Publishable Summary for 19ENV07 MetEOC-4
Metrology to establish an SI-traceable climate observing system

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.

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.

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).

Progress beyond the state of the art

Significant progress, (e.g. MetEOC projects), has been made in creating awareness of the benefits of SI-traceability and evidencing the willingness and capabilities of European NMIs to address the needs of the EO/climate community. However, the challenge remains enormous. ESA, EUMETSAT and the EU now have confidence that SI-traceability is possible and something to strive for.

This project has extended state-of-the-art pre-flight techniques to address challenges of new missions where high-accuracy SI-traceability (demands of climate) are critical. For example, the ESA FORUM mission, needs spectral scales extended from 50 to 100 µm and uncertainties equivalent to <0.1 K. TRUTHS, prototyped in MetEOC, is now an ESA Earth Watch mission, aiming to replicate NMI capabilities in space needs pre-flight calibration to match. In-flight standards to maintain traceability for limb-sounders on stratospheric balloons will also be developed. All of these have been achieved or progressed significantly as a result of this project.

Operationalisation of CEOS Cal/Val test-sites e.g. RadCalNet, needs extension from 'bright targets' to biophysical surfaces requiring challenging spectral/spatial corrections. This project has addressed the metrology needed to underpin these sites although the scale of the challenge means this is far from complete. Long-time-base datasets together with operational temporal continuity need scene/pixel dependent uncertainty characterisation – techniques using machine learning have been explored and will continue into the future. Furthermore, transformational algorithms such as radiative transfer codes have been metrologically evaluated in physical and virtual environments.

The objective to initiate development of a strategy and methods to establish traceability and evaluate associated uncertainties of retrieved GHG inventories at power-station/city-scale has progressed significantly and there is now a prototype certification service under-development partly as a result of this project. The project has continued work to quantify the uncertainty of Carbon stored in sinks such as forest biomass and ocean phytoplankton and again as expected, remains work in progress. This includes retrieval algorithms and 'ground-truthing'. The optical domain provides critical insight on health and classification of the biosystem, and this has been complemented by Synthetic Aperture Radar (SAR) where clouds are transparent. This project has expanded validation methods to combine drone-based SAR and optical observations assigning, for the first time, uncertainties based on combined observation techniques have been realised.

The artefact-based WRR (World Radiometric Reference) is close to replacement by an SI standard, CSAR, having participated in two WMO comparisons. However, for full acceptance, further work to operationalise and remove associated uncertainty in the measurement of window transmittance and diffraction was required. Other scales e.g., WISG (World Infrared Standard Group) has received attention in MetEOC-3, with an initial design of a calibration source. This source required full characterisation before calibrating the WISG radiometers. This project has also made possible spectral and spatially resolved measurements of infrared sky radiance resulting in information to understand the observed discrepancies between different pyrgeometer types and unexplained dependence with atmospheric opacity. A new pyrgeometer taking account of these effects was designed and built.

The project has contributed to extending traceability and performance to the full NDMC (Network for the Detection of Mesopause Change). This will be combined with a complementary space measurement of the mesopause using a next-generation spectrometer to close the metrological circle, on-board a CubeSat, fully calibrated in this project.

