Research efforts in the absolute calibration of a Raman water vapor lidar

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Background

- A Raman water vapor lidar can be calibrated absolutely.
- But, because of existing error sources which make the resultant total calibration error >10%, calibration has traditionally been done with respect to other water vapor sensors such as radiosonde or microwave radiometer
- There have been two dominant error sources:
  - The knowledge of the ratio of Raman scattering cross sections for water vapor and nitrogen (current best= Penny and Lapp, 1976: +/- 10%)
  - The ability to simulate the Raman water vapor spectrum, including trace and anisotropy contributions (+/- 8%)

Background

- Previous efforts of Vaughan et al (1988) and Sherlock et al (1999) have achieved absolute calibrations with errors in the 10-15% range.
- The more recent, very thorough, Sherlock effort ascribed 8% error to water vapor anisotropy, 3% to water vapor mixed state contribution, 5% to normalization of the water vapor Raman cross section and 5% to normalization of the nitrogen cross section
- Due to the recent work of Avila et al (1999), it is now possible to simulate the water vapor spectrum with high accuracy. These simulations include both anisotropy and ?$_3$ contributions.

Background

- Furthermore, the extensive work done through the U. S. Department of Energy (DOE) Atmospheric Radiation Measurements (ARM) Program has established the Cloud and Radiation Testbed (CART) Microwave Radiometer (MWR) as a source of total atmospheric column water amount with an achievable absolute accuracy of approximately +/- 1.5% based on Stark effect measurements (Clough et al, 1999). Current accuracy is +/- 3-4%.
- Also, the DOE CART Raman Lidar (CARL) has established a long calibration record with respect to the MWR. This record should allow the ratio of Raman cross sections for water vapor and nitrogen to be determined with accuracy of ~ +/- 5-6%. As MWR errors are reduced, knowledge of the cross section ratio will improve.

The equations

- The water vapor mixing ratio can be expressed as

$$w(r) = C_w \frac{S_H(r)}{S_N(r)} \Delta t \left(l_L, l_R, r \right)$$

$$C_w(r,T) = \frac{O_N(r) \int k_N(l) \frac{ds_N}{d\Omega}(l,T,p)\,dl}{O_H(r) \int k_H(l) \frac{ds_H}{d\Omega}(l,T,p)\,dl} \frac{M_H}{M_{dry}} \frac{n_N}{n_{dry}}$$

The functions F_H and F_N

- By integrating over the wavelength interval containing Raman scattered energy for water vapor or nitrogen, all the temperature dependence of a given lidar channel can be contained in a single term, F_H or F_N.

$$\int_{\Delta l_H} k_H(l)\frac{ds_H}{d\Omega}\left(l',T,p\right)dl = F_H(T)\frac{ds_H}{d\Omega}(p)k_H(l_H)$$

$$\int_{\Delta l_N} k_N(l)\frac{ds_N}{d\Omega}\left(l',T,p\right)dl = F_N(T)\frac{ds_N}{d\Omega}(p)k_N(l_N)$$

Temperature dependent water vapor mixing ratio equation

- Using these new formulations, the water vapor mixing ratio equation becomes

$$w(r) = C_w^*(r,T)\frac{S_H(z)}{S_N(z)}\Delta t\left(l_N, l_H, r\right)$$

$$C_w^*(r,T) = \frac{O_N(r)}{O_H(r)}\frac{F_N(T)}{F_H(T)}\frac{\dfrac{ds_N(p)}{d\Omega}}{\dfrac{ds_H(p)}{d\Omega}}\frac{k(l_N)}{k(l_H)}\frac{M_H}{M_{dry}}\frac{n_N}{n_{dry}}$$

