MERLIN: The Franco-German mission to perform innovative spaceborne LIDAR measurements of atmospheric methane

Matthias Alpers[a], Peter Bartsch[b], Philippe Bousquet[c], Gerhard Ehret[d], Achim Friker[a], Philippe Landiech[e], Gilles Rougier[f] and Inés Usandizaga[a]

[a] *DLR, German Space Agency, Bonn, Germany*
[b] *Airbus Defence and Space GmbH, Ottobrunn, Germany*
[c] *Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Gif sur Yvette, France*
[d] *DLR, Institute of Atmospheric Physics, Oberpfaffenhofen, Weßling, Germany*
[e] *Centre National d'Études Spatiales (CNES), Toulouse, France*
[f] *Airbus Defence and Space SAS, Toulouse, France*

Matthias.alpers@dlr.de

Abstract: The MEthane Remote sensing LIDAR missioN (MERLIN) is a joint French and German project, which will demonstrate the first active measurement of atmospheric methane from space. The main scientific objective of MERLIN is the delivery of dry-air mixing ratio columns (XCH_4) in the Earth's atmosphere for all latitudes: expected to be launched in 2028/2029, the satellite will provide data throughout the year with unprecedentedly small systematic errors. This will significantly improve surface CH_4 flux estimates and the identification of methane sources on global and regional scales. The paper presents the programmatic background of the mission and gives an overview about the advanced status of its development.

1 Introduction

Methane (CH_4) is, after carbon dioxide (CO_2), the second most important anthropogenic greenhouse gas. CH_4 has a Global Warming Potential of 23 relative to CO_2 on a time scale of 100 years [1]. Emissions of methane from thawing permafrost in the Arctic and changing patterns of wetland inundation around the globe are expected to substantially increase this century due to rapid climate warming.

Therefore, monitoring and quantifying these methane fluxes is of high scientific importance. However, natural methane fluxes and other diffuse mankind methane sources (e.g. from oil and gas extraction, combustion, gas leaks, and landfills) require unbiased measurements with good global coverage in order to measure the small concentration gradients and deduce the underlying fluxes. This requires highly accurate measurements of the methane atmospheric column.

The Franco-German space mission MERLIN is using a cutting-edge active technology to open a new path to access methane atmospheric concentrations at all latitudes and for all seasons. The mission complements global passive missions (GOSAT/GOSAT-2, S5P, GOSAT-2, S5, CO2M, etc.) as well the numerous new space approaches using nano- and microsatellites, targeting strong point source emissions of methane with very high spatial resolution, but with limited precision, accuracy and spatial coverage. MERLIN is also a strategic mission for Europe as it will provide reliable information for European policies on climate change mitigation.

2 The MERLIN mission

2.1 Mission overview

The MERLIN mission is a joint French-German cooperation on the development and operation of a CH_4 monitoring satellite, which will be launched in the timeframe of 2028/2029.

The goal of MERLIN is to measure the spatial and temporal gradients of atmospheric CH_4 columns with high precision and unprecedented accuracy.

The satellite will be developed and operated by both countries in joint partnership. Germany contributes the payload, a LIDAR system for CH_4 column density measurements, based on a German heritage with airborne DIAL systems for O_3 and H_2O as well as the helicopter-based CH_4 LIDAR for pipeline monitoring and on up-to-date innovative concepts of pulsed high-power laser systems for space application. France contributes its new satellite platform MYRIADE Evolutions and will operate the satellite. Joint management and science teams guarantee efficient project implementation and optimum scientific results.

As mission orbit, a near-polar sun-synchronous orbit with an orbit height of about 500 km, a Local Time Ascending Node of 06:00 (or 18:00) and a repeat cycle of about 28 days is foreseen.

2.2 MERLIN basics

An Integrated Path Differential Absorption (IPDA) LIDAR uses the laser light scattered back from a surface to obtain measurements of the column content of a specific atmospheric trace gas between instrument and target. For this purpose, the difference in atmospheric transmission between a laser emission with a wavelength placed at or near the center of a methane absorption line (λ_{on}) and a reference wavelength (λ_{off}) with significantly less absorption is used. As a special feature for MERLIN, λ_{on} is accurately positioned close to the center of the trough formed by a multiplet of CH_4 absorption lines in order to dramatically relax the laser frequency stability and pointing requirements. Close collocation of the on- and off-line wavelength positions is required to avoid biases by the wavelength dependency of aerosols, other trace gases, clouds and the scattering surface. A telescope collects the backscattered photons and focuses them onto the detector. Since the return signals are very weak, it is necessary to accumulate several single measurements of the return signals along the track in order to achieve the required measurement sensitivity. From the ratio of the two return signals, the Differential Atmospheric Optical Depth (DAOD) can be calculated.

