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METHANE MONITORING FROM SPACE

AN OVERVIEW ON THE MERLIN INSTRUMENT

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Abstract—**Methane is one of the strongest anthropogenic greenhouse gases. It contributes by its radiative forcing significantly to the global warming. For a better understanding of climate changes, it is necessary to apply precise space-based measurement techniques in order to obtain a global view on the complex processes that control the methane concentration in the atmosphere. The MERLIN mission is a joint French-German cooperation, on a micro satellite mission for space-based measurement of spatial and temporal gradients of atmospheric methane columns on a global scale. MERLIN will be the first Integrated Path Differential Absorption LIDAR for greenhouse gas monitoring from space. In contrast to passive methane missions, the LIDAR instrument allows measurements at all-latitudes, all-seasons and during night.**

Keywords—*LIDAR; laser; methane; micro satellite,*

I. INTRODUCTION

Methane (CH_4) is after carbon dioxide the strongest anthropogenic greenhouse gas [1]. The radiative forcing caused by methane contributes significantly to the warming of the atmosphere. A major problem in the understanding of CH_4 source- and sink-processes is the lack of precise global measurements of atmospheric CH_4. Ground based in-situ observations are insufficient because the existing measurement network is too coarse [2]. Source regions of key importance to the global CH_4 cycle such as the Arctic permafrost, Boreal forests and Tropical wetlands are difficult to access and hence underrepresented or not sampled at all. Therefore, it is necessary to apply space-based measurement techniques in order to obtain global coverage at high precision. Today, the Greenhouse Gases Observing Satellite (GOSAT) has the ability to measure CH_4 from space. Their observation strategy is based on measuring spectra of sunlight backscattered by the Earth's surface and atmosphere in the shortwave infrared spectral region. Main problem of these passive methods is that undetected aerosol layers or thin ice clouds produce systematic measurement errors of unknown magnitude, because of the complexity of the retrieval algorithms and the limited availability of independent measurements for validation [3]. To counter these limitations, the use of active remote sensing instruments like the integrated path differential absorption (IPDA) LIDAR, was proposed [4].

The MERLIN Mission is a joint French-German cooperation on the development and operation of a CH_4 monitoring satellite with a launch in the timeframe of 2016. The goal of MERLIN is to measure the spatial and temporal gradients of atmospheric CH_4 columns with high precision and unprecedented accuracy. MERLIN will be the first space-borne IPDA LIDAR for greenhouse gas monitoring. This paper focuses on the MERLIN instrument and its status after the completion of Phase A. For more details on the MERLIN mission please refer to [5] and [6]. Figure 1 shows how the future MERLIN satellite (in launch configuration: solar panel locked) might look like. In the lower part, the MYRIADE Evolutions platform can be seen. The main components of the MERLIN instrument: receiver telescope with baffle for thermal control (blue tube), transmitter telescope (small green tube), optical bench (black plate), laser (blue box on optical bench), energy calibration unit (red box next to laser), frequency reference unit (green box), laser electronics (gray box), instrument control unit (light green box), detection chain (red structure on the upper part of the optical bench) and radiator for thermal control (brown panels). Other components that can be seen in that figure are the star sensor (yellow cone next the radiator), and folded solar panel (large gray panel in the back).
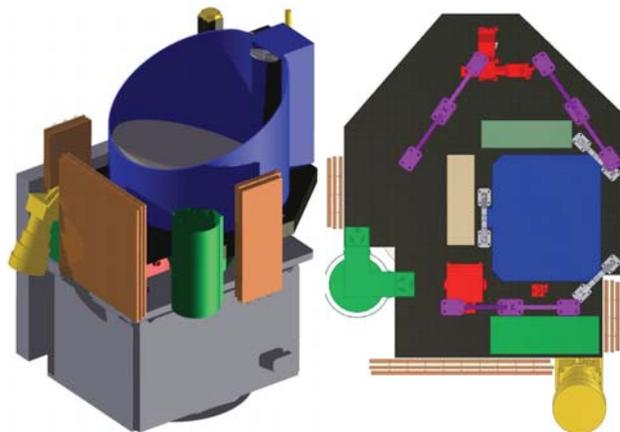

Fig.1. View on MERIN satellite in its present design status (left: side view, right: view on lower of the optical bench)

II. SCIENTIFIC BACKGROUND

A. IPDA Principle

An 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 scattering surface. For this, the difference in atmospheric transmission between a laser emission with a wavelength placed at or near the center of a CH_4 absorption line and a reference wavelength with significantly less absorption is used. 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. A detailed description of the measurement principle can be found in [7].

