Final Publishable JRP Summary for JRP ENV04 MetEOC European Metrology for Earth Observation and Climate

Background

This project has established new transfer standards and methods to enable improved accuracy and traceability for the calibration of remote sensing sensors (satellites/aircraft), for both laboratory-based 'pre-flight' calibration as well as 'in-flight' measurements of incoming and reflected radiation in the optical, thermal infrared and microwave wavelengths. In some cases this has involved the development of bespoke instrumentation to enable libraries of reference data to be collected that can ultimately be used to validate satellite performance.

The scale of the challenge is very large and not solvable within the resources and timescales of a single project. However, specific aspects have been improved and demonstrated by case-studies using existing or planned sensors and will contribute to scoping the long-term vision; a European virtual centre of excellence of metrological support to Earth Observation (EO) and climate.

Need for the project

Climate forecast models, which remain the only method to predict the future evolution of climate change, are underpinned by remotely sensed data. Thus improving the traceability and accuracy of this data is at the top of the agenda of space and research agencies. A factor of 10 improvement in measurement accuracy is required to discriminate between the natural variability of the climate system and the 'anthropogenic' (human-caused) signal in the shortest time possible. Such an improvement would result in more trustable climate forecasts and increased confidence in the resulting adaptation and mitigation policies.

To achieve this order of magnitude reduction of measurement uncertainty, there is an urgent need to address the following challenges:

- Ensure pre-flight calibration (laboratory-based) methods are traceable and flexible to ensure full interoperability between different sensors
- Improve calibration of sensors in the post-launch phase. The rigours of launch and harshness of space results in a drift in sensor performance and consequently, accuracy, after terrestrial calibration, requiring some means of re-checking the calibration post-launch.
- Improving the above involves the evolution of laboratory-based metrology and its associated uncertainties, transferred to field (and space) situations. The key metrology challenges related to the sensor are: its large scale, operating conditions (e.g. vacuum), wide dynamic range and fast time response due to orbital speed. In remotely viewing the Earth such sensors have a wide range of spatial resolutions (from coarse -1000's of metres to fine -10s of metres), necesasitating reference data on the same scale for all types of Earth scene: land, ocean and atmosphere.

Scientific and technical objectives

- **Pre-flight and post-launch (on-board) calibration and validation (Cal/Val) of satellite and aircraft sensors to meet the needs of Land, Ocean and Atmosphere 'Essential Climate Variables' (ECVs)**.

This involved developing new transfer standards, developing techniques to enable traceability back to the fundamental SI unit, and giving direct access to the uncertainties achievable by primary standards. In this project, instruments measuring the visible and infrared wavelengths are targeted as case studies, as the majority (around 2/3rds) of 'Essential Climate Variables' (key climate parameters needed to fully understand the climate system) are measured using optical radiation and closely matches the expertise of the core team.

- **Provide the EO community with improved methods to validate satellite derived data with known uncertainties.**

This required the development of measurement techniques/transfer standards with robust estimates of uncertainty that could be used in remote locations and in some cases autonomously for surface reflectance as a test site for satellites. It included SI verification of commonly used EO models (i.e. radiative transfer codes) used to link satellite measurements of radiance to bio/geophysical parameters and collection of data to parameterise them.

- **Develop and test aspects of an "in-flight" SI traceable calibration methodology for benchmark measurements of radiation for climate.**

These techniques are the prototype for the creation of a satellite that will allow fully traceable measurements in space; i.e. creating a "National Measurement Institute (NMI) in space". To achieve the factor of 10 improvement in accuracy stated above, the techniques targeted an uncertainty of 0.01 % for incoming solar radiation, and 0.3 % for reflected radiation. In addition to prototyping the in-flight calibration system, the in-flight primary standard, known as the 'Cryogenic Solar Absolute Radiometer' (CSAR), is also validated to uncertainties less than 0.01 % for 'total solar irradiance' and less than 0.1 % for 'spectral radiant power'.

