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THE ABSOLUTE FREQUENCY REFERENCE UNIT FOR THE METHANE-SENSING LIDAR MISSION MERLIN

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I. INTRODUCTION

The French-German Methane Remote Sensing LIDAR Mission (MERLIN) planned for launch in 2020 aims to provide a global methane concentration map. The instrument is a differential absorption LIDAR (DIAL) system measuring the column-weighted dry-air mixing ratios of methane with a horizontal resolution of 50 km employing an absorption line at 1645 nm [1]. The orbit of operation will be near-polar and sun synchronous with a mean altitude of 506.3 km. The transmit pulses are generated at a wavelength of 1064 nm by a q-switched Nd:YAG Master Oscillator - Power Amplifier based on the FULAS development [2] and converted to the 1645 nm wavelength range by an optical parametric oscillator (OPO) [3]. Seeding of the OPO at two different wavelengths spaced by about 30 GHz provides the on- and off-resonance wavelengths required for the DIAL measurement. The system is designed to deliver 9 mJ pulse energies at repetition rates of up to 24 Hz. Stabilization and control of the seed sources and frequency control of the OPO output is provided by the frequency reference unit (FRU) which is an autonomously operating subsystem controlling all optical frequencies required for the LIDAR operation of the MERLIN instrument. The required functionality of the FRU can be separated into three main tasks: seeding of the laser oscillator, second, seeding of the OPO at two offset locked wavelengths absolutely referenced to methane and third, measurement and wavelength stabilization of the OPO transmit pulses. This is accomplished by deriving an absolute frequency reference point from a low pressure methane absorption cell and performing a set of relative frequency measurements by a calibrated wavemeter. In this paper we present the preliminary FRU design and baseline concept as well as results of the breadboard performance characterization obtained in Phase B, and an overview of the next steps towards the engineering model (EM) in Phase C/D.

II. SYSTEM DESCRIPTION

A. System overview

To provide these functions, the FRU contains the necessary distributed feedback laser diodes (DFB LD) at 1064 nm and 1645 nm with the associated optical fiber harness, fiber switches, drive electronics, a methane gas cell, a wavemeter including a Fizeau wedge and a CMOS camera, and an FPGA for controlling of the FRU and the feedback loops for the frequency stabilization of the OPO. Fig. 1 shows the functional diagram of the FRU baseline concept and the interfaces to other subunits of the MERLIN instrument. The FRU is designed as an autonomously operating unit. Secondary power for the operation of the FRU is derived from the primary power (PP) on a dedicated power board inside the FRU. In nominal operation, the power consumption of the FRU is less than 24 W. Before switch on, the instrument control unit (ICU) sets the required operational parameters for the FRU and initiates the transition into the operational mode. For synchronization, a pulse repetition interval (PRI) trigger is distributed by the ICU to the laser electronic unit and the FRU which defines the starting point of the operation sequence. Within the sequence, the seed lasers are switched to the OPO input and the wavemeter for seeding and measuring the OPO output as well as a lock on the methane reference cell is performed with the reference laser diode. The error signal for stabilizing the OPO cavity to the seed wavelength is obtained as well within this sequence and a control command is sent to the laser electronic unit via the ICU. After each PRI, housekeeping data can be collected by the ICU from the FRU data registers.

The mechanical design is depicted in Fig. 2. The unit is built of individual modules which are fixed to a common base plate. The modules accommodate PCBs, electronic and optic components. The wavemeter and the methane gas cell are mounted in separate hermetically sealed housings. The envelope of the box measures 190 mm in width, 232 mm in height, and 237 mm in length. The allowed total mass is 6.3 kg and Eigen modes with a modal effective mass > 10% have to have frequencies above 140 Hz. The mechanical requirements for the FRU are specified in terms of sine, random and shock loads. The qualification levels for sine loads are 12 g / 18 g for in-plane and out of plane excitation, respectively, the random loads are 16.1 g_{rms} / 23.6 g_{rms}, and shock loads are 1000 g at a 1000 Hz corner frequency. It has to be noted that the random loads drive the structural design of the FRU unit. The physical interfaces, including three optical fiber sockets, are located on the top. Thermal control is achieved via conductive coupling through the base plate to the instrument platform where a

