Metrology for Earth Observation and Climate

EMPIR EURAMET

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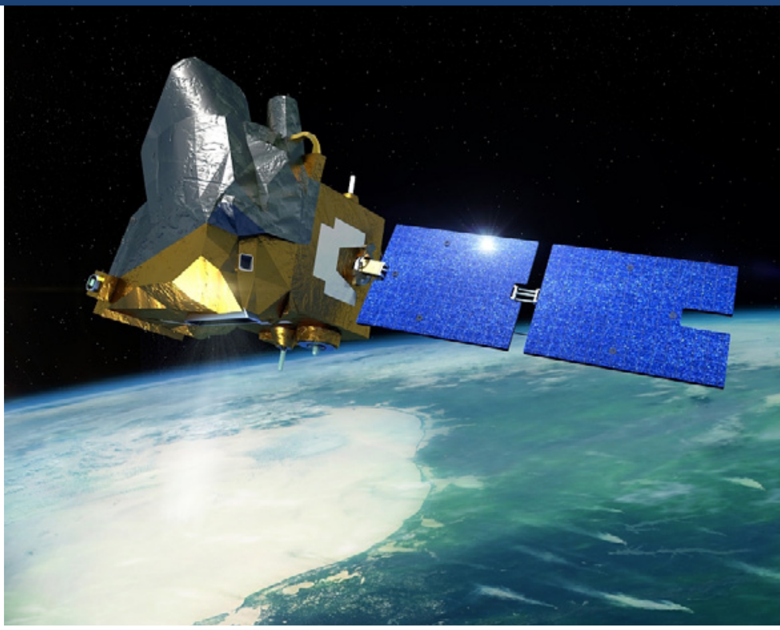
Calibration of the CNES/UKSA MicroCarb optical instrument

A satellite-based validation method will be essential for ensuring long-term trust in the global emission reporting system used to track progress towards goals of the 2015 Paris Climate Change Agreement. Indeed, in December of that year, and after an extensive feasibility and tendering process by the French National Centre for Space Research (CNES), the MicroCarb micro-satellite concept was presented at the Paris Climate Change Conference (COP21) with a mission to map, on a global scale, sources and sinks of carbon dioxide (CO_2), the main greenhouse gas. AIRBUS Defence and Space won the contract to develop an onboard instrument to quantify global and local CO_2 emissions. However, distinguishing human from natural sources will require additional knowledge of carbon cycles. Critical to mission success will be effective pre-flight calibration and validation of onboard instruments, but available methods were costly, complex, and time-consuming.



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MicroCarb is designed to map sources and sinks of carbon dioxide

Challenge

A fundamental component of the 2015 Paris Agreement is The Global Stocktake, a five-yearly review of the impacts of climate actions of nations, used to evaluate collective progress towards achieving global climate goals.

The flows of carbon attributable to national territories are assigned using a bottom-up approach based on estimated emissions from all sources, combined and adjusted via 'emission factors'. However, a top-down satellite-based method able to verify and refine reporting systems will be essential for ensuring long-term trust and societal acceptance of emission reduction strategies dependent on such systems.

Satellite-based observations will be able to quantify global atmospheric greenhouse gas concentrations, and provide continuous global coverage. However, what can be observed is the combined effects of both human activities and natural processes, as overall atmospheric carbon dioxide CO_2 levels are influenced by influxes from various natural processes as well as human-sourced emissions.

While human carbon dioxide emissions are the main driver of climate change, tilting a pre-existing balance by adding around 10 gigatons to a total annual positive global CO_2 flux of around 200 gigatons. About half of total emissions are currently absorbed by natural 'sinks', such as the oceans, land, and vegetation, with the remainder adding to atmospheric concentrations and further driving global heating. At any given time, fluxes of human and naturally produced emissions add to overall concentrations, minus what is absorbed by carbon sinks. However, these natural 'carbon cycles' are poorly understood, not least for how they may respond in future climate scenarios. Therefore, accurately measuring the effects of global carbon cycles, that isolates anthropogenic contributions, will be critical to developing important new knowledge — and precise ways to detect emission trends and the effects of climate policies.

