

Mission preparation and instrument end-to-end test using the MERLIN airborne demonstrator CHARM-F

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ABSTRACT

The Methane Remote Sensing Lidar Mission (MERLIN), a joint initiative by the French and German space agencies (CNES and DLR), is designed to measure atmospheric methane columns with unprecedented accuracy. Scheduled for launch in early 2030, MERLIN employs an Integrated Path Differential Absorption (IPDA) lidar to retrieve column-averaged dry air mixing ratios of methane (XCH₄). This technology enables spaceborne methane observations at all latitudes and seasons, independent of sunlight, while penetrating clouds and aerosols to reduce uncertainties in the global methane budget.

Pre-launch preparation and validation rely on CHARM-F, DLR's airborne demonstrator. CHARM-F supports critical pre-launch field campaigns, including a scheduled deployment in Brazil (July–September 2026), and is pivotal for validating Level-1 and Level-2 products post-launch. Furthermore, CHARM-F serves as a testbed for ground-based testing such as an end-to-end instrument verification requested by the MERLIN Scientific Advisory Group.

To minimize costs and mission risks, ground support equipment (GSE) featuring a methane absorption cell is currently under development. Compatible with both CHARM-F and the flight instrument, this GSE simulates atmospheric conditions for testing. By comparing CHARM-F measurements with data from the absorption cell under identical spectral properties, this cost-effective approach allows for the quantitative verification of MERLIN's suitability for atmospheric measurements, ensuring the instrument meets all user specifications.

Keywords: Lidar, active remote sensing, greenhouse gases, methane, satellite, aircraft, ground support equipment

1. INTRODUCTION

The Methane Remote Sensing Lidar Mission MERLIN, jointly developed by the French and German space agencies (CNES and DLR), is designed to measure atmospheric methane columns with unprecedented accuracy [1]. This capability promises to bridge a significant knowledge gap in quantifying natural emissions from space using a top-down approach. Consequently, MERLIN is expected to improve the quantification of global and regional sources, thereby reducing uncertainties in the global methane budget through inverse modelling [2].

To achieve this, MERLIN will rely on its Integrated Path Differential Absorption (IPDA) lidar to retrieve column-averaged dry air mixing ratios of methane (XCH₄) [3] at all latitudes and in all seasons. Due to its independence from sunlight and capability to measure through cloud gaps, the instrument will provide spaceborne methane observations even in regions with significant cloud cover, as well as at high latitudes during winter and shoulder seasons. Since IPDA measurements are insensitive to thin clouds and atmospheric aerosol loading, they will provide highly valuable data to fill knowledge gaps regarding methane distributions at global and regional scales.

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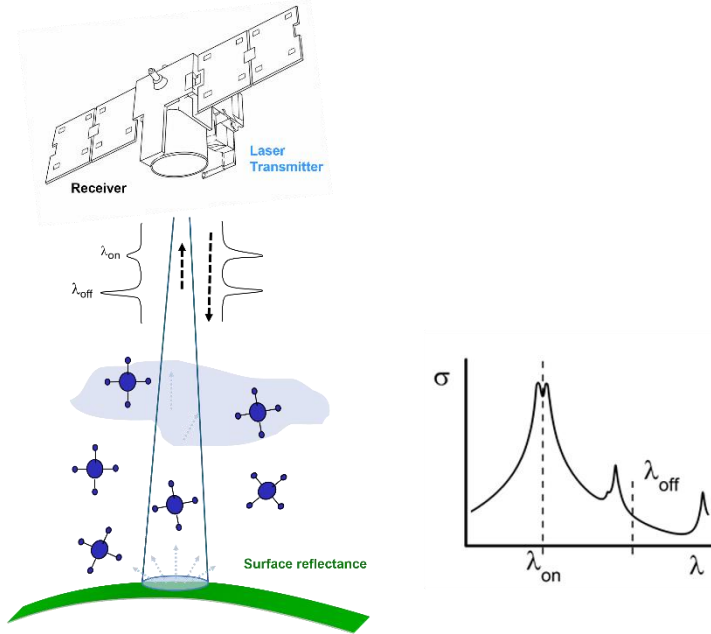


Figure 1. Conceptual sketch of MERLIN's IPDA lidar measurement principle. The Methane Remote Sensing Lidar Mission (MERLIN) retrieves column-averaged dry-air methane mixing ratios (XCH_4) using Integrated Path Differential Absorption (IPDA) lidar. The instrument alternately transmits high-power ($> 9\text{mJ}$), nanosecond laser pulses at a strong methane absorption wavelength ("on" line) and a nearby non-absorbing reference wavelength ("off" line). Backscattered radiation from Earth's surface (and cloud tops) is received, and detected. Because atmospheric methane attenuates the "on" wavelength more strongly than the "off" wavelength, the logarithmic ratio of the two returned signals directly encodes the Differential Absorption Optical Depth (DOAD) from which XCH_4 is retrieved [3].

