EPJ Web of Conferences **362**, 09011 (2026) https://doi.org/10.1051/epjconf/202636209011
ILRC31/CLRC22-2024

Upper tropospheric water vapor profiles derived from Raman lidar over France territories for contrail investigations

Dunya Alraddawi[(a)], Philippe Keckhut[(a)], Florian Mandija[(a)], Alexis Mariaccia[(a)], Christophe Pietras[(b)] , Jean-Charles Dupont[(C)], Guillaume Payen[(d)], Hélène Vérèmes[(d)], Alain Hauchecorne[(a)] ,Alain Sarkissian[(a)] ,Jean-François Mariscal[(a)] , Jacques Porteneuve[(e)], Jean-Luc Baray[(f)], Nadège Montoux[(f)], Patrick Fréville[(g)], Sergey Khaykin[(a)]

[(a)] LATMOS-IPSL, UMR8190, UVSQ – UPMC – CNRS, Guyancourt, France
[(b)] Laboratoire de Météorologie Dynamique, École Polytechnique, CNRS, Palaiseau, France
[(c)] Institut Pierre-Simon Laplace, École Polytechnique, UVSQ, Université Paris-Saclay, Palaiseau, France
[(d)] LACy, UMR8105, CNRS – Université de la Réunion – Météo-France, Réunion, France
[(e)] Gordien Strato, Verrière le buisson, France
[(f)] LaMP, UMR6016, Université Clermont Auvergne – CNRS, Clermont-Ferrand, France
[(g)]OPGC, UAR833, Université Clermont Auvergne – CNRS, Clermont Ferrand, France

dunya.alraddawi@latmos.ipsl.fr

Abstract: Accurate water vapor measurements in the upper troposphere at cruise altitude are required to investigate contrails formation. We present 4 Raman lidars having these capabilities in France. Water vapor mixing ratio is proportional to the ratio of H_2O and N_2 Raman signals for the same altitude by a scale factor called calibration factor. Coaxial systems can be calibrated with independent measurement of water vapor total column. A more universal external method able to calibrate any lidar (co/non-axial system) is adopted, using co-located ERA5 hourly water vapor profiles. Full night calibration factor is estimated as the mean of hourly coefficients, daily calibrations are inspected to detect any instrumental changes. Final coefficients are then considered for quasi stationary periods. Calibrated profiles are validated against available radiosondes ones. This new software can be used to force models to better understand contrails contribution in future air traffic regulation as part of European project BeCoM.

1. Introduction

Contrails, as cirrus clouds formed along cruise trajectories, have significant radiative feedback, necessitating urgent mitigation efforts[1]. Raman Lidar offers a method for characterizing cloud vertical location and structure [2] as they pass over measurement sites. This technique induces a wavelength shift through the Raman effect, enabling the analysis of contrails within the necessary vertical range. Additionally, it allows for simultaneous water vapor vertical profiling, crucial for continuous monitoring of atmospheric humidity, albeit limited by low cloud presence [3].

Despite its capabilities, lidar water vapor measurements face hardware challenges, such as removing elastic scattering and ensuring sufficient signal strength to reach the tropopause where contrails form. To ensure accuracy, an external calibration approach is mostly adopted, relying on collocated measurements from radiosondes, CFH sondes, and models. However, uncertainties persist due to imperfect alignment between balloon and lidar profiles [4-6]. Advanced techniques involve calibrating with total water vapor columns measured independently but require a coaxial lidar configuration [7].

Lidar-based water vapor measurements, sensitive to atmospheric conditions variability, require a careful calibration strategy. The current research discuss a united long-term calibration approach across multiple lidar sites (systems). As part of the BeCoM project, this research aims to explore the potential contributions of these lidars to contrail investigations. Now, let's briefly overview the current capabilities of the four French lidars.

2. Description of the French lidars

Developed by LATMOS/CNRS and its spin-off company Gordien-Strato, all four lidars feature similar rejection efficiency, with demonstrated removal of elastic signals and unaffected water vapor profiles. Recent designs prioritize avoiding fluorescence effects by omitting optical fibers based on preliminary experiences. More details about these lidars in Table 1.

