The French-German climate mission MERLIN

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MERLIN is a small satellite mission for the measurement of atmospheric methane (CH_4) by the method of integrated-path differential-absorption (IPDA) lidar. CH_4 is the second most important anthropogenic greenhouse gas after carbon dioxide (CO_2) that will contribute to global warming, significantly. Large uncertainties exist for example in the estimation of CH_4 emissions from tropical and boreal wetlands which are regarded as the largest natural sources of atmospheric methane. The lidar measurements from space will provide spatial and temporal gradients of the weighted column-integrated $_{CH4}$ mixing ratio along the satellite sub-track that can be used to derive $_{CH4}$ surface emission by means of inverse modeling. For MERLIN a low sun-synchronous dawn-dusk orbit has been selected to provide best conditions in terms of measurement performance, global coverage, and instrument stability. It is planned to launch the MERLIN satellite in the time frame of 2017 with at least 3 years of operation in space.

1. Introduction

The acronym MERLIN (Methane Remote Lidar Mission) stands for the Franco-German climate monitoring initiative that will make use of the IPDA lidar principle for the measurement of atmospheric methane from space. Atmospheric CH_4 is the most abundant non-CO_2 greenhouse gas in the atmosphere today. It's atmospheric mole fraction in dry air of about 1.8 µmol/mol is about 2.5 times higher than that of the pre-industrial time period used as the reference. It is important to note that this value is even higher than that observed in the existing ice-core record which spans the past 800.000 years as reported in the literature. The strong increase in atmospheric methane since pre-industrial times is mainly caused by anthropogenic emissions due to agriculture and fossil full exploration. Also human-derived emissions from waste treatment and biomass burning play an important role. On the other hand, natural emissions are dominated by the wetlands that account to about one third of the total emissions. Most of the wetland emissions come from the tropics and are rather uncertain because they are strongly coupled to the water cycle (precipitation, flooding areas) and temperature variability. Further uncertainties are connected to climate warming in the Arctic regions. This might foster melting of permafrost soils that contain significant amounts of carbon in organic form which under anaerobic conditions might be converted to CH_4 and partially released to the atmosphere. There exist also very large deposits of CH_4 as hydrates on ocean shelves that are vulnerable to ocean warming. Paleo records indicate that both processes can have important feedbacks in the climate system. Regarding the sinks, methane is removed from the atmosphere primarily as a result of atmospheric oxidation by the hydroxyl radical (OH^-). Through this reaction, CH_4 in the atmosphere is strongly linked to the complex atmospheric chemistry that creates in addition a positive climate feedback mainly though production of tropospheric ozone and the increased methane lifetime in the atmosphere.

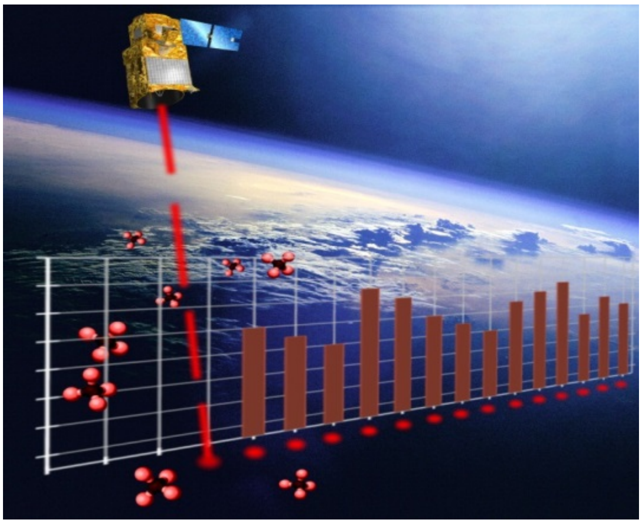

Fig. 1: Observational principle of the MERLIN instrument. Red bars symbolize the amount of XCH_4 along the satellite ground track. Credit: CNES for satellite artist view, NASA for background photo