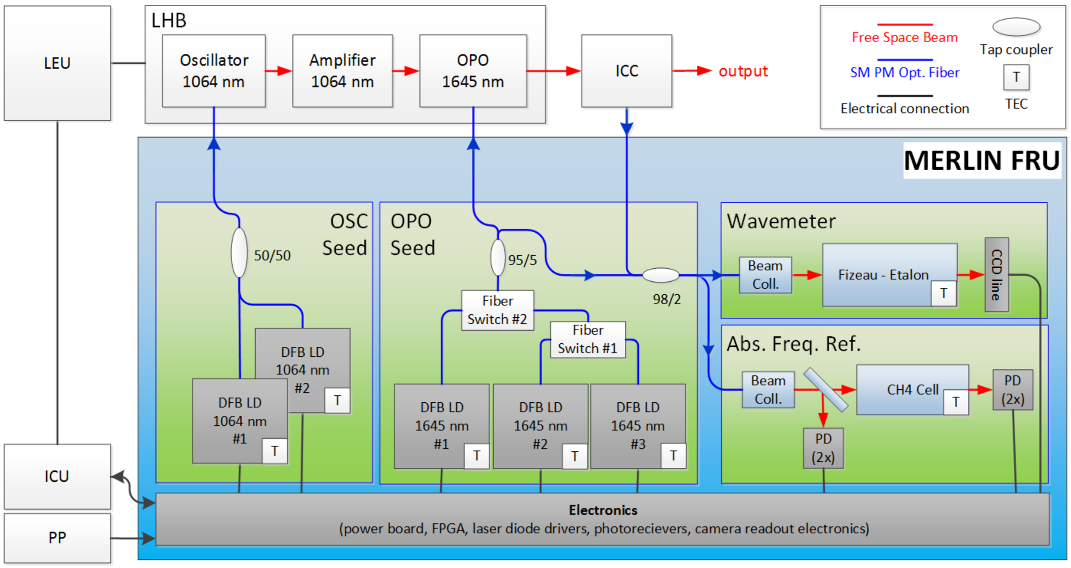

Fig. 1: Functional Diagram of the FRU and interfacing to the laser head box (LHB), instrument control unit (ICU), internal calibration chain (ICC) and primary power (PP).

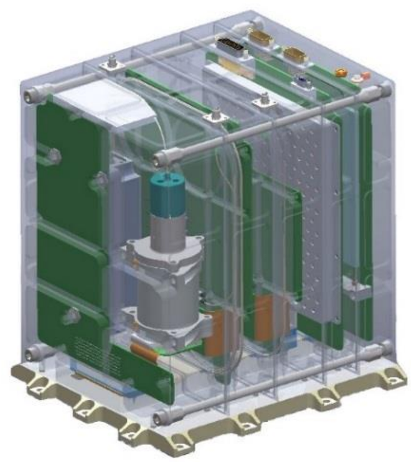

Fig. 2: Mechanical design of the FRU

common radiator is installed. The full performance temperature range is 0 to 40°C. The expected temperature variation per orbit is smaller than +/- 5°C.

B. Optical performance requirements

The main functions of the FRU are as follows:

- Seeding of the 1064 nm oscillator with an optical power of 10 mW. The seeder wavelength range is 1064.2 nm ± 0.5 nm and the required linewidth better than 1 MHz.
- Absolute frequency referencing to the 1645 nm (6077 cm^{-1}) methane line by stabilizing a laser diode to the local transmission maximum[1] (‘lambda_ref’) of a low pressure methane gas cell at this wavelength.
- Seeding of the OPO at two wavelengths, ‘lambda_seed_on’ and ‘lambda_ seed_off’, referenced to the absolute frequency reference. The nominal frequency offsets relative to ‘lambda_ ref’ are 200 MHz for the ‘lambda_seed_on’ and 30 GHz for ‘lambda_ seed_off’. The optical power delivered to the OPO needs to be larger than 5 mW and the linewidth below 2 MHz. The frequency stability of ‘lambda_seed_on’ needs to be better than 10 MHz and better than 20 MHz for ‘lambda_ seed_off’.
- Measurement of the emitted OPO laser pulses ‘lambda_Tx_on’ and ‘lambda_Tx_off’ relative to ‘lambda_seed_on’ and ‘lambda_seed_off’.

