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Ongoing activities at LMD to prepare the CH4 space lidar mission MERLIN

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Abstract: MERLIN (MEthane Remote LIdar missioN) is a space mission developed by France and Germany to monitor the atmospheric methane using an IPDA (Integrated Path Differential Absorption) lidar. The mission is scheduled for launch at the end of the decade. Currently, the LMD (Laboratoire de Météorologie Dynamique) is working on improving spectroscopy data, end-to-end modelling of the instrument to study the sensitivity of measurements to different sources of uncertainty, developing an inversion system to study the impact of certain data processing parameters, setting up measurement campaigns to better understand methane variability and fluxes, as well as developing a ground-based differential absorption lidar for CH_4 profiling.

1. Introduction

MERLIN is a space mission developed jointly by CNES and DLR [1]. It is currently being implemented by Airbus Defence and Space. Scheduled for launch at the end of the decade, it will monitor atmospheric methane levels using an Integrated Path Differential Absorption (IPDA) lidar. The lidar emits and receives two frequencies: ν_{on}, which is absorbed by methane, and ν_{off}, which is not.

In the ground segment, the Differential Absorption Optical Depth (DAOD $\delta\tau_{full}$) between the two frequencies is determined from the signal strength measurements for the satellite-target round trip (P_{on}, P_{off}) and for the calibration channel (E_{on}, E_{off}).

$$\delta\tau_{full} = -\frac{1}{2} ln\left(\frac{P_{on}}{E_{on}}\frac{E_{off}}{P_{off}}\right) \quad (1)$$

The calculation of the Scattering Surface Elevation (SSE) involves the angle of incidence of the laser beam (θ), the altitude of the satellite (H_{sat}) and the radius of the Earth (R_{Earth}). The distance between the satellite and the target (dist) is determined from the recorded round trip time between them.

$$SSE = H_{sat} - distcos(\theta) + \frac{\left(distsin(\theta)\right)^2}{2R_{Earth}} \quad (2)$$

The Beer-Lambert law states that the DAOD ($\delta\tau_G(P)$) for a gas G and an echo at a surface pressure P can be calculated using the following equation:

$$\delta\tau_G(P) = \int_0^P X_G\,(p')WF_G(p')dp' \quad (3)$$

$$WF_{G(p)} = \frac{1-q(p)}{g_{(lat,p)}M_d}\left[\sigma_G^{eff}{}_{(\nu_{on},p,T_{(p)})} - \sigma_G^{eff}{}_{(\nu_{off},p,T_{(p)})}\right] \quad (4)$$

where $X_{G(p)}$ is the mole fraction profile with respect to dry air, $g_{(lat,p)}$ is the gravity at the target location (determined by its latitude and pressure), M_d is the mole mass of dry air, T(p) and q(p) are the temperature and specific humidity profile respectively and $\sigma^{eff}{}_{G(\nu np,T)}$ is the effective absorption cross section of one mole of G-Gas at ν-frequency, p-pressure and T-temperature. Absorption cross section (ACS) of the different gases in the MERLIN spectral domain (mainly CH_4, CO_2 and H_2O) are computed from atlases built with the radiative transfer code STRANSAC and the spectroscopic database GEISA. The effective ACS is an average value over the spectral distribution of the laser emission around wavenumber $\nu_{on/off}$.

2. Spectroscopic studies

To improve $\sigma^{eff}_{G(\nu np,T)}$ several studies [2, 3] have focused on the representation of the methane absorption band used by MERLIN.

A new series of R(6) multiplet spectra of the $2\nu_3$ band of methane in air were recorded at LIPhy using a ring cavity spectrometer (CRDS). The spectrometer combined a spectrally narrow and stable (sub-kHz) laser source with a temperature-controlled high-brightness optical cavity. The spectra were recorded between 243 K and 313 K, with a temperature step of 10 K, and for total pressure values of 50, 100, 250, 500, and 750 Torr. The frequency scale of each spectrum was determined with great accuracy.

The spectroscopic parameters and temperature dependence of the line shape parameters for each of the six components of the multiplet are obtained using the Hartmann-Tran line profiles, which include a line mixing parameter. A multi-spectrum fitting procedure is employed.

Comparisons with measurements from the TCCON network indicate a significant improvement in the modelling of methane absorption in this spectral region [4].

Studies are planned to investigate the impact of wet air in absorption line broadening coefficients.

3. Spatial averaging

Due to instrumental noise and speckle [5], single shot-pair measurement cannot be used to derive methane content and averaging must be done over cells of 140 shots-pairs (about 50 km). However, over this distance, variations in meteorological conditions and, more important, changes in ground elevation and reflectivity introduce new sources of variability.

There are several ways to average shot-to-shot data: methane column averaging (AVC), DAOD and IWF averaging (AVD), signal averaging (AVS) or quotient averaging (AVQ). The AVQ method mixes biases of different origins, which cannot be corrected afterwards. Its performance is poor. In the remaining three methods, the mean DAOD estimate must be corrected from a bias due to the non-linearity of the logarithmic function. This bias is SNR dependent.

According to [6], the AVS method outperforms the other two methods, particularly when the estimations of the various terms of the IWF are weighted by the relative signal intensity. This gives more weight to shots-pairs with stronger signals, as in the measurements average.

4. LIDSIM and PROLID

Two software packages have been developed: LIDSIM (LIDar SIMulator) to simulate MERLIN data and PROLID (PROcessor LIDar) to retrieve XCH_4 [7].

