ENV04 MetEOC

Metrology for Earth Observation and Climate

EURAMET

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JRP-Coordinator	
Name, title, organisation	Nigel Fox, Dr, National Physical Laboratory
Tel:	+44 208 943 6825
Email:	nigel.fox@npl.co.uk
JRP website address	http://www.emceoc.org
Other JRP-Partners	Aalto, Finland INRIM, Italy JRC, European Commission LNE, France MIKES, Finland PTB, Germany SFI Davos, Switzerland BUW, Germany DLR, Germany FGI, Germany FZJ, Germany

REG1-Researcher (associated Home Organisation)	Joanna Coote, United Kingdom ZiNIR, United Kingdom	Start date: 01 June 2012 Duration: 24 months
REG2-Researcher (Associated Home Organisation):	Andreas Hueni, Switzerland UZH, Switzerland	Start date: 01 April 2012 Duration: 30 months
REG3-Researcher (Associated Home Organisation):	Petra D'Odorico, Switzerland UZH, Switzerland	Start date: 01 April 2012 Duration: 15 months
REG4-Researcher (Associated Home Organisation):	Eija Honkavaara FGI, Finland	Start date: 01 January 2013 Duration: 12 months

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1 Executive Summary

Introduction

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.

The Problem

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.

The Solution

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.

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.

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'.

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.

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).

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.

2 Project context, rationale and objectives

"*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 the IPCC has strengthened its conclusion, governments are reluctant to act, and the public remain confused. This is fuelled by the large uncertainty in climate model forecasts and the arguments of climate sceptics. The data to constrain and test the models and their inputs must be collected globally and reliably over long time scales which can only be done through satellites. However no single satellite can provide the temporal or spatial coverage necessary and, so although in principle only change needs to be monitored, this requires harmonised data sets across observation platforms, space, air and in-situ. At present, this is hard to achieve, since instruments, even if consistent pre-launch, change calibrations during launch and degrade in orbit due to the harshness of launch and environment. The world's Earth Observation and climate community currently require improved accuracy (in the case of climate this is typically a factor of ten) and SI traceability, particularly in the post-launch environment to try to overcome some of these challenges. In many cases traceability is based on unsubstantiated or debated claims, resulting in high uncertainties for climate forecasting, and weak evidence to counter the claims of climate sceptics. This delays key actions by policy makers and citizens.

> *"The temperature of the Earth responds to changes in the radiative energy balance maintained between the incoming solar radiation and the outgoing reflected solar radiation and emitted thermal radiation. Accurate total and spectral, space and surface measurements of these radiation components at various spatial and temporal scales are critical for understanding the long-term trends in and processes effecting the Earth's climate. Moreover, these measurements must be tied to the SI to ensure their comparability independent of time, locale, or sensor. The measurement problem is extremely challenging since the accuracy required is commensurate with the state of the art for spectral radiance and irradiance measurements performed in environmentally controlled laboratories at National Metrology Institutes."* WMO / BIPM Workshop Recommendations 'Measurement Challenges for Global Observation Systems for Climate Change Monitoring: Traceability, Stability and Uncertainty' - 2010

This drive for reduced uncertainty together with the need to synergistically combine data from a variety of sources (space and in-situ) has placed "traceability" and its reliable quantification at the top of the agenda of space agencies and the wider 'Group on Earth Observation' (GEO) community. In the case of satellites, improvements in uncertainty and traceability are needed throughout all stages of data production: pre-flight and post-launch calibration and validation and all the intermediate processing steps. The necessary technical scope spans the full electro-magnetic spectrum and requires the evolution of laboratory-based metrology into field (and space) situations whilst maintaining (and in some cases improving), the uncertainty available from nominally 'primary standards' and facilities. The Committee on Earth Observation Satellites (CEOS) recently led the EO community in the development of a Quality Assurance Framework for Earth Observation (QA4EO) www.QA4EO.org. The key principle is that *"data and derived knowledge information* *products must have associated with them a quality indicator (QI) based on documented evidence of its degree of conformity to community defined, ideally SI[1], traceable reference standards."* This project makes a close linkage with these initiatives and communities, by aligning its research effort to these and other international initiatives it increases critical mass and ensures maximum uptake and benefit to the community aa a whole.

There are many examples that demonstrate the inconsistencies and biases between in-flight sensors and where normalisation has been used to enable long-term records to be established. The most commonly used example is that of Total Solar Irradiance however, others exist such as the NOAA (National Oceanic and Atmospheric Administration) AVHRR series of satellites which shows an apparent "greening" of the deserts as the sensors drift with time. In addition air temperature observations between sondes and microwave sounders have led to significant debate on the nature of global warming. The work-plans of the international coordinating bodies on Earth Observation Satellites are focussed on the development of improved traceability strategies and comparisons to evaluate biases. Such activities are particularly prevalent in the optical domain, where efforts are underway to establish networks of SI traceable post-launch reference standards, based on natural targets in preparation to underpin the needs of virtual constellations of sensors. Significant research is needed to ensure that these can attain and maintain SI traceability in the long-term in a cost effective manner. This involves the evolution of laboratory-based metrology, and its associated uncertainties, transferred to field (and space) situations.

The long-term challenge for the metrology community is to establish the capability to make SI traceable measurements from space at uncertainties commensurate with those obtained in the laboratory through direct use of a primary standard, in effect transferring an "NMI into orbit". This requires uncertainties of 0.01% for incoming radiation, 0.3% for reflected radiation, all globally from space. These are close to those achievable by the primary standards in the laboratory. This requirement has been championed by the international EO community to address the exacting needs of climate science. In particular, it is needed to constrain and improve the accuracy of forecast models to decadal rather than multi-decadal timescales allowing policy makers the ability to develop prioritised mitigation and adaptation strategies. The US has initiated studies on a mission called CLARREO to address this topic, which in part follows on from a European Mission concept called TRUTHS. Research to prototype and de-risk these concepts is undertaken in this project. The Conférence générale des poids et mesures (CGPM) has highlighted the importance of this overall topic, including the specificity of traceability or an "NMI in space" in resolution 11 of its 23rd meeting in 2007 [10]

> *"…**recommends** relevant bodies to take steps to ensure that all measurements used to make observations which may be used for climate studies are made fully traceable to SI units,*
>
> *and **further recommends** appropriate funding bodies to support the development of techniques which can make possible a set of SI-traceable radiometric standards and instruments to allow such traceability to be established in terrestrial and space based measurements" .*

Whilst it is essential that sensors are well characterised pre-flight, and this project addresses the topic with new methods and standards, and if possible are calibrated or monitored in-flight using on-board standards, again a topic of this project, this only characterises the signal as detected at the satellite above the atmosphere. This is fine when the signal comes from space, but when observing surface or internal atmospheric properties, correction has to be made for the passage of radiation through the atmosphere. It is thus imperative that any retrieval model is evaluated and corrections for atmosphere and surface characteristics are properly accounted for. Provision of validated, 'ground-truthed' data goes some way to address this requirement and is also a topic of this project.

It is only with a full aperture end-to-end calibration that an instrument builder can demonstrate compliance with a performance specification. If the instrument is intended for space flight it is essential that this calibration be carried out under the full range of conditions it is likely to see in orbit, (environmental temperature fluctuations, source inhomogeneity and vacuum), as many components will exhibit different characteristics in space. The target uncertainty for spectral radiance measurements varies depending on the technology and mission aim:

- Geostationary Earth Radiation Budget (GERB) (using integrated spectral radiance) had a target of <1 %

[1] SI, Système international d'unités / International System of Units

- Earthcare of ESA will require <2 %
- Sentinel 2 and 3 (using spectrally resolving optical sensors) are targeting uncertainties of <2 %

The required uncertainty for climate measurements s up to a factor of ten better than this and will ultimately require sensors with on board primary standards such as TRUTHS/CLARREO. Detailed spectral characterisation is usually done with a broadband lamp-illuminated radiance source. However, the desire to make the technologies more suitable for climate science means the ideal calibration solution would be a spectrally tuneable large-area spatially-uniform source of known radiance. This project targets a required uncertainty of <0.5 % so that this can be demonstrated for the future and the prospect of improved performance of the Sentinels themselves.

To increase confidence and understanding in climate change predictions, accurate measurement of temperature trends in the lower atmosphere is crucial. Satellite microwave radiometers operating over the 50-200 GHz band, sampling the earth's near-atmosphere and providing information on temperature and water vapour, require greater validation and calibration. Pre-flight traceability of such sensors is relatively weak, and therefore the International community is demanding improvements as these sensors advance from operational weather to climate measurement.

Significant improvements in the calibration strategies of future IR atmosphere measuring sensors are required to ensure that the SI traceable uncertainties now required can be achieved:

- Uncertainty of absolute radiance measurement of <1 %
- Uncertainty of relative radiance measurement (spatially and spectrally) of <0.1 %

In limb sounding it is important to reduce spectrally uncorrelated uncertainties. At moderate spectral resolutions a number of interfering trace species have to be retrieved simultaneously. The uncertainties uncorrelated between the various spectral windows degrade the accuracy of the retrieved trace species more strongly than errors correlated over a wide spectral range. In order to achieve the scientific objectives of future limb imager missions spatially and spectrally uncorrelated radiometric uncertainties have to be reduced to 0.1%.

This project recognises that there is a need to establish greater coordination and focus more effort on the underpinning metrology that is needed to realise a practical, efficient and cost effective means of establishing "fit for purpose" traceability for the European EO community. To build a long-term evolving and sustainable set of capabilities, infrastructure and expertise with minimal duplication requires a "European centre of excellence". **The long-term goal of this project is to initiate a virtual European Metrology Centre for Earth Observation and Climate (EMCEOC).** The complexity and scale of the challenge means that this project can only be considered as the first phase towards this vision. This will be done through the following 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'.

This project specifically looked to address:

Measurement parameter	**Current state of the art**	**project Target**
Pre-flight calibration of filter radiometers	Relative radiometric performance	Absolute radiometric performance
Filter radiometers in vacuum	3-5 %	0.3 % to 0.5% (for polarising filter radiometer) 0.5 % (imaging radiometer)
Vacuum black body thermal stability	~ 100 mk	<30 mK (at 193 K, over 2 hours)
Vacuum black body (spectral radiance 5 um to 14 um	Uncertainty 0.2 K (from AIRS)	Target uncertainty <0.1 K
Test site spectral reflectance	4 % to 5 % uncertainty	1 % uncertainty
400 mm source uniformity of spectral radiance 300nm – 1000 nm	40 cm exit port, 1 % at best	<0.5 %
Hyperspectral imaging camera stray light	>10 %	<1 % uncertainty following correction
Ocean colour measurement	Uncertainty 5 %	1 % (though 2.5 % would be a major breakthrough)
Multi-angle leaf reflectance (field) 400-800 nm, 0-80 degrees	>10 %	< 3 %

In summary, although initially focussed on the remote sensing community and in particular the needs of climate, this project will seek to identify detailed requirements for the future and build partnerships to ensure full use is made of all relevant European metrological expertise. This will include organisations not eligible for funding by this project, co-aligning where possible with other related projects within Europe and elsewhere. It will seek to expand its scope to encompass the metrological aspects of all Earth Observation application domains and provide the basis for a "one-stop-shop" to support the needs of those in industry and academia engaged in the calibration and validation of Earth Observation instrumentation and associated products.

3 Research results

3.1 Overview of MetEOC Pre-flight Calibration Standards Activity

Pre-flight calibration standards and methods

We 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) we:

- o 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.
- o 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.
- o 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.

- An evaluation of traceability needs of microwave sensors has been carried out and a roadmap to achieve this 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 Researcher Excellence Grants (REG) the consortium 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

A key objective of MetEOC was to develop improved methods for pre-flight calibration of EO instruments. Although several national metrology institutes, particularly NPL, NIST and PTB, have been offering calibration services to the EO community for 10+ years, these services have often been based on adapted classical techniques, relying on minor modifications to standard measurement services. The adaption to the specific needs of the EO community have often had to be carried out by the scientists and engineers working in the space community, rather than by metrologists and metrological requirements. In particular rigorous uncertainty analysis has not always been possible.