2.1 IPRAL/SIRTA

A multi-wavelength lidar with six receiving channels, including elastic, Nitrogen, and Water Vapor channels, and polarization channels. It has a signal-to-noise ratio exceeding 3 at altitudes of 10-12 km for a 20-minute integration time, and can operates in automatic mode, ready for simultaneous water vapor and cloud measurements, signal analysis improvement are carried out for water vapor measurements (more details in section 3).

2.2 Lid1200/OPAR

Developed within NDACC, focuses on studying water vapor transport through the tropopause [7]. Built using the historical french expertise, with a coaxial configuration without optical fibers, with 5 channels, including 3 elastic channels for temperature and aerosol retrieval, it provides accurate water vapor observations crucial for assessing meteorological analyses, even if minimal contrails are detected nearby it.

2.3 LTA/OHP

Established in 1995 at the Observatory of Haute Provence, is among the pioneering water vapor lidar systems. Initially built on a Rayleigh system from 1978 for temperature and aerosol measurements. The system underwent modifications for better calibration, including transitioning to a coaxial configuration and thereby removing the optical fibers to address fluorescence effects. hardware modification successfully in place, though signal optimization is pending completion during an upcoming campagne.

2.4 COPLid/CO-PDD

Situated at Cézeaux University near Clermont-Ferrand, this lidar included 355nm channels with Raman and depolarization channels from 2009 to 2021 [8]. Since 2022, it includes also channels at 532 and 1064 nm in order to meet the requirements of EARLINET-ACTRIS [9].The telescope field of view of 0.25 mrad detects signals beyond 500 meters. Being non-coaxial, calibration is feasible with the strategy described later in this paper. In nominal conditions, water vapor profil upper limit is near 10 km, and elastic backscatter profiles reach the low stratosphere, its data are then used within the BeCoM project.

Table 1. Short Descriptive Caption of french lidars zoomed by this study

LIDAR name/ infos	LTA	Lid 1200	IPRAL	COP Lid
Emitted wl (nm)	1067	355	355	355
Raman N_2 wl (nm)	608	387	387	387
Raman H_2O wl (nm)	660	408	408	408
Telescope diameter (mm)	800	1200	500	400
Laser power mj/pulse	300	400	375	100

3. WVMR Treatement channel

Water Vapour mixing ratio is proportional to the ratio between water vapor and nitrogen raman backscattered signals returned at specific wavelengths (Table 1). Corrected for background noise and scaled by a calibration coefficient [3]. The signals are quantified in terms of the number of photons per bin per shot. It has been shown that the relative transmission of the raman returns due to the cirrus clouds is negligibly small for altitudes above 4 km [10]. Consequently, no attenuation corrections have been applied.

The current WVMR treatement involves hourly screening to generate vertical profiles up to 12 km altitude, as longer periods may result in unrealistic profiles due to mixing of atmospheric situations. This hourly profiling strategy facilitates calibration and preserves valuable information about local concentration variability. Additionally, in some cases, prefiltering is applied to include only nighttime measurements, especially if the system operates continuously on a day/night cycle (as with IPRAL).

Historical analysis of Lidar signal-to-noise ratios (SNRs) from 2001 to 2010 indicates that signals above 20 km for H_2O wavelengths and above 50 km for N_2 wavelengths are predominantly noise. Therefore, the background noise model is determined by calculating the median photon counts (signal) for altitudes above these thresholds. The error associated with noise calculation is estimated using statistical bootstrapping, computing bootstrapped medians, and determining the standard deviation of these medians to estimate the error in the noise calculation.

The raw signals from Lidar require smoothing for quality enhancement. An adaptive Blackman window filtering is employed, adjusting window sizes based on altitude and incorporating a decay factor beyond signal altitude limits. The cleaned signal is the result of signal smoothing and noise removal, ensuring only relevant components are retained. Figure 1 illustrates raw and cleaned Raman signals, along with their noise levels. In this example, the water vapor signal extends up to 11 km, while the nitrogen signal is detectable up to about 43 km.

Lidar WVMR systematic errors are expected to be reduced by hard-ware design, Thus, the signal processing related to measurement uncertainties is based on random errors [10]. The two principal error sources considered here are photon counting and skylight background estimation, one evident extra error source will be related to the calibration factor estimation.

