WHITE PAPER

THE LEMON FRUIT: AN ABSOLUTE FREQUENCY REFERENCE CONCEPT FOR FUTURE SPACEBORNE MULTI SPECIES DIFFERENTIAL ABSORPTION LIDAR INSTRUMENTS

Grant Agreement number: 821868

Project acronym: LEMON

Project title: Lidar Emitter and Multispecies greenhouse gases Observation iNstrument

Funding Scheme: Research & Innovation Action (RIA)

Start date of the project: 01/01/2019

Duration: 48 months

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 821868.

The LEMON FRUIT: An absolute frequency reference concept for future spaceborne multi species differential absorption Lidar instruments

The knowledge of the emitted laser wavelengths is important to obtain accurate column-integrated greenhouse gas concentrations from DIAL measurements. The accuracy of the measured concentration depends directly on the accuracy of this frequency knowledge. For the LEMON instrument (refer to [1] for an overview of the system), the task of measuring the laser pulses sent out by the transmitter module is delegated to the so-called Frequency Reference UnI^{2}T (FRUIT).The key task of the FRUIT is to provide a reliable and traceable frequency standard. In contrast to single species DIAL instruments, like the methane-sensing mission MERLIN [2], this is particularly challenging considered the generic approach followed within the LEMON project. The objective of the LEMON instrument is to cover a large spectral range (1.98 to 2.3 µm) to target different species with the same instrument. Additional challenges are imposed due to the operation in an aircraft environment with vibration loads during operations as well as ground-to-flight temperature and pressure variations.

During the conception phase, various design approaches for the FRUIT have been evaluated. The key challenges are to span the wide wavelength range in general, but also to bridge the gaps between the desired online and offline wavelengths. A demonstrated approach for a LIDAR frequency reference is the combination of using laser spectroscopy of an atomic or molecular species to provide a fixed and well reproducible pivot point determined by an absorption line, and a wavemeter to transfer the stability and accuracy to the desired wavelengths in the vicinity of the pivot. This is for example the case in MERLIN [3]. This approach is well suited if the reference can operate with the same species as the DIAL instrument, the frequency spacing of online and offline pulse is small (few tens of GHz), and the stability and accuracy requirements are moderate (MHz-level). For LEMON and future spaceborne multi-species differential absorption lidar systems, these requirements deviate. First, the targeted absorption lines are widely spaced (H_2O and DHO around 1982.5 nm, CO_2 at 2051 nm, CH_4 at 2290 nm) and the online-offline separation can be several 100 GHz. In contrast, the transfer of a wavemeter is most accurate for a narrow bandwidth around its design wavelength. Second, laser stabilisation based on high-resolution spectroscopy of absorption lines located in the DIAL operating ranges is challenging in terms of linewidth and absorbance on short interaction lengths. Possible candidates of atomic or molecular species for spectroscopy at the second or fourth harmonic wavelengths like iodine or acetylene exist, but their use adds significant complexity. Since the ultimate goal for the FRUIT is to establish a universal concept, which is not limited to a specific band, as it is true for the emitter concept (GFCU: generic frequency conversion unit [4]), a different concept was chosen.

The ruler which the FRUIT employs to measure the frequencies is based on a frequency comb. The frequency comb acts as a transfer oscillator to transfer the stability and accuracy of a GPS disciplined oscillator into the optical domain. Since more than 20 years, the concept of using frequency combs for bidirectional transfer between the radio-frequency and optical domains is well established [5], in particular in the scientific lab environment for atomic and optical clock comparisons [6]. Applications of frequency combs in the field and outside the lab [7,8,9] as well as their use as frequency references for LIDAR systems [9] only start to emerge. A frequency comb-based solution suggests itself when considering the broad spectral range required by the LEMON instrument and the universal approach for the GFCU. Wavelength conversion or expansion is intrinsically required for stabilisation of a comb and straightforward to implement. Due to ultra-short pulse duration and high peak powers associated with the mode-locked laser producing the frequency comb, nonlinear wavelength conversion in bulk, and more efficiently in fiber or waveguides are possible. The

