Accuracy of Boundary Layer Temperature Profiles Retrieved with Multi-frequency, Multi-angle Microwave Radiometry

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***Abstract*—Observations by a state-of-the-art ground-based microwave profiler during the LAUNCH campaign in Lindenberg, Germany are used to derive temperature profiles with high vertical resolution in the boundary layer. The comparisons with observations from a 99 m mast and from radiosondes reveal the high accuracy achieved by combining angular and spectral observations (overall less than 1 K below 1.5 km). Especially, the profiler is able to observe the height and strength of low-level temperature inversions. The retrieval performance of different angle and frequency combinations is investigated by employing statistical algorithms derived from long-term radiosonde time series.**

***Index Terms* — Remote sensing, ground-based microwave radiometry, boundary layer profiles, vertical resolution.**

I. Introduction

MICROWAVE PROFILERS which measure several frequencies along the 60 GHz oxygen absorption complex are well established for observing the atmospheric temperature profile from the ground as well as from space. From the ground, observations are typically taken in zenith direction at about 5 to 10 frequency channels from 50 to 60 GHz [1]. The RMS accuracy of this method is about 0.6 K close to the surface and degrades to about 1.5-2 K in the middle troposphere [2, 3, 4]. The vertical resolution decreases rapidly from about 500 m at 300 m height to 1 km in 500 m height [2, 3].

Because the development of the atmospheric boundary layer (ABL) is of special interest due to the large transfer of energy between the surface and the atmosphere, an increased vertical resolution is desired. Therefore one channel systems operating around 60 GHz have been developed [5, 6], which derive profile information from elevation scanning. By assuming horizontal homogeneity of the atmosphere the observed radiation systematically originates from higher altitudes the higher the elevation angle. Since these brightness temperatures vary only slightly with elevation angle, the method requires a highly sensitive radiometer which is typically realized by using wide bandwidths up to 4 GHz. The resulting vertical resolution has been estimated using the Dirac delta function to decrease from 8 m at 10 m height to about 300 m at 400 m height and the accuracy to better than 1 K by comparison with observations from a 300 m tower [7]. The use of a single highly opaque channel limits the information content to altitudes below 600 m.

In order to extend the vertical range of the boundary layer temperature profiles, frequency channels with less opacity need to be used. Caddedu et al. [8] performed a theoretical study through a multi-resolution wavelet technique for different radiometer configurations (angles/channels/ bandwidths). Her simulations suggest that the scanning configuration with high accuracy (large bandwidths) is favorable for altitudes below 1 km while above 1 km a multi-frequency system with fixed elevation gave a better performance.

In this paper, we investigate whether state-of-the-art microwave radiometers can observe an optimal temperature profile throughout the atmosphere by a combination of spectral *and* angular information. For experimental validation, observations from the LAUNCH campaign 2005 in Lindenberg, Germany are used.

II. Observations

A. Microwave Radiometer

The Humidity and Temperature Profiler (HATPRO) [9] was designed as a network-suitable low-cost microwave radiometer which can observe liquid water path (LWP), humidity and temperature profiles with high (1s) temporal resolution. HATPRO comprises total-power radiometers utilizing direct detection receivers within two bands. The first band contains 7 channels from 22.335 to 31.4 GHz and second 7 channels from 51 to 58 GHz. The receivers of each frequency band are designed as filter-banks in order to acquire each frequency channel in parallel. In addition, this approach allows setting each channel bandwidth individually. Because profiling the boundary layer temperature depends strongly on the sensitivity and accuracy of the channels close to the oxygen band center, the channels from 56.66 – 58.00 GHz

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TABLE I
HATPRO RECEIVER PROPERTIES

Center Frequency (GHz)	Bandwidth τ (MHz)	Channel Sensitivity ΔT_B[a] (K)	Bias[b] T_B-T_{Rs} (K)	St. dev.[b] T_B-T_{Rs} (K)
58.00	2000	0.007	0.24	0.43
57.30	1000	0.009	-0.06	0.39
56.66	600	0.012	-0.04	0.38
54.94	250	0.018	-1.02	0.24
53.86	250	0.018	-.27	0.58
52.28	250	0.018	-0.41	0.96
51.26	250	0.018	3.21	0.98

[a]channel sensitivity is calculated for a Dicke type system with a noise temperature T_{sys}=800 K and an integration time Δt=30 s via the radiometer formulae $\Delta T_B = 2 \cdot T_{sys}/(\Delta t \cdot \tau)^{1/2}$

[b]Bias and standard deviation are calculated from a set of 53 radiosoundings launched at Lindenberg using the Rosenkranz gas absorption model

have a much higher bandwidth than those at lower opacity (standard 250 MHz; see Table 1).