[1] At wavenumbers around 6077 cm^{-1} two triplets of absorption lines exist giving rise to a double-peaked structure in the absorption spectrum for gas pressures around 100 mbar.

- Stabilization of the difference between 'lambda_seed_on' and 'lambda_Tx_on' based on the relative frequency measurement and via a control signal to adjust the OPO cavity length.
- Stabilization of the difference between 'lambda_seed_off' and 'lambda_Tx_off' in order to lock 'lamda_seed_off' to 'lambda_Tx_off', which is determined by the OPO cavity resonances.
- Absolute frequency metrology providing a frequency knowledge better than 8 MHz for the online and 50 MHz for the offline frequency.

The methods in terms of absolute frequency stabilization and relative frequency measurement to achieve these performance requirements are described in Section III and IV, while a preliminary operation mode test of the FRU on breadboard level is presented in Section V.

C. Selected hardware and qualification status

As seed sources for the oscillator and the OPO, DFB laser diodes with integrated single-stage optical isolators are used. Their design is based on a space-qualified package with flight heritage. However, a full qualification approach is required for package redesign with the integrated optical isolator. The laser diodes are assembled in a hermetically sealed butterfly package with internal thermo-electric cooler (TEC) and thermistor. For oscillator seeding at a wavelength of 1064 nm, at least 20 mW of power from the laser diode package are required. The baseline concept includes two laser diodes in cold redundancy with the outputs combined by a fiber optic tap coupler. The DFB laser diodes at 1645 nm provide about 14 mW of optical power at a drive current of 120 mA. This allows to reach a nominal output of the seeder of 7 mW to the OPO. Three laser diodes are implemented in a logic arrangement that allows for each laser diode to serve as 'lambda_seed_on', 'lambda_seed_off', and 'lambda_ ref'. A 2/3 redundancy scheme using only two laser diodes where the functionalities of 'lambda_seed_on' and 'lambda _ref' are covered by the same laser diode is currently under investigation. Accelerated lifetime tests have been performed on breadboard models of the laser diodes to ensure operation over the expected 3.25 years of mission duration.

The optical switches are based on magneto-optic switching with a latching 'mechanism'. The number of switching cycles over the mission duration when operating at a PRI of 24 Hz exceeds $2 \cdot 10^9$. The switches are qualified to telecommunication standards and possess some space heritage and reach 10^{11} cycles before failure. Full qualification is performed by SpaceTech in cooperation with the manufacturer.

The optical harness employs single mode polarization maintaining fibers for the corresponding wavelengths. A common fiber procurement for all fiber optic components is planned. Using fiber from the same batch for all fiber components minimizes the loss and improves the efficiency of splicing process.

For operation of the laser diodes, low noise laser diode drivers were developed. The design focusses on the use of electronic parts where space-qualified versions are available. The achieved performance in terms of current noise and associated relative intensity noise of the laser diodes are comparable with commercially available laser diode drivers. By using a self-heterodyne measurement technique, it has been confirmed that the laser diode driver supports the linewidth requirement of 1 MHz within 1µs.

The wavemeter employs a CMOS line camera for measuring the interference fringes of the Fizeau wedge. The InGaAs sensor of the breadboard contains 1024 pixels with dimensions of 12.5 x 250 µm. The flight design may use less and larger pixels and will be defined during the EM phase. The optical power of the seed lasers entering the wavemeter is 10 µW and the integration time of the camera is 10 ms. For the OPO pulses, the energy per pulse coming from the ICC is 100 nJ. Due to the short pulse length of 20 ns, a short integration time of 100 µs can be chosen. This allows to have the seeder and the pulse on the camera at the same time, but to measure only the pulse since the seeder is suppressed due to its low energy and the short integration time.

