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 develops 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 is 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 focuses 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.

Objective-1: This project will extend 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.

Objective-2: 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 addresses the metrology needed to underpin these sites. Long-time-base datasets together with operational temporal-continuity need scene/pixel dependent uncertainty characterisation – techniques using machine learning will be explored. Furthermore, transformational algorithms such as radiative transfer codes will be metrologically evaluated in physical and virtual environments.

Objective-3: This objective initiates development of a strategy and methods to establish traceability and evaluate associated uncertainties of retrieved GHG inventories at power-station/city-scale. The project will continue work to quantify the uncertainty of Carbon stored in sinks such as forest biomass and ocean phytoplankton. This includes retrieval algorithms and ‘ground-truthing’. The optical domain provides critical insight on health and classification of the biosystem, and this is complemented by Synthetic Aperture Radar (SAR) where clouds are transparent. This project will expand validation methods to combine drone-based SAR and optical observations assigning, for the first time, uncertainties based on combined observation techniques.

Objective-4: 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 is 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 needs full characterisation before calibrating the WISG radiometers. This project will make 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 will be designed and built.

This project will contribute 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 particular challenges demanding nearly an order of magnitude improvement in accuracy compared to other missions.
- 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 candidate '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.
- 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.
- An updated design of a calibration system for the AtmoCUBE A1 satellite sensor for measuring temperature of the Mesosphere, via skyglow has been built and the nature of its wavefront (radius of curvature) measured using a large shearing interferometer and specially developed software. Other properties such as homogeneity are under evaluation so that the resultant uncertainty budget can be evaluated.

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.
- 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 radiance 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.

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 under investigation to assess the critical dependencies and sensitivities.
- Work to develop guidelines for assessing uncertainty for ocean colour measurements (GHG sink) is progressing with some early analysis being undertaken to assess variances between satellite observations and those in-situ from reference networks such as Aeronet-OC Current results indicated consistency within uncertainty budgets.

- For land biomass applications and GHG sinks, fieldwork has been delayed due to COVID. However, preliminary work to further improve the software model rendition of the Wytham woods site has been carried out but awaits new data when travel restrictions ease. 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 is also progressing to evaluate the retrieval code and how optical and SAR data for the same scene, Wytham woods, can be compared.

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 are currently being analysed.
- Two new pyrgeometers, as prototypes for a spectrally-flat version, have been designed, differing by either flat or curved diamond window, and the thermopile heads coated with carbon nano tubes. The characterisation and assembly will take place during the summer of 2021.
- Initial diffraction calculations for the CSAR have been carried out and are now being refined to account for atmospheric properties e.g. aerosols, ozone, water vapour

Impact

At this stage of the project it is too early to have any specific impact emanating from its results.

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 will 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 will 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 micro-satellites.

International test-sites (radiometric and bio-physical) and networks together with associated ‘good practices’ will be supported with traceability and uncertainty evaluations to help validate post-launch satellite Level-1 and Level-2 measurements and other climate variables.

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 contributes to 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.

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 will support the new EMN for Climate and Ocean Observation.

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 will help to build these ‘thesaurus bridges’.

Impact on relevant standards

The project’s activities will be 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 will ensure 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 way 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.

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 helps to mitigate against, that sets this project apart and underlines its urgency.

Environmentally – This project is 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 provides 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 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 will lead to better data and fewer expensive site visits. In the longer-term carbon trading markets using forests as stores such as REDD+ [1] and the carbon stocktake will need remote auditing to confirm declared inventories. The size of this market is estimated as many $B per annum.

List of publications

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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: www.meteoc.org</td></tr>
<tr><td>Internal Funded Partners:
1. NPL, United Kingdom
2. Aalto, Finland
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