The antenna beamwidth for the channels along the oxygen line is 2° full width at half maximum with a side lobe suppression of better than 30 dB avoiding problems with surface contamination at low elevation angles. The radiometer is enclosed in a radome which is protected from dew formation by a strong blower system. Precipitating conditions are reported by precipitation detector. Furthermore, environmental sensors for temperature, humidity and pressure as well as a GPS clock are present.

The absolute radiometer calibration was performed once at the start of the campaign using a liquid nitrogen target and continuously for the channels along the water vapor line using the tipping curve procedure. Relative calibration (gain adjustment) is performed every 5 min by looking at the in-built ambient load.

B. *Intercomparison Data*

The results presented below were gathered during the LAUNCH (International **L**indenberg campaign for **A**ssessment of h**u**midity a**n**d **c**loud profiling systems and its impact on **h**igh-resolution modeling) 2005 campaign at and around the Richard-Aßmann Observatory of the German weather service (DWD) at Lindenberg, Germany (52.17 N, 14.12 E). The observatory is located ~ 65 km southeast of Berlin and launches Vaisala RS-92 radiosondes operationally four times a day (00, 06, 12 and 18 UTC). DWD further operates a boundary layer measurement site at Falkenberg 4 km south of Lindenberg. Here, HATPRO was deployed in order to compare the retrieved temperature profiles with observations of temperature and humidity taken at 6 levels (10, 20, 40, 60, 80 and 98 m) along a 99 m mast. The Falkenberg observations are complemented by SODAR/RASS and a ceilometer [10]. The area around Lindenberg and Falkenberg is dominated by farmland and varies between 50 and 120 m altitude.

C. *Intercomparison Setup*

Microwave radiometer observations were taken at Falkenberg starting on September 8, 2005 at 9 UTC and ended

TABLE II
HATPRO SETTINGS DURING BOTH OBSERVATION PERIODS

	Period A	Period B
Begin (UTC)	8 September 05, 9	17 October 05, 12
End (UTC)	17 September 05, 18	1 November 05, 8
Angles used for BL scans (°)	90.0, 42.0, 30., 19.2, 10.2	90.0, 42.0, 30., 19.2, 10.2, 5.2
BL duration (s)	320	320
BL repetition time (min)	30	20

on November 1, 2005 7 UTC. Unfortunately, on September 17, 18 UTC the GPS clock failed which led to an omission of relative calibrations until this was corrected for on October 17, 12 UTC. Because the data in this time interval are of minor quality they are ignored in the following. The instrument settings during the two considered periods are given in Table 2. The elevation scans lasted about 5 min each with an integration time of about 30 s at each angle. In between the scans zenith observations for liquid water path (LWP) measurements were taken.

III. RETRIEVAL RESULTS

A. *Simulation*

Statistical retrieval algorithms were developed in a similar fashion as described in detail by Löhnert and Crewell [11], Crewell and Löhnert [12]. Here we used a data base consisting of more than 10000 Lindenberg radiosoundings from 1994 to 2002 with high vertical resolution. The analysis of the soundings emphasize the importance of boundary layer temperature observations because obviously here the largest temperature variations occur (Fig. 1). On average the soundings show a temperature gradient (dt) close to zero at the ground which approaches a typical value of -0.6 K/100m in about 400 m height. If only clear cases (diagnosed if relative humidity is less than 95% throughout the profile) are considered the temperature gradient even becomes positive close to the ground indicating the frequent occurrence of temperature inversions caused by radiative cooling during night.

