ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

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International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 105621W · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296197

ON THE BENEFIT OF AIRBORNE DEMONSTRATORS FOR SPACE BORNE LIDAR MISSIONS

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I. INTRODUCTION

Light detection and ranging (lidar) using lasers is an attractive technique to remotely detect a variety of atmospheric parameters from space. It is independent of sunlight, provides accurate ranging information, and high accuracy of the target parameters.

In the past years, various missions using different lidar techniques were proposed for Earth observation. Current European lidar missions are ADM-Aeolus and EarthCARE in the framework of ESA's Living Planet Programme, as well as the German-French climate mission MERLIN jointly prepared by DLR and CNES. ADM-Aeolus is foreseen for launch in 2017 and will provide global wind information by means of a direct detection Doppler wind lidar. EarthCARE comprises a high spectral resolution lidar (HSRL) for cloud and aerosol studies and is foreseen for launch in 2018. MERLIN is an integrated path differential absorption lidar (IPDA) dedicated to measure the atmospheric column of the second most important anthropogenic greenhouse gas after carbon dioxide: methane. MERLIN's launch is scheduled for 2020.

Furthermore, two lidar mission proposals were investigated by ESA up to the level of phase-A studies namely WALES (WAter vapour Lidar Experiment in Space) and A-SCOPE (Advanced Space Carbon and Climate Observation of Planet Earth) but were put on hold due to missing heritage or lacking technology readiness level.

Within this contribution we would take up the cudgels for the development and application of airborne demonstrators to advance current and upcoming space borne lidar missions. Airborne lidar demonstrators help to address technological challenges associated for example with laser development, frequency stabilisation, or detection schemes in a relevant environment. Due to their downward looking geometry they are indispensable for algorithm development, improvement, and testing. In addition, all these instruments constitute important validation capabilities not only for active but also for passive space borne remote sensors.

At the Institute of Atmospheric Physics of the German Aerospace Centre (DLR) there has been a long-standing tradition in developing airborne lidar systems. Those systems have widely been used in airborne campaigns on the DLR Falcon and German HALO aircraft (Fig. 1) to address current scientific issues in atmospheric research. At the same time, the technological and scientific results stimulated new ideas for space borne instruments or missions.

In the following, an overview will be given spanning from early investigations to latest developments.

(a) (b)

Fig. 1. Photographs of the airborne platforms carrying the DLR lidar systems.
(a): DLR's Falcon 20 (D-CMET); (b): HALO, the German High Altitude Long Range research aircraft (D-ADLR). Here, the bellypod which can e.g. accommodate a radar antenna and an optical window aperture simultaneously is mounted below the aircraft's fuselage.

II. AIRBORNE LIDAR DEVELOPMENTS AT DLR

A. *Early investigations*

One of the first applications of a lidar developed at DLR for the benefit of a space borne mission dates back to as early as 1994 when simultaneous and co-located backscatter data of cirrus clouds were taken with the first space borne lidar instrument (LITE) [1][2]. The objective of the NASA LITE program was to demonstrate the measurement capabilities of a lidar system in orbit [3]. It was operated between 2 September and 19 September 1994 aboard the space shuttle and measured the range resolved backscatter of laser pulses at 1064 nm, 532 nm, and 354 nm wavelengths. To validate the LITE data products, DLR performed correlative measurement using the airborne lidar experiment (ALEX) on board the research aircraft Falcon (Fig. 1). This airborne lidar system was based on a flashlamp-pumped Nd:YAG laser with frequency doubling and tripling an thus was almost identical to the space borne experiment. Fig. 2 shows the backscatter ratio at 532 nm of one out of seven underflown orbits of the shuttle, recorded during night time over the North Sea. There is an excellent agreement between the two instruments despite the fact that the airborne measurement took about 30 minutes whereas the shuttle flew over the same scene in less than a minute. An important finding was that for the space geometry multiple scattering becomes an issue and must not be neglected in the aerosol optical depth calculations.