In this project there was a considerable programme to look at improved calibration methodologies for the EO community. This covered both the optical (typically 400 nm – 2000 nm) and the microwave spectral regions. In the optical spectral region, radiometric calibrations are more advanced and the focus was on developing new facilities for the calibration of imaging spectroradiometers, which are typical devices on board EO satellites. Three facilities were developed, and used: at PTB in Berlin a facility was made for the radiometric calibration of large field-of-view camera systems (Section 3.1.1), at PTB in Braunschweig a facility was made for the spectral characterisation and stray light estimation of imaging spectroradiometers (Section 3.1.2) and at NPL a portable facility was developed for the spectral characterisation of such imagers within a vacuum chamber (Section 3.1.3). The two PTB facilities were also used for the calibration of (two different) DLR imaging sensors used on-board DLR research aircraft for airborne remote sensing. These three facilities are described in sections 3.1.1 to 3.1.3. Collaboration between PTB and DLR was very active and included mutual visits, sharing of expertise and mutual assistance in solving problems faced during the work. The research results could be achieved only by both partners working together as a team. If to compare the areas of expertise by the partners relevant to this specific subject before the project and after the project, the overlapping of the areas was increased dramatically thanks to the efficient collaboration and the transfer of knowledge.

In the microwave spectral region the community is less advanced. Here our focus was on providing guidance to the space community on how metrologically rigorous calibrations of microwave sounders could be made. NPL developed a roadmap in consultation with the space community for how calibration could be improved and developed, with the help of PTB, some reference standards for a measurement service for microwave emissivity measurements. This is discussed in Section 3.1.4.

3.1.1 The research undertaken

Development of a large area variable radiance source

Most EO imaging systems have a large field of view and require a large, uniform, stable radiance source for their calibration. For example, DLR need homogeneous radiation sources for high-precision calibration of focal planes and systems for the EnMAP, MERTIS, Sentinel-4 Detectors, etc. The requirements for homogeneity and temporal stability are extreme for systems that have up to 16 bit resolution. As an example cross-talk measurement for S-4 should be measured for sensor signal differences of 82dB (14 bit). Existing sources used at DLR have been sufficient to meet the requirements of previous customers, but there is no margin for future developments.

Therefore, this project developed, optimised and provided a full radiometric characterization of a novel, integrating sphere based, large-aperture variable-radiance source (LAVRAS) at PTB. Developed and constructed in cooperation with an industrial partner, the 1.2 m diameter integrating sphere has an aperture diameter of 40 cm and uses 64 individually-controllable 50 W tungsten halogen lamps as optical radiation sources covering the spectral range from the ultraviolet to the near infrared. The optical radiation is coupled into the sphere via 32 synchronously adjustable apertures placed between the sphere and the lamps. Due to this unique concept, the spectral radiance of the integrating sphere can be modified over more than two orders of magnitude while keeping the spectral shape of the radiance constant. The radiometric characterization was performed in terms of:

- **Temporal stability:** The radiance change ultraviolet (UV), visible (VIS) and near infrared (NIR) wavelength range was monitored by means of three broad-band monitor detectors and with a high accuracy radiance meter at 650 nm for a period of more than 60 hours. The source was stable to better than 0.1 % per hour in the UV, VIS and NIR wavelength range.
- **Lateral radiance distribution:** The homogeneity over the full aperture plane was measured by scanning a 5 mm × 5 mm with a radiance meter at 650 nm and 900 nm; additionally, the horizontal radiance distribution along the central line of the aperture was measured at 400 nm, 550 nm, 800 nm and 1000 nm for a symmetric 4-, 12-, 24- and 32-lamp pairs operational. Uniformity of ± 0.3 % in the VIS and NIR and ± 0.7 % at 410 nm was achieved (Figure 1).
- **Angular radiance distribution:** setting the focus in the centre of the radiating area for angles ranging from ±30° horizontally and ±10° vertically, seven different lamp operation configurations, including deliberately chosen asymmetric illuminations were measured at a wavelength of 650 nm. Within a viewing angle of ± 10° horizontally and vertically, the spectral radiance is nearly constant i.e. 1% change at 650 nm.
- **Absolute radiance calibration:** To provide the mandatory traceability to the SI, the spectral radiance of LAVRAS was calibrated in the wavelength range from 350 nm (UV) to 1100 nm (NIR) and ten different lamp configurations by comparison with the Spectral Radiance Primary Standard of PTB, the High Temperature Blackbody HTBB3200pg. The spectral radiance can be varied within a range of two orders of magnitude, typical maximum achievable radiance values in the VIS and NIR are 0.3 $W \cdot m^{-2} \cdot nm^{-1} \cdot sr^{-1}$; Within the whole radiance variability range the maximum variation of the spectral shape (with reference at 650 nm) was found to be 5 % in the VIS/NIR- and 10 % in the UV spectral range.

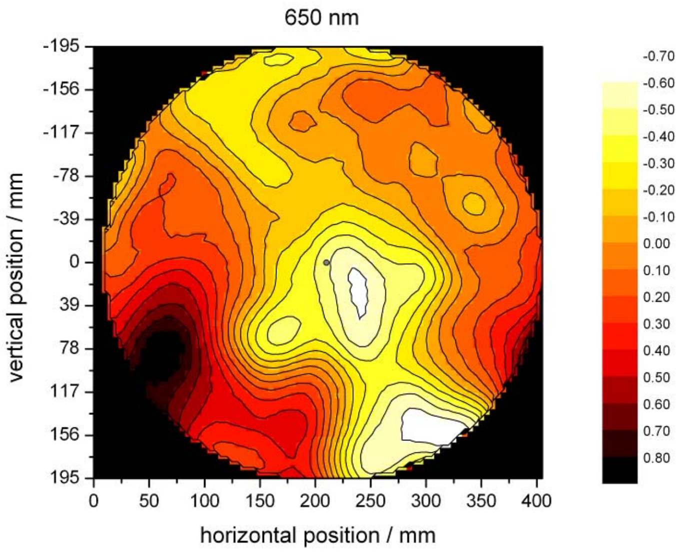

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Figure 1 Example uniformity scan of the full aperture of the LAVRAS

These results demonstrate that LAVRAS is particularly suitable for linearity investigations as well as for flat-field calibrations of imaging and non-imaging remote sensing instruments especially when large radiating source with homogeneity below 1% is required and compare to typical commercially available large area sources, which achieve homogeneities of ~3 %. The facility was successfully used for the radiometric calibration of a DLR airborne camera system and DLR commented "The new sphere is leading in terms of accuracy of the representation of radiance and irradiance homogeneity for large entrance apertures and temporal stability. The use gives us new opportunities."

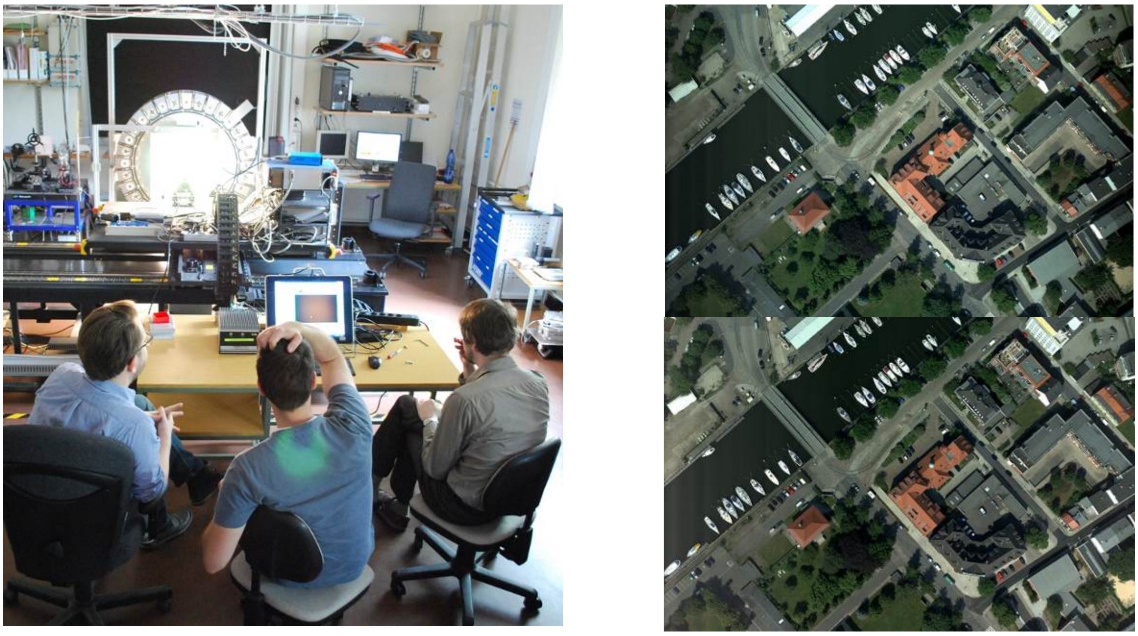


Figure 2 Calibration of the DLR camera system at PTB in front of the LAVRAS and "before" and "after" images captured by the camera. The unnatural darkening of the corners of the top picture is removed in the second picture by correcting for linearity and flat-field effects using the LAVRAS calibration.

<u>Stray light characterisation of a hyperspectral imager</u>

The aim of this research was to develop, evaluate and transfer to stakeholders procedures for the characterisation and correction of stray-light characteristics of hyperspectral imaging spectroradiometers.

The stray-light property of the instruments is one of the most important characteristics limiting their performance in the measurement of ground scenes.

Within this framework and in collaboration between PTB and DLR, a measurement service was prepared and validated for stray light characterisation of a push-broom type hyperspectral imaging spectroradiometers for airborne applications. The aim of the characterisation is to determine the response of the instrument to a monochromatic radiation when a single spatial pixel is targeted. This was achieved by combining a wavelength-tuneable laser source and a high quality mirror collimator with a small aperture at its focal point. By tuning the laser wavelength and angular orientation of the spectrometer with respect to the aperture irradiated by the laser radiation, the response of the instrument, expressed in terms of the so called Line Spread Function (LSF) (see Figure 3, left), could be probed for any pair of spatial pixel and spectral channel under excitation. The data collected in an automated characterisation procedure could then be used for determining the spatial-spectral stray light distribution tensor (see Figure 3, right) and finally the respective correction taking care of the crosstalks in the instrument in both spatial and spectral directions.

The case study within this research revealed importance of the infrastructure used for the stray light characterisations. The radiation source should be adequate for the task considering both spectral and geometrical aspects. I.e. spectral and geometric purity of the tuneable source should be better than the respective stray light characteristics of the instrument expressed in terms of the LSFs.

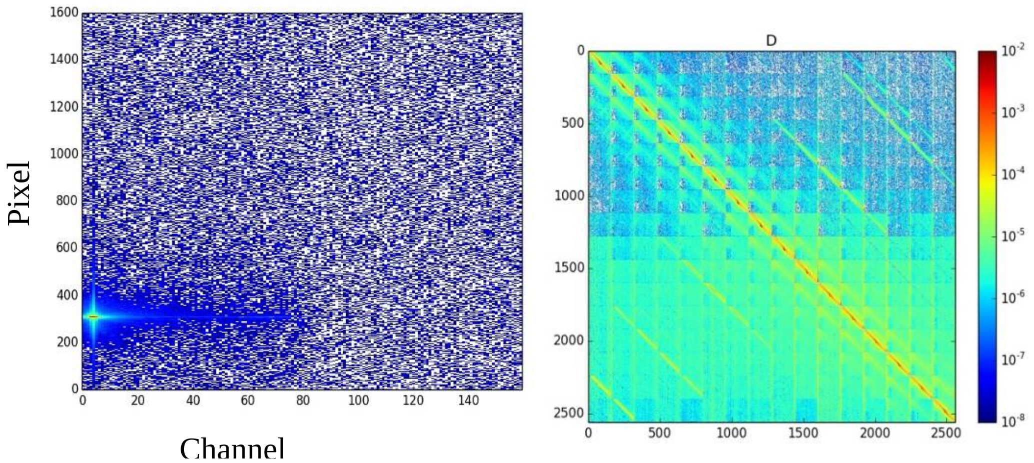


Figure 3 Left) An example of the response of a push-broom type instrument to a monochromatic radiation aimed at a single pixel. Right) Graphic representation of the stray light distribution tensor determined on the basis of measured responses for a set of pixel-channel pairs.

