Metrology for Earth Observation and Climate

Final Publishable JRP Summary Report for ENV53 MetEOC2 Metrology for earth observation and climate

Overview

Remote sensing of the Earth from space is vital for obtaining the global data needed to underpin climate change research and its impacts, (e.g. 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 (identified by experts for the United Nations Global Climate Observing System (GCOS), such as a few tenths of a percent per decade change in total solar energy or sea surface temperature. However, the performance of satellite instruments is prone to degrade due to the harshness of launch and environmental conditions in space. Therefore they generally need to be re-calibrated and always validated in orbit to guarantee the reliability of the data they collect. This project addressed these issues and aligns with on-going international efforts, by establishing tools, methods and infrastructure to help assign reliable traceable confidence levels to climate change monitoring data.

Need for the project

The Earth is changing dramatically as a result of global warming. Our 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 Essential Climate Variables (ECVs), such as atmospheric and surface temperature as well as biophysical ECVs 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 small fluctuations which may reveal changes in the Earth system. In most cases, detection of changes of a few tenths of a percent 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 geophysical and biophysical parameters (e.g. the ECVs) that are important for understanding the state of the planet. End to end assessment of uncertainty and traceability has been recognised as an urgent challenge that needs to be addressed by the climate community with support from metrology experts.

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

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Scientific and technical objectives

The aim of MetEOC2 was to establish 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. To do this the project further developed the outputs of the previous project ENV04 MetEOC and had the following scientific and technical objectives.

Objective 1: Level 1 satellite traceability

- Make 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/geophysical parameters typical of ECVs and ultimately to the long time-series needed to establish a Climate Data Record (CDR).

Objective 2: Atmospheric ECVs

- Further development of in-flight large aperture Infrared 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
- Establish an SI-traceable method for ground based measurements of Atmospheric Optical Depth 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 (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 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) CDR.
- 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.

Results & Conclusions

SI traceability for measurements of the Earth’s radiance and reflectance from space

The primary optical measurement for satellites viewing the Earth from space is either radiance or reflectance, from these other biophysical parameters are derived and corrections for atmospheric transmittance and others start to play a significant role. Thus it is critical that these starting point measurements at top of the atmosphere are consistent, traceable and have assigned to them a robust uncertainty estimate. Post-launch calibration and validation and cross-comparison is essential to address these issues. In the absence of SI-traceable reference satellite in space, ground based targets such as deserts are used.

The Committee on Earth Observation Satellites (CEOS) initiated a project in 2014 to establish a network of SI- traceable instrumented sites, called RadCalNet (www.radcalnet.org), to provide satellite-to-ground comparisons for satellite product validation. This was part of a broader initiative which also considered inaccessible deserts, the moon and clouds etc. RadCalNet was first opened to public access in October 2016 and has already been used by approx.15 different users (e.g. 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.

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 (see below) 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 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 a Researcher Excellence Grant at the University of Zurich (REG(UZH)) to improve the calibration of the airborne hyperspectral imager APEX.

All aspects of this objective were fully achieved and have made a major contribution to the community, many activities being undertaken in collaboration with broader international efforts.

SI-traceability for atmospheric ECVs

The atmosphere and its composition is the principle link between the Earths system, absorbing both energy from the sun and re-emitted energy from the Earth and transporting this between land and ocean domains. Understanding the dynamics, (local and global) and composition is critical for our ability to study and interpret climate change. This project addressed a number of aspects related to improving the traceability of measurement systems characterising the atmosphere at various heights.

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 NDMC ground stations 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.

The activities addressing this objective were completed successfully, but because of the additional work to evaluate safety aspects of the CNT black coating and concerns over its handling under heavy usage conditions, this was not used for the blackbody coatings as was originally intended. However, adequate performance was achieved without it.

<u>End to end traceability for biophysical ECVs</u>

The biosphere, land and ocean is a key part of the Earth's carbon cycle and responsible for absorbing, as a natural sink, half of emitted carbon dioxide, one of the principle causes of climate change. The forests, particularly the tropical rain forests, are also long tern stores of carbon and the rapid release of carbon though deforestation is a major concern. It is thus critical that we have a good benchmark of the state of the planet and continue to monitor change to assess the impact of climate change.

To support this, the project:

- 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 2017Sentinel 3 validation team meeting.

The activities within this objective were all fully completed and the outputs are being embodied into other international projects. For example, the Wytham woods site is now one of two European sites being used by ESA to validate Sentinel 2.

<u>Traceability for EVCs impacting radiation balance</u>

The temperature of planet Earth is driven by the balance of absorbed solar radiation and emitted thermal radiation. The total amount of solar radiation which hits the Earth is measured with solar radiometers on spacecraft. In the absence of robust in-flight SI traceability this project aimed to make those measurements traceable to ground based standards.

The CLARA solar radiometer was developed and built by SFI Davos. It was launched into space in 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.

Most of the planned work addressing this objective was completed. 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 due to the limited availability of key experts, hence there was no time to build the complete instrument.

Actual and potential impact

Dissemination of results

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 18 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).

13 training courses were run for delegates outside of the project consortium. The five courses entitled Uncertainty analysis for Earth Observation instrument calibration attracted the highest number of delegates, predominantly from the scientific community in higher education and public research organisations. In addition, on-line training material developed during the previous project ENV04 MetEOC and updated during this project has been downloaded more than 2000 times.

The terrestrial laser scanning work from the project was showcased on BBC news http://www.bbc.co.uk/news/science-environment-38335348

Members of the consortium were also interviewed about TLS and PAR networks for an Oxford University documentary series called “the Laboratory with Leaves” http://www.ox.ac.uk/content/wytham-woods-laboratory-leaves

The project contributed to good practice guides for a biodiversity source book https://ec.europa.eu/jrc/en/publication/gofc-gold-2017-sourcebook-methods-and-procedures-monitoring-essential-biodiversity-variables and for a sourcebook of methods and procedures for monitoring, measuring and reporting Reducing greenhouse gas emissions from deforestation and degradation in developing countries http://www.gofcgold.wur.nl/redd/

Early impact

- The project assisted the CEOS in the development of its RadCalNet network, through the provision of traceability, and the development of best practices. More than 15 satellite owners took part in the 6 month beta testing phase of the RadCalNet network and presented results endorsing its high value.
- The consortium also 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 first station of the NDMC network was fully traceably calibrated, removing ambiguity and allowing the density of hydorxyl radicals to be determined. (This provides a pre-cursor for further improvements in the follow-on EMPIR project 16ENV03 MetEOC3)
- The European reference body, BOUSSOLE, one of two in the world used for the system vicarious calibration of ocean colour monitoring satellites has had its uncertainty fully evaluated.
- The Quality Assurance 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 ESA and EU ‘Invitations

to tender'. This has supported further funding for NMIs to help improve uncertainty (and the recognition of the importance of uncertainty) in climate and Earth observation.
- The retrieval algorithms of atmospheric composition parameters from GLORIA were significantly improved, including end to end uncertainty analysis, which has led to a specification improvements for future work.

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.

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