FINAL PUBLISHABLE REPORT

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1 Overview

Earth's climate is changing. The potential for societal catastrophe is unprecedented. Remote sensing from space is the major means of obtaining the global data needed for climate change research and resultant knowledge enabling policy-makers to adopt appropriate mitigation and adaptation strategies. Changes in measurands are only a few tenths of a percent/decade requiring accuracies only realisable in NMI laboratories. This project has developed calibration/validation standards and methods, addressing pre- and post- launch of observation systems and complimentary in-situ networks, for land, ocean, and atmosphere-extending the capabilities of the SI into the 'field' as a key enabler for a global climate observing system.

2 Need

More than half of the Essential Climate Variables (ECVs) can only be measured from space. Improving traceability and accuracy of this data is top-of-the-agenda of space agencies. In many cases, a factor of ten improvement in accuracy is required to differentiate between natural variability of the climate system and 'anthropogenic'(human-caused) signal in the shortest time possible. Such improvement would result in more trustworthy climate forecasts and increased confidence in adaptation and mitigation policies. The forthcoming carbon stocktakes (Paris-agreement 2015) require robust audit, placing an urgency on the creation of a 'fit-for-purpose' climate observing system and addressing these challenges:

- Pre-deployment (space/air/'field') (laboratory-based) calibration methods that are traceable and flexible, enabling uncertainty assessment and confidence in sensor performance, plus efforts to increase the frequency of observations through lower-cost access to space as well as ground networks.
- Improved calibration and validation of sensors in the post-launch/operational phase, enabling interoperability, removal of biases and assessment of uncertainty in long/multi-decadal time-series of observations.
- Techniques to assess, improve and report on the degree of traceability and associated uncertainties in biophysical parameters and associated transformational algorithms based on end-to-end metrological analysis.

Although some underpinning measurement capabilities need improvement, in general, success necessitates evolution of existing laboratory-based metrology transferred to the harsh environment of 'field' (and space) situations. The residual key metrology challenges relate to the assessment of uncertainty from often localised 'spot' measurements of a physical measurand and its scaling to the footprint of a remote sensor; transformation to a biophysical parameter and finally to information that can be assimilated by a non-expert.

Representativeness of observations across the globe require networks of in-situ 'test-sites'/'observatories' (often under the auspices of the World Meteorological Organisation (WMO), and the Committee on Earth Observation Satellites (CEOS)). These require travelling transfer standards tied to the SI to ensure consistency and remove any instrumental effects.

3 Objectives

The overall goal of this project was to build on the outputs of previous projects (EMRP/EMPIR, others funded by the EU and European Space Agency (ESA) for example) to create the metrology tools and framework needed to underpin a global climate observing system. The scale of the challenge is vast, and this project focused efforts on the following objectives, selected to capitalise on synergy with other international initiatives, prioritised to address needs of forthcoming European climate focused sensors and related ECVs.

1. Develop a robust metrological chain (infrastructure and methods) to trace to the SI a new generation of highly accurate, cost-effective sensors, for a space-based climate observing system, suitable for pre- and in-flight measurements, prioritising the needs emerging from current mission studies such as TRUTHS and FORUM.
2. Develop SI traceable measurement methods with associated uncertainties for bio-geophysical parameters at pixel level and accounting for scene specific characteristics including the means to optimally parameterise, validate and assess the uncertainties of retrieval algorithms. This will consider harmonisation of sampling methods including optical and SAR based techniques.

3. Develop satellite derived SI traceable measurement methods (including uncertainty assessment, associated validation and interoperability) for greenhouse gases emissions and natural carbon sinks, including robust monitoring of implemented policies to reduce the anthropogenic carbon emission (in accordance with the Paris Agreement of 2015 and Vienna 2018).
4. Develop instrumentation and standards for traceable climate quality measurements, including temperature of the Mesopause and thermal infrared sky radiance, from surface-based networks such as those operated under the WMO and UN e.g. NDMC.
5. Facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (Calibration laboratories, instrument manufacturers), standards developing organisations 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: Develop a robust metrological chain to evidence SI-traceability of a Remote-sensing-based climate observing system, prioritising needs of the next generation of missions.

4.1.1 Introduction.

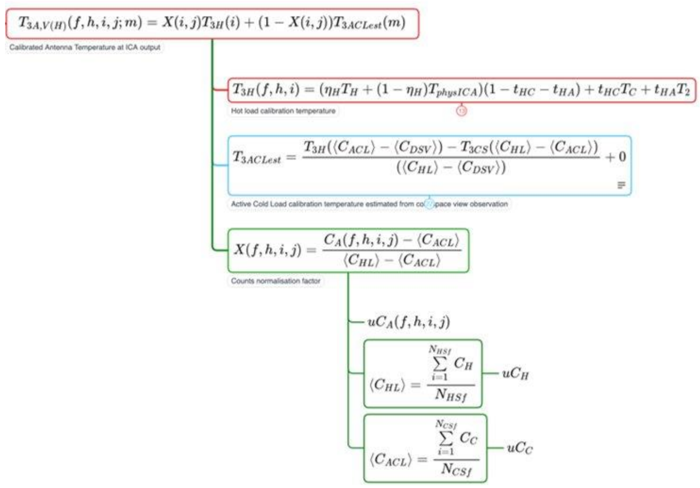
Although the ultimate challenge related to this objective is the operational ‘in-flight’ performance and SI-Traceability of a sensor and its delivered data, the process has to begin with the means to assess and report planned performance during the design phase followed by pre-flight calibration and characterisation and subsequently post-launch. In this project, we have demonstrated methodologies to aid assessment and presentation of SI-Traceability early in the design phase of new missions in partnership with ESA and industry as exemplars for the future. Designed, developed and evaluated novel facilities for the pre-flight calibration of a number of satellite and airborne sensors in the optical domain. In some cases optimising and extending 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.

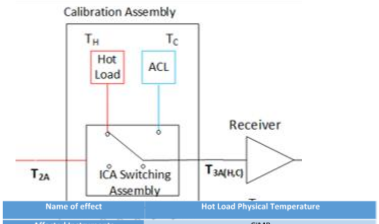
In addressing this objective we also considered that it was very common for correction coefficients derived from the pre-flight calibration to change on transference to orbit, in the case of space flight, and also change during operation due to environmental effects (space and airborne). Our project thus also undertook research on standards and methods that can be used and deployed during useage, both on the same observing platform, this objective, and also remotely using vicarious methods like test-sites and sensor to sensor comparisons, objective 2 and 3. As part of this latter activity CMI completed work initially started in MetEOC 3 to complete a novel field spectrometer for use as a transfer standard to compare between testsites.

Our achievments related to the scope of this objective were significant and clearly show progress to the community and indeed illustrated by the up-take of the outputs.

4.1.2 Metrological Traceability assessment

Main stream satellite instruments can typically take 5 to 10 yrs from design to launch. The major European satellite program is that funded by the EU and called Copernicus, which is around halfway through its first phase of missions. As an operational focussed program the first phase was based around a flight program of typically consecutive pairs of satellites to ensure continuity, e.g. the build of four largely replica missions launched in sequence with a view to maintain at least one instrument operating at all times and thus this means two in-flight. The EU together with ESA are now looking to the phase 2 where design evolutions of existing sensors may take place and also new instruments may be added to fill gaps in the portfolio. As metrology, partly as a result of the MetEOC series of projects, has become embedded as a key requirement it is timely to look to build enhanced metrology thinking into these design phase (Phase A) of these missions.





Name of effect		Hot Load Physical Temperature	
Affected Instruments		CIMR	
Contribution identifier		See unc tree	
Measurement equation parameter(s) subject to effect		T_H	
Correlation form/type	Channel (h)	Random	Random
	Feed (f)	Random	Absolute
	Scan (i)	Absolute Triangular	Absolute
	Sample (j)	Absolute Rectangular	Absolute
Correlation scale	Channel (h)	Random	Random
	Feed (f)	Random	[-inf:inf]
	Scan (i)	[-Nscans/2:Nscans/2-1]	[-inf:inf]
	Sample (j)	[-Nscans/2:Nscans/2-1]	[-inf:inf]
Channels affected	List of channels	All	All
	Error correlation coefficient	None	None
Uncertainty PDF shape		Gaussian	Gaussian
Uncertainty & units		0.1 K	0.5 K
Sensitivity coefficient		$\frac{\partial T_{L1}}{\partial T_{MB}}\frac{\partial T_{MB}}{\partial T_A}\frac{\partial T_A}{\partial T_{1A}}\frac{\partial T_{1A}}{\partial T_{2A}}\frac{\partial T_{2A}}{\partial T_{3A}}\frac{\partial T_{3A}}{\partial T_{3H}}\frac{\partial T_{3H}}{\partial T_H}$	
Correlation(s) between affected parameters		/	
Validation		/	

Figure 1: Uncertainty tree and effects table for CIMR mission

Assessing, evidencing and reporting SI-traceability in a consistent manner was one of the topics of this project. Here we use the principles of the EU FIDCUEO project, also used in MetEOC 3, to demonstrate its utility for one of these ;Next Generation' Copernicus missions, in this case the Copernicus Imaging Microwave Radiometer (CIMR). Partnering with one of the industrial consortia undertaking the design, together with ESA, NPL and UoR undertook to analyse the anticipated traceability and uncertainty of the mission based on its prototype design. Figure 1 illustrates the uncertainty tree for the instrument and an example element of an effects table. These were created using a dedicated set of open source software, http://www.comet-toolkit.org, developed by NPL for ESA. Primarily in a partner project but enhanced and refined through feedback from its utilisation in this project.

ESA and the industrial consortium have been very positive with the outcomes and are looking to expand the methodology to other missions and projects.