It was also important to characterise other instrumental properties of the hyperspectral imagers, e.g. noise level, dark signal stability and radiometric linearity of the device, to obtain reliable stray light results. The results for the instrument characterised in the case study showed higher variation of the LSF in the spectral than in the spatial domain. Thus, it was possible to interpolate the required LSFs for all pixel-channel pair combinations using a few measurements across the detector array. The determined spatial-spectral stray light correction tensor was validated using both laboratory data and data collected during airborne measurements over Lake Starnberg (see Figure 4). The Lake Starnberg results showed small variations in the spectrum when the stray light correction was included. These small changes made significant differences to the depth estimates of the lake, and yielded results significantly closer to independently determined water depths (see Figure 4).

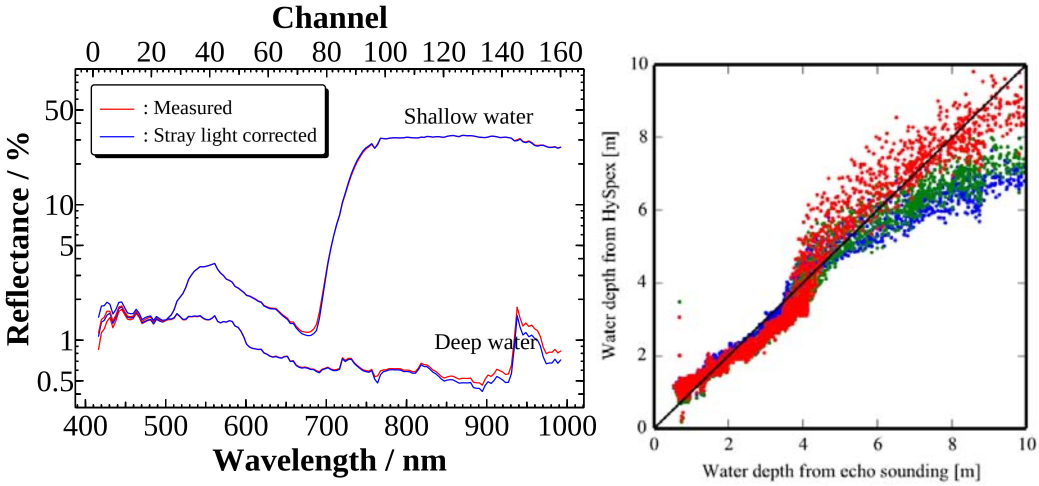


Figure 4 Left. Reflectance spectra obtained from the data of one pixel collected during airborne measurements above Lake Starnberg. The reflectance spectra were calculated from the radiance measurements and respective atmospheric corrections. Right – water depth calculated from spectrum compared to that from echo sounding. Blue dots are using manufacturer calibration, green include radiometric calibration and red are for radiometric calibration and stray light correction.

For the first time the stray light characterisation of a push-broom type hyperspectral spectrometer for the stray light including spectral and geometrical aspects was carried out leading to a single correction tensor. Although stray light characterisation of non-imaging array spectrometers in terms of wavelength-tuneable lasers had already been mastered at PTB before the project, this capability was now expanded to include also the hyperspectral imaging spectrometers. Moreover, equivalent measurement capability based on infrastructure similar to that at PTB now is available also at DLR and will possibly be used for the characterization of the space-borne mission EnMAP.

Spectrally tuneable portable transfer source

NPL developed a transfer standard source for both radiometric and spectral characterisation of imaging spectrometers, mimicking some of the capability of the PTB facilities, but in a portable source that could be used within a vacuum chamber, as many EO space instruments are calibrated within vacuum. Until this project there was limited work on providing large area sources with anything other than a sphere. A sphere-based source requires an extremely bright laser as the sphere is very inefficient at converting power into radiance. It also is physically large and generally operates outside a vacuum chamber, meaning that windows have to be used, the transmittance of which needs separate characterisation, and they can cause interreflections back to the sphere.

NPL has developed an instrument that can make a large uniform radiance field in a much smaller device that can operate within a vacuum chamber. The source consists of a large (170 mm × 170 mm) flat panel (30 mm thick) that is a uniform, monochromatic, tuneable radiance source. The source chosen was a Fianium white-light (supercontinuum) laser. NPL investigated possible mechanisms for providing wavelength tuneability for the source. The method chosen was to use a Volume Bragg Grating filter as it had a better compromise between signal throughput, rejection of unwanted radiation at other wavelengths and physical size and portability than other more traditional techniques such as acousto-optic filters (which had too high throughput at other wavelengths) and double grating monochromators (which are large, difficult to transport and slow to operate). Although both supercontinuum lasers and Volume Bragg Gratings were available, prior to the project, the use of the two together had not been attempted.

A feedback system was developed using an external photodiode and the laser power supply and this successfully stabilised the laser system to a stability of 0.01 % for timescales greater than 100 s.

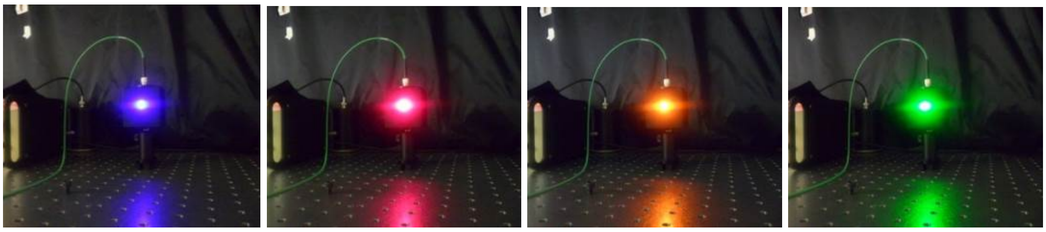


Figure 5 The source operating in irradiance mode at four different wavelengths

NPL worked with a company called Polymer Optics who developed a flat-panel uniform source that could be illuminated by a fibre-fed laser, including the output of the monochromatic tuneable source. The panel was designed to spread the light from the fibre uniformly over an area 170 mm × 170 mm with a beam spread of ±30°. This was achieved by shining the output of the fibre into a white box on the top of which was a plastic or glass cover with small scattering centres (glass broken in a controlled manner with a laser to provide lots of white dots). By having more scattering centres further away from where the light enters the box, and few closer in, it is possible to control the uniformity of the panel. NPL made measurements of the uniformity of the first iteration of the panel and the manufacturer then provided a new, improved, dot pattern to correct for non-uniformities. Uniformities of 4 % (brightest to dimmest across full area) have been achieved, meeting specification, and the manufacturer has promised one more iteration of the design to improve this further. The box also contained films that controlled the light output to the angles close to normal so as to avoid wasting light in directions it was not needed. In the forward direction the source has an angular distribution close to that of a 'perfect' (Lambertian) diffuser.

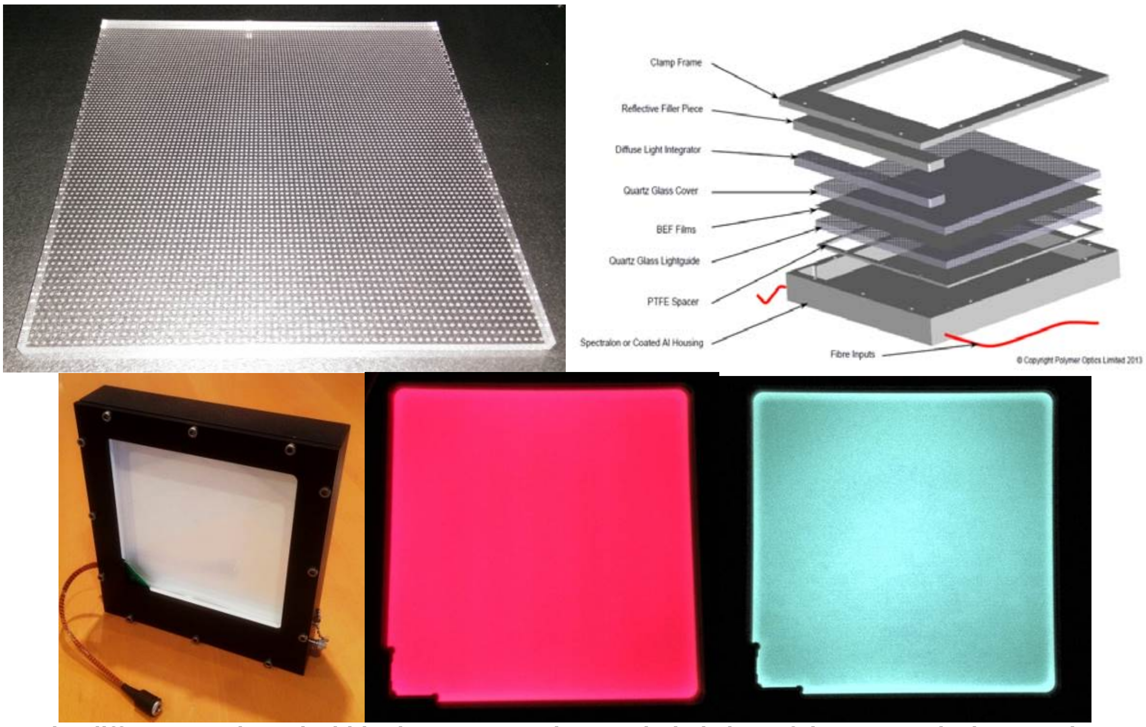


Figure 6 The diffuser panel used within the source and an exploded view of the source design © Polymer Optics and photographs of the completed source unilluminated and illuminated with red and green radiation from the laser.

Some other groups have developed similar sources using weaved fibres as the background to the source, but the source developed in this project is the first using the etched glass technology. One of the advantages of this approach is the efficiency of the technique. The measured radiance is 57 % of the theoretical maximum radiance (when all input power is uniformly emitted over the surface area into an angular field of view of 60°); note that this number includes losses within the fibre, which are likely to be dominant.

Finally NPL made a portable radiometer to measure the radiance of the source. NPL used the source for the calibration of different detectors including the ocean colour radiometer and the transfer radiometer for TRUTHS that were developed and characterised during this project.

Microwave calibrations

During the project NPL both reviewed the needs of the EO community for improved metrological traceability and calibration in the microwave, millimetre-wave and sub-millimetre wave parts for the spectrum and developed a prototype facility (proof-of-principle) for improved satellite pre-launch calibration.

NPL attended meetings with key organisations in the microwave EO community, including a meeting of the UK space community on satellite applications for Agri-tech and food security and several visits to the UK MetOffice and with STFC's RAL space, as well as ESA. At these meetings NPL talked about the opportunities for improved pre-flight calibration and described the measurement needs. NPL also found out the needs of the space industry and produced a 'roadmap' for a future strategy for this area in collaboration with the space industry partners. It is clear that improved metrology in this spectral region will have a significant impact on improving climate predictions.

NPL and PTB collaborated on the investigation of carbon nanotube coated reflectivity standards for use as hot/cold loads for THz calibrations. This provided, for the first time, knowledge of their performance at lower frequencies. The reflectivity from these absorptive devices above 1.5 THz was relatively small (as hoped for), but at frequencies below 0.5 THz the reflectivity increased significantly. NPL also developed a prototype calibration facility for emissivity calibration in the 50 GHz – 140 GHz spectral region suitable for satellite pre-launch calibration.