Over the past few years, DLR has deployed its airborne MERLIN demonstrator, CHARM-F, during several field campaigns aboard either the German research aircraft HALO or the French ATR 42 operated by SAFIRE. CHARM-F, which has just completed its next deployment during a seven-week field campaign in Brazil from July to September 2026, has become an essential tool for pre-launch mission preparation. It will also be pivotal for validating Level-1 (Differential Absorption Optical Depth, DOAD) and Level-2 (XCH_4) products after launch.

Concurrently, CHARM-F functions as a critical testbed for instrument validation. Specifically, the MERLIN Scientific Advisory Group requested an end-to-end ground test to verify the MERLIN instrument's capability to quantify total atmospheric column methane concentrations using the Integrated Path Differential Absorption (IPDA) lidar technique, in accordance with user specifications.

Therefore, and to avoid costs, delays and associated potential mission risks, a suitable ground support equipment (GSE) is currently under development. This GSE contains a suitably prepared methane absorption cell and is designed to be compatible with both CHARM-F and the MERLIN instrument, requiring minimal modifications. Initially, CHARM-F measurements at the MERLIN wavelengths will be used, and compared with the DOAD derived from the absorption cell. This cell simulates atmospheric conditions for the MERLIN instrument in a subsequent step. In this way, the absorption cell acts as a proxy for the real atmosphere. By maintaining constant cell conditions and ensuring identical spectral properties between CHARM-F and the MERLIN instrument, this cost-effective approach allows for the quantitative verification of the MERLIN's suitability for atmospheric measurements.

2. THE MERLIN MISSION AND INSTRUMENT

MERLIN uses the Integrated Path Differential Absorption (IPDA) lidar technique [3] to access column-averaged dry air mixing ratio of methane (XCH_4) at all latitudes and in all seasons. MERLIN will fly at an altitude of $\sim 500\text{ km}$ on a sun-synchronous dusk-dawn orbit. Due to its independence of sunlight and even capability to measure in cloud gaps and over water bodies, the instrument will provide spaceborne methane observations even in regions with high cloud cover, and at

high latitudes also during winter and shoulder seasons — conditions where passive instruments struggle significantly. The IPDA measurements are insensitive to thin clouds and atmospheric aerosol load and will therefore provide highly valuable information for closing knowledge gaps concerning global to regional methane distributions. Due to the small footprint of ~ 140 m on the ground (see Table 1), MERLIN is well-suited to measure through gaps in cloud cover and can utilize cloud slicing—the differentiation of signals from ground versus cloud tops—to reconstruct vertical information under broken cloud conditions. A sketch of MERLIN’s IPDA measurement principle is depicted in Figure 1.

5.1 Spacecraft

The MERLIN spacecraft is built upon the Myriade Evolutions bus, a standardized 100 kg-class modular microsatellite platform developed by CNES in collaboration with Thales Alenia Space and Airbus Defence & Space. The bus architecture is designed to support integration with a broad spectrum of European institutional launch vehicles, commercial launch services, and emerging micro-launcher systems. Engineered for operational scalability, the platform accommodates a maximum payload mass of 150 kg and delivers approximately 150 W of electrical power dedicated to payload subsystems. The assembly of the MERLIN spacecraft has been completed, and is currently in storage awaiting the instrument integration.

The instrument’s flight hardware is currently being assembled in the cleanroom facilities of Airbus Defense and Space, the instrument prime. The next key milestone involves finalizing the flight laser assembly, conducting final tests, and integrating the unit into its housing. Launch readiness for the MERLIN satellite is anticipated by early 2030.

5.1 Instrument

The main instrument submodule comprises instrument control unit, frequency reference unit, laser head and electronics, internal calibration chain, active pointing control, transmitter and receiver optics, detector electronics, and signal chain. The core of the lidar transmitter is a high-power, narrow-linewidth, nanosecond optical parametric oscillator (OPO) optimized for the methane absorption band (at ~ 1645 nm) pumped by a diode-pumped Nd:YAG laser. The technique of injection seeding is employed to achieve narrow band width and high spectral purity ($>99.95\%$) for the OPO. Several key parameters of the instrument are listed in Table 1.

