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MERLIN: AN INTEGRATED PATH DIFFERENTIAL ABSORPTION (IPDA) LIDAR FOR GLOBAL METHANE REMOTE SENSING

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I. INTRODUCTION

The Methane Remote Sensing LIDAR Mission (MERLIN) is a joint French-German cooperation on the development, launch and operation of a climate monitoring satellite, executed by the French Space Agency CNES and the German Space Administration DLR. It was initiated in February 2010 when the Franco-German Council of Ministers decided to start a microsatellite focused on global measurements of the spatial and temporal gradients of atmospheric Methane (CH_4) with a precision and accuracy sufficient to constrain Methane fluxes significantly better than with the current observation network [1]. A better knowledge about the spatial and temporal pattern of the CH_4 sources and sinks as derived from MERLIN observations in combination with the existing and forthcoming surface network will provide urgently needed process information about the global methane cycle. In particular, it will help constraining three key regions: Arctic, Eurasia, and the Tropics where emissions are large and yet poorly quantified by present observations.

The satellite will be developed and operated by both countries in a joint partnership. Germany will contribute the payload, an Integrated Path Differential Absorption (IPDA) LIDAR for Methane column density measurements, based on a long-time German heritage with airborne greenhouse gas LIDAR systems and on up-to-date innovative concepts of pulsed high power laser systems for space application. France will contribute a modified version of its proven small satellite bus (MYRIADE Evolutions), the launcher, and will operate the satellite. Joint data processing and science activities in France and Germany will be established, science activities are led by two Co-Principle Investigators (PIs) from the French Laboratoire des Sciences du Climat et de l'Environnement from CNRS and the German Institute for Atmospheric Physics (IPA) from DLR, with additional support of several French and German Research Institutes [2].

Airbus Defence & Space has been selected by the German Space Administration (DLR) as the prime contractor for the Mission Phases B, C/D, to design, develop, and manufacture the MERLIN payload, a LIDAR Instrument using the Integrated Path Differential Absorption (IPDA) principle. It relies on the different absorption at two laser wavelengths – on-line and off-line – both around 1.645 µm, reflected by the Earth's surface or by cloud tops. The attenuation due to atmospheric Methane absorption is strong at the on-line wavelength; the off-line "reference" wavelength is selected to be only marginally affected by Methane absorption. Being an active instrument with its own light source, the MERLIN LIDAR Instrument does not have to rely on sun illumination of the observed areas and can therefore continuously operate over the orbit.

II. BACKGROUND

Being the strongest anthropogenic greenhouse gas after carbon dioxide (CO_2), Methane (CH_4) significantly contributes to the warming of the Earth's atmosphere, while the detailed processes of this contribution are still not fully understood [3]. 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. 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 underrepresented [4].

Therefore, it is necessary to apply space-based measurement techniques in order to obtain global coverage at a high precision. Currently, following the sudden loss of the European climate satellite ENVISAT in April 2012, the Japanese Greenhouse Gases Observing Satellite (GOSAT), already launched in 2009, is the main source of CH_4 measurements from space. Its observation strategy is based on measuring spectra of sunlight backscattered by the Earth's surface and atmosphere in the shortwave infrared spectral region. The main problem of these *passive* methods is that they are limited to daylight observations and 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.

These limitations can be overcome by the use of an *active* LIDAR (Light Detection and Ranging) instrument as satellite payload, because it uses its own onboard laser transmitter as light source. Such an instrument can be operated even during the night and it provides reliable measurement data even through thin cirrus cloud layers. The Integrated Path Differential Absorption (IPDA) principle uses the laser light scattered back from the Earth's 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 (λ_{on}) and a reference wavelength (λ_{off}) 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.