B. Main Data Product

The main data product of MERLIN will be column-weighted dry-air mixing ratios of CH_4, (XCH4) measured over the satellite sub-track:

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

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.

C. Scientific Requirements

TABLE I. SCIENTIFIC MISSION REQUIREMENTS

Parameter	Target	Breakthrough	Threshold
Data product	XCH_4		
Relative random error	8 ppb	18 ppb	36 ppb
Relative systematic error	1 ppb	2 ppb	3 ppb
Coverage	Global		
Horizontal resolution:	50 km		
Vertical resolution	Total column		
Accuracy of scattering surface elevation	10 m		

During the Phases 0 and A, scientific user requirements were formulated in order to provide a solid scientific basis for the mission. These requirements are based on the random and systematic error of the instrument. The MERLIN user requirements are shown in table I. The requirements were chosen in such a way that the following quality levels can be reached: to resolve large wetland fluxes, inter-hemisphere gradients, seasonal and annual budgets on continental scale (threshold), to resolve seasonal and annual budgets on country-scale (breakthrough), highest Methane flux estimate quality, and Kyoto protocol like monitoring (goal).
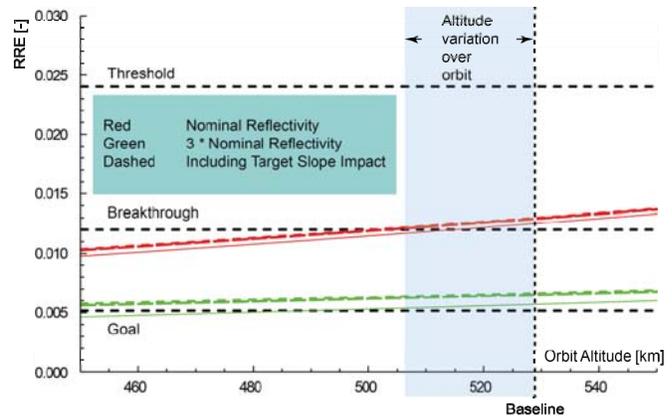

Fig.2. RRE as a function of the orbit height

During Phase A, parametric analyses were performed to check whether the mission can be compliant with the scientific requirements. The following geophysical assumptions were taken: Integration distance for a single column measurement: 50 km, nominal ground Albedo: 0.31 and worst case solar nadir angle: 58°. The assumptions for the instrument baseline parameters are: PRF of 12 Hz (double pulses), pulse energy of 9 mJ, telescope diameter of 690 mm, NEP of 60 fW/SqrHz. For the performance of the instrument the relative random error (RRE) is an important parameter and was therefore taken as quality measure in these analyses. The RRE of the DAOD is plotted as a function of the orbit height. As horizontal lines the threshold, breakthrough and goal requirements are included. The results in figure 2 show that for the MERLIN baseline orbit altitude of 506 km, the breakthrough requirements can be almost reached. Estimations show, that with some instrument improvements also the breakthrough requirements for the random error will be met in the future.
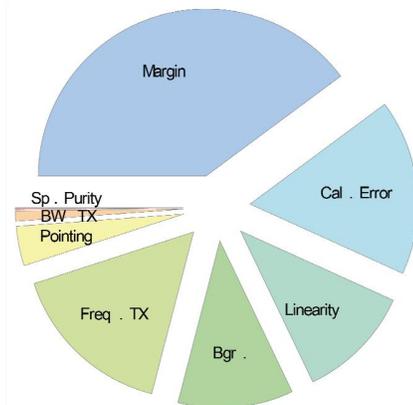

Fig.3. RSE contributions

Aside from the RRE, also the relative systematic error (RSE) has influence on the instrument performance and was therefore specified in the user requirements. The RSE requirement in the URD 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 its 50 km resolution cell. Figure 3 shows the relative magnitude (linear representation) of predicted RSE of DAOD error components in relation to margin with respect to the threshold requirement. As can be seen there, especially laser stability, accuracy of the calibration devices and detector linearity are of great importance

III. MERLIN INSTRUMENT

The MERLIN mission concept foresees the use of the CNES MYRIADE Evolutions micro satellite platform [8]. This platform provides a payload allocated power of about 110 W (during eclipse phase) and can carry a payload with a maximum mass of about 95 kg. From these values one can see, that one of the main technical challenges of the MERLIN mission is to implement the complex LIDAR instrument on such a micro satellite platform with very limited resources. The main parameters of the MERLIN instrument are summarized in table II.