Table 1. Key instrument parameters of MERLIN

Parameter	Value	Unit
Wavelength (online)	1645.552	nm
Wavelength (offline)	1645.846	nm
Pulse energy	~ 10	mJ
Pulse width	20 - 30	ns
Repetition rate (double pulse)	20 (~ 350 m on ground between subsequent double pulses)	Hz
Double pulse separation	300 (~ 2 m on ground between online and offline ground spot)	ns
Ground spot diameter (99% encircled energy)	~ 140	m

3. CHARM-F, THE MERLIN AIRBORNE DEMONSTRATOR

In recent years, DLR has developed and deployed an airborne demonstrator for the MERLIN mission, referred to as CHARM-F [4]. The system is primarily intended to support pre- and post-launch validation campaigns and advance the development and refinement of atmospheric retrieval algorithms. While its airborne configuration necessitates certain design modifications compared to the spaceborne MERLIN instrument, CHARM-F shares several key technological components with the space platform. As an example, both systems utilize an injection-seeded optical parametric oscillator (OPO) at the same operating wavelength and employ identical avalanche photodiodes in their detection chains. A major

distinction is that CHARM-F was specifically designed to simultaneously measure both methane (CH_4) and carbon dioxide (CO_2). To our knowledge, it is currently the only airborne IPDA lidar capable of measuring the column-integrated dry-air mixing ratios of both greenhouse gases at the same time—specifically, CH_4 at ~ 1645 nm and CO_2 at ~ 1572 nm. Consequently, CHARM-F represents a state-of-the-art airborne lidar for accurate greenhouse gas measurements, making it an essential tool for atmospheric research focused on inferring greenhouse gas budgets [5-7].

Originally designed for the German research aircraft HALO (operated by DLR), CHARM-F has also been certified on the French ATR42 operated by SAFIRE (the French facility for airborne research). In recent years, CHARM-F participated as part of the scientific payload in the CoMet series of large-scale field campaign across Europe, Canada, and Brazil under the auspices of DLR. Additionally, it was deployed during two field campaigns organized by French partners CNRS and CNES: MAGIC2021 and AB2CD. In addition to scientific objectives, those field campaigns, which were also partly supported by ESA, aim to promote technological developments necessary for new and future Earth observation satellites, and validate current greenhouse gas satellite measurements. To date, the system has clocked up around 400 flight hours. Further campaign activities are anticipated during the upcoming years.



Figure 2. Photo of CHARM-F inside the German research aircraft HALO showing the optics box with the lidar transceiver in the foreground and its two electronics rack in the background.

Beyond its primary role as a scientific payload, CHARM-F also serves as a technical testbed. Notably, it facilitated critical validation tests for the internal calibration chain (ICC) design of the MERLIN mission. Because IPDA-based CH_4 monitoring requires the precise determination of the ratio between outgoing on- and off-line pulses, measurement accuracy is paramount. During testing, speckle effects were identified as a potential source of systematic error. A decorrelation strategy—achieved by introducing controlled variation and averaging over time—proved effective [8]. A decorrelation mechanism was subsequently incorporated into the MERLIN design.

Another important test prior to MERLIN's launch is the end-to-end (E2E) test of the instrument which was requested by the MERLIN Scientific Advisory Group. The purpose of this test is to verify the functionality of the entire instrument to accurately quantify total vertical methane columns in accordance with the user specifications.

4. MERLIN END-TO-END TEST

To minimize costs, schedule delays, and mission risks, this verification will be conducted in two sequential stages. First, CHARM-F will perform atmospheric methane measurements at the MERLIN operating wavelengths. By maintaining stable cell parameters and ensuring identical spectral response characteristics between CHARM-F and the satellite instrument, this methodology enables a cost-effective transfer of calibration results. Consequently, the MERLIN instrument's readiness for atmospheric sensing can be quantitatively verified, fully satisfying the overarching goals of the E2E test.

For this E2E-test, the methane concentration in a representatively filled gas cell will be measured with the instrument in different albedo cases. Similar tests have been performed for the ACDL spaceborne instrument for IPDA measurements of CO₂ [9]. To minimize mission costs and mitigate risk, the plan calls for the development of ground support equipment compatible with both CHARM-F and the satellite instrument, requiring only minor interface adaptations. This approach facilitates the transfer of results from the well-characterized CHARM-F using a calibrated methane absorption cell to the satellite instrument without significant delay, as critical preparatory work is conducted in parallel. This establishes a direct measurement link between real atmospheric observations and satellite instrument validation. The test procedures have been consolidated and the equipment is under development.

