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

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1. Introduction

Photo1: Contrails at Saint-Malo (May 2024, France)
Credit: Dr. Chacroune.M

Contrails, as cirrus clouds formed along cruise trajectories (Photo1), 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. Additionally, Raman Lidars allow for simultaneous water vapor vertical profiling, crucial for continuous monitoring of atmospheric humidity, albeit limited by low cloud presence [3-4].

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. Hence, Lidar-based water vapor measurements require a careful calibration strategy.

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 [5-7]. Advanced techniques involve calibrating with total water vapor columns measured independently but require a coaxial lidar configuration [8].

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 4 French lidars to contrail investigations.

2. BeCoM Participated French Lidars

- 4 lidars developed by LATMOS/CNRS and its spin-off company Gordien-Strato
  - Similar rejection efficiency/demonstrated removal of elastic signals without affecting WVMR profiles
  - Recent designs omitted optical fibers (to avoid fluorescence effects)
- More details related to water vapor observations by these lidars are in the following table (Table 1)

LIDAR name	LTA	Lid1200	IPRAL	COPLid
Localisation	(43.9 N°, 5.7°E)	(21°S, 55.4°E)	(48.7 N°, 2.2°E)	(45.7 N°, 3.1°E)
Emitted wavelength (nm)	532	355	355	355
Raman N2 wavelength (nm)	608	387	387	387
Raman H2O wavelength (nm)	660	408	408	408
Telescope diameter (mm)	800	1200	500	400
Laser Power (mj/pulse)	300	400	375	100

3. From Raman Lidar signals to WVMR

- Water Vapour mixing ratio (WVMR) is proportional to the ratio between water vapor and nitrogen raman backscattered signals returned at specific wavelengths (Equation 1) by a scale (calibration) factor C.
- Signals are quantified in terms of the number of photons per bin per shot. Figure 1 shows raman signals before/after background noise correction.

$$WVMR(z) = C \cdot T(z) \cdot \frac{S_{H_2O}(z) - B_{H_2O}(z)}{S_{N_2}(z) - B_{N_2}(z)} \quad \text{(Equation 1)}$$

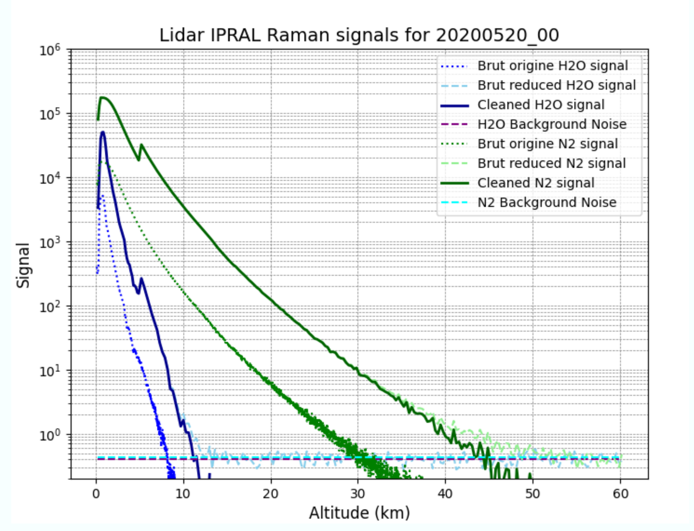

Figure 1: IPRAL (48.7 N°, 2.2°E) one hour summed raman signals used to retrieve midnight WVMR profile, green colors are for N_2 signals, Blues for H_2O ones. Continued lines refer to cleaned signals, noise levels are presented in horizontal dashed lines (Cyan for N_2 noise, purple for H_2O one)

$S_{H_2O}(z)$: H_2O raman signal (summed for certain period)
$S_{N_2}(z)$: N_2 raman signal (summed for certain period)
$B_{H_2O}(z)$: H_2O noise estimated as median of signals > 20 km
$B_{N_2}(z)$: N_2 noise estimated as median of signals > 50 km
$T(z)$: The Raman signal relative transmission due to cirrus clouds (Ignored for altitudes above 4 km) [9]