The various interactions of the beams with the atmosphere and the Earth's surface are modelled. The emitted energy is assumed to be spectrally distributed according to a Gaussian or other distribution. Spectral impurities may be added.

The Doppler effect due to wind or Earth rotation is negligible, and the spectral broadening due to particles is also negligible compared to that due to molecules.

The absorption properties computed from the thermodynamic properties and composition of the atmosphere (ECMWF data) are used to simulate the photon fluxes arriving at the detector, together with an incident solar spectrum, surface reflectances (MODIS mission data) and various optical features of the instrument, as well as geoid data and a digital elevation model.

The photon fluxes from the measurement and calibration channels are converted into electrical currents and then into discretised potential differences based on the detector and electronic chain specifications.

Random realisations of different noises are considered: speckle noise due to interference on the detector, shot noise due to fluctuations in the number of photons arriving during a given time interval, amplified by the statistical characteristics of the photoelectric and avalanche effects in the photodiode, and electronic noise from the transimpedance amplifier.

The digital counts of the data stream from the satellite are used to evaluate the instrument response function, the statistical characteristics of the dark current and the noise amplification coefficient.

To estimate $P_{On/Off}$ and $E_{ON/OFF}$, the signals are convolved with a function that transforms the instrument response function into a Gaussian.

Then, SSE and X_{CH4} are estimated for each shot and on average for each cell of 140 shots.

These tools have been used in several studies conducted by varying the knowledge of emitted wavelengths, pulse shape, spectral impurities, reflecting surface dispersion, and signal processing parameters.

We simulated a complete orbit and compared a simulation without clouds or aerosols with a simulation with optical properties for clouds and aerosols based on ECMWF data.

In the presence of clouds, in order to estimate the SSE restitution by comparison with the DEM value, it is necessary to filter the shots corresponding to partial columns. By keeping only the shots that reach the ground, we get similar results for the simulations with and without clouds.

Finally, using the measured or estimated instrument characteristics at the end of Phase C, LIDSIM and PROLID confirm that the 'breakthrough' level for X_{CH4} measurement is reached (2 ppb systematic error and 18 ppb random error).

5. Impact of meteorological errors and interpolations

To estimate the error due to uncertainties in the meteorological data we use the 50 members of the ensemble forecast from ECMWF which represent the uncertainties on the meteorological values. In LIDSIM, the atmospheric column over the DEM is simulated with the mean forecast. PROLID then retrieves XCH_4 using the different members.

The errors in the retrieval of XCH_4 were estimated to be 0.4~±~0.6~ppb [8]. These errors are expected to decrease in the future as the ECMWF model improves over time.

Further errors are introduced by horizontal, vertical and temporal interpolations.

Several extrapolation methods, which differ in their assumptions about the temperature and specific humidity gradient below the surface, are compared with each other and with the Apache approach developed at Météo-France. The Apache approach maintains a boundary layer near the ground, regardless of the target topography's elevation relative to the model.

In LIDSIM, the atmospheric column over the DEM is simulated from ECMWF data using one of these interpolations. PROLID then retrieves XCH4 using a different interpolation.

Errors due to vertical interpolation remain below 3 ppb in the worst case, and their standard deviation is 0.1 ppb when relief variations exceed 1 m/km [8]

The effect of tidal waves on time interpolation needs to be investigated, although it seems negligible for a sun-synchronous satellite at 6 am or pm.

6. MAGIC initiative: field experiments for GHGs

The MAGIC initiative, led by the LMD, was launched in 2017. MAGIC has created a multi-team, multi-mission, and multi-instrument framework for the French scientific community. Its objective is to enhance our understanding of the atmospheric distribution of anthropogenic GHGs and their associated fluxes, as well as to validate current and prepare future space missions dedicated to anthropogenic GHGs.

MAGIC is based on the development of measurement networks and annual campaigns. It monitors GHGs concentrations using simultaneously various methods, including ground-level measurements with Picarro, vertical profiles with AirCore, Amulse, and Falcon20, and weighted columns with EM27, Chris, Tccon, Oco-2, Tropomi, and Iasi.

MAGIC currently brings together more than ten European teams.

In 2018, 2019 and 2020, campaigns were carried out at several sites in France to compare the different instruments and to highlight the impact of spectroscopy on the retrieved weighted GHG columns.

The campaigns then focused on studying processes in several key regions: MAGIC2021 in Kiruna (northern Sweden) to study natural and anthropogenic CH_4 and CO_2 emissions at high latitudes, MAGIC2022 and MAGIC2023 near Reims (France) to study anthropogenic CH_4 and CO_2 emissions from a medium-sized city and from nearby biogas plants and industrial sites.

In the near future, contributions to the MicroCarb and IASI-NG cal-val campaigns are planned, as well as a campaign in the tropics awaiting the MERLIN cal-val.

7. MEDAL: CH_4 DIAL development

MEDAL (Methane Differential Absorption Lidar) is a 3-D ground-based differential absorption lidar (DIAL) operating at 1.645 µm. It is currently being developed at LMD and is designed on the same spectral line as MERLIN. MEDAL will contribute to MERLIN in-flight validation by providing optical thicknesses and methane profiles. It will also document the spatio-temporal variability of methane concentration and the heterogeneity of methane surface fluxes. Please refer to the additional paper about 1.645 µm DIAL Er:YAG emitter in this conference for more information.

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