Metrology for Earth Observation and Climate

EURAMET

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1 Executive Summary

Overview

Remote sensing of the Earth from space is vital for obtaining the global data needed to underpin climate change research and its impacts, including flooding and agriculture, and to identify potential environmental issues such as pollution and coastal erosion. Satellites need to detect often subtle changes in Essential Climate Variables (ECV; identified by experts for the United Nations Global Climate Observing System, (GCOS), such as total solar energy and sea surface temperature, of a few tenths of a per cent per decade. The performance of satellite instruments is prone to degrade due to the harshness of launch and environmental conditions in space. They therefore generally need to be re-calibrated and always validated in orbit to guarantee the reliability of the data they collect.

This project aligns with and contributes to the international effort establishing some of the tools, methods and infrastructure to help assign reliable traceable confidence levels to climate change monitoring data, with the long term aim to meet stakeholder needs by establishing a virtual centre of excellence.

Need for the project

"Warming of the climate system is unequivocal. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased. It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century". Intergovernmental Panel on Climate Change (IPCC) - Sept 2013. Although true, society needs to understand what the scale and timing of these changes are, and needs to understand what actions we can take to slow the change down. It is also important to know the optimum adaptation strategies and the impact our actions are having.

Remote sensing of the Earth from space is in many cases the only way of obtaining the global data needed to underpin climate change research. Physical ECVs, such as atmospheric and surface temperature as well as biophysical such as leaf area index and ocean colour which can act as sinks to absorb carbon dioxide, (its anthropogenic emission generally believed to be the cause of warming), are monitored to detect the small fluctuations which may reveal changes in the Earth system. In most cases, detection of changes of a few tenths of a per cent per decade of the physical measurand are required, relying on measurements with uncertainty levels currently only realisable in National Metrology Institutes (NMIs).

The harshness of the launch and operational environment in-space, as well as the environmental conditions on aircrafts and at extreme remote earthbound observation sites can cause significant and unpredictable changes in the performance of the instrumentation for remote-sensing of ECVs. Re-assessment of the accuracy of satellite instrumentation post-launch as well as regular recalibration of airborne- and ground based instrumentation is therefore essential before the validity of basic satellite data (such as reflectance and radiance) can be guaranteed. Calibration against, and traceability to, the international system of units (SI) guarantees long-term confidence, accuracy and reliability in the data and ensures consistency between instruments.

These basic data products are additionally processed through complex non-linear retrieval algorithms to obtain the geo-physical and bio-physical parameters (e.g. the ECVs) that are important for understanding the state of the planet. End–to-end assessment of uncertainty and traceability was recognised as an additional challenge that needed to be urgently addressed by the climate community and where support from metrology experts was vital.

The international community has for many years established networks to provide some degree of global sampling of the environment, and in some cases uses these as test sites to validate satellite measurements. Many of these are not formally traceable to the SI. Recognising this, the space agencies have initiated efforts to establish globally distributed traceable networks and one is for the calibration of the primary satellite data for top of the atmosphere reflectance and radiance measurements. The community also has a need for an SI traceable satellite for climate and calibration, such as TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio-Studies).

This project further developed the outputs of the previous project ENV04 MetEOC to address these needs.

Results & Impact

The project set out to do this by suporting the establishment of the Committee on Earth observation Satellites (CEOS) RadCalNet (www.radcalnet.org) as a network of instrumented test sites to provide satellite-to-ground comparisons for satellite product validation. The project also analysed the climate sensitivity of the mesosphere and its impact on uncertainty requirements for the emitted radiance measurements and thus the transfer standards needed for traceability.

Further to this, the project characterised field instrumentation in both lab and field conditions, as well as conducted a comparison of terrestrial laser scanners. The project developed and demonstrated techniques for establishing and maintaining SI traceability 'in-flight' for both airborne sensors and on-board spacecraft and Finally, the project worked towards making the measurements from solar radiometers on spacecraft traceable to ground based standards.

Impact

This project, MetEOC2 has made great strides towards establishing a new harmonised European metrology infrastructure to enable the Earth observation and climate change community to provide robust information and advice to support far-reaching socio-economic decision making.

Some of our standards and methods are now being used by European instrument manufactures and calibration centres to improve their calibration uncertainties e.g. in support of Sentinel 2, 3 and 4 and RadCalNet. Knowledge gained in MetEOC2 has also helped support new collaborative projects through European Space Agency (ESA) and H2020 (e.g. QA4ECV). The QA4ECV project obtained detailed support on metrological methods from this project ensuring its prototyped quality assurance (QA) component of a future climate service was implemented rapidly. This is now being developed further as part of the EU Copernicus Climate Change service.

The outputs of MetEOC2 have also been used in the development and de-risking of the TRUTHS satellite concept. TRUTHS is a satellite mission designed to provide climate data ten times more accurately than is currently possible and upgrade the performance of the global Earth observation system so that it is fully traceable to SI and is uniquely led by a metrology institute. This step-change in satellite observational capability was made possible through the development of a novel calibration concept, which will effectively put a 'national metrology institute' into orbit. The calibration system has been experimentally proven in a vacuum by this project, overcoming previous technical hurdles. This has raised the Technology Readiness Level of the TRUTHS calibration system, as well as enabling it to have sufficient maturity to be proposed as a candidate mission to ESA's Earth Explorer programme and identified explicitly by international organisations such as GCOS as an essential component of a future space based climate observing system.

Initiated in ENV04 MetEOC and built upon in this project, MetEOC2, a training course has been developed that provides a structured approach to uncertainty analysis applied to the radiometric and spectral calibration of instruments used in Earth observation applications. The course focuses on how to apply uncertainty analysis, taking users through a step-by-step application of concepts to real laboratory and field examples. A comprehensive understanding of uncertainty underpins the usefulness and value of Earth observation. This course has been designed to be accessible to the community, and has also been presented at multiple workshops including the International Ocean-Colour Coordinating Group summer school.

The Network for Detection of Mesospheric Change (NDMC) is an international network of 55 ground-based experiments which monitor temperature and atomic oxygen concentration in the mesopause region in the atmosphere. Temperature changes in the mesopause are a very sensitive indicator for CO_2 induced global warming. This project provided a new radiance source that was SI traceable in order to provide traceable measurements of mesospheric temperature with a sufficiently low uncertainty to enable identification of temperature changes at the level of 1 K per decade.

Vegetation is one of the primary natural sinks of CO_2, understanding its health/existence and ultimately the amount carbon stored within it is fundamental to the long-term sustainability of our planet and society. Reliable monitoring and auditing on a global scale can only be achieved by translating remote satellite measurements into meaningful biophysical ECVs and requires validation (and tuning) with reliable ground truth observations. Understanding the directional scattering properties of light in an open forest canopy is essential to verify the end-to-end traceability between field measurements at a given test-site and concur recently acquired satellite observations of the same target. However, this is inherently complex, and previous efforts have assumed either constant illumination conditions or perfectly uniform reflectance. By developing techniques for SI traceable spectroscopy on Unmanned Aerial Vehicle's, this project was able to extract reliable Bidirectional Reflectance Distribution Function information from multiple flight paths, thereby delivering for the first time ever, rapid and robust background information of directional scattering properties for open canopy vegetation sites.

The World Radiometric Reference (WRR) is the reference standard of the World Meteorological Organisation (WMO) corresponding to the SI unit of irradiance, but tailored to the Sun. It was introduced in-order to ensure world-wide homogeneity of solar radiation measurements and has been in use since 1977, but it is based on the mean of a set of, now ageing radiometers. Every five years, a global intercomparison exercise takes place to ensure consistency between ground-based Total Solar Irradiance measurements. This project has upgraded the Cryogenic Solar Absolute Radiometer (CSAR), developed in-part during the previous project ENV04 MetEOC. This upgrade has allowed CSAR to perform continuous sequences of fully automated solar irradiance measurements, to incorporate improved cavity absorbance to reach near 100 %, to reduce the uncertainty of window transmittance measurement and to reduce residual noise to allow measurements at close to 0.01 % uncertainty level. This work has enables CSAR to be formerly recognised by WMO as a 'candidate' to become a new WRR and one which is fully SI traceable.

2 Project context, rationale and objectives

This project was constructed to work in collaboration with the climate science and Earth observation community to address the urgent need for accurate measurements of sensitive climate indicators which will improve our understanding of the Earth system. The goal was to to establish some of the tools, methods, and infrastructure to enable reliable confidence levels to be assigned to data used for climate change monitoring and information derived from Earth observation. The project had the following scientific and technical objectives.

Objective 1: Level 1 satellite traceability

- Make the Level 1 data products (Top of Atmosphere (TOA) and ground: reflectance and radiance) consistent between satellites sensors and eventually, SI-traceable.
- Improve the traceability chain for propagating uncertainties from these primary physical measurands, (Level 1 products), to higher level bio/geo physical parameters typical of ECVs and ultimately to the long time-series needed to establish a Climate Data Record (CDR).