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stabilised and referenced frequency comb provides a ruler against which the emitted laser pulses can be measured. Thinking towards a spaceborne system, the complexity should be reduced as much as possible. Therefore, SPACETECH decided to investigate a system design without employing a transfer laser, measuring the transmitter pulses with heterodyne beat frequency detection directly with individual comb modes. This requires a wide spaced frequency comb. Menhir Photonics [11] offers a femtosecond laser with a repetition rate of 1 GHz operating at a wavelength of 1.5 µm. The laser provides the performance allowing for frequency comb stabilisation [12], the required large comb mode spacing, and it is constructed to withstand the loads associated with operation in an airplane. During LEMON project, SPACETECH will perform pre-qualification tests to validate the suitability of this laser for a space development.

When heterodyning an optical signal against one teeth of a frequency comb, the index number of the comb mode needs to be known in order to obtain an absolute frequency value. One method to determine this mode index is the use of a low resolution, but calibrated auxiliary wavemeter, to make a coarse measurement of the wavelength of the optical signal. The resolution of this measurement needs to be better than the comb mode spacing or repetition rate of the frequency comb. Hereby, a frequency comb with a higher repetition rate is of benefit as well, since it relaxes the resolution requirement of the wavemeter.

Figure 1 shows a schematic of the FRUIT system. The output of the laser is amplified in an erbium-doped fiber amplifier (EDFA). After dispersion compensation, a supercontinuum (SC) spanning an octave and covering the LIDAR spectral range is generated. One part of the supercontinuum is split off for detecting of the carrier envelope offset frequency of the comb. Together with the repetition rate, after stabilisation of the two degrees of freedom of the comb, the frequency of the comb modes is fixed and known. The second part of the supercontinuum is filtered and overlapped with the light from the optical parameter oscillator (OPO). The OPO pulses are frequency doubled (SHG: second harmonic generation) to shift the detection to 1 µm. This allows to use standard silicon detectors. With a fast analog-to-digital converter (ADC) the heterodyne beat signal between comb mode and OPO pulses is sampled [13]. Together with a wavemeter measurement, the control unit can determine the absolute frequency of the OPO pulse. This value is used for data analysis, but also for providing a cavity control signal for stabilisation of the OPO.

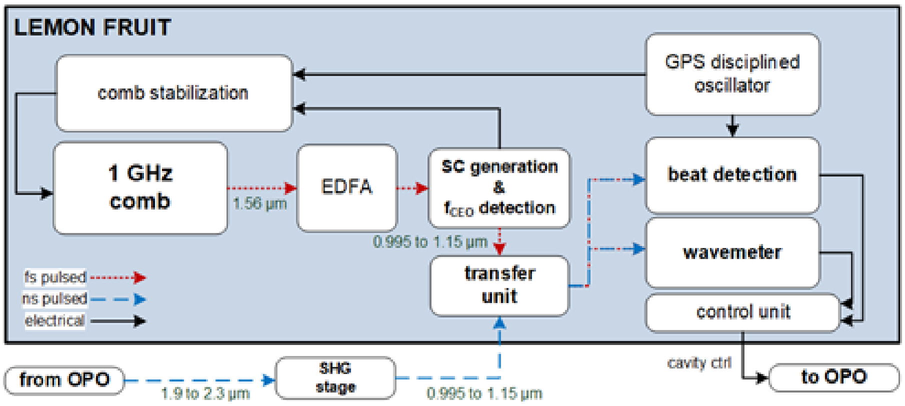

Figure 1: Schematic of the FRUIT system.