Results

Objective 1: Pre-and 'on-board' calibration of satellite/airborne sensors

- Analysis of the detailed requirements for the TRUTHS mission have identified the primary challenges that need to be addressed from a pre-flight calibration facility: 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. First design plans have been carried out and submitted to ESA for review. A paper summarising the facility has been submitted and undergoing final peer review. The limitations and areas needing to be addressed to improve the uncertainty in the traceability to SI have been completed and a realisable development plan and anticipated uncertainty budget developed.
- In terms of FORUM the requirements for a Far Infrared gonio reflectometer to characterise the reflectance coatings needed by the sensor and its calibration system have been completed and the first design study performed. In parallel, the reflective properties (closeness to Lambertian) of a number of candidates 'surfaces' has been modelled and the best candidate (machining with 3D printing) has been prototyped and modelled angular reflective properties verified using a THz laser. The integrating sphere based on this surface has been manufactured and tested successfully for vacuum compatibility. A new calibration reference black body has also been designed to allow traceability to 100 µm requiring uncertainty in T to <15 mK around ambient. All components to realise the capability have been purchased and are due for installation by November with final testing by early 2024.
- In the Mid-IR range, black coatings for the target, and white for thermal management, have been evaluated for use as the reference black body for the GLORIA balloon experiment together with surface topology to provide an optimum, mass to performance, in-flight calibration system. The prototype balloon blackbody together with previously built Black Bodies for the aircraft GLORIA have all been calibrated and shown to have adequate performance also demonstrating long-term stability. A first flight indicated some residual effects due to sunlight and this has resulted in an updated design which is now waiting for a flight test.
- An updated design of a calibration system for SHIPAS (Spatial Heterodyne Interferometer Performance Assessment in Space, a satellite sensor for measuring temperature of the Mesosphere, via airglow) has been completed and the characterization of the wavefront (radius of curvature) using a shearing interferometer with specially developed software and a reference collimator is in progress. Other properties such as homogeneity is under evaluation so that the resultant uncertainty budget can be assessed. More recently a simulation study leading to a strategy for in-flight stray light evaluation has been completed and will be ready for implementation following launch. This has been complemented by a rigorous experimental stray light evaluation under vacuum and flight representative conditions. This has allowed an improved baseline for the subsequent in-flight characterisation using the moon and Venus post-launch.

This objective was achieved with successful case studies illustrating significant progress in different spectral domains.

Objective 2: Calibration, validation, and uncertainty of 'delivered' bio-geo physical data/information products from remote sensed data.

- Software tools to evaluate the impact of spatial uniformity, angular views, and spectral differences between sensors viewing test-sites have been developed and tested to evaluate uncertainties achievable for different types of surface test-site (deserts, snow, water, vegetation etc) and the respective number of samples needed for a particular uncertainty level to be realised. An agreement has been reached to allow data from the hyperspectral sensor PRISMA to be used for these evaluations. These tools have been made available to the community via an ESA managed website and their use has been reported on by several research groups.
- The inherent stability of the moon makes it an ideal calibration reference providing a robust radiometric

value can be assigned to its radiance as a function of its cycle. A software model of the moon irradiance and consequently reflectance as a function of phase based on surface-based observations derived from an independent ESA project is progressing well, as are discussions on the proposed collaboration and comparison with the NASA Air-LUSI project which will make aircraft based lunar observations.

- A sensitivity analysis using the ERADIATE RT code has been carried out to assess the optimum criteria for the characteristics of an artificial target capable of assessing the performance of the code. This work proved more challenging than anticipated but has now been completed. In parallel, choice of suitable materials for the target has been carried out and a design developed. Samples of the candidate materials have now been characterised within the goniometer facility and have been analysed. A paper presenting the results is in the process of completion.

The case studies we undertook were successful and addressed the needs expressed by the objective which by its nature remains an on-going challenge.

Objective 3: Satellite-based methods to support GHG monitoring for the Paris agreement: emissions and sinks.

