Integrated Raman Lidar and Microwave Radiometer Retrieval of Atmospheric Water Vapor

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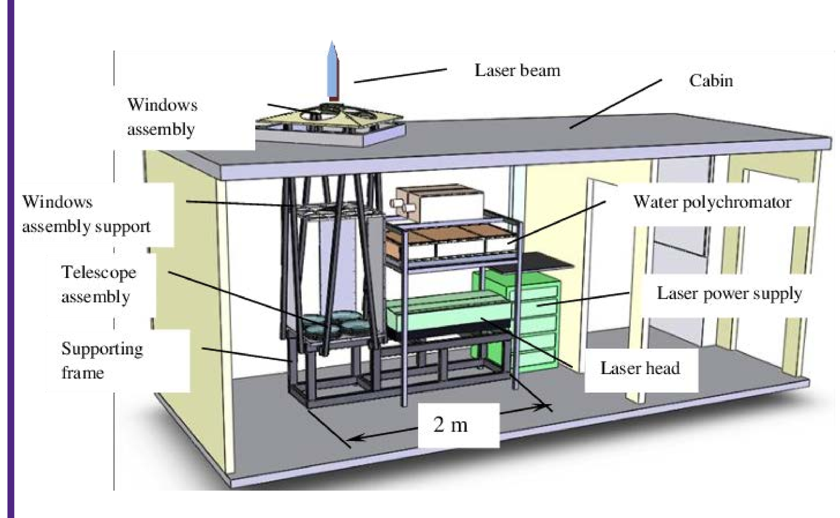
Instruments we use to measure water vapor

Instrument	Advantages	Disadvantages
Radiosonde (weather balloon)	• Widely used at meteorological stations globally (GCOS Upper-Air Network) • Launched during any weather	• Limited observation period (launched 2 times/day) • Corrections needed for low temperatures (<-40°C) and humidity (<5% RH)
Cryogenic Frostpoint Hygrometer	• Doesn't require low temperature/humidity correction	• More expensive than radiosonde (even more limited observation period) • Minor wet bias • Does not work well in cloudy skies
Raman Lidar	• Very good height (m/km)/temporal (min/hours) resolution for remote sensing instrument • Very high precision at lower altitudes	• Observes only during clear weather • External calibration needed (usually based on radiosonde)
Microwave Radiometer	• Operates all the time (except during precipitation) • Absolute calibration (hot/cold load)	• Poor height resolution (>10km)

Take-home point: No single instrument can be used for a comprehensive analysis of atmospheric water vapor!