Results

Pre-flight and post-launch (on-board) calibration standards and methods

The project developed and demonstrated through case studies a variety of new measurement facilities and techniques which can be tailored to meet the foreseeable radiometric calibration needs of most optical sensors. Examples of these case studies include:

- For a typical airborne hyper-spectral imager (used to measure land surface reflectance) the project:
  - Determined and corrected 'stray light characteristics' using tuneable laser radiation, and in doing so also identified and addressed various secondary issues which demonstrates the versatility and benefit of this technique.
  - Constructed and tested a novel portable tuneable laser facility that was initially used to calibrate ocean colour sensors, but was further developed to include the construction of a 'flat panel' vacuum compatible radiance source. This allows full calibrations of imaging sensors at uncertainties of <0.5% in a highly compact format compared to more traditional methods, making it easier to perform calibrations in-situ. This facility is already being used operationally and is included in plans for future ESA projects.
  - Developed a large aperture (40 cm) radiance source with high uniformity (<1%) and used it to calibrate a wide field of view spectral camera for airborne remote sensing of Earth's reflectance facilitating an increased range of applications.
  - The project supported the in-flight calibration of the 'GLORIA' experiment (Atmospheric Limb sounding spectrometer), where our measurements involved the full pre- and post-operation characterisation of a novel IR calibration system, allowing its measurements to have an uncertainty less than 0.1 K (which were independently verified by two NMIs). This work has been extended to balloon-based experiments, resulting in several publications, and have been used by ESA to specify the requirements for future satellite missions.
- An evaluation of traceability needs of microwave sensors has been carried out and a roadmap to achieve has been drafted based on discussions with key stakeholders in the satellite and user community. A proof of concept for a pre-flight SI traceable calibration facility was carried out and also an evaluation of an improved coating for black body reference targets in the microwave range.

Through work with external collaborators via universities, research institutes and industry the project additionally:

- Carried out an uncertainty evaluation of an ESA hyperspectral imager, APEX, the analysis of which was used as a case study in a training course on uncertainty assessment in EO
- Completed and published a baseline design of a novel 'semi-conductor mm scale spectrometer', as a low mass and volume sensor which is now seeking sponsors to build a prototype

Post-launch Calibration and Validation through test-sites and associated models

The below has largely been carried out in collaboration with the international EO community and are formerly being incorporated into operational calibration and validation networks for the forthcoming EU/ESA Copernicus missions:

- An analysis and optimisation of the methods used to provide traceability of the Aeronet-OC network, (Cal/Val of ocean colour sensors) was completed leading to a documented best practise and a reduction in the radiometric component of the uncertainty by a factor of two.
- For test sites used to calibrate satellites measuring land surface reflectance, a first prototype 'self-monitoring (stability) radiometer has been designed and a first prototype tested in both laboratory and field situations
- A small (25 cm diameter) field instrument to measure the hyperspectral reflectance of individual leaves has been constructed, undergone laboratory testing and field trials. Provisional data for an open access database has been collected, and will serve as an ongoing and updateable library of the spectral response of leaves to help the EO community validate satellite outputs.
- We calibrated 3D targets that simulate an Earth target (e.g. a forest) to link satellite measurements with real bio-geophysical parameters. The full set of data are now available on line to allow Radiative Transfer code users and developers to compare with software based codes

Through complimentary work via external collaborations the project has:

- Carried out an analysis of the variance and uncertainty of different methods to establish vegetation related indices. The published results has led to further work in the follow-on EMRP MetEOC 2 project.
- A strategy to achieve SI traceable calibration of unmanned aerial vehicles (UAVs), to provide local measurements of the reflectance of vegetation (which are used as test sites for satellites), has been developed, implemented and will be further exploited in MetEOC 2.

Prototyping methods for achieving SI traceable benchmark measurements of radiation from space

- The aforementioned cryogenic solar absolute radiometer (CSAR) has had its performance evaluated and part of the instrument has undergone significant redesign, resulting in a reduction in its noise related uncertainty by nearly an order of magnitude. This will be a step forward in enabling the replacement of the WMO (World Meteorology Organization) World Radiometric Reference of solar incident radiation levels.
- The project evaluated the means to achieve SI traceable calibrations using a primary standard (CSAR) in space. In doing this a multi-spectral filter radiometer was developed that could be used as a radiometric transfer standard in space (tested in a vacuum). The instrument is capable of a radiometric accuracy of 0.3%; a factor of 10 improvement on previous transfer standards. This demonstrates the viability of the calibration method proposed for the proposed TRUTHS satellite mission and has led to significant follow-on funding to develop the concept further.