Objective 2: Atmosperic ECVs

- Further development of in-flight large aperture IR reference standards for hyperspectral limb-sounding.
- Give traceability to the ground-based Network for the Detection of Mesospheric Change (NDMC, a global program that promotes cooperation amongst research groups investigating the mesapause region: 80 – 100 km).
- Establish an SI traceable method for ground based measurements of Atmospheric Optical Depth (AOD) and assessment of its end to end uncertainty.

Objective 3: Biophysical ECVs

- Quantify the apparent biases that can be expected when comparing biophysical ECVs based on different definitions.
- Use both Monte Carlo and experimental approaches to determine the uncertainty budget of a number of selected (widely used) field protocols.
- Deliver SI-traceable reference measurements on the overall measurement quality of devices typically used in field campaigns to quantify biophysical ECVs, including Ocean Colour.
- Make recommendations for best practices regarding the choice of field protocols and instrumentation for *in-situ* estimations of biophysical ECVs.
- Develop instrumentation, databases and methodologies to enable adequate inventories of vegetated test-sites.

Objective 4: Radiation ECVs

- Application of metrology best practice to enable SI traceability of a new satellite-borne (Total Solar Irradiance (TSI) radiometer CLARA, pre- and post-launch.
- Design and development of new ‘field-deployable’ radiometers for SI traceable calibration and validation commensurate with the uncertainty needs of a SST (Sea Surface Temperature) and LST (Land Surface Temperature) climate data records (CDRs).
- Defining best practice protocols to assess, minimise impact and treat, observational gaps, natural variability, instrument cross-comparisons, (Ocean buoys, surface thermometers etc.) to establish a trusted reliable SI traceable CDR.

The above objectives then translasted in the following aims for the project's technical workpackages (WP):

- WP1. To establish a network of desert/ice/forest test-sites to calibrate satellites when in orbit; combine and analyse data and uncertainties from multiple satellite instruments; prototype the climate satellite Traceable Radiometry Underpinning Terrestrial- and Helio- Studies, (TRUTHS).
- WP2. To improve measurement of sensitive climate indicators such as emitted radiance of the mesosphere; develop in-flight standards for traceable monitoring of temperature and chemical composition in the atmosphere; determine aerosol quantities, water vapour etc. by measuring absorption/scattering losses through the atmosphere.
- WP3. Establish best practice for end-to-end SI traceable uncertainty for key biophysical ECVs e.g. Leaf Area Index (LAI) and Fraction of absorbed photosynthetically active radiation (fAPAR) and Ocean Colour (OC).
- WP4. To measure Essential Climate Variables (ECVs), impacting Radiation Balance, (RB); provide traceability for incoming Total Solar Irradiance, (TSI) and thermally-emitted radiation from the Earth's surface temperature; land and ocean.

3 Research results

WP1: To establish a network of desert/ice/forest test-sites to calibrate satellites when in orbit; combine and analyse data and uncertainties from multiple satellite instruments; prototype the climate satellite TRUTHS

The scope of this work was to develop instruments, procedures and appropriate analysis tools to quantify and remove biases between satellites once in-orbit, and assess their post-launch uncertainty.

Many ECVs and subsequent Climate Data Records (CDR) are derived from basic Level 1 radiance or reflectance measurements called Fundamental Climate Data Records (FCDR). The Global Climate Observing System (GCOS) criterion for a meaningful CDR requires decadal stability in the associated measurand such as surface reflectance of better than 1 % for some ECVs. At present it is not unusual for individual satellite instruments to differ by several percent and therefore there is insufficient robust metrological harmonisation for current operational requirements, let alone for establishling a decadal time-series of climate quality observations.

Efforts to remove these instrument biases and improve post-launch uncertainties are a key focus of the Committee on Earth Observation Satellites (CEOS) and other organisations and comparison exercises have been carried out. However such comparisons are challenging (different detailed sensor characteristics) and, even when using simple test-sites such as deserts and snow, the choice of measurement method and mathematical analysis introduces data variances of several percent.

The activities in WP1 centred around the two parts of objective 1:

1. To make the Level 1 data products (TOA and ground: reflectance and radiance) consistent between satellites sensors and eventually, SI-traceable.
2. To improve the clarity and robustness of the traceability chain for propagating uncertainties from these primary physical measurements (Level 1 products), to higher level bio/geo physical parameters typical of ECVs and ultimately to the long time-series needed to establish a CDR.

These were achieved primarily through three activities,

- Establishing an automated network of test sites that will be used to test and improve the consistency of Level 1 data products (CEOS RadCalNet).
- Development of a UV stable diffuser for calibration of satellite optical sensors in space and field instrumentation e.g. spectrometers
- Prototyping and testing the in-flight calibration system of TRUTHS

These activities all make a small, but essential step, towards achieving objective 1 as they will improve the characterisation, calibration and validation of satellites on orbit. The latter two bulleted activities are also key steps towards providing the required SI-traceability, from orbit, to the test site network set up as indicated in the first bulleted activity.

The final activity provides a set of mathematical techniques to enable data from test-sites and sensors to be appropriately analysed, resampled and combined to ensure traceability and an appropriate uncertainty budget can be developed.

The sucessful achievment of these activities and hence objective 1 rested on the successful collaboration of partners NPL, CMI, CNAM, CSIC, INRIM, VTT and STFC. The different organisations brought differing skills and experience, for example CMI and INRIM developed new instrumentation whilst CSIC and CNAM provided expertise from the photonics domain to look at the perfomance of laser diodes for TRUTHS. STFC has specific domain expertise to evaluate the traceability of Sea surface Temperature (as an ECV) and NPL had a wide range of expertise in satellite calibration, testsites and necessary interfaces to the broad international satellite community through CEOS. This thereby ensured that the projects work was aligned with and fully integrated to meet the needs of the relevant space agencies and a good example of this, is how the project has assisted CEOS in the development of its RadCalNet network (see below). The RadCalNet is now approaching operational readiness and includes as a European contribution a new testsite in Namibia. This European site has been developed by NPL through this project in partnership by the European Space Agency (ESA) and

Centre National d'Études Spatiales (CNES, the French Government Space Agency). RadCalNet had more than 15 satellite owners take part in a 6-month beta testing phase and presented results declaring the high value of the network and encouraged it to be fully open as soon as possible and encourage additional sites to join.

The following 'case studies' summaries highlight the projects achievements in relation to objective 1.

Global network of satellite radiometric test sites nears fully operational status

Spatially uniform, bright and ideally stable land based targets typified by deserts are used to provide post-launch radiometric calibration/validation of Earth viewing satellite optical imagers. CEOS is developing a network of sites called RadCalNet, which have been instrumented with autonomous sensors to monitor surface reflectance change and associated atmospheric properties in order to allow satellites to compare their measurements against them. NPL, in part supported by this project, has helped to create a test site in Gobabeb, Namibia as a European contribution to RadCalNet in partnership with CNES and ESA. NPL is also helping to evaluate traceability and uncertainty of all the individual member test sites and their consistency with each other.

This project has been instrumental in developing the tools to improve SI-traceability of the sites and in developing mathematical techniques to understand site effects (such as viewing and solar angles, spectral effects and inhomogeneity of the sites).

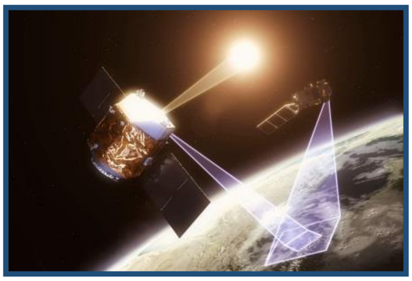
Partner INRIM in collaboration with NPL, has designed, and built an autonomous sensor web composed of 5 self-calibrating radiometers with bandwidth selective LED detectors and an associated 'self-calibration' mechanism for potential deployment at existing or future test sites to help monitor stability of spatial uniformity of large area test sites.

Partner CMI has additionally designed and built a hand held 'reference spectrometer' called MuSTR which, after calibration at NPL, will be used to compare measurements and ensure consistency and SI traceability between the current and future test sites of the CEOS Working Group on Calibration and Validation (WGCV) for RadCalNet.

The work undertaken in this project MetEOC2 provides space agencies and small commercial satellite operators with valuable post-launch calibration information without the need for dedicated field campaigns or expensive on-board calibration systems. It helps to improve interoperability between sensors – allowing scientists to combine different sources of data to provide a more holistic understanding of long term climate change, and enables more accurate and more valuable climate services.