For the MERLIN instrument, the online wavelength λ_{on} is accurately positioned in the trough of one of the CH_4 absorption line multiplets in the 1.64 µm region, in order to dramatically relax the required laser frequency stability/knowledge. The on- and off wavelengths are spectrally close enough to consider the atmospheric and surface properties to be identical with the exception of the CH_4 absorption. From the ratio of the LIDAR echoes P_{on}/P_{off} (as mean values) the differential optical depth and with that the column averaged CH_4 volume mixing ratio are calculated. From analyzing the waveform of the backscattered pulses, information on the vegetation height with respect to the ground, clouds, and strong aerosol layers can be derived with high vertical resolution.

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

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

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 (p,T) is the weighting function describing the altitude sensitivity of XCH_4.

III. MERLIN MISSION REQUIREMENTS

The main goal of the MERLIN Mission is the improvement of the understanding of the Global Methane Cycle and the exploration of the nature of the processes which govern the exchange of methane between atmosphere and biosphere. Space-borne observations of the spatial and temporal variability of atmospheric CH_4 will be performed by this mission with high accuracy, which permits a better quantification of the regional sources, as presently is the case, by use of the current observational network. Moreover, the data are expected to serve as an estimate of the anthropogenic Methane emissions for control of emission inventories and international agreements (Kyoto protocol and follow-up). Observations in connection with model activities and the soil network are to be used to improve terrestrial biosphere models and trend analyses.

The nadir viewing LIDAR instrument measures the reflected signals from ground along the track in a quasi-continuous operation mode. The distance between successive on-/off-line laser pulses is a few 100 meters and depends on the pulse-pair repetition frequency. Because of the small footprint of the laser beam on ground which is in the order of 100 m, large gaps remain between successive orbits, especially in the tropics. Nevertheless, the envisaged sun-synchronous polar orbit permits 15-16 orbits per day and thus providing measurements around the globe. The latter is based on the fact that the MERLIN instrument can measure at all latitudes at day and night time conditions. With appropriate model activities the MERLIN measurements will therefore provide information on a global basis.

An important aspect in the mission design is the orbit selection. For MERLIN, a near-polar sun-synchronous orbit (SSO) with an orbit height of about 500 km, a Local Time Ascending Node (LTAN) of 06:00h or 18:00h and a repeat cycle of about 28 days is foreseen. One main scientific requirement for the MERLIN mission is to get measurements on a global scale. The selection of a near-polar sun-synchronous orbit ensures that measurements at high latitudes are possible since in these regions areas of special interest such as the Arctic permafrost regions are located.

For an efficient LIDAR performance, the orbit should be as low as possible in order to get a return signal with an appropriate signal-to-noise ratio. The lower limit here is set by the platform and its qualification status since in low altitudes atomic oxygen and atmospheric drag are an issue. The LTAN selection is mainly based on satellite power issues. Per revolution, the eclipse duration is reduced as far as possible in order to guaranty that the satellite solar generator can produce enough power around the year so that the instrument can be operated continuously. In addition, in order to increase the probability to find a co-passenger, two LTAN are analyzed: 06:00h and 18:00h, with a preference for 06:00h due to power reasons.

The repeat cycle determines on one hand the spacing between two subsequent revolutions and on the other hand the re-visit time on certain areas on the globe. With a repeat cycle of 28 days, the spacing between two subsequent re-visits is about 100 km at the Equator. For shorter repeat cycles, this spacing becomes larger and thus also the measurement density coarser. The re-visit time mainly affects the on ground based validation site overflies. During the mission it will be necessary to validate the MERLIN data on a regular basis with ground based and airborne measurements.

The geophysical parameter XCH_4 will be the primary data product which is needed by the users for flux inversion calculations. The following Tab.1 lists the scientific driving parameters which need to be fulfilled to guarantee a substantial reduction in the present-day flux uncertainty by the MERLIN observations. The required measurement precision for the XCH_4 data product results from synthetic model simulations for the determination of the relationship between the CH_4 flux accuracy for a given measurement precision and measurement density.