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The underlying functional operating principle of the FRUIT is depicted in more detail in Figure 2. The frequency of each mode of the frequency comb is determined by the two degrees of freedom of the comb: repetition rate and offset frequency. Knowledge of these two values allows to calculate together with the integer mode-index n the absolute optical frequency of each comb mode. With the transfer unit, a part of the comb spectrum is selected and heterodyned with the OPO pulse. A single frequency comb mode is isolated by suppressing neighbouring modes with a filter. This leads to the interference of a quasi-cw wave with the nanosecond OPO pulses. In the photodetection process low-pass filtering occurs and the results is a radio-frequency waveform representing the OPO pulse but with a centre frequency determined by the distance between the centre of the OPO spectrum and the closest frequency comb mode. This waveform can be sampled by a fast ADC. A subsequent Fourier transformation gives the centre frequency of the waveform. Together with the values for the repetition rate and offset frequency of the frequency comb and the mode-index n determined from a wavemeter measurement, this allows to determine the absolute optical frequency of the OPO pulse from the heterodyne beat signal.

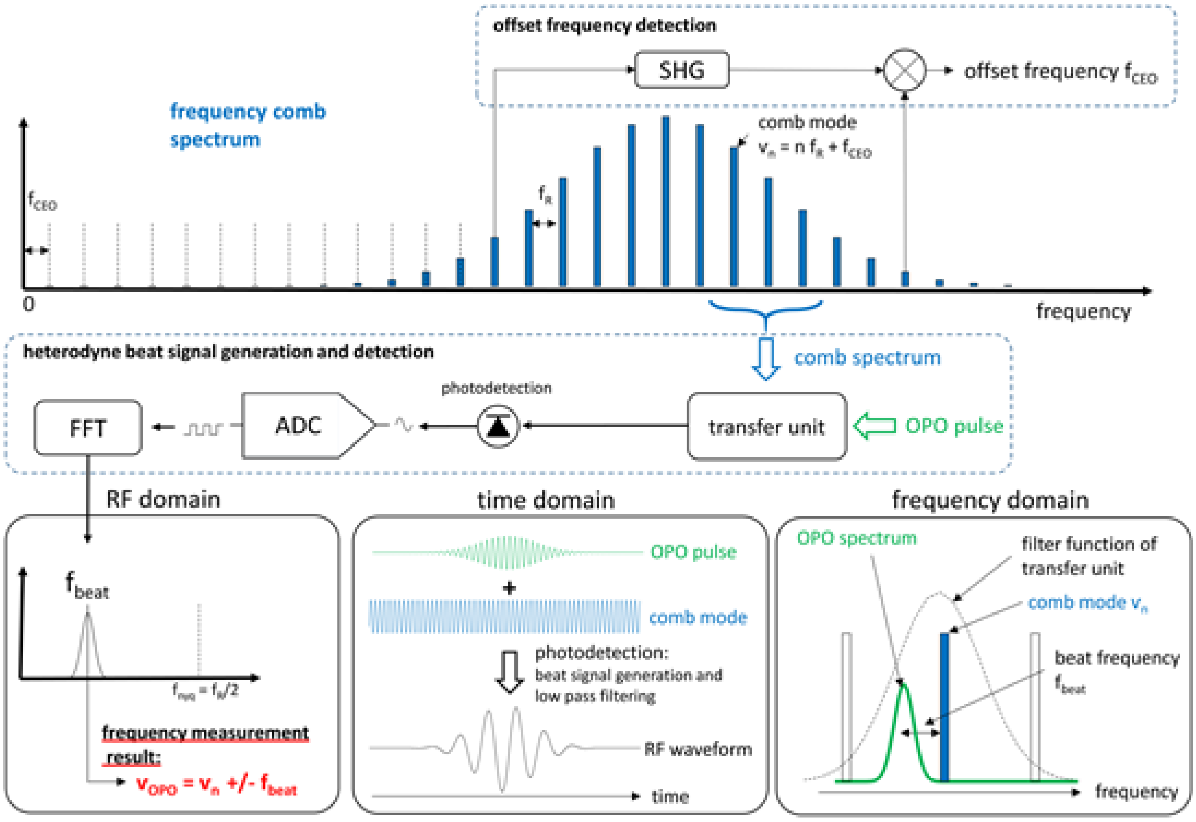

Figure 2: Functional operating principle of the FRUIT.

Figure 3 shows the stability requirements for the LEMON instrument. Due to the different integration path length between airborne and space operation of a DIAL instrument, the requirements of the two cases are different. By using a GPS-disciplined oscillator as time base for comb stabilisation and heterodyne beat sampling, the required stability and accuracy can be well reached.