(a) (b)

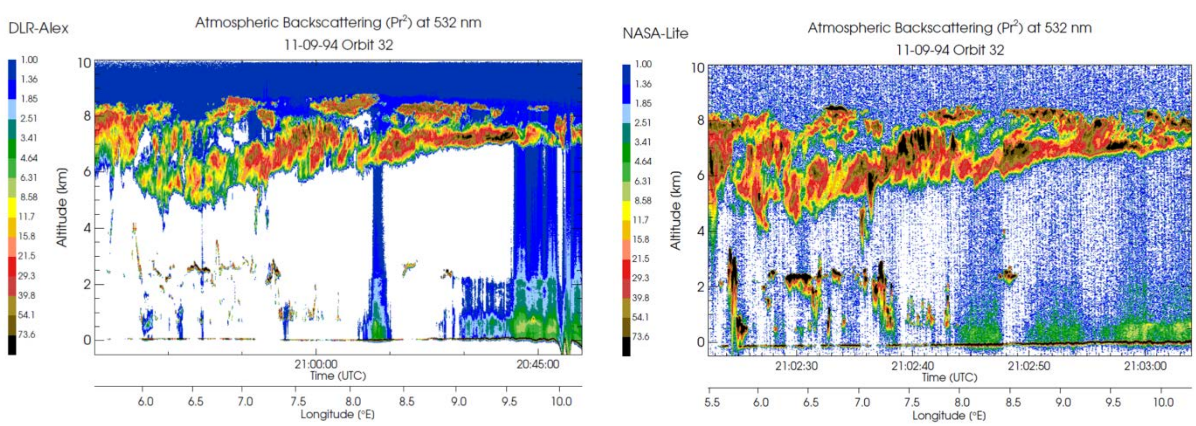

Fig. 2. Comparison between the airborne DLR lidar ALEX on board the Falcon (a) and the shuttle lidar LITE of NASA (b).

The experience gained from LITE are considered indispensable for conducting the CALIPSO mission and equally are for the upcoming EarthCARE mission of ESA scheduled for launch in 2018.

B. AEOLUS airborne demonstrator (A2D) for wind measurements

Measurements of winds throughout the atmosphere and their assimilation into numerical models are crucial for both numerical weather prediction and climate studies. ESA's Atmospheric Dynamics Mission ADM-Aeolus scheduled for launch in 2017 will be the first mission worldwide to provide global observations of wind profiles throughout the whole troposphere and stratosphere. The single payload consists of the direct-detection wind lidar ALADIN (Atmospheric Laser Doppler Instrument) operating at an ultraviolet wavelength of 355 nm and separately analyses the Doppler shift by aerosols and molecules using a Mie and Rayleigh interferometer [4].

At the time when ADM-Aeolus was selected for implementation as ESA's second Earth Explorer Core Mission, the feasibility of the measurement concept had not been proven in a downward looking configuration. Therefore it was decided to start the development of an airborne demonstrator (A2D: the ALADIN airborne demonstrator) representative of the space instrument. Its purpose is to validate the instrument principle with real atmospheric signals and to provide an independent instrument for future validation of the ALADIN instrument. It is the first of its kind to demonstrate the measurement technique of ADM-Aeolus in a downward-looking geometry.

After realisation of A2D [5], a multi-year pre-launch validation project including ground-based and airborne campaigns on the Falcon (Fig. 1) was performed. Algorithms and measurement principle were validated by means of a second wind lidar using a coherent detection method at a wavelength of 2 µm on-board the same platform (Fig. 3a) [6]. In the course of the campaigns relevant experiences were gained. Those resulted in more than hundred recommendations to the ADM-Aeolus mission related to characterization, alignment, testing, in-orbit operation, calibration, and retrieval optimisation. As a measurement example performed during the pre-launch validation activities, Fig. 3b shows the retrieved wind velocity of A2D's Rayleigh and Mie channels in comparison to the 2-µm lidar during a flight leg near the Greenlandic coast [7].

(a) (b)