For more information about RadCalNet, see https://www.radcalnet.org/#!/

Proposed satellite mission TRUTHS moves a step closer to launch

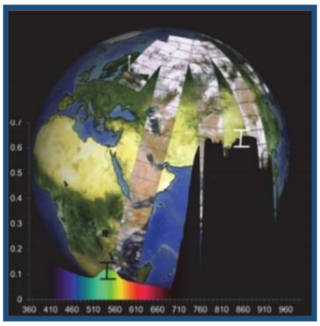


TRUTHS is an NMI led satellite mission designed to provide climate data ten times more accurately than is currently possible and upgrade the performance of the global Earth observation system. It is considered as a key element of an aspirational space climate observatory. This step-change in satellite capability is made possible through the development of a novel calibration concept, which will effectively put a 'national metrology institute' into orbit.

The calibration system has been experimentally proven in a vacuum by this project, in conjunction with aligned projects funded by the UK Space Agency and in partnership with Airbus Defence and Space, overcoming previous technical hurdles such as those related to speckle on the diffuser, and an implementation that utilises very few movements. This has raised the Technology Readiness Level (TRL) of the state-of-the-art TRUTHS calibration system to Level 5/6, as well as enabling it to have sufficient maturity to be proposed as a candidate mission to ESA's Earth Explorer programme. Although not funded as yet it remains a high priority of the international community and remains on a path for implementation at some point in the near future, a position enhanced by the outputs of this project.

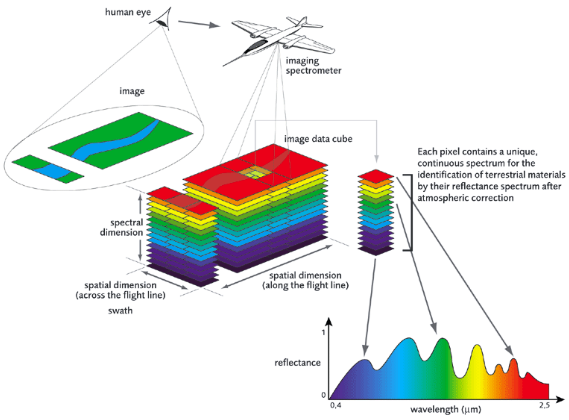
Find out more about TRUTHS at http://www.npl.co.uk/truths/

MetEOC delivers training to thousands on uncertainties in Earth observation



Through both the previous project ENV04 MetEOC 1 and this project MetEOC2, a training course has been developed that provides a structured approach to uncertainty analysis applied to the radiometric and spectral calibration of instruments used in Earth observation applications. The course focuses on how to apply uncertainty analysis, taking users through a step-by-step application of concepts to real laboratory and field examples.

A comprehensive understanding of uncertainty underpins the usefulness and value of Earth observation. This course has been designed to be accessible to the end user community, and has also been presented at multiple Earth observation community workshops and the International Ocean-Colour Coordinating Group summer school.



The course text book and presentations are freely available for download http://www.meteoc.org/resources/

An e-Learning programme has also been developed, which can be accessed here

In addition, the project was supported through a Researcher Excellence Grant (REG) at the University of Zurich (REG(UZH)) in the development of a full uncertainty model for the airborne Hyperspectral imager, APEX. This not only involved the development of a full traceability and radiometric sensitivity chain for the sensor in order to allow an uncertainty to be derived but also various measurements to assess effects such as temperature sensitivity, linearity and stray light. The outcome was a representative model and a set of corrections for the sensor. The knowledge from the representative model and a set of corrections for the sensor will provide valuable input for future new designs of sensors and the criticality of different characterisations.

Further to this, hyperspectral imagery provides the most detailed spectral knowledge of the Earth's surface. Given that everything has a unique spectral signature it is a tool (under-development in the space domain) that can provide insight not only into classifications of scenes but also detailed knowledge of the health of vegetation e.g. stress in crop growth etc. Therefore, the development of a full uncertainty model for the airborne Hyperspectral imager, APEX by REG(UZH) will support this.

Conclusions

In summary the project successfully achieved objective 1 regarding Level 1 satellite traceability and made a major contribution to the Earth observation community. The project did this by supporting the establishment of RadCalNet. The CEOS initiated a project in 2014 to establish a network of SI traceable instrumented sites, called RadCalNet, to provide satellite-to-ground comparisons for satellite product validation. This was part of a broader initiative which also considered inaccessible deserts, the moon, clouds and so on. RadCalNet was opened to first public access in October 2016 and has already been used by about 15 different users, mostly commercial satellite operators such as Digital Globe. These initial users provided positive and helpful feedback at a workshop in March 2017, and RadCalNet is currently completing testing ready for a full public launch in June 2018.

The project supported RadCalNet by:

- This project supported the establishment of RadCalNet by:
- Performing a field campaign with CNES (the French Space Agency) to find the optimum location for an European Space Agency (ESA)/CNES site in Namibia. (Autonomous measurement instruments were installed during 2017 to make this site a RadCalNet site).
- Writing good practice guidance on the establishment of a new field site, and creating a framework of guidance documents for new sites, both available from the RadCalNet portal.
- Developing instruments, such as LED radiometers, to be used at these sites. In addition, developing ways to perform site-to-site comparisons and provide SI-traceability to the network. This included the MuSTR instrument which provides a transportable SI-traceable way to measure spectral radiance at the sites, and through characterising tarpaulin diffusers, can be used as comparison reflectance artefacts.
- Developing mathematical techniques to perform satellite-to-satellite and TRUTHS-to-satellite comparisons over the sites.
- Performing rigorous uncertainty analysis on the RadCalNet site radiance product, and on propagating uncertainties from ground measurements to the satellite using an atmospheric correction model (radiative transfer codes), in collaboration with NASA scientists.

In addition to supporting ground based post-launch calibration, the project supported future concepts such as a calibration satellite in space and improving the underpinning technologies used to provide calibration of primary quantities:

- Supporting the development of the TRUTHS satellite concept: TRUTHS is a satellite which, if launched, will carry its own SI-traceable calibration system into orbit, mimicking the calibration chain at NMIs. This would enable the calibration of other satellites from orbit and would also provide, through TRUTHS a “climate benchmark” i.e. the most accurate measurements of the state of the planet. This could be used in the future a as measurement comparison to understand climate change, and to inform climate models. The consortium built and tested a prototype of the calibration system of TRUTHS to increase the technology readiness level of the concept to level 5/6. The project also performed theoretical analysis on the uncertainties associated with using TRUTHS to calibrate other satellites.
- Evaluated alternative (potentially more stable) technologies to replace current diffusers used in on-satellite calibration systems and also as references for field campaigns, including studying the ageing mechanisms for such diffusers.
- Initiating further work with REG(UZH) to improve the calibration of the airborne hyperspectral imager APEX.

WP2: To improve measurement and demonstrate value of SI traceability of sensitive atmospheric ECVs

Understanding of the atmosphere: composition, temperature, dynamics is an essential aspect of climate change. Change in the emissions of greenhouse gases is widely accepted as the dominant cause of climate change, and thus understanding how it is changing is an essential element of climate change studies. Short term dynamic effects impact weather and the atmosphere provides the most rapid transport mechansim of energy between the Earth systems (Land and Ocean). Therefore studies of local and global dynamics and its temperature are important in addition to chemical composition. In order to address objective 2 on Atmosperic ECVs this project has primarily undertaken activities using techniques developed from radiometry and radiation thermometry as part of the following 2 case studies:

1. Traceability for the ground-based Network for the Detection of Mesospheric Change (NDMC)
2. Further development of in-flight large aperture infrared (IR) reference standards for hyperspectral limb-sounding

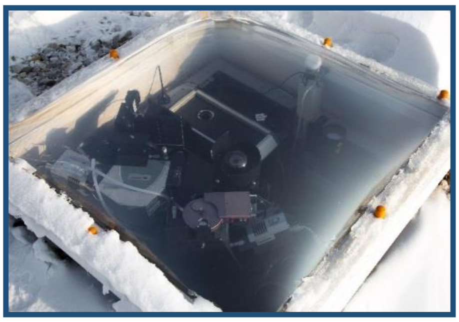
Significant expertise gained within the previous project ENV04 MetEOC was used, in particular this related to the design and traceable radiometric characterisation of large aperture reference standards (LARS) for air- and balloon-borne limb-sounding experiments. Limb-sounding provides some degree of height resolved information on the composition and structure of the atmosphere through spectroscopic observations of the atmosphere which is aligned to view a path through the atmosphere beyond the Earth's limb i.e. directly through and not effected by any surface emissions. In this way different thicknesses of the atmosphere can be sampled.

Building from the sucesses of the previous project ENV04 MetEOC a new lightweight source was developed and characterised for limb-sounding on regular and long-duration balloon flights. These developments have paved the way for a future satellite-borne limb-sounding standard in the mid- and far IR spectral range. When traceable to the spectral radiance scale and International Temperature Scale (SI units), the limb- sounding techniques provide absolute temperatures and trace gas concentrations in the Upper Troposphere/Lower Stratosphere (UTLS) region with unrivalled 3D spatial resolution. The highly dynamic structure and chemical composition of the UTLS play an essential role in the Earth’s climate system, causing prominent changes in the surface temperature via changes in the atmospheric radiative forcing.

