CHALLENGES AND SOLUTIONS FOR FREQUENCY AND ENERGY REFERENCES FOR SPACEBORNE AND AIRBORNE INTEGRATED PATH DIFFERENTIAL ABSORPTION LIDARS

Andreas Fix*, Mathieu Quatrevalet, Benjamin Witschas, Martin Wirth, Christian Büdenbender, Axel Amediek, and Gerhard Ehret

*Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, *Email: Andreas.Fix@dlr.de*

ABSTRACT

The stringent requirements for both the frequency stability and power reference represent a challenging task for Integrated Path Differential Absorption Lidars (IPDA) to measure greenhouse gas columns from satellite or aircraft. Currently, the German-French methane mission MERLIN (Methan Remote Lidar Mission) is prepared. At the same time CHARM-F, an aircraft installed system has been developed at DLR as an airborne demonstrator for a spaceborne greenhouse gas mission. The concepts and realization of these important sub-systems are discussed.

1. INTRODUCTION

The Integrated Path Differential Absorption Lidar (IPDA) technique using hard target reflection in the near IR has the potential to deliver methane and carbon dioxide column measurements from satellite or aircraft with unprecedented accuracy [1].

Carbon dioxide and methane are the two most important anthropogenic greenhouse gases contributing to global radiative forcing and have significantly increased since the beginning of the industrial era. CO2 has grown from a pre-industrial average atmospheric mole fraction of about 280 parts per million volume (ppm) to 396 ppm in 2013 which is an increase of 42 %. The increase of methane was even higher than for CO2: it rose by 153% from ~700 parts per billion volume (ppb) in the pre-industrial period to 1824 ppb in 2013 [2]. CH4 has an estimated global warming potential per molecule 25 times greater than CO2 over a 100 year horizon and, despite its much lower abundance, thus is the second most significant anthropogenic greenhouse gas.

Large uncertainties in their budget, however, and feedback mechanisms which are, if at all, only partly understood, limit the accuracy of climate change projections. In order to reliably predict the climate of our planet, and to help constrain political conventions on greenhouse gas avoidance, adequate knowledge of the sources and sinks of these greenhouse gases and their feedbacks is mandatory. In spite of the recognized importance of this issue, our current understanding about sources and sinks of the gases CO2 and CH4 is still inadequate. In order to improve our current knowledge about methane fluxes the German-French methane mission MERLIN has been initiated. The goal of MERLIN is to measure the spatial and temporal gradients of atmospheric CH4 columns with high precision and low bias. MERLIN, which is currently in its definition phase and whose launch is scheduled for 2019 will be the first IPDA lidar for greenhouse gas monitoring in space. At the same time DLR has accomplished to develop CHARM-F a state-of-the-art airborne demonstrator which is able to simultaneously measure both greenhouse gases, CH4 (at ~1645 nm) and CO2 (at ~1571 nm), onboard the German research aircraft HALO (Fig. 1). Recently, its first test flights have successfully been performed.

Figure 1. Artist's view of MERLIN (source: CNES) and photograph of HALO starting.

In many aspects and sub-systems the instruments resemble each other. Both use e.g. optical parametric oscillators (OPOs) in a double-pulse mode as the transmitter [3]. Of particular importance for both instruments are the sub-modules required for the frequency stabilization of the transmitter wavelength and, since the IPDA technique, in contrast to DIAL, requires the exact knowledge of the energy ratio of outgoing on-line and off-line pulses, the energy calibration chain. Wavelength accuracy and energy calibration represent a potential source of systematic error contribution to the measurement of XCH4 and XCO2, the weighted averages of the greenhouse gas dry-air volume mixing ratio which is the primary data product.

2. REQUIREMENTS

In preparation of the MERLIN mission, feasibility studies have been undertaken (e.g. [4]). The target, breakthrough and threshold mission requirements for the accuracy of XCH4 have been set to 1 ppb, 2 ppb, and 3 ppb, respectively, for an observation averaged over 50 km along track. The allowed target, breakthrough and threshold values for the random error are a factor of 8-12 higher, thus 8 ppb, 18 ppb, and 36 ppb, respectively. Using inverse modelling, such error margins would allow constraining the CH4 observations to the point where regional to continental scale CH4 fluxes can be estimated to generally within less than 20% of their mean values on average [5].