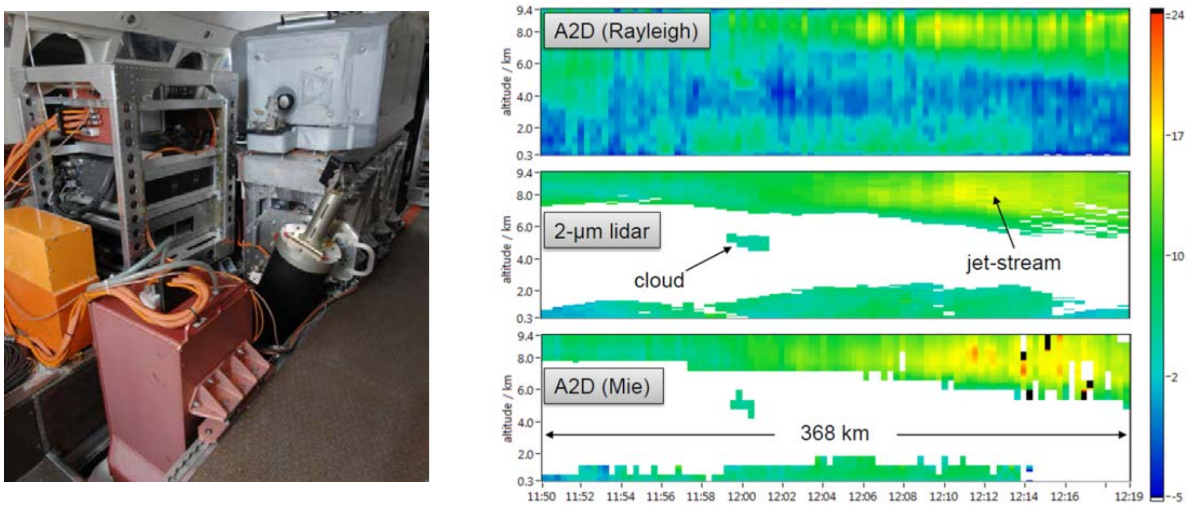

Fig. 3. (a): The ALADIN airborne demonstrator (A2D), in the background, mounted together with the 2-µm wind lidar onboard the Falcon. (b): Wind measurements from a 367 km long flight track along the East coast of Greenland with the 2-µm wind lidar (middle), the A2D Rayleigh (top) and Mie channel (bottom) on 26 September 2009.

Currently, the payload described above is prepared to take part in The North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX) which is an international field experiment targeted at increasing the physical understanding about the effects of diabatic processes on disturbances to the jet stream near North America, their influence on downstream propagation across the North Atlantic, and consequences for high-impact weather in Europe. In parallel, the laser of A2D is upgraded with higher power and efficiency.

C. WALES airborne demonstrator for water vapour measurements

Water vapour is a key component for virtually all atmospheric processes related to weather, cloud formation, radiative transfer, chemistry, and climate. Our ability to measure water vapour on global scales from the boundary layer to the lower stratosphere thus is considered of utmost importance. Despite large efforts in the past, the global observation system which is mainly based on radiosondes and passive satellite sensor does not fulfil contemporary needs. The former do not cover the globe uniformly and do not provide reliable water vapour observations in the upper troposphere and lower stratosphere, the latter suffer from insufficient vertical resolution and accuracy. Radio occultations show promise but suffer from poor horizontal resolution.

In contrast, water vapour differential absorption lidar (DIAL) in space has the potential for high accuracy measurements of humidity throughout the entire troposphere and lower stratosphere with high horizontal and vertical resolution. The technique is self-calibrating and not prone to biases resulting from aerosol or cloud contamination. Moreover, water vapour profiles can be retrieved during day and night, at all latitudes, and during all seasons.

This has long been recognized and first proposals for space-borne H_2O-DIALs date back more than 30 years ago [8]. In contrast to the situation with wind measurements where no instrument for the direct Doppler detection lidar from aircraft had existed, several airborne H_2O-DIALs had been developed at NASA, DLR and CNES/CNRS and demonstrated their potential. However, those early systems were based on technologies not suitable for space, such as dye lasers, had significant problems in achieving the required spectral properties, and some were lacking coverage of the upper troposphere.

In response of an ESA call for core mission ideas for the Living Planet Programme in 2000 the "Water Vapour Lidar Experiment in Space (WALES)" was devised and subsequently investigated at the level of a phase A study [9]. However, this mission idea was finally put on hold due to insufficient technology readiness level, mainly concerning the missing maturity of highly efficient solid-state laser systems in the 935-nm absorption band of H_2O which was identified as the wavelength of choice [10]. The mission concept foresaw the use of four individual wavelengths within a narrow spectral interval each one especially adapted to a restricted altitude range of the atmosphere. In this way relatively large absorption coefficients can be chosen, which allows for short averaging times even at high noise levels, thus lowering the system's power-aperture product considerably.