3.1.2 Key outputs and conclusions

Through the reasearch in this theme we have developed and demonstrated a range of new radiometric calibration techniques for the pre-flight calibration of optical imaging spectrometers (airborne and space). The standards include a complementatry mix of relatively conventonal broad band large aperture sources though to the use of tuenable lasers. The latter have been shown to be valuable for both radiomeric gain and stray light calibrations.

These techniques have been applied to test sensors (aricraft and ground) and shown to be highly valuable with several of the techniques already finding use in other related applciations. For example tuneable lasers are being specified for the pre-flight calibration of Sentinel 4 and 5 as a means of carrying out stray light analysis and spectral bandwidth measurements.

The new standards have provided a means to link the NMI community to key stakeholders and to demonstrate that previously developed laboratory techniques can find valueable roles in sensor pre-flight calibration..

3.1.3 New measurement capabilities and knowledge developed

Although large aperture sources are routinely used, in this project we have developed a very large aperture source with unprecedented uniformity for the calibration of wide field of view aricraf sensors. In contrast to this we have also developed a novel flat panel radiance source illuminated by tuneable laser radiation suitable for use within a vacuum chamber.

Following a detailed study on the traceabiliy needs for microwave sensors we have generated a roadmap of technology steps needed to achieve this challenge.

3.1.4 Collaborations

In developing and demonstrating these techniques we (the consortium of NMIs) have collaborated together and with DLR, ESA, RAL space, Universtiy of Zurich and the UK met office, together with the worlds space agencies though CEOS to demonstrate the value and benefit of the new standards and methods that we have developed.

3.1.5 Scientific progress beyond the state of the art

As described in more detail above this project has established large aperture radiance sources of greater spatial uniformity and spectral tuneability than has existed previously. In the context of spectral tuneablility, this is the first time that a white light supercontinuum laser has been utilised as a transpotable radiance calibration source for EO instrumentation. Coupled to a highly novel flat panel it has the ability to sit inside the vaccuum tank to calibrated a satellite as opposed to through a window in more conventional methods.

3.2 Overview of MetEOC On-board Calibration Standards Activity

For on-board calibration systems 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.

The research project substantially and sustainably contributed to an improved traceability and reduced uncertainty of infrared spectroscopic data provided by earth observation sensors. In a first step, this was achieved by developing fit-to-purpose instrumentation for pre-flight and on-board calibration of remote sensing instruments. Then this instrumentation was characterized at the highest metrological level and, finally, it was applied in a case study for traceable infrared atmospheric measurements with the state-of-the-art limb sounding experiment GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere).

Using the Reduced Background Calibration Facility operated a PTB an instrument has been permanently established in Europe which is capable of giving direct pre-flight calibration to infrared detector systems as well as of characterizing the radiation temperature and spectral radiance of on-board calibration sources at the required uncertainty level of the earth observation community.

A series of state-of-the-art Large Aperture Radiance Standards has been developed and thoroughly radiometrically and thermometrically characterized at the Reduced Background Calibration Facility. These standards can now serve as highly suitable transfer on-board source standards of spectral radiance and radiation temperature for aircraft-, balloon- and satellite borne earth observation instruments.

The capability of the Reduced Background Calibration Facility and the Large Aperture Source Standards to provide practical and very efficient traceability at the required uncertainty level to the stakeholders has been proven with a case study. Two calibrated source standards have been applied to give traceability to the GLORIA experiment in two extensive scientific measurement campaigns.

Overall, the research has made a long-lasting contribution to improving confidence, giving strict traceability and reducing the uncertainty of infrared remote sensing data through close cooperation with European national metrology institutes and stakeholders from the earth observation community.

3.2.1 The research undertaken

Reduced Background Calibration Facility: PTB operates the Reduced Background Calibration Facility for traceable measurement of infrared spectral radiance and radiation temperature under vacuum. At the beginning of the project in cooperation with PTB and stakeholders from the earth observation community, represented by the BUW, FZJ and the KIT, the specifications for a calibration facility suitable for the radiometric and thermometric characterization of in-flight source standards for atmospheric remote sensing via limb sounding have been derived. PTB extended, improved and characterized its Reduced Background Calibration Facility according to these specifications. In detail the source chamber of the facility was modified to host large aperture on-board calibration standards for pre- and post-flight calibration, the temperature stability of the vacuum reference blackbody source, which provides traceability to the International Temperature Scale, has been improved to better than 30 mK over several hours of operation and the temperature uncertainty of the reference source has been reduced to smaller than 100 mK over the complete relevant temperature range for atmospheric remote measurements from -70 °C to 50 °C. The radiation temperature and spectral radiance of the reference blackbody has been compared to the national primary radiation temperature standard of PTB and to the radiation temperature scale of NPL. The comparison with NPL has been performed via the AMBER (Absolute Measurement of Blackbody Emitted Radiance) instrument of NPL.

Large Aperture Radiance Standards: BUW built and tested the Large Aperture Radiance Standards (LARS-1 and LARS-2) for their deployment on board different research aircraft. Strict design requirements had to be applied in order to meet the scientific goals. Besides the highest precision of the optical surfaces with maximal emissivity (> 0.997) and minimal temperature gradients (< 0.15 K), weight and space limitations must also be considered. Table 1 gives the relevant technical specifications which had to be fulfilled. Along with weight-optimization, minimal power consumption had to be ensured.

Table 1 Technical/metrological specifications for LARS-1 and LARS-2

optical surface	126 mm x 126 mm
LARS-1 temperature	= ambient temperature – 10 K
LARS-2 temperature	= ambient temperature + 30 K
Temperature uncertainty	< 0.1 K
Emissivity	> 0.997
Temperature homogeneity	< 0.15 K
Temperature stability	< 0.025 K/min

Figure 7 illustrates the LARS design. The optical surface of a LARS consists of an array of 7 x 7 single pyramids made of aluminium. The pyramids as well as the casing are varnished with NEXTEL-Velvet Coating 811-21. The pyramid array is temperature-controlled by a cooler consisting of four two-stage Thermo-Electric Coolers (TECs). The aluminium casing surrounding the optical surface has an aperture of 102 mm x 102 mm and is partly thermally decoupled with the front part serving as a stray light baffle which is temperature-controlled by TECs also. The in-flight calibration sources are suspended by Glass-Fibre-Reinforced-Plastic (GFRP) tubes for thermal decoupling. In order to reduce the adverse influence of the thermal environment, the GBBs are covered with polystyrene foam sheets. The overall weight of one GBB is 9.5 kg. As shown in Figure 7 an electronics box, which houses the temperature control unit as well as the power supply, is part of the GLORIA in-flight calibration system.

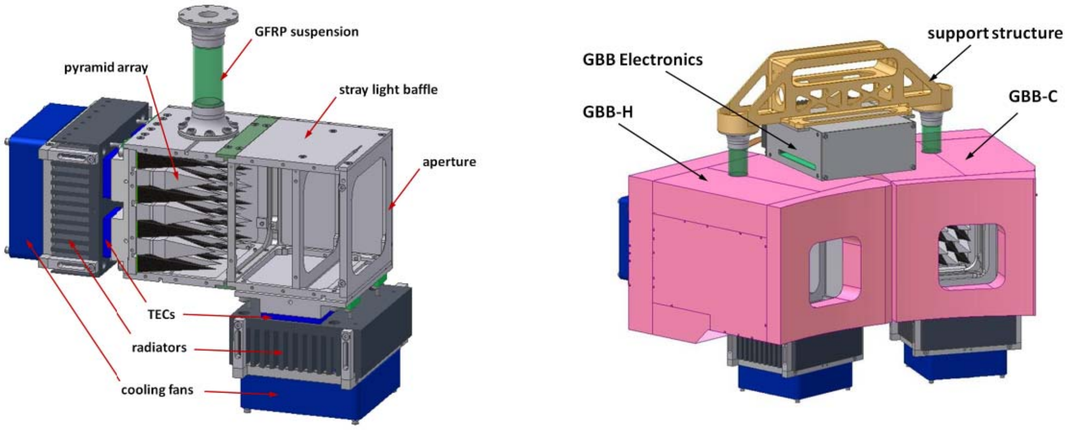


Figure 7 LARS Design (aircraft borne version): structural design (left) and configuration including electronics box on top (right)

GLORIA scientific measurement campaigns: GLORIA was deployed on two campaigns. The first campaign was a technical test campaign on the Russian high-altitude aircraft M55 Geophysica. The second campaign was the TACTS/ESMVAL campaign with the German research aircraft HALO. The campaign provided a latitudinal cross section from 65°S to Spitsbergen as well as dedicated flights into regions of strong stratosphere-troposphere exchange. At this campaign measurements were taken for approx. 100 flight-hours. GLORIA measures the thermal emission of the Earth's atmosphere in the mid infrared (7.5 µm – 14 µm) from the Earth's limb. The inversion of infrared radiances and retrieval of temperature and trace species requires a highly accurate instrument characterization. This includes in-flight calibration of the radiance with the two black-body sources. For the first time, infrared imaging is employed for limb sounding. By use of a Michelson spectrometer and a highly- sensitive 2D infrared detector array, approx. 6000 infrared spectra are taken simultaneously.

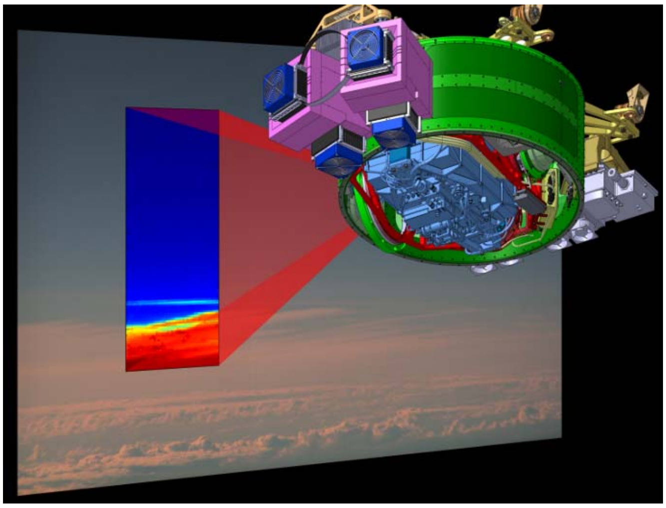


Figure 8 Schematic drawing of the GLORIA instrument (blackbody calibration units in pink) viewing towards the Earth's horizon. The cloud picture in the visible and the smaller infrared image (48 x 128 pixels) show the same scene taken during the TACTS/ESMVAL campaign.

3.2.2 Key outputs and conclusions

Using the Reduced Background Calibration Facility an instrument has been established which is capable of giving rigorous traceability to the International Temperature Scale and to the infrared spectral radiance scale at an uncertainty level as is required for climate research from earth observation. In the relevant temperature range of earth observation (-70 °C to 50 °C) radiation temperature uncertainties below 100 mK have been achieved. This facility is now a permanent infrastructure to provide traceability to the European infrared earth observation community. It has been interlocked with the temperature and radiance scale of NPL via a transportable infrared detector system capable of absolute temperature measurement.

During two successful aircraft measurement campaigns (ESSENCE and TACTS/ESMVAL) it has been demonstrated that LARS-1 and LARS-2 are suitable for the in-flight calibration of the GLORIA instrument at the highest metrological standard. LARS-1 and LARS-2 meet and even exceed in some cases the stringent requirements for a successful deployment on board various aircraft such as the German HALO or the Russian M55 Geophysica. An example of the resultant spectrum derived from GLORIA can be seen in Figure 9.

With the GLORIA measurement campaigns the inversion of limb data requires a highly accurate radiance calibration. Of particular importance is the vertical gradient of the measured radiance. For a traditionally-used limb-scanning experiment a single detector measures the radiance at the various altitudes. In the novel limb-imaging instrument the different altitudes are measured by different detector pixels. For the vertical gradient therefore not only the absolute accuracy of the calibration is relevant, but also the spatial homogeneity over the detector array. This requires calibration with black-body sources which have a very low temperature gradient over the entire field of view of the instrument, which was obtained by optimizing the design of the black-body sources. The radiance calibration is one example that a limb imager also calls for new calibration concepts. Details are provided by Kleinert et al. (2014).