General Approach

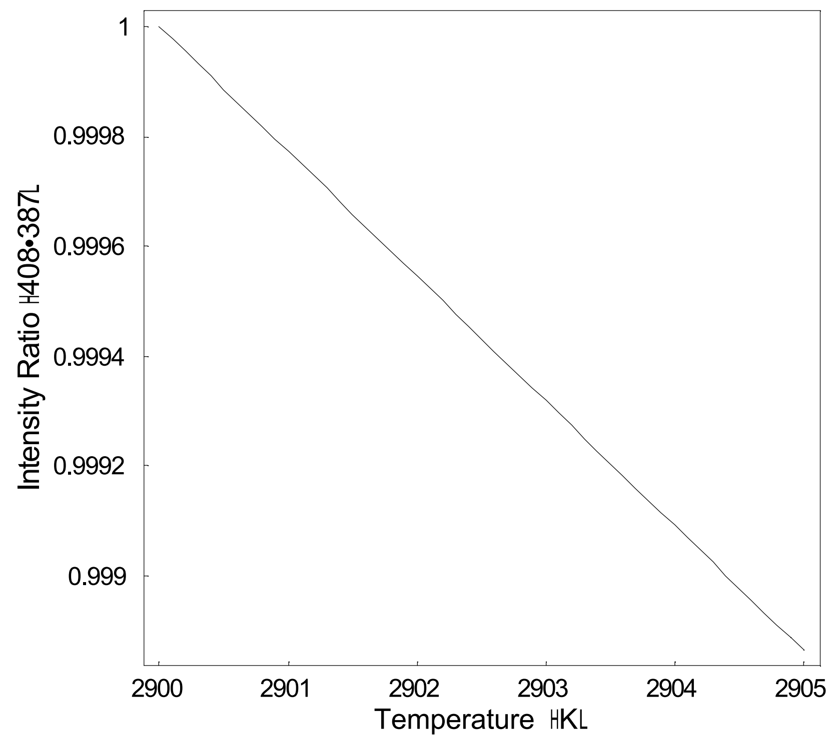
1. Perform radiometric calibration of the CARL Lidar
    - Calculate Differential Transmission
        - Molecular profile from model
        - Aerosol extinction profile from the Raman Lidar
            - Angstrom coefficient
    - Ratio of Lidar channel efficiencies versus wavelength
        - Use calibrated tungsten lamp to determine the relative system efficiencies in the water vapor (~407.4 nm) and nitrogen (~386.7 nm) bands.
2. Use recent work of Avila et al (1999) to simulate Raman water vapor spectrum with high accuracy and calculate $F_{H.}$ F_N comes from similar effort for $N_{2.}$
3. Use the CARL/MWR calibration record to determine the ratio of Raman water vapor and nitrogen cross sections
4. The goal is to determine the ratio of Raman cross sections to better than 5%. This would allow *any* Raman lidar to be absolutely calibrated with high accuracy.

Errors

- *Differential transmission*: Aerosols are largest error source. But even for AOT = 1.0, 10% change in Angstrom coefficient yields <0.5% change in differential transmission. Variation of Angstrom coefficient well known at CART site.
- *Lidar Channel Efficiency Ratio*: recent effort (Sherlock, et. al., 1999) used atmospheric skylight to measure this. Errors of >6% resulted. Use a calibrated tungsten lamp instead: ratio of intensities traceable to NIST to <1%.
- *Determination of F_N and F_H*: N_2 q-branch temperature insensitive, Relative intensity of rotational lines well known, relative intensities of H_2O transitions now known to ~ 1%.
- *Ratio of Raman cross sections*: best available number is 2.5 +/- 10% (Penny and Lapp, 1976). The stability of the calibration record of the CARL system should allow the uncertainty in this ratio to be reduced to ~4%.

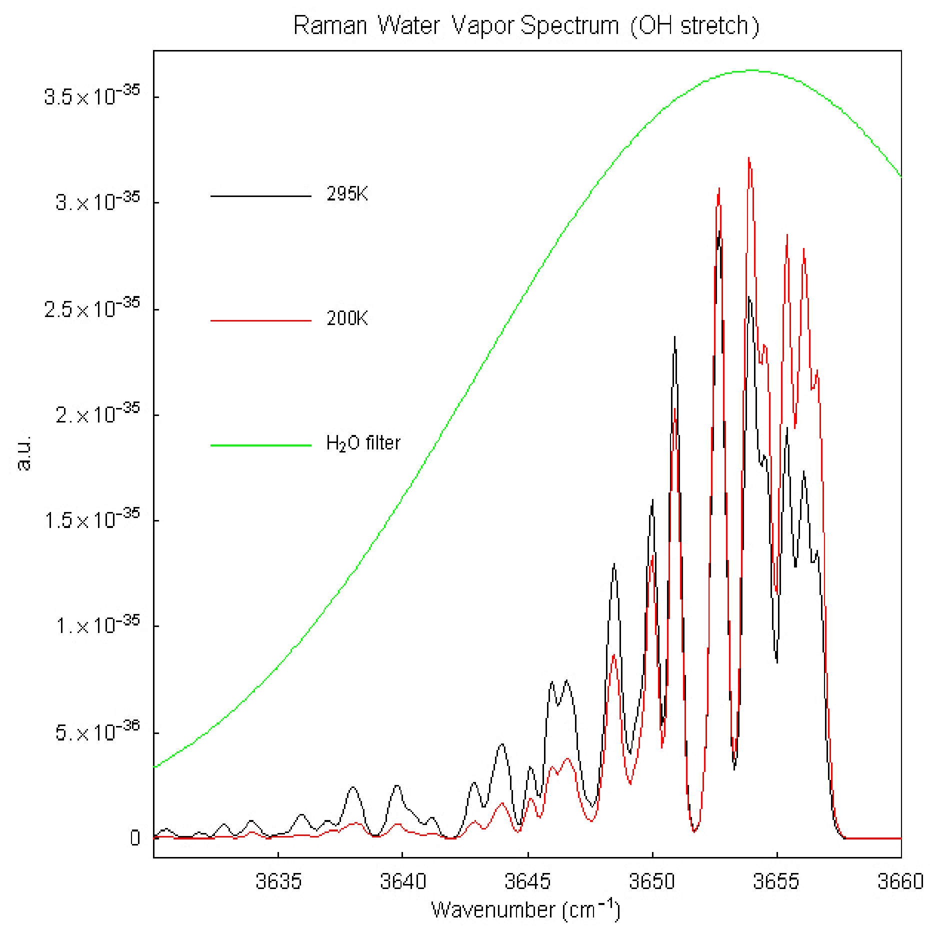
Calibrated Tungsten Lamp Intensity *ratio* Stability

