Double-Lidar airborne mission over Scandinavia for atmospheric transport assessment of CH4 and CO2

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Abstract. An international campaign named MAGIC-2021 took place in August 2021 in Scandinavia to study CH_4 and CO_2 regional emissions and transport. During this campaign, a double-lidar airborne experiment was carried on to perform simultaneous measurements of CO_2/CH_4 with an IPDA lidar as well as range-resolved wind profiles with a coherent wind lidar. This paper details the lidar payload of this experiment, and reports very preliminary results obtained for both lidars.

Keywords: Airborne, Dial, Doppler, CO_2, CH_4.

1 Airborne lidars for the MAGIC 2021 Campaign

In August 2021 took place in northern Scandinavia the MAGIC-2021 campaign, dedicated to the Monitoring of Atmospheric composition and Greenhouse gases through multi-Instruments Campaigns. Gathering an international consortium of about 80 scientists (17 research teams from 7 countries), the campaign involved a large suite of instruments and payloads (ground-based, balloon-borne, and airborne). Among them, an original combination of two airborne lidars was deployed onboard the same aircraft (French SAFIRE ATR42): on one side DLR's CHARM-F direct detection lidar for CH_4 and CO_2 measurement in IPDA mode (Integrated Path Differential Absorption), and on the other side ONERA's LIVE coherent lidar for range-resolved vertical wind vector profiles.

The scientific goal of this double-lidar experiment was to record greenhouse gas (GHG) concentration and wind data with very good temporal and spatial matching, so as to characterize GHG atmospheric transport and then infer regional fluxes. Indeed, the boreal region is known to host significant sources of CH_4, either anthropogenic (gas and oil platforms) or natural (wetlands, peat bogs, lakes…). Moreover, high latitudes are generally considered to be a sink for atmospheric CO_2 (though this effect could be strongly impacted by the rapid climate warming at these latitudes). However, due to the low population density and harsh environment, the boreal area is poorly covered by in-situ instrumentation. Airborne measurements appear as a well-suited solution for monitoring GHG on large spatial scales, especially in such areas.

The airborne campaign was based in Kiruna (Sweden), and lasted 10 days. Though it suffered from poor weather conditions, six flights were successfully completed by the ATR42 above northern Sweden, Finland, and Norway. CHARM-F and LIVE lidars operated nominally during those flights, collecting hours of data in various sky conditions (clear, haze, broken clouds…). In this paper, we detail the lidar setups on board the aircraft and we show preliminary results from selected flights.

2 Double-Lidar airborne payload

2.1 The aircraft

The F-HMTO ATR42 belongs to the French SAFIRE fleet. It is a twin-engine regional propeller aircraft, modified to carry and operate scientific instruments. It is equipped with a comprehensive flight test instrumentation (FTI): inertial measurement unit, radio altimeter, pressure and temperature sensors. The usual scientific payload of the aircraft is 2 500 kg, and the power supplied is up to 20 kVA. The aircraft can fly up to 7 000 m high, and its flying speed ranges from 70 up to 134 $m.s^{-1}$. It is equipped with many portholes dedicated to sensors. The two lidars used the largest ones, located in the belly of the aircraft and oriented to nadir.

2.2 DLR CHARM-F IPDA Lidar for CO_2 and CH_4 monitoring

CHARM-F in an integrated path differential absorption lidar (IPDA) and was developed for the simultaneous measurement of atmospheric CO_2 and CH_4 onboard aircraft [1]. The purpose is to derive the weighted, column-averaged dry-air mixing ratios of the two gases, commonly denoted as XCO2 and XCH4, with high precision and accuracy between aircraft and ground, or cloud tops. Originally, CHARM-F was developed for operation in the German research aircraft HALO (High Altitude and Long Range Research Aircraft) and acts as a demonstrator for the upcoming German-French spaceborne methane mission MERLIN [2]. During MAGIC, the system was deployed for the first time onboard the ATR42 aircraft. This deployment required specific modifications of the instrument concerning e.g. the optical windows, electrical power supply and mechanical integration (Fig. 1).

Fig. 1. Left: Photograph of the CHARM-F integrated path differential absorption lidar as installed into the French ATR42 aircraft. The instrument consists of two electronics racks and the central optics box containing the lasers, telescopes and detectors. Right: Picture of the optical viewport integrated into the fuselage of the aircraft.