4. Raman Lidar WVMR CAL/VAL

- External Calibration Method (Figure 2a) using hourly ERA5 model [10]
- Altitude range of calibration: 4 - 6 km (Figure 2b, the bleu cercle)
- One calibration factor per hour of nocturnal measurements
- WVMR calibrated profile error (Figure 2b, dashed green)
  - Signal detection error
  - Noise estimation error
  - Calibration error

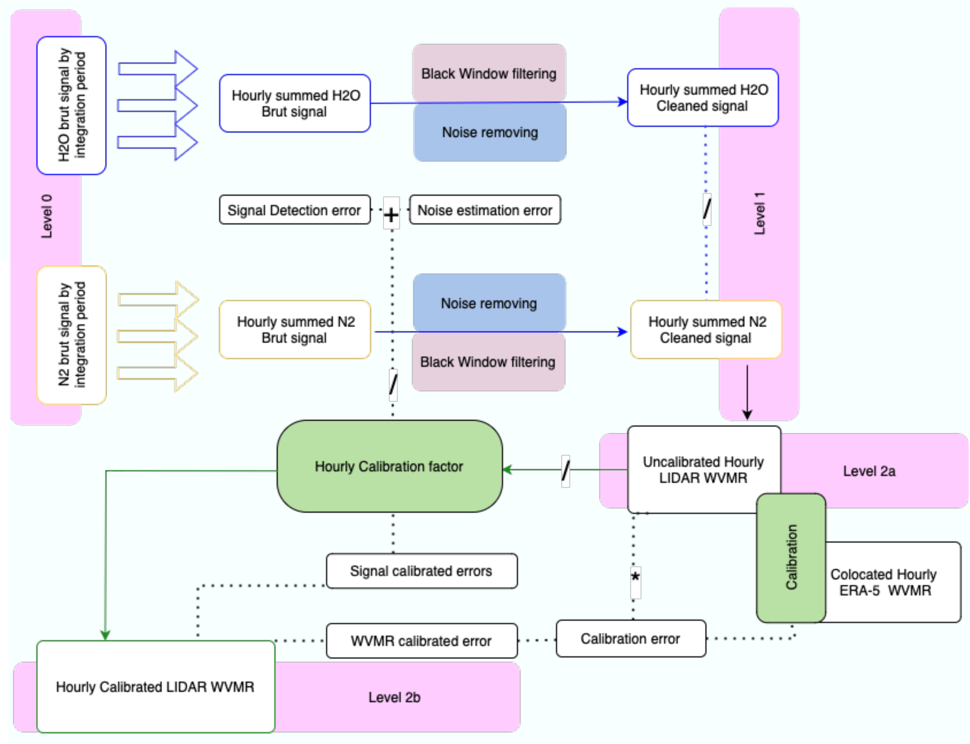

Figure 2a: Diagram to detail the Lidar WVMR External calibration with respect to ERA5 at the hourly scale. Starting from Raman signal profiles by integration period and altitude bin (Level 0), passing by summed cleaned signals for one hour(Level 1), and calculating the uncalibrated WVMR profile(Level 2a), to be compared to the ERA5 colocated hourly WVMR between 4 and 6 km and hence to calculate this hour calibration factor (green) . Errors estimation is represented respectively.

