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# Accuracy assessment of an integrated profiling technique for operationally deriving profiles of temperature, humidity and cloud liquid water

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## Introduction

Precise quantification of the atmospheric state is essential for climate research and weather prediction. Historically most of the operational atmospheric profiling is performed by radiosondes, but this network is under pressure due to the high costs, and operational alternatives are not available. Clearly, radiosondes state benchmark measurements for profiling the atmosphere, but are usually operated only on a 12-hourly basis, hence short-lived weather events may not be captured. Also, ascents need typically one hour to profile the troposphere and underlie wind drift effects. Furthermore a method to measure condensed water with radiosonde operationally does not exist. Cost-effective and operational measurements of cloud liquid water content would be of high value for the evaluation and development of numerical weather prediction (NWP) and climate models. A pressing question still is to what extent a ground-based remote sensing profiling station could complement or partially substitute an operational radiosonde network.

Passive microwave radiometry has the potential of retrieving the atmospheric thermodynamic state in a quasi continuous and instantaneous way<sup>1)</sup>. This requires a retrieval model which transforms the measured radiative quantities into thermodynamic information. In general, the retrieval problem is underdetermined. No unique solution exists but a wide range of possible thermodynamic structures give rise to the same set of measured radiative quantities. Further assumptions and additional measurements are needed to narrow down the number of valid solutions. Moreover, the vertical resolution of a typical stand-alone microwave profiler for temperature and humidity retrieval is rather coarse.

To overcome these shortcomings sensor synergy may prove beneficial. In the approach presented here, a continuous retrieval of the vertical structure of temperature, humidity and condensed water is achieved by employing synchronous and co-located measurements obtained with a microwave profiler, a cloud radar and a lidar ceilometer. These measure-

ments are combined with a priori information from the nearest operational radiosonde. The cloud radar and lidar ceilometer can unambiguously locate a cloud in the vertical, filling a major gap left by the radiometer. The Integrated Profiling Technique<sup>2)</sup> (IPT) combines these measurements in an optimal estimation framework.

This chapter addresses the accuracy of the IPT in describing the actual atmospheric state. The research is timely because remote sensing technology is becoming more accurate and affordable and operational systems are already being deployed at a number of stations mainly over Europe and the US.

In general it is not possible to assess the accuracy of the retrieval method because the 'true' state required to validate the retrieved state is unknown. This applies in particular to the cloudy component. E.g. in situ liquid water measurements are only sparsely available from aircraft and exhibit large measurement uncertainties. Moreover, it is impossible to measure instantaneously by aircraft the vertical column probed by a ground-based profiling station. To overcome the problem inherent in validating the IPT technique with real world data an accuracy assessment has been performed within a state-of-the-art model environment. There the atmospheric state and the measurements are exactly known at an arbitrary time and location. A further benefit is that the impact of the a priori information required by the IPT can be evaluated as a function of time and space with respect to the remote sensing measurements. For a detailed discussion on the implementation and results see Löhnert et al., 2007<sup>3)</sup>.

## Accuracy assessment strategy

We apply an atmospheric model to create an artificial 'true' atmospheric state. This is the state we like to recover by applying the IPT to remote sensing measurements (Figure 1). Within the model world, measurements from real instruments do not exist. Instead, virtual instruments or forward models are used to calculate simulated measurements from the given atmospheric state (i.e. temperature, pressure,

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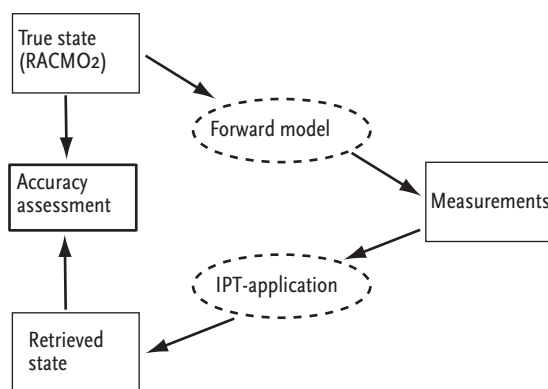


Figure 1. Concept of the experimental setup applied in this study.

humidity, cloud position and microphysics). The advantage is that we can exclude systematic measurement errors and systematic errors due to uncertainties in radiative transfer, which are almost impossible to quantify in reality. To produce realistic retrieval results, noisy errors typical for each measurement have been included.