To reduce large uncertainties about the global methane budget and climate feedback, monitoring of atmospheric CH_4 is of paramount interest. In view of the existing and forthcoming observational network, MERLIN will provide complementary data on atmospheric methane for reliable estimates of the natural and anthropogenic emissions in terms of location, magnitude, and variability on a global basis. The lidar instrument will measure the column-integrated dry-air mixing ratio of CH_4, commonly referred to as XCH_4, along the satellite sub-track (figure 1). Together with appropriate modelling activities, these data can be used to infer CH_4 sources and sinks by means of inverse models that describe atmospheric transport and mixing. In addition, XCH_4 measurements above dense stratiform clouds used as reflective targets can provide even profile information. MERLIN will also provide information on surface retro reflectance, canopy height, and cloud boundaries.

2. The observational method

The space-instrument of the MERLIN mission will be a nadir-viewing CH_4 IPDA lidar system which represents a selective and sensitive method for measuring the number of CH_4 molecules in the path. The Earth surface or cloud tops provide the return (backscattered) signals at two, namely "on-line" and "off-line", transmitted wavelengths denoted as λ_{on} and λ_{off}, respectively as shown in figure 2. In principle, the IPDA technique is based on comparing the attenuation throughout the atmosphere of the two laser pulses at on-line and off-line wavelengths. From the measurement of the ratio of the pulse energy corrected lidar echoes S_{on}/S_{off} the path-integrated averaged gas mixing ratio is calculated using the following definition[1]:

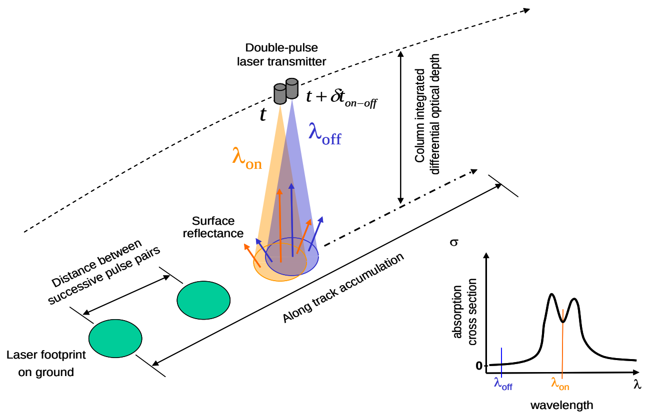

Fig. 2: Principle of IPDA lidar measurement using surface targets

$$XCH_4 \equiv \frac{\int_0^{p_{surf}} [CH_4] \mathrm{w}(p)dp}{\int_0^{p_{surf}} \mathrm{w}(p)dp} = \frac{\ln \dfrac{S_{off}(p_{surf})}{S_{on}(p_{surf})}}{2\int_0^{p_{surf}} \mathrm{w}(p)dp}$$

In this equation, p denotes the atmospheric pressure, p_{surf} is the surface pressure, $[CH_4]$ is the CH_4 mixing ratio profile, and w(p) is the weighting function defined as:

$$w(p) = \frac{\sigma_{on}(p) - \sigma_{off}(p)}{\left(1 + \dfrac{M_{H_2O}}{M_{air}} \rho_{H_2O}(p)\right) \cdot g \cdot M_{air}}$$

where M_{H2O}, M_{air} denote the molecular masses of water vapour and dry air molecules, respectively, ρ_{H2O} is the dry air volume mixing ratio of water vapour, g is the acceleration of gravity, and σ_{on} - σ_{off} is the differential absorption cross section for the selected wavelength pair that is a function of pressure.

In general, the spectral requirements with respect to the frequency stability of the laser transmitter and platform pointing knowledge to reduce the Doppler error are very demanding[2]. For MERLIN, some significant relaxation on instrument and platform requirements can be obtained by tuning the on-line wavelength to the absorption minimum that is formed by two or more overlapping CH_4-lines as schematically indicated in the insert of figure 2. This selection of the on-line wavelength position enables a high sensitivity on ground due to a favorable weighting function in the column measurement. Further criteria of proper line selection are the interference from geophysical parameters (temperature, pressure, and humidity) which should be kept to a minimum[3].

