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Validation of the MERLIN Data Products by the Airborne Demonstrator CHARM-F

Sabrina Zechlau[1,2], Gerhard Ehret[2], Andreas Fix[2], Christian Fruck[2], Mathieu Quatrevalet[2], Martin Wirth[2], and Sebastian Wolff[2]

[1]Meteorologisches Institut München, Ludwig-Maximilians-Universität (LMU), Munich, Germany
[2]Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt (DLR)
D-82234 Oberpfaffenhofen, Germany
Lead Author e-mail address: Sabrina.Zechlau@dlr.de

Abstract: Validation of the MERLIN data products by the airborne demonstrator CHARM-F is regarded a key mission element. Deployment of this instrument on the German HALO or French ATR aircrafts during several scientific campaigns enabled to improve the measurement performance and data reduction capability, enormously. Thus CHARM-F is on the right track to meet the stringent measurement requirements for MERLIN. It is found that the systematic error of CHARM-F can be kept smaller than 3 ppb which is the target performance requirement for MERLIN. Preliminary direct comparisons to WMO certified In-Situ measurements, however, show still an almost constant bias of about 1.5 % which is subject to further investigations.

1. Introduction

The Methane Remote Sensing Lidar Mission (MERLIN) is a joint French-German co-operation on the development, launch and operation of a climate monitoring satellite, to be launched in the timeframe 2028/29. This mission focuses on global measurements of atmospheric CH_4 with a precision and accuracy sufficient to constrain the methane emissions on the Earth's surface significantly better than with the current observation network [1-2]. Validation is an important part of MERLIN. The overall goal is to assess the data quality by comparing the products to data from other sensors which are regarded as a reference for MERLIN. For statistical purposes a comprehensive set of correlative data is needed, either from long-term monitoring networks, other special programs, or acquired during a specially designed short-period validation campaign. The advantage of airborne validation measurements is the possibility to bridge the spatial scales stepwise from ground via airborne to space-borne measurements. Aircrafts provide observations with a wider geophysical coverage and, in addition, offering high flexibility to achieve tight space and time coincidence with satellite overpasses almost anywhere on the globe and under most weather conditions. Nevertheless, dedicated airborne validation campaigns will only allow for a limited statistical analysis of the entire data set. Therefore, such campaigns are preferably carried out to complement routine measurements in situations that cannot solely be addressed by ground-based instrumentation.

In this paper we report on CHARM-F - DLR's airborne integrated-path differential-absorption lidar for carbon dioxide and methane observations, which is regarded as a potential candidate instrument for the validation of the MERLIN data products.

2. The MERLIN Data Products

The main scientific objective of MERLIN is to deliver column-weighted dry-air mole fractions of CH_4, referred to as XCH_4 along the satellite sub-track with a targeted random error better than 22 ppb along the satellite track of 50 km, and a systematic error better than 3 ppb. The latter performance is regarded outstanding which is the key parameter for reliable emission calculations using the top-down approach [2] on regional and country scale domains. XCH_4 in nadir direction is defined by:

$$XCH_4 = \frac{\int_0^{p_{surf}} [CH_4(p)] \cdot WF(p)dp}{\int_0^{p_{surf}} WF(p)dp} \qquad (1)$$

where $[CH_4(p)]$ describes the CH_4 volume mixing ratio profile at pressure level p and p_{surf} is the surface pressure of the location where the laser footprint hits the ground. The MERLIN instrument specific weighting function WF(p) is given by:

$$WF(p) = \frac{\sigma_{on}(p) - \sigma_{off}(p)}{g(m_{air} + m_{H_2O}[H_2O](p))} \qquad (2)$$

where σ_{on}, σ_{off} denote the molecular absorption cross sections of the on- and off-line wavelengths, m_{air}, m_{H2O} are the molecular masses of the dry-air molecules and water vapour, and [H_2O] is the dry-air volume mixing ratio of water vapour. Eq. 1 is directly linked to the measurement of the Differential-Absorption Optical Depth (DAOD) using the two-wavelength IPDA lidar instrument aboard theMERLIN satellite by:

$$\begin{aligned} DAOD &\equiv \frac{1}{2} \ln\left(\frac{S_{off}}{S_{on}}\right) \\ &= \int_0^{p_{surf}} [CH_4(p)] WF(p) dp \end{aligned} \qquad (3)$$

where $S_{off/on}$ denote the pointing angle and pulse energy corrected ground lidar echoes from on- and off-line soundings. The DAOD and XCH_4 products are commonly denoted as the Level 1 and Level 2 data products of the MERLIN mission.

A further parameter that requires validation is the so-called surface scattering elevation (SSE) which is needed for the calculation of the local surface pressure for the integrated weighting function in Eq. 1. The accuracy requirement on SSE is 10 m. This parameter can be determined from laser ranging algorithm using the off-line ground echo signal and knowledge on the lidar off nadir angle and the platform height H_{sat}. In a simplistic approach (flat Earth) SSE is given by:

$$SSE = H_{sat} - r\cos(\mu) \qquad (4)$$

where μ is the off-zenith angle and r the range of the ground return for an ellipsoid shaped Earth surface. Digital elevation models (DEM) are considered as appropriate tools for validation of the SSE parameter under complex terrain conditions.