The wavemeter requires a large input beam diameter of 12.5 mm and a good wave front stability. As beam collimator, a fiber injector using an aspheric lens with the fiber directly spliced to the lens is employed. It follows the design of a fiber injector developed by SpaceTech used in the laser ranging interferometer (LRI) for the GRACE follow-on mission [4]. In order to keep the collimator as compact as possible, a high NA fiber is used which allows for a short focal length of the asphere.

The FPGA design is based on a radiation hard Microsemi ProASIC3 FPGA.

Preliminary vibration tests with optical and fiber-optic breadboard models and/or COTS parts, depending on availability, up to qualification levels have been performed without failures.

III. ABSOLTUE FREQUENCY REFERENCE

A. Stabilization using wavelength modulation spectroscopy

To stabilize the DFB laser diode to the methane absorption feature, the laser wavelength is periodically modulated around a center wavelength which leads to a periodically modulated intensity transmission through the cell. From this periodic intensity change, the error signal is obtained. The error signal is passed through a loop filter and fed back to the laser diode for stabilization. The error signal generation employs phase sensitive detection in order to generate a locking signal with a zero crossing at the valley position of the absorption feature [5]. This technique is also referred to as Lock-In. A short gas cell with a length of 6 cm filled with methane gas at a pressure of 100 mbar is used for the absolute frequency reference. The maximum absorption reaches 50 % while the transmission around the locking point given by the local transmission maximum is 90 %. The laser diode is modulated at a frequency of 10 kHz and 100 µW of optical power are sent through the gas cell and detected on a photoreceiver developed for this parameter set. The update rate of the modulation waveform, as well as the sampling rate of the photoreceiver, is 250 kHz. Digital demodulation is performed with the digitized signal within the FPGA. The error signal is fed through a proportional–integral–derivative controller (PID) and the feedback is applied to the laser diode by changing the set current. The low-pass filter of the Lock-In step has a cut-off frequency of 300 Hz. Fig. *3* shows the scan across the methane absorption feature, the photoreceiver signal, and the calculated error signal. Besides using the local transmission maximum for stabilization, it is also possible to lock to the two transmission minima by introducing a 180° phase shift to the demodulation signal.

B. Performance Test

In order to evaluate the stability of the absolute frequency reference, two identical absolute frequency reference setups are used. The references share a common power supply and are controlled through the same FPGA software, allowing to modulate them synchronously. Choosing a slightly different modulation amplitude leads to a shift in the absolute lock point. By obtaining a heterodyne beat signal between the two laser didoes of the absolute frequency references, their relative stability to each other can be measured. The shift in the absolute lock point leads to a non-zero heterodyne beat frequency. Fig. 4 shows the beat signal between the two references in the free-running and in the locked case measured over several hours with a frequency counter using a gate time of 1 s. Glitches or outliers in the frequency measurement caused by the frequency counter are removed using a 5 times median absolute deviation (MAD) criterion. For the free running case, the standard deviation of the measurement is 8.9 MHz and the peak-to-peak maximum frequency deviation is 72 MHz. For the measurement comparing the two locked frequency references, the standard deviation of the measurement is 100 kHz and the peak-to-peak maximum frequency deviation is 600 kHz. Similar measurements have been performed on the other possible lock points (transmission minima), leading to comparable results and ruling out influences from a common drift of the two absolute frequency reference setups.