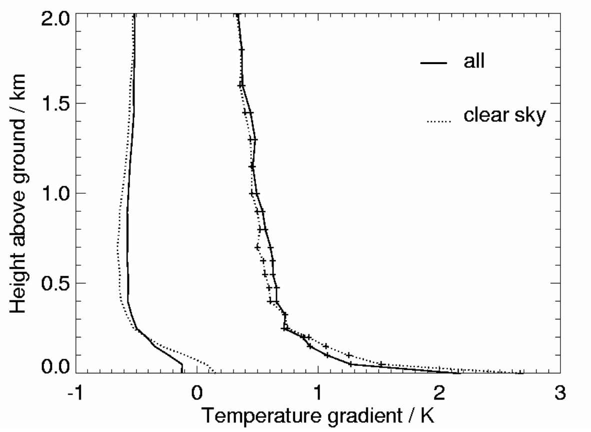

Fig. 1. Mean temperature gradient of radiosounding data set and its standard deviation (+). During clear sky scenes (dotted) temperature gradients show highest values close to the surfaces.

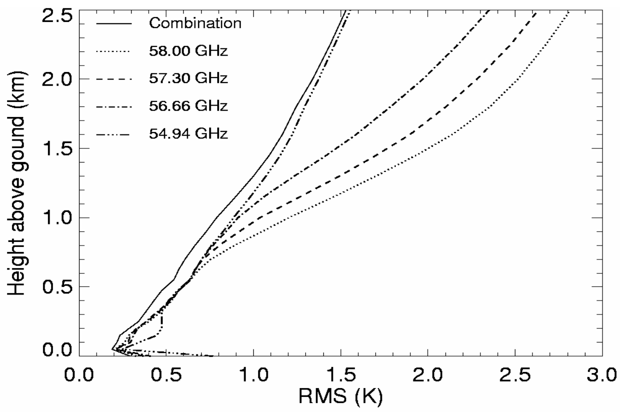

Fig. 2. Root Mean Square (RMS) error of boundary layer temperature retrievals based on elevation scans (6 angles) at four selected frequencies (dashed and dotted lines indicated in the figure). The solid line shows that the combination of brightness temperatures measured at four frequencies and six angles gives the best performance. The noise level was assumed to be 0.1 K considering the specifications of the HATPRO frequencies (Table 1).

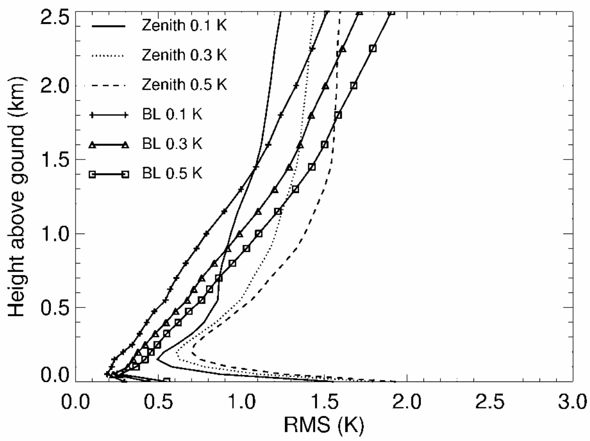

Fig. 3. Performance of boundary layer temperature retrievals for zenith (7 channels) and elevation scanning (4 channels, 6 angles) mode in terms of RMS error. Three different noise levels (0.1, 0.3 and 0.5 K) in brightness temperatures are considered.

The data are divided into a training (N= 5334) and a test data set (N=4954). For each sounding the radiative transfer for all HATPRO frequencies was calculated based on the Rosenkranz gas absorption model [13]. It should be noted that at the considered frequencies between 54.94 and 58 GHz the use of the Liebe 1993 model results in very small differences. We chose in total 6 elevation angles which are spaced evenly in terms of air mass factor, i.e. 90.0°, 42.0°, 30.0°, 19.2°, 10.2° and 5.2° corresponding to air mass factors between 1 and 3.5. Algorithms were developed on a 50 m vertical grid close to the ground which gradually degrades to 1 km in the upper troposphere (see Fig. 1). Note that this grid is still finer than the true vertical resolution of the retrievals but similar to the one used by current weather forecast models.

