COMBINING GROUND-BASED AND SATELLITE MEASUREMENTS IN THE ATMOSPHERIC STATE RETRIEVAL: ASSESSMENT OF THE INFORMATION CONTENT

Kerstin Ebell (1), **Emiliano Orlandi** (1), **Anja Hünerbein** (2), **Susanne Crewell** (1), **Ulrich Löhnert** (1)

(1) University of Cologne, Inst. of Geophysics and Meteorology, Zülpicher Str. 49a, 50674 Köln, Germany, kebell@meteo.uni-koeln.de
(2) Leibniz-Institute for Tropospheric Research, Permoserstraße 15, 04318 Leipzig, Germany, anjah@tropos.de

ABSTRACT

Accurate, highly vertically resolved temperature and humidity profiles are needed for many applications. This study, which focuses on improving tropospheric profiling strategies, is embedded in the European COST Action ES0702 EG-CLIMET, which investigates the potential of novel remote sensing techniques for operational profiling. Ground-based measurements in the microwave and infrared (IR) spectrum give information on the temperature and humidity profile, but mainly in the lower troposphere. Here, it is shown for different clear-sky situations that satellite measurements provide complementary information. Thus, the combination of ground-based and satellite measurements can considerably increase the number of independent pieces of information in the temperature and humidity profiles and decrease their uncertainties. In this analysis, the amount of information in temperature (humidity) is roughly doubled (tripled) compared to a standard ground-based microwave radiometer (MWR), when additional ground-based spectral IR, as well as MWR and IR observations from satellite are included.

1. MOTIVATION

Accurate profiles of temperature and humidity are essential for climate monitoring, a better process understanding and weather forecasting. Such profiles may not only be used to initialize and evaluate numerical weather prediction models but also to assess the atmospheric stability and to assist in nowcasting of intense convective weather. Radiosonde measurements provide this information but only typically every 12 hours. In order to continuously monitor the thermodynamic state, measurements of remote sensing systems which are operated on a 24/7 basis need to be exploited.

Various temperature and humidity profiling techniques exist for ground- and satellite-based microwave radiometer (MWR) observations [e.g., 1, 2, 3, 4]. Löhnert et al. [5] have shown that for a mid-latitude site, the number of independent pieces of information in the temperature and humidity retrievals from ground-based MWR profiler observations is in the range of 3.5-4.5 and 1-3, respectively. These profiles can further be improved if spectrally resolved IR observations are included in the retrieval. The benefit of this combination is significant compared to the individual observations in cold-dry (through IR observations) and humid conditions (through MWR observations) [5]. One shortcoming of ground-based observations is that they are mainly sensitive to the lower parts of the troposphere and provide less information in levels above. In upper height levels, satellite measurements could therefore provide complementary information and are thus expected to improve the estimates of the atmospheric state considerably.

In this study, we therefore assess the benefit of sensor synergy in tropospheric profiling using ground- *and* satellite-based measurements. The key questions in this respect are: 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

An atmospheric profile **x** (here, profiles of temperature T and absolute humidity q) can be derived using the optimal estimation theory [6]:

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

This 1D-VAR approach implies the knowledge of some a priori profile $\mathbf{x_a}$, as well as of the a priori and measurement/forward model uncertainties $\mathbf{S_a}$ and $\mathbf{S_e}$, respectively. **K** is the Jacobian, i.e. the sensitivity of the forward model with respect to changes in the atmospheric state. The posterior error covariance matrix **S**, which provides the estimated uncertainty of the most probable solution, is given by

$$\mathbf{S} = \left(\mathbf{K}^T \mathbf{S}_e^{-1} \mathbf{K} + \mathbf{S}_a^{-1}\right)^{-1}. \quad (2)$$

The information content of an observation in the retrieved atmospheric state is described by the number of degrees of freedom for signal (DOF). The DOF is the number of independent pieces of information that are determined from the measurement and is the trace of the averaging kernel matrix **A**:

$$\mathbf{A} = \mathbf{S} \cdot \left(\mathbf{K}^T \mathbf{S}_e^{-1} \mathbf{K} + \mathbf{S}_a^{-1}\right). \quad (3)$$

3. EXPERIMENTAL SETUP

The analysis is performed for different clear-sky atmospheric conditions. T and q uncertainties as well as the DOF can be directly calculated from Eqs. 1-3 given the matrices $\mathbf{S}_e$, $\mathbf{S}_a$, and $\mathbf{K}$.