3. Mission description

The overall goal of MERLIN is to develop, launch and operate an earth observation satellite in French-German cooperation to provide relevant information for the climate change forecast. In addition, this mission shall serve as a technology in space demonstrator experiment employing space-borne IPDA lidar in future application. The MERLIN measurements shall serve as input data in flux inversion models on weekly/monthly basis to infer quantitative information on the seasonal cycle in the CH_4 emissions. The mission lifetime should cover at least three years of continuous operation in order to capture part of the inter-annual trend of methane emissions where the uncertainties are large and the observed variability is not well understood. To meet the MERLIN mission objectives, XCH_4 shall be measured with unprecedented accuracy with respect to the systematic error (< 3ppb) and measurement bias. This shall be achieved by operating a pulsed laser transmitter for both wavelengths in conjunction with a range-gated receiver. The measured data is expected to be not prone to biases that may arise from aerosol scattering or scattering from thin cirrus layers, which is a well-known error source of passive instruments. Since the measurement precision is dominated by the surface reflectivity in the respective spectral region which can vary up to an order of magnitude, several shot-pairs need to be averaged for a precision of better than 2% which is regarded as the threshold value along an accumulation distance of 50 km. A sun-synchronous low Earth orbit (~500 km orbit height) and a satellite crossing time of the equator at 6h/18h will be selected to ensure best measurement conditions and to provide a high measurement density on a monthly repeat cycle, globally. It is important to note that a "polar orbit" allows for a dense observation net at high latitudes during all seasons that in principle would give new insights into climate feedback from changing wetlands and thawing permafrost, since current observations of methane emissions in those regions are sparse.

4. Instrument/mission concept

MERLIN is based on a joint instrument/mission concept where France delivers the satellite bus from their MYRIADE series and DLR provides the IPDA lidar instrument (Fig. 3). Both share the development and exploitation of the ground segment. In analogy to former instrument concepts that have been successfully applied in airborne and ground-based measurements, a Nd:YAG-laser pumped OPO serves as a suitable MERLIN transmitter (Fig.4). This technical concept strongly benefits from ESA's laser development efforts within the FULAS (Future Laser System) project (Fig.5). Further heritage on the instrument readiness level is provided by NASA's CALIPSO mission that uses high average power Nd:YAG lasers as lidar transmitters to be operated in space during several years. This suggests that a mission lifetime for MERLIN of three years is feasible if a Nd:YAG laser is used for the OPO as the pump source.

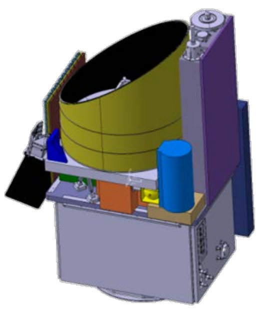

Fig. 3: View of future MERLIN satellite

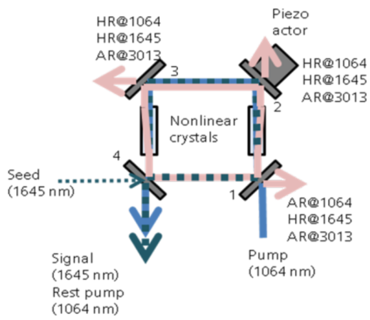

Fig. 4: View of OPO cavity for generation of the on-/off-line wavelengths.

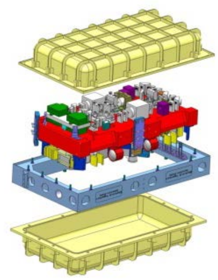

Fig. 5: View of ESA's FULAS development

5. Measurement Performance

In general, the MERLIN measurement performance in terms of random error strongly depends on the surface reflectivity and cloud coverage along the satellite flight track whereby both parameters can vary significantly. A suitable means to achieve more or less similar measurement precision everywhere on the globe is the method of signal averaging along the satellite flight track. In figure 6 the required horizontal integration length is plotted for a measurement precision of 1 %, as indicated by the color bar. The results show that in the case of the envisaged 1 % precision level, the spatial resolution of statistically independent MERLIN observations can be kept reasonably small (<50 km) for most regions over land. Over the ocean, the situation is more difficult because of the strong surface winds and