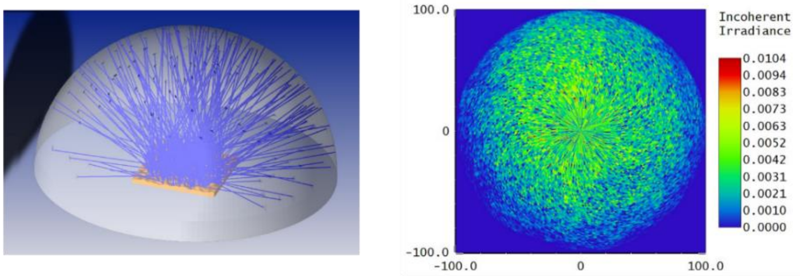
4.1.3 Thermal IR: pre-flight Calibration of ESA FORUM mission

Change in the balance of the Earth's incoming and outgoing radiation, at the top of the atmosphere, is fundamentally the cause of Earth warming and climate change. Although uncertainty in the measurements of this radiation needs to be improved across the full spectral range, to date there is no spectrally resolved information beyond around 20 um, ~ half the total outgoing flux!. The recently selected ESA Earth Explorer Mission 9 FORUM features an on-board Fourier-transform spectrometer which will measure the spectral radiance of the earth from space in the wavelength range from 5 µm to 100 µm and will allow the quantification of the outgoing infrared radiation for the first time in the complete relevant spectral range.

The uncertainty requirements on the measurements of the FORUM mission are demanding with required uncertainties in spectral radiance temperature of 33 mK in the spectral range from 9 µm to 33 µm and 66 mK in the spectral range from 33 µm to 50 µm (all given as 1σ or k=1).

To achieve this uncertainty for space-based measurements traceable to the SI, an appropriate and stable onboard reference source is required which will be a large aperture FIR blackbody. For its pre-flight characterization, stability investigation and calibration, appropriate ground-support equipment and in particular an appropriate in lab reference blackbody is required. Currently only one NMI in Europe, PTB, is able to provide spectral radiance in vacuum up to wavelengths of 100 µm. The uncertainty of their current reference source is 40 mK in radiance temperature whereas to fulfil the FORUM requirements 20 mK over the whole spectral range are required.

In this project the underpinning metrology for such a new reference blackbody was developed as a basis for an improved in-lab in vacuum reference blackbody able to provide spectral radiance from 3 µm to 100 µm in a temperature range from -50 °C to +50 °C with a standard uncertainty in spectral radiance of better than 20 mK.



a) b)

Figure 2 a)Randomly textured surface located at the center of a hemispherical detector. (b) The angular distribution of reflected rays

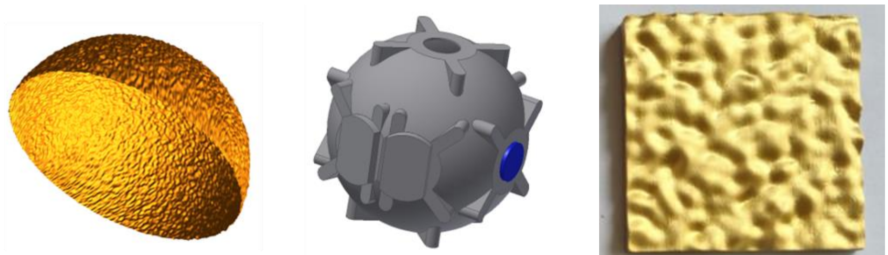

a) b)

Figure 3 a)Randomly textured surface located at the center of a hemispherical detector. (b) The angular distribution of reflected rays (c) the gold textured surface

One of the critical design requirements for a black body is knowledge of its spectral emittance properties and for this the emissivity of the coating need to be determined. In this project we needed to design a facility to measure total emissivity, typically undertaken using an integrating sphere, but in this case needing a coating which is Lambertian to 100 um. Although gold has the appropriate reflectance we need a surface texture to make it Lambertian. Using a computer simulation see figure 2 an optimum surface was designed and a sphere constructed using 3D printing see Fig 3.

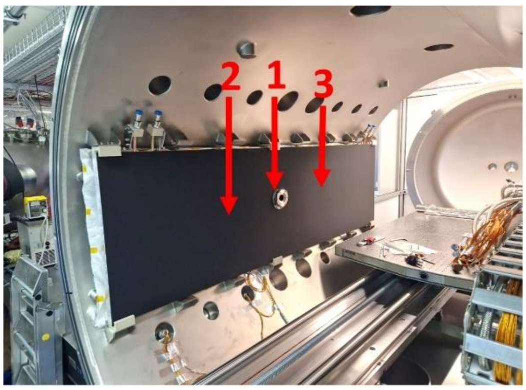


Figure 4. Integrated Coldscreen with the three positions of installed calibrated PT100 thermometers.

The ground reference black body needs to operate in vacuum and be isolated from other sources of thermal contamination. This required the design and build of a new cold shield for the facility see fig 4.

In addition to the background the extremely low thermal uncertainty of the black body, 10 mk, required needed a small dedicated research program to assess mounting and adequacy of contact.

The new reference black body will be operational from Nov 2024 and then undergo full testing in readiness to use with the design and build of the space hardware.

4.1.4 Thermal IR: in-flight calibration of balloon-borne Limb sounder GLORIA

KIT and PTB supported by BUW have completed the build, test and upgrade of lightweight black bodies for the inflight calibration of the GLORIA limb sounder. This instrument can be flown on aircraft and balloon and is a pre-cursor to a potential space-based version designed to measure atmospheric composition profiles by viewing the sun through atmosphere at the edge of the Earth. Here, although hampered with Covid, two flights have been completed demonstrating the successful performance of the black bodies i.e. <100 mK uncertainty over the field of view of the instrument during flight.

Figure 5, back plate of blackbody.

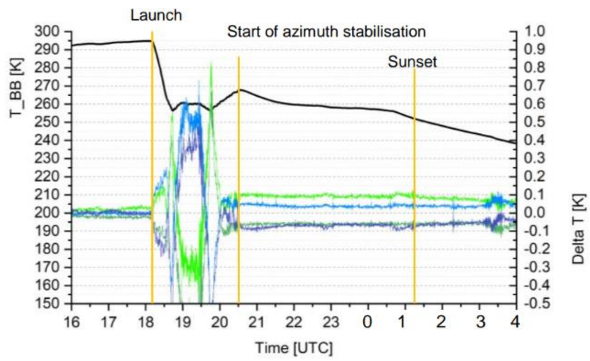


Figure 6. Temperature stability of the black body as measured during flight.

Fig 5 shows the pyramidal cone black bodies for which a new coating was optimised and figure 6 illustrates the achieved performance in flight commensurate with the target.

4.1.5 Measuring the temperature of the mesosphere

The mesopause region, situated at the boundary between the mesosphere and thermosphere at altitudes of about 80-100 km, stands as a critical indicator and respondent to climate change. As one of the coldest places in the Earth’s atmosphere, it is highly sensitive to both exogenic and endogenic influences, making it a unique diagnostic tool for climate variability and change. The Network for the Detection of Mesopause Change (NDMC) is an international collaborative initiative focused on observing and understanding long-term changes in the mesopause region from a set of ground-based observations and its support is described in Objective 4. However, the limited spatial coverage of the NDMC limits its ability to observe dynamic and global variations hence the driver for space-based observations.

The AtmoLITE instrument has been chosen for an In-Orbit Demonstration/In-Orbit Validation (IOD/IOV) activity as part of the European Union’s Horizon 2020 program. This activity is titled SHIPAS, which stands for Spatial Heterodyne Interferometer Performance Assessment in Space. The project is currently in the implementation phase. It has successfully completed the critical design review, and the flight model is approaching its delivery phase. Comprehensive calibration and stray light characterization measurements have been conducted within MeoEOC4 by FZ JUERLICH to ensure the instrument’s efficacy and reliability. Similar to the ground based instrument discussed in objective 4 the satellite instrument is a spatial heterodyne interferometer, simplistically a Michelson interferometer with no moving mirrors, the fringes being detected by an array detector.

An updated design and build of a calibration system for SHIPAS (Spatial Heterodyne Interferometer Performance Assessment in Space, a satellite sensor for measuring temperature of the Mesosphere, via airglow) was completed and the characterization of the wavefront (radius of curvature) using a shearing interferometer with specially developed software and a reference collimator carried out indicating distortion in the image quality, but following calibration and use of an appropriate correction model the uncertainty due to residual inhomogeneity is acceptable.

The effect of stray-light can be one of the most significant sources of error for optical instruments. For this mission FZ JUERLICH made characterisation measurements and derived correction schema for the instrument pre-launch. However, the biggest potential source of remaining error will result from optic contamination from storage and in-flight. A modelled assessment has been carried out based on realistic assumptions and resulting in a potential error of around 1 K in the worst case see Fig 7.

However, whilst this remains to be assessed though methods such as observations of the limb of the moon and/or Venus in-flight this combined with the other uncertainties remain consistent with those required to complement the observations made by NDMC.

4.1.6 Pre-flight calibration facility for optical imagers/spectrometers

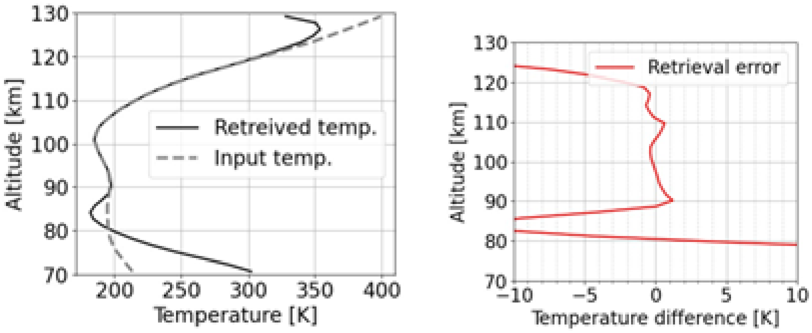
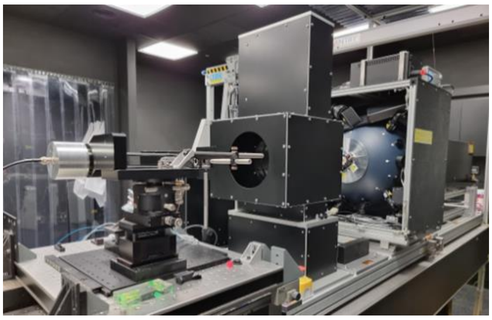


Figure 7. Results of end-to-end simulation considering scattered straylight due to contamination scattering from optics; (a) input temperature compared to retrieved temperature; (b) difference between input and retrieved temperature;

Pre-flight characterisation and calibration of optical sensors is critical even if as is normal there is the expectation that some of the critical characteristics such as gain are likely to change on transition to and subsequently during operation in orbit. Without a robust baseline to confirm performance even if there are on-board calibration systems, it can be difficult to assign, in a quantitative manner, errors and corrections to the contributing elements impacting the measurement.