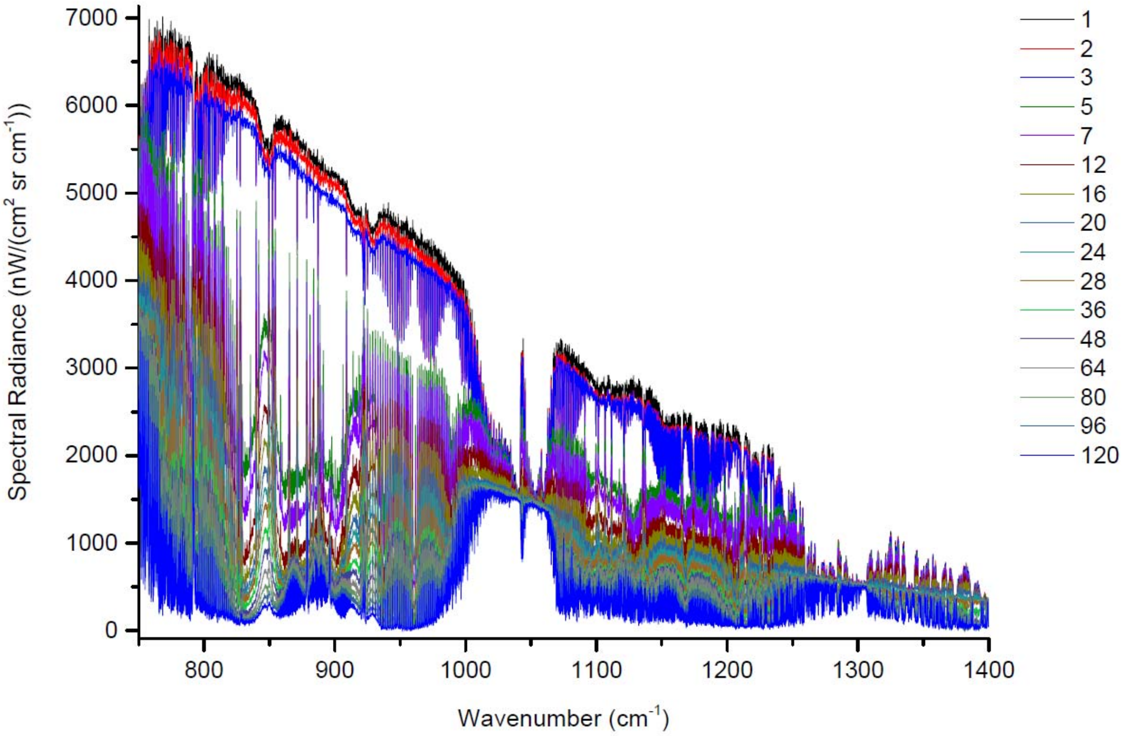


Figure 9 Selected calibrated spectra measured above the North Atlantic Ocean during TACTS/ESMVAL on 26 September. Each line represents a spectrum averaged over one pixel row, colour code gives the row number. Altitude increases (radiance decreases) from low to high numbers. The thin peaks are not noise but single emission lines. Signatures from a wide range of trace species such as CO2, ozone, HNO3, various freon species and water vapour can be recognized. Figure from Friedl-Vallon et al. (2014)

3.2.3 New measurement capabilities and knowledge developed

With the project the Reduced Background Calibration Facility has been purposefully developed into a facility to provide traceability to infrared atmospheric remote sensing instruments via calibration of on-board calibration sources in air, under vacuum and under the pressure conditions of the high atmosphere.

For the first time SI traceable Large Aperture Radiance Standards flew on board an aircraft and were used successfully for in-flight calibration of a Fourier-Transform-Spectrometer. Even in the hostile environment of the Upper Troposphere / Lower Stratosphere (UTLS) with mutable low temperature and pressure, LARS-1 and LARS-2 operated as required. Thermo-Electric Coolers are excellent devices for very precise temperature control of Large Aperture Radiance Standards on board an aircraft.

Extremely high data rates can be acquired with the GLORIA instrument and this provides the ability to sound the atmosphere with unprecedented spatial resolution. In a Michelson interferometer the length of the interferometric scan determines the spectral resolution: longer scans result in higher spectral resolution but require more time, shorter scans can enhance the spatial resolution along the flight track at the price of somewhat reduced spectral resolution. This way, GLORIA can either measure a multitude of trace species at a vertical resolution of approx. 1 km or a reduced set of trace species at a vertical resolution of 300 m. In addition, targeted regions may be surrounded by the aircraft in a closed flight pattern (hexagon) of approx. 500 km diameter. By multi-view observations tomography can be applied and the atmospheric structures can be reconstructed in 3D (an example is given in Figure 10 below). GLORIA is designed for an improved understanding of the UTLS region which is a key-region in the radiative forcing of the Earth's climate. Since these regions shows many fine-scale structures, the improved spatial resolution of GLORIA is essential for understanding the processes in the UTLS.

3.2.4 Collaborations

The unique set of complementary skills provided by the consortium members allowed a wide range of subjects to be addressed that would not have been possible by the individual organisations themselves.

In cooperation with PTB and stakeholders from the earth observation community, represented by BUW, FZJ and KIT, the specifications for a calibration facility suitable for characterizing on-board large aperture infrared source standards were determined. PTB extended, improved and characterized its Reduced Background Calibration Facility according to these specifications.

In cooperation with BUW, FZJ and KIT the specifications for air borne Large Aperture Radiance Standards were specified. BUW supported by PTB designed and realized the Large Aperture Radiance Standards according to these specifications. PTB and BUW jointly characterized the source standards at the Reduced Background Calibration Facility. From the experience with the air borne source standards BUW in cooperation with PTB, FZJ and KIT designed improved “next generation” source standards, applicable also for balloon borne experiments. These were, again, jointly characterized and calibrated by PTB and BUW at the Reduced Background Calibration Facility.

PTB and NPL cooperated to link the spectral radiance scale and the International Temperature Scale maintained at the Reduced Background Calibration Facility with the radiometric temperature scale maintained at the National Physical Laboratory via a transportable absolute radiance measurement detector system of NPL.

Based on the experience with the balloon borne source standards BUW, in cooperation with PTB, FZJ and KIT made a draft design of satellite borne source standards.

BUW and PTB supplied two completely characterized and documented large aperture radiance standards to FZJ and KIT for the two scientific measurement campaigns of the limb sounder GLORIA on board the Russian research aircraft M55-Geophysica and the German research aircraft HALO. The source standards were calibrated before and after flight to learn about the stability of the standards. They will also be calibrated before and after future missions to maintain their uncertainty level. PTB, BUW, FZJ and KIT have established a long-term cooperation and closely exchanged information about pre-, in- and post-flight performance of the source standards to continuously improve the design of the series of source standards.

3.2.5 Scientific progress beyond the state of the art

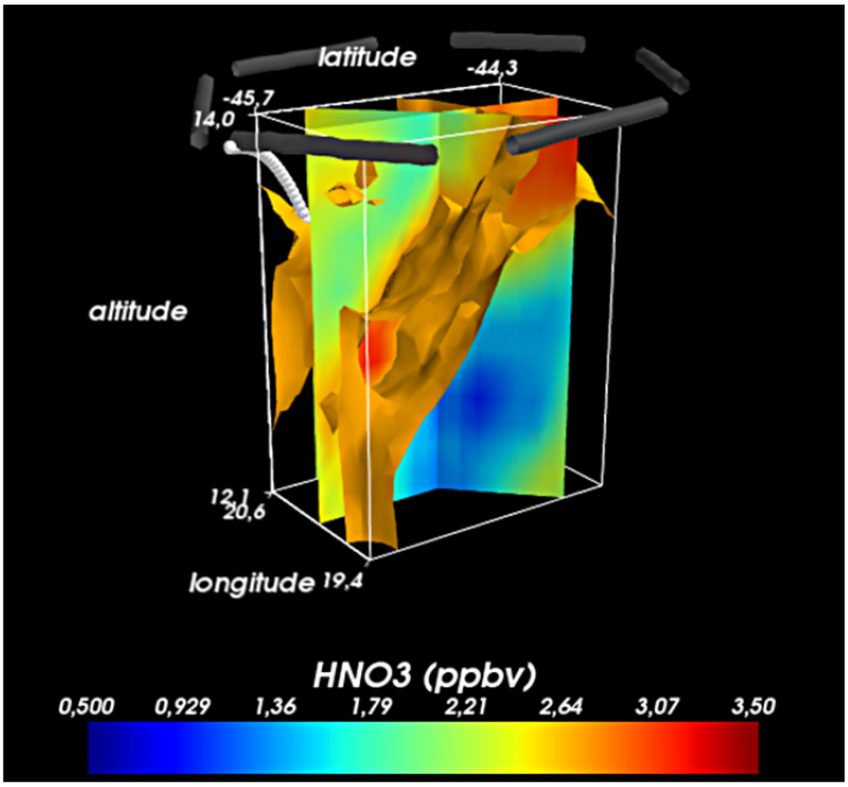
With the advancements of the Reduced Background Calibration Facility a unique facility within Europe has been permanently established to provide sound traceability to infrared remote sensing instruments at an uncertainly level needed for climate research. The instrumentation is now a unique facility at the European metrology institutes.

There have been no SI traceable Large Aperture Radiance Standards successfully operated on aircraft before.

GLORIA measurement campaigns:

One highlight from the TACTS/ESMVAL campaign was the first 3D reconstruction of an atmospheric trace species structure. The data were taken at a southbound flight from Cape Town at the lower edge of the southern polar vortex. HNO_3 is a trace species which is abundant in the stratosphere, but has very low concentrations in the troposphere. Figure 10 below shows the picture of an air volume of 100 km x 150 km extent in the horizontal and only 2 km in the vertical shows: the filament is very thin (only a few hundred meters in the vertical) and tilted, i.e. slopes down from north to south. The small dimensions demonstrate that only the novel GLORIA instrument is adequate to resolve this structure.

Figure 10 Tomography flight over the Antarctic Ocean. The grey cylindrical bars show the flight-path of the air craft forming a hexagon. White spheres indicate the target points (tangent-points) of a single limb-image. By



panning the instrument, the air-volume is viewed under multiple view angles for each flight-segment of the aircraft. The shown HNO_3 structure is reconstructed from of the order of 2.5 million spectra, reduced by pre-binning to 50.000 observations for each trace gas. Picture from Riese et al. (2014; http://www.atmos-meas-tech.net/7/1915/2014/amt-7-1915-2014.pdf

3.3 Overview of improved methods to validate satellite derived data with known uncertainties

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

The main project objective was to improve uncertainty and traceability for the needs of the European Earth Observation community. This part of the project focused on post launch aspects related to satellite data quality assurance by recovering/establishing in-flight traceability through reference standards measurement and field test-sites. There were two primary aims of this research: a) improved accuracy and traceability of the on surface based 'test sites' that are used for post launch calibration and validation of land and ocean imaging radiometers; and b) development and validation of the models to improve traceability of radiative transfer codes (RT) that are used for land geophysical product retrieval.

The 'test sites' related activities covered uncertainty reduction for Ocean Colour in situ measurements achieved by robust calibration and uncertainty budget evaluation. For land site applications a first prototype self-monitoring (stability) radiometer has been designed and a first prototype tested in both laboratory and field situations.

RT code validation has been performed using, as an input, data from SI traceable physical measurements of manmade targets carried out under controlled conditions. Additionally, a new instrument which allows rapid acquisition of multi-angular reflectance and transmittance during in-situ measurements of the spectral properties leaves has been developed. 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.

3.3.1 The research undertaken

Ocean Colour:

Ocean Colour related research focused on AERONET–OC (Aerosol Robotic Network – Ocean Colour) test sites and instruments that are used currently for in situ water leaving radiance measurements. Instrument characterisation work included the development and application of methods for the characterisation of in-air and in-water cosine response of irradiance sensors and investigation into absolute radiometric calibration uncertainty.