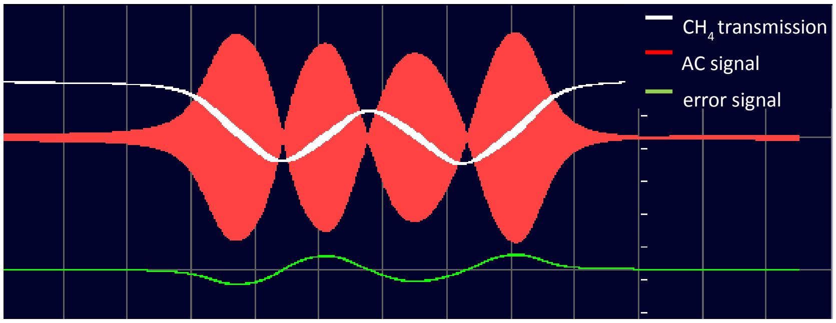

Fig. 3: Wavelength scan with additional current modulation by temperature tuning across the methane absorption feature showing the absorption, the AC photo receiver signal and the derived error signal for locking. The frequency span of the scan is about 10 GHz.

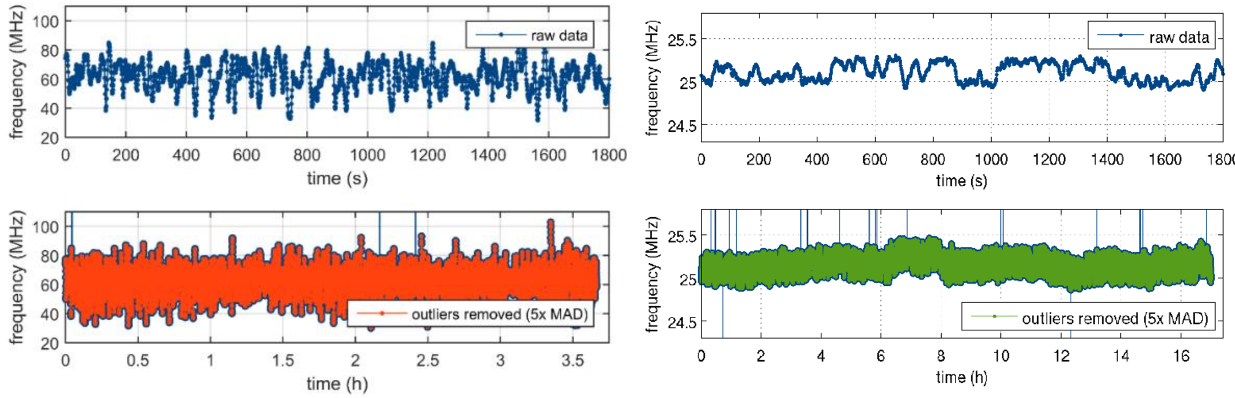

Fig. 4: Stability analysis of two independent absolute frequency references free running (left), locked (right). The upper parts are magnifications of the first half hour of the measurement. Please note the different vertical scaling between locked and unlocked data sets.

IV. WAVEMETER

The wavemeter is the most challenging free space optical system of the FRU, due to the stringent requirement on relative frequency measurement accuracy of 8 MHz (online wavelength) for the seeder and OPO pulse frequencies. It consists of the three main components: a beam collimator, a Fizeau wedge and a CMOS line.

A. Fizeau Design and Fringe Pattern Analysis

The Fizeau wedge acts as a spatial frequency filter for the laser signal out of the collimator. Depending on the frequency f of the signal, it can pass the etalon only at a certain position (roughly where $f = m \cdot c/(2 \cdot n \cdot L)$ is true), with m being an integer number, c the speed of light, n the refractive index and L wedge thickness (the length between the two interferometer surfaces). Due to the multiple reflections in the wedge, the interference signal becomes asymmetric with more or less pronounced 'side lobes', depending on the reflectivity, the wedge thickness, the wedge angle and the angle of incidence of the laser signal on the wedge [6]. Fig. 5 shows a typical interference fringe measured in the wavemeter. The free spectral range of the employed Fizeau is 3.745 GHz which results in a frequency dependency of 6.17 MHz per pixel. The spacer of the Fizeau wedge is made of Zerodur to reduce the temperature sensitivity of the wavemeter.

