# Microwave Radiometer and Lidar Synergy for High Vertical Resolution Thermodynamic Profiling

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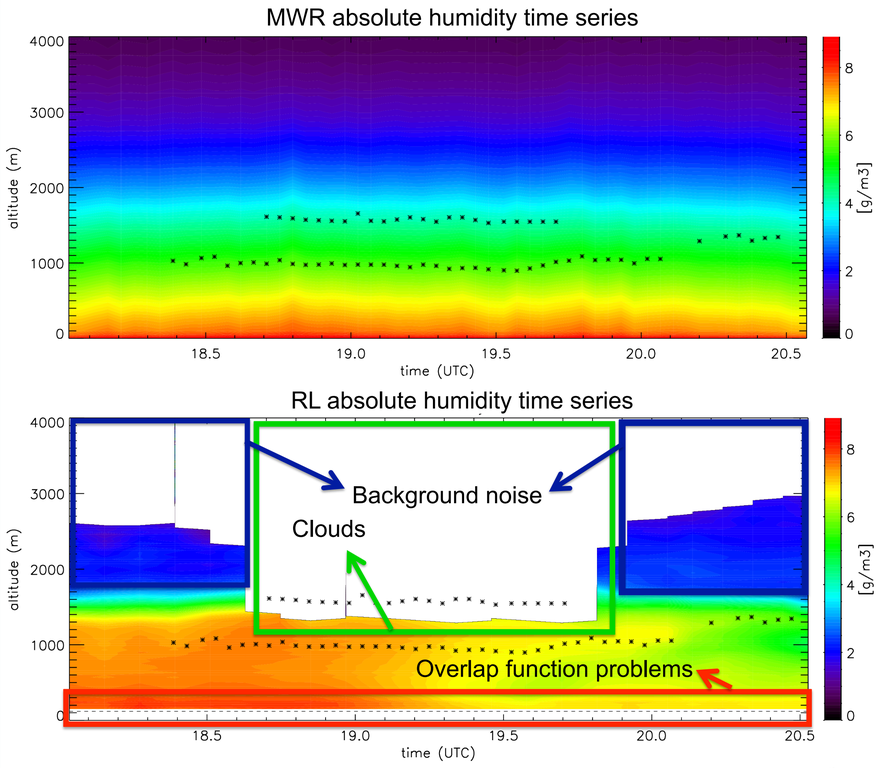
## Lidar and Microwave Radiometer




*Absolute humidity time series on the 4th of May 2013, from 18 to 20.5 UTC for (top) MWR statistical retrieval and (bottom) Raman lidar. Black dots represent cloud base and top. Measurements taken at JOYCE (Jülich Observatory for Cloud Evolution)*

**Microwave radiometer (MWR)**

✔ Continuous data acquisition
✔ All weather conditions except rain
✔ Calibrated with internal references
✗ Limited vertical resolution

**Raman lidar (RL)**

✗ Difficult automated operation
✗ No observations in and above clouds. Noisy during daylight. No full vertical profile
✗ No internal calibration
✔ High vertical resolution

**New Retrieval**

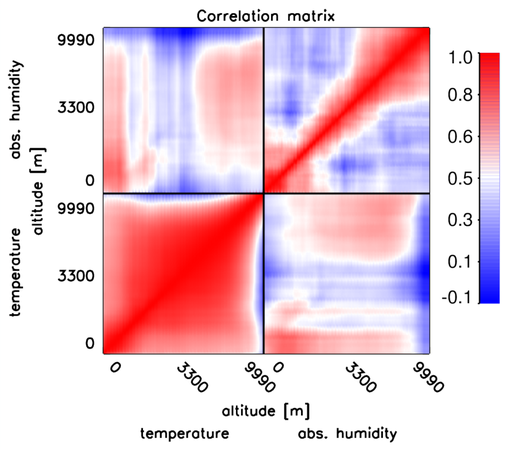
Combine RL with MWR to:

- Overcome limitation of individual sensors
- Retrieve **simultaneously** absolute humidity (AH), relative humidity (RH) and temperature (T)

## RL and MWR joint retrieval

**Optimal Estimation Scheme:**

$$x_{i+1} = x_i + \left(K_i^T S_e^{-1} K_i + S_a^{-1}\right)^{-1} \times \left[K_i^T S_e^{-1}\left(y - y_i\right) + S_a^{-1}\left(x_a - x_i\right)\right]$$