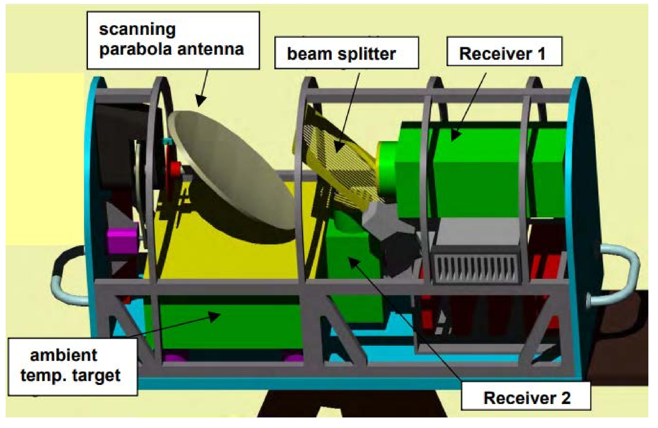
A Tale of Two Instruments

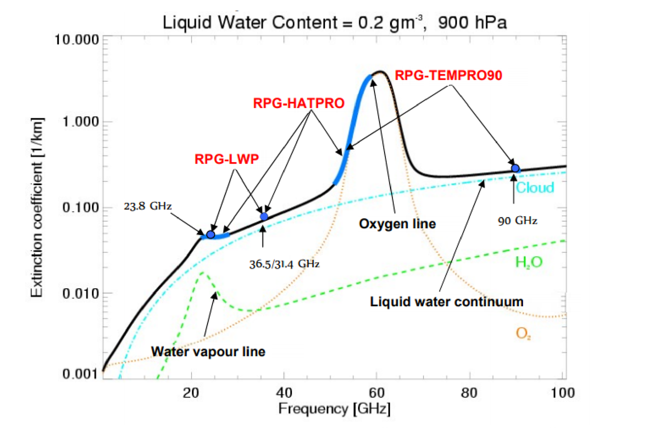
RALMO (Raman Lidar for Meteorological Observation)



Dinoev et al. 2013, [1]

RPG-HATPRO (Humidity And Temperature PROfiler)





RPG-HATPRO manual, [5]

Optimal Estimation Method Retrieval

Goal: To develop a single forward model that includes lidar and radiometer information, which uses the radiometer's total water measurement to calibrate the lidar profile continuously.

a priori information (x_a, S_a)

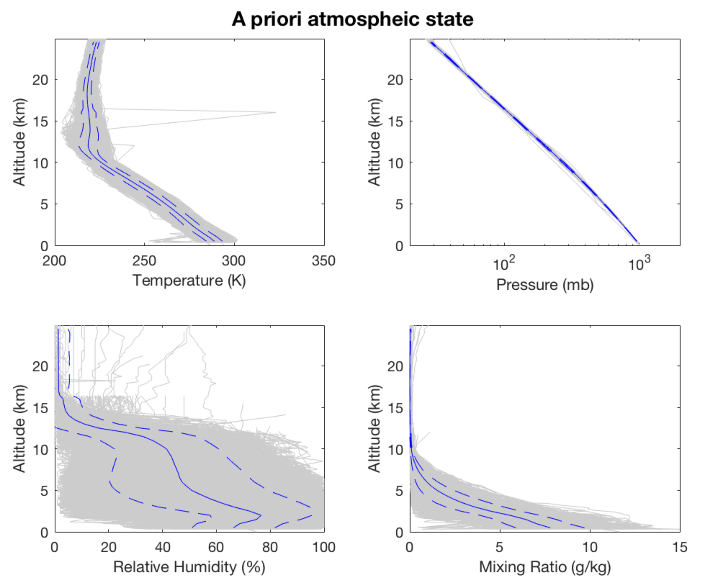


Figure: Atmospheric state data compiled from radiosonde profiles. The solid and dotted lines represent the mean profiles and standard deviation.

Determining *a priori* covariance matrix:

$$S_{ij} = \sigma_i \sigma_j \exp\left(\frac{-2|z_i - z_j|}{l_i - l_j}\right)$$

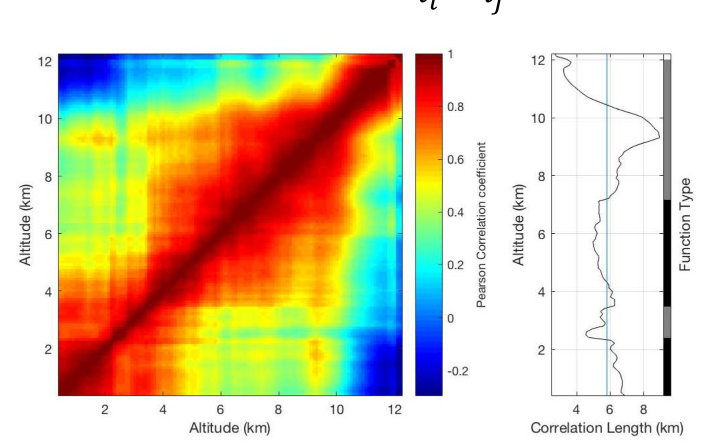


Figure: **(Left)** Autocorrelation of mass mixing ratio using radiosonde climatological data. **(Right)** Fit of matrix rows to determine correlation length, and function type (grey=exponential, black=tent, white=Gaussian) for the *a priori* covariance matrix.