Analysis of the detailed requirements for the TRUTHS mission, intended as a gold standard SI-traceable reference in orbit with an uncertainty goal an order of magnitude lower than other missions have identified the primary challenges that need to be addressed from a pre-flight calibration facility. In addition to overall radiometric gain, knowledge of the response shape and effective wavelength of the imager (<0.1%) and stray-light evaluation are challenges demanding nearly an order of magnitude improvement in accuracy compared to other missions. It should be noted, that in the special case of TRUTHS, which flies its own cryogenic radiometer as a primary SI standard, pre-flight radiometer gain should be considered a comparison and not a calibration as the uncertainties of the two routes should be comparable.

NPL has analysed the requirements of the ESA TRUTHS mission and compared them to the performance and capabilities of their Spectroscopically Tuneable Absolute Radiance (STAR) calibration and characterisation (c&c) Optical Ground Support Equipment (OGSE) facility, see fig 8.



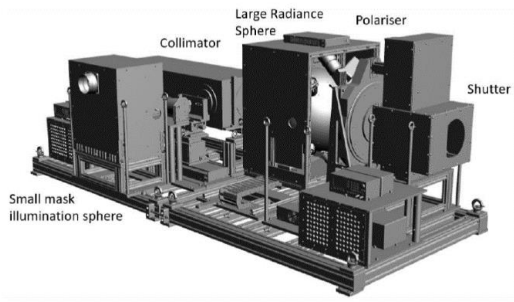


Figure 8 The STAR-cc-OGSE at NPL and in CAD form.

STAR-cc-OGSE, partly developed in MetEOC 3 is already highly novel and state of the art, utilising a tuneable CW laser (260 – 2600 nm) to illuminate a large aperture integrating sphere or collimator as a radiance source. The radiance being measured in vacuum via a solid state detector SI-traceably calibrated in terms of monochromatic spectral radiance. The integrating sphere can also be illuminated with broadband radiation from tungsten halogen lamps and can be coupled through a rotatable linear polariser.

STAR has been used to calibrate and characterise the GHG satellite sensor MicroCARB and shown in Table 1 that it can achieve <0.5% k=1 In spectral radiance limited primarily by relative spectral response, a value more than adequate for this mission.

Table 1: limiting uncertainties in existing STAR facility.

			Si		InGaAs	
Symbol	**Source of Uncertainty**	**Probability Distribution**	**Value**	**ui**	**Value**	**ui**
uAbs	Photodiode Absolute Calibration	Normal	0.15%	0.15%	0.15%	0.15%
uRel	Photodiode Spectral Response Calibration	Normal	0.26%	0.26%	0.44%	0.44%
uSp	Spectroradiometer NEdL	Uniform	0.08%	0.04%	0.08%	0.04%
UC	**Combined Uncertainty (k=1)**			**0.31%**		**0.47%**
U95	**Expanded Undertainty (k=2)**			**0.61%**		**0.94%**
	Photodiode Abs + Rel only (k=1)			**0.30%**		**0.47%**
	Photodiode Abs + Rel only (k=2)			**0.61%**		**0.93%**

In MetEOC we have assessed the TRUTHS mission and designed a characterisation/comparison strategy see Fig 9 and assessed the realism and means of reducing the above uncertainty by at least a factor of two so that it is at a level commensurate with the goals of TRUTHS. To address the uncertainty reduction we have focussed on changing the calibration of the photodiodes so that the relative and absolute calibration can be determined at the same time directly against the primary standard cryogenic radiometer at a number of spectral points across the spectrum. Interpolation being carried out using a spectrally flat pyroelectric detector, essentially responding to thermal energy and not photon energy. The estimated improved uncertainty budget is shown in table 2. This represents a near factor of 10 improvement and thus fully adequate to meet the needs of TRUTHS.

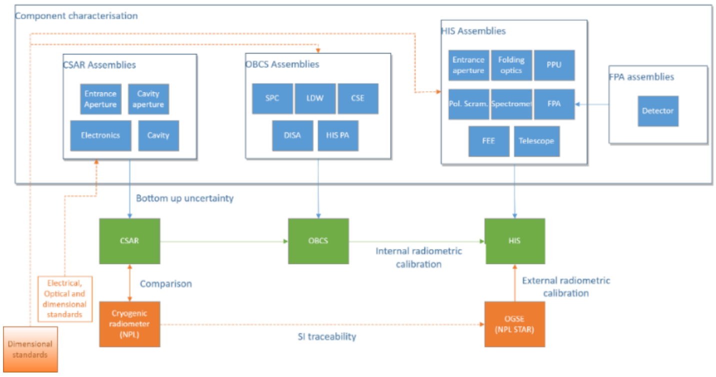


Figure 9. Comparison philosophy for TRUTHS.

Table 2 4

Source of Uncertainty	Value	Prob Distribution	Divisor	Ui
CPD75 Temperature Variation	0.02	Rect	1.73	0.01
CPD75 non-linearity	0.05	Rect	1.73	0.03
CPD75 non-uniformity	0.04	Rect	1.73	0.02
Chopper stability	0.005	Rect	1.73	0.00
LIA non-linearity	0.05	Rect	1.73	0.03
DVM linearity	0.0016	Norm	1.00	0.00
DVM drift	0.0005	Rect	1.73	0.00
Source Stability	0.005	Rect	1.73	0.00
Beam Size	0.005	Norm	1.00	0.01
Positional Reproducibility	0.005	Norm	1.00	0.01
Stray Light	0.01	Rect	1.73	0.01
Combined Uncertainty (k = 1)		Norm		0.05

4.2 Objective 2: Calibration, validation, and uncertainty of 'delivered' bio-geo physical data/information products from remote sensed data including the transformation between top and bottom of atmosphere.

4.2.1 Introduction.

This objective is focussed on assessing and potentially correcting post-launch performance of satellites and in particular their delivered data products. One of the critical drivers for this is to enable the creation of long time series of Fundamental Data Records (FDR) and ultimately Climate Data Records (CDR). The small signals of climate change are typically so small that we need decades to have sufficiently large signals that can be detected from a background of natural variability and for this we need to link observations from multiple satellites in a robust manner that instrumental biases and drifts do not impact the merged long time series.

We know from experience that whilst we can rightly and necessarily expend significant effort in the pre-flight characterisation activities, highlighted in objective 1, the launch and harshness of the environment means that these will typically change and comparison with other satellites and or 'targets' are essential to validate and correct performance.

However, to undertake such comparisons and utilise the results in a meaningful metrological manner requires an assessment and correction for lack of common representativeness of observations. In some cases this is 'simply' a convolution to the same spatial and spectral characteristics but often further complicated by differences in observational paths i.e. the transmittance through an atmosphere.
In this objective we describe efforts and the creation of software tools and their metrological robustness to facilitate meaningful comparisons.

As illustrated below we made significant progress towards the goals of this objective which by its nature and scope is an on-going challenge.

4.2.2 Sensor to sensor harmonisation/interoperability

To harmonise sensors requires the means to assess biases for observations of nominally the same measurand, across the full range of observational conditions. This ideally means comparisons of different sensors at the same locations at the same time or at least correctable for differences in observation time. Our vision within this objective is to create a suite of software/methods that can be combined into a tool to enable harmonisation of and F(C)DR. Figure 10 illustrates this vision, where the aim is to have a means to find data for locations suitable for comparison, means to correct imagery for spatial/spectral/angular etc effects, means to apply corrections to a sensor measurement equation and also validation against independent targets.

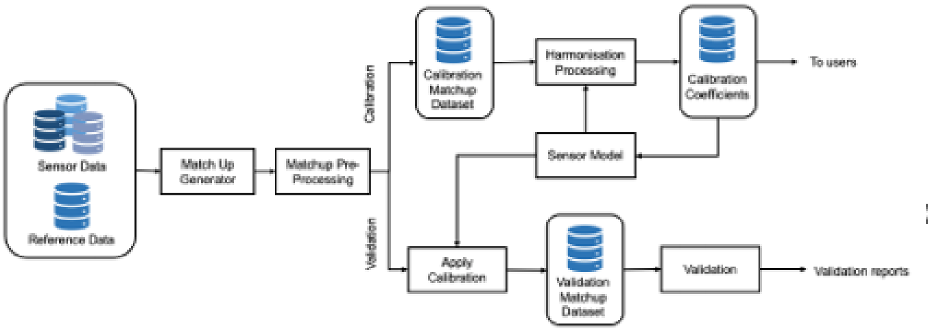


Figure 10 : harmonisation system processing chain for FCDR development

Match-up generation required the development of an orbit propagation tool to allow for future satellite missions the means to predict overlaps with either other sensors or specific locations. This of course also requires the clear definition of what constitutes a colocation. In terms of number of pixels, and of target area/shape and any time constraint. It also requires the extraction and storage of the relevant data as a colocation file.

In MetEOC-4 most of our effort related to the factors impacting the harmonisation of representativeness and in particular that between two nominal sensors, a reference, here we use TRUTHS, and one under test, as an example we use Sentinel 2. Figure 11 provides a flow diagram illustrating these harmonisation steps.