The temperature and chemistry of the upper mesosphere/lower thermosphere (mesopause, ca. 80-100 km height) is another sensitive climate indicator. The international NDMC allows the determination of temperature and atomic oxygen concentration in this transition region between mesosphere and thermosphere provided that the spectral distribution (shape) of the absolute spectral responsivity of the ground-based near infrared (NIR) detection systems is known. As part of a case study, several GRound-based Infrared P-branch Spectrometers (GRIPS) of the NDMC have now been linked to the radiation temperature scale via a novel calibration concept based on a dedicated low-flux large aperture travelling reference source which is linked to the primary standards of the radiation temperature scale of partner PTB via a very sensitive NIR radiometer.

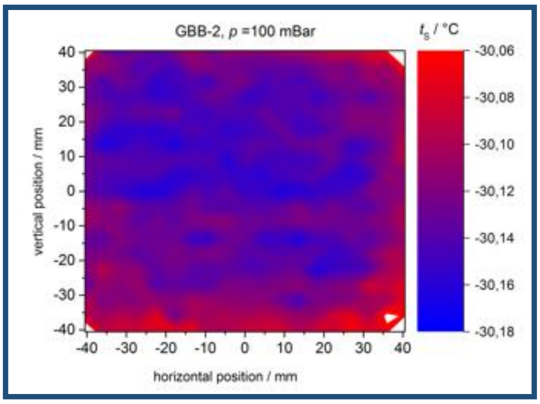
MetEOC2 provides traceability for the NDMC

The NDMC is an international network of 55 ground-based experiments which monitor temperature and atomic oxygen concentration at the mesopause region, the area of the atmosphere that forms the boundary between the mesosphere and thermosphere, at around 85 km above the Earth. Temperature changes in the mesopause are a very sensitive indicator for predominantly CO_2 induced global warming. This project provided a new radiance source traceable to SI to give traceability to measurements of mesospheric temperature with a sufficiently low uncertainty to enable identification of temperature changes at the level of 1 K per decade.



The first ever SI-traceable, large-area blackbody developed for calibrating IR limb-sounding interferometers on-board long duration stratospheric balloons

The **G**imballed **L**imb **O**bserver for **R**adiance **I**maging of the **A**tmosphere (GLORIA) is a newly developed unique atmospheric remote sensing instrument that bridges the gap from scanning to imaging in the infrared spectral domain.



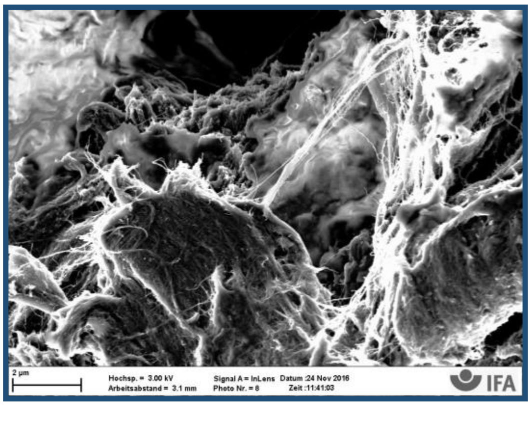
Within this project, enhanced reference blackbodies for the GLORIA hyperspectral imager were characterized and calibrated under stratospheric conditions and show a remarkably good temperature uniformity. The achieved non-uniformity at - 30 °C was 33 mK, which is an improvement of about 10 times and now meets the requirement of the GLORIA mission.

Limb-sounding imaging using Fourier Transform (FT) interferometers provides height and spatially resolved measurements of a range of atmospheric molecules - indicators of climate change and anthropogenic induced emissions. Following the successful development of the first ever large area traceable black bodies for the airborne GLORIA instrument, this project has extended the capability to long duration stratospheric balloon borne instruments. Here the challenge was to maintain (and in part improve) performance but with a lower weight.

In addition to evolutionary upgrades to the blackbody targets the project introduced innovative commercial 'phase change material' thermal packs to control temperature rather than complex and massive conventional electrical power. Temperature spatial non-uniformity of <100 mk was achieved and temperature stabilities of >300 hrs. Such systems now allow significantly improved measurements over long timescales to evaluate dynamic changes. This is an improvement compared to current transitions with aircraft which although offering wider spatial scales offer only very limited time domain studies.

Carbon nanotubes tested and qualified for use in scientific instruments

Reference standards for IR measurements (spectral radicance) make use of targets of known (ideally controlled) uniform temperature, which are configured in such a way that they can be considered Planckian radiators i.e. the emitted spectral radiance can be predicted by knowledge of their temperature and emissivity (ideally close to unity). This tends to be achieved using spectrally neutral low reflectance 'black' coatings often paints or dyes of some form. Thus the higher the emissivity (lower reflectance) the better the performance (smaller size/mass and uncertainty).



Recently a major advancement in black coatings was achieved through the use of Carbon nanotubes (CNTs), which provided coatings with a factor ten reduction in reflectance across the whole spectral region (Ultra Violet to Thermal Infra-Red (TIR). CNTs are lattices of carbon atoms that are tube-shaped, providing a material with a diameter on the nanometer scale, or a one-billionth of a meter. CNTs have exciting applications for science, being at least 100 times stronger than steel but only one-sixth as heavy, as well as excellent conductors of heat and electricity. If arranged as vertically-aligned 'forests', CNTs can possess a remarkably high emissivity (close to 1 i.e. a perfect blackbody), making them extremely useful for radiometry. However, nano-particles have the potential to be hazardous to human health particularly if ingested into the lungs.

This project investigated, for the first time ever, the 'release rate' of CNTs under different handling conditions to ensure their safe use in scientific instrumentation. The outputs of this study have defined a range of conditions and procedures to ensure CNTs can be used safely to enhance performance in a number of applications.

Development of techniques for charcterising Aerosols in the Laboratory

A REG from The University of Berlin (REG(UBER) undertook novel research to develop a design for a system for the optical characterisation of the mean cluster size of aerosols in a pulsed supersonic molecular beam using Rayleigh scattering. A new particle detector based on the piezo-electric effect was designed and produced and systematically evaluated in different configurations thereby providing monomer density and particle velocity. REG(UBER) also developed a model for time-dependent detector output based on three excitation modes of the piezo-electric foil, which can be used to explain undershoot and subsequent oscillations. The new particle detector allows the derivation of absolute cluster sizes as a function of cluster source conditions and is the subject of further resarch. Aerosols in addtion to being the main component required to characterise the transmittance of the atmosphere for satellite measurements of the surface are, through their light scattering properties, a key element impacting the radiation budget in the atmosphere and as such are an ECV.

Conclusions

In summary the project successfully achieved objective 2 regarding Atmosperic ECVs. The project achieved this through the following:

- The consortium submitted a report on uncertainty propagation through the GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere) retrieval algorithms to provide a threshold value for the uniformity of the two in-flight reference black bodies (LARS1 and LARS2), that provided calibration and SI-traceability. The temperature sensors and control electronics of the blackbodies were improved, and it was verified that the blackbodies now conform to the required uniformity (33 mK was achieved). The black bodies LARS1 and LARS2 were successfully used during the extensive research campaign POLSTRACC (Polar Stratosphere in a Changing Climate) in winter 2016, StratoClim in summer 2017 and NASA's WISE mission in autumn 2017. A follow up reference blackbody intended for future long duration balloon missions in the stratosphere, and using phase change material as a heat reservoir and for temperature stabilisation was successfully built. It was fully characterised and verified to fulfil the same uniformity requirements as the LARS1 and LARS2 black bodies, over the intended time of operation of at least 8 hours without any external energy consumption.
- CNTs (carbon nanotubes) are tube shaped lattices of carbon atoms which have very low reflectance. The application of CNT black coating, as novel high emitting backplanes for LARS1 and LARS2 (black bodies), was reviewed. This was from a scientific perspective and also as a potential hazard to health since these tubes are nanoparticles. The release rates of single CNTs, bundles of CNTs and fragments from CNT coated surfaces, were determined during extensive tests of lab handling of coated samples and during modelled black body operation conditions (airstream, vibration). Under the conditions no released CNTs could be found, indicating a concentration well below the WHO threshold value. This meant that under these conditions no health risk could be assessed. A set of test substrates was successfully coated and their performance was tested. One CNT based coating was identified with a very high emissivity. However, due to the remaining risk of damaging the CNT coated surfaces and release of CNTs when handling air-borne black bodies in the field, the LARS1 and LARS2 black bodies will not be equipped in the near future with backplanes featuring a CNT based coating. The promising properties will be further investigated with lab based large aperture black bodies in the future.
- The climate sensitivity of the mesosphere and its impact on uncertainty requirements for the emitted radiance measurements was analysed, and used to select suitable transfer standards. This was more demanding than originally thought, requiring a 30 mK uncertainty (originally 1 K was anticipated). The coupling of a travelling reference spectrometer (TRSP) and travelling reference source (TRSO) was selected and modified accordingly. A complementing transfer radiometer (NIRTR) for in-lab scale transfer was finalised and used successfully to transfer the scale to the TRSP and TRSO with the

required uncertainty. Three Network for Detection of Mesopheric Change (NDMC) ground stations at DLR in Oberpfaffenhofen, Schneefernerhaus Zugspitze and in Slovenia were successfully calibrated during 2017, enabling traceable measurements in absolute radiance of GRIPS instruments for the first time. In addition to this, the density of the hydroxyl radicals is now possible. An aging investigation of the TRSO and TRSP was also successfully performed with help of the NIRTR instrument, and revealed sufficient stability of both instruments.

