Combining ground-based and satellite measurements in the atmospheric state retrieval: assessment of the information content

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1. Introduction

Context:

➢ Accurate profiles of temperature and humidity are essential for climate monitoring, a better process understanding and weather forecasting

➢ Ground-based measurements in the microwave and infrared (IR) spectrum give information on the temperature and humidity profile of the lower troposphere

➢ Satellite measurements provide complementary information

Key questions:

➢ Given some a priori knowledge on the atmospheric state as well as realistic a priori and measurement uncertainties, how much information is added by different ground-based and satellite sensors?

➢ Do the results depend on the atmospheric situation?

2. Retrieval strategy

➢ 1D-Var approach to retrieve an atmospheric profile **x** (here, profiles of temperature **T** and absolute humidity **q**) from observation **y**:

optimal estimation equation [1]

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \left(\mathbf{K}_i^T \mathbf{S}_e^{-1} \mathbf{K}_i + \mathbf{S}_a^{-1} \right)^{-1} \times \left[\mathbf{K}_i^T \mathbf{S}_e^{-1} \left(\mathbf{y} - \mathbf{y}_i \right) + \mathbf{S}_a^{-1} \left(\mathbf{x}_a - \mathbf{x}_i \right) \right] \quad \text{with} \quad \mathbf{K}_i = \frac{\partial \mathbf{F}(\mathbf{x}_i)}{\partial \mathbf{x}_i}$$

➢ Given an a priori profile $\mathbf{x}_a$, as well as the a priori and measurement/forward model uncertainties $\mathbf{S}_a$ and $\mathbf{S}_e$, respectively, the posterior error covariance matrix **S** and the degrees of freedom for signal (DOF), i.e. number of independent pieces of information from **y**, can be calculated:

posterior error

$$\mathbf{S} = \left(\mathbf{K}^T \mathbf{S}_e^{-1} \mathbf{K} + \mathbf{S}_a^{-1} \right)^{-1}$$

degrees of freedom for signal

$$\text{DOF} = trace(\mathbf{A}) \quad \text{with} \quad \mathbf{A} = \mathbf{S} \cdot \left(\mathbf{K}^T \mathbf{S}_e^{-1} \mathbf{K} + \mathbf{S}_a^{-1} \right)$$

3. Experimental setup

➢ analysis is performed for
  ▪ different clear-sky atmospheric conditions (Fig. 1)
  ▪ different combinations of ground-based and satellite MW and IR sensors (Tab. 1)

➢ climatological mean profile ($\mathbf{x}_a$) and corresponding $\mathbf{S}_a$ from 12-year data set of 6-hourly clear-sky radiosonde ascents in Lindenberg, Germany

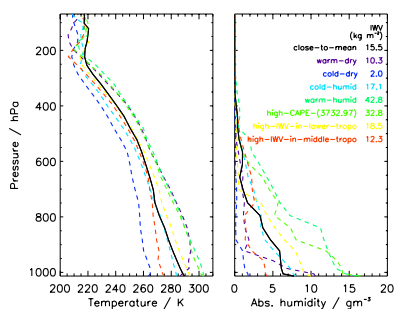➢ random instrument noise (Tab. 1) used in $\mathbf{S}_e$

Figure 1. T (left, in K) and q (right, in gm^{-3}) profiles of the analysed atmospheric conditions. IWV values (in kgm^{-2}) are reported close to the profile names.

Table 1. Sensor names and channels included in the study. Since measurement noise depends on the channel, values are given as min/max. RU is mW/(m^2 sr cm^{-1}).

