CHARM-F: THE AIRBORNE INTEGRAL PATH DIFFERENTIAL ABSORPTION LIDAR FOR SIMULTANEOUS MEASUREMENTS OF ATMOSPHERIC CO_2 AND CH_4

Mathieu Quatrevalet[1], Axel Amediek[1], Andreas Fix[1], Christoph Kiemle[1], Martin Wirth[1], Christian Büdenbender[1], Sebastian Schweyer[1], Gerhard Ehret[1], Dieter Hoffmann[2], Ansgar Meissner[2], Jens Löhring[2], Jörg Luttmann[2]

[1] *Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, 82234 Weßling, Germany*
E-mail: mathieu.quatrevalet@dlr.de
[2] *Fraunhofer Institut für Lasertechnik (ILT), Steinbachstr. 15, D-52074 Aachen, Germany*

ABSTRACT

CHARM-F (CO_2 and CH_4 Atmospheric Remote Monitoring – Flugzeug) is DLR's airborne Integral Path Differential Absorption lidar for simultaneous measurements of the column weighted-average dry-air mixing ratios of atmospheric carbon dioxide and methane, designed to be flown on board DLR's new High-Altitude, LOng-range research aircraft, HALO. After recalling the context of the project, the measurement principle and the technological challenges, we report on the design of the instrument.

1. INTRODUCTION

While anthropogenic carbon dioxide and methane have the highest greenhouse warming potential in the atmosphere and have contributed to an estimated global warming of 0.74±0.2 K over the past hundred years [1], the carbon fluxes at the Earth's surface remain poorly quantified, which impairs future climate predictions and the determination of mitigation targets. More specifically, a large uncertainty remains associated with the biological CO_2 land sink, while this is true for all CH_4 sources in general, especially in the case of wetlands, permafrost and shelf areas.

Surface sources and sinks may be inferred by the use of column-averaged measurements with suitable sensitivity near the Earth's surface as input to inverse models that describe atmospheric transport and mixing. However, recent studies [2] reveal that the required relative measurement precision and accuracy is exceptionally high especially for CO_2, of the order of 2.10^{-3} and 2.10^{-4} respectively, for a spatial cell of 200 km. On one hand, such performance cannot be provided by the available spaceborne passive sensors, due to their low sensitivity in the lower troposphere, high sensitivity to aerosol interference and incapacity to cover high latitudes because of the unfavorable Sun angle; on the other hand, the network of in-situ surface sensors is too sparse especially in remote but key areas like Amazonas, Central Africa, South East Asia, Siberian Taiga, and the North Atlantic and South Polar Oceans.

By contrast, the Integral Path Differential Absorption lidar technique is thought to be able to close the gap thanks to a truly global coverage with a sufficient spatial and temporal resolution for a more accurate knowledge of the location, magnitude and variability of carbon sources and sinks. In Europe, this has led to a phase 0 study for a spaceborne mission dedicated to CO_2, A-SCOPE, in the frame of the third cycle of the European Space Agency's Earth Explorers Core Missions programme [3]. This mission was eventually not selected for phase A due to a lack of technological maturity and insufficient experience in inverse modeling with lidar data. It is the purpose of the CHARM-F instrument on board HALO to address these two key issues by:

- serving as a demonstrator of the observational principle foreseen in the A-SCOPE mission concept in the 1.6 µm spectral region,

- serving as a demonstrator of the use of active optical instruments for flux inversion of CO_2 and CH_4 by providing simultaneous measurements of CO_2 and CH_4 gradients on a regional scale with the required high precision and accuracy.

In addition to the A-SCOPE phase 0 activities, the CHARM-F project builds on the pulsed DIfferential Absorption Lidar (DIAL) heritage at DLR, namely the helicopter-borne pipeline monitoring system CHARM [4] and, more recently, the WALES water vapour DIAL system [5].

