AIRBORNE FREQUENCY COMB FOR GREENHOUSE GAS MONITORING

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ABSTRACT

In order to measure the two most important anthropogenic greenhouse gases CO_2 and CH_4 by means of the integrated path differential absorption (IPDA) lidar technique, stringent requirements with respect to the frequency stability of the transmitter need to be fulfilled In order to measure and optimize the frequency stability of the on-line and off-line wavelengths of an airborne IPDA lidar, a compact optical frequency comb (OFC) was for the first time employed and its performance characterized on board of an aircraft. This compact and rugged device could successfully been operated under tough in-flight conditions. Previously, such measurements were only possible in the laboratory.

1. INTRODUCTION

In the past two hundred years the concentrations of the well-known GHGs: CO_2 and CH_4, have grown around 46% and 157%, respectively. Particularly, anthropogenic GHGs contributing to global radiative forcing have significantly increased since the beginning of the industrial era [1]. In order to accurately predict the future climate of our planet and support observing emission targets in the framework of international agreements, the investigation of sources and sinks of the GHGs and their feedback mechanisms is indispensable. However, the current WMO Greenhouse Gas Observing Network is sparse, leaving large gaps in many key areas, especially the tropics. It was verified that the trace gas columns can be measured using the IPDA method, from which the hard target reflection from the Earth's surface in the near IR has been identified to measure the column averaged dry air mixing ratio of CO_2 and CH_4 with high accuracy and low bias [3]. For that purpose, an airborne demonstrator (CHARM-F) has been developed at DLR which enables the simultaneous measurement of CO_2 (at 1572 nm) and CH_4 (at 1645 nm) on board of the German Research aircraft HALO [4,5]. The laser transmitters from CHARM-F are based on two injection seeded optical parametric oscillator (OPO) systems [5]. In order to achieve the highest accuracy, the frequency stability of the seed laser for OPO should be < 0.2 MHz at 1.6 µm for CO_2 [3,6]. This requirement is rather difficult to achieve by using a traditional absolute frequency stabilization scheme like a multi-pass absorption cell along with a wavemeter [7]. The OFC can easily fulfill the stability requirements, not only in the laboratory, but also under the tough in-flight conditions with a compact, portable, automatic Menlo Systems SmartComb.

2. EXPERIMENTAL SETUP

2.1 The compact optical frequency comb (OFC) - SmartComb

The frequency comb is generated by a mode locked fiber laser [8,9]. Phase-locked loops lock two radio frequencies, the pulse repetition rate f_{rep} and the carrier envelope offset frequency f_{ceo} of them. An optical spectrum is then generated with evenly spaced lines, following the comb equation $f_c = f_{ceo} + n \cdot f_{rep} + f_b$ (with n being a natural number), where f_b is the beat between a comb line with the ready-to-measured continuous wave (cw) laser with the frequency of f_c. Usually, the femtosecond lasers are mechanically sensitive to vibrations and temperature variations. However, using polarization maintaining fibers the laser can be sufficiently decoupled from perturbations such as vibrations or variations of temperature, humidity, and air pressure. Menlo's frequency comb laser is based on nonlinear amplified loop mirror as implemented in Menlo Systems' proprietary Fig 9 technology, with erbium as the gain medium [10,11]. As shown in Figure 1, besides the 100 MHz oscillator, the comb also includes an erbium based main amplifier and f-to-2f interferometer for the stabilization of the offset frequency,