In order to prove the novel four-wavelength concept and to advance the technology readiness level, DLR developed a WALES airborne demonstrator. This instrument not only implements the basic concept envisaged for a space borne system, but is also based on laser technology which is suited for in-space operation by using high efficiency solid state lasers and non-linear conversion techniques. The system's transmitter system is robust, highly compact and efficient and fulfils all spectral requirements for a water vapour DIAL [11]. It consists of two identical diode-pumped Nd:YAG lasers in a master-oscillator power amplifier architecture at a repetition frequency of 100 Hz. The fundamental of the two lasers are frequency converted to 532 nm. This radiation pumps two optical parametric oscillators (OPO) using potassium titanyl phosphate (KTP) as their nonlinear material. Each OPO generates two adjacent wavelengths whose wavelength is defined by means of injection seeding from four individual distributed feedback diode lasers (DFB). By means of a water vapour absorption cell and a wavemeter all four wavelengths are controlled to achieve their set wavelength to better than 60 MHz.

(a) (b)

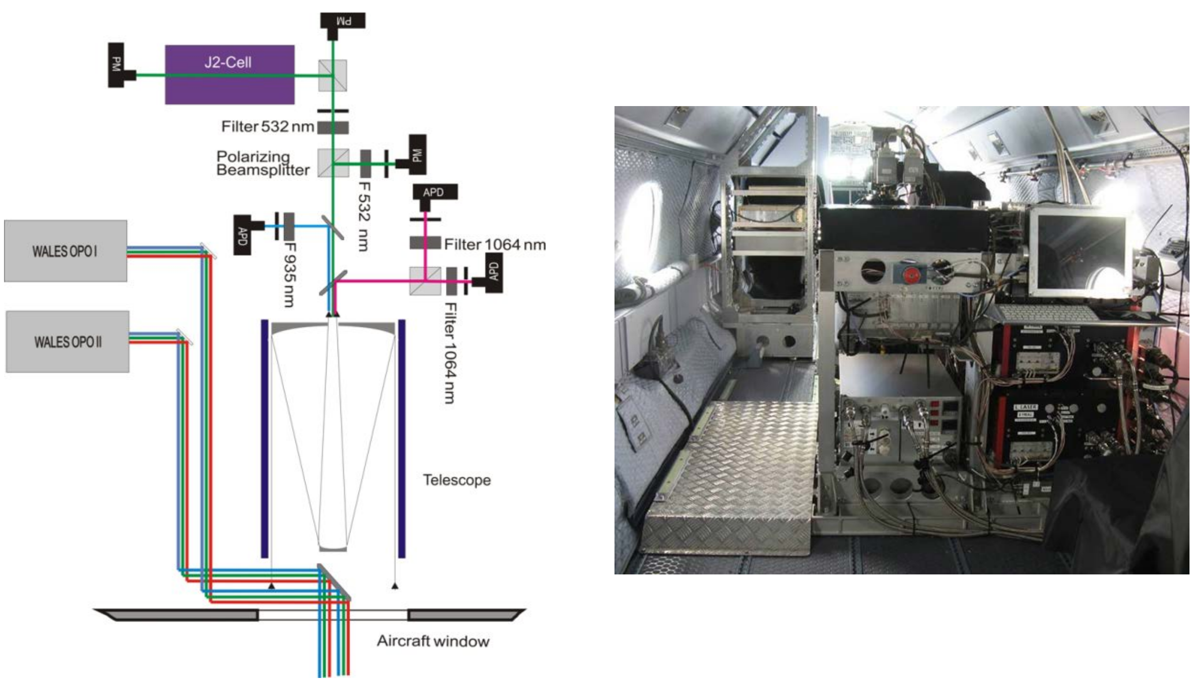

Fig. 4. (a) Schematic set-up of the WALES system and (b) a photograph of the system installed on-board HALO.

Up to 9 W of 935-nm radiation is emitted and the pump light which is not converted by frequency conversion is also transmitted into the atmosphere and used for aerosol measurements. The receiver uses 48-cm Cassegrainian telescope which can either be mounted in nadir or zenith-looking configuration. The different wavelengths are separated by dielectrical beamsplitters and individually detected (Fig. 4a). In addition, the receiver section simultaneously features a high-spectral-resolution lidar (HSRL) receiver for aerosol and cloud investigations (see section D).

The instrument was flown on board both research aircraft, Falcon and HALO (Fig. 4b), whereby it could be proven that using four different wavelengths in the 935-nm absorption band of H_2O as proposed for WALES are indeed adequate to retrieve highly resolved and accurate water vapour profiles from the boundary layer to the lower stratosphere. Due to its capabilities the WALES airborne demonstrator has turned into a state-of-the-art instrument for topical climate and meteorological research. Currently it has successfully completed several hundreds of flight hours within national and international field campaigns. Fig. 5 shows an example of the water vapour distribution over the Atlantic Ocean during a HALO flight from Europe to Barbados.