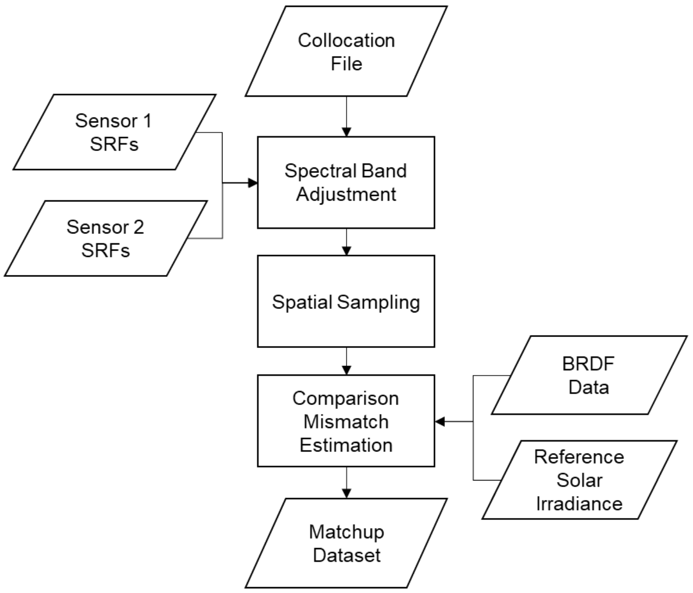


Figure 11: Match-up pre-processing for two sensor observations in satellite-to-satellite comparisons

For each of the characteristics we have performed an assessment of S2 data with that simulated for TRUTHS over a range of different terrain types e.g.: desert, snow, cloud, forest. As an example in Figure 12 we show the impact of the combined uncertainty after applying appropriate corrections for a comparison of TRUTHS with Sentinel 2 bands. Note that the spectral region between 1000 nm and 1500 nm appears anomalously hight but this is in practise only two spectral bands both of which are for water vapour or cloud detection and hence in regions of high spectral variability and where absolute uncertainty is of low importance. For 750 nm the high sensitivity when viewing rainforest is due to the very sharp spectral feature due to vegetation known as the red edge. However, in the main a comparison of <0.5% is achievable (5X improvement on the mission declared uncertainty.

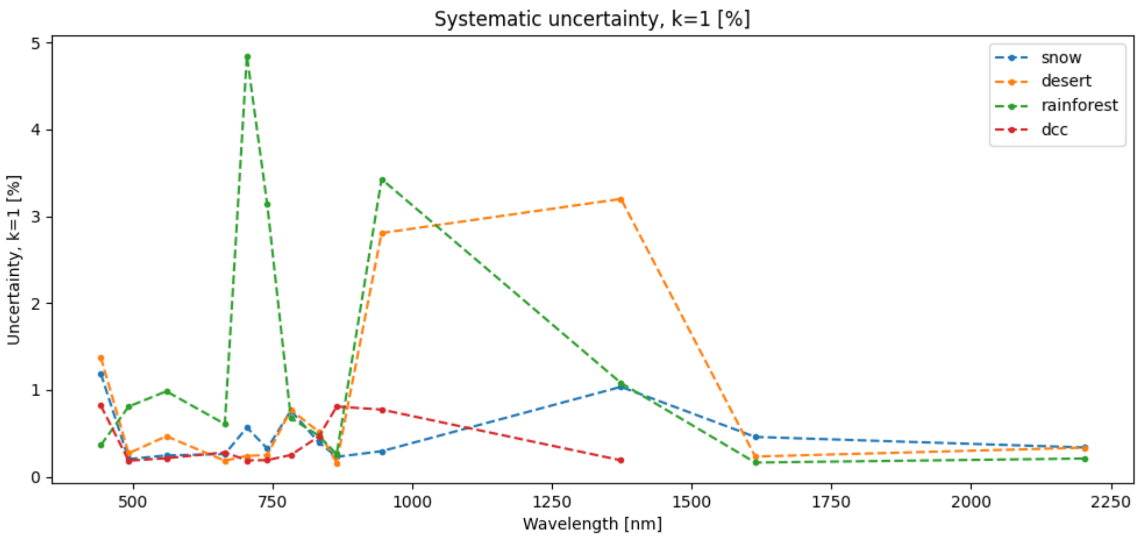


Figure 12: Mean systematic uncertainty for Sentinel 2 bands using TRUTHS as a reference sensor.

4.2.3 The moon

Absolute calibration of Earth observation sensors is key to ensuring long term stability and interoperability, essential for long term global climate records and forecasts. The Moon provides a spectro-radiometrically stable calibration source, which is unaffected by atmospheric effects and has been observed by many historical as well as current sensors. The observed lunar reflectances depend on changes in the Sun-Earth-Moon geometry (e.g. phase and libration angles). The Lunar Irradiance Model of the European Space Agency (LIME), is a new lunar irradiance model developed from ground-based observations acquired using a lunar CIMEL 'photometer' (although in common use the term should not be confused and should really be called a spectroradiometer) operating from the Izaña Atmospheric Observatory and Teide Peak, located in Tenerife, Spain. In addition, hyperspectral observations using an ASD spectrometer were made at the same location to provide information on the spectral variability between the CIMEL measurements. The ESA LIME project was led by NPL, enabling this collaboration to take place efficiently.

In MetEOC-4 we have developed a complementary LIME_TBX is a toolbox which allows the calculation of the lunar reflectance and irradiance for a given time and location (or given geometry) from the LIME model and compare these to Earth observing sensors. This is done by using the LIME model which was fitted to years of observations of the moon using a CIMEL photometer (corrected to TOA using the Langley method). This LIME model is then used within the LIME-TBX to calculate the lunar reflectances for a given set of angles (calculated from the user inputs) at the CIMEL wavelengths. These model reflectances are then combined with hyperspectral ASD measurements in order to obtain hyperspectral LIME-TBX reflectances. Finally, the lunar irradiances are calculated from these (using the TSIS-1 solar irradiances from (Coddington et al., 2021)) and spectrally integrated with the spectral response function of the instrument the user is comparing the lunar data to. Figure 13 illustrates the variation in lunar spectral irradiance as a function of phase angle, each line corresponding to a 10° change.

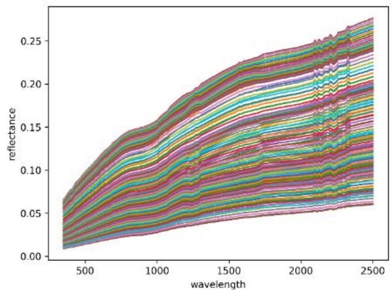


Figure 13: variation in lunar spectral irradiance from + 95 to -95 degree phase angle in steps of 10 degrees.

To enable the propagation of rigorous uncertainties up to the final model simulated hyperspectral irradiances, a Monte Carlo approach is implemented throughout the processing chain using the CoMet toolkit (www.comet-toolkit.org). The process is broken down into multiple steps. First, uncertainties on the TOA (Langley-corrected) lunar reflectance from the CIMEL measurements are determined. Next, these data are used in fitting the LIME model. Finally, uncertainties in the spectral adjustment process are detailed and combined with a solar irradiance model to calculate the lunar hyperspectral irradiance uncertainties.

4.2.4 Metrological validation of Radiative Transfer (RT) code: Eradiate

In comparing satellite sensors ToA observations with those derived from the surface and indeed in deriving surface properties from satellite observations requires the means to account for losses incurred from scattering and absorption in the atmosphere and also the interaction of the radiation with the surface. This is achieved by the coupling of various models e.g. that of the atmosphere and the surface and utilization of Monte-Carlo (MC) simulations to evaluate the multiple scattering paths that can take place. These, so called, Radiative transfer codes have been built by different groups over the years and all perform slightly differently due to choice of assumptions and simplifications.

Eradiate (www.eradiate.eu) was initially designed in MetEOC- 3 by Rayference and subsequently developed as an open source physically and metrologically based code with funding from ESA and EU. The code, continues to develop and is finding a wide range of uses. Validation of the performance of such RT codes and indeed the development of any figure of merit is challenging and largely limited to community comparisons assessing equivalence to each other in representing propagation of similar surface features e.g. trees.

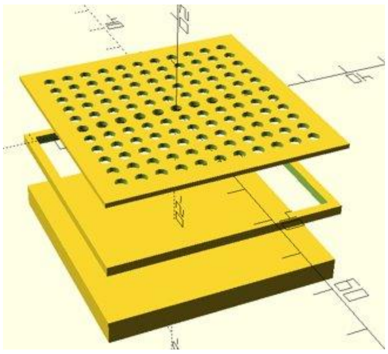


Figure 14: schematic representation of the aluminium target.

In MetEOC-4 we undertook to carry out a more rigorous SI-traceable approach to validate the Eradiate RT code. This involved the design, manufacture and characterization: mechanical and optical reflective properties of a target that could be replicated in a digital form and a comparison carried out between an RT simulation and a real observation. There were many challenges to achieving this goal at an uncertainty level that is meaningful. Not least the design and build of a target of sufficiently uniform and characterizable properties but also with enough complexity to be considered a realistic test.

Figure 14, shows the 50 X 50 mm target manufactured and characterized by NPL. After some research a near Lambertian coating was applied through plasma electrolytic oxidation and the coatings reflectance measured as a function of angle to determine its BRDF so that these properties could be utilized to create a digital simulation for the RT code.

To characterize the optical reflective properties of the target, as a proxy for an earth based surface observed by a satellite, a 3D goniometer developed by AALTO in MetEOC 3 for characterizing desert sand was optimized to enable measurements of reflectance to be made close to the illumination angle as possible see figure 15.

Collimated radiation in beams of various sizes but sufficient to illuminate several holes and with different wavelengths were used leading to the type of BRDF pattern shown in Fig 16.