A possible disadvantage of this approach is that the model atmospheric states may not cover the full range of observable states; the accuracy assessment is restricted to the model world itself. To transfer the findings to the real world, we must assume that the state-of-the-art atmospheric model represents the atmospheric state in a realistic manner for both mean and variability. The validity of this assumption can be tested by evaluating atmospheric models with measurements from long term observational campaigns like the European CloudNET and the US Atmospheric Radiation Measurement projects.

### State vector, measurement vector and forward model

We have used the KNMI regional climate model RACMO2<sup>4)</sup> to generate a time series of 'true' atmospheric states that must be reproduced by the retrieval. An uninterrupted model run, laterally forced by ECMWF analyses, has been performed for a 2-month period synchronous to the BBC1-campaign (August-September 2001).

The model output consists of vertical profiles at selected grid boxes of temperature, absolute

humidity and cloud liquid water content (LWC), hereafter referred to as the atmospheric state vector. A forward model operator is applied to project this vector on the measurement vector containing the measured parameters, namely brightness temperatures from the microwave profiler, radar reflectivities from the cloud radar, and surface meteorological measurements of temperature and humidity.

The brightness temperatures are obtained from the given atmospheric state by applying a radiative transfer operator at the microwave profiler frequencies. In the retrieval scheme, cloud radar reflectivities are used to determine the altitude of the cloud. In addition a power law relation is used to relate radar reflectivity to the in-cloud liquid water content. Near surface values of temperature and humidity, required by the retrieval method, are taken from the lowest model level.

To make the experimental set-up realistic, random noise is added to the measurement vector. Variations in the aerosol loading are represented using a relation between radar reflectivity and liquid water content which depends on the cloud droplet concentration. Since aerosol amount is not a variable in RACMO, wind direction is used as a proxy to prescribe the variation in cloud droplet concentration in the range between 50 and 300 per cm<sup>3</sup>, thereby mimicking air of maritime and continental origin, respectively.

### Inversion of the measurement

The IPT is applied to the measurement vector in order to retrieve the atmospheric state vector in an optimal way. Determining the state vector from the measurement vector is an underdetermined and ill-conditioned problem. No unique solution exists and small errors in the measurement can lead to huge deviations in the retrieved profile. Therefore measurements are combined with a priori information, which can be regarded as a first guess solution. The optimal estimation equations<sup>5)</sup> are suited for combining a set of instantaneous measurements with a priori information. Solving these equations requires knowledge of the a priori atmospheric state vector, the a priori covariance and the error covariance accounting for the combined measurement and forward modelling uncertainties.

In the real world, the a priori information will typically be taken from a climatology, a radiosonde ascent or a model forecast. In the model world we simulate the radiosonde information with model output from a grid column positioned at distance  $\Delta d$  from the measurement site and valid at time  $\Delta t$  prior to the measurement. In the now-casting mode we only utilize information from the most recent radiosonde ascent prior to the measurement. The now-casting mode reflects the IPT application to calculate thermodynamic profiles in real-time, once measurement and a priori data have been collected. The a priori covariance is constructed likewise by quantifying the assumption that the 00 (12) UTC

sounding may serve as a proxy for the temperature and humidity profiles between 00 and 12 (12 and 24) UTC. In the model world, the calculation of the a priori covariance is straightforward, since model output of thermodynamic profiles is known at arbitrary temporal resolution. In the real world, the determination of the a priori covariance requires frequent radiosonde information, at least once per three hours. This is only feasible during intensive field campaigns like the BBC campaigns in 2001 and 2003 at Cabauw.

As a priori for liquid water we use an average LWC profile derived from many realizations of a cloud microphysical model<sup>6</sup>). The LWC components of the a priori covariance are independent of temperature and humidity. Therefore the a priori covariance between these parameters is set to zero.

The error covariance matrix is constructed from considerations on propagation of errors corresponding to instrumental accuracy levels, radar calibration errors, but also uncertainty estimates associated to assumptions made e.g. in the relationship between radar reflectivity and liquid water content or in the interaction of microwave radiation with gaseous absorbers.

### Retrieval of temperature and humidity profiles at the radiosonde site

A priori information in the now-casting approach. Also, the a priori information and the measurement vector are collocated. The results for temperature and humidity are shown in Figure 2. The IPT RMS (root mean square) errors that result from the IPT application are shown together with the RMS errors that come from assuming persistence of the a priori information (a priori RMS). The difference between these two RMS errors is the retrieval profit, i.e. the benefit due to the use of all measurements compared to the radiosonde alone. For temperature, the highest retrieval profit is in the lowest 2 km where the information added by the microwave profiler is highest. Also shown is the uncertainty associated with the error propagation, the so-called theoretical IPT error. When this error is comparable to the IPT RMS, the retrieval system is considered well balanced. Compared to temperature, the retrieval profit for humidity is more pronounced and extends to higher altitudes.