Tab.1: Measurement precision requirements for the XCH_4 data product

Parameter	Threshold	Breakthrough	Target
Random Error	36 ppb	18 ppb	8 ppb
Systematic Error	3 ppb	2 ppb	1 ppb
Horizontal Resolution	50 km	50 km	50 km

The threshold values refer to an improvement factor of > 5 with respect to the present-day knowledge of the annual CH_4 fluxes for the key observational regions. The error margins of the posterior flux uncertainties are expressed as the one sigma error for the altitude independent measurement sensitivity to a CH_4 molecule. For the alternative pressure-dependent measurement sensitivity the corresponding measurement precision shall be scaled using the relationship between surface sensitivity and pressure weighting function. The random error for the threshold requirement expresses the need to resolve spatially integrated permafrost hot spots on regional scale as well as moderate boreal and tropical wetland fluxes.

The requirement for a very small systematic error is based on the fact that even a small measurement bias which varies from region to region could substantially impact on the result of the retrieved methane sources using the inverse modelling approach. As a result, the collective constraint of the measurements on the fluxes can only be effective if the individual measurements contribute largely independent pieces of information. Therefore, the MERLIN mission calls for almost non-biased observations of the methane columns where the level of systematic error (bias) should be substantially below that of the precision. A global constant bias has no impact, as only the gradients are linked to the sources and sinks.

The 50 km horizontal resolution of the XCH_4 data product corresponds to the spatial resolution of CH_4 sources and sink estimation through inverse modelling that will be feasible when the mission is in operation. Even if for small study domains, higher resolutions of the transport model will be used, the MERLIN mission targets on ranges from regional (e.g. several million square kilometers) to global. With respect to the vertical resolution, a weighting function must be selected which has a strong contribution in the PBL (Planetary Boundary Layer) total column measurements on order to achieve the required measurement sensitivity near the ground where the methane sources reside.

IV. MERLIN SPACE SEGMENT

A. Platform

The MERLIN mission will be executed using the last generation of the MYRIADE Evolutions platform, a program directly funded by the French government and managed by CNES, specifically aiming for the development and qualification of a platform product line suited for governmental and commercial use. The in-flight qualification of this new platform will be demonstrated through the MERLIN mission. Since 2010, the beginning of the program, MERLIN and MYRIADE Evolutions are being developed in parallel with a high level of interaction on programmatic and technical aspects. The MYRIADE Evolutions platform is designed to meet the MERLIN needs, but also other future commercial missions.

While earlier versions of the MYRIADE (Evolutions) platform were designed as a micro-satellite, compatible with the SOYUZ ASAP external position, that can only accommodate satellites weighting up to 250 kg, the latest version of the MYRIADE Evolutions platform, to be used for the MERLIN mission, is designed to be compatible with the SOYUZ internal position, accepting a satellite up to 400 kg in total. The main satellite characteristics are summarized in the following Tab.2.

Tab.2: Main satellite characteristics of the MYRIADE Evolutions platform

Parameter	Unit	MYRIADE Evolutions
Satellite Mass	kg	400
Satellite Power	W	416
Platform Volume	mm^3	570 × 940 × 940
Mission Data	MBits/s	160
Mass Memory Data	GBits	512

The MERLIN satellite is supposed to be launched as secondary passenger along with other satellites. The limitations of the envelope, especially in launch direction, have direct influence on the identification of compatible launchers and launch opportunities. As design baseline, the envelope requirement asks for compliance with the SOYUZ ASAP internal position, accommodating a 400 kg satellite as secondary passenger.

B. Payload

The MERLIN payload is a LIDAR instrument using the Integrated Path Differential Absorption (IPDA) principle. It relies on the different absorption at two laser wavelengths – on-line and off-line – both around 1.645 μm, reflected by the Earth's surface or by cloud tops. The attenuation due to atmospheric Methane absorption is strong at the on-line wavelength; the off-line "reference" wavelength is selected to be only marginally affected by Methane absorption. The main instrument parameters are summarized in the following Tab.3.