The main data product of MERLIN will be column-weighted dry-air mixing ratios of CH_4 (XCH_4), measured over the satellite sub-track:

$$XCH_4 = \frac{\frac{1}{2} \cdot ln\left(\frac{P_{off} \cdot E_{on}}{P_{on} \cdot E_{off}}\right)}{\int_0^{p_{surf}} \mathrm{WF}(p,T)dp} \qquad (1)$$

with the received signal powers P_{off} and P_{on}, normalized by the associated ratio of transmitted pulse energies E_{on} and E_{off}. P_{surf} is the surface pressure at the location where the laser beam hits the ground and WF is the weighting function, describing the altitude sensitivity of XCH_4. For a detailed description of the measurement principle see [2].

The scientific mission performance is driven by the random and systematic errors of the instrument [3]. Numerical performance analysis at the Critical Design Review demonstrates, that with its instrument baseline parameters MERLIN will meet the scientific breakthrough requirements (to resolve seasonal and annual budgets on country-scale, to resolve country-scale gradients). Supplementary scientific impact studies show furthermore, that MERLIN data will enhance substantially the accuracy of CH_4 flux estimates compared to GOSAT in most regions of the globe [3].

2.3 Satellite overview

Figure 1 shows the MERLIN satellite. The MYRIADE Evolutions platform on which the instrument is mounted can be seen on the lower part.

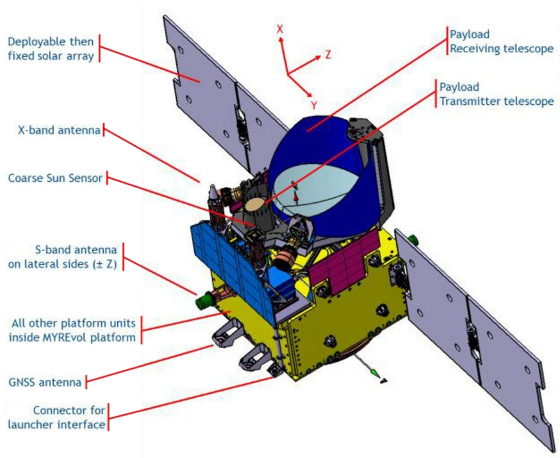

Figure 1. The MERLIN satellite

The MYRIADE small satellite series started in 1998. The MYRIADE Evolutions program is an enhancement of the original platform concept and provides the payload more allocated power and mass.

The main components of the MERLIN LIDAR are the optical bench, receiver telescope with baffle for thermal control, transmitter telescope, laser emitter, radiators for thermal control and the units for energy calibration, frequency reference and instrument control, ICU. Other components that can be seen in Figure 1 are the star sensor and the deployed solar arrays.

2.4 MERLIN instrument details

MERLIN will be the first satellite-based methane IPDA LIDAR system. One of the main challenges of the MERLIN mission is to implement a complex LIDAR instrument on a small satellite platform with very limited resources. Important aspects for the selection of sub-systems are power, mass and volume consumption. The system has to operate in a stable manner under the harsh space conditions. Degradation due to radiation needs to be minimized.

In Figure 2 the basic scheme of the instrument is shown.

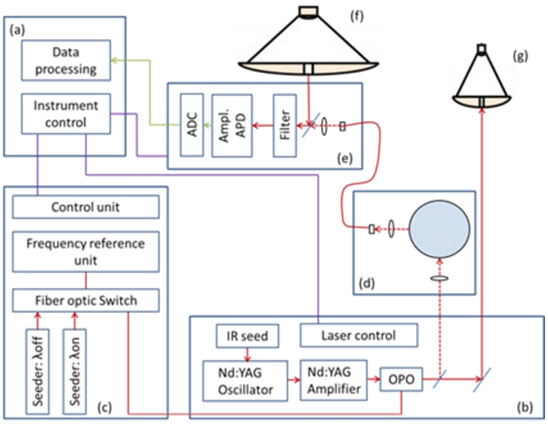

Figure 2. IPDA LIDAR instrument setup: (a) ICU, (b) Laser, (c) frequency reference, (d) energy calibration, (e) & (f) receiver and telescope, (g) transmitter optics

Table 1 gives a brief overview over the main satellite parameters of MERLIN. For more details on the MERLIN instrument design see [4].