### Retrieval of temperature and humidity profiles away from the radiosonde site

Next we carry out a sensitivity study with the central question: How accurate is the IPT if the a

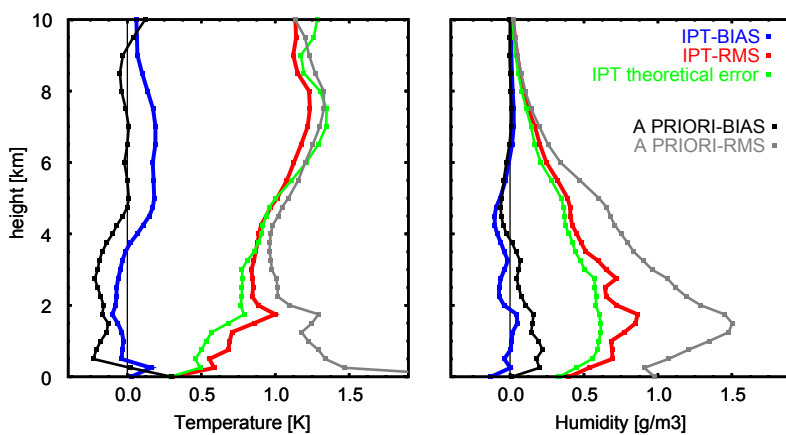


Figure 2. Accuracies of temperature and absolute humidity profiles for the now-casting mode.

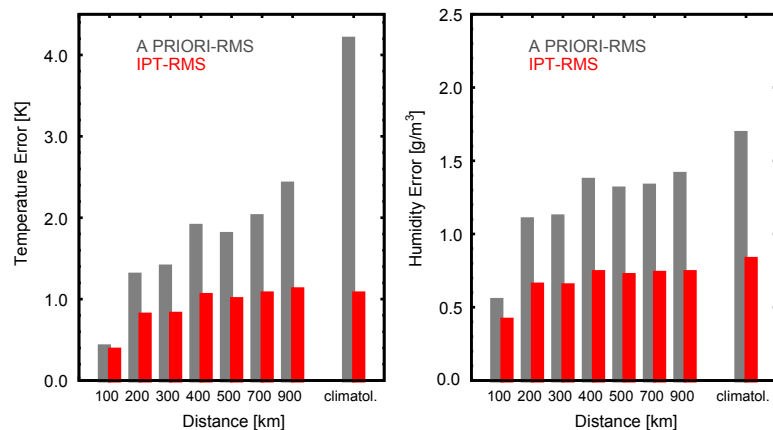


Figure 3. IPT and a priori accuracies for temperature and humidity averaged over the bottom 4 km of the atmosphere as a function of the distance between the radiosonde launch site and the remote sensing site. Grey bars: a priori RMS errors (assuming the persistent validity of the nearest and most recent radiosonde ascent), red bars: the IPT RMS errors, The last pair of bars (climatol.) shows results for a priori data inferred from a climatology.

## IPT can add a significant retrieval profit to the profiles in the times between two radiosonde ascents

priori information comes  $\Delta d$  km away from the profiling station and from a discrete time period  $\Delta t$  hour prior to the actual measurement? The results shown in Figure 3 are relative to the combination 0km/0h, which represents the optimal result, because then the a priori information is already equal to the model truth and additional measurements can not improve on that. (In the previous paragraph a priori profiles were taken at  $\Delta d = 0$  km, but  $\Delta t$  was encompassing all values from 0 to 12 h.) Applying Taylor's hypothesis all results have been expressed in terms of a spatial distance. The RMS values have been averaged over the lowest 4 km where the retrieval profits are largest. Not surprisingly the a priori temperature RMS increases with distance, but performs better than an a priori estimate from climatological data. For large distances the IPT RMS error is rather constant with values close to 1 K. Interestingly, a comparable value for the IPT RMS error is obtained, if a priori information is derived from climatological data. When a high accuracy is not demanded, the IPT can lead to a retrieval profit of more than 3 K in the lowest 4 km.