2. MEASUREMENT PRINCIPLE

2.1 IPDA Principle

IPDA lidars make use of the strong lidar echoes from the Earth's surface or cloud tops at two wavelengths in the vicinity of a gas absorption line: one so-called "on-line" channel close enough to the line that significant absorption takes place (λ_{on}), one so-called "off-line" channel far enough that negligible absorption takes place (λ_{off}) (Fig. 1, bottom-right corner). For a pulsed, direct detection lidar with receiving aperture A, the corresponding return incident energies per pulse on the photodetector, $R_{on/off}$, are given by the simplified hard target equation:

$$R_{on/off} = \frac{A}{R^2} \cdot \rho_{on/off} \cdot e^{-2 \cdot \Delta_{on/off}} \cdot E_{on/off} \cdot D_{on/off} \quad , \quad (1)$$

where R is the distance from the instrument to the ground/cloud top, $D_{on/off}$ is the overall optical efficiency of the transmit/receive optics, $\rho_{on/off}$ is the average ground reflectance over the laser footprint, $\Delta_{on/off}$ is the one-way integrated atmospheric optical depth from instrument to hard target and $E_{on/off}$ are the emitted energies in each channel.

Differences between ρ_{on} and ρ_{off} may arise from the combination of an imperfect overlap of the on-line and off-line laser footprints and spatial variability of the target reflectance. This can be avoided by simultaneous emission and reception of both pulses which requires two transmit-receive systems, or by using a single, tunable transmitter with a short inter-pulse delay δt_{on-off} compared to the instrument's velocity and footprint size. The latter solution is the one adopted for CHARM-F, as illustrated on Fig. 1. Dedicated airborne measurement campaigns of the ground reflectance variability at 1.6 µm performed by DLR [6] have shown that a co-registration of better than 10% of the laser footprint size keeps the associated error under control, for footprint sizes of the order of 100 m.

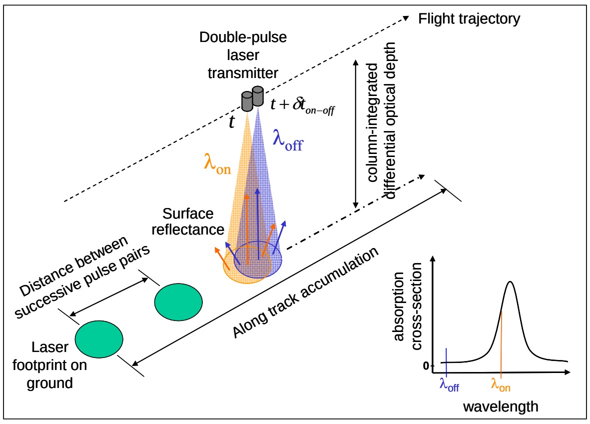

Figure 1. Illustration of the double-pulse IPDA lidar principle used for CHARM-F.

Provided that this condition is fulfilled, i.e. $\rho_{on} \approx \rho_{off}$, the ratio of returned energies, corrected for the ratio of emitted energies and overall optical efficiencies, gives access to the integrated differential optical depth $d\Delta$:

$$d\Delta = \Delta_{on} - \Delta_{off} = \frac{1}{2} \cdot \ln\left(\frac{R_{off}}{R_{on}} \Big/ \left(\frac{E_{off}}{E_{on}} \cdot \frac{D_{off}}{D_{on}} \right) \right) \quad (2)$$