Table 1. MERLIN satellite parameters

Altitude	~500 km
(Wet) Satellite Mass	430 kg
(Wet) Platform Mass	260 kg
Payload Mass allocation	~150 kg
Satellite Power	~500 W
Payload Power allocation (eclipse)	150 W
Platform Volume [mm^3]	570 × 940 × 940
Payload Volume allocation [mm^3]	820 × 830 × 1010

Furthermore, the instrument design is driven by the random and systematic performance requirements. The random error is mainly driven by the size of the receiver telescope (due to launcher volume allocations), the available laser pulse energy (due to platform power allocation) and the minimal orbit altitude (limited due to atomic oxygen constraints and fuel tank size for orbit maneuvers). Aside from the random error, the systematic error also has an influence on the instrument. The systematic error requirement serves to characterize the capability of the measurement setup to determine characteristic trends in the measured data at accuracies significantly better than the random error in the resolution cell (integration length: 50 km). This error depends mainly on the accuracy and stability of the energy calibration as well as the stability and knowledge of the laser frequency, of the pointing and of the detector linearity.

The main parameters of the MERLIN laser are shown in Table 2.

Table 2. MERLIN laser parameters

On-line λ	1645.552 nm
Off-line λ	1645.846 nm
Pulse energy at 1645 nm	9 mJ
Pulse repetition rate (double pulses)	20 Hz
Pulse length	20 – 30 ns

Industrial contractors for MERLIN satellite platform and instrument are Airbus Defence and Space SAS in Toulouse (France) and Airbus Defence and Space GmbH in Ottobrunn (Germany), respectively.

2.5 Mission development status

The MERLIN mission successfully passed the design phase C review in 2020. With this final satellite design the expected random and systematic errors of the XCH_4 data product are calculated at 18.4 ppb and 1.8 ppb, respectively. These values meet the scientific breakthrough requirements of the mission.

The detailed design work on the German methane IPDA payload faced various technical and organizational challenges, especially regarding the demanding laser emitter. This delayed both phase C and D for the whole satellite significantly.

The French MYRIADE Evolutions flight model has been finally assembled and tested in 2023 and is in storage waiting for the finalization of the German payload. Figure 3 shows the finally integrated and tested flight model of the MERLIN MYRIADE satellite platform.

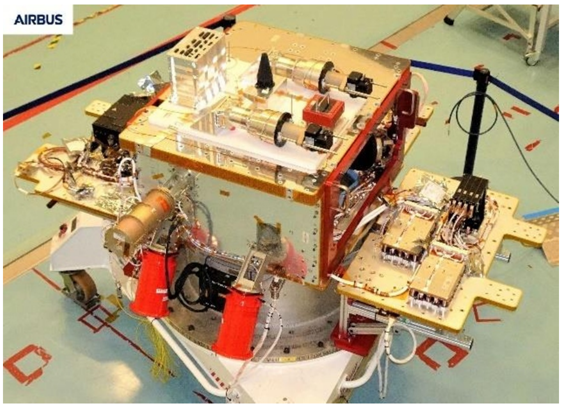

Figure 3 Flight model of the MYRIADE satellite platform after integration and test. (Picture: Airbus SAS)

The German payload is in an advanced status of construction. Assembly, qualification and test of all payload subsystems and the payload structure with its transmit and receive optics is progressing well.

Figure 4 shows the qualification model of the laser subsystem. The laser remains the most demanding part of the payload development. Due to the stringent mass and size constraints of a small satellite mission, the whole laser including pressurized housing measures just 44x32x21 cm^3. For more details on the MERLIN laser design see [5].

The laser subsystem assembly, integration and test progress has improved significantly during the year 2023. The laser qualification model is almost finally assembled, showing excellent technical performances. After wedding with its pressurized housing and thermal control unit, the laser Engineering Qualification Model (EQM) test phase together with its supporting subsystems laser electronics LAE, frequency reference unit FRU, and instrument control unit ICU is scheduled to start end of 2024 and will last until third quarter of 2025. The flight model of the laser optics is expected to be finished in the same time frame. Finalization of the payload and satellite launch readiness are now expected for 2027 and 2028/2029, respectively.

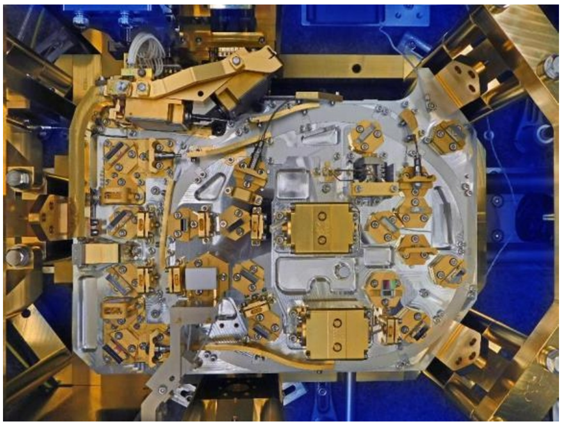

Figure 4 Qualification model of the MERLIN laser subsystem (oscillator side of the laser bench). (Picture: Fraunhofer ILT).

Acknowledgements

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3 References

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