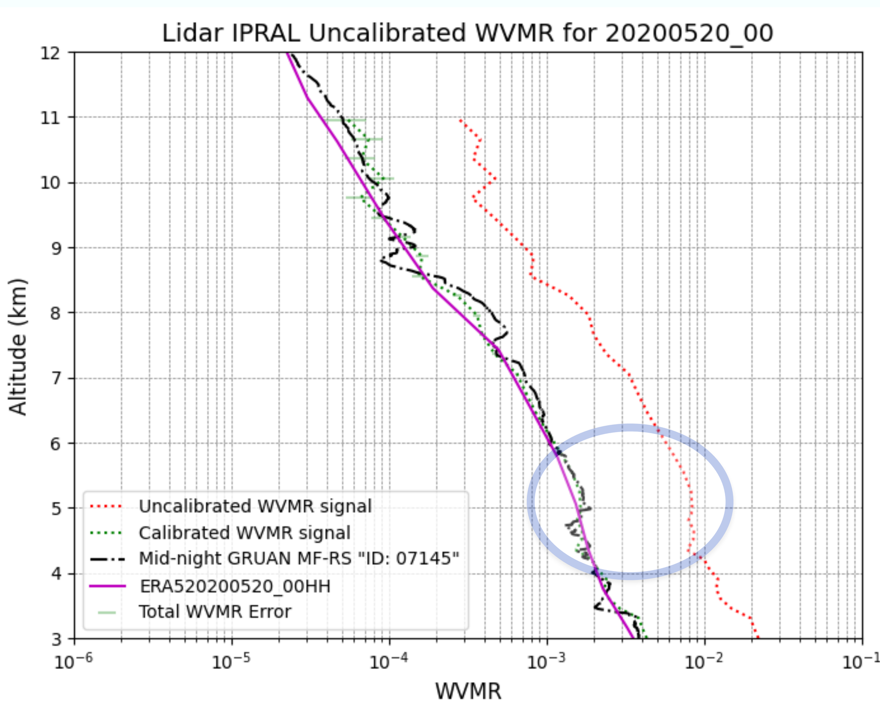

Figure 2b: IPRAL WVMR profile at midnight of 20/05/2020, before calibration (Red), calibrated (Green) with respect to colocated same hour ERA5 profile (Purple), WVMR total error is shown in dashed green, midnight launch WVMR profile by RadioSonde Modem M10 GRUAN corrected is also shown (Black) to check consistency. The blue cercle indicates the altitude range used to calculate the calibration factor of this hour (it's value here is around 5).

- Nightly calibration factors as mean of hourly validated ones of each night
- Single calibration factor generalized by stable period (see Figure 3 for the final calibration factors of the IPRAL WVMR dataset, do you guess the stable periods?, calibration factor value for 2020?)
- Periods of Instrumental changes affect calibration values throughout the data processing (See Figure 3: do you mark at least one of the IPRAL instrumental changement periods?!)