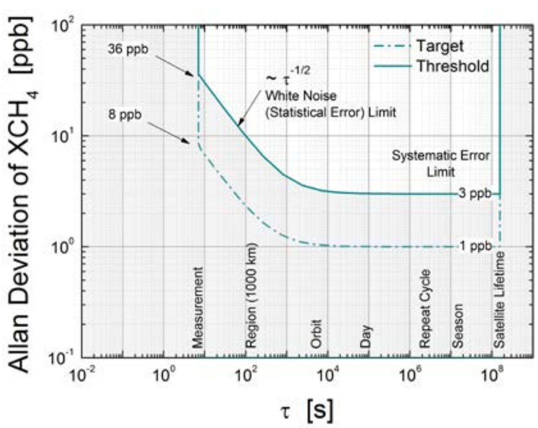

Figure 2. Template expressing MERLIN random and systematic error requirements in terms of Allan deviation.

The concepts of “random error” and “systematic error” may be interpreted in terms of uncorrelated and correlated measurement noise, respectively. It is, however, important on which timescales these specifications have to be met. Therefore, a methodology is implemented that gives rise to the individual timescales involved and serves as a benchmark to assess the observing of requirements. It uses the well-known overlapping Allan variance which is a powerful tool to identify and quantify these different types of noise sources. Figure 2 gives an example of how the requirements are transferred into a template.

3. ENERGY REFERENCE

For the monitoring of the on-line to off-line ratio of outgoing pulse energies an accuracy of the order of $2{\cdot}10^{-4}$ to $8{\cdot}10^{-4}$ is pursued to meet the above given requirements. The preferred set-up would use an identical detector for both lidar signal and pulse energy monitor to circumvent potential detector ageing effects. It is thus important to employ pick-up, attenuation, transmit and detection schemes that do not alter the energy ratio. For this purpose, the use of integrating spheres appear to be beneficial since those are insensitive to beam pointing and intensity profile variations and can be fibre-coupled. Integrating spheres also provide an adequate means for wavelength-independent attenuation. Using established theory [6], the attenuation can be accurately predicted also for double integrating sphere arrangements.

However, given the coherence of the lidar transmitter, speckle effects need to be considered in detail [7]. Therefore, the OPO was used within a laboratory testbed to investigate possible monitoring schemes.

One of the main challenges when determining the accuracy of the energy ratio measurement is the lack of a reference system that may serve to provide the “true” value against which the experimental set-up can be referenced. Therefore the energy ratios had to be simultaneously measured twice using the same or different measurement technique and analysed using statistical methods. Again, the Allan variance is used to identify uncorrelated and correlated measurement noise. Since thermal detectors are generally to slow to resolve individual pulses, only detectors based on the pyroelectric or photoelectric effect are to be considered.

In a series of experiments it could be shown that the speckle patterns at the exit port of integrating spheres of two subsequent pulses within a double-pulse sequence of ~ 360 µs appear to be partly correlated. This is exemplarily depicted in Fig. 3. While the Allan deviation of the energy ratio of single pulses with a separation time of 10 ms results in an almost ideal -0.5 slope, this is not true for the double pulse mode.

In order to destroy this correlation, several methods have been evaluated. Reasonable results were achieved by means of reducing the speckles by angular diversity, i.e. the bare fibre ends were mechanically vibrated (Fig. 3). Unfortunately this is no viable option for space use. An alternative approach uses oscillating diffusors that rapidly vary the speckle pattern and which are currently tested within the CHARM-F system.

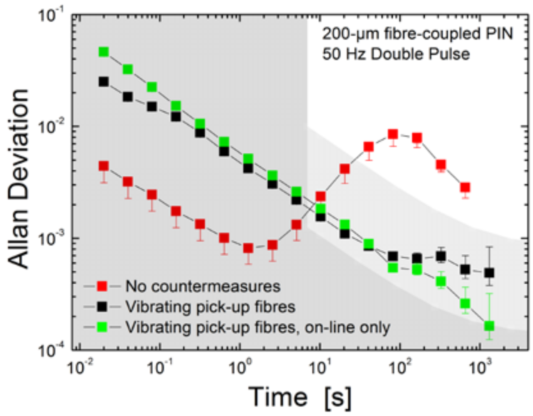

Figure 3. Allan deviations of the pulse energy ratio of two subsequent pulses divided by the same ratio recorded with a second detector. Shown are three cases: without countermeasures against the speckle correlation, and employing vibrating pick-up fibers for the nominal on-/offline sequence and for on-line only, respectively

4. FREQUENCY REFERENCE

Concerning frequency stabilization CHARM-F and MERLIN are following different concepts. CHARM-F's frequency stabilization has been developed consisting of various DFB lasers. In general, two reference lasers are stabilized onto absorption features of CH_4 and CO_2, respectively, using a multipass absorption cell filled with defined quantities of both gases. The on-line and off-line wavelengths are generated by individual seed lasers locked with a defined offset to their respective references using the offset-locking technique.

The frequency stability for the seed lasers have been verified using a frequency comb. For CH_4 and CO_2 less than 3 MHz p-p and 70 kHz p-p was achieved, respectively, which fully meets the requirements which are approximately 10 MHz for CH_4 and 100 kHz for CO_2, respectively.