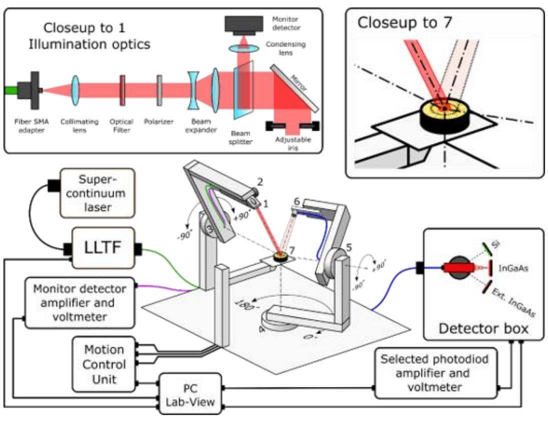


Figure 15: 3D goniometer for BRDF measurements of the target.

These observed results were then compared with those obtained from the simulation performed by Rayference using Eradiate, along transects and an uncertainty analysis performed using some of the software tools developed by NPL.

Figure 17 shows the results of the comparison. The left hand showing the BRF values and the right hand panel showing the relative percentage difference and associated uncertainty. It can be seen that other than a few anomalies there is good agreement within the combined uncertainties of around 2%. This is the first

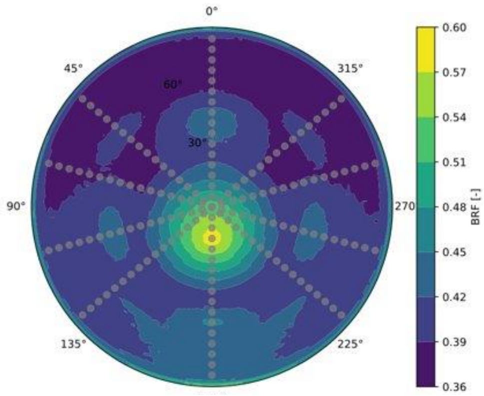


Figure 16: Typical observed pattern of reflected light from the target.

time such a comparison has been performed with this degree of rigorous uncertainty analysis and this level of agreement.

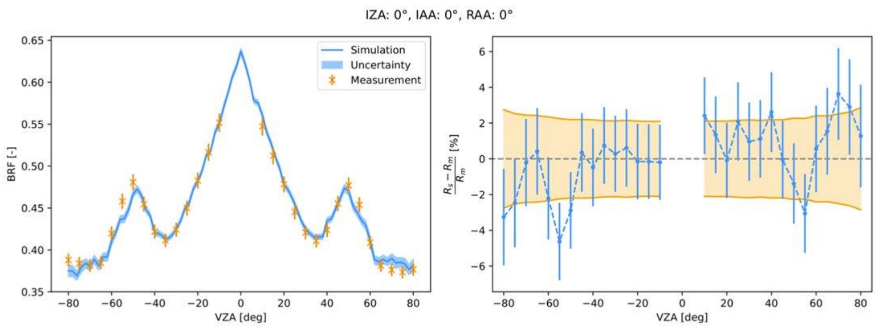


Figure 17. Results of comparison between observations and simulations of the target. Left is the BRF values and Right the relative difference and associated uncertainty.

4.3 Objective 3: Develop satellite derived SI traceable measurement methods (including uncertainty assessment, associated validation and interoperability) for greenhouse gases emissions and natural carbon sinks, to support the Paris Agreement of 2015 and Vienna 2018).

4.3.1 Introduction

The Paris agreement and subsequent national and international initiatives have established the need to not only reduce but also to evidence net carbon with a view to as a minimum a net zero ambition by ~2050 with demanding reduction targets by 2030. Although at present much of the evidence is based on a bottom up accounting basis there is the expectation that nations will increasingly look to space to support this process. In addressing the issue, it is essential to note that it is a net zero ambition with sequestration of emitted carbon by natural and artificial means being a significant part of the equation. Around Half of emitted CO2 is absorbed by natural sinks equally divided between land and ocean, with their respective biospheres playing the major role. It of course should be noted that these, particularly land based, domains can also be a source of carbon with deforestation, land change and disturbance and in particular peat land damage/erosion.
In this project and objective, we were focussing on the health and quantification of the biosphere and associated ECVs where observation from space is essential to provide the global coverage necessary. Since many of the bio related ECVs are complex and the ultimate measurand not directly a simple physical

quantity, nor highly homogenous and are located below the atmosphere we require significant efforts to establish robust validation metrics for the satellites.
This project established SI-traceable methods and test-sites to improve satellite harmonisation and validation as well as digital-based simulation environments where we can look to undertake realistic sensitivity analysis without the complexity and cost of field work. We also explored the means to report and assess uncertainties within the algorithms used to retrieve ECVs and derived information.

The successess illustrated below make clear the progress that this project has made to the overarching objective scope which by its nature is on-going. This success is demonstrated by the buy-in of other international projects and partnering with agencies like ESA to create exemplars.

4.3.2 Evolution of Wytham woods CEOS test site: observed and virtual.

For vegetation related variables such as fAPAR and LAI, canopy radiative transfer models are used to predict these values based on the observed signal. This is known as model inversio n, since the original purpose of the model is to produce the expected reflectance given a range of canopy structural and radiometric properties. These models are typically simplistic in their treatment of the architecture of vegetation canopies and the illumination conditions and as a result incur errors. A means of understanding the magnitude of these errors involves building complex 3D replications of real vegetation canopies to understand how they should behave and compare that to how they do behave when the model conditions are met.

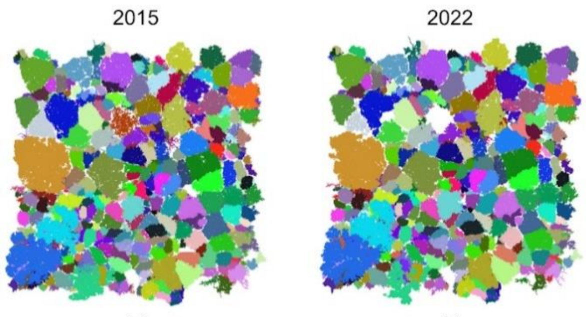


Figure 18: segmented point cloud of the 1 ha wytham woods model area

Figure 19 Shows the observed changes in a tree during the two observational periods.

To do this we have to create a model derived from real observations. In this project we use Wytham woods, a CEOS endorsed super site. In 2015 (MetEOC 2) NPL carried out a detailed Lidar based survey of the site and subsequently transformed the point cloud into the virtual world after linking the points into trunks/branches and leaves. In MetEOC-4 we revisited this site together with UGhent and undertook a remeasurement and transformation to evaluate change. Fig 18 shows the difference in the two point clouds. Note that the 2022 model has 31 fewer trees than the 559 in the 2015 model and one clear example of this is the absence of the brown canopy in the top middle, probably due to a fallen tree within the 7 year period. In figure 19 a comparison of the same tree shows clearly the loss of branches.

In MetEOC 4 we have extended the models in time, carried out validation comparisons and also explored the extension in the spatial domain using ML methods with a view to the credible simulation of models for larger Swath sensors without the necessity to fully experimentally map the whole terrain.

4.3.3 Utilisation of drone sampled test site for validation of Sentinel 2

There is an increasing recognition, including the creation of a dedicated label CEOS-Fiducial Reference Measurements (CEOS-FRM) that measurements made in support of satellite validation require as much rigour in terms of evidenced SI-Traceability as the satellite itself. In particular, documented uncertainties associated with the results of a comparison which not only include the instrumentation used but also the representativeness of the measurement and comparison process itself.

Near simultaneous, Drone and Sentinel 2 overpass flights of the same 100 m X 100 m forest area were flown by the NLS team together with necessary atmospheric composition measurements in in 2021. In addition to pre-flight characterisation, the Drone also flew over four reference reflectance panels of varying reflectance levels to enable in-flight calibration, see Fig 20. Five weather successful comparison flights took place in Finland between July and October 2021. This covered a large range of Sun Zenith angles (SZA).

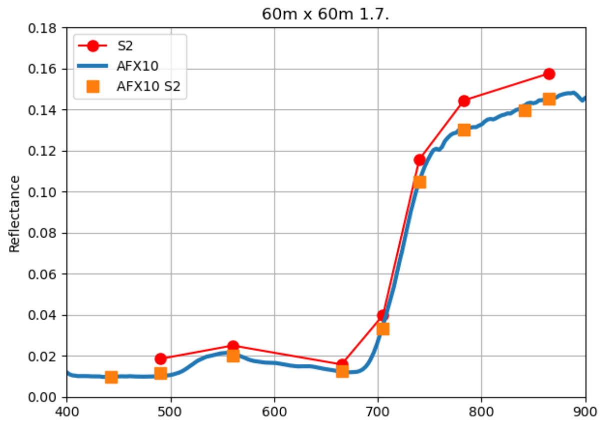


Figure 21: Reflectance values of forest determined by Sentinel 2 (red) equivalent bands of Drone (orange squares) and hyperspectral Drone (blue).

Figure 20: Reference reflectance panels being levelled in the field.

Figure 21 shows the results for one date in July which is somewhat typical illustration of the overall results. The red points are the S2 centre bands the blue curve the Drone hyperspectral observations and the orange squares the Drone results resampled to match those of Sentinel 2. They show reasonably good agreement for wavelengths below 700 nm but with significant differences in the near infrared. The reasons for the discrepancies is not fully determined as yet, but may have some relationship to SZA as the following figure 22 illustrates. Figure 22 (left) shows the results from the measurements as a function of band and sun zenith angle and Figure 22 (Right) for the 800 nm value. In both cases the correlation with SZA it is clear and that

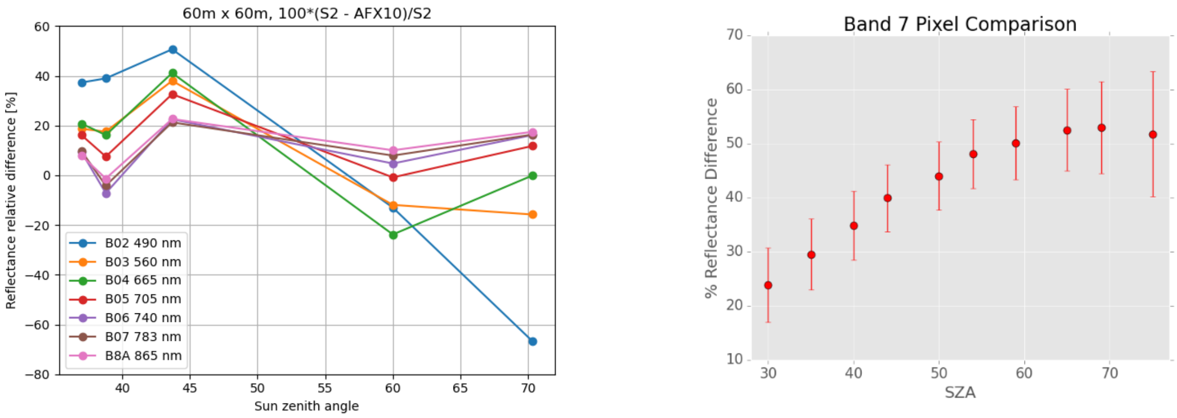


Figure 22 (Left) shows relative difference between S2 and Drone as a function of SZA and wavelength and (Right) for simulated results using a virtual forest and for S2 B7 ~ 800 nm.

the
best period for comparison is in the summer, with relatively low SZA.