3. CHARM-F

CHARM-F is an airborne IPDA lidar system for the simultaneous measurement of carbon dioxide and methane. Originally designed for the deployment aboard of the German HALO (High Altitude and Long-Range Observatory) which is a Gulfstream 550, it has also been successfully tested aboard of the French SAFIRE ATR42 aircraft. The use of both aircrafts is considered to complement each other for dedicated under flights of the MERLIN satellite. The advantage of HALO is its long flight endurance of about 10 h and a maximum cruising altitude of up to 15 km. But access to this aircraft is expensive and cannot be considered on a routine basis.

Fig. 1 shows the instrumental setup of CHARM-F, schematically. A dedicated description of the system parameters and subsystems is given in [3].

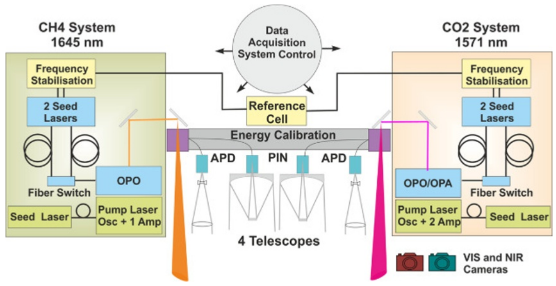

Figure 1. Schematic view of CHARM-F's system according to [3]

The optical head consist of two lasers and receiving optics both connected with two aircraft racks carrying the electronics and the laser cooling system. The separated laser heads for CO_2 and CH_4 share common laser electronics and cooling devices as well as the wavelength stabilization electronics.

Figure 2. CHARM-F deployed on HALO

A special feature of the system is the integration of four receiving telescopes, two of which for CO_2 and two for CH_4 with different sizes. For each trace gas there is a large telescope (200 mm Ø) with a PIN photodiode as the detector and a small telescope (60 mm Ø) with an avalanche photodiode (APD) available. This allows for comparison of the characteristics of these two detector types under real operation conditions. The spectrally narrow-band laser pulses are generated by Nd:YAG laser-pumped optical parametric oscillators (OPOs) that are injection seeded by stabilized low-power continuous-wave distributed-feedback lasers. For the absolute wavelength reference and for the stabilization of the seed lasers, a 36 m multi-pass absorption cell is used, filled with both 2 and CH_4. The temporal separation between the on-line and off-line pulses is 500 µs to ensure a good overlap of both ground spots, while the double-pulse repetition frequency is 50 Hz. The internal energy reference measurement is implemented by using integrating spheres for the collection and attenuation of the laser radiation. The nanosecond pulses, the bandwidth of the receiving chain (3 MHz), and the sampling rate of the signal digitizers (100 MHz) allow a high-precision ranging for the determination of the column length for each single laser shot. Pulse energies of 10 mJ result in high signal-to-noise ratios (SNRs), even on a single-shot basis over almost all ground surfaces.

A key feature of CHARM-F comprises its high flexibility to choose suitable on- and off-line wavelengths for the airborne IPDA lidar measurements. Selection of the MERLIN wavelengths and operating CHARM-F onboard of the high-flying HALO aircraft thus offers the unique possibility to validate a large portion of the MERLIN level 1 data product (see Eq. 3) without knowledge on details of the weighting function (e.g. line parameters and the meteorological parameters such as the pressure temperature and the water vapour profile).

4. Campaign Data

A prerequisite for the validation of the MERLIN data products is the proof of the performance of CHARM-F during scientific campaigns. After the first successful test in 2015, CHARM-F has been deployed during three major scientific campaigns (CoMet-1.0 in Central Europe, 2018, MAGIC-21 in Northern Europe, 2021, and CoMet-2.0 in Canada, 2022. Large sets of CHARM-F data are now available to investigate the random and systematic error sources, e.g. the overall performance in various geophysical locations. For comparison purposes the cavity-ring-down spectrometer (CRDS) "JIG" (Jena Instrument for Greenhouse Gas Measurements, Max Planck Institute) provided In-Situ measurements of CO_2, CH_4, CO, and H_2O on HALO. This allows to link the CHARM-F data products to the recommended compatibility requirements of WMO [34].

5. CHARM-F: XCH4 Gradients

This is an example where CHARM-F level 2 data from the CoMet-1.0 campaign have been compared to model data which are available from the Copernicus Atmospheric Monitoring Service (CAMS) system on an operational basis. Figure 3 depicts a trace of XCH_4 data (left plot) measured with CHARM-F on HALO during a long-range flight starting in southern Germany heading to Finland and back. The gradient of enhanced XCH_4 observed in the westerly part of the flight pattern agrees nicely to the CAMS data (right plot). A closer look on the air mass transport gave some evidence that this elevated CH_4 distribution could have its origin from CH_4 emissions in the Upper Silesian Coal Basin (USCB) located in Poland. Underground coal mines from USCB are regarded as a hot spot in Europe and are responsible for about 30 % of anthropogenic CH_4 emission in Poland (USCB: ~466 kt CH_4 / yr).