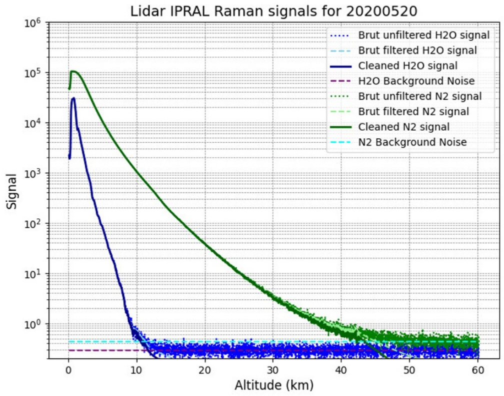

Figure 1. Example of Raman lidar signals: Raw, filtered, cleaned with the associated noises. Blues for H_2O , and greens for N_2 .

4. WVMR Calibration

Hereafter, will describe the united calibration appraoch adopted for any lidar system (co/non axial). External calibration is carried out based on hourly gridded reference data provided by ERA5 with a spatial resolution of 0.25° x 0.25° and 37 pressure levels [11].

Forced by radiosondes, ERA5 shows a good quality to make climatological studies, but are suspected to miss local short term events. Trying to assess their limitations with respect to the M10 Meteo-France radiosondes, relative humidity profiles cases were chosen if colocated to lidar measurements. The results show a dry radiosonde bias that gets more important with altitude, the best agreement being found on altitudes between 3 and 5 km.

Based on previous investigations. Collocated and simultaneous Lidar water vapor mixing ratio (WVMR) hourly profiles from cleaned signals are calibrated using hourly ERA-5 reanalysis data, between 3 & 5 km. The collocated 37 pressure levels reference is considered allowing a maximal spatial drift of 0.1° and the best temporal coincident (same lidar measurements dominant hour). The External calibration strategy undergoes many steps: Altitude range selection; Data preparation; Hourly calibration factor calculation; error estimations; and nightly calibration coefficient; full period calibration.

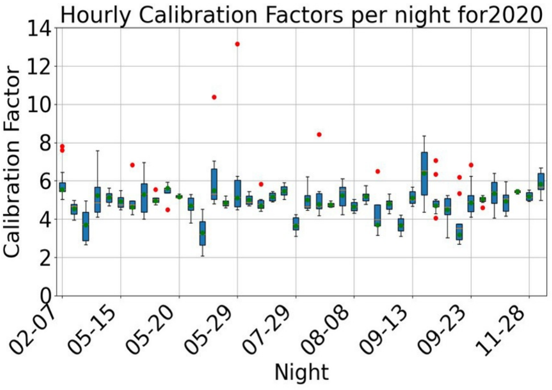

Figure 2. Boxplot of the IPRAL Hourly calibration factors per night of the year 2020.

Figure 2 shows results from pioneering calibration of IPRAL lidar, where hourly calibration factors during the year 2020 per night are presented. Green balls are nightly calibration factors (mean of valid hourly calibration factors of the night), red points are hourly calibration coefficients outliers per night. A yearly full period calibration factor of 5 can be concluded in 2020 as the mean nightly values of the year are all around 5.

5. Conclusion and perspectives

Four lidars participating in BeCoM will offer water vapor density profiles, each serving distinct roles: The powerful lidar (Lid1200/OPAR) will calibrate ECMWF and satellite observations, delivering accurate profiles up to the stratosphere; The OHP lidar will be the primary tool for obtaining collocated, precise water vapor profiles and contrail altitudes, undergoing significant design evolution for improved calibration in providing profiles from the ground; The IPARL Lidar aims to provide promising water vapor profiles with contrail detection, requiring adaptation of software used on other sites, with added value from regular balloon launches within GRUAN for well-calibrated measurements [12]; The Clermont-Ferrand observatory's lidar, though more modest, is better suited for lower-mid troposphere investigations and potential inclusion in a future network dedicated to contrail monitoring.