Tab.3: Main characteristics of the MERLIN IPDA LIDAR instrument

Parameter	Unit	Value
Online Wavelength	nm	1645.552
Offline Wavelength	nm	1645.846
Pulse Energy	mJ	9
Pulse Length	ns	20 - 30
Repetition Rate	Hz	12 (for double pulses)

The accommodation of the preliminary design of the MERLIN payload on the MYRIADE Evolutions platform is illustrated in the following Fig. 1. Similar to other LIDAR instruments under development (e.g. for EarthCARE), the MERLIN instrument uses two separate telescopes for the transmission (Tx) and reception (Rx) of the laser pulses. Both telescopes are mounted on the same optical bench, which accommodates also the laser transmitter, the detection unit as well as two star trackers for verification and control of the pointing. The main structural element of the payload is the optical bench, made of CFRP and designed for maximum stiffness and lowest CTE. Primary and secondary mirrors of both Tx and Rx telescopes are made of Zerodur. The aim of the optical bench is to ensure a proper operational alignment of the two telescopes with the start tracker, and to decouple thermally and thermo-elastically the payload from platform for greater stability.

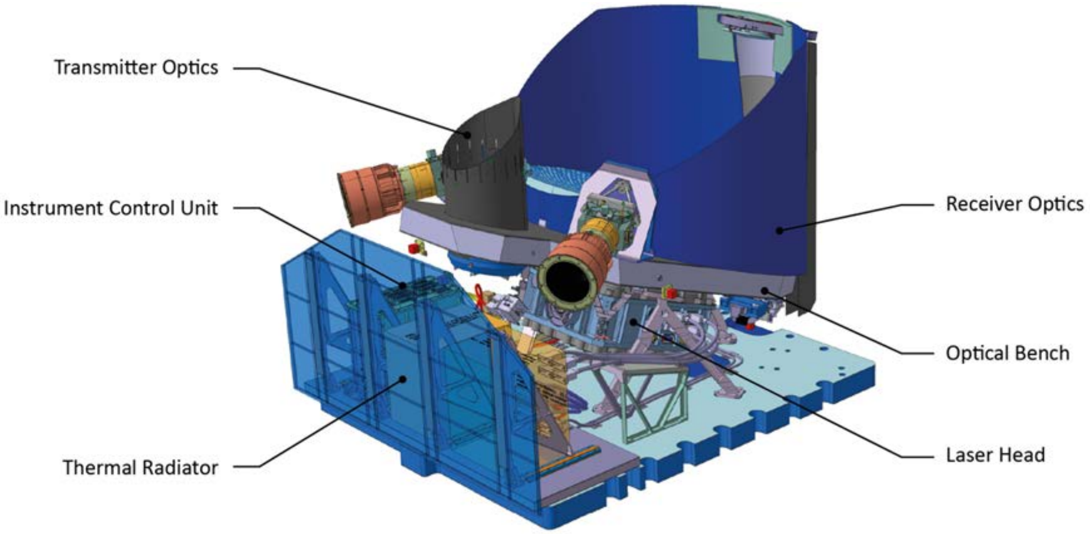

Fig.1: MERLIN payload accommodation

The Rx telescope is an afocal design consisting of two conical mirrors and an achromatised collimator lens, which generates an image of the entrance pupil on the detector. The main design driver for the telescope has been the compact envelope, especially in launch direction, required by the SOYUZ ASAP internal position. The telescope together with the collimating lens group has been designed for 1.645 µm and 633 nm, in order to allow the alignment in the visible wavelength range. The Rx telescope tower consists of a stiff sandwich with CFRP skins. It is directly connected to the optical bench via dedicated bonded brackets. The shape is determined as the best compromise between stiffness, thermo-elastic performance and ease of manufacturing. The baffle of the telescope is a thin structure out of a light material, e.g., a CFRP laminate. While no stringent requirements on the eigenfrequency of this structure apply, due to the limited mass, stiffening rings are planned to keep a correct shape and avoid strength issues e.g. during acoustic tests. As the optical system is relatively insensitive to straylight, the baffle has mainly a thermal function.