TABLE II. INTRUMENT PARAMETERS

Parameter	Value
Power Consumption [W]	108
Weight [kg]	93
Telescope diameter [mm]	690
Dimensions [mm^3]	820x880x920

Aside from these platform constraints, the main driver for the instrument design is the necessity to reach the scientific requirements. The RRE is mainly driven by orbit altitude, size of the receiver telescope and available laser pulse energy. The minimal orbit altitude is limited by the platform (due to atomic oxygen constraints), maximum telescope size due to volume allocations of the launcher and the pulse energy due to power allocations by the platform. Aside from the random error, also RSE has to be taken into account. This error depends mainly on the accuracy and stability of the energy calibration, stability and knowledge of the laser frequency, stability and knowledge of pointing and detector linearity.

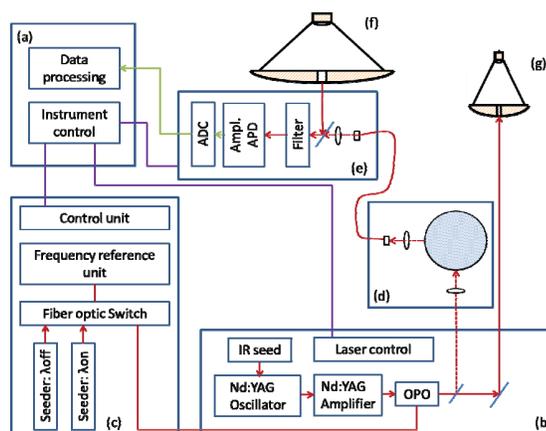Figure 4 shows the basic scheme of the MERLIN instrument with its main subsystems.

Fig.4. Instrument setup: (a) instrument control unit, (b) laser, (c) frequency reference, (d) energy calibration, (e) receiver, (f) Rx telescope, (g) Tx optics

Due to power, mass and volume limitations, no redundancy for complete subsystems are foreseen in MERLIN. In order to reach the required mission duration of 3 years, a careful design and the avoidance of critical components is necessary. In the laser for example, the pump modules for oscillator and amplifier will be redundant.

A. Laser

TABLE III. LASER PARAMETERS

Parameter	Value
On-line λ [nm]	1645.552
Off-line λ [nm]	1645.846
Pulse Energy [mJ]	9
Repetition Rate (for double pulses) [Hz]	12
Pulse Length [ns]	20 - 30
Power consumption[W]	57
Weight (incl. electronics & harness) [kg]	32.5

As experiences and problems in other missions like EarthCARE (Earth Clouds, Aerosols and Radiation Explorer) and ADM-Aeolus (Atmospheric Dynamics Mission) demonstrate the design and realization of space-based lasers is sophisticated and involves several risks which have to be taken into account. These risks are mainly contributed to stable operation under space conditions and lifetime aspects of components. In contrast to the ALADIN instrument (Atmospheric Laser Doppler LIDAR Instrument) of the ADM-Aeolus mission, the laser used for the MERLIN mission is not a completely new development but deduced from the ESA EQM FULAS (Future Laser System) which is currently under construction. The main parameters of the current MERLIN laser are shown in table III.

The first step in the laser design was the selection of the appropriate measurement wavelength which depends mainly on these factors: CH_4 absorption bands, detector efficiency and eye safety considerations. In the short-wave infrared where eye safety is less critical, CH_4 lines are abundant, but the presence of water vapor and carbon dioxide lines drastically constrains the selection. Essentially two atmospheric water vapor transmission windows around 1600 and 2300 nm allow CH_4 measurements. Detector performance is significantly better in the 1600 nm region where low-noise photodiodes (InGaAs APDs) are available. Since no direct pumped laser at this wavelength is available up till now, or its technology level is too low, a laser concept based on a Nd:YAG pumped optical parametric oscillator (OPO) was selected.