Actual and potential impact

The project has provided new techniques and facilities which allow significant improvements to be made to the calibration and validation of instruments used to collect the data to better understand climate change. As these techniques start to be used to calibrate sensors, this will lead to more robust information and advice delivered to policy makers, ultimately supporting far-reaching socio-economic decisions on mitigating and adapting to climate change. To ensure our outputs are adopted and utilised quickly, with as many stakeholders as possible have been engaged with:

- In total, 15 peer-reviewed papers describing MetEOC scientific achievements have been published in journals and more than 40 contributions have been made to international conferences (including approximately 30 meetings to key international organisations such as CEOS, ESA, WMO, Eumetsat and BIPM).
- The coordinator has represented the project and the metrology community in general at 12 international 'standardising' committees, leading to members of the project consortium being sought out for other EO/Climate projects where SI traceability is considered important.

- Good practice guides, technical/public reports and committee (CEOS, WMO) publications have also been used to disseminate the project's outputs. This was reinforced by the provision of training course on uncertainty evaluation which was widely acclaimed and in such high demand a re-run will be carried out in 2015.

In providing new methods and standards with partners, as well as working closely with the international Committee on Earth Observation Satellites (CEOS) – the Cal/Val experts of the World's space agencies – the project was able to gain greater visibility from the broad community and to ensure the most urgent areas can be focussed on to avoid duplication with others. Direct beneficiaries and stakeholders of the project's outputs include: instrument developers, operators and "validators" (from organisations, industry and academia). These parties will benefit from:

- Raised profile of calibration, validation and traceability to a level that it cannot be ignored during satellite mission evolution. Metrological traceability is now being explicitly specified in work procurement specifications from ESA & EU on climate and space based work.
- Good practice guides, reports and committee publications have been used to disseminate the project outputs, these include traceability for Ocean colour (OC) and the work output has subsequently led to ESA requesting support to improve traceability of operational projects. Visibility of the new pre-flight calibration standards and techniques has been well received by international committees and are now finding use in currently developed satellite missions and field instrument calibrations.
- New reference standards and instruments have allowed:
    - New measurements to be undertaken which were not possible before. These include but are not limited to: newly built black bodies on-board the GLORIA aircraft allowing a 3D reconstruction of trace molecules near the southern vortex and a factor of 2 improvement in performance. We also made in-situ leaf BRF reflectance measurement for the first time from a portable goniometer built in the project.
- In part due to the proven viability of achieving reliability and traceability in this project, the international satellite community established a project to establish a global network of SI traceable test sites. The new 'RADCALNET network', will reduce cost and improve post-launch calibration and validation to the world's satellite imagers removing biases between them in an internationally coordinated manner
- 'Fit for purpose' data on the effectiveness of carbon sinks and mitigation strategies will be improved by further work by a number of EU projects including MetEOC 2, triggered by work on uncertainty case studies carried out in this project and also the analysis of different vegetation indexes.

In the longer term other direct beneficiaries include: space agencies, and their major sub-contractors, the EU 'Copernicus' programme (Europe's satellite system for monitoring the Earth for environment and security), policy makers both at national and European level, and international bodies such as GEO, CEOS, and WMO. They will benefit from:

- The upgrade in the performance of existing instrument designs, since these tend to be limited by calibration uncertainty rather than sensitivity
- New transfer standards and methods for pre-flight calibration of imagers both in air and vacuum will enable climate quality performance to be achieved from existing sensors designed for "operational measurements". Although their first full use for satellite systems has not taken place as yet, they are being discussed and envisaged for future sensors such as later models of the Sentinels (EU 'Copernicus' programme). These will allow uncertainties needed for some climate processes to be realised and will also facilitate improved sensitivity on land product classification and albedo measurements.
- The successful demonstration of the prototyping of TRUTHS calibration methodology has been used to de-risk the concept. The results have been used to form inputs to other national space agency funded studies which now place TRUTHS on a potential path for implementation, subject to funding. The concepts have already been adopted by the Chinese space agency who are looking to build a version for launch in 2018.
- Improvements to the CSAR mean it is now ready to participate in the next step to its potential adoption as an SI replacement for the current scale of solar irradiance of the WMO, the World Radiometric Reference (i.e. a new international standard).

Together, in the longer term, these will lead to improved reliability and consistency of the Earth observation data used to assess climate change variables and will ultimately contribute to improved climate modelling.

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The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union