The OPO cavity is matched to the seed wavelengths using a heterodyne technique whereby the frequency difference between the outgoing OPO pulse and the incoming cw seed radiation is measured on a shot-by-shot basis [8]. This is done by mixing part of the seed light which is acousto-optically frequency shifted with the outgoing OPO pulse by using a fast photo diode. From the beat spectrum of each pulse, its power spectrum is calculated by fast Fourier transform and the error signal for the loop control generated from the difference between the two frequencies.

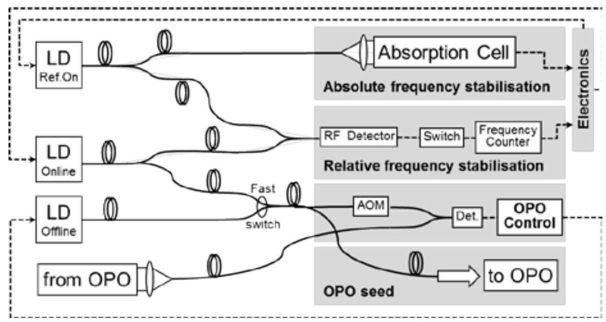

Figure 4. Schematic set-up of the frequency reference of the CHARM-F system. For simplicity only the branch for one greenhouse gas is shown.

Figure 4 shows the beat spectrum for the CH_4 transmitter. An OPO bandwidth of ~35 MHz is derived. The offset frequency from the nominal 500 MHz value (given by the AOM frequency) is used for the OPO control.

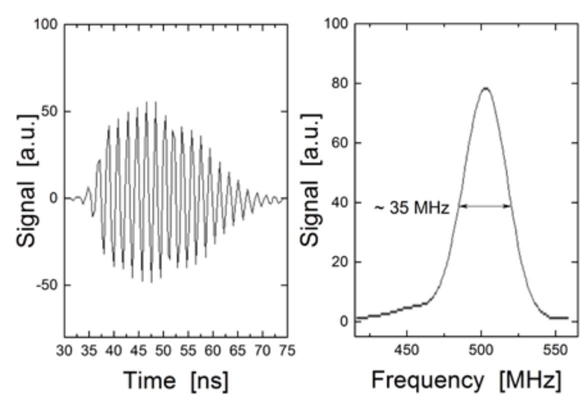

Figure 5. Beat spectrum (left) and power spectrum (right) of the OPO at a wavelength of 1645nm.

For MERLIN, however, a different baseline was chosen that seems more favorable in terms of power demands and recurrent parts for the sake of space qualification. Here, the reference is likewise stabilized to an absorption cell, but relative frequency stabilization and OPO control will be performed using a Fizeau interferometer [9]. The respective fringes are imaged onto a linear

InGaAs array. Using a laboratory set-up, first experimental tests have been performed directed to optimize the parameters of the interferometer. Using a frequency comb and changing the wavelength in defined steps the response of the Fizeau interferometer was analyzed. After pre-processing, a long-term stability of < 5 MHz was achieved (Fig. 6).

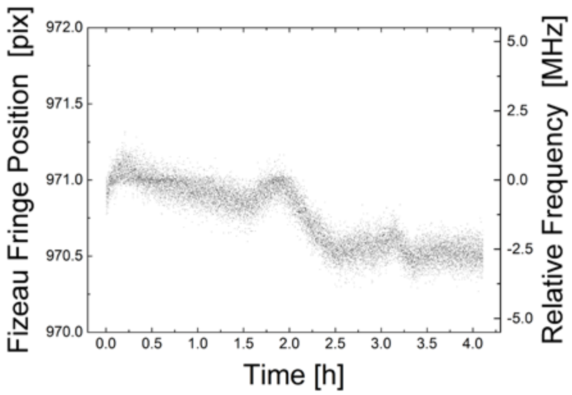

Figure 6. Time series of the peak position of the Fizeau fringe. The left axis shows the respective frequency deviation.

These investigations are to be continued within the design phase of MERLIN.

5. CONCLUSIONS

As a conclusion, frequency and energy reference are fundamental to both airborne and spaceborne IPDA to measure the most important anthropogenic greenhouse gases. Detailed investigations have been performed on both issues within the development and design phase of CHARM-F and MERLIN. The coherence of the lidar transmitter gives rise to speckle effects which have to be considered for the monitoring of the energy ratio of outgoing on- and off-line pulses.

For the frequency reference of CHARM-F, a very successful stabilization scheme has been developed which will also serve as the reference for MERLIN, for which a differing variant was chosen due to space qualification issues. Preliminary results show good prospects. Further investigations are in progress and will be reported.

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