- The *ratio* of Lidar optical channel efficiencies (water vapor and nitrogen) is needed to calibrate the lidar.
- Lamps with +/- 1% calibration (NIST traceable) available. Calibration to +/- 2% are much cheaper. What is needed for this job?
- Lamp calibration of 2% corresponds to blackbody temperature variation of ~4.5K at 2900K.
- But the *ratio* of intensities at the water vapor and nitrogen wavelengths changes by *much* less than 1%.
- Transfer to CARL possible with errors ~ 1%



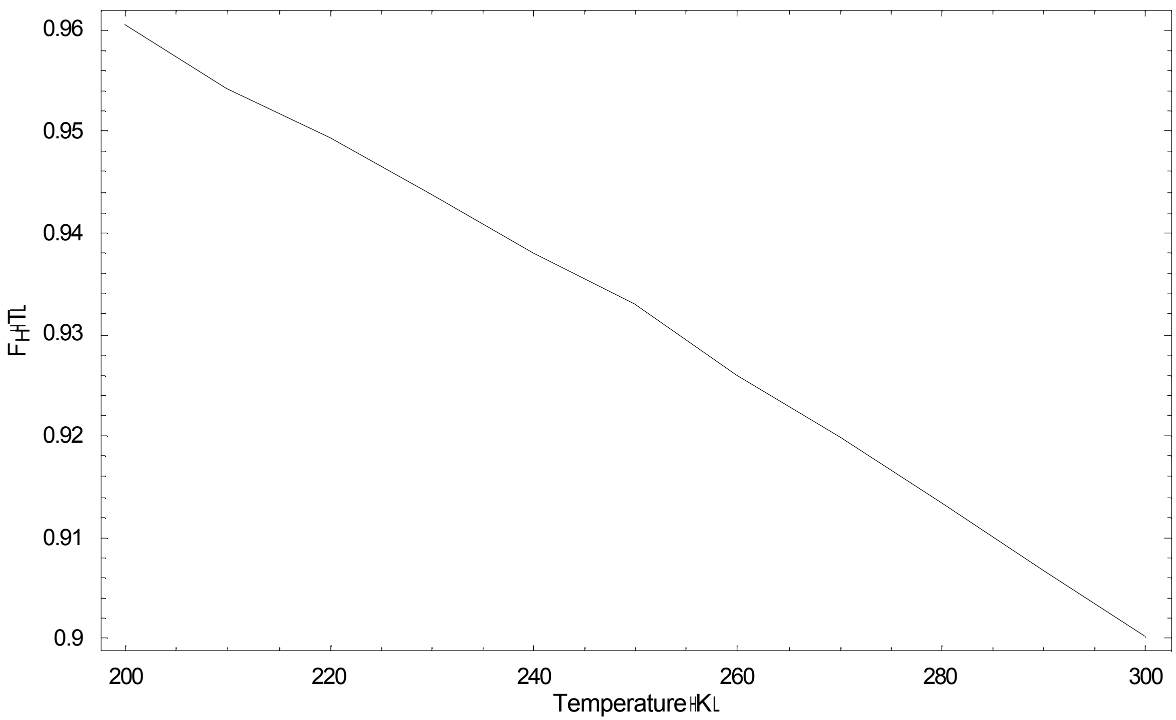
CARL channel efficiencies

- Must determine at higher resolution than filter widths and convolve with H_2O and N_2 spectra
  - Spectral variation of N_2 is well known
- Recent work (Avila et. al., 1999) allows very high (relative) accuracy water vapor spectra
  - H_2O spectrum temperature sensitivity!