For carefully selected sounding wavelengths, i.e. in a spectral region with minimal interference from other gases and for a distance between on-line and off-line small enough that no other wavelength-dependent effects come into play, $d\Delta$ is given by:

$$d\Delta = \int_{r=0}^{R} q_{gas}(r) \cdot WF(r) \cdot dr \, , \quad (3)$$

$$WF(r) = \frac{p(r)}{k \cdot T(r)} \cdot \frac{1}{1 + q_{H_2O}(r)} \cdot \begin{pmatrix} \sigma(\lambda_{on}, p(r), T(r)) \\ -\sigma(\lambda_{off}, p(r), T(r)) \end{pmatrix}, \quad (4)$$

where k is Boltzmann's constant, r is the range, $p(r)$, $T(r)$, $q_{gas}(r)$, $q_{H_2O}(r)$ are vertical profiles of pressure, temperature, dry-air mixing ratio of the probed gas, and dry-air mixing ratio of water vapour respectively, and $\sigma(\lambda, p, T)$ is the absorption cross-section. In eq. (3), $d\Delta$ appears proportional to a weighted-average of the gas' dry air mixing ratio. Moreover, independent knowledge of all parameters on the right-hand side of eq. (4) is available: absorption cross-sections from spectroscopic laboratory measurements, and pressure, temperature and water vapour profiles from Numerical Weather Prediction (NWP) models. Therefore, the proportionality factor is known and $d\Delta$ can be converted into the column weighted-average dry-air mixing ratio, $X[CO_2]$ or $X[CH_4]$, which is the quantity of scientific interest:

$$X[gas] = d\Delta \Big/ \int_{r=0}^{R} WF(r) \cdot dr \quad (5)$$

As illustrated on Fig. 1, along-track averaging over many pulse pairs is necessary. Averaging can be carried out on the return signals before applying eq. (2), on $d\Delta$ before applying eq. (5), or on $X[gas]$ itself. The determination of the best averaging strategy is a complex problem which CHARM-F will also help to investigate using real-world data.

2.2 Sounding wavelengths

Many criteria govern the selection of the exact absorption line to be used, and the fine-tuning of the sounding wavelengths in its vicinity. Detailed studies of these aspects have been carried out at DLR in the past years [7], leading to a robust catalog of suitable wavelengths both for carbon dioxide in the 1.57 µm spectral region and for methane in the 1.64 µm spectral region. These analyses have been partly iterated for the airborne case using the latest update of the HITRAN spectroscopic database [8], but the differences are small thanks to the high flight altitude of HALO (see part 4). For each on-line wavelength, the off-line wavelength is positioned in view of minimizing the impact of unknown water vapour variability on the retrieval, in a similar approach to that of Caron and Durand [9], using water vapour vertical error covariance matrices representative of typical NWP model performance.

2.3 Technological challenges

While the much lower flight altitude and platform velocity in the airborne case allow a better horizontal resolution to be reached with a relaxed power-aperture product compared to the spaceborne case, equally challenging for both is the required accuracy of 2.10^{-4}, which impacts several key technological requirements, namely:

- For CO_2, on-line long-term spectral stability of less than 100 kHz and spectral purity better than 99.95% (less critical values of 5 MHz and 99.9% apply for CH_4 thanks to the use of a trough-like spectral feature),

- Calibration of the relative outgoing pulse energies corrected for the relative overall optical efficiencies (last two factors in eq. (2)) with an accuracy of 2.10^{-4}.

To a lesser extent, the rather large laser footprint of 30-50 m associated with the wish to mimic the spaceborne case, introduces additional difficulties because of the available detector size (paragraph 3.4).