The receiver chain clearly dominates the design of the payload, due to the larger complexity and physical dimensions. Most of the work has been therefore focused on the Rx path, in order to identify critical aspects in terms of feasibility or system performance. Nevertheless, the Tx telescope cannot be neglected. It consists of a separate structure with the primary mirror; a CFRP baffle is used as the structural element and supports the secondary mirror. In this way, the baffle provides the spacer function between the mirrors and no additional structures are used, with positive effects on the resulting total mass. The CFRP baffle and the primary mirror are supported by an Invar ring-shaped component that is directly connected to the optical bench. The Invar ring lends interfaces for the mounting of an Active Pointing Control mechanism, which folds the beam from the laser to the Tx mirror. Similar to what is done for the receiver chain, the CFRP baffle supports a slanted cut in order to avoid sun illumination into the telescope during nominal operation.

The functional MERLIN payload architecture is illustrated in Fig.2 and consists of three main functional parts: The receiver chain, including the receiver (Rx) telescope, internal power calibration and the detection unit, the transmitter chain, including the transmitter (Tx) telescope, the laser head and laser electronics, the frequency reference unit, and the instrument control unit (ICU).

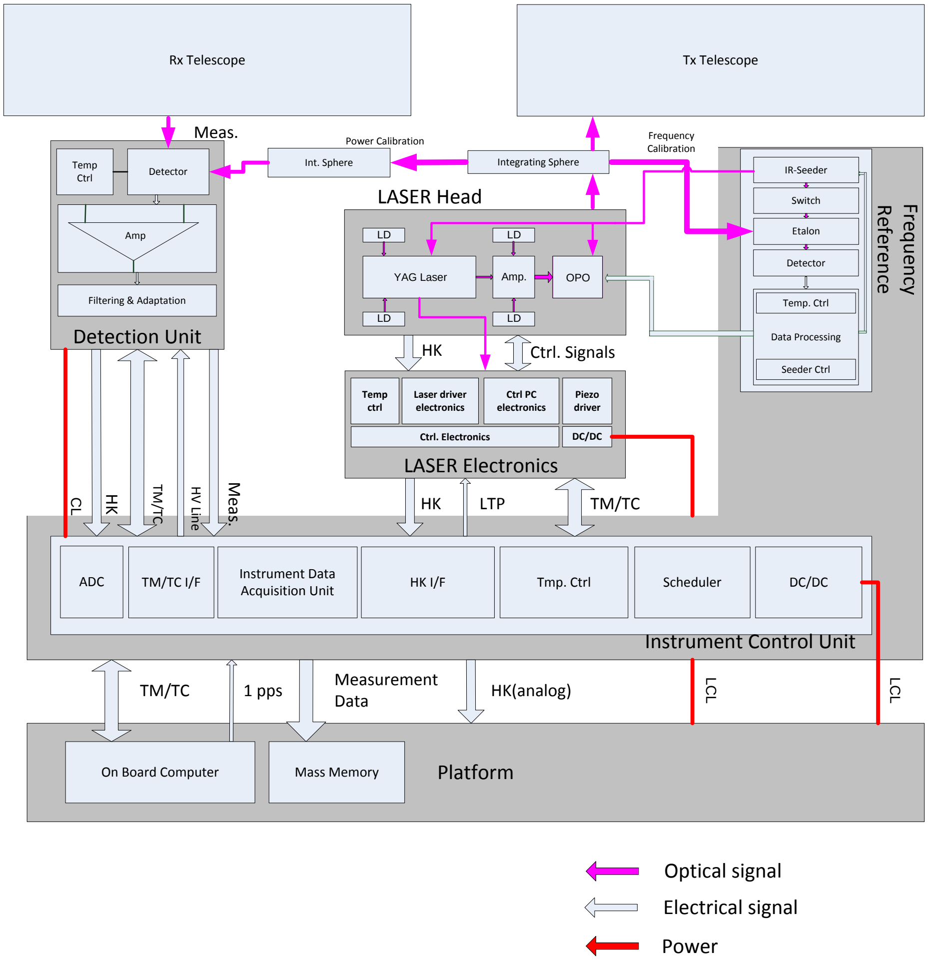

Fig.2: MERLIN functional payload architecture

The Instrument Control Unit (ICU) is the sole command interface between the platform and the payload. It provides the command interface and the science data interface. The command interface will be used to receive commands and to send telemetry, the science data interface will be used to provide the measurement data and all ancillary data, which is required for the on-ground post-processing of the measurement data (e.g. timestamps, signal energy data, detector temperature, etc.).

The laser concept is based on a two stage concept comprising a single frequency high power Nd:YAG master oscillator power amplifier (MOPA) stage which generates ns pulses at a wavelength of 1064 nm (see Fig.3). The temporal, spectral and geometrical properties of the pump beam at 1064 nm are generated in a low power frequency stabilized oscillator. This beam is amplified in the subsequent amplifier stage which optimally only increases the pulse energy without changing the other properties. The output is then converted into the final wavelength of 1645 nm in a second stage using a nonlinear converter. The most established technology for the conversion is an optical parametrical oscillator (OPO). This architecture has been demonstrated by different groups in various flight campaigns.