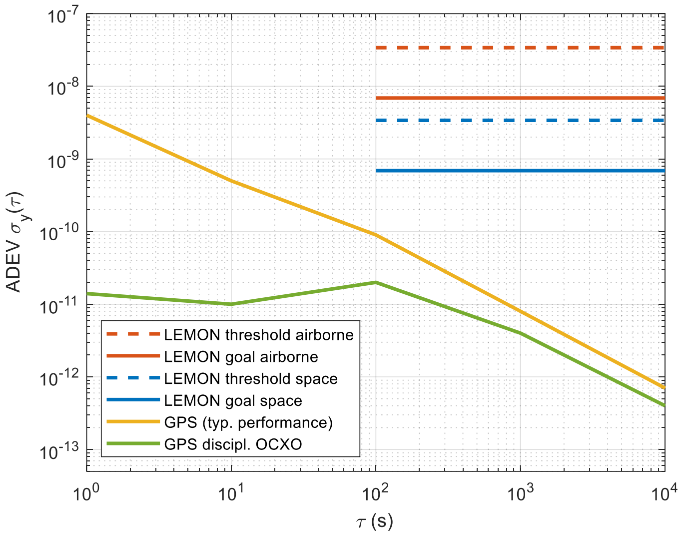

Figure 3: Stability requirements for the LEMON airborne instrument and future spaceborne instruments together with typical stability performance of GPS and a GPS-disciplined oven-controlled quartz crystal oscillator (OCXO).

In the early phase of the LEMON project, before starting with the procurement, first tests were required in order to settle the baseline concept and to minimise the development risks associated with the approach. In close cooperation with the manufacturer, a 1 GHz laser was successfully evaluated. By now, a laser with a specific repetition rate and repetition rate tunability matched to the expected operation condition in the airplane has been procured. Together with an amplifier and suitable dispersion compensation the nonlinear spectral broadening stage has been implemented and the required spectral coverage has been reached. Figure 4 shows the generated supercontinuum and the targeted absorption regions at the second harmonic wavelength of the DIAL. Using the octave spanning spectrum, a first implementation of measuring and stabilisation of the offset frequency has been successfully implemented. Together with measurement and stabilisation of the repetition rate, this gives full control of the degrees of freedom of the frequency comb and absolute knowledge of the frequency of the frequency comb modes. The full characterisation of the stability of the comb is currently under way.

On the side of the wavemeter, the design process was also supported by preliminary tests using a breadboard setup. This allowed to iterate parameters like the free spectral range and to estimate the stability and accuracy. After this evaluation period, the hardware was selected and is now integrated in an elegant breadboard setup. After performance verification, this setup will be adapted to serve as the actual flight model for the airplane campaign.