3. INSTRUMENT DESIGN

3.1 Architecture

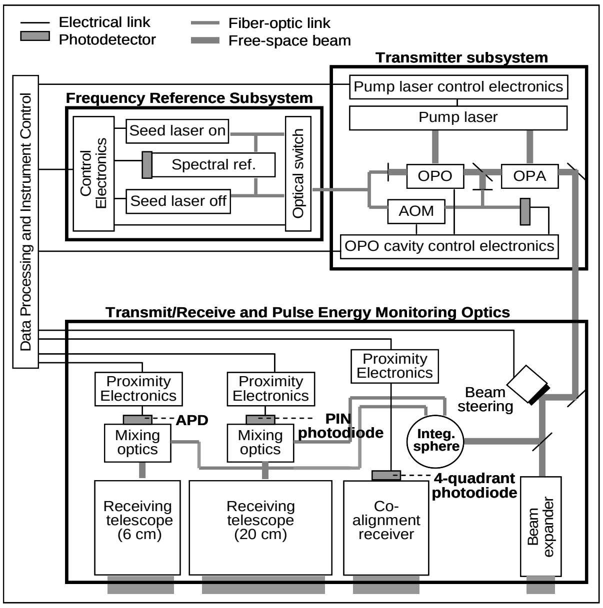

Figure 2. CHARM-F architecture (for one trace gas).

CHARM-F consists of two largely independent and identical lidar systems (one per trace gas), each including one Frequency Reference Subsystem, one Transmitter Subsystem, and one set of Transmit/Receive/Pulse Energy Monitoring Optics and detection chains, as depicted on Fig. 2.

3.2 Transmitter Subsystem

Each Transmitter Subsystem includes a pump laser and a frequency conversion stage.

The pump lasers are two identical double-pulse, Q-switched, diode-pumped Nd:YAG lasers developed by Fraunhofer Institute for Laser Technology (ILT), delivering double pulses at a pulse-pair frequency of 50 Hz with an inter-pulse delay of 250 μs, corresponding to a footprint co-registration of better than 0.1 m. The frequency conversion stages, under development at DLR, make use of a Master Oscillator/Power Amplifier architecture. Single-mode operation at the required on-line and off-line wavelengths with high spectral purity is achieved by injection seeding of the Optical Parametric Oscillators (OPO). Both the OPO and the Optical Parametric Amplifiers (OPA) are pumped by the same pump laser; the non-linear material of choice for both is KTA. Continuous tuning of the OPO cavities to the seeding wavelengths is achieved by monitoring the beat note between the outgoing pulses and a frequency-shifted portion of the seeding light, in a similar way to the WALES system [5].

In parallel to the MOPA developments at DLR, a solid-state laser with Erbium-doped laser crystal for direct generation of the required wavelength is under investigation at ILT as an alternative transmitter technology. The expected benefits are a very high spectral purity and excellent beam profile.

3.3 Frequency Reference Subsystem

Each Frequency Reference Subsystem includes a set of continuous-wave lasers dedicated to injection seeding of the OPO, suitable spectral references for frequency-locking the seed lasers at the required frequencies, and a fast telecom-type optical switch for alternatively seeding the OPO with the on-line and off-line seed laser in a synchronized way with the pulse pairs.

For CH_4, Distributed Feed-Back laser diodes deliver the seeding radiation while for CO_2, fiber lasers provide the "cleaner" behavior (linewidth < 5 kHz, good short-term stability) required for precise and reliable locking at the sub-100 kHz level. Currently investigated locking methods include the combined use of a tunable, relative spectral reference with sharp spectral features and good short-term stability such as a temperature-stabilized confocal Fabry-Pérot Etalon and an absolute reference - multipass absorption cell filled with low-pressure CO_2 or CH_4 - for locking the relative reference itself.

The development of this subsystem is greatly facilitated at DLR by a GPS-stabilized Frequency Comb (FC-1500, Menlo Systems), serving as an absolute reference with an estimated long-term stability of 500 Hz for real-time monitoring of the performance of the investigated stabilization schemes.

3.4 Transmit/Receive Optics and Detectors

Nine optical heads are accommodated on an optical bench above one of HALO's 50-cm floor windows: one beam expander and two receivers per trace gas, plus one co-alignment receiver and two contextual cameras (not shown on Fig. 2).