As a European contribution to the global observation system, the French space agency CNES (funded by the national research agency ANR in partnership with the United Kingdom Space Agency) proposed the MicroCarb satellite mission. to deliver information on vertical CO_2 column concentrations and be the first mission to measure CO_2 flux from space.

To achieve mission objectives, CO_2 concentrations were specified to be measurable to a precision of 1 ppm and an accuracy of 0.3% with high spectral resolutions resulting in low signal-to-noise ratios. Global distributions of CO_2 were to be monitored every month; cover the Earth's surface within three days; collected over land and oceans; and provided as accessible data.

A pre-requisite was MicroCarb would have a relatively low-cost development and launch budget of around €100 million, and be compatible with the Myriade micro-satellite platform.

AIRBUS Defence and Space developed a versatile, compact, low-cost spectrometer (the imaging instrument to measure solar radiation after reflection from the Earth's surface or atmosphere). This instrument addressed spatial, spectral, and radiometric requirements: applying passive sounding techniques and operating in four narrow wavelength bands using an echelle grating to achieve spectral dispersion. The design offered a 'city observing mode' to take higher spatial resolution spectral images with a ground resolution of 2 by 2 km^2 over specific areas.

RAL Space developed an onboard Pointing and Calibration System (PCS) to be integrated in front of the imaging telescope, to direct it to targets on the ground and maintain accuracy. The PCS includes two calibration sources: a sunlight diffuser to calibrate instrument radiometric response in absolute terms, and a white lamp to calibrate instrument radiometric response in spatial and spectral relative terms.

Essential for mission success will be pre-launch calibration and sensor performance validation, a service provided using optical ground support equipment (OGSE). Typically, such equipment requires redesign and development stages for each new satellite. However, for lower-cost missions such as MicroCarb, the costs and development time of a bespoke OGSE system would be disruptive, as moving sensitive instruments to a calibration facility would be more complex than using a mobile facility.

After an expected launch in 2030, the TRUTHS satellite will carry two main instruments: the Cryogenic Solar Absolute Radiometer and the Hyperspectral Imaging Spectrometer as well as a novel onboard calibration system. Together, these instruments will make continuous measurements of both incoming solar radiation and Earth-reflected radiation. These two observations will be used to evaluate the energy-in to energy-out ratio.

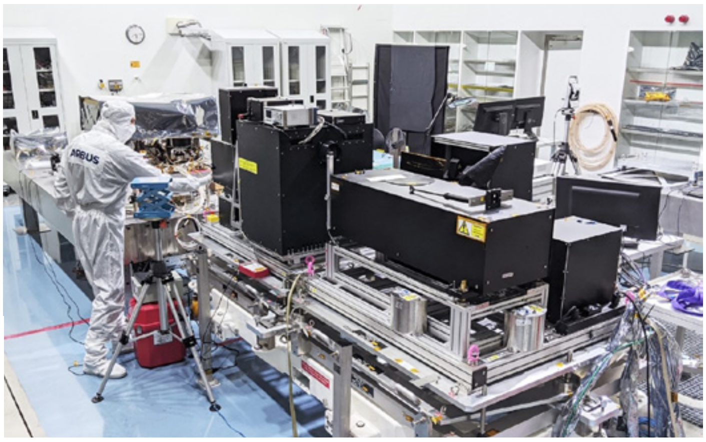
Solution

Applying its considerable experience in calibrating optical sensors, and advances part-supported by the MetEOC series of projects, NPL developed a more universal and affordable way to provide radiometric calibrations and characterisations of satellite sensors.

The NPL STAR-cc-OGSE, or spectroscopically Tuneable Absolute Radiance (STAR) calibration and characterisation Optical Ground Support Equipment facility, provides comprehensive calibration and characterisation services for satellite and other optical sensors. The transportable facility offers significant cost and flexibility benefits by enabling NMI standard calibrations at customer locations.

The facility applies two reference illumination sources for calibrating and characterising the performance of satellite sensors; radiometrically, spectrally, as well as for geometric and image quality. First, a white light source (continuous from 350 nm to 2500 nm) mimics the Sun to test the sensor in a mode similar to how it would view the Earth. In a second mode, an *M-Squared Lasers* tuneable laser delivers radiation that varies in spectral wavelength with bandwidth of less than 0.1 pm, in precise tuning steps between 260 and 2600 nm for detailed spectral calibrations.

