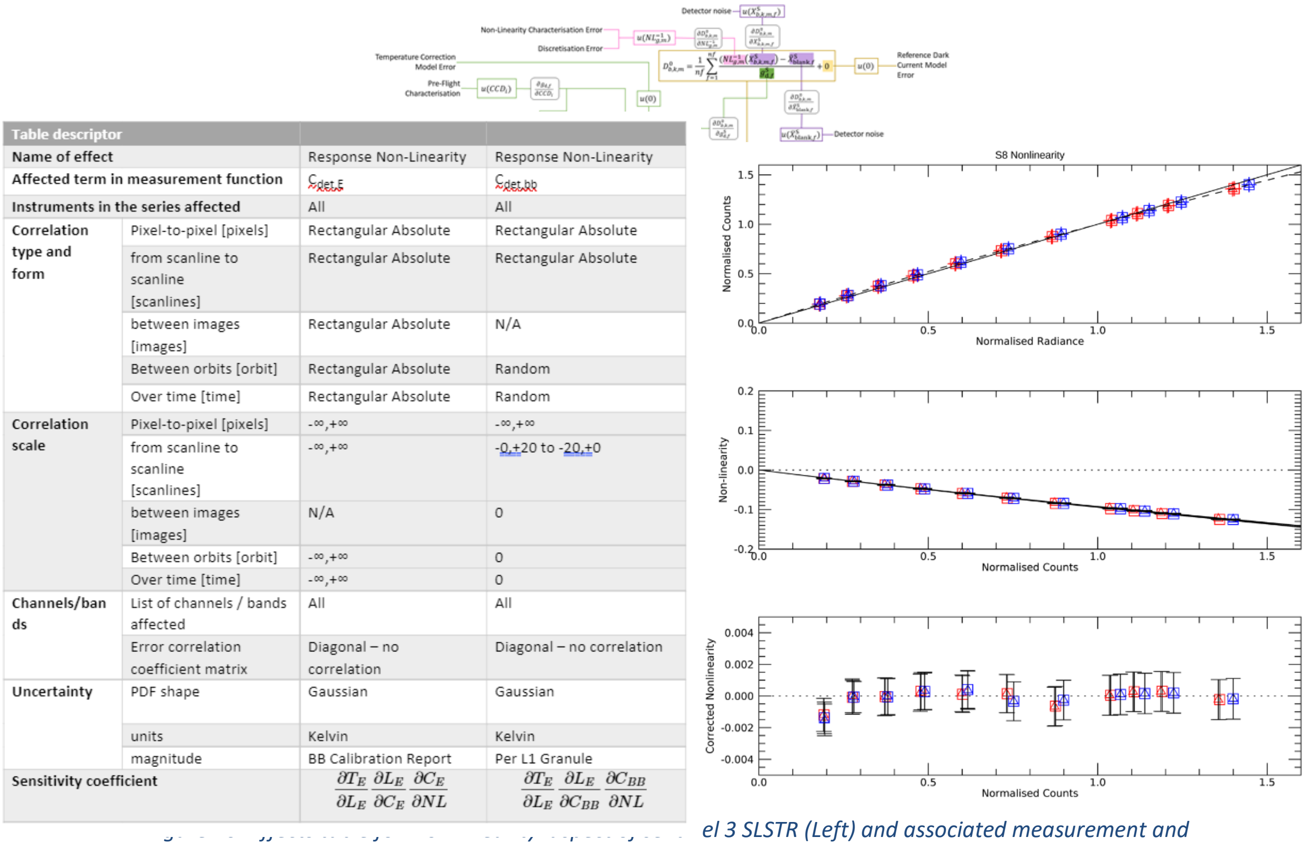


Table descriptor			
Name of effect		Response Non-Linearity	Response Non-Linearity
Affected term in measurement function		$C_{det,E}$	$C_{det,bb}$
Instruments in the series affected		All	All
Correlation type and form	Pixel-to-pixel [pixels]	Rectangular Absolute	Rectangular Absolute
	from scanline to scanline [scanlines]	Rectangular Absolute	Rectangular Absolute
	between images [images]	Rectangular Absolute	N/A
	Between orbits [orbit]	Rectangular Absolute	Random
	Over time [time]	Rectangular Absolute	Random
Correlation scale	Pixel-to-pixel [pixels]	-∞,+∞	-∞,+∞
	from scanline to scanline [scanlines]	-∞,+∞	-0,+20 to -20,+0
	between images [images]	N/A	0
	Between orbits [orbit]	-∞,+∞	0
	Over time [time]	-∞,+∞	0
Channels/bands	List of channels / bands affected	All	All
	Error correlation coefficient matrix	Diagonal – no correlation	Diagonal – no correlation
Uncertainty	PDF shape	Gaussian	Gaussian
	units	Kelvin	Kelvin
	magnitude	BB Calibration Report	Per L1 Granule
Sensitivity coefficient		$\frac{\partial T_E}{\partial L_E}\frac{\partial L_E}{\partial C_E}\frac{\partial C_E}{\partial NL}$	$\frac{\partial T_E}{\partial L_E}\frac{\partial L_E}{\partial C_{BB}}\frac{\partial C_{BB}}{\partial NL}$

...el 3 SLSTR (Left) and associated measurement and correction values (right): measurements (top), non-linearity (middle) corrected signal (bottom)

Table 1 provides a summary of the resultant uncertainty budget for Sentinel 3 SLSTR (A & B) following the metrological assessment.