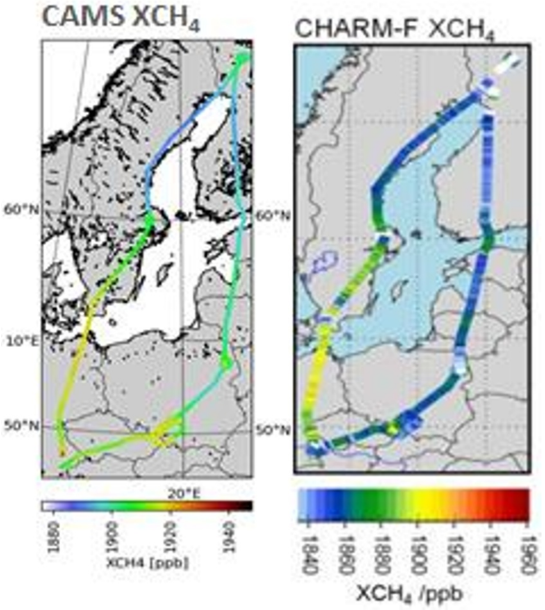

Figure 3. XCH_4 gradients on regional scale from CoMet-1.0 campaign, 2018

6. CHARM-F: Precision & Accuracy

Due to the high SNR inherent to the lidar returns from ground surfaces, the XCH_4 data product can be calculated for each shot-pair using Eq. 1.

The individual XCH_4 measurements are statistically independent which allows to improve the measurement precision just by data averaging as depicted in Fig. 4. In various geophysical locations CHARM-F data averaging follows the 1/sqrt(t) rule without systematic deviations that proves the above assumption on random noisy data. After an averaging time of about 20 s which corresponds to a flight distance of about 3600 m, the MERLIN measurement requirement of 3 ppb will be achieved which is a prerequisite for MERLIN validation up to this accuracy level.

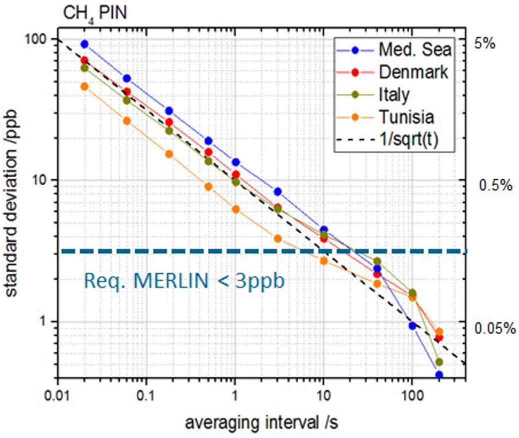

Figure 4. CHARM-F's measurement precision on HALO versus the measurement time t

To answer the question about the traceability to WMO requirements, we compared the CHARM-F data to the In-Situ data from JIG instrument on HALO.

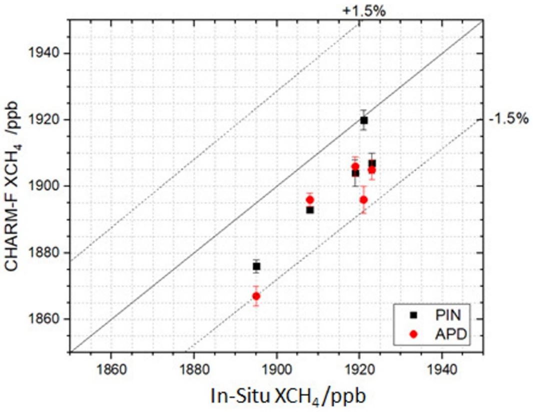

Figure 5. CHARM-F data versus In-Situ data

For this a spiral-like pattern at certain location was flown to measure the CH_4 profile with the CRDS sensor. The results are shown in Fig. 5. For both detectors, PIN and APD, a nearly constant bias of about 1-1.5% against the In-Situ data is clearly visible. For the time being the origin of this bias is not clear and requires further investigations. Potential error sources could be uncertainties of the weighting function caused by erroneous spectroscopy parameters or uncertainties caused by the solar background filter curve where we assume that the transmission is identical for on-and off-line pulses. The latter could be mitigated by calibration to the In-Situ data.

7. Conclusion

The CHARM-F airborne demonstrator has been developed to support satellite based lidar measurements of the greenhouse gases CO_2 und CH_4. For MERLIN it will serve as a key validation instrument because of its weighting function which is quite similar to the satellite instrument. This enables the direct validation of the MERLIN level 1 product without further knowledge on the CH_4 profile and spectroscopic parameters. Due to signal averaging, the systematic error of CHARM-F can be kept smaller than 3 ppb which is the target performance requirement for MERLIN. Preliminary direct comparisons to In-Situ measurements show a nearly constant bias of about 1.5 % which need further investigations.

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