The wavemeter fringe signal has to be evaluated such that a unique and reliable mapping of the signal onto a certain frequency is guaranteed. The position of the most prominent peak of the fringe on the wavemeter CMOS camera is sufficiently sensitive to frequency shifts, to ensure a mapping as precise as necessary. Moreover, compared to other features of the fringe signal, the profile of the peak is the most resilient to noise and pixel errors. The algorithm that determines the position of the peak has been kept flexible and simple to be able to adjust to the signal of the complete system and to implement the algorithm in hardware only.
In a first step, the fringe pattern is low pass filtered with a bandwidth which approximates the fringe size. During the filtering, bad pixels are excluded based on a bad pixel map. After filtering, the derivative of the fringe pattern is generated. In the new pattern, the zero crossing determines the peak position. The algorithm allows determination of the peak position with subpixel resolution.

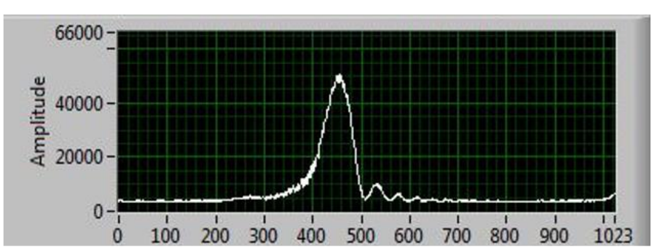

Fig. 5: Typical fringe produced by the Fizeau wedge measured with the CMOS line camera.

B. Performance Tests

For evaluation and feasibility studies, a breadboard model of the wavemeter has been set up and its performance has been tested. Fig. 6 a) shows a scan with a laser diode across the wavemeter by tuning of the set current. Tuning the current by 4 mA leads to a frequency tuning of about 8 GHz. Since the FSR of the Fizeau is 3.745 GHz two FSR jumps occur within this tuning range. In order to characterize the linearity of the Fizeau, linear fits were applied to the three segments and the remaining residuals are shown in Fig. 6 b). The measurement shows that a careful characterization of the wavemeter is required in order to ensure sufficiently accurate frequency measurements. In addition, the ability to stabilize a laser diode to a set pixel was investigated as well. Fig. 7 shows the measurement of the peak position of a DFB laser diode in the free running and in the locked case. The wavemeter is sampled every 10 ms, acquiring 100,000 data points. In case of the lock being active, the set point is 460. For the free running case, the standard deviation is 1.42 pixels = 9.14 MHz and in the locked case it is 0.57 pixels = 3.67 MHz.

V. PRELIMINARY OPERATION TEST ON BREADBOARD LEVEL

As part of the Phase B activities, a test of the FRU operation mode in conjunction with the laser breadboard developed at the Fraunhofer Institute for Laser Technology (Fraunhofer ILT) has been conducted. Besides testing the operation concept of the FRU, the spectral purity of the MERLIN OPO was characterized, which requires the on- and off-line seeding scheme [7]. The measurements were supported by the Institute of Atmospheric Physics of the German Space Agency (DLR IPA) by providing a long path length absorption cell and the DIAL data acquisition system. Fig. 8 shows a functional diagram of the test setup. The PRI trigger was

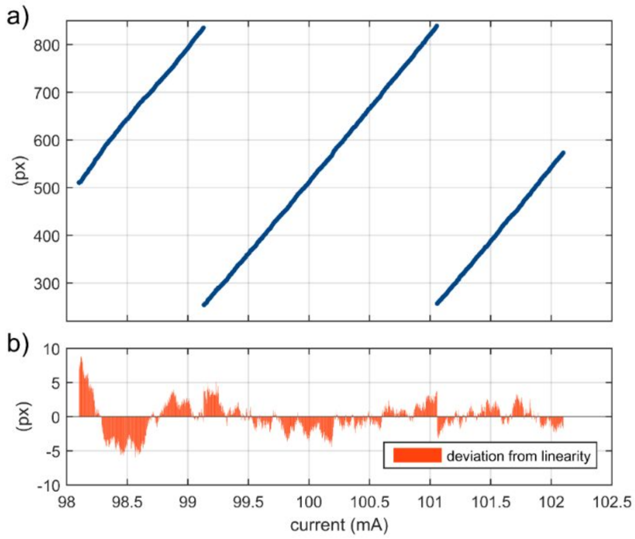

Fig. 6: Scan of the wavemeter by current tuning of the laser diode a) and characterization of the deviation from linearity due to pixel non-uniformity b) by applying a linear fit to the measurement data.

