

Title: Metrology for comparable and trustworthy greenhouse gas remote sensing datasets

Abstract

Satellite remote sensing of global greenhouse gas (GHG) concentrations provides invaluable information about GHG sources and sinks, supporting efficient climate mitigation policies. Recently, the accuracy targets of upcoming GHG satellite missions have become increasingly stringent (2 ppb of CH₄; 1 ppm of CO₂), requiring improved standards, underpinned by traceable spectroscopic data. Proposals addressing this SRT should aim to improve the accuracy of underlying spectral line parameters for satellite GHG retrievals for the most important anthropogenic GHGs, as well as O₂, and validate the accuracy and comparability of satellite measurements with *in situ* and ground-based observations. Submitted proposals should aim to establish traceability to the SI and generate equivalence among ground-based sites through interlaboratory comparisons using a range of techniques.

Keywords

Traceable spectral line data, satellite remote sensing, greenhouse gases, GHG, ground-based atmospheric measurement, atmospheric measurement, carbon dioxide, atmospheric greenhouse gases monitoring

Background to the Metrological Challenges

There is an increasing need from the World Meteorological Organisation (WMO) and the Global Climate Observing System (GCOS) for international standards to monitor greenhouse gas (GHG) emissions, including quantity, sources and transport routes. The availability, transparency, traceability and credibility of Earth atmospheric monitoring data has become critical for policy making, negotiation of emission levels, emission verification, and carbon taxing. However, global satellites, as well as ground-based remote sensing observations, need traceable spectroscopic information in order to be linked to existing *in-situ* surface observations and to the results of atmospheric chemical transport models. In particular, for the estimation of CO₂, CH₄ and N₂O sources and sinks, the required precision and accuracy of the observations must be 0.1 % - 0.24 %, an order of magnitude better than typical remote sensing applications. Recommendation of issue #1A.5 from the BIPM-WMO Metrology for Climate Action workshop identified that “Accurate and consistent spectroscopic parameters for trace gases are vital to the success of remote sensing products”, and an action plan is required implemented to update the HITRAN and GEISA spectroscopic databases.

Recent studies have shown that spectroscopic line intensity, previously considered independent of pressure, can significantly decrease with pressure due to intermolecular collisions causing biases and limiting retrieval accuracy. Measurements and theoretical predictions of line intensity depletion effects have been performed for HCl and CO and, more recently, for self-broadened CO₂, showing a large impact of intensity depletion and continuum absorption on the accurate determination of the line intensity and the modelling of the molecular absorption spectrum. For CO, highly accurate sub-permille line intensity has been measured through complementary spectroscopic techniques and advanced *ab initio* calculations, demonstrating agreement within 0.1 %, and through international comparison organised by the CCQM Task Group on Advanced Spectroscopy, demonstrating agreement within 0.03 %. However, this effect has not been studied for air-broadened CO₂, CH₄, N₂O and O₂. This intensity depletion effect is also accompanied by the presence of a broad continuum under the line, which also needs to be characterised and accounted for to precisely model the molecular absorption spectrum. These effects, as well as other spectroscopic data such as line position, line intensity at zero pressure and line-shape parameters, must be accurately quantified for GHGs and O₂.

Metrological standards of length and pressure, and temperature measurements for the spectroscopic setups are needed to meet the target accuracy. Additionally, H₂O absorption features in the atmosphere strongly interfere with CO₂, CH₄ and O₂ bands used in remote sensing retrievals and thus need to be investigated.

Future GHG remote sensing satellites also need retrieval accuracies of the order of 0.1 %-0.25 %. Therefore, traceable spectral line data measurements with a much-improved uncertainty budget are urgently needed. National Metrology Institutes must also ensure comparability and compatibility between line data measured with different spectroscopic techniques. The Voigt line shape simplifies the molecular collisional model but is no longer sufficiently accurate. The Earth Observation community has to adopt next-generation line shape models, which can account for the weaker, but accuracy-limiting, effects during collisions, such as Dicke-narrowing, speed-dependence, line-mixing, and intensity depletion effects. The accurate interpretation of the observations requires the adaptation of these new line-shape models.

The impact of these new spectroscopic parameters on the satellite and ground-based remote sensing data products will need to be examined. First, the differences in GHG column concentrations concerning previous versions of the satellite and ground-based data need to be quantified, not only in terms of global biases but also in terms of dependencies on geophysical parameters such as geographic latitude and observation angles. Second, it needs to be verified with atmospheric data that the new spectroscopic parameters produce improved atmospheric GHG data products. This is particularly important as the pressure and temperature ranges under which atmospheric data are collected will exceed the laboratory ranges, so some extrapolation will be required.