Critically, STAR-cc-OGSE is traceable to a primary radiometric standard, NPL's cryogenic radiometer, offering calibrations of unprecedented uncertainty: below 0.5% across a wide spectral region.



STAR-cc-OGSE pre-flight satellite calibration facility being used at Airbus Toulouse to characterise the CNES/UKSA MicroCarb instrument

Towards SI-traceable climate observations

Together with national funding, from 2011 the MetEOC series of projects helped develop capabilities to improve pre- and post-launch calibrations and consequential performance of satellite-borne instruments. Historically, pre-flight calibrations of optical remote sensors were performed using radiation from incandescent lamps diffused into a large area quasi-spatially uniform (Lambertian) source to overfill the aperture from plate diffuser or integrating spheres. For both SI-traceability was obtained via source-based radiometric scales, in turn, traceable to underpinning detector-based realisations. The numerous steps involved and spectrally continuous nature of these sources meant spectral calibration uncertainty was limited and required separate facilities to provide sensor spectral characterisations. Through the MetEOC series of projects, NPL helped transform pre-flight calibrations, by enabling achievable uncertainty via a new paradigm: tuneable laser radiation as the source and calibrating directly to the SI primary standard detector.

- EMRP project ***Metrology for earth observation and climate*** (MetEOC, ENV04, 2011–2014), supported development and demonstration of detector-based (SI-traceable) measurement facilities tailored to remote sensing instruments.
- EMRP project ***Metrology for earth observation and climate 2*** (MetEOC2, ENV53, 2014–2017) showed how such measurement facilities could be used within and together with vacuum systems.
- EMPIR project ***Further metrology for earth observation and climate*** (MetEOC-3, 16ENV03, 2017-2021) integrated a tuneable laser manufactured by M-Squared Lasers, enabling OGSE facilities such as STAR-cc-OGSE to perform spectral calibrations of narrow spectroscopic instruments suited to retrieving localised measurements of CO_2 (such as MicroCarb).
- EMPIR project ***Metrology to establish an SI-traceable climate observing system*** (MetEOC-4, 19ENV07, 2020-2023) supported advancements to the NPL STAR-cc-OGSE system, to serve increased metrological performance requirements of future climate sensors such as TRUTHS.

Outcome

NPL's first major customer for the STAR-CC-OGSE test suite was Airbus Defence and Space, the prime contractor for the MicroCarb Instrument.

In December 2020, RAL Space's onboard Pointing and Calibration System and the STAR-cc-OGSE were delivered to Airbus Defence and Space's facility in Toulouse, France. Over an extensive 56-day testing period from September 2022, the MicroCarb instrument's optical performance was checked and validated for geometric, spectral, and radiometric performance using STAR-CC-OGSE. At the same time, the thermal performance of the cryostat cooling system was verified at 150 kelvin (-123.5°C).

Then, in January 2023, the successfully calibrated and characterised MicroCarb instrument was delivered to Thales Alenia Space UK for mounting on the Myriade spacecraft bus, ahead of an expected launch onboard a Vega C rocket sometime after 2025.

High accuracy, SI-traceable pre-flight radiometric and spectral calibration of the MicroCarb spectrometer provided by STAR-cc-OGSE will be crucial for ensuring that CO_2 measurements will be accurate and trusted. As a result, climate scientists can be confident that MicroCarb can provide a highly valuable service for validating carbon stocktakes, so support efforts of policymakers to mitigate and plan for climate change.

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For more information visit www.meteoc.org

From 2011 to 2023, the NPL-coordinated MetEOC series of projects — supported by EURAMET's European Metrology Research Programme (EMPR) and European Metrology Programme for Innovation and Research (EMPIR) — encouraged collaboration between European National Metrology Institutes (NMIs) and partners in industry or academia. MetEOC combined ground, atmosphere, and space-based measurements to develop metrology tools and frameworks to support climate observation systems capable of increasing understanding of the drivers of climate change.

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