Sensor	Frequency, Wavenumber/-length	# obs	Noise min/max	Forward model for K calculation
MWR HATPRO	22.24-31.4, 54.94-58 GHz (zenith + elev. scans)	34	0.1/0.2 K	PAMTRA [2]
AERI	559-1344 cm^{-1}	46	1.8/0.25 RU	LBLRTM [3]
SEVIRI	3.9-13.4 µm	8	0.1/0.37 K	RTTOV [4]
AMSU-A	23.8, 31.4, 50.3-57.617, 89 GHz	15	0.3/1.2 K	PAMTRA [2]
MHS	89., 157., 184.311, 186.311, 190.311 GHz	5	0.22/0.51 K	PAMTRA [2]

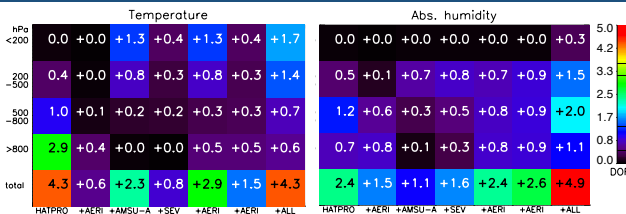## 4. Information content and retrieval uncertainty

Figure 2. DOF for T (left) and q (right) close-to-mean profile (Fig. 1). For HATPRO, the actual DOF are shown, while for all other sensor combinations the increase in DOF compared to HATPRO is depicted.
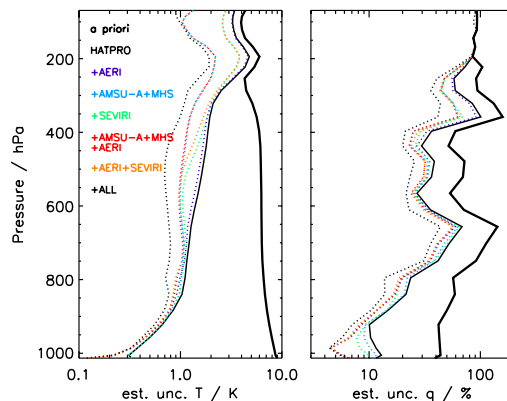

Figure 3. : Estimated uncertainties in T (left, in K) and q profiles (right, in % relative to radiosonde truth) for different sensor combinations. Close-to-mean profile.

➢ ground-based sensors provide most information below 500 hPa (Fig.2)

➢ benefit due to satellite sensors especially in upper part of troposphere

➢ results depend on atmospheric condition, e.g. for HATPRO+ALL:
  ▪ warm-humid: maximum DOF for **T** (9.7), minimum for **q** (6.0) due to saturation of IR channels
  ▪ cold-dry: minimum DOF for **T** (7.9), maximum for **q** (10.6)

➢ benefit of sensor synergy hardly affected by surface emissivity uncertainties

➢ doubling measurement uncertainties or halfing $\mathbf{S}_a$ reduce information content from additional sensors by 0.1-0.3 (0.2-1) in **T** (**q**)
  → variability in DOF due to atmospheric condition much higher

5. Summary and outlook

➢ amount of information in **T** (**q**) is roughly doubled (tripled) compared to ground-based MWR, when additional ground-based spectral IR, as well as MWR and IR observations from satellite are included

➢ analysis will be extended to 500 profiles which are representative of the whole data base

➢ full retrieval including HATPRO, AERI and SEVIRI measurements under development

➢ subsequent inclusion of cloud properties in the retrieval

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[2] Mech, M., Orlandi, E., Crewell, S., Ament, F. & Hirsch, L. (2012). HAMP - the Microwave Package on the High Altitude and LOng Range Aircraft HALO. manuscript in preparation
[3] Clough, S.A., Shephard, M.W., Mlawer, E.J., Delamere, J.S. , Iacono, M.J., Cady-Pereira, K., Boukabara, S. & Brown, P.D. (2005). Atmospheric Radiative Transfer Modeling: a Summary of the AER Codes, Short Communication. J. Quant. Spectrosc. Radiat. Transfer **91**, 233-244.
[4] Saunders, R. W., Matricardi, M., & Brunel, P. (1999). An Improved Fast Radiative Transfer Model for Assimilation of Satellite Radiances Observations. Q. J. R. Meteorol. Soc. **125**(556), 1407-1425.