Table 1: Summary table of uncertainties of brightness temperature of Sentinel 3 SLSTR.

Effect	SLSTR-A Uncertainty in BT (mK)			SLSTR-B Uncertainty in BT (mK)		
	S7	S8	S9	S7	S8	S9
NEDT*	**40.0**	**13.4**	**20.2**	**37.6**	**14.8**	**18.2**
BB1 Noise	0.4	0.2	0.2	0.7	0.3	0.2
BB2 Noise	6.7	1.9	1.9	11.3	2.5	1.5
BB1 Temperature Measurement	3.4	2.3	2.3	3.7	2.5	2.4
BB1 Temperature Gradients	1.7	1.2	1.2	6.2	4.2	4.1
BB1 Emissivity	2.0	1.0	1.1	2.1	1.1	1.2
BB1 Background	0.1	0.1	0.1	0.1	0.1	0.1
BB2 Temperature Measurement	14.1	15.6	15.6	13.8	15.4	15.4
BB2 Temperature Gradients	3.1	3.4	3.5	5.0	5.6	5.6
BB2 Emissivity	1.5	0.8	0.9	1.6	0.9	1.0
BB2 Background	1.1	0.6	0.7	1.0	0.6	0.7
Non-Linearity	>0.1	0.1	0.1	0.1	0.1	0.1
ISRF Band Centre	0.1	>0.1	>0.0	0.1	>0.1	>0.1
Combined standard Uncertainty (k = 1)	**16.8**	**16.4**	**16.4**	**20.3**	**17.4**	**17.3**
Combined expanded Uncertainty (k = 3)	**50.4**	**49.1**	**49.3**	**60.9**	**52.1**	**52.0**

4.3.3 Metrological uncertainty analysis of Level 1 to Level 2 transformation algorithm for Ocean colour climate data records SeaDAS.

4.3.3.1 Introduction

In 4.3.2 we describe how this project developed a traceability diagram and uncertainty evaluation for ToA measurements from the ocean colour sensor OLCI of Sentinel 3. In section 4.2.5 we showed the importance of surface measurements and atmospheric propagation/retrieval algorithm for anchoring the satellite performance and obtaining the necessary accuracy for the climate relevant product- in this case water leaving radiance.

To aid satellite to satellite consistency and avoid some of the issues illustrated in section 4.2.6 due to different definitions and assumptions in retrieval algorithms, NASA has created a tool and database called SeaDAS. The aim of SeaDAS is to serve as a common processor to take level 1 ToA signals from ocean colour monitoring sensors and then process them through a common atmospheric correction algorithm (populated

with parameters specific to the sensor and its observations e.g. atmospheric state at the time) to allow more harmonised CDRs to be created.
In this project NPL and JRC have used the same approach described in 4.3.2 to extend the uncertainty analysis to the Level 2 product, water leaving radiance and in particular a review of the SeaDAS algorithm.

4.3.3.2 Analysis
In a similar manner to 4.3.2 we establish the measurement equation and create a traceability diagram and effects tables, see fig 21.
In performing the detailed uncertainty analysis, we found that the contributions from ancillary data such as Relative Humidity, wind speed, pressure, Total column wate vapour etc can result in a not insignificant contribution to the overall uncertainty budget (a few percent). As the demand for improved uncertainty increases and sensor ToA performance improves these contributors need to be considered in more detail.

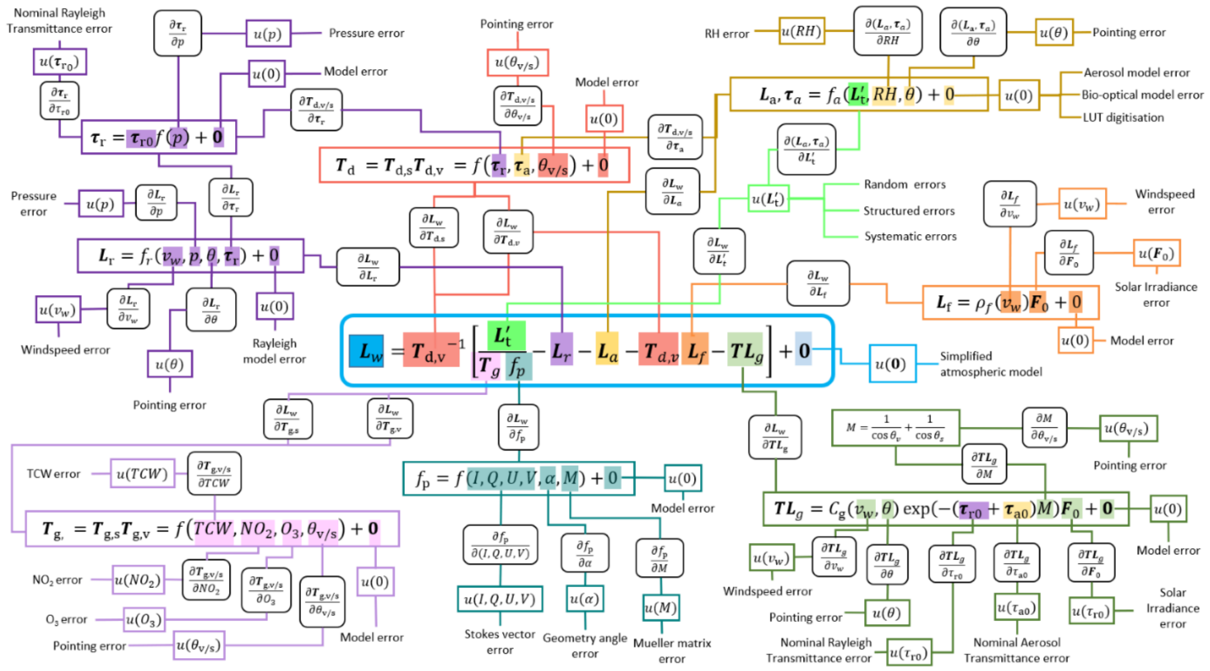


Figure 21: Traceability diagram for the SeaDAS algorithm transposing satellite Level 1 to water leaving radiances.