4.3.4 Impact of Temperature variation on Flox meters (designed to validate ESA FLEX satellite mission)

The ESA Flex mission to measure fluorescence and consequently bio activity of vegetation and ultimately its carbon storage capabilities is due to launch in 2025. The Flox meters were designed for surface based validation of the Flex observed fluorescence and consequently require high radiometric and spectral accuracy. In MetEOC 4 UZH undertook some experiments to evaluate the performance of the Flex meters and in particular in response to some observed anomalies from field based measurements occurring as a function of diurnal cycle.

As a postulate and confirmed by measurement, spectral shifts (and thus response change) can be sensitive to temperature, with significant variation as observation moves away from solar noon see fig 23 which shows the impact in relation to the field conditions.

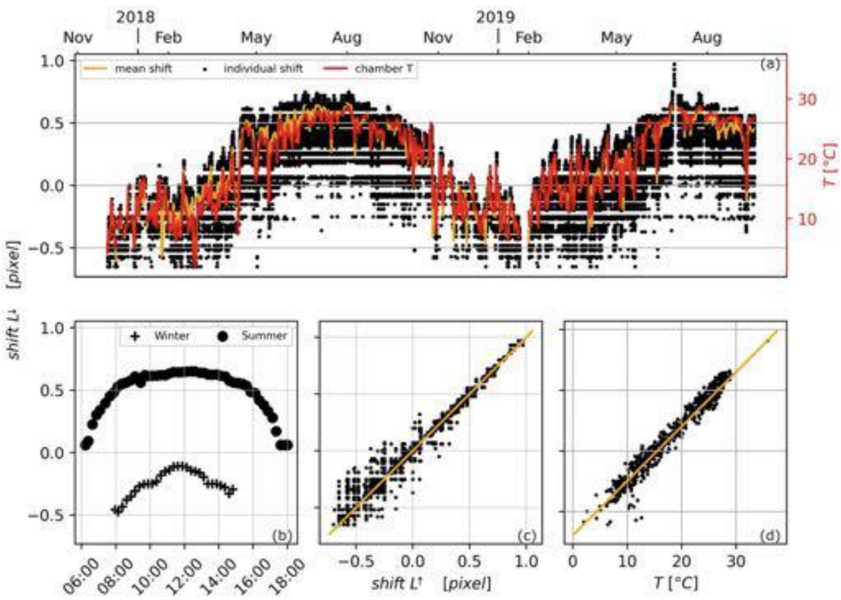


Figure 23: Impact of change of temperature and the variation of temperature with diurnal cycled..

4.3.5 Uncertainty dashboard for Ocean colour observations

The Oceans absorb half of the biologically absorbed emitted green house gases (approx. 25% of the total emitted) through photosynthesis by phytoplankton and subsequent biological life cycles of the ocean. Although some considerable work has been undertaken within the community and in previous MetEOC projects on determining and combining uncertainties it remains quite complex to interpret and effort to revaluate for any changes. In MetEOC 4 NPL together with JRC developed a dashboard to help practitioners assess and visualise the impact on uncertainty as parameters change. Figure 24 shows the front screen GUI of this tool that has been welcomed by the International Ocean Colour community (IOCCG) and comes with a guide to aid users assess their uncertainties in a metrologically robust manner.

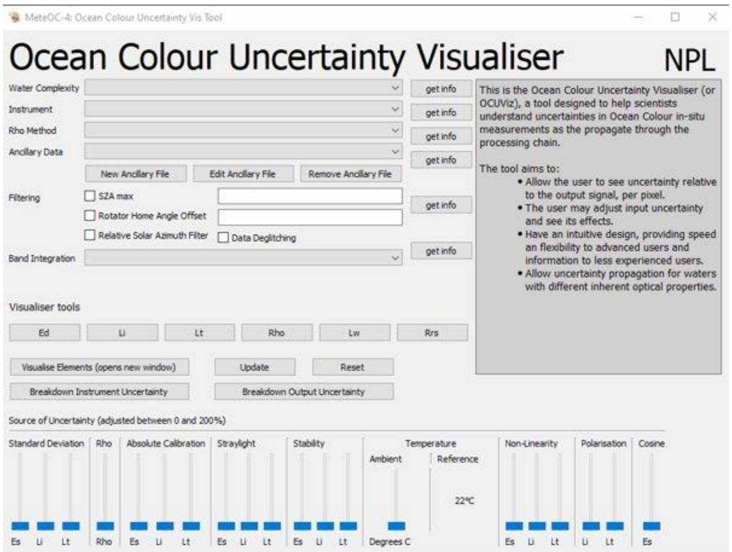


Figure 24: GUI of ocean colour uncertainty visualiser.

4.3.6: Sensitivity of OC climate records to parameter uncertainties.

Long time base studies, Climate Data Records, of ECVs like Ocean colour are essential to assess any change in the efficacy of carbon sequestration. These CDRs consequently require harmonisation of time series of different sensors. In MetEOC 4 we assess the sensitivity of various satellite missions to uncertainties in parameters contributing to their determination of an OC CDR, for example Aerosols, water vapour, wind speed etc. Figure 25 provides an illustration of this sensitivity analysis.

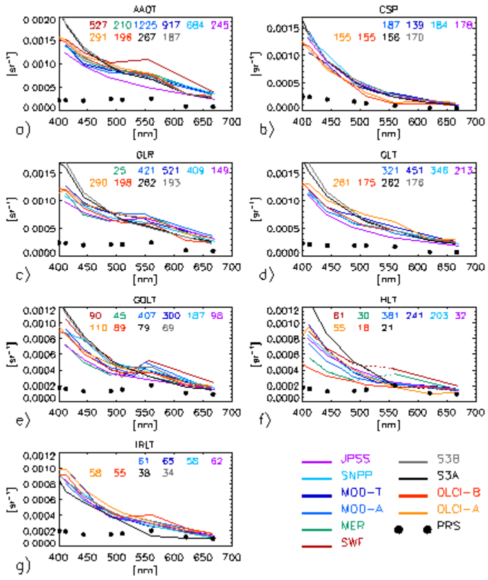


Figure 25: sensitivity to various parameters for various satellite missions in determining water leaving radiance.

This study was further extended by an uncertainty assessment of the impact of this uncertainty in the derivation of the higher level biological product (primary production) in effect health of the ocean phytoplankton. This propagates uncertainty from water leaving radiance in combination with biomass transformation models.

4.3.7 Uncertainty in satellite methane detection

There are a rapidly increasing number of satellites designed specifically to measure GHGs, with many commercially operated, particularly targeting local, high volume methane as an emitting source. In MetEOC 4, NPL explored from first principles, uncertainties associated with the retrieval methods for detecting Methane from satellites. Since most retrieval algorithms are considered commercially sensitive, NPL built a basic retrieval algorithm to enable sensitivity testing.

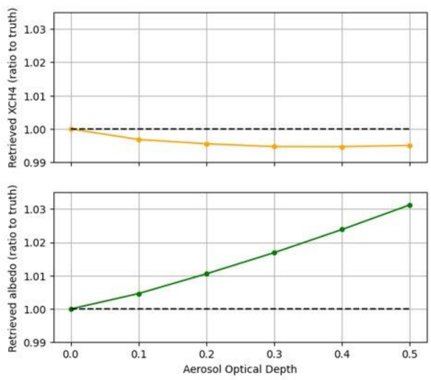


Figure 26: Sensitivity of methane retrieval to Aerosol.

The Methane atmospheric signature is in effect an enhancement of the background signal in the spectral region around 1600 and 2300 nm. However, except where the background signal from the surface or atmosphere is highly uniform and sufficiently low compared to that from the methane that allows a simple contrast to be used, we need to account for these sources of error. Fig 26 shows the sensitivity analysis for the major atmospheric correction, aerosol and its impact on surface albedo. For Aerosols the effect of a 0.4 AOD error lead to a 0.5% underestimate of methane and also around 2.5% error in determining albedo, which correlates exactly with the ability to detect a signal. Future work will refine this study utilising real retrieval algorithms and uncertainties associated with other satellite observation characteristics.

Objective 4: Develop instrumentation and standards to improve traceability and performance of remote sensing techniques used in ground-based networks.

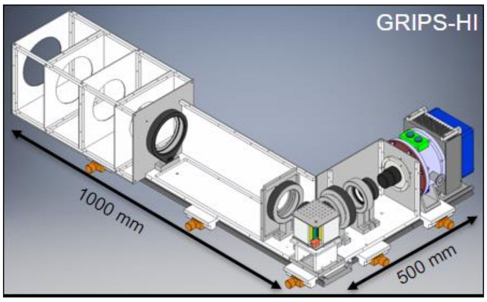
4.4.1 Introduction

Although MetEOC-4 concentrates on improving remote sensing techniques of the Earth from space/airborne platforms, to facilitate the global large area sampling needed for climate, some observations are most effectively made from the surface. For these, to obtain some degree of global representativeness, we need to establish networks of sensors. These networks need to make coherent and consistent observations and utilise similar instrumentation under a wide range of environmental conditions.