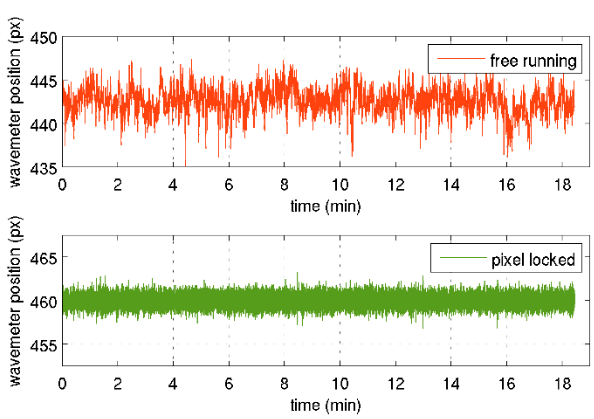

Fig. 7: Free running measurement of a DFB laser diode with the wavemeter and stabilization of a DFB laser diode a set pixel on the wavemeter.

provided by the electronics unit of the power laser and distributed to the FRU and the data acquisition system of absorption measurement setup. The implementation is similar to the final operation concept of the MERLIN instrument, with the exception that the stabilization of the OPO cavity to the 'lambda_seed_on' wavelength is accomplished by using a heterodyne beat signal between a wavelength shifted portion of the seeder input and the OPO output [7]. The performance of the heterodyne based control loop can be monitored by the FRU. Fig. 9 shows the wavemeter fringes of all five signals of ten subsequent repetition intervals which have to be measured by the FRU. For each acquired fringe pattern, the peak position is determined and the corresponding pixel value is used as input for the control loops, compare Fig. 8. This first system test on breadboard level already showed a very robust performance. As a measure for the stability, the standard deviation is computed for the time series of measured frequency values for each signal, see Tab. 1. They are calculated for a time span of 80 s for the offline signals and 160 s for all other measurements. In addition, the maximum frequency deviation values within this time span are given as well.

