Metrology for Earth Observation and Climate

EURAMET

Publishable Summary for 16ENV03 MetEOC3
Further metrology for Earth Observation and Climate

Overview

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

Need

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

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

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

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

Objectives

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

1. To improve the accuracy, accessibility, and usability of SI traceable standards in pre-flight and post-launch calibration and validation and enable interoperability and harmonisation of 'at sensor' remote sensed 'level 1' (e.g. radiance, reflectance, irradiance) products. This focused on transportability and the needs of small satellites (mass/size) through development of spectrally tuneable laser-based sources with an uncertainty of 0.5 – 2 % for pre-flight calibration. Post-launch mathematical methods to enable bias removal and sensor to sensor interoperability including further prototyping to increase the readiness and early implementation of an SI traceable reference satellite such as TRUTHS/CLARREO was also undertaken.
2. To further enhance the capabilities of autonomous 'SI traceable' networks of test-sites for the post-launch calibration and validation of sensors and their derived bio-geophysical products. This included uncertainty analysis, accounting for the "non-representativeness" of sampling, scaling and propagation to the sensor at Top of Atmosphere. It primarily focused on the uncertainty needs of Copernicus Sentinels S2 and S3 and their applications e.g. Ocean colour (Uncertainty <3 %) and vegetation Essential Climate Variables (ECVs) e.g. Leaf Area Index (LA) (accuracy <20 %).
3. To establish a method for assigning aggregated quality metrics to a broad range of bio-geophysical ECVs, long term climate data records (CDRs) and the monitoring of mitigation strategies, through 'end to end' analysis. This involved identifying gaps and weaknesses in retrieval algorithms, validation processes and use of historic data from extinct and not comprehensively characterised sensors such as the ATSR series.
4. To develop methods for enhancing the SI traceability of ground-based networks used for climate monitoring e.g. Broad band Solar Radiation Network (BSRN) of WMO and Network for Detection of Mesopause Change (NDMC). Emphasis was given to address community-based scales (e.g. World Infrared Standard Group (WISG) and World Radiometric Reference (WRR).
5. To facilitate the take up of the technology and measurement infrastructure developed in this and previous projects by the standards developing organisations, measurement supply chain (accredited laboratories, instrument manufacturers) and end users (environmental monitoring and regulation bodies such as the WMO and Group of Earth Observations (GEO)).

Progress beyond the state of the art

Much of the EO community now recognises the benefit of SI-traceability and its meaning. This has been enhanced through the development and application of visualisation diagrams describing the results of metrological analysis of sensors and their derived bio-geophysical products. However, the challenge to meet climate quality uncertainties for the majority of parameters still remains an aspiration that will take many years to achieve.

Laboratory pre-flight radiometric calibration methods have been established that largely meet user needs and this project has expanded these techniques further: increasing portability into clean room/vacuum conditions, wider and more automated spectral tunability and flexibility to allow easy adaptation to suit the emerging needs of small/micro satellites and spectrometers. In-flight on-board methods have continued to be developed and, in some cases, such as in-flight black bodies in earlier EMRP projects, have been further improved.

New sensors have been built and traceably calibrated to improve the sensitivity and accuracy of a range of in-situ field-based measurements, in particular, networks for monitoring change in ECVs, as well as those providing calibration or validation of satellite observations. This has included efforts to remove or reduce dependency on 'artefact' based standards, through development of SI traceable alternatives, for example the WMO networks for downwelling sky radiation and solar irradiance, improving uncertainty by a factor of two to ten.

Work started in EMRP project ENV53 MetEOC-2 to validate satellite observations of vegetation-based ECVs has been extended from the initial demonstration test site in Oxfordshire to evaluate how a virtual forest can be used to assess satellite performance and differences arising from definitions and assumptions.

Methods to enable sensor to sensor harmonisation and assess the resultant uncertainties in an internationally coherent manner have continued to be developed in collaboration with the world's space agencies through

CEOS (Committee on Earth Observation Satellites), leading to a major conference and report. The Metrological satellite reference TRUTHS has also been selected by ESA and is under formal development as part of the EarthWatch program.

Results

The project has undertaken a number of specific tasks to address the overall objectives.