In MetEOC-4 we consider the needs of some of these networks where remote sensing techniques are used. In some cases, they complement other observations and in others they are standalone. In all cases the networks are international in nature, and many are operated under the auspices of WMO.
Our example case studies described below show the progress made by MetEOC in demonstrating the benefit of SI-traceability to ground networks, partiuclarly those of NDMC and WMO – WRR and WISG radiation scales. Both these latter two are now fully SI-Traceable a major step forward for the WMO.

4.4.2 Traceability for Network for Detection of Mesospheric Change (NDMC)

The mesopause region of the atmosphere is a sensitive indicator of climate change. ‘Airglow’ emissions in the near infrared (~1500 nm) as a result of OH reactions are measurable from the earth’s surface and are sensitive to temperature. The NDMC network has a number of stations around the globe but require improved sensitivity and uncertainty.
In MetEOC-4, PTB and BUW continue progress from previous MetEOC projects with an evolution of the design of a spatial heterodyne spectrometer (similar to that flown in space in object 1) called GRIPS-HI and its characterisation see Fig 27.



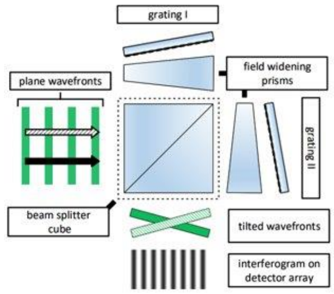


Figure 27: schematic showing GRIPS-HI spectrometer.

The performance of this new version of GRIPS compared to that developed under MetEOC -3 can be seen in Fig 28 where a near 10 fold improvement in performance is obtained, leading to temperature detection change of around 1 K as needed by the network.

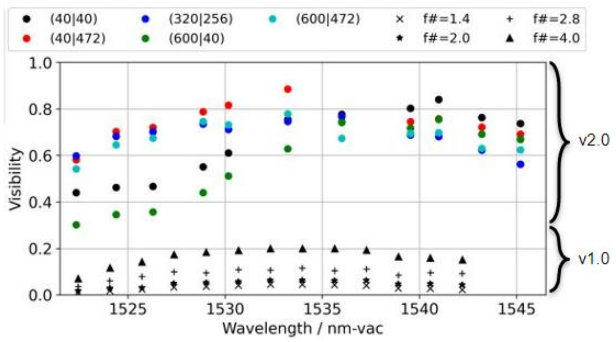


Figure 28: Change in visibility (sensitivity) of emission lines of version 2 of GRIPS, compared to that of V1

4.4.3 WMO World Radiometric Reference (WRR)

During the MetEOC series of projects, SFI-Davos supported by NPL have been developing and refining the Cryogenic Solar Absolute Radiometer (CSAR) and associated facilities to be adopted as an SI-Traceable replacement for the artifact based WRR. The WRR being a reference scale for the measurement of incoming Total solar irradiance at bottom of Atmosphere a key value in terms of understanding radiation budget. In this project PMOD evaluated the impact of diffraction and the scale/uncertainty of its correction for different atmospheric composition and paths. The results of this assessment can be seen in Fig 29.

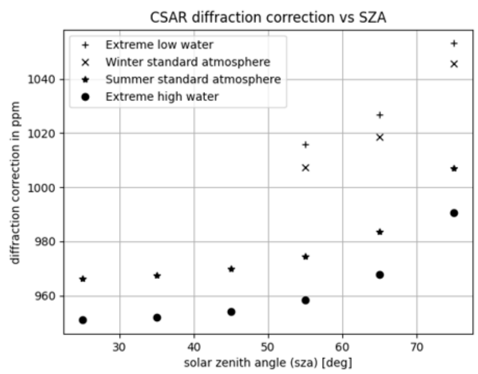


Figure 29: CSAR diffraction correction as a function of season (Water vapour/aerosol content) and solar zenith angle (amount of atmosphere).

SFI-Davos, NPL and PTB as part of the WMO expert team reviewed the results of CSAR and other instruments from the world solar measurement community that took part in the 5 yrly international comparison. The conclusion was a recommendation that the scale be changed to that derived from CSAR leading to a correction of ~0.3% to the previous scale see Fig 30.

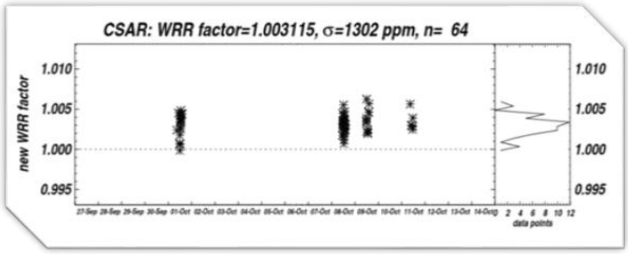


Figure 30: correction to WMO WRR from CSAR based realisation.

4.4.4 Atmospheric downwelling infrared radiation

The amount and spatial distribution of thermally emitted (infrared) radiation from the sky is an important contribution to our understanding of the Earths energy imbalance and associated attribution. In MetEOC-4, SFI-Davos supported by PTB have developed and characterised instrumentation to improve the primary reference scales and observations. This work has been complemented by the commercial instrument manufacturer HUS to take forward some of the improvements into the market place facilitating wider exploitation and international uptake.

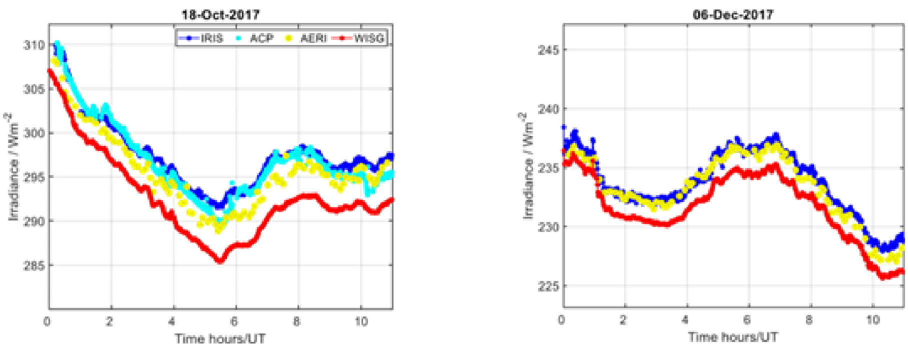


Figure 31: Downwelling longwave irradiance measurements from IRIS (blue), ACP (magenta), AERI (yellow), and pyrgeometers traceable to the WISG (red) at SGP for 18 October 2017 (left) and 6 December 2017 (right). The IWV was 11.2 mm on 18 October and 5.3 mm on 6 December.

The WISG, maintained by SFI-Davos on behalf of WMO, is an artifact-based scale reference for downwelling atmospheric infrared radiation. However, it has been noticed that two candidate technologies to replace the current reference instruments have shown significant (5 wm-2) differences and seasonal variation, which given an uncertainty goal of 0.5Wm-2 is of great concern, See Fig 31 showing results of a comparison in 2017 where the red represents the WISG, blue IRIS, magenta ACP and AERI yellow, (ACP and IRIS are the candidate replacements with AERI a complementary instrument).

In MetEOC 4 following a series of comparison experiments between the two candidates and the WISG SFI-Davos have confirmed that the cause is due to a high sensitivity to water vapour for the existing WISG radiometers see fig 32.

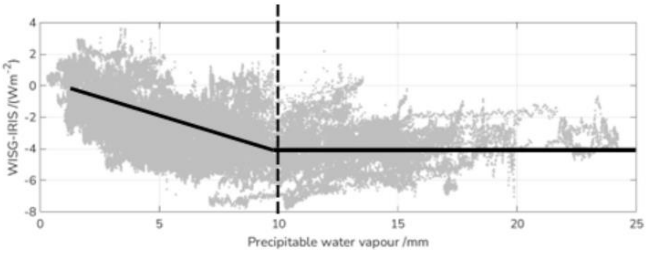


Figure 32 sensitivity of WISG compared to IRIS one of the candidate missions

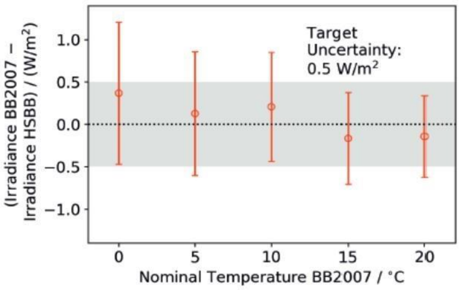


Figure 33: Difference between the BB2007 and HSB radiometers with the error bars indicating the combined standard uncertainty.

SI-Traceability for the IRIS radiometer has also been affirmed through a comparison of its calibration against two independently realised black body scales: the BB2007 of SFI-Davos and the HSBB designed and built by PTB in MetEOC 3. The results shown in Fig 33 show agreement within the combined uncertainties and at a level commensurate with the target of 0.5 Wm-2.
Traceable to the WISG (IRIS) SFI-Davos have built a radiometer for angular resolved infrared sky radiance. The IRCCAM has a resolution of 480 X 640 pixels and has been calibrated to an uncertainty of ± 0.5K at ~260 K brightness temperature against the BB2007 and the camera has a homogeneity of response of ±138 mK. see fig 34.

Figure 34: IRCCAM deployed in Davos.

Fig 35 shows the results of using the IRCCAM, and its ability to be used for night cloud detection and validation of satellite observations.

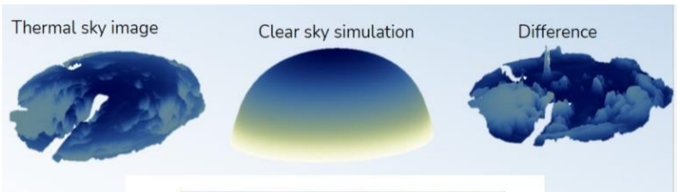


Figure 35: Utilisation of IRCCAM to detect angular variation through comparison of simulation and observations.