A review of the uncertainty budget of AERONET-OC data with emphasis on the minimisation of uncertainty sources was performed. This review included application of the GUM (Guide to the Expression of Uncertainty in Measurements) framework as a tool for uncertainty estimation.

As Europe is waiting for the launch of the new Ocean Colour satellite sensor a comprehensive strategy for the validation of the new sensor data products by the application of AERONET-OC data to the assessment of MERIS radiometric products was performed.

Sensor web:

To improve the accuracy and traceability of reference test sites, a first prototype self-monitoring (stability) radiometer has been developed and tested in both laboratory and field situations. The radiometer uses Light Emitting Diodes (LED) as both optical detectors and as part of the self-monitoring functionality. LEDs have the advantage to be intrinsically sensitive to a spectral band that is related to their emission spectrum. Four LEDs have been selected to cover four spectral regions between 400 nm and 900 nm. The radiometer can be electrically powered by a solar panel and it has a wireless connection to a master unit that gives instructions to the radiometer and collect the measured data.

The radiometer was tested in the laboratory to establish its stability in order to develop an optimal measuring and self- calibration sequences in the field. Then the radiometer was calibrated using NPL spectral irradiance and reflectance standards. The temperature sensitivity tests were conducted in an environmental chamber where the temperature was varied from -10 ºC to 30 ºC.

Leaf goniometer:
In the project new portable goniometer was developed that is able to measure leaf multidirectional scattering properties over a short time scale. The instrument is based on a spectral camera which simultaneously acquires the spectra from 80 different directions at 388 wavelengths between 400 nm and 1000 nm. At each direction the light is collected through a 600 µm core optical fibre. The 80 detection angles are distributed across a 25 cm diameter hemisphere in a manner that favours measurements of the forward scattering directions. This setup was chosen to enable a better characterization of the specular reflection component while maintaining sufficient sampling of the principal and orthogonal planes as well. Five directional illumination sources have been arranged at the same azimuth angle in the hemisphere, above the leaf, and one diffuse illumination source is placed below the leaf.

RT codes:
Three targets were manufactured and had their mechanical and optical micro and macro scale properties measured under controlled laboratory conditions in extended range of viewing geometries. The results of the SI traceable micro scale measurements were used as input for the 3-D RT model. The comparison between the model output and macro scale SI traceable measurements was used to assess the performance of these RT codes.

3.3.2 Key outputs and conclusions

Ocean colour:
AREONET-OC uncertainty budget estimated by GUM framework was in agreement with previous uncertainty budget. This finding confirms that a robust uncertainty budget can be estimated using one method and validated using a different one and they both would have similar values. A way toward uncertainty reduction for in situ measurement was proposed with a potential of reducing current uncertainties to between 5 % and 3 %.

Sensor web:
The new LED based radiometer with wireless communication and built in appropriate source LED to provide a means to control the instrument stability, and even self-calibrate the instruments in the field. This addresses the drive for more accurate test site measurements by a new self-calibrate system.

Figure 13: LED radiometer trial deployment

Leaf goniometer:

A new leaf goniometer called PHYTOS (Portable Hyperspectral Transmission Optical Scattering) that enables leaf measurements was developed. This goniometer allowed a web based database with 46 species of leaves that been measured during the summer (optically and chemically) to be created. SI traceability via calibrated reflectance and transmittance targets was therefore enabled.

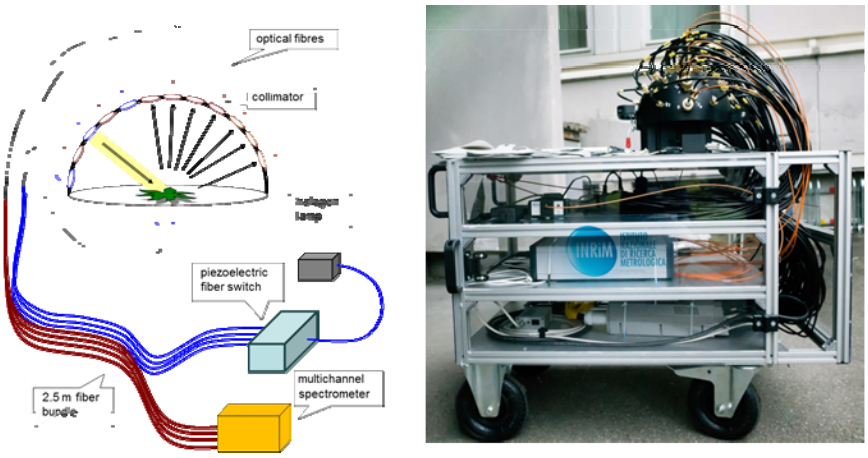


Figure 14: PHYTOS left – schematic, right photograph of the instrument

RT codes:

Online RT code models checker with the artificial target physical measurements, the structure representations for the Non-anodized Aluminium Cubes (NAC) target and the Green Anodized Aluminium Cubes (GAC) target have been created and are available through the RAMI On-line Model Checker (ROMC). ROMC allows users to evaluate the performance of their reflectance model against a set of reference data obtained from 3-D radiation transfer models. The structural properties of each target, the experimental set up, spectral properties of blank and measurements characteristics are available on line.

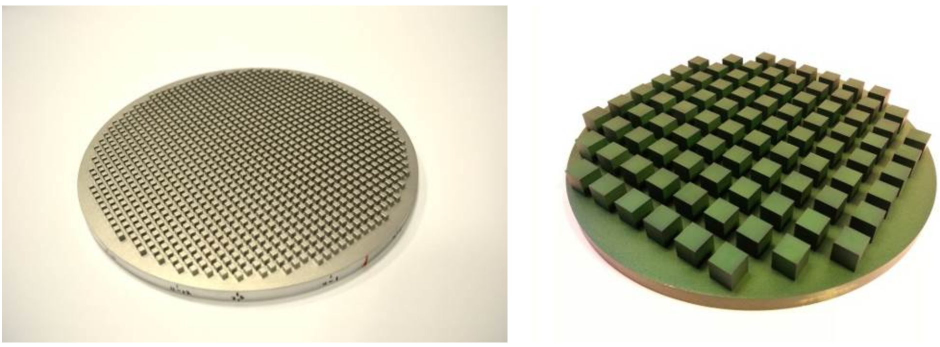


Figure 15: Two of the three targets manufactured. NAC target (left) is machined out of a single piece of aluminium, so that an array of 1188 cubes with 3.3 mm edge length is formed. GAC target (right) comprises 88 anodised aluminium cubes with 12 mm edge length assembled on a baseplate. Each visible surface of every cube has been characterised for reflective properties separately.

3.3.3 New measurement capabilities and knowledge developed

A self-calibrated LED based radiometer that has the ability to wirelessly transmit the data to a home base. This radiometer has a high quality analogue to digital signal converter which makes this instrument more sensitive to low signal levels than other existing LED radiometers. Additionally it has built in light sources that can be used in situ as means of radiometer performance checks and self-calibration.

PHYTOS, the portable goniometer, is a new instrument that allows for rapid acquisition of hyperspectral and multi-angular scattering properties of individual leaf in-situ. The goniometer has the ability to illuminate a single leaf sample from five different directions and detect reflected or transmitted signal at 80 different viewing directions for the wavelength range 400 nm – 1000 nm. This gives a very rapid means of collecting data on leaf properties before they start to degrade. A new calibration procedure has been developed for this instrument using two references (white and black) to reduce the effect of unwanted light being scattered inside the goniometer dome during the measurements.

An NPL multi-angular measurement facility has been adapted to accommodate larger samples and illumination launching. Part of the measurement system has been changed allowing for the sample illumination beam to have a specific shape and adjustable size.

3.3.4 Collaborations

JRC provided NPL with instruments that are used for Ocean Colour measurements in situ. NPL investigated measurement uncertainties related to absolute radiometric calibration using these instruments as an example. A joint report was produced about the sources of uncertainty in the measurement of primary radiometric products from above-water radiometer systems.

Work on a sensor web was started by a collective NPL and INRIM literature review that indicated LED sensing technology was a good candidate for the basis of a new sensor web constructed from a number of identical instruments. NPL prepared a preliminary instrument test plan; INRIM constructed the instrument, which was then transported to NPL for absolute radiometric calibration and field tests. FGI has experience in field measurements thus they acted as a consultant in the process of developing the sensor web that meets the future needs of the test sites.

JRC and INRIM worked closely together on designing the new leaf goniometer. JRC acted as an end user thus the instrument design was fully driven by the needs of the RT community. The instrument was built according to agreed specifications by INRIM. NPL prepared a set of calibrated reflectance and diffuse standards that provide SI traceability to the leaf goniometer. NPL created software enabling users to visualise and manipulate the output generated by the instrument. JRC used the PHYTOS over the summer to measure the leaves and create a web based database with the results of these measurements.

The RT codes aspect was driven by the JRC requirements of the artificial target design. The targets were manufactured at MIKES/ALTO and the mechanical and micro scale optical tests were performed at MIKES/AALTO. The macro scale measurements of the same target were conducted at NPL. The modelling of the physical test results took placed at JRC and AALTO.

3.3.5 Scientific progress beyond the state of the art

This project goes beyond state of the art by defining a new concept of “dynamic” uncertainties for Ocean Colour, i.e., the quantification of the uncertainty for each individual measurement accounting for instrument field performance, site characteristics and measurement conditions. This solution may provide the capability of selectively applying in situ data products as a function of their estimated uncertainties (e.g., selectively supporting regional vicarious calibration, assessment of satellite radiometric data products and bio-optical modelling, which have different requirements).

LED based radiometers have already been used as the wireless communication systems for the instruments that operate in remote locations. However, the instrument developed in this project was designed to achieve a closer SI traceability link and to have a self-calibration option. This is a novel concept and does not exist in other land reflectance /radiance measuring devices.

PHYTOS is the first portable leaf goniometer that can be taken into the field and allows a rapid acquisition of hyperspectral and multi-angular reflectance and transmittance of leaf measurements.

3.4 Overview of the development and test aspects of an "in-flight" SI traceable calibration methodology for benchmark measurements of radiation for climate.

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.

The earlier work packages develop and test methods to improve the traceability of satellite sensor measurement. However, to adequately meet the accuracy demands of key climate variables, regular direct traceability is required. The rigors of storage and launch and the harsh environment of space will inevitably increase the radiometric uncertainty ascribed pre-flight and require post-launch validation strategies via on-board and 'test-site' methods.

The climate, meteorological and emerging commercial sector of EO, is calling for improved accuracy and traceability of EO data. WMO-GSICS, GCOS and CEOS have requested a 'benchmark mission' capable of providing SI traceability in space, to facilitate the calibration of other sensors i.e. a 'standards lab in space' for the exacting needs for climate. A proposed mission called Traceable Radiometry Underpinning Terrestrial and Helio Studies (TRUTHS) has been designed to achieve the above and received support from the international community including ESA and EUMETSAT.

This work package developed & tested crucial aspects of the 'in-flight' SI traceable calibration methodology of TRUTHS, from radiometric performance validation of the in-flight primary standard, CSAR, to the prototyping of vital elements in the in-flight calibration chain such as the optical fiber link and transfer instrumentation. The work package culminated in bringing these elements together to demonstrate the method in the laboratory.

In each aspect the current state-of-the-art has been advanced, producing reduced uncertainties in filter radiometry and terrestrial TSI measurement, as two examples and demonstrating rigorous traceability in a vacuum advancing the technology TRL level towards space implementation.