In our project NPL supported by JRC undertook sensitivity analysis using monte-carlo simulations to assess the impact and thus potential uncertainty contribution from a number of these parameters, namely: Relative Humidity, choice of Aerosol model, windspeed, water vapour, ozone, humidity. We varied each parameter individually and as a combination to assess effects of correlation etc. Fig 22 shows the results of the Standard deviation of the mean (SD) and thus relative sensitivity against wavelength for different ancillary data for two scenes (left Australia and right Atlantic).

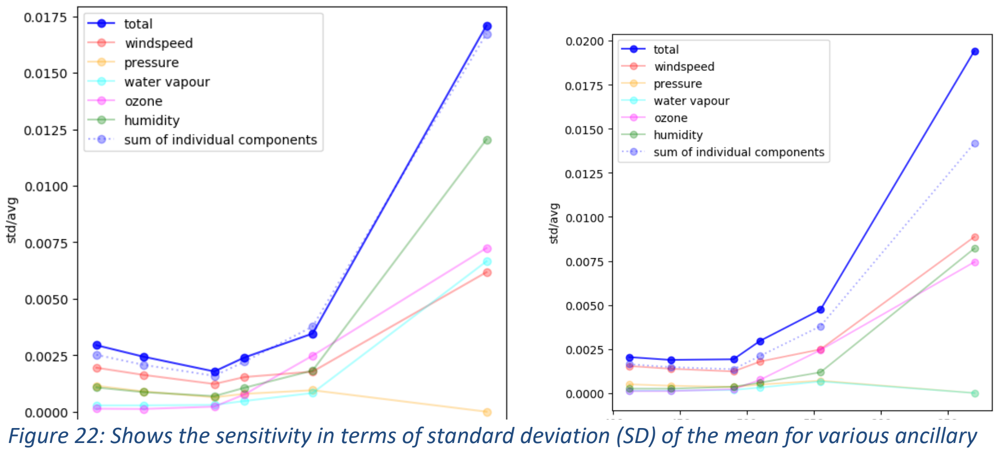


Figure 22: Shows the sensitivity in terms of standard deviation (SD) of the mean for various ancillary parameters on calculated water leaving radiance for an Australian scene (left) and Atlantic (right).

Fig 23 shows the effect of windspeed in the satellite derived values of sea reflectance at 443 nm as an example and fig 24 the difference between two different sources of data for water vapour on the same measurement of reflectance.

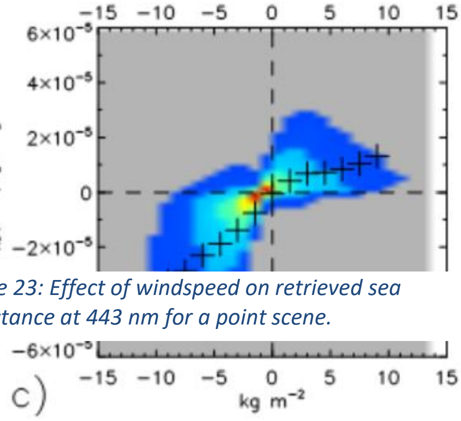


Figure 23: Effect of windspeed on retrieved sea reflectance at 443 nm for a point scene.

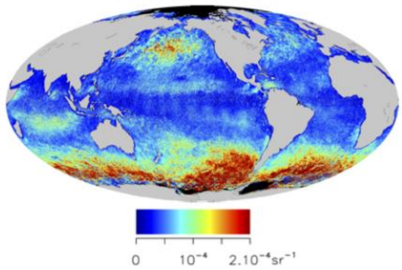


Figure 24: Impact of choice of two different sources water vapour data on global retrieved sea reflectance at 443 nm.

Uncertainty assessment of trace-gas retrievals

Following from the experimental work carried out 4.1.2 on the calibration of the GLORIA Limb sounder and the uncertainty contribution to retrievals due to temperature inhomogeneity, KIT also undertaken a fuller analysis of the impact on retrieval uncertainty for the trace-gas HNO3 due to the major contributors. This includes the effects of linearity, pixel responsivity changes, pointing error, spectroscopy, measurement noise, temperature, Fig 25. A similar analysis was performed for temperature retrievals. This was the first time such analysis has been performed.