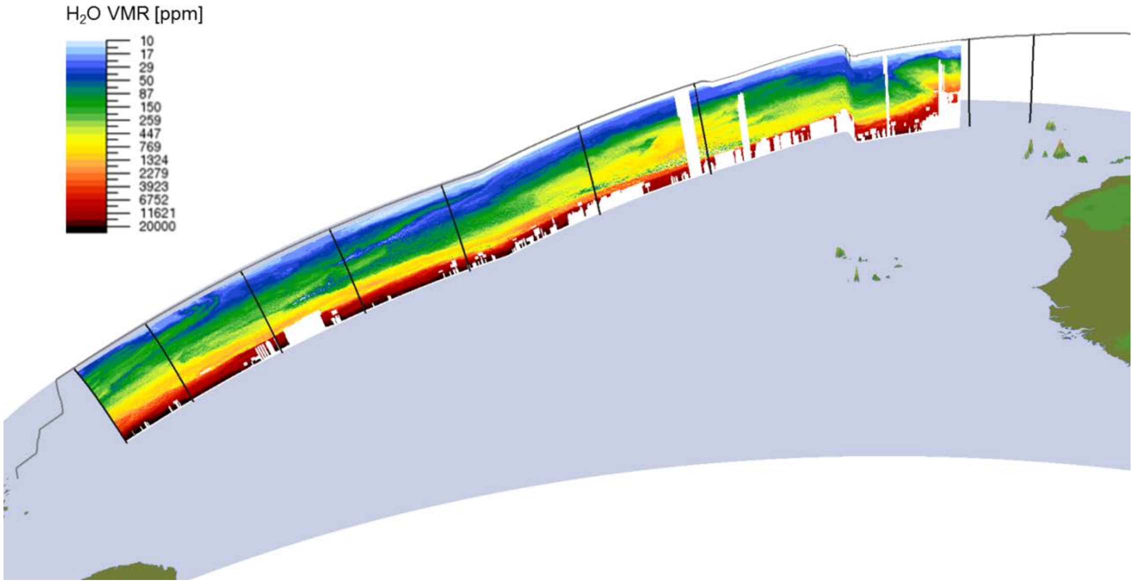

Fig. 5 Example of a water vapour measurement perfomed onboard HALO from a flight level of ~13 km on a flight off the African coast over the Atlantic to Barbados.

D. The WALES system as an EarthCARE demonstrator

To characterize the effects of aerosols in global climate models, the spatial and temporal distribution of different aerosol types has to be known. Owing to the high variability of aerosols, and their different impact on the Earth's climate system, aerosol type classification from satellite measurements is of high importance. Polarization sensitive lidar measurements on board the future EarthCARE satellite mission will provide information that can be used to distinguish different aerosol types [12].

As mentioned above, the WALES demonstrator - next to its water vapour profiling capacity - also operates as a High Spectral Resolution Lidar (HSRL) for aerosol and cloud studies. This is realised by means of an iodine cell in the receiving path of the 532-nm radiation (see Fig. 4a) which allows separating the molecular from the particulate backscatter signal [13]. Together with depolarisation channels at both, 1064-nm and 532-nm wavelengths important aerosol parameters can be retrieved: lidar ratio (extinction-to-backscatter ratio) and particle linear polarisation ratio. Based on data from past campaigns and back-trajectory analyses a classification scheme was devised to identify different aerosol types from such lidar measurements [14].

This is an important result for the upcoming EarthCARE mission since the ATLID lidar on board this satellite will also provide information about polarization and lidar ratio. Next to the ATLID lidar, three more instruments will be on board. Particularly noteworthy is the 94-GHz Cloud profiling radar (CPR) which is a provision of the Japanese Aerospace Exploration Agency (JAXA) to the EarthCARE mission and the first atmospheric radar in space with Doppler capability. The combination of lidar and radar not only provides a much more complete height-resolved detection of the presence of clouds but can also provide quantitative information on the cloud particle size and water content by exploiting the different response to particle size between the two wavelengths [12].

In order to investigate the lidar-radar synergy, HALO has been equipped with a microwave package including a 36-GHz radar (jointly operated by Max-Planck-Institute Hamburg and DLR). In order to accommodate the radar antenna a bellypod is mounted below the fuselage of HALO. To enable unobstructed view for the lidar through this structure, the bellypod also comprises a section that hosts a large optical viewport. This structure can be seen on the photograph in Fig. 1b.