CHARM-F's lidar transmitter is based on two optical parametric oscillators which are pumped by means of diode-pumped, injection seeded, and Q-switched Nd:YAG lasers in a master-oscillator power-amplifier configuration. Two sets of wavelengths are generated in double pulses at ~1645 nm (for CH_4) and ~1572 nm (for CO_2). At both wavelengths, an energy of ~ 10 mJ per pulse is generated within a pulse length of ~ 20 ns. The laser beams are emitted perpendicularly to the aircraft axis. The receiving system consists of two telescopes for each wavelength range, one (200 mm diameter) attached to an InGaAs pin diode, and another smaller telescope (60 mm) equipped with an InGaAs avalanche photodiode (APD). This redundant measurement capacity proves to be valuable for an independent quality assessment of the data. Typical measurement precision is below 0.5% for 10-km averages along the flight track.

2.3 ONERA LIVE coherent wind Lidar

LIVE is a coherent wind lidar (CWL) developed at ONERA. It is built around a homemade 1.55 µm fiber laser, delivering nearly two times the peak power of a commercial fiber laser. LIVE already flew onboard SAFIRE ATR42 [3], so it was implemented in a similar way for the MAGIC-2021 campaign. Fig. **2** (right) shows a picture of the lidar installed onboard, with an operator in front of the lidar bay. The telescope, mounted in a monostatic setup, is set on top of the 400x700 mm porthole in the back of the aircraft. Fig. **2** (left) is a digital mockup showing how the gimbal scanner is set below the floor. The scanner performs conical scans with a cone's half angle of 15°, and a main axis in the nadir (relative to the aircraft frame of reference). The blue rack inside the bay is the laser rack, placed very close to the top of the telescope, due to the short length of the output fiber of the laser. LIVE delivers and records in real-time line-of-sight wind projections and CNR (Carrier to Noise Ratio). These data can then be post-processed to retrieve vertical profiles of 3D wind vectors under the aircraft. The vertical resolution is about 100 m (pulse-length limited) and the horizontal resolutions is typically 2-3 km depending of the aircraft speed and altitude. Vertical and horizontal wind speed accuracies are typically 0.15 $m.s^{-1}$ and 0.5 $m.s^{-1}$, but of course, they depend of the available aerosol load.

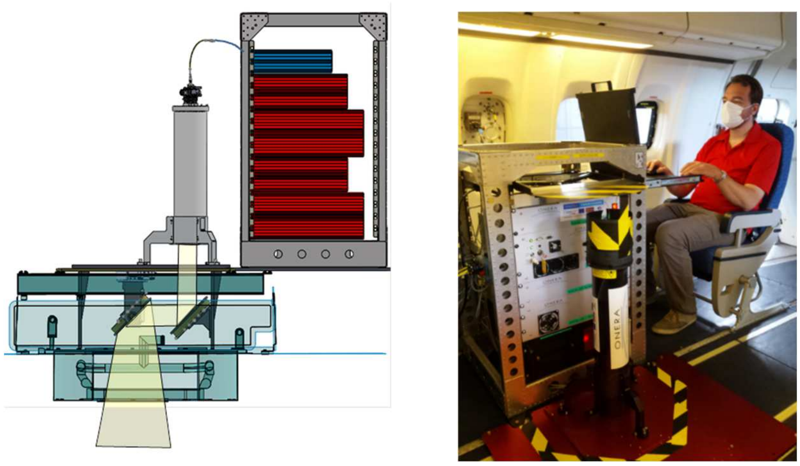

Fig. 2. Left: a digital mockup of the LIVE lidar with its laser and electronics bay, its telescope and gimbal scanner. Right: picture of the lidar setup inside the aircraft.

3 Preliminary results from the MAGIC 2021 flights

3.1 IPDA lidar measurements of CH4 and CO2 with CHARM-F

XCH4 and XCO2 are retrieved according to the method described in [1]. In most cases, the flight altitude of 180kft (~5.5 km) was chosen which appeared to be a good compromise between achieving a good SNR for LIVE down to the ground and inhibiting biases due to overlap issues or detector saturation for CHARM-F. Due to the adverse weather situation and frequent abundance of low and mid level clouds, the data evaluation is not quite straightforward. As a very preliminary example, Figure 3 shows the measurement of XCO2 (left) and XCH4 (right) on a research flight on 23 Aug. 2021 in the vicinity of wetlands in Northern Sweden. The CO_2 concentration is, as expected, very homogenous, while the CH_4 distribution appears to show a gradient with slightly higher values towards the west. Since also an aircraft with in-situ instrumentation onboard was in that area, comparisons are possible to substantiate the results and will be performed in due course.