Objective 1

Results summary

- Two independent tuneable laser-based calibration systems have been assembled and tested. The STAR facility, based on a tuneable CW laser, capable of a comprehensive range of pre-flight calibration and characterisation has being tested and deployed in France to calibrate the MicroCARB Greenhouse Gas (GHG) satellite sensor in France. The facility is a world first being able to provide a full range of radiometric calibrations both spectrally resolved and integrated at uncertainty levels below 0.5% and has attracted international interest. The complementary pulsed laser facility has also been used to perform a calibration of the Tropolite cubesat satellite instrument and showed a factor two improvement over conventional calibration methods.
- A simulation of how well the STAR system would improve the calibration of a hyperspectral sensor (airborne APEX sensor) has been made and led to a more detailed assessment of the impact of slit shape in radiometric performance.
- A novel method for evaluating and correcting for temperature non-uniformities of black bodies has been developed and tested in the laboratory but due to inherent detector temporal variations cannot be directly incorporated into the processing chain of GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere). However, an assessment of how the improved homogeneity obtained impacts the retrievals of trace gases has been carried out
- Although not fully implemented, a new facility for the calibration of the spatial heterodyne interferometer for the cubesat sensor ATMOCUBE A1 has been built and tested demonstrating adequate spatial uniformity.
- The TRUTHS satellite mission has been selected for development by ESA and analysis work carried out to evaluate the optimum spectral bandwidths and wavelength accuracy are needed to achieve <0.3% uncertainty in cross-calibration of other sensors.

Objective 2

Results summary

- All documentation and procedures for Committee on Earth Observation Satellites (CEOS) Radiometric Calibration Network (RadCalNet) have been written. The latter following a field campaign to the European Space Agancy/Centre National d'Etudes Spatiales (ESA/CNES) site in Gobabeb Namibia where both drone and surface measurements were undertaken and a review of the impact of spectral resolution used to improve the performance of the RadCalNet service. Since opening to the public it has more than 700 unique customers registered and a paper on the network has now been published. This network is highlighted by space agencies and commercial satellite developers as a major asset.
- New facilities to allow SI traceable measurements of BRDF (Bidirectional reflectance distribution function) in the horizontal plane for materials such as sand have been built and tested. Although the facility exists and operates successfully, results indicate that sand changes significantly between the field and the laboratory, probably in terms of grain size mixing and resulting biases mean further work is needed for this to find useage in the intended remote sensing application. However, the facility will find use for calibrating BRDF of similar materials such as powders
- The woodland site at Wytham woods has formally been designated a ‘CEOS super-site’ for validation. It has been used as a site to develop methods for comparisons of different field sensors and methods for an ESA funded CEOS project. A characterisation of a Finish forest test site has been carried out with a new hyperspectral camera on-board a drone. Evaluation of sampling (height, flight path etc) were undertaken as a basis to develop an optimal strategy. Comparisons of the site as viewed by satellite sensors such as Sentinel 2 and that created as a virtual model have shown that there can be significant differences for land products such as Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) and Leaf Area Index (LAI). However, when taking account of differences in definitions and assumptions these differences can

be significantly reduced illustrating the importance of clear consistent definitions.

- A community workshop and questionnaire has led to a comprehensive specification of a new SI traceable radiative transfer code, now called ERADIATE. A dedicated website for community interaction has been created and the significant interest and momentum attracted additional funding from ESA to enable its full development. The general design document (architecture/interfaces) has been written and published on the ERADIATE website.
- A detailed analysis of the non-linearity characteristics of existing in-situ radiometers for measuring the reflectance of the ocean has been carried out and an assessment made of the impact of these and their correction on ocean colour products. This has been further extended to develop a specification for an optimal next generation sensor, which has been prototyped and tested. The new prototype provides a factor ten improvement in performance over the existing radiometers and will look to be developed into a commercial product.