The schematic of this ground support equipment is depicted in Figure 3. A small part of the outgoing OPO beam is transmitted into an optical fiber that is coupled to a gas cell, while the remainder is monitored with respect to power and beam profile. Here, the different divergence and beam size of the two instruments need to be considered. With the help of in-line fiber attenuators the fiber throughput can be controlled in order to simulate various ground albedo values and adapt the photon budget of the two systems. A long optical delay line will provide a delay of 150 μ s in order to be able to properly record the signals using the onboard signal chain.

By choosing a favorable optical absorption length, and tuning air and methane partial pressures inside the cell, it is designed to match both the atmospheric differential optical depth (DAOD) and the online second derivative of the optical depth within a $\pm 1\%$ margin, thereby optimizing the replication of atmospheric absorption conditions at the MERLIN wavelengths.

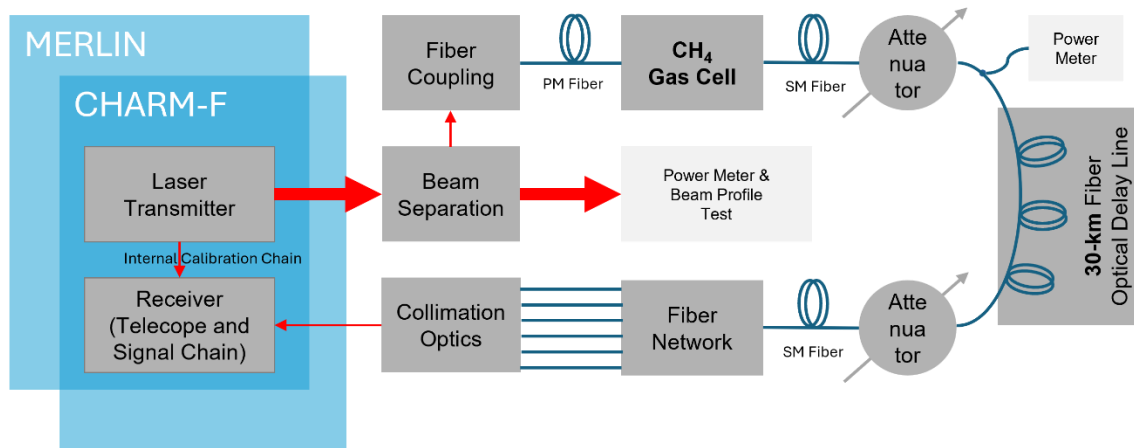


Figure 3. Schematic diagram of the E2E test setup

In order to illuminate the receiver telescope, the output of the fiber is evenly distributed to eight fiber-coupled collimators that are carefully aligned using a flat mirror and positioned in front of the 60-cm receiving telescope. Since CHARM-F's telescope is much smaller, here, only 4 collimators will be used.

When changing the z-axis position of the collimating telescopes, a phase shift will be introduced. This way, different speckle characteristics in the detector plane are achieved which can also be analyzed.

5. SUMMARY

Preparations for the MERLIN mission are advancing toward an anticipated launch in early 2030. MERLIN aims to measure column-averaged dry-air mixing ratios of methane (XCH₄) globally using Integrated Path Differential Absorption (IPDA) lidar technology. A pivotal component of these developmental efforts is the airborne demonstrator CHARM-F, which serves a dual purpose: it plays a central role in refining retrieval algorithms and validating satellite lidar systems, while also functioning as a state-of-the-art platform for independent investigations into greenhouse gas fluxes. Drawing on extensive flight campaigns under diverse geophysical conditions, this study highlights the enduring utility of CHARM-F for MERLIN-related testing. Specifically, this work presents an end-to-end test utilizing a fiber-coupled gas cell to verify

the functionality of the entire satellite instrument chain for the accurate quantification of total vertical methane columns. Ultimately, these findings underscore the indispensable added value of airborne demonstrators in the development and qualification of spaceborne remote sensing technologies.

ACKNOWLEDGEMENTS

The German contribution to the MERLIN mission is funded by the Federal Ministry of Research, Technology and Space (BMFTR) on the basis of a decision by the German Bundestag. The CoMet series of HALO missions is funded in by German Aerospace Center (DLR) and Max Planck Society (MPG). CoMet 1.0 and CoMet 2.0 received partial funding by German Research Foundation (DFG) within its Priority Program HALO-SPP 1294. Parts of the scientific data analysis were supported by Federal Ministry for Research and Education (BMBF) within its AIRSPACE project, and by European Space Agency as part of the AMPAC, AB2CD, and BRACCIOLE initiatives.

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