The calibration method is applicable across the diverse sites, Encouragingly, primarly results (not shown) exhibit a robust agreement with both ERA5 reanalysis and Meteo France Modem 10 radiosonde observations within the lower troposphere (3-7 km), thereby validating its efficacy in this altitude regime. However, deeper uncertainty assessment are required.

Acknowledgements

This project has received funding from the Horizon Europe Research and Innovation Actions program under Grant Agreement N°101056885.

References

[1] Sausen, R., Hofer, S., Gierens, K., Bugliaro, L., Ehrmanntraut, R., Sitova, I., Walczak, K., Burridge-Diesing, A., Bowman, M., and Miller, N., 2023: Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world? Meteorol. Z., in press.

[2] Keckhut, P., Borchi, F., Bekki, S., Hauchecorne, A. and SiLaouina, M., 2006: Cirrus classification at midlatitude from systematic lidar observations. *Journal of applied meteorology and climatology*, *45*(2), pp.249-258.

[3] Hoareau, C., P. Keckhut, A. Sarkissian, J-L. Baray, And G. Durry: Methodology for water monitoring in upper troposphere with Raman lidar at observatory of Haute-Provence, Journal of Atmospheric and Oceanic Technology, 26(10), 2149-2160, 2009,

[4] Bock, O., Bosser, P., Bourcy, T., David, L., Goutail, F., Hoareau, C., Keckhut, P., Legain, D., Pazmino,A., Pelon, J., Pipis, K., Poujol, G., Sarkissian, A., Thom, C., Tournois, G., and Tzanos, D.: Accuracy assessment of water vapour measurements from in situ and remote sensing techniques during the DEMEVAP 2011 campaign at OHP, Atmos. Meas. Tech., 6, 2777–2802, 2013..

[5] Dionisi, D., Keckhut, P., Courcoux, Y., Hauchecorne, A., Porteneuve, J., Baray, J. L.,Leclair de Bellevue, J., Vérèmes, H., Gabarrot, F., Payen, G., Decoupes, R., and Cammas, J. P.: Water vapor observations up to the lower stratosphere through the Raman lidar during the Maïdo lidar calibration campaign, Atmos. Meas. Tech., 8, 1425-1445,2015 .

[6] Leblanc, T., McDermid, I. S., and Walsh, T. D.:Ground-based water vapor raman lidar measurements up to the upper troposphere and lower stratosphere for long-term monitoring, Atmos. Meas. Tech., 5, 17–36, 2012.

[7] Vérèmes H., Payen G., Keckhut P., Du ot V., Baray J.-L., Cammas J.-P., Evan S., Posny F., Körner S., Bosser P.: Validation of the water vapor profiles of the Raman lidar at the Maïdo observatory (Reunion Island) calibrated with global navigation satellite system integrated water vapor,Atmosphere, MDPI 2019, 10, pp.713.

[8] Fréville, P., Montoux, N., Baray, J.L., Chauvigné, A., Réveret, F., Hervo, M., Dionisi, D., Payen, G. and Sellegri, K., 2015: LIDAR developments at Clermont-Ferrand—France for atmospheric observation. *Sensors*, *15*(2), pp.3041-3069.

[9] Baray, J.L., Deguillaume, L., Colomb, A., Sellegri, K., Freney, E., Rose, C., Van Baelen, J., Pichon, J.M., Picard, D., Fréville, P. and Bouvier, L., 2020: Cézeaux-Aulnat-Opme-Puy De Dôme: a multi-site for the long-term survey of the tropospheric composition and climate change. *Atmospheric Measurement Techniques*, *13*(6), pp.3413-3445.

[10] Sherlock V., Garnier, A., Hauchecorne, A., and Keckhut, P.: Implementation and validation of a Raman lidar measurement of middle and upper tropospheric water vapor, Applied Optics, 38,5838-5850, 1999.

[11] Hersbach, H., Bell, B., Berrisford, P., Biava , G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey,C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS),

[12] Dupont, J., Haeffelin, M., Badosa, J., Clain, G., Raux, C., and Vignelles, D., 2020: Characterization andCorrections of Relative Humidity Measurement from Meteomodem M10 Radiosondes at Midlatitude Stations. J. Atmos. Oceanic Technol., 37, 857–871.