A new method for first principles calibration of water vapor Raman lidars

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The Raman method for lidar water vapor profiling uses Raman-shifted backscatter from atmospheric water vapor $P_{H_2O}(r)$ and nitrogen $P_{N_2}(r)$ to retrieve water vapor mixing ratio $q(r)$ at a distance r as:

$$q(r) = k_{H_2O} \frac{P_{H_2O}(r)}{P_{N_2}(Rr)} \tau(r) \qquad (1)$$

where and $\tau(Rr)$ is a term correcting for the differential atmospheric transmission at the water vapor and nitrogen Raman wavelengths. The parameter k_{H2O} , known as the lidar calibration constant, is actually a complex function of distance and wavelength and can be presented as:

$$k_{H_2O} = \frac{M_{H_2O} n_{N_2}}{M_{air} n_{air}} \frac{O_{N_2}(r)}{O_{H_2O}(r)} \frac{\int T_{N_2}(\lambda,r)\eta_{N_2}(r,\lambda)\sigma_{N_2}(\lambda,r)d\lambda}{\int T_{H_2O}(\lambda,r)\eta_{H_2O}(r,\lambda)\sigma_{H_2O}(\lambda,r)d\lambda} \qquad (2)$$

where: M_X and n_X are the molecular mass and the number density of species X (air denotes dry air), $\sigma_X(\lambda,r)$ is the Raman cross-section of species X, and $O_X(r)$ $T_X(\lambda,r)$ and η_X (r, λ) are respectively the overlap, the instrument transmission function, and the PMT efficiency of the Raman channel X.

The calibration constant is commonly obtained by comparison of a lidar profile to data from a reference instrument: a collocated radiosonde, a microwave radiometer, or a GPS receiver. The thus derived calibration constant has low accuracy mostly because of the limited accuracy of the reference instruments. Another essential drawback of this calibration method is that the lidar and the reference instrument nearly always sample different air masses with different time and space resolutions, leading to additional systematic errors. Furthermore, the implicitly included atmospheric differential transmission $\tau(R)$, induces an additional systematic error.

In another approach, known as independent calibration, k_{H2O} is calculated using Equation 2 from measured or modeled cross sections and instrumental parameters. The first applications of the method had low calibration accuracy mostly due to the low accuracy of the Raman cross-sections. Improvements in cross sections modeling allowed better accuracy but still the estimation of the instrumental functions is cumbersome, with limited accuracy and possibilities for systematic errors.

In the calibration method, presented here, k_{H2O} is derived using Equation 1 and backscatter signals measured with the lidar receiver in a calibration cell filled with a reference water vapor/air mixture. The reference mixture is prepared gravimetrically. Since the preparation relays on fundamental principles and basic units of measurements the reference mixture can be regarded as primary humidity standard and the obtained in this way lidar calibration constant has the potential to be traceable to national standards. The new calibration method eliminates the unavoidable in the cross-calibration methods errors and uncertainties induced by the reference instrument and by the calibration procedure. Furthermore, the new method does not require modeling of the Raman cross sections and estimation or measurement of the instrumental efficiencies, thus avoiding the related systematic and random errors characteristic for the existing independent calibration methods. Essential conditions for the successful application of the method however, is the reduction to negligible levels the range dependence of: a) the overlap functions ratio and b) the ratio of the integrals in Equation 2. The High Spatial/Temporal Resolution Raman Lidar (HSTRRL) and the Raman Lidar for Meteorological Observation (RALMO) built at the EPFL were specially designed to satisfy the above mentioned conditions.

A lidar calibrated with the described method has the potential to become reference instrument for atmospheric profiling of water vapor and can be used for validation and calibration of other remote instruments for humidity measurements, such as microwave radiometer, balloon sondes, and GPS.