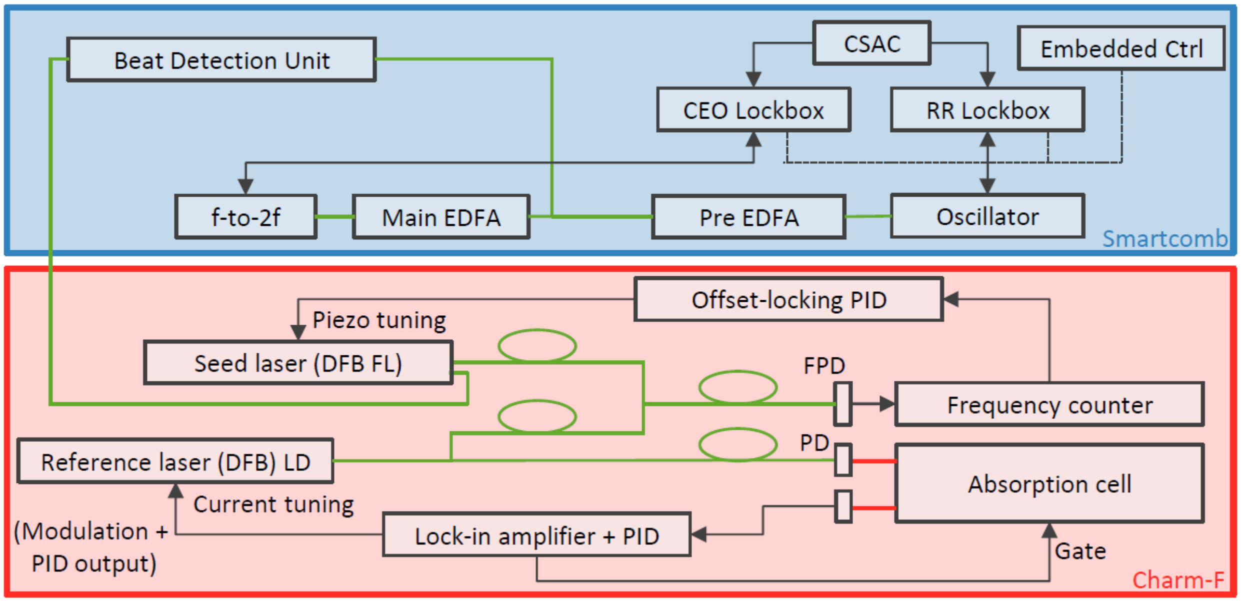

Fig. 1. Simplified block diagram of the SmartComb optical assembly (top) and the CHARM-F seed unit (bottom). Both systems are connected via a fiber optical link. The frequency comb consists of a 100 MHz oscillator, preamplifier, main amplifier, and a f-to-2f interferometer. The comb light at 1572 nm is mixed with an auxiliary output of the one CHARM-F seed laser in the beat detection unit.

fully automated locking electronics, fully automated beat detection, and fully automated measurement and stabilization together with the optical package, which are integrated into a standard 19", 3U unit offer the great flexibility of using an OFC not only in the lab but also under airborne and space-born conditions. It is a unique system, where the user plugs in the optical fiber of the laser being measured or stabilized - SmartComb does the rest fully automatically. Depending on the reference used for the SmartComb, the frequency stability and accuracy can reach 5E-13 in 1 second and better than 1E-14 in 120 seconds, respectively, or the same as the reference, whichever applies first. Owing to the compact, rugged, reliable design and the unique all polarization-maintaining fiber mode-locking technology [10, 11], which is the core technology employed by the SmartComb, the single– and dual-comb systems have been successfully operated and tested on a sounding rocket flights during the microgravity missions TEXUS 51 and 53, which is operated by DLR [12, 13].

2.2 The seed laser systems measured by SmartComb

An airborne demonstrator for simultaneous IPDA measurements of CO_2 and CH_4 has been developed at DLR [5]. This system, CHARM-F, consists of several sub-systems including two Nd:YAG pump lasers, two OPO units, and a seed laser system for narrowband operation of the OPOs [6]. DFB fiber lasers are used for injection seeding of the OPO, and two of these lasers at slightly different wavelengths (on- and off-line) are coupled to a fast fiber switch to deliver seed radiation at the selected wavelength to the OPO on a shot-to shot basis. The accuracy and precision of IPDA measurements are very sensitive to laser frequency uncertainties. In order to provide the highest possible measurement accuracy and stability, it is necessary to monitor the frequency stability of the on-line and off-line seed lasers.

As shown in Figure. 1, one reference laser (DFB LD) is stabilized onto absorption features of CO_2 using an absorption cell filled with defined quantities of CO_2. The on-line wavelengths are then generated by locking the on-line seed laser with a defined offset to its reference laser using an offset-locking technique. The frequency stability for the seed laser then can be verified using the SmartComb by simply plugging an auxiliary port of the seed lasers into input port of the