3.1. Data

We performed the following analysis for Lindenberg, Germany, which is characterized by a mid-latitude, continental climate. The a priori covariance matrix was set up using a 12-year data set of 6-hourly clear-sky radiosonde ascents. The quality controlled radiosonde data are interpolated to a 43 level pressure grid. Only those radiosondes are included which reached at least the 69 hPa height level (~20 km). Standard atmospheric profiles are used to extend the T and q profiles up to 10 hPa, i.e. the highest model level. Since the limit of humidity measurements by radiosondes is approximately 200-300 hPa, q profiles of standard atmospheres are used for height levels above 200 hPa. In this way, a data set of 4854 radiosondes has been created which has been used to derive a mean climatological profile as a priori profile and corresponding variances and covariances for $\mathbf{S}_a$.

Eight profiles have been selected from the radiosonde data base to study the impact of different atmospheric situations on the retrieval performance. Profiles have been chosen using two objective indices, namely their path integrated water vapor (IWV) and an index quantifying their "distance" to the mean temperature profile. This procedure allows for the extraction of soundings representing extreme atmospheric situations and the sounding that is closest to the mean atmospheric state (Fig. 1).

3.2. Instrument systems and forward models

From a ground-based perspective, two instruments are included in the study: the 14-channel MWR profiler HATPRO and the Atmospheric Emitted Radiance Interferometer (AERI). Since MWRs became a standard tool for T and q profiling, the HATPRO retrieval is regarded as the baseline to which the combined instrument retrievals are compared. Satellite instruments included in this study are SEVIRI and AMSU-A together with MHS (Tab. 1). All measurement uncertainties are assumed to be uncorrelated which makes $\mathbf{S}_e$ a diagonal matrix. In this study, the diagonal entries only include the contribution due to typical random instrument noise (Tab. 1).

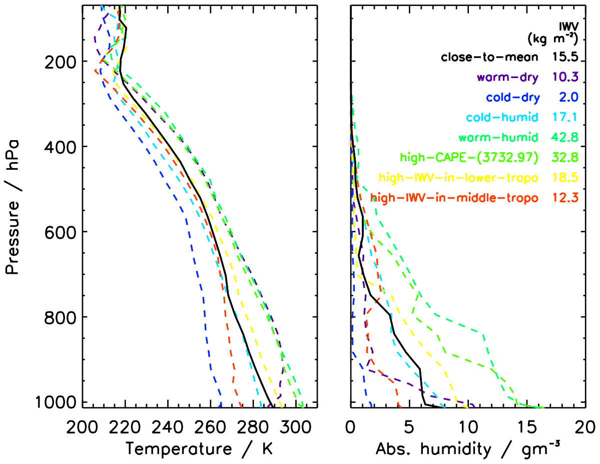


Figure 1. T (left, in K) and q (right, in gm^{-3}) profiles of the analysed atmospheric conditions. IWV values (in kgm^{-2}) are reported close to the profile names.

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 $mW/(m^2\ sr\ cm^{-1})$.

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

In order to calculate the Jacobian $\mathbf{K}$, forward models have been applied to the eight selected profiles to simulate the different sensor observations. MWR observations have been simulated with the newly developed radiative transfer model (RTM) Passive and Active Microwave TRAnsfer model [7]. The fast RTM RTTOV [8] is used to create synthetic SEVIRI measurements, while for the highly-resolved spectral AERI measurements in the IR, the LBRTM [9] has been applied.