*Correlation matrix for 217 radiosondes. Correlation is shown between temperature and absolute humidity as a function of the altitude (from 0 to 10 km).*

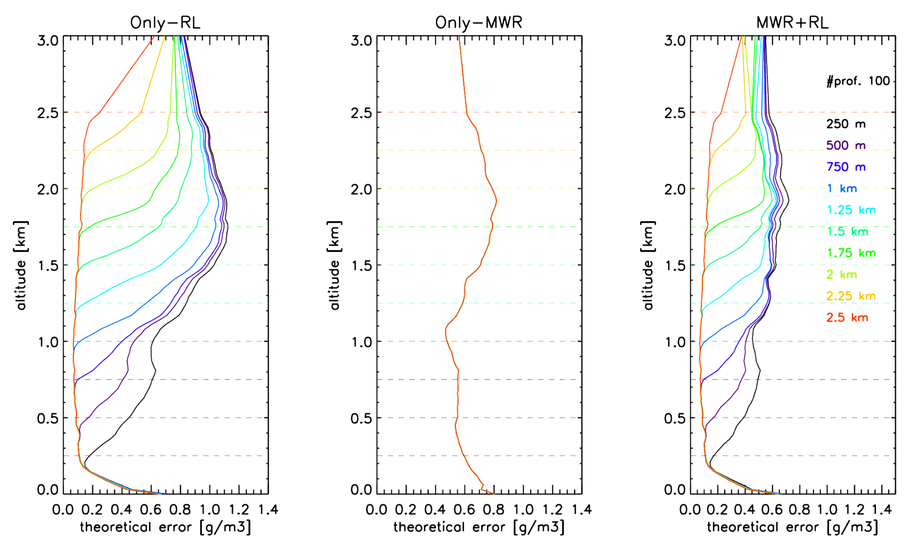
where: $K_i = \frac{\partial F(x_i)}{\partial x_i}$

A posteriori or **theoretical error**:

$$\hat{S} = \left(\hat{K}^T S_e^{-1} \hat{K} + S_a^{-1}\right)^{-1}$$

- A priori information, $\mathbf{x_a}$, $\mathbf{S_a}$
  - E.g. radiosonde climatology
- Measurements, $\mathbf{y}$, $\mathbf{S_e}$
  - Lidar temperature and humidity profiles
  - TBs from MWR
- Retrieved parameters, $\mathbf{x}$, $\mathbf{S_{opt}}$
  - Temperature and humidity
- Jacobian, **K**
- Forward model, **F**
  - Radiative transfer model
  - Mixing ratio to absolute humidity

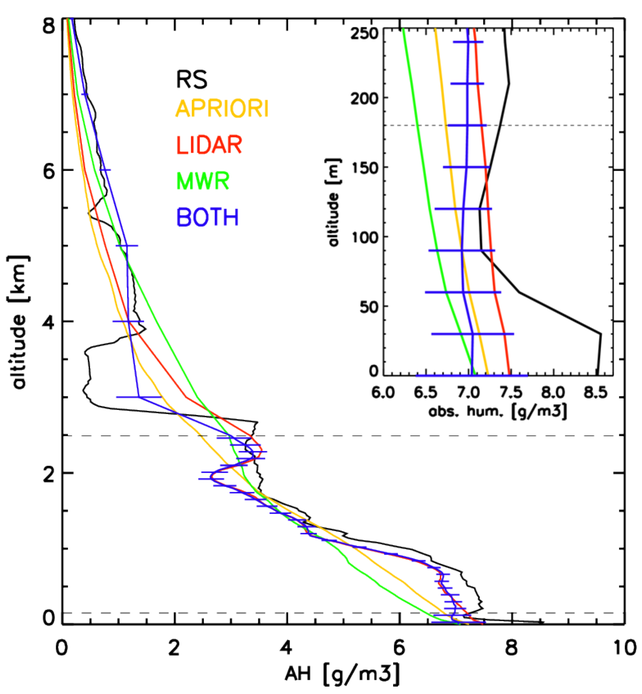
## Synergy benefit




*From left to right: average theoretical error for only-RL, only-MWR and MWR+RL, over 100 clear sky profiles, in the months of April and May 2013. Each colour represents a different clipping altitude (horizontal dashed lines) where lidar has been artificially cut.*