The calculation of F_H

- A numerical integration can be performed of the Raman scattered intensity transmitted by the filter shown in the previous slide
- Normalizing to the total band intensity yields the function F_H

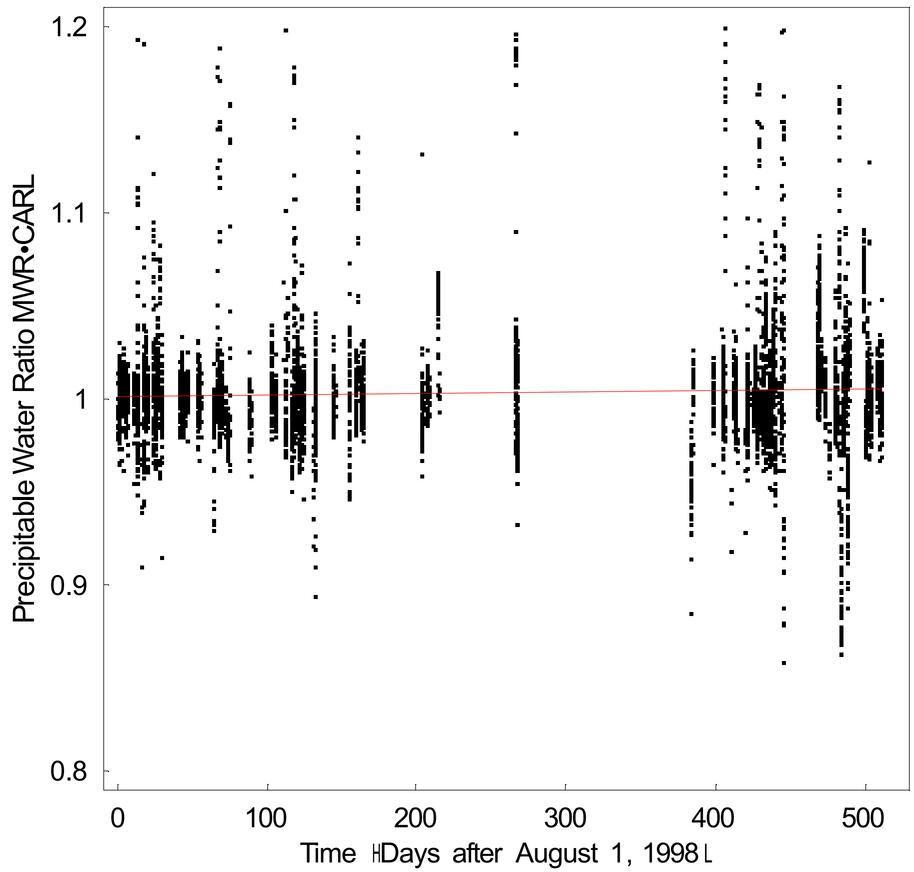


H_2O/N_2 cross-section ratio

- Atmospheric Lidar measurements have been used before to calculate this ratio
  - Melfi et. al. (1969) 3.8 +/- 25%
  - Cooney et. al. (1970) 5.1 +/- 75%
- Current best value is 2.5 +/- 10% (Penney and Lapp, 1976)
- The uncertainty in this ratio has led to the Raman lidar "tradition" of calibrating with respect to some other sensor
- The CARL calibration constant
  - pegged to a source currently believed accurate to 3-4%. 2% believed achievable.
  - excellent stability, large number of measurements ($\sqrt{N}$!)
  - If the errors in determining CARL calibration constant are purely random, it can be used to determine H_2O/N_2 cross-section ratio to 5% or better
  - As MWR accuracy improves, so can CARL (and *all other* Raman lidars)

CARL/MWR calibration record

- The calibration record of the CARL vs MWR is stable (outside of startup periods) and has a well determined mean
  - 6209 calibration comparisons
  - Slope = 8.6×10^{-6}
  - Standard Error = 0.0004
- Work needs to be done to verify that there are no systematic biases in the data record



Calibration spikes are due to system restart fluctuations

Summary

- Raman water vapor lidars can be absolutely calibrated
- Current error sources dictate, however, that the accuracy that can be achieved will be > 10%
- The water vapor calibration work occurring under the DOE/ARM program and accurate simulations of the Raman water vapor spectrum should permit a first-principles Raman water vapor lidar calibration with accuracies of ~5%.

References

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