- A metrological review of satellite GHG retrieval algorithms has been carried out and compared with the likely capabilities of next generation sensors. As a case study, a model of the retrieval algorithm for the GOSAT, GHG mission in terms of uncertainty has been constructed and used to investigate the critical dependencies and sensitivities.
- Work to develop guidelines for assessing uncertainty for ocean colour measurements (GHG sink) has progressed well and resulted in seven publications and presentations leading to the initiation of a formal report within the international coordinating body. Analysis to assess variances between satellite observations and those in-situ from reference networks such as Aeronet-OC was completed showing consistency within uncertainty budgets and have now been published. A tool to aid users assess uncertainty for OC measurements has been developed and made available via a community website and an assessment of the end-to-end uncertainty of the marine carbon cycle has been advanced significantly with a metrology approach embedded in the assessment of the effectiveness of this natural carbon sink.
- For land biomass applications and GHG sinks, all fieldwork needed to produce a new forest model have been completed and are currently being processed. This is moving towards an estimate of the change in biomass at Wytham Woods over 7 years. This follows from a newly published article which shows that the carbon storage of Wytham Woods (and by implication much of the UK and Europe) is actually close to two times larger than previously thought. A new drone for solar reflective measurements has been procured as has one for SAR measurements. The latter has been optimised with the SAR system and has been tested over a local site. This test flight has allowed the specially developed processing software to be tested demonstrating capabilities to retrieve detail in the 30 m high tree canopy that it observed. Work has been carried out to evaluate the retrieval code and how optical (lidar) and SAR data for the same scene, Wytham woods, has been compared. The optical drone has been used to perform comparisons with Sentinel 2 and further evaluations carried out to optimise sampling strategies. This has been enhanced in an international domain through collaborations within a sister ESA funded project to define community best practises. An assessment of the uncertainty of the in-situ FLOX meters, to serve as references for the fluorescence measurements of the ESA FLEX mission has been completed; this has included measurements of spectral and stray-light characteristics.

The example activities we undertook demonstrated significant progress towards the overarching ambition expressed by this objective, in particular continued progress to better quantify the efficiency of carbon sinks in the oceans and land was a success.

Objective 4: Traceability for surface-based networks using remote sensing.

- The new reference black body for the WISG, developed in MetEOC-3 has been compared with the primary ammonia reference heat pipe black body. It has subsequently been compared against a pyregeometer, an IRIS radiometer and a previous reference black body of the World Radiation Centre, the results have shown consistency within the necessary 0.5 Wm2. The blackbodies have been used to evaluate other commercial pyrgeometers identifying similar differences due to spectral issues with window/domes as previous comparisons.
- Two new pyrgeometers, as prototypes for a spectrally-flat version, have been designed, built and

characterised differing by either flat or curved diamond window, and the thermopile heads coated with carbon nano tubes. These have now been compared with the WISG. Although proving highly stable after a 2-year deployment there appears to be an absolute difference when compared to the IRIS pyrgeometers that needs further investigation but can be effectively utilised through a relative calibration.

- A new angular resolving sky radiance meter has been designed built and tested resulting in a new capability to evaluate variations in sky radiance with an uncertainty of <0.5K effective Temperature. This instrument has been used to determine cloud fractional cover over the Davos site.
- Initial diffraction calculations for the CSAR have been carried out and to account for atmospheric properties e.g., aerosols, ozone, water vapour. These corrections are now being applied to the CSAR observations.
- A new reference instrument (GRIPS-Hi) for the NDMC network has been built and is undergoing uncertainty evaluation. The built instrument is a factor 10X better in sensitivity than originally anticipated and so it is hoped this will manifest itself in the necessary improved uncertainty. A full report summarising the successful activity is currently being written.

Under this objective we successfully demonstrated SI-Traceability for the WMO WISG scale and the refinements to the CSAR made it acceptable as a replacement for the previous WRR artifact-based scale. Together with achievements for the NDMC we have shown the benefit of SI-Traceabiliy to the surface network communities.

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. This 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 i2 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.

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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1st September 2020, 36 Months</td></tr>
<tr><td colspan="3">Coordinator: Professor Nigel Fox, NPL Management Ltd Tel: +44 20 8943 6825 E-mail: nigel.fox@npl.co.uk
Project website address: MetEOC Home - Metrology for Earth Observation and Climate</td></tr>
<tr><td>Internal Funded Partners:
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2. Aalto, Finland
3. CMI, Czech Republic
4. PTB, Germany
5. SFI Davos, Switzerland</td><td>External Funded Partners:
6. FZ-Juelich, Germany
7. JRC, European Commission
8. NLS, Finland
9. Rayference, Belgium
10. SURREY, United Kingdom
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