4.3.4 in have all non- see an

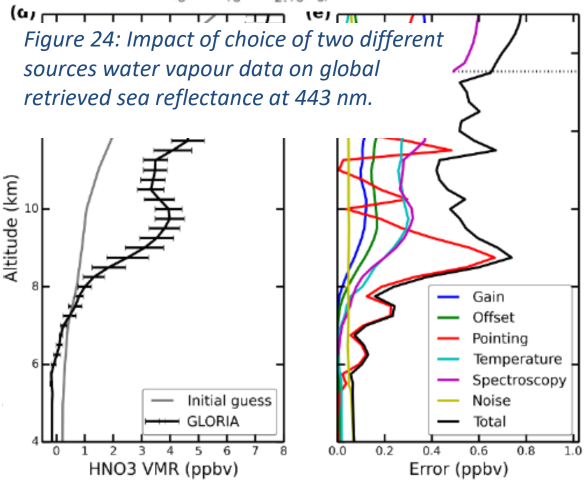


Figure 25: Uncertainties in retrievals of the HNO3 by GLORIA as a result of a full uncertainty analysis.

4.3.4 Uncertainty assessment of sensors under development.

In addition to the above review of operational sensors, STFC also undertook to do analysis of principle sources of uncertainty of some prototype sensors currently under development. Early metrological analysis during the design and prototyping phase allow instrument developers to focus on the most demanding aspects of the design at an early stage. An assessment following the same FIDUCEO methodology was carried out for a static Fourier transform spectrometer and a laser heterodyne spectrometer, both intended for spectroscopic monitoring of the atmosphere.

4.3.5 Tools to present uncertainty information at image level.

One of the challenges of Remote sensing and the creation of images as opposed to discrete point measurements is that when it comes to assessing and presenting uncertainty to a user it can become quite complex. This is because in general, the uncertainty for each individual pixel is a discrete value and not common across the scene. This can be because of physical differences in pixels of detectors e.g. noise or response variations but also because of imperfections in the optics and the variability in the scene, significant variation can occur on a pixel level due to the effect of what it is viewing within the scene itself. Until recently, most remote sensing imagery was presented to the user with a global uncertainty per scene or dataset, but as stakeholder interests start focussing on to the pixel scale there is a desire to provide pixel level uncertainties.

In this project, NPL and STFC have developed tools and methods to create uncertainty images to accompany the image for Sentinel 2 and Sentinel 3 respectively, see fig 26.

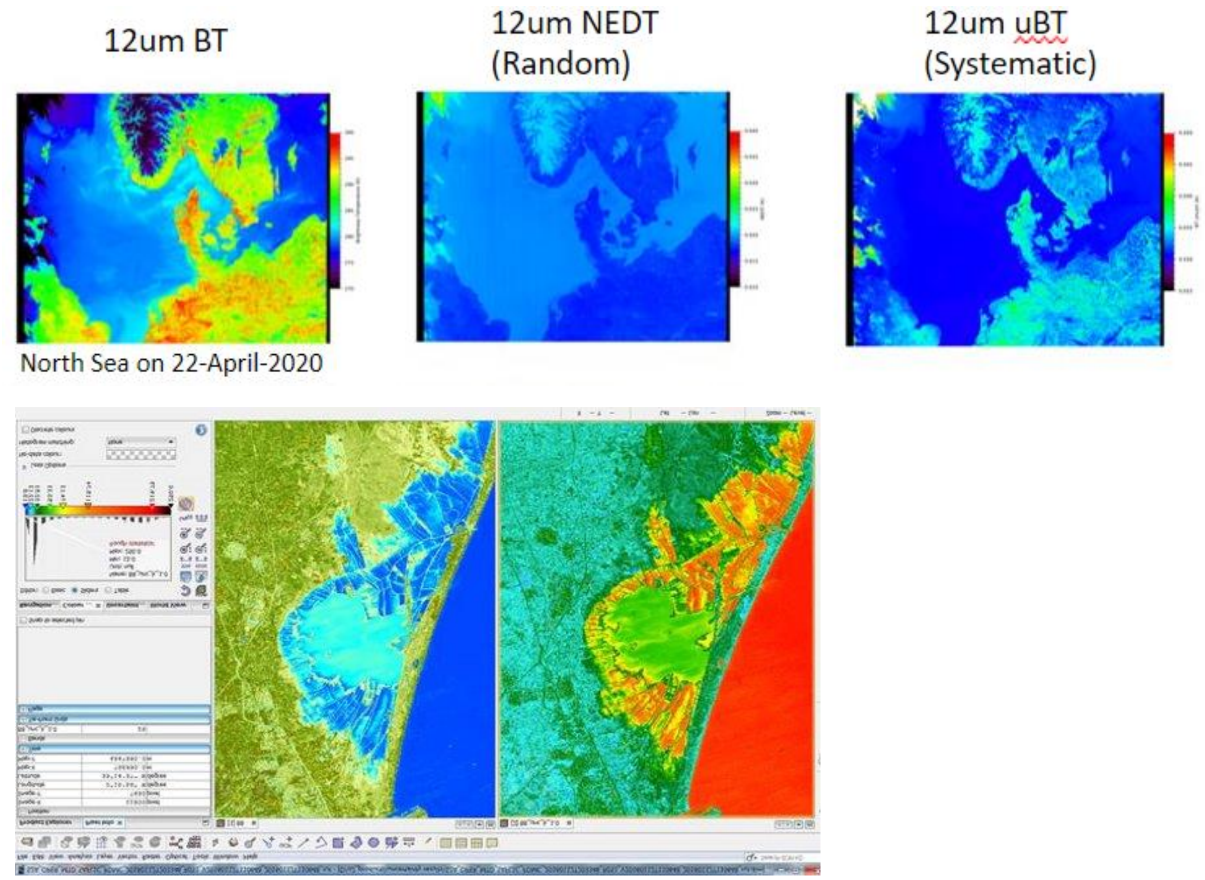


Figure 26: Graphical representations of uncertainty maps. (Top left) SLSTR brightness temperature, (Top middle and right) random and systematic uncertainties for brightness temperature. (Lower) Sentinel reflectance (Left) and Uncertainty map (right)