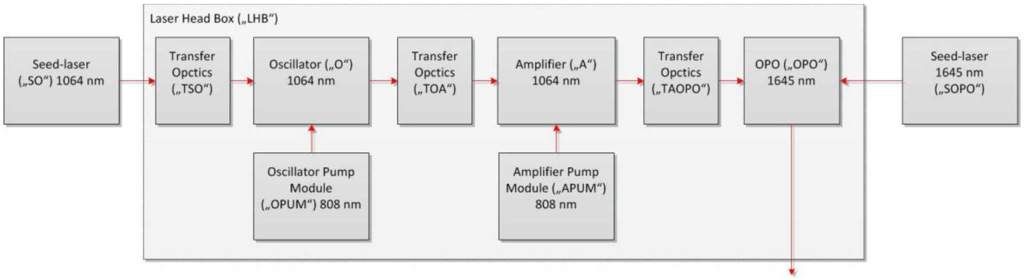

Fig.3: MERLIN laser concept

The frequency reference provides a seed to the various laser frequencies and ensures the correct wavelength of the outgoing pulses. It provides a 1064 nm seed laser to give preference to a defined harmonic of the pulsed 1064 nm laser and to be able to control the 1064 nm cavity in a continuous closed loop manner. Also, the frequency reference provides the seeds for λ_{on} and λ_{off} to the OPO. The additional task of the frequency reference is to measure the outgoing pulses with respect to the desired wavelength and to provide the error signal for control of the OPO to precisely match λ_{on}. λ_{off} is of less importance, but is chosen to also be in resonance with the optical path length of the OPO as tuned for λ_{on}.

The practical realization of the MERLIN laser transmitter is based on the results of the FULAS (FUtureLASer) project that has been initiated by ESA, in cooperation with DLR, to develop and built a technology demonstrator and to verify its suitability for potential space missions [5]. In order to cover the common need of possible future LIDAR missions, requirements for a generic laser source had been defined to achieve maximum usability of the laser concept and technology for future LIDAR missions.

FULAS is built as a pressurized and hermetically sealed housing with an isostatic mounting I/F for accommodation. As shown in Fig.4, the housing central main frame provides several hermetical feedthroughs for electrical and optical connectors, thermal-hydraulic feedthroughs for miniature loop heat pipes (LHP) and a beam exit window. An external cold plate attached to the central frame of the housing serves as condenser for the LHPs and as overall system thermal I/F. The mounting of the laser optical bench is optimized for decoupling from the surrounding structure. By isostatic mounting inside the housing central frame, the optical bench is insulated from stress induced by the instrument environment. Particularly it features a maximum tolerance with respect to mechanical deformation due to environmental pressure changes.