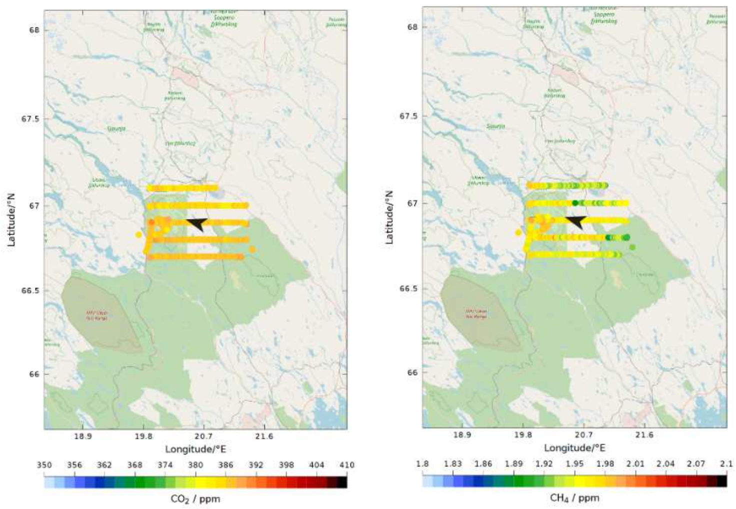

Fig. 3. Very preliminary measurements of CHARM-F from a research flight in northern Sweden. Left: XCO2 along the flight track. Right: Same, but for XCH4.

3.2 3D wind field measurements with LIVE

LIVE signal post processing relies on two algorithms also reviewed in [1] and detailed in [4]: the maximum of the function of the accumulated spectra (MFAS) and wind vector maximum likelihood (WVML). Those algorithms achieve excellent performance for wind vector estimation in conditions of low carrier to noise ratio (CNR), because they perform a global analysis of the spectral data from the whole scan, compared to algorithms considering each line of sight independently from the others. The MFAS and WVML algorithms are therefore able to recover Doppler signal even when the single-line-of-sight signal is very noisy. The following figures show preliminary results of LIVE data recorded during a flight in August 26th morning over Norwegian mountains and sea

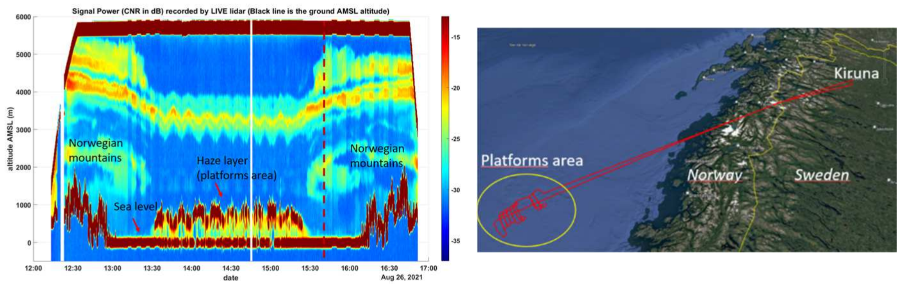

Fig. 4. (Left) CNR profiles recorded with LIVE as a function of time and altitude AMSL (Above Mean Sea Level), during the flight shown at right. The vertical dashed line indicates the time at which the wind profile shown on **Fig. 5** has been computed.

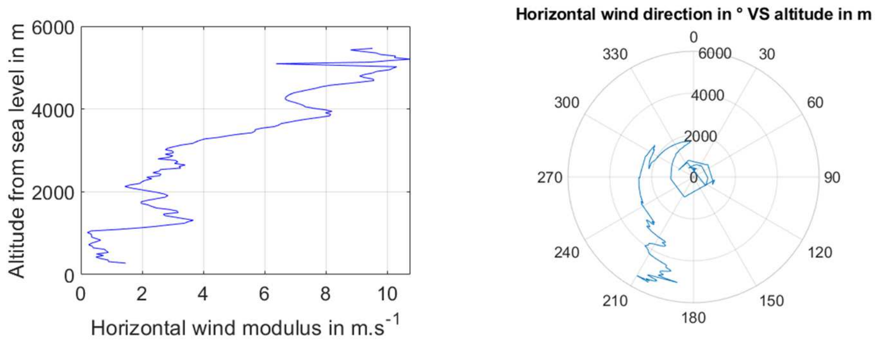

Fig. 5. Vertical wind profile reconstructed from LIVE data on 2021/08/26 at 15:37':18'' (see vertical dashed line on **Fig. 4**). The left and right plots show respectively the wind modulus and direction as a function of altitude.

3.3 Conclusion and future steps

CHARM-F and LIVE lidars have been operated successfully in a simultaneous way to characterize GHG emissions and transport during an airborne campaign in Scandinavia. Future steps will include thorough signal processing of complete flight data, identification of favorable data segments for wind & gas data fusion, and finally attempts to derive emission rates of GHG by combining wind & gas data.

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