4.3.6 Key outputs – Objective 3

- A metrological review of the traceability of two sensors on the Sentinel 3 satellite has been carried out and the results presented visually in the form of a 'traceability tree' diagram. Analysis included development of uncertainty budgets and sensitivity analysis of a variety of parameters. The results of this has encouraged ESA to undertake similar analysis for other sensors.
- An uncertainty assessment has been performed during the design phase of two novel interferometer sensors enabling an optimisation before building.
- A metrological review of the retrieval algorithm for ocean colour was undertaken and a sensitivity analysis performed for a range of ancillary parameters. The analysis included an assessment of relative impact of different parameters on local and global observations.
- Uncertainty assessment form sensor to retrieval has been carried out for the GLORIA Limb sounding interferometer for the first time.
- Methods and tools to evaluate and present image maps of uncertainty at pixel level for satellite sensors

4.4 Objective 4: Methods for improving the traceability of surface networks using remote sensing techniques

4.4.1 Introduction

Most of the effort in this project is concerned with remote sensing techniques deployed in space or air for wide geographical coverage together with networks for localised measurements to support their calibration and validation. However, In this objective we focus on the needs of surface-based networks using remote sensing methods to make measurements from point locations around the globe. In these cases, primarily observing the atmosphere or radiation passing through it from the sun.

In principle, providing each sensor in the network is well-calibrated with a robust assessment of uncertainty then the network can input all data and provide uniform and consistent results. However, as in all measurement situations some form of comparison between network members and locations is considered best practise to ensure harmonised coherent data.

In some cases, network sensors can be calibrated or compared against each other, or a reference, by geographically co-locating. For example, for total solar irradiance measurements there are 5 yrly comparisons held in Davos where around 100 instruments gather and view the sun through the same atmospheric conditions, comparing to an internationally agreed world reference. For others, particularly where environmental effects may impact the measurement or sensor performance, it is more convenient for a reference to travel between network locations and carry out bilateral comparisons or calibrations on a node by node basis.

Although in principle, for many applications, including climate, it can be considered that the primary requirement for such networks is consistency between network nodes and long-term stability, as even for climate the main objective is to look for change, not necessarily an absolute level. For many networks this has led to strategies which whilst aiming in principle for SI traceability are more fundamentally concerned with ensuring stability. In this project we consider that achieving SI-traceability at sufficient uncertainty level can be more robust in meeting both the stability and consistency requirements and is now being requested by some of the main network owners such as WMO. In this project, we have been working to develop new SI-traceable primary standards/methods to underpin or replace current artifact based 'world references' with SI and also new transfer standards to facilitate transference of traceability from the laboratory to field locations.

4.4.2 Network for Detection of Mesospause change (NDMC)

4.4.2.1 The NDMC consists of a set of largely similar instruments distributed around the globe to measure the temperature of the mesosphere from 'sky glow', radiation at ~1550 nm emitted from ozone (O3) to OH transitions which are highly temperature sensitive. This project has continued work started earlier in the Meteoc series and looks to improve performance by introducing new sensors and transfer standards for their calibration and comparison.

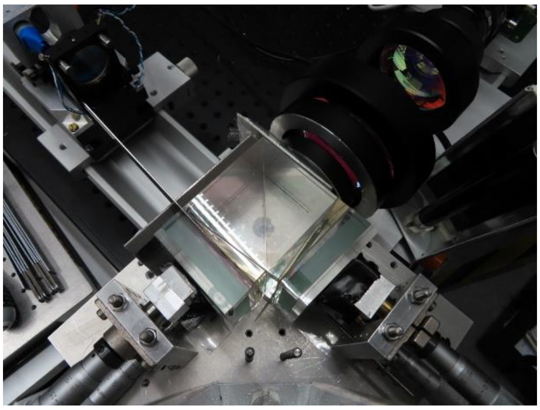


Figure 27: Photograph of SHI being assembled, centre of image.

BUW, supported by FZJ and in collaboration with the Max planck institute has designed, built and tested a new spectrometer based on a Spatial heterodyne interferometer (SHI) similar in principle to that described in section 4.1.4 for space flight but utilising a different spectral region. Fig 27 shows the crystal of the spectrometer being assembled in the centre of the photo. This new spectrometer is not only more sensitive radiometrically but also has higher spectral resolution and is more accurate and less influenced by environmental factors such as local temperature. Its performance is about an order of magnitude improvement over previous grating-based instruments.