4.4.5 Development of a spectrally flat pyrgeometer

Pyrgeometers are widely used instruments for measuring sky irradiance and are typically the working instrument used by radiation networks for climate and weather and are calibrated traceable to the WISG. Such instruments often have silicon domes to filter our sunlight allowing the instruments to be used night and day.
However, one of the challenges for these instruments is the calibration over a very large spectral range typically to 100 microns and spectral variations in the detector head and In transmittance of the window limits attainable performance and calibration costs.

In MetEOC 4 SFI-Davos, PTB and the commercial manufacturer HUK have developed a new spectrally flat pyrgeometer. In this case making use of carbon nano tubes as the spectrally flat thermopile detector coating and a diamond window. The resultant instrument is shown in fig 36 together with the spectral properties of its coating and window.

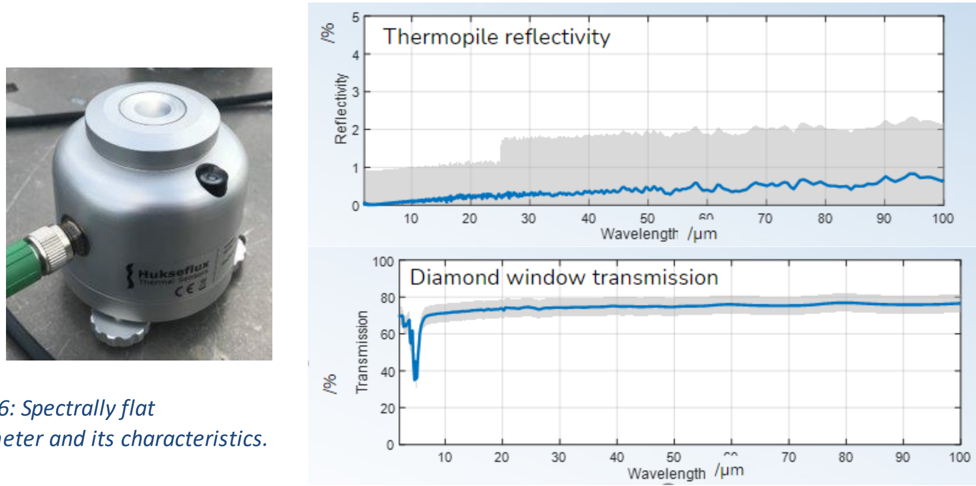


Figure 36: Spectrally flat pyrgeometer and its characteristics.

The new pyrgeometers have been deployed on the external measurement platform in Davos for more than a year and shown very good stability, see Fig 37 making them highly suitable as transfer standards and operational network use. HUK is now looking to commercially exploit the new instruments.

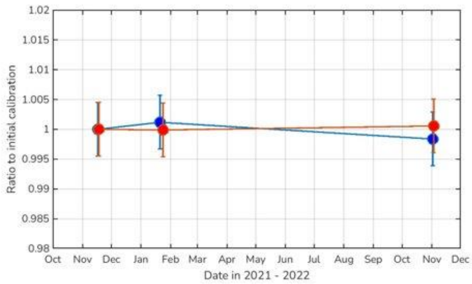


Figure 37: Comparison of two pyrgeometers against the IRIS reference instruments.

5 Impact

At conclusion of this project, we have published 28 papers, presented 47 papers at 26 international conferences, and supported two WMO standards committees, the latter by three separate institutes of the project. There are several papers that have or will be submitted based on work performed in this project and In addition, significant effort has been started to refresh and update the external website to make it more accessible and navigable to stakeholders. The value and heritage of this website is such that it will be maintained and updated going forwards as a resource to the community.

The primary impact of this project stems from its contribution to provide trustworthy evidence to policy makers on the scale and timescales of climate change so that they can implement timely and measured mitigation/adaptation strategies to ensure a sustainable environment and quality of life for European citizens. As part of this activity we (Surrey supported by NPL) undertook a small non technical study to assess how QA metrics may have an influence on decision making in mitigation and adpatation strategies.The overall goal has and continues to be achieved by improving the quality of remote sensed data, and will lead to the following impact:

Impact on industrial and other user communities

Satellite builders now have access to flexible, multi-functional transfer standards to improve pre-flight accuracy whilst reducing time and cost for calibrations, demonstrating the potential of high-quality data from microsatellites. The NPL STAR-cc-OGSE facility, built with funding in MetEOC3 (and developed further in this project) has successfully completed the pre-flight calibration of the CNES/UKSA MicroCarb CO_2 satellite in

November 2022, the MicroCarb payload is now in an integration phase before launch in 2024. The facility has also been identified as suitable for the TRUTHS mission.

International test-sites (radiometric and bio-physical) and networks together with associated 'good practices' have been supported with traceability and uncertainty evaluations to help validate post-launch satellite Level-1 and Level-2 measurements and other climate variables. This is an ongoing impact with more than 800 registered users using the RadCalNet data that this project has supported.

Development and calibration of novel instrumentation for both satellites and ground measurements will 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.

Robust data and methods developed in the project to assess and ascribe uncertainties on EO/climate information that is also readily interpretable will be invaluable to policy makers and climate risk-sensitive sectors such as insurance, energy, and agriculture. This will become particularly critical as governments look towards regulations for mitigation and the means to audit for example the carbon stocktake stemming from Paris-2015.

Although not necessarily climate driven, the exponential growth in commercial EO and climate services are driving the need for 'Analysis Ready Data' (ARD), and seamless supply of interoperable data to fuel the appetite for 'information-on-demand'. Interoperability fundamentally requires knowledge of biases and uncertainties under a range of conditions explicitly enabled by this project.

Impact on the metrology and scientific communities

This project has contributed to the creation of long-time-series datasets from multiple sensors with robust quality metrics, allowing European 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. The science community has engaged with the project team to build-upon ideas developed in MetEOC and is now exploiting them through other complementary projects, of ESA, Eumetsat and EU.

Coordination of metrology efforts across NMIs reduces costs and unnecessary duplication leading to more efficient use of resources and comprehensive delivery to the stakeholder community. This project has supported the new EMN for Climate and Ocean Observation, through the provision and assessment of needs from its already established stakeholder community to the benefit of other NMIs. Similarly, this has been undertaken within the BIPM/WMO workshop where many of the results from this project were presented.

The performance demanded by the EO/Climate community leads, in some cases, to solutions migratable into other sectors.

The primary intermediary stakeholder for EO/climate data is the science community, who are looked to for the interpretational science to translate the data into useable information for the higher-level user such as policy makers. These scientists will not only benefit from more reliable data to anchor and test models but also tools to help engage with users and sensor builders – the language of metrology when used correctly pervades across all user types and disciplines. This project has helped to build these 'thesaurus bridges'. One outcome was the creation of a schematic framework to help guide how metrology and climate can interact and this was presented at the BIPM/WMO workshop.

Impact on relevant standards

The project's activities were carried out in close collaboration with key international coordinating bodies (e.g. CEOS, WMO ensuring good practices are established, and any community references become de-facto standards. The project team has ensured that they work closely with the community to encourage the uptake and inclusion of SI-traceability in any standardisation process particularly as we move into a realm of ARD and climate services. Formal ISO-like standards for many 'remote-sensed' observations are still some ways away due to the complexity and variety of sensor types. However, some efforts are in progress for specific sensor types e.g. IEEE (hyperspectral sensors) and WMO CIMO. Community specific 'standards', such as those derived from ESA/EUMETSAT or EU services like Copernicus are all being expressly engaged as part of the project, through active participation in their working groups, for example in the WMO expert team on radiation four members of the MetEOC team from 3 institutes have revised the underpinning guidance documents defining the standards: world radiometric reference and world infrared standard group. The IEEE hyperspectral standard is nearing its final voting stages with inputs from the team and a CEOS good practise guide for validation of surface reflectance and use of drones is nearing completion in a coaligned ESA project.

Longer-term economic, social and environmental impacts

The societal challenges and consequences this project addresses are second to none - climate change and its impact on quality of life of EU and global citizens. Robust unequivocal evidence of the scale of change, its attribution and the results of mitigation can only be determined by remote sensing. These data/information sources need to be immune from ambiguity and challenge and trusted sufficiently that they can be considered of litigation quality. These fundamentally require evidenced traceability to community accepted references, at the highest-level, SI units, and the means for these to be independently assessed. In essence, it is the consequences and costs - financially and lives - that this project has helped to mitigate against, that sets this project apart and underlines its success and urgency for continuance.

Environmentally – This project has been fundamental to our understanding and long-term sustainability of our environment. Climate change itself and its likely consequences are well-understood but the benefit to operational monitoring of the environment through remote sensing should not be ignored. Greater accuracy and reliability lead to more sensitivity and ability to de-convolve information. This in turn leads to earlier identification of potential issues and more reliable quantification of environmental challenges, including pollution, land-cover change and coastal erosion.

Socially – This project has provided information to enable fit-for-purpose mitigation and adaptation strategies to be defined and implemented. This will ensure that citizens' health and standards of living are optimum in a world suffering from a changing climate. It will help to ensure long-term food security for those most seriously impacted by climate change and timely decisions on investments for flood protections such as a new 'Thames barrier'.

Financially – The most obvious benefit stems from optimising the European response to climate and other environmental effects as a result of more timely and reliable information, derived from instrumentation with better more trustworthy calibrations, as a consequence of this project. Additionally, tailored standards and reduced uncertainty allow more efficient and cost-effective calibration, which in a space project can be very expensive due to the special facilities required. Similarly, automation of test-sites has and will continue to lead to better data and fewer expensive site visits. In the longer-term carbon trading markets using forests as stores such as REDD+ and the carbon stocktake will need remote auditing to confirm declared inventories. The size of this market is estimated as many $B per annum.

6 List of publications

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