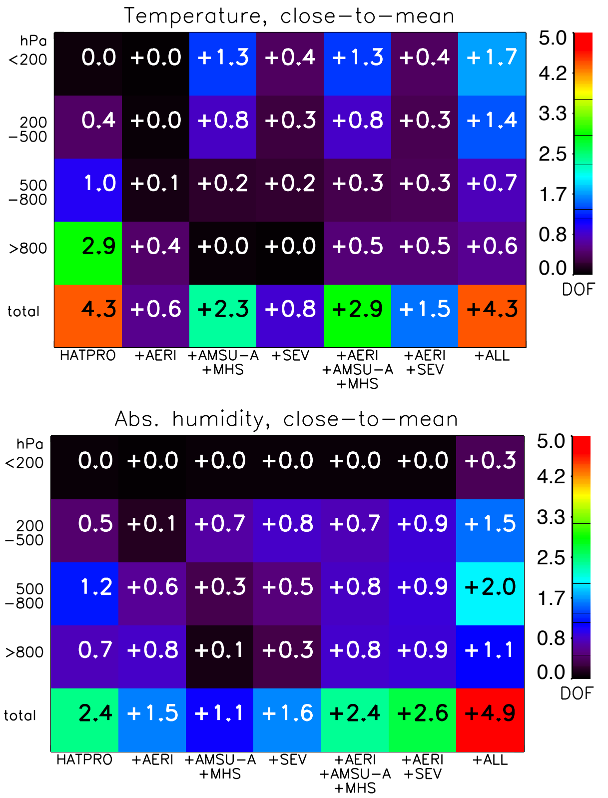
4. INFORMATION CONTENT AND RETRIEVAL UNCERTAINTY

For the T profile which represents mean conditions (close-to-mean, Fig. 1), HATPRO gives 4.3 independent pieces of information (Fig. 2, top). Note, that the HATPRO measurements not only include zenith observations but also measurements from 5 lower elevations angles for the channels 54.94-58 GHz. For humidity (Fig. 2, bottom), the DOF is smaller, i.e. 2.4. Most information comes from the lower troposphere, e.g. 67% of the T information originates from heights below 800 hPa. Spectral IR measurements from AERI increase the T and q information content in this atmospheric situation by 0.6 and 1.5, respectively, but do not provide significant information above 500 hPa either.

Though, combining HATPRO with satellite measurements, the DOF above the 800 hPa level increase considerably. AMSU-A+MHS add about 1 DOF in the T and q profile between 200-800 hPa and 1.3 DOF in the T profile above. Compared to AMSUA+MHS, SEVIRI provides more information in the tropospheric humidity profile, even in the lowest level. When combining HATPRO and AERI with one satellite sensor, the DOF is roughly the sum of the single contributions from AERI and AMSU-A+MHS /SEVIRI. The inclusion of all sensors in one retrieval results in the largest information content, 4.3 for the T and 4.9 for the q profile. Although the other retrievals do not provide significant information on the humidity above the 200 hPa level, the combined measurements do. This may be due to the fact that the AMSU-A measurements, which provide significant information on the temperature in these heights (<200 hPa), constrain the T profile in such a way that the SEVIRI measurements can be better exploited with regard to humidity. In general, the addditional information from the single sensors is not just additive but may even be larger when combining them. This behaviour reflects the benefit of sensor synergy and the complex, non-linear interplay of measurement information in the retrieval.

For the HATPRO and HATPRO+AERI retrievals, the DOF are similar for the different atmospheric conditions whereas AERI adds least information on q in humid conditions (Tab. 2). In humid conditions, AERI measurements become less sensitive to water vapor variations due to the saturation of the channels. Special atmospheric conditions to mention are the warm-humid and the cold-dry cases. In warm and humid conditions, the satellite and AERI observations provide largest information on T and and lowest on q, resulting in largest DOF of 9.7 and smallest DOF of 6.0, respectively, for the HATPRO+ALL retrieval. In humid conditions, the SEVIRI water vapor channels are saturated by humidity at higher atmospheric levels leading to a lack of information for lower levels. In cold and dry conditions, the DOF for T of the combined retrieval is smallest compared to the other atmospheric situations. This is related to the small information content provided by the satellite IR measurements. The DOF for q of the HATPRO+ALL retrieval is largest for the cold and dry atmospheric situation (10.6) which is primarily due to the large information content from the AERI measurements.