The Collaborative Carbon Column Observing Network (COCCON) and Total Carbon Column Observing Network (TCCON) are the backbone for validating GHG column concentrations derived from satellite measurements, covering ground-based Fourier transform spectroscopy (FTS) operating at moderate and high spectral resolution worldwide. It has been shown that these TCCON FTS can inform on spectroscopic deficiencies that map into GHG retrieval errors. The satellites OCO-2 and GOSAT, due to their high spectral resolution, have been demonstrated to be able to identify errors in spectroscopic parameters. However, the current official release of the TCCON retrieval software 'GGG' does not yet employ higher-order line shape functions. This leads to systematic errors in the retrieval of O₂, CO₂, CH₄, etc. with correction factors based on a limited set of intercomparisons against in-situ measurement systems. In addition, systematic differences can occur in column retrievals obtained from high-resolution and moderate-resolution solar FTS measurements. A full traceability and uncertainty evaluation would enable performance and comparability to be robustly assessed. This could be achieved using methodologies initially developed under collaborative European activities, such as the Fiduceo and GAIA-CLIM projects, and would enable a product model to be developed that includes all elements influencing the final results. This model can then be used to determine its overall uncertainty behaviour by applying uncertainty evaluation tools such as Monte Carlo analysis.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The proposal shall focus on the development of metrology capability in spectroscopy for atmospheric greenhouse gas analysis using satellites and ground-based measurement data.

The specific objectives are

1. To build the foundation for spectroscopic equivalence and comparability among different GHG satellite observations by greatly improving the precision and accuracy of spectral line data for CO₂, CH₄, N₂O (as well as their leading isotopologues), O₂ for Air Mass determination, and interference H₂O features. This includes 1.60 µm and 2.05 µm bands for CO₂, 1.67 µm, 3.7 µm and 7.9 µm bands for CH₄, 2.25 µm, 3.9 µm, 4.5 µm and 7.8 µm bands for N₂O, 1.27 µm and 0.76 µm bands for O₂, at a target accuracy of 0.1 % - 0.24 % on essential line parameters.
2. To ensure accuracy and comparability of data measured in Objective 1 through metrological inter-laboratory comparisons using multiple techniques (Fourier-transform spectroscopy, comb-assisted cavity ringdown spectroscopy, cavity mode dispersion spectroscopy), comparing the homogeneity of spectral line intensity to advanced *ab initio* calculations. Molecular dynamics simulations should be performed and compared to spectral measurements to investigate line intensity depletion effects and findings used to standardise line shape models needed in remote sensing retrievals of GHGs.
3. To calibrate and validate current GHG satellite missions (OCO-2, Tropomi, GOSAT/-2) and prepare for upcoming ones (e.g., MERLIN, MicroCarb, MethaneSAT) by a) applying the improved spectroscopic datasets in selected satellite retrievals of GHGs and O₂ that are derived from

Objectives 1 & 2; b) organising annual campaigns, network measurements and building numerical tools; c) combining ground-based, airborne and satellite observations.

4. To evaluate the uncertainty of retrieval products using metrological traceability and uncertainty assessment tools developed for atmospheric and Earth Observation measurements to ensure comparability among different datasets and identify the dominant sources of uncertainty in the final data products leading to prioritised steps for future improvements.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project through the CIPM Sectorial Task Group on Climate Change and Environment (CIPM-STG-CENV) and the EMN Climate and Ocean Observation, the measurement supply chain, standards developing organisations, European and International spectroscopy databases (HITRAN, GEISA), satellite remote sensing community (ESA, NASA) and environmental monitoring and regulatory agencies (NDACC, WMO, IPCC, UNFCCC).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that meets documented needs, in particular those supporting the European Green Deal. To enhance the impact of the research, the involvement of the appropriate user community such as industry, standardisation and regulatory bodies is strongly recommended, both prior to and during methodology development.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the Metrology Partnership project 22IEM03 PriSpecTemp and how their proposal will build on those.

Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.8 M€ and has defined an upper limit of 3.5 M€ for this proposal.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 35 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g., letters of support) is also encouraged.

You should detail how your proposal's results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability, or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the satellite climate observation sector.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of the Metrology Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Timescale

The project should be of up to 3 years duration.