Objective 3

Results summary

- Following initial discussions with ESA and other relevant parties, this project undertook an initial gap analysis and understanding of the basic measurement equation for both SLSTR and OLCI sensors on-board Sentinel 3. As a result, a more detailed metrological analysis has been carried out with uncertainty tree diagrams completed for both sensors and parametrisation of the equations. This activity allowed training to be given not only internally but also externally at several workshops (ESA and FRM4SOC), using the diagrams as an example of the approach. The uncertainty budget developed for SLSTR has been validated from results obtained during the Tandem phase of Sentinel 3A and B. Similarly, for OLCI work, ESA is now looking to enable the uncertainty philosophy to be embedded in the ground segment.
- A detailed analysis of the Ocean Colour system vicarious calibration method has resulted in a graphical uncertainty tree representation (FIDUCEO like). This has been parametrised with realistic uncertainty estimates for many of the ancillary parameters, such as wind speed, water vapour, aerosols etc. Analysis of the total end to end uncertainty budget has been carried out for local specific sites and global maps. The results show that uncertainties of a few percent can result from uncertainties in some of the parameters and/or choice of their source. Whilst not dominant in current applications, with the arrival of sensors like TRUTHS these will start to become significant.
- Similar end to analysis has been carried out for the atmospheric products of the GLORIA instrument extending the work of Objective 2.
- The use of uncertainty trees was also applied to some new sensors under development during the design phase as a means to carry out a sensitivity analysis on the critical design aspects.
- The success of the methods developed and demonstrated in objective 3 has led to several new projects from ESA seeking to further explore and exploit the methodologies.

Objective 4

Results summary

- For the NDMC (Network for Detection of Mesospheric Change), a reference spectrometer design based on a spatial heterodyne spectrometer, has been found suitable to meet the design criteria. A first prototype instrument has been built and a calibration reference source also built and characterised. Although due to COVID the new sensor has not yet been calibrated by the new source its performance is expected to be enhanced by a factor of ten compared to previous instruments and significant interest from the NDMC annual conference.
- A design for a reference black body to provide traceability to the World Meteorological Organisation (WMO) World Infrared Standard Group (WISG) has also been completed and two versions to evaluate different coatings built and tested demonstrating adequate temperature uniformity. Traceability to a reference ammonia heat pipe black body has shown consistency over an operating range of -25 to 45 C. The black body has been used to perform an initial calibration of a pyrgeometer and indicates that the intended factor two improvement in accuracy will be achieved.
- The IR spectral response and temperature sensitivity of the current reference instrument of WISG has been completed.
- A new reference block for the window transmittance facility needed as part of the World Radiometric

Reference (WRR) realisation has been built to reduce noise. Software to improve the operational mode of the CSAR has been built and tested. The software allows a more dynamic control which allows faster measurements less sensitive to ambient changes.

Impact

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

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

Impact on industrial and other user communities

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

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

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

Impact to metrological and science communities

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

Impact on standards

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

Longer-term economic, social and environmental impacts

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

- Upgrade in performance of instruments

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

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

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

List of publications

- Talone, M., (2018). *Non-linear response of a class of hyper-spectral radiometers*. Metrologia, *55* (5), 747-758, https://doi.org/10.1088/1681-7575/aadd7f
- Calders, K., (2018). *Realistic Forest Stand Reconstruction from Terrestrial LiDAR for Radiative Transfer Modelling,* Remote Sensing, https://www.mdpi.com/2072-4292/10/6/933
- Bouvet, M., (2019), *RadCalNet: A Radiometric Calibration Network for Earth Observing Imagers Operating in the Visible to Shortwave Infrared Spectral Range*, www.mdpi.com/2072-4292/11/20/2401
- Bialek, A., (2020). *Monte-Carlo based quantification of uncertainties in determining ocean remote sensing reflectance from underwater fixed-depth radiometry measurements*, https://doi.org/10.1175/JTECH-D-19-0049.1
- Berg, S., (2021), *Calibration of a CubeSat spectroradiometer with a narrow-band widely tunable radiance source*, https://doi.org/10.1364/AO.417467
- Smith, D., (2021), *Traceability of the Sentinel-3 SLSTR Level-1 Infrared Radiometric Processing*, https://doi.org/10.3390/rs13030374
- Hunt, S., (2020), *Comparison of the Sentinel-3A and B SLSTR Tandem Phase Data Using Metrological Principles*, https://doi.org/10.3390/rs12182893
- Ma, L., (2020), *Uncertainty Analysis for RadCalNet Instrumented Test Sites Using the Baotou Sites BTCN and BSCN as Examples*, https://doi.org/10.3390/rs12111696
- J. Kuusk, (2018), *Implication of Illumination Beam Geometry on Stray Light and Bandpass Characteristics of Diode Array Spectrometer*, DOI: 10.1109/JSTARS.2018.2841772

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

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

Project start date and duration:	01 September 2017 (42 Months)	
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