As expected, the estimated uncertainties in the retrieved temperature and humidity profiles are smallest when combining all sensors (Fig. 3). Below 800 hPa, the uncertainty in T and q is better than 0.8 K and 10.5%, respectively. Satellite measurements reduce the uncertainty especially above 800 hPa and in the tropopause region, where the a priori uncertainty due to the varying tropopause height is quite large. Note that for the a priori humidity above 200 hPa, a constant uncertainty of 80% is assumed since here humidity profiles from standard atmospheres are used.



Temperature, close−to−mean

hPa	HATPRO	+AERI	+AMSU−A +MHS	+SEV	+AERI +AMSU−A +MHS	+AERI +SEV	+ALL
<200	0.0	+0.0	+1.3	+0.4	+1.3	+0.4	+1.7
200 −500	0.4	+0.0	+0.8	+0.3	+0.8	+0.3	+1.4
500 −800	1.0	+0.1	+0.2	+0.2	+0.3	+0.3	+0.7
>800	2.9	+0.4	+0.0	+0.0	+0.5	+0.5	+0.6
total	4.3	+0.6	+2.3	+0.8	+2.9	+1.5	+4.3

Abs. humidity, close−to−mean

hPa	HATPRO	+AERI	+AMSU−A +MHS	+SEV	+AERI +AMSU−A +MHS	+AERI +SEV	+ALL
<200	0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.3
200 −500	0.5	+0.1	+0.7	+0.8	+0.7	+0.9	+1.5
500 −800	1.2	+0.6	+0.3	+0.5	+0.8	+0.9	+2.0
>800	0.7	+0.8	+0.1	+0.3	+0.8	+0.9	+1.1
total	2.4	+1.5	+1.1	+1.6	+2.4	+2.6	+4.9

Figure 2. DOF for T (top) and q (bottom) 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 shown.

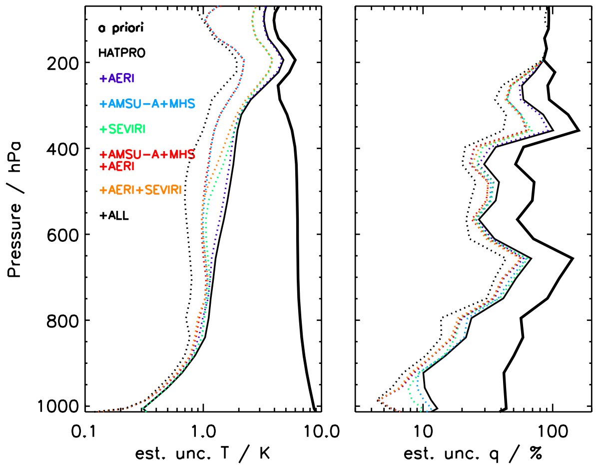


Figure 3: Estimated uncertainties in T (left, in K) and q profiles (right, in % relative to radiosonde truth) for different sensor combinations. Close-to-mean profile.

5. DISCUSSION AND OUTLOOK

The results obtained in this study show that ground-

Table 2: Number of degrees of freedom for signal for different atmospheric conditions and instrument combinations. For temperature (red) and absolute humidity (black) profiles.