WP3: Establish best practice for end-to-end SI traceable uncertainty for key biophysical ECVs

Although anthropogenic green house gases are emitted into the atmopshere, the bio-sphere, land and ocean, all have a strong interaction with the atmosphere and serve as natural sinks for more than half of the emitted carbon dioxide (CO_2). This is primarily through photosynthesis where CO_2 is extracted and initially stored in vegetation e.g. trees (Land) and phyto-plankton (oceans) before embarking on a complex carbon cycle. Cataloging and monitoring changes in these biophysical ECVs (in a global manner) is thus an essential component of any effort to understand the Earth system and mitigate against the effects of climate change. Clearly, globally trustable accounting of the biosphere can only be achieved from space, but the complexity of the end parameters compared to the measured variables and the added complexity of atmospheric transmittance make this a complex and urgent challenge for metrology to place robust and internationally consitent uncertainty boundaries on derived estimates of the amount of carbon stored. Therefore, this requires the establishment of a way to reliably validate and/or tune satellite retrieval algorithms based on ‘ground truth‘ data from well-characterised test-sites.

The validation of satellite-derived biophysical ECVs is based on a direct comparison either with ‘ground-truth’ estimates or with products from different Earth observation missions. Several issues hinder the end-to-end traceability of in-situ and satellite-derived biophysical ECVs over land and to some extent water. The first issue is because most operationally derived Land ECV products adhere to different definitions based on their respective retrieval algorithms. A second difficulty relates to the fact that most in-situ methods do not measure the target quantity directly, but rather infer it from proximate remote sensing observations using a variety of hypothesis and assumptions. This issue also affects the estimation of biophysical ECV quantities in international monitoring networks like FluxNet and Integrated Carbon Observing System (ICOS). In both networks, a multitude of measuring devices, sampling protocols, up-scaling strategies and processing algorithms are being used without proper understanding of their impact on the overall quality of the in-situ ECV estimate.

The aim of this work was to address these gaps first by quantifying the apparent biases that can be expected when comparing biophysical ECVs based on different definitions. Then, using both Monte Carlo and experimental approaches to subsequently determine the uncertainty budget of a number of selected (and widely used) field protocols and, in particular, the sampling and upscaling schemes that are applied to the estimation of biophysical ECVs. In addition, our goal was to deliver SI-traceable reference measurements on the overall measurement quality (it is not uncommon for different batches of the same instrument to provide measurements differing by more than 30 %) particularly spectral and angular properties of measuring devices typically used in field campaigns to quantify biophysical ECVs for both Land and Water applications. The project’s results have contributed to an initial set of recommendations for best practices regarding the choice of field protocols and instrumentation for in-situ estimations of biophysical ECVs.

The project has also developed instrumentation, databases and methodologies to enable adequate inventories of vegetated test-sites. Overall, the project’s work was structured into building blocks that can be considered pre-requisites for the development of rigorous end-to-end closure experiments (leaf-plant/tree-canopy-satellite). Such end to end experiments are required to verify the end-to-end traceability between field measurements at a given test-site and concurrently acquired satellite observations of the same target. Monte Carlo radiative transfer models then provide the link. While a full closure experiment was beyond the scope of this project, the characterisation and reconstruction of the Wytham Woods ecosystem site (Oxford, UK) (now classified as a CEOS WGCV LPV super-site following work supported by this project) has been trialled as a pre-cursor towards objective 3 for Land products.

In addition, the project has contributed to measurements in the ocean domain where reflectance from water related to Ocean colour included support for the primary European radiometric reference site BOUSSOLE and more ad-hoc measurements from ships in support of the forthcoming EU/ESA Copernicus Sentinel 3 mission.

The work in WP3 centred around the five parts of objective 3:

1. Quantifying the apparent biases that can be expected when comparing biophysical ECVs based on different definitions.
2. Using both Monte Carlo and experimental approaches to determine the uncertainty budget of a number of selected (widely used) field protocols.

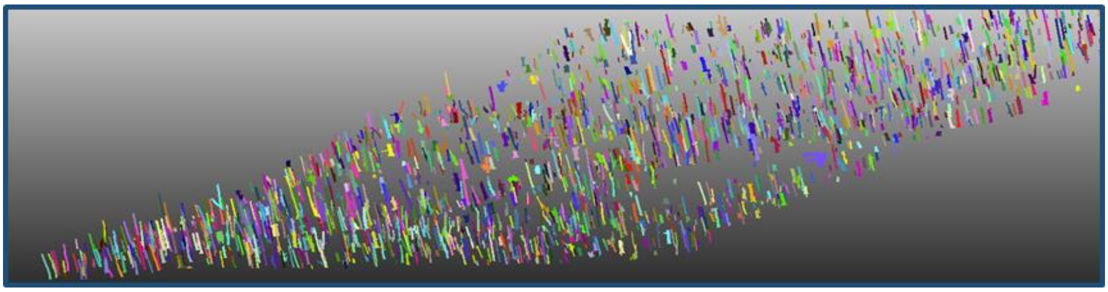
3. Deliver SI-traceable reference measurements on the overall measurement quality of devices typically used in field campaigns to quantify biophysical ECVs, including Ocean Colour.
4. Making recommendations for best practices regarding the choice of field protocols and instrumentation for *in-situ* estimations of biophysical ECVs.
5. Develop instrumentation, databases and methodologies to enable adequate inventories of vegetated test-sites.

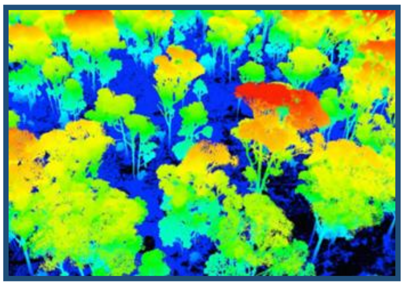
Wytham Woods mapped in a virtual model

Covering about 30 % of global land area, forests play a significant role in the delivery of ecosystem services including climate regulation, carbon storage, biodiversity, prevention of soil erosion and flood mitigation. However, uncertainties of the amount of above-ground biomass estimates (which are also a surrogate for carbon storage) are very high, as it's very hard to estimate without destructive sampling (i.e. cutting a tree down and weighing the wood and leaves).

Work within this project has started the path towards establishing reliable quantitative traceability for terrestrial and satellite measurements of key biophysical climate variables, including forest cover, so as to provide quality-assured data which decision-makers can use with confidence. The scale of this challenge is such that a single project of this size can only start the process and prototype developments of the necessary key elements of the traceability chain. However, in doing so this promotes the philosophy to the wider end user community to encourage greater consistency and documentation of practises and provides the building blocks and priorities for future work.

Terrestrial Laser Scanner (Lidar) (bottom right picture) data has been collected and used by NPL in collaboration with partner UCL to extract 3500 tree stems >10 cm Diameter at breast height (DBH) in the 6ha field site at Wytham Woods. A team at the University of Oxford have linked the stem map to the Smithsonian field inventory data for all 3500 trees (location, DBH, height, species and condition). The stems (pictured below) were modelled into trees producing a highly realistic virtual 3D representation of Wytham woods that can now be used for vegetation monitoring and satellite product validation activities.





Sophisticated mathematical modelling and remote-sensing methods were applied to the data to make accurate estimates of biomass. This data was then used to produce a highly realistic virtual 3D representation of Wytham Woods, which can be used to improve vegetation monitoring, calculation of biomass carbon storage, and improve satellite product validation activities. The Whytham woods site partly as a result of this project is probably the most comprehensively characterised site in the world and in addition to being classified as a CEOS super-site it is now planned to be used as one of two European sites to provide critical validation data for Sentinel 2 (which is an Earth observation mission developed by ESA as part of the Copernicus Programme to perform terrestrial observations in support of services such as forest monitoring, land cover changes detection, and natural disaster management).