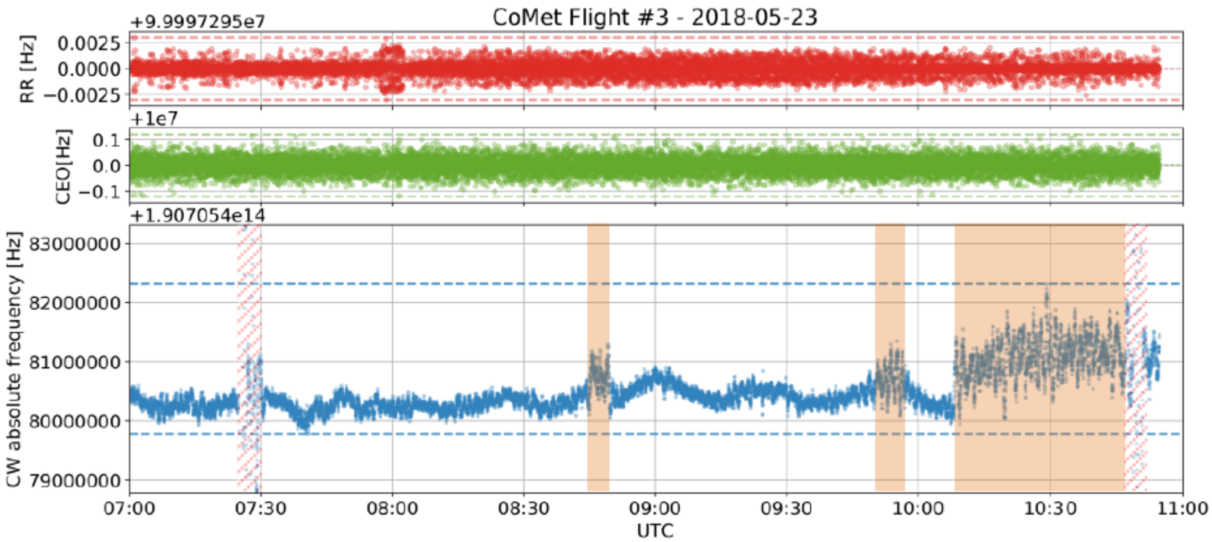

Fig. 2. Continuous measurement of the repetition rate (RR:red), carrier envelope offset (CEO:green) and the absolute frequency of the 1572 nm beat signal during flight #3 on the 23. May 2018. The comb was firmly locked in the period between 07:00 and 10:50 UTC. The derived absolute frequency of the seed laser is shown in the bottom plot (blue). While maintaining a good lock most of the time, several instances were observed, where the seed was out of lock (red) or the lock point changed/jitter increased (orange).

SmartComb via a fiber optical cable. The comb is frequency referenced to an internal atomic clock (CSAC) supporting 3E-11 stability in 1 second and accuracy of 1E-9, with pre-defined wavelengths close to the wavelengths of the seed lasers. The beat detection units (BDU) integrated inside of the SmartComb then generates the beat signals between 0 and 50 MHz by mixing the seed lasers and the closest comb line emitted by the oscillator. The beat signals are sent to the internal counters without dead time to conveniently determine the absolute optical frequencies.

3. THE COMET CAMPAIGN

The system was used inside the HALO aircraft in May/June 2018 during the DLR CoMet campaign. During nine research flights CHARM-F measured CO2 and CH4 columns over Europe.

Figure. 2 shows a 4 hour time trace during flight #3 over Germany. The top and middle traces show the combs repetition rate (red) f_{rep} and carrier envelope offset frequency (green) f_{ceo}, which were both firmly locked to < 3mHz and < 120 mHz, respectively.

Unfortunately, it appeared a few days before the start of the flight campaign that CHARM-F's frequency stabilization unit did not achieve its nominal performance due to signal issues in the offset-locking part of the system. Because of stringent flight certification constraints, it was not possible to disassemble the unit for troubleshooting before or during the campaign. The degraded stability can be observed on the bottom blue trace which shows the absolute frequency of the 1572 nm online seed laser, calculated from the detected beat signal. Two larger outliers, where the seed stabilization was inactive are marked in red. During the majority of the measurement period, the seed was well locked within approximately 200 kHz. However on several occasions, irregularities in the locking mechanism were detected (marked in orange). In these cases, the system was not able to identify such subtle changes in the frequency lock, the changed lock point or increased jitter was however easily detectable on the measured beat frequency. In this way, SmartComb proved to be an invaluable tool as real-time frequency monitor, enabling to optimize or restart the seed stabilization on the fly. Furthermore for the upcoming scientific evaluation of trace gas columns, such in-flight time traces can ensure the validity of measured data as well as give means to filter the data where necessary.

4. CONCLUSION

To fulfill the strict requirements on the absolute optical frequency of the emitted on-line pulses in the 1.6-micron region, an accurate stabilization and monitoring of the seed lasers up to the 10 kHz to 200 kHz level is required. By using the SmartComb as an absolute and independent reference, it has been shown that the requirements could be met with a carefully optimized yet simple top-of-fringe and offset-locking scheme relying on Doppler-broadened CO_2 and CH_4 lines observed in a multipass absorption cell. Besides its integration within the airborne system, the compact seed laser stabilization subsystem can be further optimized and characterized with the help of the OFC. In fact, in the past five years the high technology readiness level (TRL) of space OFC systems regarding robustness, automatization, form factor, and low power intake have been successfully demonstrated [13]. Thus, this technology shows much promise for future space missions such as follow-ons of the German-French methane mission MERLIN (Methane Remote Lidar Mission) [14] but even more for CO_2 IPDA lidars such as A-SCOPE since for CO_2 measurement the frequency stability requirements are the most stringent ones. [15]. Finally, as a powerful tool the compact OFC would constitute a universal stabilization scheme independent of wavelength and requirement for spectroscopic research and investigation of stabilization techniques on aircraft and spacecraft for GHG monitoring.

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