VSL have built and characterised a tuneable laser illuminated integrating sphere and associated collimation optics, see fig 28, to provide a radiance calibration of the new spectrometer. The source spectral tuneability, spatial uniformity (including despeckling), < 0.1% and absolute radiance has been determined and shown to meet the requirements of <0.5%. Unfortunately, due to covid it has not been possible to use

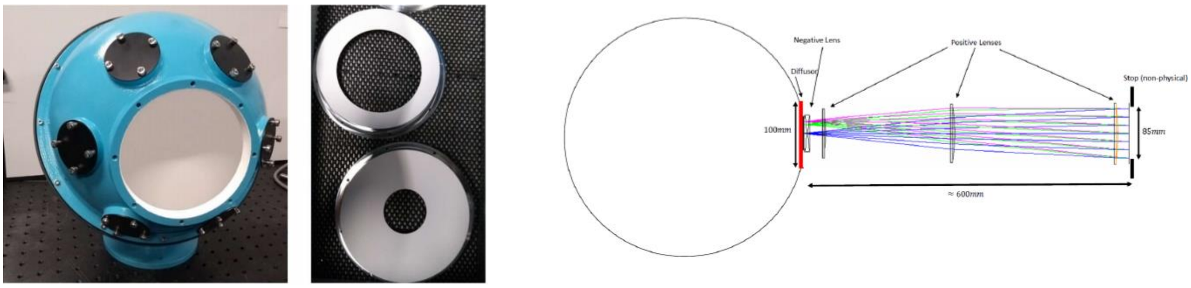


*Figure **Error! No text of specified style in document.**28: Integrating sphere (left) and schematic (right) of the calibration* the source to calibrate the new spectrometer.

4.4.3 WMO - World Infrared Standard Group (WISG)

Change in the Earths radiation Imbalance is ultimately the direct cause of global warming. Whilst in principle a measure of the global net incoming and net outgoing radiation at the top of atmosphere provides this information, the size of change is very small and it does not provide any detail on the source of change or associated attribution.

One critical component of the radiation budget is downwelling hemispherical radiation – infrared radiation incident on the Earth’s surface emitted from or reflected by the atmosphere, the natural green-house effect. As part of the WMO ‘radiation networks’, pyrgeometers (instruments designed to measure downwelling radiation) are distributed and traceably linked to a set of ‘reference pyrgeometers’ known as the WISG, maintained by SFI-Davos. In more recent times a new design, so called infrared integrating sphere (IRIS) radiometers are also being utilised.

Figure 29: IRIS (left) and Pyrgeometers (Right) used to measure downwelling radiation

The WMO and its technical working group on radiation has identified that there are some unexplained differences between these two types of radiometer when used under certain conditions and also that the route to traceability of the WISG would be better served by a more rigorous tie to SI units. This activity in this project was a direct response in support of the WMO with an aim to reduce the uncertainty of the reference scale from 5 to 2 Wm^{-2} (GCOS goal for radiation budget as a whole at ToA is 1 Wm^{-2}).

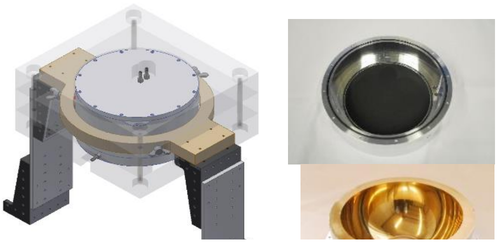


Figure 30: Design (left) and components (right) of the hemispherical blackbody to provide traceabiilty to the WISG (top) black bck plate (bottom) gold hemisphere.

As a first step PTB, supported by SFI-Davos and NPL characterised the spectral responsivity and temperature coefficients of the radiometers to determine an accurate and consistent performance model to address some of the discrepancies in the operation of the two instrument types. However, the most significant aspect of the project was the design, build and test by PTB, supported by SFI-Davos of a new reference black body to provide SI-traceable calibrations. As the radiometers measure integrated radiation from 4 to 50 um this was the optimal route to traceability.

The target uncertainty for the black body was to achieve <0.5 Wm^{-2}, equivalent to around 50 mK at ambient and operation between ± 30 °C. Although in isolation, not overly challenging, this performance needed to be achieved as a hemispherical radiation field surrounding the radiometers, placing severe demands on proximity of the sensor head to the radiometer surface and thus requiring very high emissivity of the blackbody and thermal isolation. To address this, a relatively novel blackbody was created, see fig 30 where a black base is surrounded by a hemispherical gold reflector resulting in a high emissivity radiator but where temperature variations in the walls (gold hemisphere) have a reduced impact.

The new blackbody has an effective emissivity of ~ 0.9965 with a 40 mm diameter aperture increasing to 0.999 at 20 mm diameter at ambient temperature. This corresponds to an uncertainty of ~0.2 Wm^{-2}, consistent with the design goal.

The blackbody has been used to perform some initial calibrations of pyrgeometers demonstrating success in the build of a new SI-traceable reference source. Further work is ongoing to establish full traceability and uncertainty of the WISG.

4.4.4 WMO – World Radiometric Reference (WRR)
4.4.4.1 background

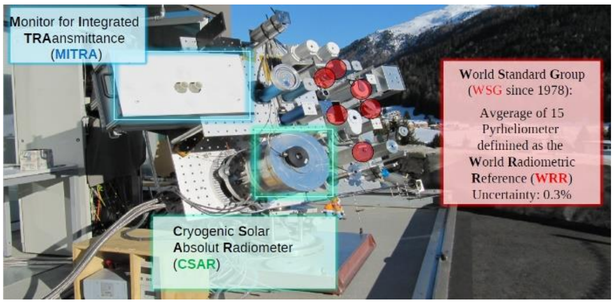


Figure 31: Photograph of CSAR, MITRA and the WSG on the solar platform at Davos.