The variation of the simulated brightness temperature with angle is rather small: in 50% of all cases the TB variation between 5.2° and 90° is less than 1.8 K at 58 GHz (2.1 K at 57.3 GHz; 2.4 K at 56.66 GHz and 6.9 K at 54.94 GHz). When the angular range is reduced, i.e. the lowest angle is limited to 10.2°, this value is reduced to 1.6 K at 58 GHz. This emphasizes that a highly accurate and stable radiometer is needed to resolve the TB variations.

If only this angular information is considered at a single frequency the three highest frequencies give a similar performance up to about 700 m height with an accuracy of about 0.7 K. In the lowest 300 m the accuracy even reduces to ~0.2 K showing how direct the measurement is related to temperature (Fig. 2). The maximum height with an acceptable RMS error of 1 K is therefore at 1 km for the 54.94 GHz channel. This channel, however, gives already minor performance at the lower level. Therefore no channels with lower opacities have been considered. Clearly the best performance is achieved when all frequencies at all angles are combined in one algorithm giving an accuracy of about 0.5 K in lowest 500 m. Note, that the ground-level itself is an exception as here the energy fluxes act most directly and the temperature is subject to much stronger variations compared to the vertical next level (50 m) where blending is already taken place.

It should also be noted that in reality other problems might occur which are not considered in this simple simulation framework. While close to the absorption center the opacity is so high that most radiation originates from along a path of about 300 m, at 54.94 GHz this path length increases to about 1-2 kilometer. Especially at the low elevations very different surfaces, for example forest, lakes or concrete might change the atmospheric temperature profile and make the assumption of horizontal homogeneity invalid.

Now the question arises how the combined boundary layer scanning algorithm (BL) compares with the standard zenith operation mode. Therefore for the same data set a retrieval algorithm making use of all seven HATPRO channels (additionally using quadratic terms) was developed. Close to the surface this algorithm performs much worse than the angular one (Fig. 3). Within the lower approx. 800 m of the atmosphere the BL algorithm performs better than the zenith one even if the noise level of the brightness temperatures is assumed higher than for the zenith algorithm (0.5 to 0.1 K). When the same noise level is assumed the zenith algorithm turns superior at an altitude of about 1500 m. This is about 500 m higher than indicated by Caddedu et al [8] and can be attributed to the use of in total 4 frequency channels in the BL algorithm. Because the atmospheric boundary layer often exceeds 1000 m, the improved accuracy should be beneficial to boundary layer studies.

In order to get one consistent temperature profile covering the full troposphere it is clear that more opaque channels need to be included into the retrieval. The simplest way, e.g. to use all HATPRO frequencies and all angles, might be problematic in practice because different air masses might be probed at the low elevation angles. Fig. 4 shows that it is sufficient to incorporate the three opaque channels only with their zenith observations (called 4vz later on) and achieve a similar

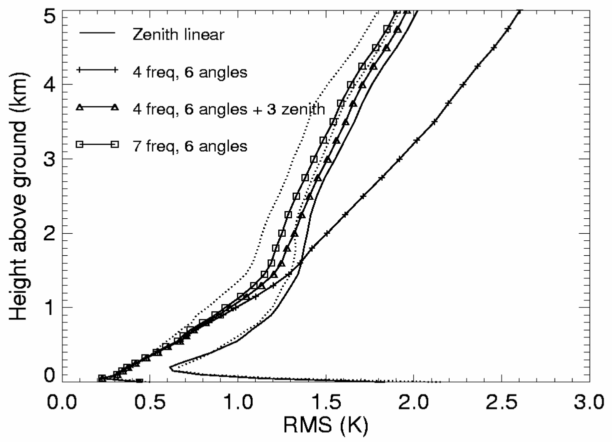

Fig. 4. Performance of boundary layer temperature retrievals for different combinations of observations. The noise level of all brightness temperatures is 0.3 K. For the zenith retrieval (7 frequencies) and the combination of all (7) frequencies and angles (6) the dotted line gives the RMS value in clear sky conditions. Please note that in clear sky conditions the error in the surface value increases to over 2 K because local heating of the surface occurs.