Despite the fact that both lidar and radar do not have the identical wavelength as their EarthCARE counterparts (532 nm vs. 355 nm and 36 GHz vs. 94 GHz, respectively) this unique instrument combination nevertheless constitutes an important asset for investigating the lidar-radar synergy and for future validation of EarthCARE. At the time of writing, HALO and this instrument package returned from a successful campaign in the Caribbean focussing on shallow clouds in the trades and is now currently preparing to also take part in The North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX), see Section B.

D. CHARM-F, an airborne demonstrator for methane and carbon dioxide IPDA

Climate Change is one of the paramount societal challenges of our time. The main cause for global warming is the dramatic increase of greenhouse gases (GHGs) in the Earth's atmosphere originating mainly from increasing anthropogenic emissions since the beginning of the industrial era. Carbon dioxide (CO_2) and methane (CH_4) are the two most important anthropogenic GHGs contributing to global radiative forcing. Large uncertainties in their budget, however, and feedback mechanisms which are poorly 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 CO_2 and CH_4 is still inadequate. Therefore, Carbon Feedbacks in the Climate System has been defined as one of the Grand Challenges of the World Climate Research Program (WCRP).

The Integrated Path Differential Absorption Lidar (IPDA) technique using hard target reflection in the near IR has the potential to deliver CO_2 and CH_4 column measurements from space with unprecedented accuracy [15]. IPDA largely eliminates the contribution of atmospheric scattering by particles and clouds which greatly affects the achievable accuracy of passive remote sensing instruments.

Comprising a nadir-viewing CO_2 IPDA instrument as the core element, A-SCOPE (Advanced Space Carbon and Climate Observation of Planet Earth) was investigated by ESA as a prephase-A Earth Explorer Mission [16]. A-SCOPE did not yet advance for later phases of the Earth Explorers core missions due to lacking technology readiness, however, technology studies are continued. NASA is pursuing a similar concept with ASCENDS (Active Sensing of CO2 Emissions over Nights, Days, and Seasons) [17]. On the other hand, it turns out that IPDA measurements of methane are easier in terms of instrument performance and thus doable from a comparatively small satellite [18]. For this reason the German and French space agencies (DLR and CNES) initiated MERLIN, the Methane Remote Sensing LIDAR Mission, planned for launch in 2020 for methane (CH4) as the target greenhouse gas [19].

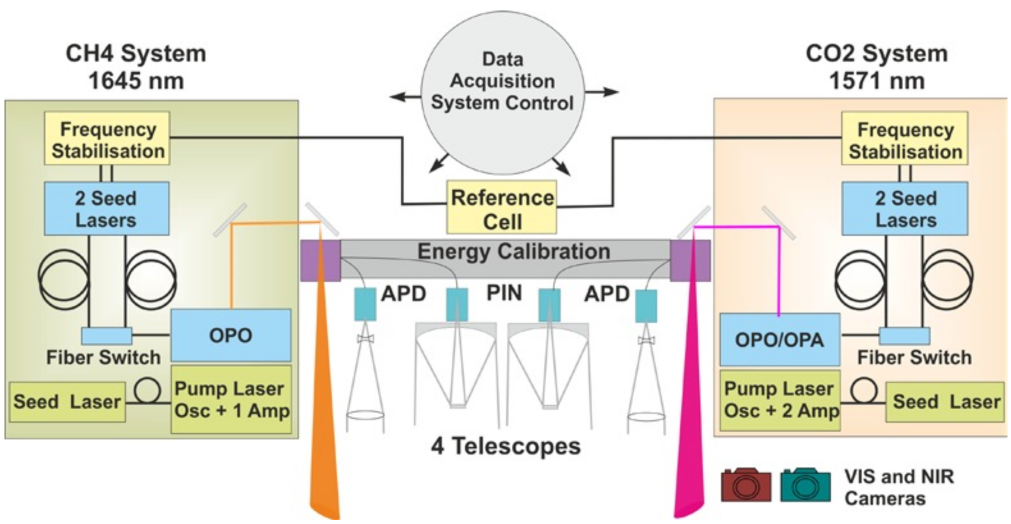

Fig. 6. Schematic set-up of the airborne CO_2 and CH_4 integrated path differential absorption lidar.