Forward Model ($F(x,b)$, K)

Lidar: Lidar Equation

$$S_H = \frac{O T_L T_H C_H n_{air}}{z^2} e^q + B_H$$

$$S_N = \frac{O T_L T_N C_N n_{N2}}{z^2} + B_N$$

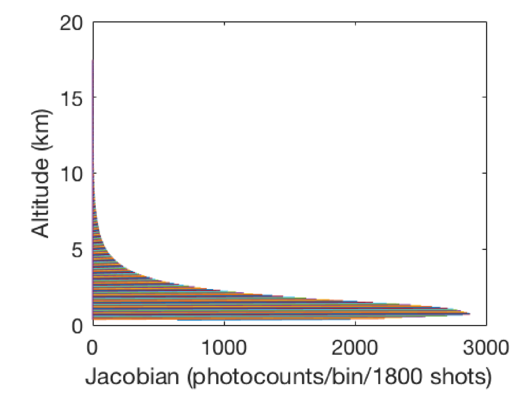
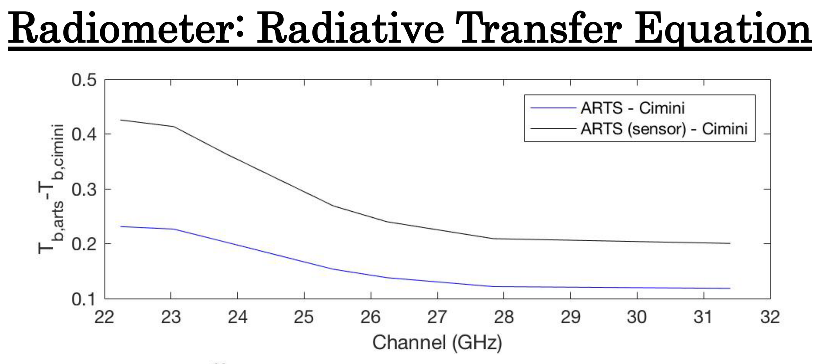


Figure: Jacobian for the photocount channels for water vapor mixing ratio.

Radiometer: Radiative Transfer Equation



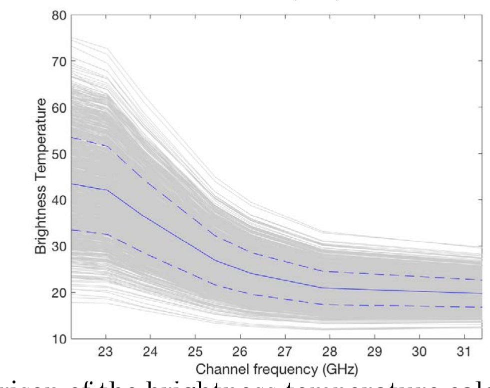
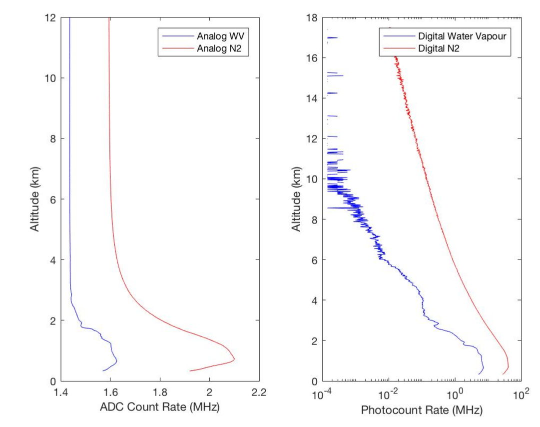