The work in this project has led to further investment in the Whytham woods site so that it can be used as an accessible testbed for techniques not only from the optical domain but also for radar to ensure that these can then be further used in more difficult terrain such as tropical rain forests.

For more information, see http://www.npl.co.uk/news/a-walk-through-a-laser-scanned-forest

Bidirectional Reflectance Distribution Function retrieved using UAV's

Understanding the directional scattering properties of light in an open forest canopy is essential in order to be able to verify the end-to-end traceability between field measurements at a given test-site and concur recently acquired satellite observations of the same target. However, this is inherently complex, and previous efforts have assumed either constant illumination conditions or perfectly uniform reflectance (Lambertian properties). By developing techniques for SI-traceable spectroscopy on Unmanned Aerial Vehicle's (UAVs), this project was able to extract reliable Bidirectional Reflectance Distribution Function (BRDF) information from multiple flight paths, thereby delivering a rapid and robust background information of directional scattering properties for open canopy vegetation sites for the first time.

This work used expertise from a REG at FGI to add an additional dimension to the Whytham woods testsite. This enabled instrumentation on the UAV to fully link to the SI through NPL and that surace based measurements on the site could be linked and compared to those from the UAV.

BOUSSOLE

The European reference buoy, BOUSSOLE, anchored off the coast of Nice, is one of two reference buoys in the world used for the system vicarious calibration of ocean colour monitoring satellites, most notably the recent Ocean Land Colour Instrument (OLCI) sensor on board Sentinel 3. As part of this project BOUSSOLE has had its uncertainty fully evaluated following a 9 month secondment of an NPL expert to the French operating team. This uncertainty evaluation places BOSSOLE on a similar footing to that of its sister, MOBY, in the USA. The accuracies required by the ocean colour community are so demanding that at present the satellites do not inherently have the accuracy required based solely on their pre-flight characterisation. This in part is due to the fact that the ocean signal being measured is only 1/10 of that seen at the satellite with the majority coming from the atmosphere itself. To try to account for this in the overall uncertainty budget of the satellite a System vicarious calibration is made which in effect uses measurements of water leaving radiance from the surface made by the reference buoys to in effect correct/adjust the satellite retrieval algorithm (sensor and atmospheric correction model). Thus the traceability of the ocean buoys are at present critical to the overall uncertainty budget of ocean colour measurements.

Conclusions

In summary the project successfully achieved objective 3 regarding Biophysical ECVs. The project achieved this through the following:

- Selected commonly used ECV definitions and implemented the illumination and structural variations that correspond to these definitions within highly realistic virtual 3D plant environments.
- Characterised field instrumentation, including PAR (photosynthetically active radiation) and LAI (leaf area index) sensors in both lab and field conditions, as well as conducted a comparison of terrestrial laser scanners (TLS). This is the first time such instruments have been SI-traceably calibrated.

- Conducted summer and winter field campaigns at Wytham Woods, Oxford using these LAI and PAR sensors as well as with ground and drone based LiDAR (in conjunction with REG(FGI)).
- Used the TLS data to create a tree stem map of the 6ha field site. Each of the 3500 trees were identified in the Smithsonian inventory and have associated species, height and diameter information.
- Installed the PAR network, which has been running since October 2015. It includes 32 sample points over ~1.5 ha of Wytham Woods. As a result of these studies, the Wytham Woods site is now formally recognised as CEOS super-site for land product validation.
- Provided an evaluation of Ocean Colour sensors to be used in spectrometers in conjunction with one collaborator and started to evaluate principle sources of uncertainty for BOUSSOLE (the European reference body for Ocean Colour).
- A laboratory based comparison of absolute irradiance and radiance calibration of hyperspectral RAMSES TRIOS sensors took place. NPL participated in this comparison with the collaborators Tartu Observatory, European Commission Joint Research Centre and TRIOS instrument manufacturers. The results were in agreement within the stated uncertainty, and were reported at the Sentinel 3 validation team meeting in 2017.

WP4: To measure ECVs impacting RB; provide traceability for incoming TSI and thermally-emitted radiation from the Earth's surface temperature; land and ocean

WP4 and hence objective 4 concerned the need to provide SI-traceability and to understand the uncertainties directly associated with three ECVs impacting RB. Climate change is fundamentally the result of a change in the balance between incoming radiation (TSI) and outgoing radiation (thermally-emitted radiation) of the Earth. Small changes in this balance, either natural variation or anthropogenic, have a major (often non-linear), impact on the Earth system; contributing to climate change. This work package is about the relatively direct measurement of 3 ECVs: (1) TSI, (2) Sea Surface Temperature (SST) and (3) Land Surface Temperature (LST), and in particular about the urgent requirement to create reliable long-term CDRs for these 3 ECVs.

TSI, is one of the longest space-based CDRs (since mid-1970s), measuring changes in the overall output of the Sun. The relatively large variance up to 1 % in absolute levels of TSI measured by different space instruments means the CDR is dependent on normalisation; a process that both increases the uncertainty of the record and, in relying on overlaps between sensors, therefore risks the loss of the entire CDR in the event of instrument failure or launch delay. Catastrophic failure of NASA's GLORY mission has delayed the replacement of the TSI instrument on **SO**lar **R**adiation and **C**limate **E**xperiment (SORCE). Therefore the risk loss of the entire CDR can only be mitigated through SI-traceable sensors. Until a high accuracy TSI radiometer, such as Cryogenic Solar Abolute Radiometer (CSAR) developed in part in the previous project ENV04 MetEOC can be launched as part of TRUTHS (or other mission), it is essential to make sensors as SI-traceable as possible and in this project it both calibrated a new TSI radiometer called CLARA and worked towards the replacement of the ground-based TSI record through the World Radiometric Reference (WRR) using CSAR.

Thermally-emitted radiation from the Earth is largely as a direct result of SST and LST and this project looked at how to ensure SI traceability of CDRs of these quantities, derived from Fundamental Climate Data Records (FCDRs) of 'effective brightness temperature'. Space based measurements of SST have been made for more than 30 years, with the most accurate data sets (~0.2 K, using on-board blackbodies as references) coming from the European Along Track Scanning Radiometers (ASTR+) series of sensors. The follow-on mission, Sea and Land Surface Temperature Radiometer (SLSTR) was launched on the Sentinel-3A platform in 2016, with a subsequent launch on the Sentinel 3B platform in 2018. SLSTR is designed to measure both SST and LST. LST is more challenging because of the wider variety of emissivity of land surfaces. Validation will be required at uncertainties <0.2 K across the full range of observation conditions (ocean and ice for SST; deserts, vegetation, snow for LST) and will have to deal with the very large footprints of these sensors. This project addressed this by developing an upgrade to the transfer radiometer Absolute Measurement of Blackbody Emitted Radiance (AMBER) which is used to provide traceabiliy to field, air and satellite instruments through calibration of blackbodies. The new AMBER transfer radiometer standard is smaller, has associated with it its own fixed point reference black body and can be directly couple into a vacuum tanks. In addition a design specification for the 'ideal' field radiometer has also been develeped following a detailed reveiw of the current state of the art in instruments and potential sub-systems that can be incorporated. It is anticpated that this design will be used in a future work to build a new reference field radiometer.

First steps towards assessng SI-traceable uncertainties for SST, as an example CDR was established in this project and the methods have formed part of a contribution to the H2020 project FIDUCEO. Since a CDR requires decadal measurements, this means combining data from multiple space-borne sensors and from ground-based measurements. In SST it also requires bridging the 3-year gap in the SST record caused by the loss of Advanced Along Track Scanning Radiometers (AATSR) with the failure of ENVISAT ("Environmental Satellite" a large inactive Earth-observing satellite which is still in orbit and operated by ESA). This gap will have to be bridged using the 'validation instruments': ocean buoys (with thermometers) and radiometers (noting that these are not all measuring the same thing in geographical location or depth). Working with the international experts on SST (The Global High Resolution Sea Surface Temperature project, GHRSST, the ESA CCI programme and FRM4STS project and CEOS Virtual Constellation (VC)-SST), this project has established best practice methods for assigning uncertainties to the CDR based on satellite data, ocean validation and the necessary gap bridging. The project has also provided a case study that can be generalised for the more generic requirements of CDR uncertainty analysis associated with other ECVs.