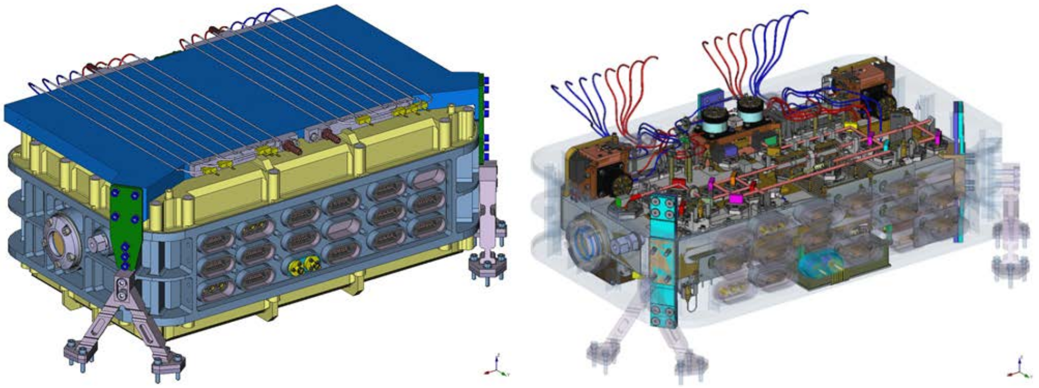

Fig.4: FULAS pressurized housing with top-mounted cold plate and internal optical bench

Due to the need of a lightweight design while providing the thermal conductivity to support thermal balancing, Aluminium was the material of choice for the housing. To provide access to both sides of the double sided optical bench, a symmetrical open frame is used, carrying the optical bench. This frame is closed by two symmetrical bolted covers, primary-sealed by special metallic gaskets, enabling easy reopening and resealing during assembly and testing. For final life-time sealing, the covers are designed to be welded, providing a reliable redundant secondary sealing.

The challenging part of the design is the need of a multitude of various feedthroughs (electrical, thermal and fibre-optical) to operate such a system, as well as a high quality optical beam exit window. To fulfil the cleanliness and lifetime requirements, only thermal joining methods as welding, brazing or glass/ceramic potting are applicable. For brittle materials like glass a CTE-matched joint is necessary, which typically leads to low CTE metals like Stainless Steel or Titanium, not compatible with an Aluminium housing and conventional joining technology. However, the applied mechanical friction stir welding (FSW) process, developed by the Airbus Group in the frame of the FULAS project, overcomes this incompatibility of the materials.

To allow an efficient rejection of the thermal load inside the pressurized housing and minimize thermal gradients across the optical bench, mini Loop Heat Pipes (LHP) are directly attached to units inside the laser housing. Four pairs, each operated in one-out-of-two cold-redundancy configuration, are connected with their evaporators directly to the main heat sources on the optical bench, enabling selective cooling directly at the source. By its semi-rigid tubing combined with dedicated housing feedthroughs, the heat is efficiently transported out of the housing towards the external cold plate. Due to the low mechanical stiffness of the tubes the optical alignment and the mechanical decoupling of the optical bench is conserved and not affected by the thermal I/F.

The laser optical bench is mounted inside the pressurized housing central frame by use of isostatic mounts. The laser is assembled on both sides of the bench, as shown in Fig.4. The lower side carrying the oscillator, while the power amplifier and the frequency conversion is situated at the upper side. 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 specially designed mounts have been developed within a DLR funded research project.

V. OUTLOOK

The joint (satellite and payload) MERLIN project has successfully passed the Satellite Preliminary Design Review (SL-PDR) in 2015 and the Payload Preliminary Design Review (PL-PDR) in 2016, performed in cooperation by CNES and DLR during the Phase B, and is currently preparing the start of the Phase C/D activities. The next milestones for the Space Segment will be the Payload Critical Design Review (PL-CDR) in Spring 2018 and the Satellite Critical Design Review (SL-CDR) in Autumn 2018.

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