The pump laser will consist of a seeded oscillator followed by a single-end pumped slab amplifier. The oscillator design includes an end-pumped rod-crystal as gain medium. The oscillator will be injection seeded and cavity controlled in order to achieve single longitudinal mode operation and to fulfill the stringent requirements on the pulse quality. For the amplifier, the so called InnoSlab concept, developed by the Fraunhofer Institute for Laser Technology, will be used. This concept (left part of fig. 5) is ideal for high energy and high efficiency power amplifiers for single mode operation. For MERLIN, the slab crystal is partially end pumped from one end. This gives the advantage that only two faces of the crystal need to be

optically polished. The heat dissipates very efficiently and homogeneously over 2 metal heat sinks soldered to the large faces of the crystal. The four optically unused surfaces of the crystal are roughened to optimally prevent internal parasitic laser oscillations. To operate the InnoSlab laser as an amplifier (right part of fig. 5) the signal beam is folded in a single pass configuration through the crystal. By choosing appropriate mirror radii and signal beam divergence the beam is widened with every pass, the fluence can be kept constant and remains far away from the damage threshold. By adapting the slab crystal width and the number of passes the InnoSlab amplifier is scalable in its output power. The MERLIN amplifier will be designed to deliver an output pulse energy of about 30 mJ at 1064 nm while the peak fluence will be smaller than 2.5 J/cm^2. Simulations showed that this output energy is the best compromise between strain of the pump modules and efficiency of the pumped OPO.
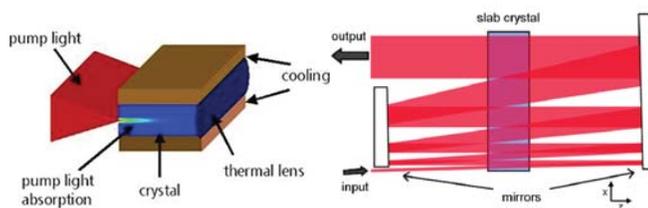

Fig.5. Left: InnoSlab concept; right: amplifier beam path

Baseline for the OPO is a 4-mirror 2-crystal setup. The same setup is also implemented in the DLR airborne demonstrator for the DLR Jet HALO [9]. Crystal material will be either KTA or KTP. Like the oscillator, the OPO will be injection seeded and cavity controlled in order to achieve single longitudinal mode operation. Tests with the CHARM-F setup and preliminary calculations in Phase A demonstrated that with this setup the required pulse energy of 9 mJ can be reached with a pump energy of 30 mJ at acceptable fluence.

In order to realize an efficient and compact space-borne laser, new mounting technologies like soldered optics will be applied. This allows a compact, precise, stable and glue free mounting of the optical laser components. These mounts are currently developed within a DLR funded research project. It was possible to design and build solder based mounts for all optical elements within the laser. Temperature cycling tests of soldered mirrors were performed. Results demonstrate that for critical components like mirror mounts the tilt deviation at the operation temperature of 20°C is kept better than 10 μrad.

The use of a pressurized and hermetically sealed housing is mandatory to meet the overall system requirements. An air relief during transfer and operational phase in orbit has to be avoided as a high power laser system needs stringently an air environment for reliable operation to avoid unacceptable degradation up to system failure. Therefore, a sealed metallic housing is necessary including all electrical, optical and thermal feed through necessary for operation. Due to mass budget limitations and thermal requirements the pressurized housing for the MERLIN laser is made out of aluminium alloy. But hermetical electrical feedthroughs, meeting the sealing, material and reliability requirements of such a laser system, are

commercially available with stainless steel or titanium bodies only. This material pairings are not conventionally weldable and the use of glues is not allowed because of the contamination and outgassing requirements. Therefore, the sealing concept between the feedthroughs and the aluminium frame is one of the most difficult tasks for the design and manufacturing of the housing. As the most promising joining process to meet the ambitious requirements, Friction Stir Welding, had been identified. Here, the participated materials are not completely melted but only plasticized. Therefore, this process can be used for dissimilar material connections. Currently, a prequalification program for this process within the FULAS Project has been started.

Figure 6 shows the MERLIN pressurized Laser housing which includes the whole laser head. The laser itself will be mounted on the laserplate. To use the available space as efficient as possible, the oscillator will be mounted on the top side of the laserplate while the amplifier and OPO are mounted on the down-side. The laserplate will be fixed at three points with isostatic mounts to a frame. The housing will be fixed only to the frame. Consequently, the vacuum forces are decoupled from the laserplate itself. Heat generating units will be decoupled thermally from the baseplate and the generated heat will be piped out of the laser housing by mini loop heat pipes.
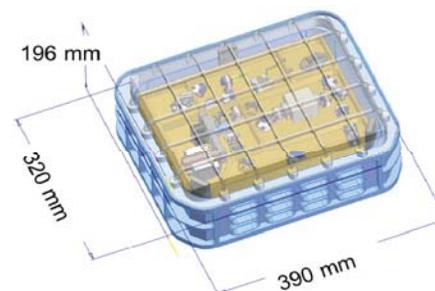