In the 1.6 µm region, preliminary performance analyses have shown that a small receiving entrance aperture of 6 cm was sufficient in combination with off-the-shelf InGaAs Avalanche Photodiodes (APDs) with a suitable bandwidth for the required ranging precision. A significant drawback of InGaAs APDs, however, is the currently limited available active diameter, a mere 0.2 mm. This, together with the large required field of view, drives the F-number of the receiving optics towards a challenging value of slightly less than 1. Considering the increased impact of pulse-to-pulse pointing and/or footprint size variations with such tight margins, it was decided to implement a second receiver built around a PIN photodiode with an active diameter of 1 mm. A larger aperture of 20 cm is used to partly compensate for the lower detectivity of this type of detector. Both receivers feature a narrow bandpass filter for solar background rejection. They will be used simultaneously during the flight campaigns.

For real-time monitoring of the transmitter/receivers co-alignment and subsequent correction of the pointing drifts via beam steering, an additional receiver with four-quadrant photodiode is considered.

3.5 Pulse Energy Monitoring Optics

In order to "calibrate" the measurement of $d\Delta$ with the relative outgoing pulse energies corrected for the relative overall optical efficiency, a small fraction of the outgoing beams is sampled out and spatially- and polarization-scrambled by means of an integrating sphere. The sphere also provides further attenuation, so that the sampled light can be measured by the very same photodetector as the backscattered light without the need for an increased dynamic range. Using the same photodetector for both avoids biases linked with unknown discrepancies in the gains and offsets of two distinct detection chains. "Mixing optics" within each receiver merge the backscatter path and the pulse energy monitoring path sufficiently far upstream of the photodetector that critical elements with a spectral response function that is highly dependent on the incident geometry - such as the bandpass filter - are "seen" by the sampled light with the same incident geometry.

4. AIRCRAFT

DLR's new High Altitude, LOng-range research aircraft (HALO) is a modified Gulfstream G550. Its range of up to 9000 km will allow a truly regional scale to be reached. Moreover, the high flight altitude (10-15 km) ensures conditions very similar to the spaceborne case, since little CO_2 or CH_4 absorption takes place above this. The aircraft is equipped with a number of permanent in-situ sensors, in particular giving access to atmospheric pressure at the flight level, which will help to constrain the auxiliary data from NWP models.

ACKNOWLEDGEMENT

Funding for the development of CHARM-F is provided by the German Federal Ministry of Education and Research (BMBF). In addition, the European Space Agency supports the MOPA activities for CO_2 at DLR.

REFERENCES

[1] IPCC, 2007: "Fourth Assessment Report of the Intergovernmental Panel on Climate Change", Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

[2] Ehret, Kiemle, 2005: "Requirements Definition for Future DIAL Instruments - Final Report" *ESA Study 10880/03/NL/FF*

[3] European Space Agency, 2008: "Advanced Space Carbon and Climate Observation of Planet Earth, Report for Assessment", *ESA SP1313/1*

[4] Fix et al, 2004: "CHARM – A helicopter-borne lidar system for pipeline monitoring", *Proceedings of the 22nd International Laser Radar Conference*

[5] Wirth et al, 2009: "The airborne multi-wavelength water vapor differential absorption lidar WALES: system design and performance" *Applied Physics B: Lasers and Optics*, vol.96, no.1, pp.201–213

[6] Amediek et al, 2009: "Airborne lidar reflectance measurements at 1.57µm in support of the A-SCOPE mission for atmospheric CO2", *Atmospheric Measurement Techniques*, vol.2, pp.755-772.

[7] Ehret et al, 2008: "Space-borne remote sensing of CO2, CH4, and N2O by integrated path differential absorption lidar: a sensitivity analysis," *Applied Physics B: Lasers and Optics*, vol.90, no.1, pp.593-608.

[8] Rothman et al, 2009: "The HITRAN 2008 molecular spectroscopic database", *Journal of Quantitative Spectroscopy & Radiative Transfer* 110, pp.533–572

[9] Caron and Durand, 2009: "Operating wavelengths optimization for a spaceborne lidar measuring atmospheric CO_2", *Applied Optics*, vol.48, iss.28, pp.5413-5422.