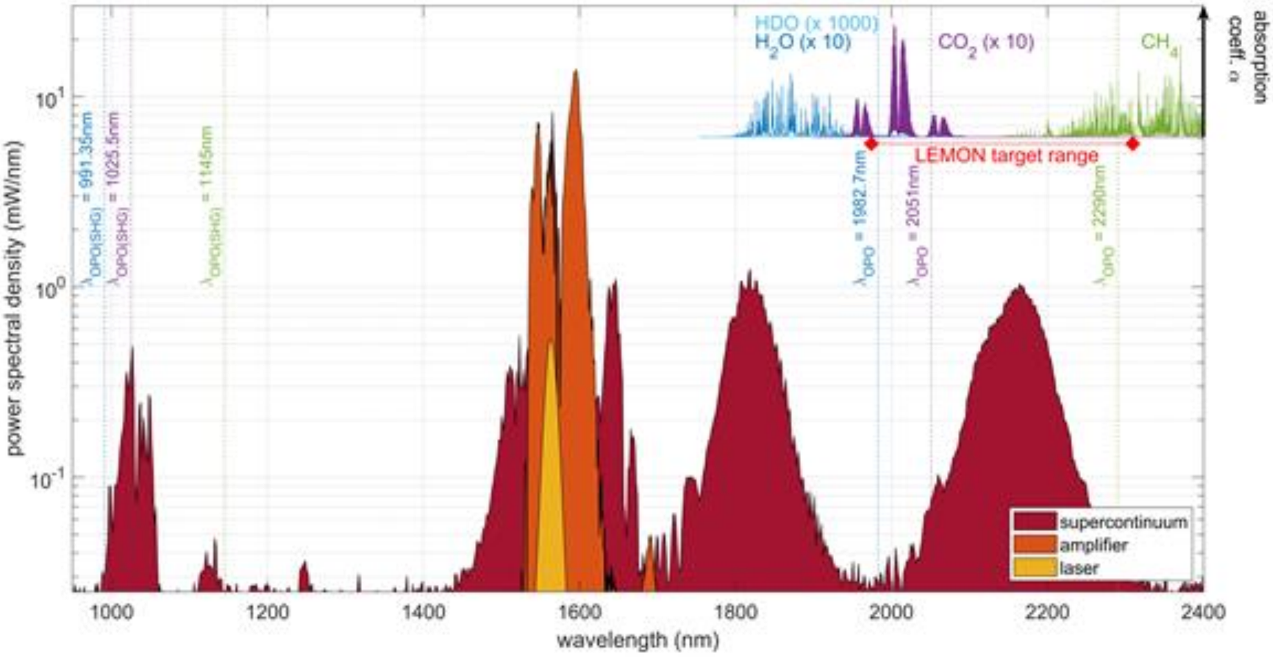

Figure 4: Laser spectrum together with spectrum after fiber amplifier and supercontinuum generated in a nonlinear fiber. In addition, the relevant absorption bands for the molecules are shown together with the interrogation wavelengths generated by the OPO.

Besides the development of the FRUIT for the LEMON airborne instrument, the current activities also cover the development of a space-compatible design of the FRUIT. This involves in particular the identification of components which are critical with respect to the space environment, an assessment on their suitability, and if required, to provide alternative solutions. In addition, a route towards a higher integration level is paved. With respect to compatibility of components and subsystems environmental testing will be performed. This includes thermal-vacuum, vibration and shock testing of components and subunits as well as radiation testing of components like crystals and fibers. A step towards the development of a spaceborne system is the investigation of waveguide devices for nonlinear frequency conversion and frequency doubling instead of using fiber and bulk material. In cooperation with Covesion [14], first results on frequency doubling of the 1 GHz comb in a periodically-poled lithium niobate waveguide could be obtained with up to 45 % [1]. Besides the frequency conversion, spectral filtering can be implemented using waveguide structures as well. This approach can benefit from the radiation hardness of the waveguide material as compared to nonlinear fibers and a more compact design since the waveguide device comprises multiple functionalities.

Despite the fact that no particular engineering in terms of size and compactness has been invested, the airborne FRUIT will already be relatively compact with a volume of about 100 l and a weight of less than 40 kg, integrated in a 19-inch rack. The power consumption of the system based on individual subunits will be in the range of 200 W. For a spaceborne system design, SPACETECH expects the volume to decrease below 20 l, a weight of less than 15 kg and a power consumption of about 50 W. These figures are all about twice than those of the MERLIN FRU [16], but given the fact that it enables a multi-species LIDAR, this corresponds to a major improvement if one considers the weight per target species.

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Finally, an interesting trade is the use of a wavemeter as compared to an alternative approach using a dual comb system. The engineering cost for a wavemeter suited for operation under airplane vibration is expected to be similar to the corresponding space compatible counterpart which only needs to withstand the mechanical loads during launch, but experiences much less vibrations during operation in the space environment. The approach using two combs with slightly different repetition rates allows to determine absolute frequencies without the need of an auxiliary wavemeter or a requirement of the initial set accuracy of the laser source, but an additional transfer laser might be needed. The feasibility of this approach strongly depends on the integration level possible. It could prove to be preferential since the wavemeter would be replaced by an identical second comb system, reducing the number of different components in the overall system.

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