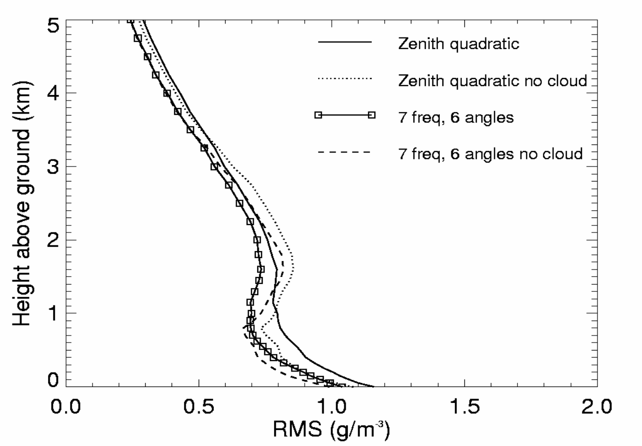

Fig. 5. Performance of boundary layer humidity profiles based on seven frequencies between 22.235 and 31.4 GHz. The dotted/dashed line gives the RMS value in clear sky conditions. Here the accuracy reduces in the altitudes which are mostly cloudy as the constraint of a fixed humidity does not hold any more.

accuracy which approaches the one of the zenith retrieval at higher altitudes. If only cloud free conditions are considered the angle information is also useful at higher altitudes (more radiation comes from here) and even up to 4 km altitude the accuracy is ~0.3 K better than the zenith retrieval.

For completeness we performed a similar analysis for the humidity profiles. Here the angular information leads only to a minor improvement in the lowest 2 km which however in reality might be misleading as the water vapor field exhibits much stronger horizontal fluctuations than the temperature. Because all frequencies channels along the water vapor line are highly transparent the assumption of horizontal homogeneity most likely will not hold true.

B. Comparison with tower observations

In order to test the retrieval performance in reality at first a comparison with observations of the 99 m mast was performed. Here one has to be aware of the fact that while the tower sensors integrate at one point for 10 min, HATPRO needs about 5 min for observing the different angles. The comparison for the second observation period B (Fig. 6) reveals the very good agreement for the lowest (10 m) and highest (98 m) level of the tower. Some single spikes occur in the HATPRO observations which might be caused by obstacles in the lowest beam or strong precipitation which has not been filtered out of the data set.

Most interesting is the capability of the system to observe the strength of ground-level temperature inversions. While the radiometer observations show a more noisy structure the overall agreement is very promising. A close look even shows that the noise is stronger during daytime (also in period A) and therefore might partly be attributed to thermals within the view of the radiometer. For a more quantitative comparison all tower and HATPRO observations which match within 30 min have been compared (Fig. 7). At the two altitude levels both observation types correlate better than 0.99. Even for the temperature gradient the correlation exceeds 0.9. At the surface level a bias can be noticed which might arise from the discrepancy between the 10 m tower level and the nominal retrieval altitude of 0 m. The RMS difference of 0.5 K at the 100 m level achieved over the large range of atmospheric

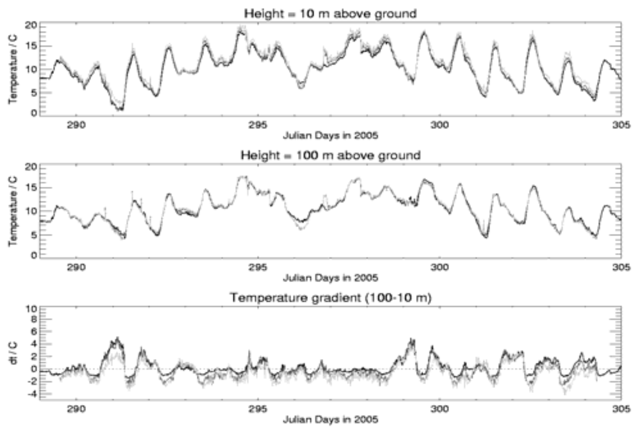

Fig. 6. Time series of mast (black) and HATPRO (grey) observations at lowest (10 m) and highest (100 m) mast level as well as temperature gradient between these for observation period B. Retrievals with 6 angles (grey) and 5 angles (light grey).

temperatures (0 to 30 °C at ground level) encountered in both observation periods demonstrates an excellent performance (Fig. 7). It should be noted that no filtering has been applied and even rainy scenes are included. The bias between HATPRO and the mast depends on the type of retrieval algorithm which is used (compare Table 3). A bias of close to zero (0.02 K) at 100 m is achieved with the angular information of the highest four frequencies and the zenith measurement of the other four channel assuming 0.1 K noise level (4νz6φ_0.1).