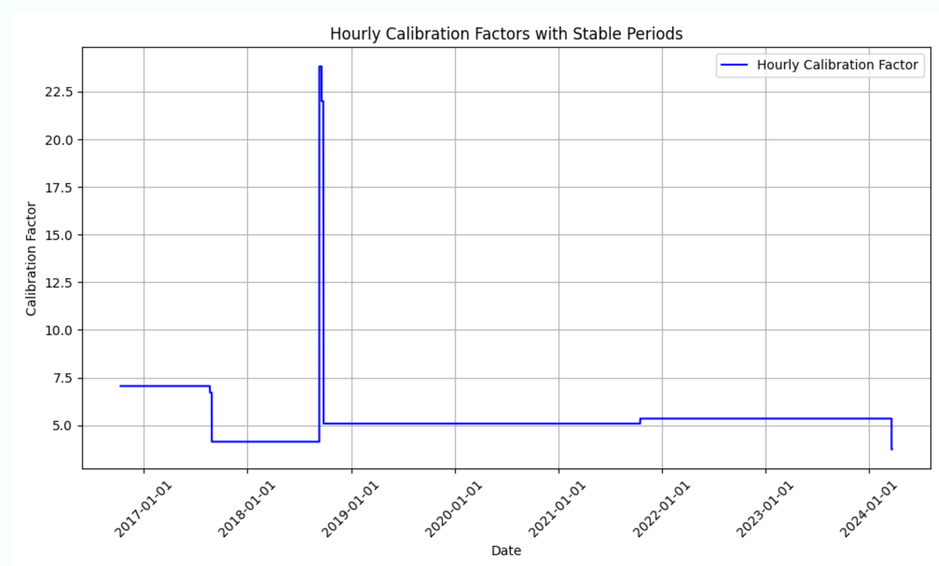

Figure 3: Generalized IPRAL WVMR calibration factors of the

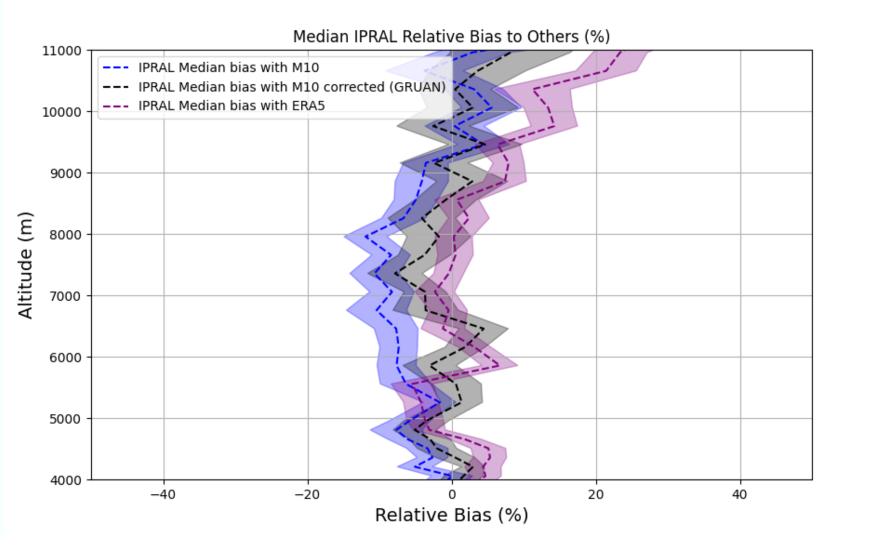

Figure 4: The median relative bias of IPRAL calibrated midnight profiles with respect to colocated ERA5 (Purple), M10(Bleu), M10 corrected GRUAN (Grey), shaded boundaries are pseudo standard deviation of the relative bias of each altitude bin normalized by number of observation points (duos) per altitude bin.

- Calibrated WVMR profiles are validated for altitudes 4-11 km (Figure 4 show the median of the relative bias with respect to lidar with the uncertainty), we use only midnight profiles for validation in order to maximise the consistency against:
  - Radiosondes WVMR profiles of midnight lunches
    - Modem M10 (not corrected)
    - Modem M10 GRUAN-corrected [11]
  - ERA5 model midnight hourly profile
- **General Agreement**: Correlation exceeds 90% (not shown)
- **Negative Bias**: around 10% bias compared to M10 below 8 km altitude
- **Excellent Agreement**: up to 10.5 km altitude with GRUAN-analyzed radiosondes
- **Positive Bias**: Up to 24% compared to ERA5 at aircraft cruising altitudes 9-11 km.

5. Conclusion

- A universal calibration approach using ERA5, independent of lidar system geometry and acquisition mode would be applicable across the 4 lidar sites. It allows a better understanding of humidity profiles uncertainties of the difference techniques (Radiosondes, Models, Lidar..), these newly developed dataset would be used to force models and cases study to raise understanding of contrails formation and persistence.
- IPRAL calibrated profiles were validated against ERA5 and midnight radiosonde (RS) profiles
  - **General Agreement**: Correlation exceeds 90%.
  - **Negative Bias**: around 10% bias compared to M10 below 8 km altitude.
  - **Excellent Agreement**: up to 10.5 km altitude with GRUAN-analyzed radiosondes.
  - **Positive Bias**: Up to 24% compared to ERA5 at aircraft cruising altitudes 9-11 km.
- The results suggest the need to correct ERA5 profiles at the upper tropospheric altitudes (> 9 km), corrections may be based on analyses of IAGOS aircraft data.

6. References

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