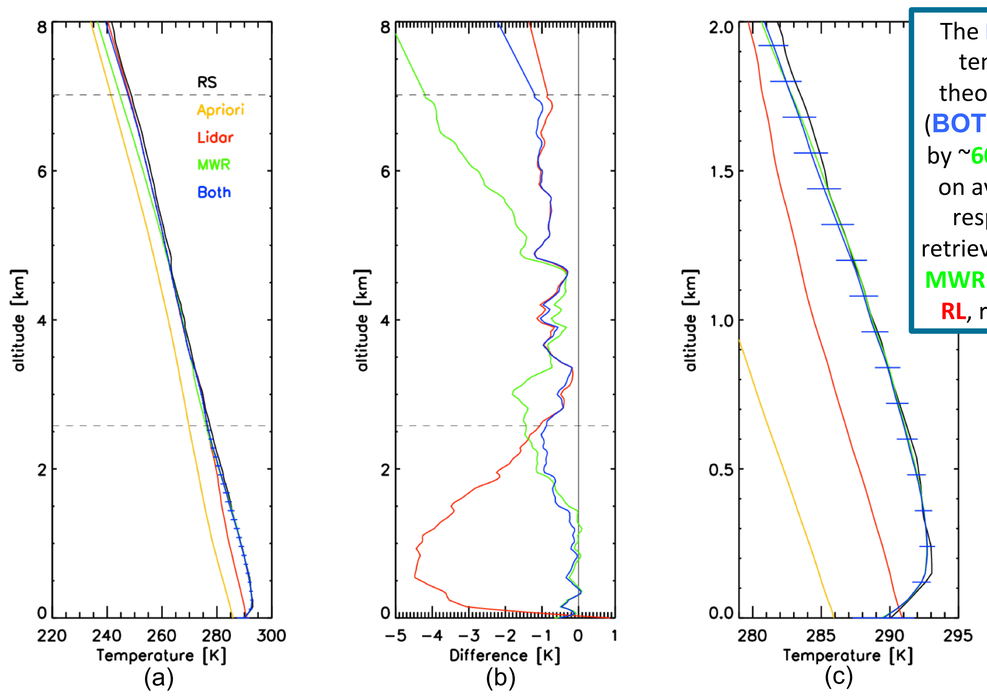
✔ Benefit of synergetic retrieval approach especially obvious when assuming different heights of lidar extinction (i.e. clouds)
✔ Lidar determines retrieval below cloud, however MWR can significantly enhance the information content above lidar extinction with respect to the a priori information.
✔ The lower the lidar extinction level, the higher the synergy benefit.