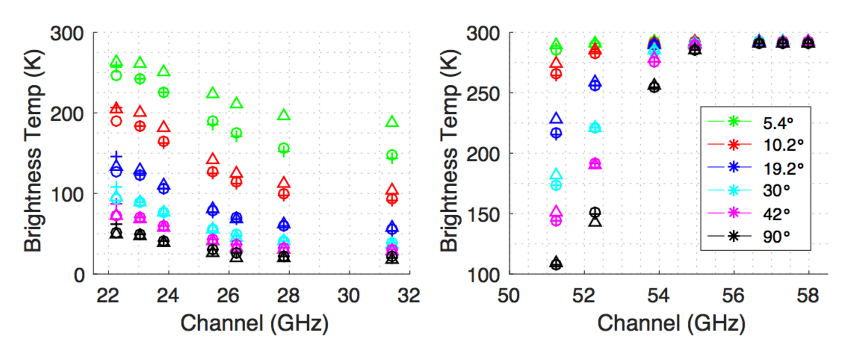
Figure: **(Top)** Comparison of the brightness temperature calculations between the Cimini and ARTS RTE forward model implementations. **(Bottom)** Superposition of brightness temperatures calculations using radiosonde profiles as the atmospheric state.

Measurement state (y, S_y)

Lidar: Height profiles of Raman-backscattered signal



Radiometer: Channel brightness temperatures

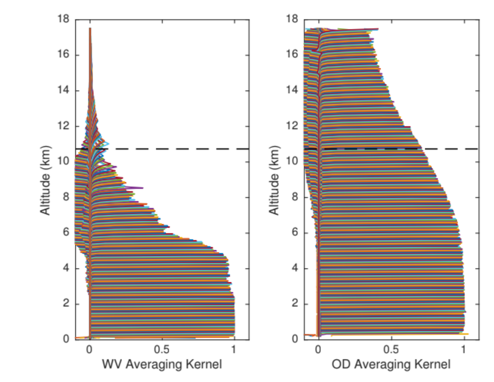


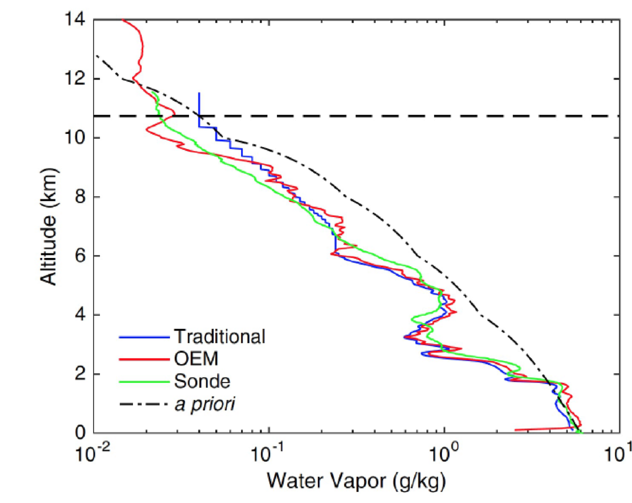
$$\hat{x} = x_a + \left(S_a^{-1} + K^T S_y^{-1} K\right)^T K^T S_y^{-1}\left(y - F(x_a)\right)$$

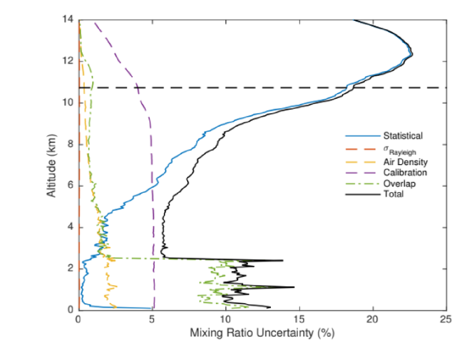
Retrieved state ($\hat{x}$)

What we want to retrieve:

- Calibrated, high-resolution height profiles of atmospheric water vapor
- Averaging Kernels
- Uncertainty budget







Sica & Haefele, 2016, [4]

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