If IPT RMS accuracies better than 1 K are required, the profiling station should be located within a radius of 200 km from the radiosonde. Within this range, the retrieval profit is generally lower (due to the higher accuracy of the a priori information). However

application of the IPT still improves the accuracy! Comparable results are found for humidity. When accuracies better than  $0.5 \text{ gm}^{-3}$  are required the distance between the radiosonde ascent and the station should be less than 100 km. Again, for distances of 400 km or beyond results with a priori information from a climatology are comparable to a priori information from radiosondes.

### Thermodynamic profile retrieval within liquid water clouds

The IPT version under investigation can handle clouds with a vertical extension up to 1500 m with a vertical resolution of 250 m. We have evaluated the IPT performance as a function of height to cloud base. Results for thin clouds (500 m) and thicker clouds (1250 m) are shown in Figure 4. In general, the IPT RMS errors increase with increasing cloud vertical extent due to larger amounts of LWC in geometrically thicker clouds. It is evident that the largest IPT RMS errors are correlated to the maximum LWC values within the profile. If the cloud layers nearest to cloud top and base are excluded from the analysis, the mean relative LWC error for clouds with vertical extent from 750 to 1500 m is approximately 30%. Also, the predicted theoretical IPT errors are found in rather good agreement with the derived IPT RMS errors.

### Discussion and Outlook

We have discussed how ground-based remote sensors can be used in an optimal way to retrieve continuously the thermodynamic state of the atmosphere. For the retrieval of temperature and humidity profile, the highest information content originates from the brightness temperature measurements of microwave profilers. Due to the limited vertical resolution remote sensing instruments cannot achieve the accuracy of a radiosonde ascent. However, we have demonstrated that IPT can add a significant retrieval profit to the profiles in the times between two radiosonde ascents, at locations of up to 300 km away from the ascent.

The results for temperature and humidity retrievals have been obtained in the now-casting approach. We expect this approach to be a major focus in future, because it is suitable for real-time applications in short-term weather forecasting and data assimilation. An alternative approach is the climate mode in which

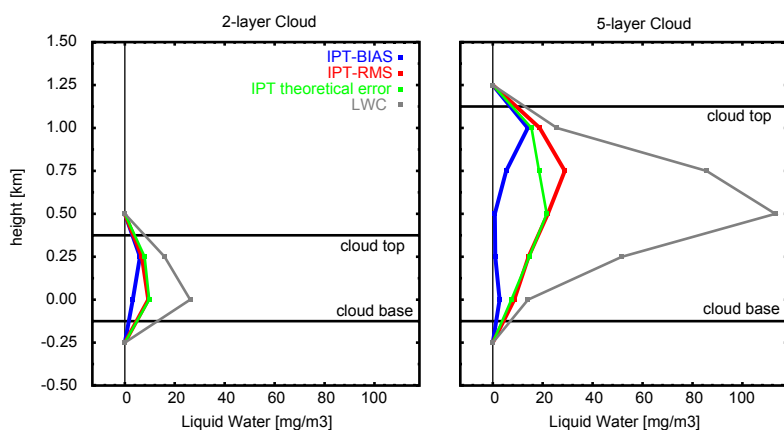


Figure 4. IPT RMS accuracies of liquid water content as a function of height above cloud base. The left panel shows the result for the class of relatively thin clouds (500 m), the right panel shows the result for the class of thicker clouds (1250 m).

the a priori information is obtained by temporal interpolation of past and future information close to the time of the remote sensing measurement. The climate mode is particularly useful for the reprocessing of data time series where it is important to produce accurate physically consistent profiles of the atmosphere using as many measurements and as much a priori information as possible.

Although the results presented in this chapter are encouraging, it must be emphasized that they are obtained in an idealized setup. Transposition to the real world might introduce systematic errors associated with uncertainties in the radiative transfer operator and the instrument calibration. The underlying causes are in the treatment of microwave

absorption due to gaseous components (oxygen and water vapour) and liquid water in standard absorption models. Also, receiver drifts and absolute calibration inaccuracies may lead to long-term instrumental offsets causing systematic deviations. Here, state-of-the-art microwave profilers (such as the RPG HATPRO<sup>71</sup>) can guarantee relatively high-accuracy and stable measurements. An advantage of the IPT-RACMO2 test-bed developed here is that systematic errors related to instrument characteristics and uncertainties in the microwave absorption may now be investigated in detail. This will help to assess whether instrument performance and forward model accuracy are really suited in getting the results close to the theoretically possible ones highlighted in this study.

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