During the observation period B the effect between using 6 vs. 5 angles can be verified experimentally. This period

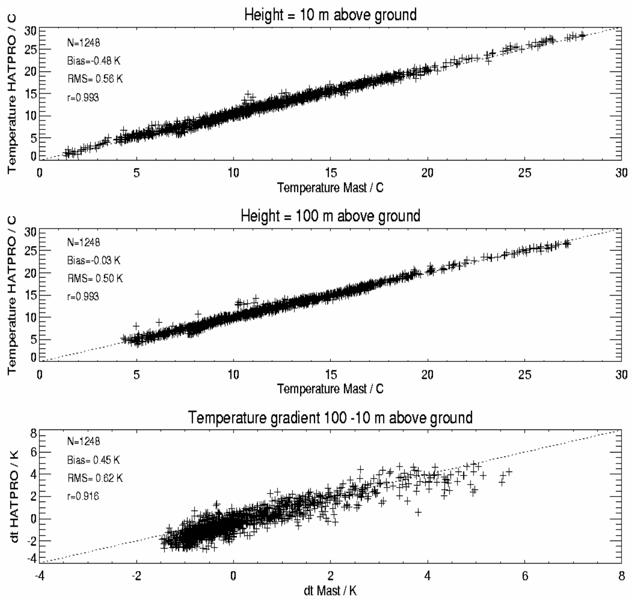

Fig. 7. Comparison of HATPRO and mast observation at lowest (10 m) and highest (100 m) mast level as well as the temperature gradient between these heights for periods A and B. HATPRO retrievals performed with 4 multi-angle frequencies, 3 zenith frequencies, 0.1 K noise level for all observations (including 120 rain events).

includes very complicated structures in the temperature profile. Therefore the combined data set including the September period generally shows a smaller RMS difference (Table 3). Within the observation period B the use of 5 angles (down to 10.2 deg) only decreases the RMS difference slightly by about 0.1 K at the 100 m level. However, for the temperature gradient the retrieval quality is reduced much stronger by about 0.3 K in RMS and a strong reduction of the correlation can be observed. This emphasizes the need for including low elevation angles but also puts demands on the angular resolution of the radiometer.

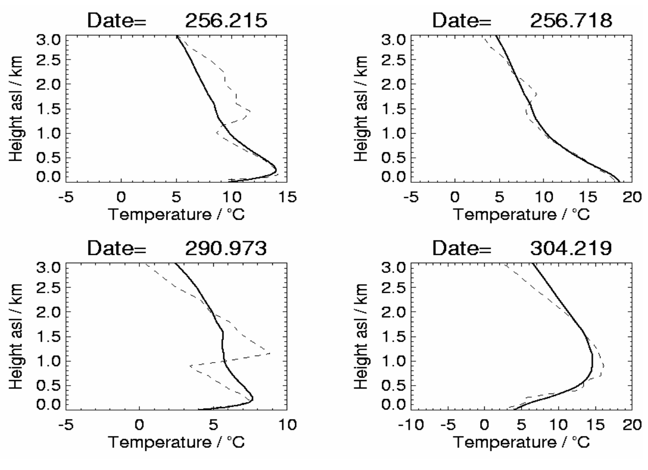

Fig. 8. Comparison of selected HATPRO retrievals with corresponding radiosoundings from Lindenberg (dashed).

The use of all angles at all frequencies (7v6φ_0.3, Table 3) leads to a minor degradation of accuracy indicating a slight problem with the assumption of horizontal homogeneity. However, for these lower altitudes the transparent channels do not contribute strongly to the retrieval and no firm result can be given here.