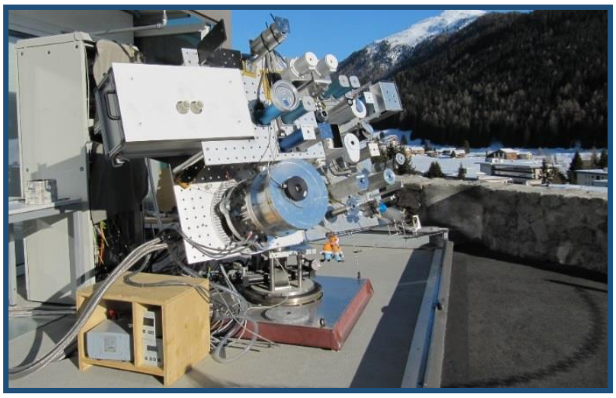
In collaboration with the appropriate international coordinating bodies of the specific ECVs, the work in WP4 has addressed the 3 parts of objective 4:

1. Application of metrology best practice to enable SI traceability of a new satellite-borne TSI radiometer CLARA, pre- and post-launch.
2. Design of new 'field-deployable' radiometers for SI traceable calibration and validation commensurate with the uncertainty needs of a SST and LST CDRs and building of an improved transfer standard to enable traceability.
3. Defining best practice protocols to assess, minimise impact and treat, observational gaps, natural variability, instrument cross-comparisons, (Ocean buoys, surface thermometers etc.) to establish trusted reliable SI traceable CDR.

CLARA TSI radiometer successfully launched into orbit

On the 14th July 2017, the NORSAT-1 microsatellite was successfully launched into orbit. This satellite is designed to investigate solar radiation, space weather and detect ship traffic, and contains CLARA. This CLARA radiometer will help ensure continuity of TSI measurements, which is a measure of the amount of solar energy reaching the Earth's upper atmosphere. TSI is an ECV and thus CLARA will help to reduce ambiguities due to existing instrumental biases and support long term (>30 year) monitoring of TSI in space. During the project partnerSFI Davos characterised and SI-traceably calibrated the CLARA radiometer.

A video of the NORSAT-1 launch can be viewed here



Towards a new World Radiometric Reference (WRR) for Direct Solar Irradiance.

The WRR is the measurement standard of the World Meteorological Organisation (WMO) corresponding to the SI unit of irradiance, but tailored to the Sun. It was introduced in order to ensure world-wide consistency of solar radiation measurements and has been in use since 1980. However it is based on the mean of a set of, now ageing, radiometers and so every five years, a global intercomparison exercise takes place to ensure consistency between ground-based TSI measurements.

This project has upgraded CSAR, developed in-part during the previous project ENV04 MetEOC. This upgrade allows CSAR to perform continuous sequences of fully automated solar irradiance measurements, incorporate improved cavity absorbance to reach near 100 %, reduce the uncertainty of window transmittance measurement and reduce residual noise to allow measurements at close to 0.01 % uncertainty level. This work has enabled CSAR to be a prime candidate to replace the WRR with a robust SI standard.

Conclusions

In summary the project successfully achieved mots of objective 4 regarding Radiation (RB) ECVs. However, a delay in launch of the CLARA instrument limited the ability to do the full planned set of experiments following launch. These experiments will be carried out independently. Similarly, although a new surface temperature was designed, this was completed late in the project lifetime due to the limited availability of key experts. Therefore there was no time left to build the complete instrument.

As part of objective 4 the CLARA solar radiometer was developed and built by project partner SFI Davos. It was launched into space on 14 July 2017. Extensive characterisation and calibration experiments were conducted prior to launch as part of this project:

- The optical efficiency (known as “blackness”) of CLARA's three radiation sensors was measured, and the homogeneity of their absorbing areas was determined at three different laser wavelengths.
- The electrical efficiency relative to the optical efficiency was determined, including losses through heater and sensing wires.
- Numerical simulations were performed to assess the heating effect of the radiometric apertures and other surfaces which are in the field-of-view of the CLARA's sensors.
- End to end calibration of the fully assembled CLARA against a NIST-traceable cryogenic radiometer was performed at a dedicated facility in Boulder, USA. This calibration used a laser source in a novel manner to generate a large irradiance field compared to traditional measurements on the ground using the sun as an irradiance source or a laser beam underfilling the aperture in power mode and then calculating irradiance from geometry.
- End to end comparison of the fully assembled CLARA against the WMO World Radiometric Reference (WRR) was performed with the Sun as a source at the World Radiation Centre in Davos, Switzerland, this also included a link to the Cryogenic Solar Absolute Radiometer (CSAR) which is being evaluated as an SI replacement for the WRR.
- The uncertainty budget for all calibration experiments was established and published.
- Cross-comparison of CLARA’s three radiation sensors were performed during the final week of the project. The planned analysis could not be finalised within the project time-frame, due to a 1.5 year delay from the original launch date of CLARA.
- The CSAR overall performance was improved by an order of magnitude to around 0.03 % through a redesign of the system used to measure window transmittance, which was previously limited by noise.
- Requirements and assessment of the state of the art (performance and traceability) of existing SST and LST radiometers were carried out as part of an ESA collaboratively funded international comparison project Action and Fiducial Reference Measurements for validation of Surface Temperature of Satellites (FRM4STS). Conclusions from this exercise have been incorporated into the design specifications for a new reference instrument. In the FRM4STS comparison project a new updated design of the NPL reference transfer radiometer AMBER was also carried out and is now being built.

Summary of key project outputs

The following table provides a summary of the key results in terms of specific requirements that have been achieved for this project, MetEOC2 and the progression from the previous EMRP project ENV04 MetEOC

Metrological Requirement	Prior State of The Art	Current State-of-The-Art (Following Completion of MetEOC2)	Comments
Improved traceability for atmospheric limb-sounders to allow retrieval of ozone, water etc. Uncertainty of <1 % in IR radiance needed (~ 30 mk at 240 K). Requires in-flight calibration due to sensor variances	No robust traceability Accuracies around 5 %	Large area Black body reference targets for in-flight calibration built with spatial uniformity <33 mK Radiance uncertainy <1% End to end sensitivity of ECV to calibration carried out. Novel use of phase change thermal pack allowing temperature stabilty of >300 hrs suitable for long durantion balloons.	Objective 2 Structured flat plate balckbodies have been built, tested used and demonstrated to provide improved end to end uncertainty in measuring atmospheric composition including propagation through the retrieval algorithms. As part of this an evaluation of the safety characteristics of a new very high emissivity CnT black coating was carried out and safe useage conditions defined.
Post launch traceability for high resolution land imagers byestablishing network of SI traceable test sites for post-launch calibration of satellites <2 % target <1 % in radiance or relative reflectance	4 % to 5 % uncertainty for individual sites No network/ coordination or traceability	Prototype network of 4 instrumented sites (RadCalNet) with uncertainties ~2-4 %	Objective 1 The CEOS RadCalNet project has already had more than 18 beta testers from satellite operators across the world including commerical constellations. It is very well recieved and will formally become operational in 2018. The network cooridnates sites from space agencies: NASA, ESA, CNES and AOE (China). This project has contributed to development of methods to ensure traceability between sites and also specifically to help establish a European site in Namibia in collaboration with ESA and CNES
Prototype operational satellite post launch calibration service	Nothing	Design to develop a concept to enalbe comprehensive evaluation of biases and means to harmonise between satellites using a range of methods from previous project ENV04 MetEOC in collaboration with CEOS WGCV IVOS. Developed mathematical analyis and sensitivity study of cross calibration between a reference sensor and another using desert sites. Possiblility to acheive uncertainties of <0.5% in the calibration process under optimal conditions	Objective 1 In addition to RadCalNet this project has started to look at uncertainties and correlations in mathematical processes needed in cross-calibration of sensors (to each other and to ground) as a basis for a future all encompassing capability and service that amalgamates information from all post-launch calibration and validation
Flexible facilities for use in industry for pre-flight spectral radiometric calibration of a satellite sensors (uncertainty <1 %) including needs of low cost cubes at sensors	Broad band calibration of 5-10 % uncertainty	Laboratory based spectral calibration methods ~<1 % level	Objective 1 Methods for pre-flight calibratoni now well established and being used to also provide calibrations of instrumentation used for field calibrations