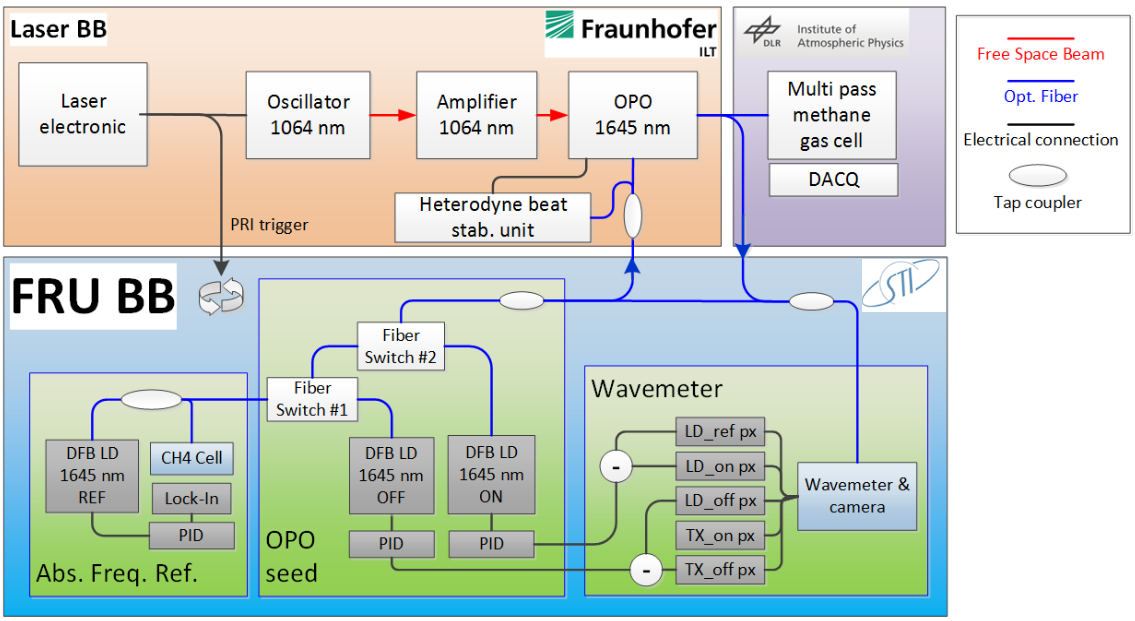

Fig. 8: Functional diagram of the test setup including the FRU breadboard (BB), the main laser breadboard developed by the Fraunhofer ILT and a multi pass gas cell for spectral purity measurements provided by the DLR IPA.

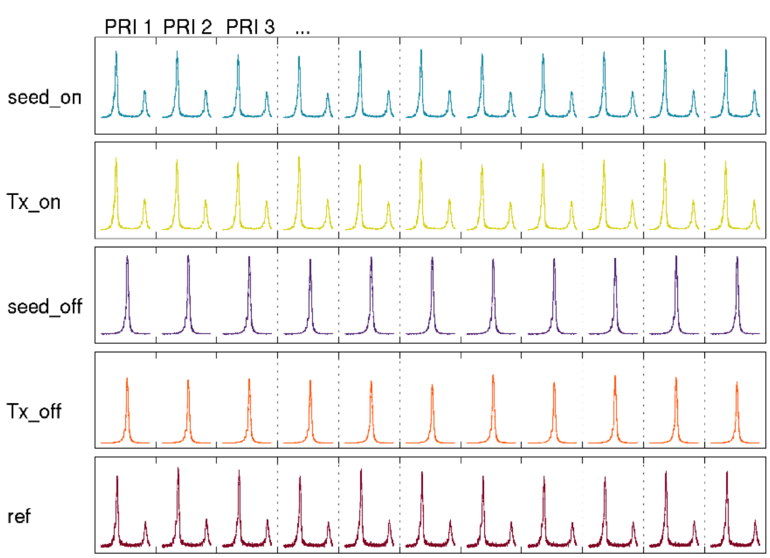

Fig. 9: Fringe pattern obtained in the operational sequence of the OPO pulses 'lambda_Tx_on' and 'lambda_Tx_off' and the two seed laser diodes 'lambda_seed_on' and 'lambda_seed_off', as well as the reference laser diode 'lambda_ref'.

Tab. 1: Achieved relative stabilities obtained in the system test measured with the FRU BB setup.

	std. dev. (MHz)	max. dev. (MHz)
'lambda_seed_off' - 'lambda_Tx_off' [open loop]	6.154 [7.974]	17.382
'lambda_seed_on' - 'lambda_Tx_on' (heterodyne beat stabilization)	9.257	31.735
'lambda_ref'- 'lambda_seed_on'	3.125	12.41
'lambda_ref' absolute	5.617	14.722

VI. SUMMARY AND OUTLOOK

This paper has summarized the current state of the development of the absolute frequency reference for the MERLIN instrument. In addition, test results obtained with the FRU breadboard in Phase B are presented. They include the successful implementation of a stabilization scheme to the methane absorption feature at 1645 nm for absolute frequency referencing. The operation principle of the wavemeter in conjunction with a peak finding algorithm has been tested successfully. The FRU operation mode has been implemented und was tested with the breadboard setup by seeding of the OPO at on-line and off-line wavelength, which allowed for the measurement of the spectral purity of the system. The performance achieved in the FRU breadboard tests verify the feasibility of the FRU baseline concept. In the upcoming Phase C/D, additional functionalities will be implemented in the FRU breadboard to verify the FRU EM design. These updates include an improved mechanical design of the wavemeter setup.

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