Fig.6. MERLIN laser housing

B. Calibration Devices

High laser stability and the actual knowledge of the laser frequency are crucial for this kind of instrument and therefore a compact and precise frequency reference is necessary. To minimize the required amount of instrument equipment, it is highly desirable to use the frequency reference not only for absolute frequency monitoring, but also to generate error signals for control of the OPO and the seed lasers. The current approach for MERLIN is to use an air spaced Fizeau interferometer and a CCD-row for fringe measurements. Preliminary studies show that for the maximum rms deviation of the seed frequencies from their required absolute values the following values must be reached: the on-line signal must provide an absolute stability of approx. 15 MHz rms over lifetime while the off-line signal must provide an absolute stability of approx. 100 MHz rms over lifetime. Phase A investigations showed that these values can be achieved with the Fizeau setup. Furthermore, the results indicate that a calibration on ground before launch and a good control of the operating parameters (mainly temperature of the Fizeau) is sufficient in order to guarantee the required long-term stability of the setup. A verification and also calibration is possible by

ground echo calibration (determination of the spectral CH_4 line center from scanning its spectral line shape).

An IPDA LIDAR is solely relying on the measurement of relative signal intensities. The intensity of the recorded return signal is a direct function of the emitted laser pulse energy. Even for very good lasers, this variation is in the area of up to 5%. Therefore it is necessary to monitor the energy of each emitted laser pulse with high accuracy and to correlate with the intensity of the corresponding optical return signals (see eq. 1). By these means it is possible to compensate pulse energy variations measurement on a pulse to pulse basis. In order to generate these internal calibration signals, a small fraction of the emitted laser pulses is extracted and fed directly through an attenuation stage to the instrument detector. Measuring the return and calibration signal with the same detector ensures that variations within the signal chain are eliminated. The challenge here is that because of the very weak return signal (for λ_{on} ~1000 photons per shot) the reference signal has to be attenuated by about 14 orders of magnitude. First breadboard activities demonstrated that this can be reached by a combination of integrating spheres and optical fibers for attenuation and removal of local hot spots in the laser pulse profile. This attenuation has to be stable over the whole operation period so that the signal is always within the dynamic range of the signal chain.

C. Receiver

Aside from the laser, the receiver telescope is the most challenging component of MERLIN. Its field of view has to be large enough so that the complete laser ground spot (150 m for 99% encircled energy) and additional margin for satellite and laser jitter is within this field. The other limiting factor is the size of the detector. For APDs, the noise is increasing drastically with detector area which means that a detector with a small active area has to be chosen. Furthermore, the overall height of the telescope is strongly limited due to the available space within the launcher fairing (MERLIN baseline: Soyuz ASAP-S inner position). These factors results in a small F-number and thus a complex optical design. Aside from the size, also the weight is a very critical value. To realize such a telescope, serious light-weighting of about 85% has to be applied. Furthermore, the thermal design of the telescope has to be in such a way, that a purely passive thermal control system is sufficient since no extra power for heating is available. Current baseline for MERLIN is a Zerodur off-axis telescope with an aperture of 690 mm and an F-number of 0.65, mounted on an optical bench made of CFRP.

Due to the limited pulse energy and telescope size, the receiver and detector noise are both critical. The detector and the following amplifier stages have to be as noiseless as possible. In the 1650 nm region, InGaAs Avalanche Photodiodes seem to be the most promising candidates and are currently the baseline for MERLIN. Also MCT detectors are very interesting. They may offer some interesting features which could be interesting for low light level detection around 1.65 μm due to their low excess noise.

D. Instrument Control Unit

The Instrument control unit (ICU) is the main control instance for the whole instrument. Its main tasks include: scheduling of the laser trigger, control of the APD sensor data acquisition and buffering, detector temperature control, payload FDIR (fault-detection, fault-isolation and recovery), telecommand decoding and execution and calculation of the range gate according to the altitude data received from the platform.

IV. SUMMARY

At the end of Phase A, the performed studies demonstrate that it is feasible to operate a complex IPDA LIDAR instrument on a micro satellite platform. Special care has to be taken in the design of the whole system since for space-borne measurements very low values for random and systematic errors are necessary in order to reach the scientific requirements. Simulations during Phase A demonstrated that MERLIN can reach the scientific threshold requirements.

ACKNOWLEDGEMENT

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