## Proof of concept – single profile of AH & T



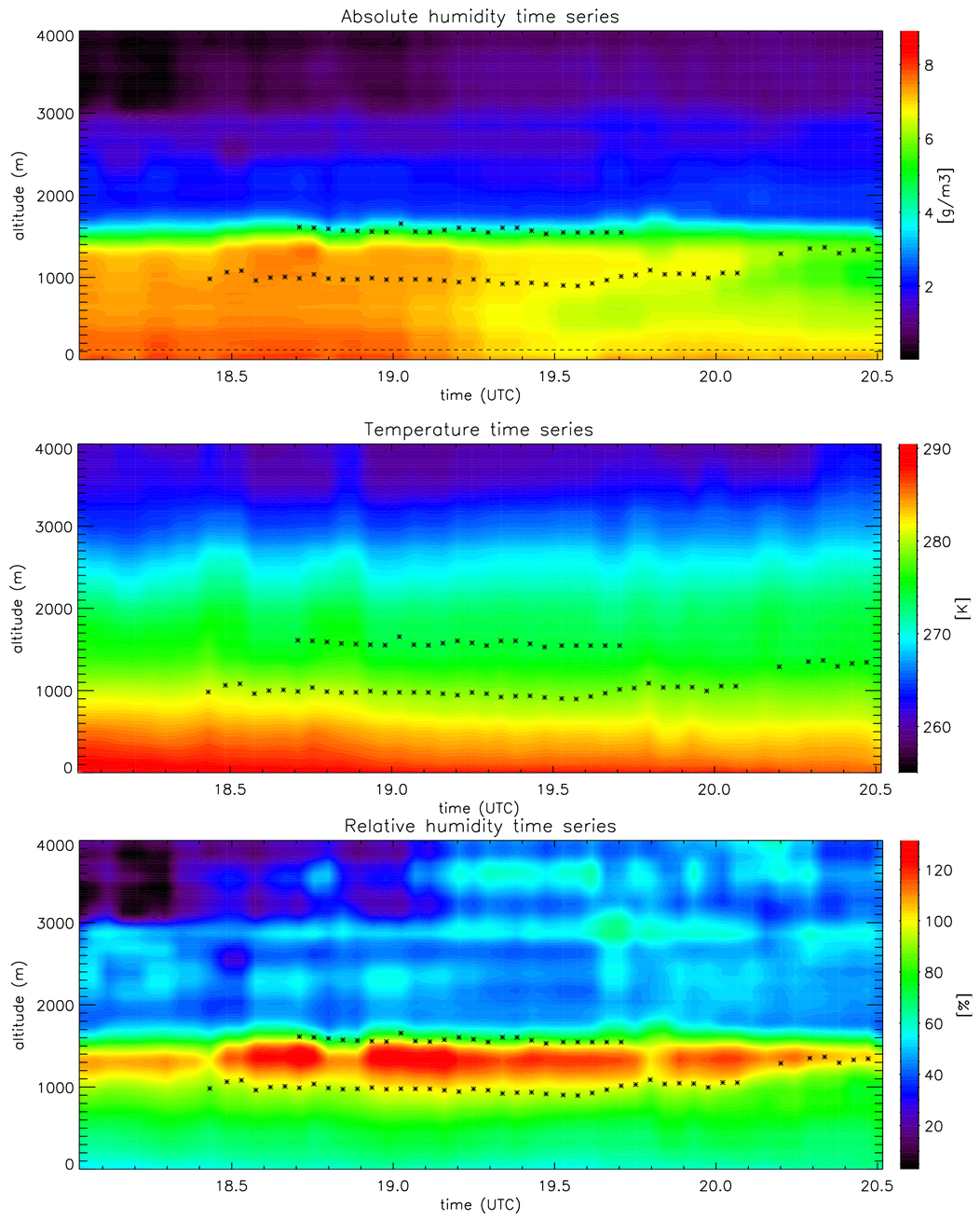

*Top: AH retrieval for a single profile, on the 24th of April 2013 at 11 UTC and a zoom to the lowest 250 meters. Bottom: Example of temperature profile on the 17th of April 2013, at 23 UTC **(a)** Complete tropospheric profiles of temperature **(b)** Bias to the radiosonde and **(c)** zoom into the lowest 2km of the atmosphere. Measurements taken at JOYCE.*

In both plots, the **RADIOSONDE** is used only as a reference. The starting point for the algorithm is the APRIORI profile. The region where there is *useful* lidar data is enclosed inside the dashed lines. Taking this piece of lidar profile and introducing it in the algorithm, the output is the complete **LIDAR** profile. When one introduces only the TBs from the MWR, the profile **MWR** is obtained. The combination of the the two sensors is **BOTH**. **Error bars** can be defined for each profile.




The **MWR+Lidar** temperature theoretical error (**BOTH**) is reduced by ~**60%** and ~**25%** on average, with respect to the retrieval using **only-MWR** data or **only-RL**, respectively.

## Cloudy scenario




*From top to bottom: time series of AH, T and relative humidity from the combination of the two sensors (MWR+RL). The period corresponds to the 4th of May 2013, from 18 to 20.5 UTC at JOYCE. The black dots represent the cloud base and top from ceilometer and radar, respectively.*

## Summary and Conclusions

- Active and passive remote sensing instrumentation can provide complementary information when operated next to each other.
- The MWR+LIDAR synergy is performed within optimal estimation framework.
- Novel synergetic retrieval for providing high vertical resolution profiles of AH, RH, temperature in clear-sky and cloudy conditions.
- Significant synergy benefit is proven in terms of:
  - Comparisons to soundings,
  - A posteriori retrieval analysis, e.g.: degrees of freedom, a posteriori error.
- The algorithm is currently applied to:
  - Ground based measurements, i.e. JOYCE measurements,
  - Airborne scenario: i.e. HALO aircraft.

**References:**

Barrera-Verdejo, M., Crewell, S., Löhnert, U., Orlandi, E., and Di Girolamo, P.: Ground-based lidar and microwave radiometry synergy for high vertical resolution absolute humidity profiling, Atmos. Meas. Tech., 9, 4013-4028, doi:10.5194/amt-9-4013-2016, 2016.