In terms of Earths radiation budget but also as a reference for the efficacy of solar photovoltaic panels, knowledge of total solar irradiance incident on the Earth's surface is a key metric. Since 1978 the SFI-Davos have maintained and disseminated the world radiometric reference for this measurement, WRR, through the mean of a group of 15 self-calibrating radiometers known as the world standard group (WSG). This WSG provides a reference against which solar instruments from across the world compare every 5 years in Davos. In establishing formal collaborations with the international metrology community in 2010, a major driver was to establish SI-traceability to the WRR. As part of the MetEOC series of projects NPL and SFI-Davos have been working to replace the dependence on the WSG through the demonstration, improvement and operationalisation of a cryogenic solar absolute radiometer (CSAR) based on similar instruments used as the primary radiometric reference of choice at NMIs. The CSAR has taken place in two of these comparisons and needs to demonstrate consistency of performance in a third, now scheduled for 2021, for the WMO to consider it a suitable replacement or enhancement of the WRR. A version of the CSAR also forms the core reference instrument in the satellite mission TRUTHS in section 4.1.5.

4.4.4.2 Operationalisation of CSAR
A key factor for CSAR to be adopted by WMO is confidence in the longevity and reliability of the instrument and its operation. In particular, removal of dependence on equipment that might not be readily available or repairable in the future. In this project, the operational electronics and associated software of CSAR has been updated to allow faster response times and more autonomous operation, minimising noise effects due to small changes in solar output and environmental conditions in performing equivalence matching between electrical and optical heating. This process also removed dependence on some specific commercial but no longer technically supported instruments. The updates allow use of electronics based on a design initially developed by SFI-Davos for space instruments, which are also more reliable than some of the instrumentation previously being used. This upgrade also provides a testbed for the future space implementation of CSAR.

4.4.4.3 Window transmittance
Although the CSAR itself performs in a similar manner to other cryogenic radiometers and as such provides low uncertainty and traceability to SI. When viewing the sun, it has additional challenges, primarily related to the need to maintain a vacuum and consequently determine transmission loss through a window. Monochromatically, as used in NMIs, this is a relatively straightforward measurement, but it becomes less so for the wide spectral range needed for the Sun and when the instrument is used in a non-laboratory environment.
To address this issue, SFI-Davos, supported by NPL, have designed an instrument called MITRA (Monitor for Integrated TRAnsmittance) in previous MetEOC projects. MITRA seeks to measure the solar integrated transmittance of an equivalent window to that of CSAR by substituting it in front of a black absorbing radiometer, with similar spectral absorptance to that of CSAR but operating in air at ambient. The ratio of signals being a simple measure of effective transmittance that can be used as a correction.

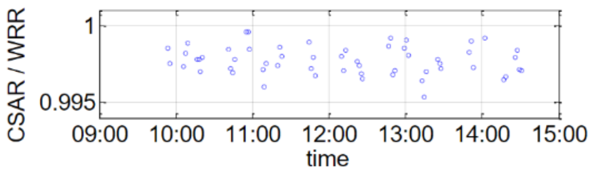


Figure 31: Results of comparison between the CSAR and WRR for a single day illustrating noise due to MITRA

Although over the last decade, CSAR and MITRA have performed consistently, identifying a bias between the WRR and SI as realised by CSAR of 0.29%, noise deriving from the MITRA, see fig 31 has meant that the overall uncertainty is currently around 0.05% nearly a factor two larger than the desired target of <0.03%. In this project, SFI-Davos have sought to address the impact of MITRA noise arising primarily from ambient temperature fluctuations and wind as well as potential differences due to window contamination between the MITRA and CSAR.
A detailed thermal model of the MITRA performance has been built leading to an upgrade in the design to incorporate an additional sensor (operating only in the dark) to remove effects of ambient changes. In addition,

the CSAR has been modified to allow a more rapid change of window (within an hour as opposed to daily) between it and the MITRA to account for contamination effects. After an initial manufacturing error by a contractor, a new MITRA instrument has been built but unfortunately due to this initial delay and subsequent COVID restrictions the updated change have not yet been tested. However the expectation is that this will reduce the overall uncertainty of the CSAR measurement to be ~0.028%, below that of the target and allowing the uncertainty of terrestrial Total Solar Irradiance measurements to be improved by a factor 10. This will also lead to CSAR/MITRA being adopted by WMO as the new primary SI-traceable reference with the more operational WSG linked to it by regular comparisons.

4.4.5 Key outputs – objective 4

- A new sensor based on a spatial heterodyne interferometer and an associated transportable calibration system has been designed built and tested to measure sky glow for the NDMC and with it the temperature of the mesosphere. Achieving a factor 10 improvement in performance.
- Global measurements of downwelling sky radiance (natural greenhouse effect) have been improved through detailed spectral characterisation and evaluation of thermal sensitivity of pyrgeometers together with the design build and test of a new reference blackbody to provide underpinning SI-Traceability. The latter to calibrate the World Infrared Standard Group of the WMO, reducing uncertainty by a factor of two.
- The CSAR, intended as an SI-traceable replacement for the WMO WRR for solar irradiance has been upgraded to allow more automated and operational measurements. Its accompanying window transmittance facility, MITRA, has also been updated to remove sensitivities to wind and environmental effects leading to a factor of two improvement in performance and a factor ten compared to the existing WRR.

5 Impact

This project participated in 43 conferences and published 8 peer reviewed open access scientific publications. An uncertainty workshop developed and supported by technical experts from this project was held at ESA attracting more than 50 researchers. This project provided key expertise to facilitate understanding in metrology and as a consequence a better trained workforce. Several science fares have been attended both in UK and in Germany to promote not only the project but the merits of SI traceability for EO and climate observations.