In order to support MERLIN but also advance the A-Scope concept, DLR devised CHARM-F, an airborne IPDA system which is able to simultaneously measure both greenhouse gases, CH_4 and CO_2. In particular, an airborne geometry is important to mimic the satellite instrument which uses the backscattered radiation from hard targets such as the ground or clouds. The schematic concept of this system is depicted in Fig. 6. The entire instrument consists of two sub-systems. The first one generates short laser pulses around 1645 nm targeted to measure CH_4 while the second one operates at wave-lengths around 1571 nm optimized for the detection of CO_2. Of paramount importance is the frequency stabilisation system since the required frequency stability of the on-line and off-line wavelength is extremely demanding. For this purpose a sophisticated frequency reference unit has been developed consisting of various distributed feedback diode and fibre lasers. In general, two reference lasers are stabilised onto well-known 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 lasers locked with a defined offset to their references. By means of fibre optic transmission lines and fast fibre-optic switches, the narrowband radiation is guided to the OPOs to generate spectrally narrow-band, powerful laser pulses by virtue of the injection seeding technique [20].

All development steps for CHARM-F concerning data acquisition, frequency reference and stabilisation concept, and energy calibration strongly benefited from the experience made during the development of other airborne lidars such as WALES and also ongoing technology studies in the framework to support future space borne lidar missions.

(a) (b)

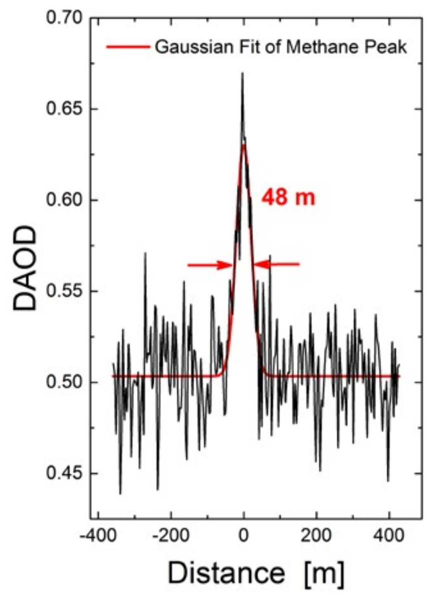

Fig. 7. CHARM-F, the combined CO_2 and CH_4 IPDA installed on-board the HALO research aircraft (a) and a narrow methane plume detected as an enhancement of the differential absorption optical depth (DAOD) along the flight path (b).

Recently, the first test flights of CHARM-F were successfully completed on-board HALO (Fig. 7a). Noteworthy results are a measured precision for 1-s averages of 0. 7% and 1.2% for the CO_2 and CH_4 column, respectively, as well as the identification of a methane plume from a ventilation shaft of a coal mine (Fig. 7b). First scientific flights employing CHARM-F in combination with other sophisticated sensors on-board HALO are foreseen in spring of 2017. During those flights it is also planned to validate the methane product of the passive TROPOMI instrument on the Sentinel-5P satellite.

III. SUMMARY

Space borne lidar is regarded as an innovative component of the meteorological and environmental observing system. It bears the potential to directly sample the four-dimensional variability of the atmosphere with unprecedented accuracy and spatial resolution. This measurement technique can establish independent sets of data products of various atmospheric parameters and species that will help to answer scientific questions related to global change analysis of the Earth's climate, atmospheric chemistry, atmospheric dynamics and the hydrological cycle.

However, in order to advance this technology we are convinced that a roadmap to support continuous development and improvement of airborne demonstrators and their deployment in airborne science campaigns is indispensable. Airborne demonstrators help to overcome technological challenges, investigate sub-systems such as innovative frequency stabilisations schemes (e.g. [21]) in relevant environments, test algorithms under realistic conditions with real data, and provide important means to increase the technological readiness level on a sub-orbital platform. This has impressively been shown in the course of the development of the series of airborne lidars at DLR in the past years. In addition those devices turn out to be state-of-the-art instruments with a remarkable and growing demand by the scientific community for airborne field campaigns. Finally, they are regarded an essential component for validation of space borne active and passive remote sensing instruments. Thus the airborne demonstrator activities at DLR aim at improving both the technology and science readiness level for current and future space borne lidar missions.

In view of the progress made, the feasibility of space borne lidar mission dedicated to water vapour and carbon dioxide should be revisited and new horizons opened in fields such as fluorescence or mesospheric lidars.

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