Atmospheric profile	HATPRO		+AERI		+AMSU-A +MHS		+SEVIRI		+AERI +AMSU-A +MHS		+AERI +SEV		+ALL	
close-to-mean	4.3	2.4	4.9	3.9	6.6	3.5	5.2	4.0	7.2	4.7	5.8	5.0	8.7	7.3
warm-dry	4.4	2.5	5.1	4.5	6.5	3.8	5.0	3.9	7.2	5.4	5.8	5.5	8.4	8.9
cold-dry	4.4	2.3	5.0	5.8	6.5	3.2	4.8	3.6	7.0	6.5	5.4	7.0	7.9	10.6
cold-humid	4.3	2.3	5.0	3.4	6.7	3.5	5.2	3.8	7.2	4.3	5.8	4.5	8.3	7.2
warm-humid	4.3	2.4	5.5	3.4	7.2	3.0	6.0	2.9	8.4	3.9	7.3	3.7	9.7	6.0
high CAPE	4.3	2.4	5.2	3.5	6.9	3.5	5.3	3.8	7.7	4.4	6.2	4.7	8.9	6.9
high IWV low trop.	4.3	2.4	5.0	4.0	6.6	3.6	4.8	4.3	7.3	4.9	5.6	5.4	8.3	7.8
high IWV mid. trop.	4.4	2.3	5.1	4.0	6.8	3.4	5.4	3.6	7.3	4.9	5.9	5.0	8.9	7.1

based and satellite observations can be optimally exploited for T and q profiling. The benefit of sensor synergy has been demonstrated, especially in the upper parts of the atmosphere where ground-based instrumentation shows lack of information. In order to provide more robust results, the analysis will be extended to a larger subset of the 4854 radiosonde profiles: 500 profiles which are representative of the whole data base will be selected and analysed.

Since the DOF and the estimated uncertainty of the retrieved profiles depend on the assumed error covariance matrices, the results may differ if other assumptions on $\mathbf{S}_a$ and $\mathbf{S}_e$ are made. The usage of seasonal profiles as a priori will probably reduce the a priori uncertainty and will thus reduce the weight of the measurements in the retrieval and with that the DOF. The assumed uncertainties in $\mathbf{S}_e$ are rather small since only instrument noise is included up to now. Calibration uncertainties, uncertainties in the forward model, uncertainties in surface temperature and emissivity would reduce the information coming from the measurements. Thus, the results shown here can be regarded as an estimate of the maximum amount of information to be expected for an indealized measurement. Sensitivity studies will be performed with respect to these issues.

Currently, a full retrieval including HATPRO, AERI and SEVIRI measurements is under development. This study, which is part of the project ICOS (Integrating Cloud Observations from Ground and Space – a Way to Combine Time and Space Information) funded by the German Science Foundation DFG, is also a pre-study for the subsequent inclusion of cloud observations in the retrieval. We will first start using synthetic data to test the retrieval and subsequently apply it to real measurement from the Jülich ObservatorY for Cloud Evolution (JOYCE). In the context of COST, we have shown the high potential of combining ground-based and satellite measurements in atmospheric profiling. Thus, this approach has also potential for monitoring the atmospheric stability and for NWP data assimilation.

REFERENCES

1. Westwater, E.R. (1997). Remote Sensing of Tropospheric Temperature and Water Vapor by Integrated Observing Systems. *Bull. Am. Meteorol. Soc.* **78**, 1991-2006.
2. Güldner, J. & Spänkuch, D. (2001). Remote Sensing of the Thermodynamic State of the Atmospheric Boundary Layer by Ground-Based Microwave Radiometry. *J. Atmos. Oceanic Technol.* **18**, 925-933.
3. Crewell, S. & Löhnert, U. (2007). Accuracy of Boundary Layer Temperature Profiles Retrieved With Multi-Frequency, Multi-Angle Microwave Radiometry. *IEEE Trans. Geosci. Remote* Sens. **45**(7), 2195-2201.
4. Liu, Q & Weng, F. (2005). One-Dimensional Variational Retrieval Algorithm Of Temperature Water Vapor, and Cloud Water Profiles from Advanced Microwave Sounding Unit (AMSU). *IEEE Trans. Geosci. Remote Sens.* **43**, 1087-1095.
5. Löhnert, U., Turner, D.D. & Crewell, S. (2009). Ground-Based Temperature and Humidity Profiling Using Spectral Infrared and Microwave Observations, Part I: Simulated Retrieval Performance in Clear-Sky Conditions. *J. Appl. Meteor.* **48**, 1017-1032.
6. Rodgers, C.D. (2000). *Inverse Methods for Atmospheric Sounding: Theory and Practice*, World Scientific, 238 pp.
7. 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
8. 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.
9. 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.