Ocean colour and related ECVs: in-situ calibration and validation (long term target 1 %)	Uncertainty 5 %	Uncertainty 3 % (on in situ reference measurements for the validation of satellite derived radiometric products) (multi-spectral) visible band.	Objective 3 A full analysis of the traceability and uncertainty of European primary reference calibration Buoy, BOUSSOLE (one of only two in the world), has been carried out placing it for the first time to be on a level (in terms of information) as the US MOBY system. This analysis is also helping to provide input to studies considering the design and traceability strategy of the next generation of reference buoys.
High accuracy SI traceable climate and calibration reference satellite	Concept for European mission, TRUTHS developed. US mission CLARREO selected as a priortity for development by USA study.	TRUTHS mission concept refined, with critical traceability concept on-board calibration system prototyped and demonstrated under vacuum to TRL 5/6 and demonstrating <0.3 % accuracy for radiance calibration (a factor of 10 better than existing technologies) CSAR primary standard also built and tested.	Objective 1 Proposed to ESA although not successful for funding. China also has plans to build a version based on the TRUTHS design concept for launch in early 2020's
End to end Traceability of Bio-physical ECVs GCOS requires: LAI 20 % accuracy, 10 % stability fAPAR 10 % accuracy, 3 % stability	Variability between satellite products >30 % No standardised field characterisation method or assessment of uncertainty. Type B (bias unknown). Type A 10-30 % Field instruments not calibrated and vary by > 30 % batch to batch	Best practice guidance established for LAI. Field Instruments validated in a traceable manner and prototyping testsite established and characterised using lidar leading to a virtual forest	Objective 3 Wytham woods test site (established as part of this project) has now been formerly endorsed as a CEOS WGCV LPV super-site for validation of satellite land products. The site has and continues to allow prototyping of new methods and techniques and from this project has also included the use of small UAVs as well as field measuements and the establishment of an autonomous network of photosynthetically active radiation sensors. It is the most comprehensively characterised test site in the world.
NDMC ability to detect 1K/decade temperature trends of the mesopause with an SI traceable network	No SI traceability and no knowledge of radiance uncertainty	Travelling standard to achieve traceability for some types of instrument in network enabling changes of 1K per decade to be detected	Objective 2 Although achieving traceability for a specifc set of instruments, this project identified the need for additional methods to extend traceability more widely including the need for future space based observations
Total solar irradiance (TSI) GCOS requirement of 0.01 % in space and ground <0.03 % Ground observations currently traceable to an artifact based scale WRR	Uncertainty 0.3 % in space and ground and WRR partly compared to SI using power but not irradiance. Prototype SI radiometer CSAR built but not fully evaluated or optimised	Uncertainty in space closer to 0.1% but no robust evidence of SI traceability in-flight Analysis of CSAR allows uncertainty 0.01 % (in space theoretically) Uncertainty 0.03 % ground but not optimised for operational efficiency	Objective 4 CLARA radiometer calibrated fully traceably to SI on ground pre-flight and launched into space. CSAR now formally under consideration by WMO as a replacement for WRR showing consistency and improved practical uncertainty following optimisation of window transmittance facility. Instrument in full operational mode at SFI Davos.

4 Actual and potential impact

Dissemination activities

The results of the JRP have been presented more than 40 times at international meetings to key organisations such as CEOS, ESA, WMO, and BIPM. In particular the project has generated 19 proceedings and publications in key journals such as Metrologia, the International Journal of Remote Sensing, Atmospheric Measurement Techniques and the European Journal of Remote Sensing. The project has also generated 44 conference presentations and posters at conferences such as the International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2017), the International Society for Optics and Photonics (SPIE) remote sensing conference 2016, IEEE International Workshop on Metrology for Aerospace and the 2016 International Geoscience and Remote Sensing Symposium (IGARSS).

The consortium have engaged with the public on 13 separate occasions by publishing newsletters and reports, hosting stands at exhibitions (such as the long night of science) and giving media interviews.

Two items worth highlighting are the Terrestrial Laser Scanning work which was showcased on BBC news http://www.bbc.co.uk/news/science-environment-38335348 and the TLS and photosynthetically active radiation sensors network (objective 2) which appeared in an interview for an Oxford University documentary series called “the Laboratory with Leaves” available from http://www.ox.ac.uk/content/wytham-woods-laboratory-leaves

This project MetEOC2 strived to inform the general public about climate change and the importance of metrology. In summer 2017, NPL exhibited an Earth observation exhibit at New Scientist Live, a major exhibition of science held in London’s ExCeL Centre (see the lefthand photo below).

NPL's stand at New Scientist Live featured a miniaturised 3D-printed satellite model that contained a spectrometer. Visitors could move the spectrometer between a range of materials that mimicked different types of landscapes, such as vegetation, bare soil, sand and inorganic material (plastic grass). By linking live measurements to a simple plot on a TV, visitors could see how each sample varied in its spectral response. Scaling it up to the real-world, this information is useful for monitoring environmental change such as urbanisation, desertification and deforestation over time. More information about the NPL exhibit is here

Meanwhile, PTB demonstrated at two public outreach events (see the righthand photo above). The fascinating world of infrared thermography was illustrated by the exhibit ‘Can you see temperatures?’ It explained how to get from a thermographic image of gas escaping a spray bottle to traceability for remote sensing of the atmosphere to about 300 guests.

Stakeholder Engagement and Standards

The key stakeholders for this project are space agencies, their international coordinating bodies and those with a key interest in climate/earth observation science from academia, from public organisations like WMO, and the space industry etc.

The consortium have attended 13 formal meetings of key international stakeholder groups around the world including Committee on Earth observation Satellites Working Group on Calibration and Validation (CEOS WGCV) and its Infrared Visible and Optical Sensors (IVOS) sub-group, the WMO Group on Satellite Inter-calibration Systems (GISCS), ESA Calibration and Validation Infrastructure (CVI) group and those of the international metrology community such as BIPM's Consultative Committees on Photometry and Radiometry (CCPR) and Consultative Committee on Temperature (CCT) and associated sub-groups of both.

All the information on the projects research activity has been promoted via its dedicated website which will be maintained through the follow-on project 16ENV03 MetEOC3.

A total of 15 training events have taken place over the course of the project. The most significant being a textbook on uncertainty analysis for Earth observation Instrument Calibration developed in the previous project ENV04 MetEOC and adapted in this project MetEOC2 which has been downloaded > 2000 times. The material for this course was also turned into an e-course using the following Support for Impact project 14SIP02, the course has been accessed nearly 50 times from people all over the world. The textbook and course have highlighted the project and its underpinning philosophy to a wide end-user community. The concepts promoted in this course clearly shows how critical metrology and SI traceability is to the earth observation and climate community. The textbook is now being used as part of the curriculum at an American University.

Early impact

- The retrievals of atmospheric composition parameters from GLORIA have been significantly improved, including end to end uncertainty analysis which has led to a specification for improvements required for future work.
- The first station of the NDMC network has been fully traceably calibrated, removing ambiguity and allowing the density of OH radicals to be determined. This provides a pre-cursor to further improvements to be carried out in the follow on project 16ENV03 MetEOC3.
- The project assisted the CEOS in the development of its RadCalNet network, through provision of traceabilitity, development of best practices, which will become operational in June 2018. More than 15 satellite owners took part in the 6-month beta testing phase of the RadCalNet network, presented results endorsing its high value, and encouraged it to be fully open as soon as possible.
- The project consortium worked with ESA/CNES to establish a new test site for the calibration of satellite radiance and reflectance in Namibia and as part of a European contribution to RadCalNet.
- The European reference buoy, BOUSSOLE, anchored off the coast of Nice, one of two in the world used for the system vicarious calibration of ocean colour monitoring satellites (most notably the recent OLCI sensor on board Sentinel 3) has had its uncertainty fully evaluated.
- The QA analysis undertaken in the project, and the promotion of SI traceability, has led to the inclusion of this traceability requirement and associated uncertainty analysis in stakeholder requirements such as (ESA and EU) 'Invitations to tender'. This has led to significant opportunities for further funded work for NMIs to help improve uncertainty (and the recognition of the importance of uncertainty) in climate and Earth observation in general, with Europe taking the lead.

Future potential impact

This project has established a strong enduring partnership of NMIs, DIs and key stakeholders, which forms the basis of a future European virtual centre of excellence: Metrology Network for Earth observation and Climate. Ultimately this will be a 'one-stop-shop' for Earth observation and climate metrology and to date has been sought by a number of external projects where complete knowledge of a sensor and its products is needed. The provision of traceable and reliable data with known uncertainties to the scientific user community will improve the understanding of climate dynamics and the ability to interpret trends. This will enable investment decisions on adaptation and mitigation by governments and risk sensitive industries like insurance to be taken with improved confidence in their outcome; the consequence is that a verifiable link can be made between the outputs of this project and society's response to the effects of climate change.

Through the direct involvement of NMIs in this project: the data from European satellite missions, European aircraft missions and ground based networks will become de-facto references. For example the SLSTR on board the Sentinel 3 satellite is being used globally as the in-flight reference satellite for sea surface temperature.

Furthermore, the consortium has participated in other external projects in the field of Earth observation, including the EU Quality Assurance for Essential Climate Variables (QA4ECV), Fidelity and uncertainty in climate records from Earth and Observations (FIDUCEO), and ESA's FRM4STS. Through this and the work of ENV04 MetEOC and this project ENV53 MetEOC2, the consortium has become a key group of metrology organisations working towards the establishment of a European Metrology Network for Earth observation and Climate.

5 Website address and contact details

A public website has been established, where project results are available as well as news about the project and related events: http://www.emceoc.org/

The contact person for general questions about the project is Nigel Fox, NPL (nigel.fox@npl.co.uk)

6 List of publications

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