Primary impact stems from the project’s contribution to provide trustable evidence to policy makers on the scale and timescales of climate change so that they can implement timely and measured mitigation and adaptation strategies to ensure a sustainable environment and quality of life for European Citizens. Achieved from improved quality remote sensed data and partnerships with the international community through WMO, CEOS and industrial collaborations this also leads to:

Impact on industrial and other user communities

Satellite manufacturers now have access to flexible, multifunctional transfer standards to improve pre-flight accuracy whilst reducing time and cost for calibrations. They are currently being used and sought out by major space agencies and companies and will ultimately be used to demonstrate the potential of high-quality data from constellations of micro-satellites.

International test-sites (radiometric and bio-physical) and networks together with associated ‘good practices’ have and continue to be supported with traceability and uncertainty evaluations to help validate post-launch satellite measurements: physical (level 1) and bio-geophysical (level 2) variables.

This project has developed and calibrated novel instrumentation for both satellites and ground measurements some of which are new and novel to provide opportunities for commercial sales from European industry, reducing dependency on imported sensors. In some cases, the novelty/size of the instruments may facilitate new applications and/or significant improvement in the nature of the retrievable information as in the case of the in-situ ocean colour radiometer prototype.

Impact to metrological and science communities

The long time-series data sets from multiple sensors with robust quality metrics enabled by the analysis and methods in this project will allow scientists to reliably detect trends from backgrounds of natural variability leading to improved climate forecast models and impacts through improved knowledge of e.g. the carbon cycle.

Impact on standards

The project's activities have been carried out in close collaboration with key international coordinating bodies (e.g. CEOS, WMO) ensuring that good practices established and any community references will become de-facto standards. The project consortium has and continues to work closely with the community and encourages the uptake and inclusion of SI traceability in any standardisation process particularly with the emergence of 'analysis ready data' and climate services. This is being taken up by ESA in some of their recent projects with a request to include NMIs in consortia and the aim to establish international QA standards underpinned by metrological practises. In November 2017 the project hosted at a member NMI a technical group of WMO CIMO on radiation (objective 4). The project team provided guidance on traceability issues in general and of course will be delivering specific technical work from this project to underpin activities in the longer term.

Longer-term economic, social and environmental impacts

This project has sought to establish a harmonised European metrology infrastructure to enable the EO and climate change community, to provide robust information and advice to support far-reaching socio-economic decision-making on mitigation and adaptation strategies facilitated by:

- Upgrade in performance of instruments
- Fitness for purpose data on effectiveness of carbon sinks
- Harmonised methods to identify and quantify trends in CDRs
- Improved awareness and consistency on the use and interpretation of 'uncertainty'
- A focal point providing advice on metrology aspects of climate data, in coordination with the EMN.
- Reliable information to address concerns of sceptics

Other beneficiaries include international bodies e.g. CEOS, WMO, EUMETSAT, ESA, GEO and the EU Copernicus program together with national space agencies and associated aerospace industry from:

- International coordinated test-sites
- Raised profile of Cal/Val and traceability
- More efficient and accurate transfer standards
- A transnational focal point allowing an alignment of Cal/Val research efforts in collaboration with the EMN

6 List of publications

- Talone, M., (2018). *Non-linear response of a class of hyper-spectral radiometers*. Metrologia, *55* (5), 747-758, https://doi.org/10.1088/1681-7575/aadd7f

- Calders, K., (2018). *Realistic Forest Stand Reconstruction from Terrestrial LiDAR for Radiative Transfer Modelling,* Remote Sensing, https://www.mdpi.com/2072-4292/10/6/933

- Bouvet, M., (2019), *RadCalNet: A Radiometric Calibration Network for Earth Observing Imagers Operating in the Visible to Shortwave Infrared Spectral Range*, www.mdpi.com/2072-4292/11/20/2401

- Bialek, A., (2020). *Monte-Carlo based quantification of uncertainties in determining ocean remote sensing reflectance from underwater fixed-depth radiometry measurements*, https://doi.org/10.1175/JTECH-D-19-0049.1

- Berg, S., (2021), *Calibration of a CubeSat spectroradiometer with a narrow-band widely tunable radiance source*, https://doi.org/10.1364/AO.417467

- Smith, D., (2021), *Traceability of the Sentinel-3 SLSTR Level-1 Infrared Radiometric Processing*, https://doi.org/10.3390/rs13030374

- Hunt, S., (2020), *Comparison of the Sentinel-3A and B SLSTR Tandem Phase Data Using Metrological Principles*, https://doi.org/10.3390/rs12182893

- Ma, L., (2020), *Uncertainty Analysis for RadCalNet Instrumented Test Sites Using the Baotou Sites BTCN and BSCN as Examples*, https://doi.org/10.3390/rs12111696

- J. Kuusk, (2018), *Implication of Illumination Beam Geometry on Stray Light and Bandpass Characteristics of Diode Array Spectrometer*, **DOI:** 10.1109/JSTARS.2018.2841772

- De Vis, P., (2022), *Ancillary Data Uncertainties within the SeaDAS Uncertainty Budget for Ocean Colour Retrievals*, https://www.mdpi.com/2072-4292/14/3/497

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

7 Contact details

Dr Nigel Fox, NPL

Tel: 020 8943 6825
E-mail: nigel.fox@npl.co.uk

Project website address: http://www.meteoc.org/