3.4.1. The research undertaken

Fibre bundle design, procurement and testing:

In collaboration between LNE & NPL a prototype optical fibre based spectral radiometric delivery system for in-flight calibration system of TRUTHS was designed and tested. NPL defined the requirement specification, based on the TRUTHS calibration system breadboard design, with the key requirement being:

- Spectral range 200 nm- 2500 nm
- High throughput >70 %
- Minimum variation in transmission with movement of the fibre.
- Hard shielding to prevent damage from radiation in space
- Special fibre arrangement (fibres at the centre of the input should be at the centre of the output)

LNE then consulted a number of manufacturers, selected a supplier and procured the test fibres. The first test phase included verification of the optical fibre number, compliance with the required spatial arrangement within the fibre and the surface quality of the input and output facets of the optical fibres bundles. The first bundles was found to not meet the requirements, with broken or obstructed fibres on each bundle and glue residue on the entry and exit facets, leading to reduced surface quality. After being returned to the manufacturer for corrective alterations, the second test phase optical (spectral) transmission and mechanical testing were undertaken at LNE (Figure 11). However, the transmission did not meet specification, so an alternative supplier was commissioned to produce the final bundle with a slightly revised requirement from lessons learnt in the first iteration. A summary of the final bundle properties are:

- The surface quality of the extremities of the bundle are clean
- The number of fibres inside the bundle has been increased of 30 %
- The arrangement of fibres inside the bundle met requirements.
- The staggered organization of the fibre inside the bundle minimize the losses of space and increase the optical transmission
    - 50 % with the first manufacturer 70 % with the new one.

- The focalisation of the optics at the end of the circular output is now correct
    - The output beam is focused at approximately 55 mm from the exit facet, with complaint minimum diameter of 5 mm.

- The mechanical stability of this bundle is exceeds the requirements.
    - Maximum losses induced by the linear displacement from -17 cm to +17 cm : 0.2%
    - This new bundle is very flexible

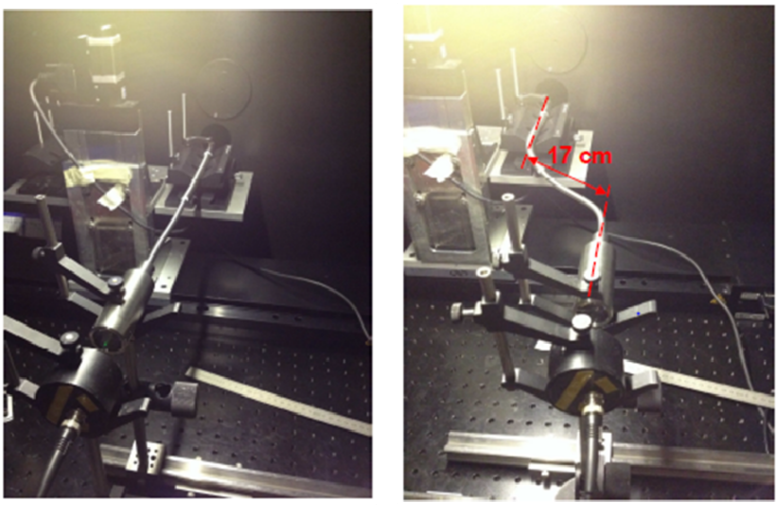


Figure 11 Shows the fibre mechanical testing in progress, measuring the change in fibre transmission with flexing of the fibre.

Following successful testing, two additional bundles were ordered, one in the UV/VIS, one in the VIS/NIR and tested as before and found to be complaint to the requirement specifications. The fibres were delivered to NPL.

Transfer radiometer design, building and testing:

The multi-channel filter radiometer (MFTR) was designed and built by NPL. The design specification was very demanding and significantly beyond the state-of-the-art in terms of accuracy (0.3% compared to 3%) and the signal sensitivity, due to the necessary low signal levels & short integration time needed on a satellite sensor, while retaining the necessary signal-to-noise ratio. In a laboratory set up, the strength of the source & signal integration time can be chosen to match the sensor sensitivity and use commercially available electronics and amplifiers within comfortable operating parameters. In a satellite sensor, the source (the view of the Earth) is not a variable the designer has any control over, nor is the time allowed to look at a particular scene, as this is defined by the velocity of the satellite in its designated orbit. These limitations can be countered with a larger collection area of the incoming light, but again this is limited by size and mass considerations for the satellite. Lastly, the components used need not be space-qualified, but have close analogues to represent a sensor that could be reasonably flown in space.

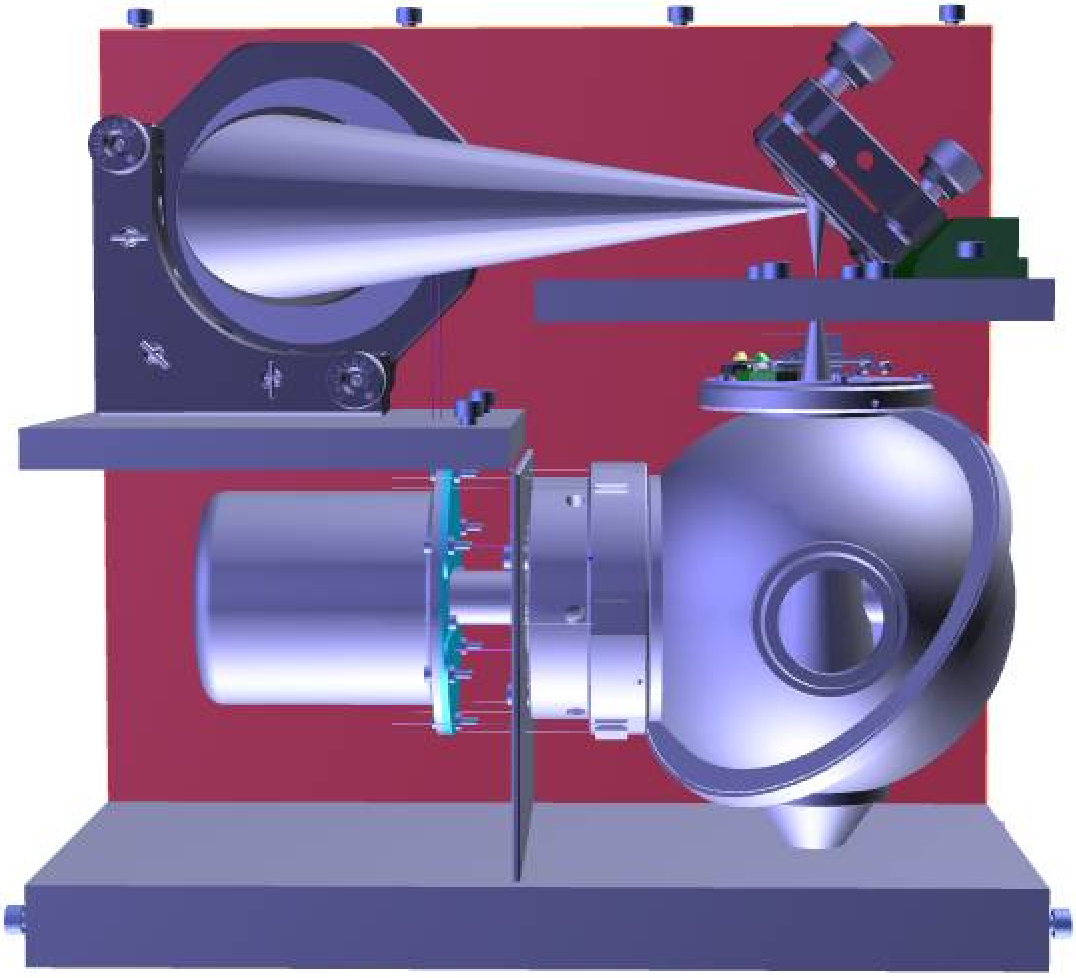


Figure 12 Engineering drawing of the MFTR showing the input optics, integrating sphere and detector cluster & electronics.

The strict requirements put tight requirements on the electronics and detectors, in the latter case, requiring the detector manufacturers to produce a custom detector with the required sensitivity and noise characteristics. The MFTR has been built and assembled at NPL.

Performance of CSAR for TRUTHS and terrestrial solar irradiance measurements:

The CSAR (Cryogenic Solar Absolute Radiometer) instrument has been used at the World Radiation Center in SFI Davos for periodic measurement campaigns since 2010. CSAR is proposed as the primary total solar irradiance (TSI) instrument to replace the World Radiometric Reference (WRR) based at SFI Davos. In this project the performance of CSAR has been significantly improved. Most significantly the temperature stability of its internal reference block has been improved around two orders of magnitudes resulting in a reduced measurement uncertainty of TSI. Lower mass, faster responding measurement cavities have been tested, potentially reducing the measurement time constant from 9 seconds to between 2.5 and 5.5 seconds. Additional upgrades have also been made to improve the robustness of the instrument and some of its key sub-components and significant progress has been made towards fully automated measurement software. These improvements have a direct impact on CSAR's performance as a terrestrial TSI instrument, but also in its role as the primary standard aboard the TRUTHS satellite; improved robustness, faster operation and improved software all directly benefit in this aspect as well.

One important contribution to the uncertainty budget in the use of CSAR in the terrestrial TSI measurement is knowledge of the window transmission. The development of a window transmission monitor (MITRA) has also been developed within the project. Results have been good, and the transmission uncertainty has been greatly reduced, albeit still slightly higher than the design goals. Following the end of the MetEOC project, CSAR and MITRA will be combined at the SFI Davos site for field testing, followed by an international comparison planned for 2015.

3.4.2 Key outputs and conclusions

The key research outputs relate back to the overall objective of this portion of the project, namely the development of key components of a benchmark mission to provide SI traceability in space for application to climate. The components, either designed and built for the first time or developed further, are all crucial pieces of the jigsaw that is the TRUTHS mission.

In addition to the TRUTHS mission driver, the development of each of these components has associated benefits in other applications, from the development beyond the state-of-the-art at the commencement of the project in terms of achievable accuracy in filter radiometer, and the provision of a vacuum-compatible calibration facility that can be used and developed further in parallel and follow on projects. The progress made with CSAR benefits both the space application and its terrestrial application.

3.4.3 New measurement capabilities and knowledge developed

The combination of the vacuum compatible CSAR, MFTR and fibre bundle have provided an impressive new measurement capability at NPL, that together with the flat panel source developed in this project is a flexible calibration facility. The introduction of a fully tuneable laser source in the 400-2500 nm spectral region extends the application area of this facility within and beyond the initially intended space application field. The improvements to CSAR, both advance the case for TRUTHS but also improve the terrestrial TSI measurement capability at SFI Davos, further advancing the case for CSAR as the primary replacement for the WRR.

Significant knowledge has been gained in generic fields such as vacuum compatible design but specifically in new filter radiometry application, nW signal measurement and the provision of new improved detector technology from one of our key suppliers. LNE have developed a new capability to characterise fibre bundles, utilising technology in the UV, visible and infra-red spectral regions, enhancing their overall optical measurement capability.

SFI Davos have built a new instrument to measure transmission, for the first time allowing a full UV to IR capability that can be applied to any window and any source within the spectral range of the sun spectra to an accuracy of 0.05%. New fabrication techniques, such as ultrasonic welding have been used for the first time, advancing measurement performance but also technical expertise.

3.4.4 Collaborations

LNE and NPL collaborated on the fibre bundle elements, with NPL providing the original requirement specification, LNE interacting with the suppliers with regular feedback to NPL on developments and changes in the requirements from lessons learnt during the development phase. The results obtained by LNE feed back into latter NPL activities.

SFI Davos and NPL continued in a long standing partnership with the terrestrial application of CSAR working in unison to develop the necessary components of the instrument to deliver higher accuracy, improved performance, easier operation and better robustness.

3.4.5 Scientific progress beyond the state of the art

The project went beyond the state of the art by developing the high sensitivity trap detectors and filter radiometer capability specifically for EO applications that will from a vital component in a vacuum compatible calibration facility unique at the European metrology institutes.

The MITRA transmission instrument allows broadband transmission throughout the UV, visible and IR spectral ranges to an unprecedented 0.05 % accuracy allowing flexibility and broad applicability.

4 Actual and potential impact

4.1 Introduction

The vision of this project was the establishment of a new harmonised European metrology infrastructure to enable the Earth Observation community, particularly those addressing climate change, to provide robust information and advice to support the far-reaching socio-economic decisions that need to be taken. Although the direct use of many of its outputs is mainly to a few key organisations, the consequences of the decisions they inform will have major impact on all nations and its citizens.