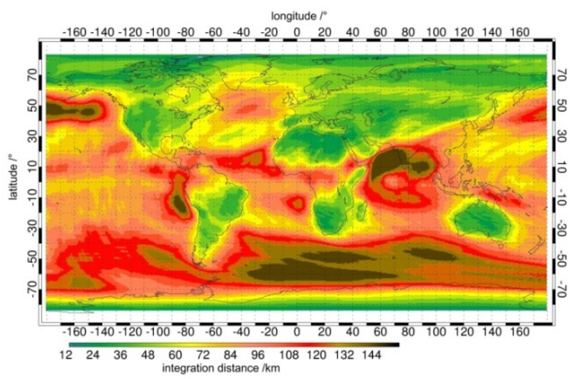

Fig. 6: Required along track integration distance in km (colour bar) required to achieve equal measurement precision of 1 % around the globe by MERLIN observations.

clouds, both of which impact unfavorably on MERLIN performance. This is also true over the tropics where cirrus clouds may require a larger averaging cell for the MERLIN observations. In figure 7, the improvement in knowledge of CH_4 surface fluxes by MERLIN observations is shown. This result was obtained by "inverse modelling" using the simulated precision field from hypothetical MERLIN observations indicated in figure 6. It is obvious that MERLIN observations will lead to a substantial (more than 50 %) reduction in the prior CH_4 flux errors in most regions of the globe on a monthly time scale, particularly over source regions of key importance to the global carbon cycle: arctic permafrost, boreal forests, tropical wetlands. The simulated precision fields have been obtained from calculation of the measurement error employing a 9mJ, 12 Hz (double-pulse) OPO transmitter, a receiver aperture opening of 70 cm in diameter, an APD as the detector module, and a satellite orbit height of ~500 km, which is the baseline instrument concept after Phase A.

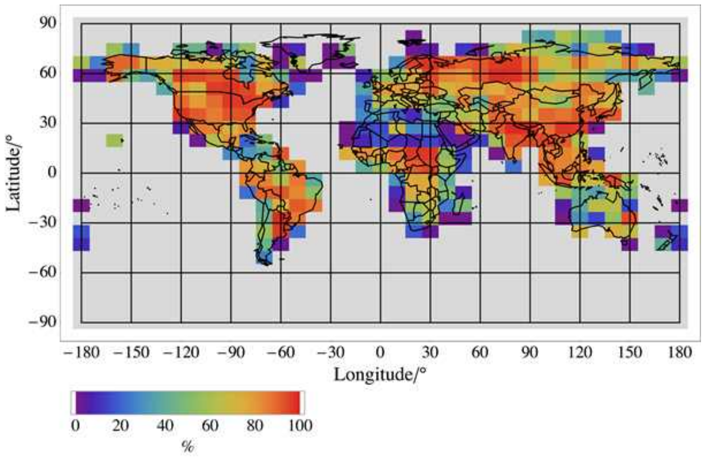

Fig 7: Relative error reduction (color bar) of monthly methane surface fluxes for July expressed by 1- $\sigma_{post}/\sigma_{pri}$ where σ_{pri}, σ_{post} correspond to the prior and posterior flux uncertainties, respectively. Credit: M. Heimann, MPI-BGC, Germany

6. Conclusion

After a successful Phase A study in 2011/12, the mission continued to Phase B in January 2013. The launch date is expected to be in the timeframe 2017. The MYRIADE Evolutions platform provides the resources for the OPO payload. No technical show stoppers were identified. The Lidar payload concept is suitable to fulfill the mission scientific objective. The development of key technology such as the laser transmitter and OPO benefits from supporting studies at DLR and ESA. An airborne MERLIN demonstrator (CHARM-F) is under development.

MERLIN is expected to be a significant step forward toward improvement of knowledge of CH_4 surface fluxes around the globe. On longer time scales, an active IPDA lidar mission for CO_2 may become feasible, whereby MERLIN is regarded as a valuable space-based demonstrator.

Acknowledgements

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