The provision of traceable and reliable data with known uncertainties improves our understanding of climate dynamics and our ability to interpret trends with greater certainty. This enables investment decisions to be taken with improved confidence as regards their outcome; the consequence is that a verifiable link will ultimately be made between the outputs of this project and our response to the effects of climate change. However, the timescales on which these decisions are made is decades and so will only be visible in the longer term. All we can point to as evidence is quotes from key stakeholders and the recognition that the project is formally linked with other key projects (EU, ESA etc) in an ongoing manner. Good examples are the FP7 project QA4ECV, H2020 FIDUCEO and ESA ACTION and FRM4CEOS projects all reference MetEOC as contributors or precursors.

There are two distinct and influential relevant sets of stakeholders. The first, comprising international organisations such as GCOS, GEO, WMO, GEWEX and CEOS are responsible for defining the requirements for climate measurements. The second comprises those organisations with the resources to fund remote sensing in Europe, the immediate focus of this project, and include the European Commission (EC) and associated bodies, European Space Agency (ESA) and Eumetsat, complemented with public funding from national space agencies and academic research bodies. These two sets of bodies are the origin of the metrological "requirements" driving this project. Meeting these requirements (at least some of) is seen as a key European contribution to the global community.

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 for ew 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.

As European satellite mission start to utilise the pre- and post-launch cal/val standards from this project their data will become de-facto references upon which others will build and serve as a challenge to the rest of the world to improve the quality of their data. The availability of state-of-the-art data will also ensure that European scientists can rapidly capitalise on its value and that its policy makers are appropriately informed during international discussions on climate mitigation/adaptation strategies. The methodologies and standards developed that we have developed are starting to be become the basis of international best Practices, enabling European industry and academia to be in a position of readiness to exploit the advantage of being involved during their pre-cursor developments.

Participation within key international committees and projects where metrology is important e.g. CEOS WGCV, GEO and QA4EO, WMO GSICS has ensured that the outputs are widely and rapidly disseminated for the benefit of the community as a whole, see above quotes.

Environmentally – This project is fundamental to our understanding and long-term sustainability of our environment. Climate change itself and its potential consequences are well understood but the benefit to "operational monitoring" of the environment through remote sensing should not be ignored. Greater accuracy and reliability leads to more sensitivity and the ability to separate the information. This in turn leads to earlier identification of potential issues and more reliable quantification of things like pollution, land cover change, coastal erosion etc. In this project deforestation and its capacity for carbon storage were used as a case study. This project has also demonstrated that big issues remain for land cover change monitoring through variances in methods for determining vegetation indices.

Socially – This project provides the underpinning framework to establish the information to enable fit-for-purpose mitigation and adaptation strategies to be defined and implemented. This will ensure that citizens' health and standards of living are optimum in a World suffering from a changing climate.

Financially – The most obvious benefit stems from optimising the European response to climate and other environmental effects as a result of more timely and reliable information derived from instrumentation with better calibrations as a consequence of this project. Additionally, better tailored standards and reduced uncertainty allow more efficient calibration, which in a space project can be very expensive due to the special facilities required. In this project, a tuneable laser radiation has been developed that can simultaneously deliver calibrations of spectral response, radiance, linearity and stray light, previously all individual measurement facilities. Similarly in terms of test-sites, automation leads not only to better data but also fewer expensive site visits and this project sees the birth of RADCALNET as a prototype international network for interoperability and traceability. This work continues in the follow-on MetEOC 2.

4.2 Metrology achievements

Specific examples of how the metrology outputs are impacting the community are highlighted below cross referenced to the objectives of the project. In many cases several objectives are addressed by achievements in parallel:

Overarching objectives:

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

2. Post-launch calibration and validation through field test-sites and associated models

3. Prototyping methods for achieving SI traceable benchmark measurements from space

- **Accurate uncertainty analysis of remote sensing data**, which comes from both the dedicated training course, but also the examples and case studies from many of the specific project outputs for example in Ocean colour where a full breakdown of uncertainties is presented in a publication which shows how the overall uncertainty can be reduced by targeting some of the statistical/random components separately. This has been called 'dynamic uncertainty' and may allow more regional assessments for different applications: satellite validation and bio-optical modelling. Similarly, for the in-flight black bodies where a rigorous analysis can be seen as an exemplar to the community. Procurement tenders being issued by EU and ESA now emphasise uncertainty budgets and metrological uncertainty and traceability. As these concepts become more widely used it will lead to lower overall uncertainties as some components, when separated, can be more easily reduced. **(Obj. 1 and 2)**

- **Training in uncertainty analysis** (creating a work force able to specify and test complex instruments, reducing over and under specification, and improving the understanding of remote sensing limitations). Development and delivery of a specialised training course was in great demand with more than 40 attendees from around the world as far afield as Malaysia attending. To meet on-going requests a re-run will be carried out in 2015 and a modified version delivered specifically to ESA staff. This illustrated the requirement and how well MetEOC has started to serve the need. (**Obj. 1 and 2)**

- **Raised profile of Cal/Val and traceability** to a level that it cannot be ignored during mission evolution. Metrological traceability is now being explicitly specified in work procurement specifications from ESA & EU on climate and space based work for example the FP7 project QA4ECV. The need for traceability and rigorous cal/val with uncertainty budgets is now being specified in ESA and EU projects for example: Sentinel 4, Meteosat Third Generation, Sentinel 2 and 3 validation projects. Outputs of the work on in-flight black bodies has become adopted by ESA as best practice guidance for future limb sounding missions and similarly need for traceability and the strategies developed in this project for Ocean Colour are being widely used by the community. NPL has become a member of the Sentinel 3 Cal and Val team and been asked by ESA to support traceability of the OC buoy Boussolle. **(Obj. 1, 2 and 3)**

- **Good practice guides, reports and committee publications** have been used to disseminate the JRP outputs, these include traceability for Ocean colour (OC) and the work output has subsequently led to ESA requesting support to improve traceability of the CNES/ESA funded Bousolle deep ocean radiometric Cal system for OC. Visibility of the new pre-flight calibration standards and techniques has been well received by international committees such as CEOS, WMO-GSICS and member space agencies. The calibration standards and techniques, integrating spheres, tuneable lasers are now finding use with missions such as EnMAP and Sentinel 2, 3 and 4 and field instrument calibrations for land and Ocean applications. A roadmap to guide metrology needs including a specialised one for Microwave sensors has been developed and used to guide international NMI (via BIPM) and EURAMET strategies. **(Obj. 1, 2 and 3)**

- **New reference standards** such as the on-board black bodies built and used with the limb-sounder GLORIA on board an aircraft have allowed new measurements to be undertaken for example a 3D reconstruction of the trace molecule HNO_3 near the southern vortex. Such sensors require very spatially uniform sources to avoid potential errors in altitude resolution due to the 2D nature of the array detector, a major achievement of MetEOC. Similarly tuneable laser radiation, both conventional and from super-continuum sources has allowed stray light correction of EO instruments to be made enabling more than a factor 2 improvement in performance and also resulted in identifying other error sources such as temperature and non-linearity effects of the array detectors. The large broadband source LAVRAS, prompted DLR to say *"The new sphere is leading in terms of accuracy of the representation of radiance and irradiance homogeneity for large entrance apertures and temporal stability. The use gives us new opportunities."* **(Obj. 1)**

- The leaf goniometer PHYTOS has allowed for the first time, **in-situ measurements of the BRF of leaves,** without the additional uncertainty caused by cutting and transportation. This instrument has already facilitated the construction of a library of 42 different species and will be a key resource for RT code development and ability of the community to de-convolve spectra from remote sensed images. **(Obj. 3)**

- **New measurement capabilities** have been established such as the Reduced Background Calibration Facility which has demonstrated SI traceability at uncertainties below 100 mk over the range -70 - +50 °C (those needed by EO) confirmed by two NMIs and allowing a full linkage of atmospheric sounder GLORIA with Sentinel 3 and EarthCARE., Land/Ocean and Cloud/Radiation respectively, the latter calibrated using a different but now linked facility. **(Obj. 1 and 2)**

- **The upgrade in the performance of existing instrument designs**, since these tend to be limited by calibration uncertainty rather than sensitivity. Although due to the heritage and relatively slow evolutionary nature of the Space sector, new standards have not as yet been used on satellite sensors. However, there are plans to evaluate their usage on some upcoming missions in the near future for example later Sentinel missions. However, they have been used to support those used on aircraft and balloon sensors. Most notably with the GLORIA instrument for black bodies, Spectrometer and wide FOV cameras of DLR (tuneable lasers and LAVRAS) and the APEX hyperspectral imager (STAIRS). **(Obj. 1)**

- **"Fit for purpose" data on the effectiveness of carbon sinks and mitigation strategies**, will be improved by further work on various aspects of land product validation funded 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, all preparation for Sentinel 2 (launch 2015). Improved traceability of post launch Ocean Colour Cal/Val instruments will also build readiness for Sentinel 3 (launch 2015) for this aspect of the carbon mitigation cycle validation. **(Obj. 2)**

- During this project the international satellite community, through CEOS, established a project to establish **a global network of SI traceable test sites**. This in part came about through the viability of achieving reliable traceability as a result of work from this project. 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. The (The LED sensor web will be deployed on at least one of the test-sties in the network as a prototype and then potentially used at all. RADCALNET involves ESA, NASA, CNES and the Chinese Academy of Sciences, with NPL providing the link to traceability using methods developed in MetEOC 1 and continued in MetEOC 2. **(Obj. 2 and 3)**

- **New transfer standards and methods for pre-flight calibration of imagers both in air and vacuum** were developed. These 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 (version C) of the sentinels. 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. **(Obj. 1)**

- **Community grand challenge projects like an NMI in space** have moved closer to implementation. 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 Meteorological administration who are looking to build a version for launch in 2018. **(Obj. 3)**

- Improvements to the Cryogenic Solar Absolute Radiometer (CSAR) mean it is now ready to participate in the next WMO IPC in 2015, the next step to its potential adoption as **an SI replacement for the current artefact based scale of solar irradiance of the WMO, the World Radiometric Reference.** The improvements to the field window transmittance facility MITRA result in an order of magnitude better uncertainty for this aspect alone. **(Obj. 3)**

- **New partnerships with MetEOC a focal point for the community** have been established with four Researcher Excellence Grants awarded and delivering high quality complimentary science outputs together with the projects unfunded partners (all re-joining) the follow-on MetEOC 2 showing the value to their organisations, with the increased demand of others to join as partners or collaborators in MetEOC 2. **(Obj. 1,2 and 3**)

- **Traceability for models and retrieval algorithms** has been investigated through the full characterisation (mechanical and optical) of manufactured 3D targets and its comparison, via digitisation with a monte carlo Radiative transfer (RT) model. The data is now available on-line for the community to use to test the performance of other RT models and is a step on the route to methods to evaluate traceability and uncertainty of such models to physical SI standards**. (Obj. 2)**

4.3 Dissemination activities

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, 22 peer-reviewed papers describing MetEOC scientific achievements have been submitted to 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.

5 Website address and contact details

A public website has been established, where project deliverables 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 Dr Nigel Fox, NPL (nigel.fox@npl.co.uk).

6 List of publications

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Ocean Sciences, 2012, 8, 567-586.

[2] Comparison of the radiation temperature scales of the PTB and the NPL in the temperature range from −57 °C to 50 °C
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[4] Experimental evaluation of Sentinel-2 spectral response functions for NDVI time-series continuity.
D'Odorico, P., Gonsamo, A., Damm, A. and Schaepman, M.E.
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Proceedings 9th International Temperature Symposium (ITS-9) by AIP, 2013, AIP Conf. Proc. 1552, 722-727. (http://dx.doi.org/10.1063/1.4819631)

[6] Assessment of MERIS Ocean Color Data Products for European Seas
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