TABLE III
COMPARISON BETWEEN 99 M MAST AND HATPRO DATA
(Xv[z]Yφ_RR, X: number of frequencies with elevation scanning, Y: number of elevation angles, RR: noise level in K. The index z indicates that additionally 3 zenith observations for 50.26 – 53.86 have been included in retrieval development)

Algorithm	100m Bias/ K	dt Bias/K	100m RMS /K	dt RMS /K	100 m Corr.	dt Corr.
October (B)						
zenith	-1.75	0.36	1.16	1.33	0.929	0.284
4v6φ_0.3	-0.33	0.18	0.57	0.60	0.982	0.894
7v6φ_0.3	-0.21	0.48	0.58	0.64	0.982	0.881
4vz6φ_0.3	-0.53	0.06	0.57	0.60	0.983	0.896
4vz6φ_0.1	0.02	0.46	0.53	0.58	0.986	0.928
4vz5φ_0.3	-0.45	-0.20	0.63	0.94	0.979	0.723
4vz5φ_0.1	-0.04	0.97	0.60	0.84	0.991	0.807
Sept./Oct. 4vz5φ_0.1/ 4vz6φ_0.1	*(A+B)*					
all	-0.03	0.45	0.50	0.62	0.993	0.918
no rain	-0.02	0.47	0.50	0.62	0.994	0.921

C. Comparison with radiosoundings

To further explore the retrieval quality for higher atmospheric layers a comparison with the high quality radiosoundings from Lindenberg was performed. Here it is most important to investigate to which degree complex temperature structures can be resolved from microwave radiometry. In the lowest ~400 m where the theoretical accuracy is below 0.5 K and the vertical resolution for a single channel around 300 m [7] an excellent agreement can be observed (Fig. 8). At higher altitudes the agreement is still good, however the degradation in vertical resolution causes an averaging of the temperature profiles to take place. Especially in situations with more than one inversion only the lowest one can be resolved. These limitations are inherent to the observation technique, however for some applications like model evaluation this might not pose a strong handicap as long as the vertical resolution can be specified and taken into account.

Because Lindenberg is located 40 m higher than Falkenberg no comparison for the surface level can be made. At 100 m altitude a comparison between all three observation techniques is possible. For the 80 samples matched within +/- 20 min the radiosoundings are about 0.3 K colder than the mast with a RMS difference of 0.37 K. This is on the same as the one between HATPRO and the mast (bias ~0K, RMS 0.5 K) indicating the similar quality of all observation types for the 100 m temperature.

When higher altitudes are compared additional discrepancies between radiometer and radiosonde observations can occur due to the spatial difference between the observations. Assuming an average wind speed of 10 m/s the balloon has drifted about 6 km away from the site when it reaches 3000 m. Because Falkenberg is already 4 km away from Lindenberg the maximum difference is 10 km depending on wind direction. Because the terrain is quite homogeneous significant difference are only expected in broken cloud situations. While in the comparison for the lowest 100 m, e.g. with mast data, no degradation in accuracy occurred during rain events it is important to eliminate these in the comparisons with radiosondes. The reason is that the emission by rain drops at the transparent frequencies is significant and is not included in the training data set.

The comparison (Fig. 9) shows that the RMS difference between radiosonde and HATPRO is best at 100 m. The lowest level (50 m) is slightly worse because at an altitude of 10 m in Lindenberg surface effects play a role. Above 100 m the RMS difference increases with height to about 1 K at 1 km, staying more or less constant at higher altitudes. Compared to the standard zenith mode the temperature retrieval using angular information in the lower 2 km is significantly improved. The lower the assumed noise level within the retrieval development, the better the RMS difference. The average difference between a 0.1 and a 0.5 K noise level is about 0.3 K with respect to RMS temperature difference.

In terms of bias errors the radiometer observations containing angular information are slightly warmer than the radiosoundings close to the ground consistent with the mast observations. The zenith retrieval gives a much stronger bias which might be due to bias errors at the higher frequencies (Table 1). If the angular information of the four most opaque channels is used the bias increases to unacceptable values above 1.5 km. At these altitudes hardly any information is contained in the measured brightness temperatures and the retrieval relies on the statistics of the training data set. In order to use only one retrieval algorithm for the full troposphere the best results were achieved when the three more transparent channels were added with their zenith observations only. It turned out that the best results (lowest bias) were achieved when the noise level of the training data set was at a higher level (0.5 K). If lower values were used (not shown) the bias error increased strongly with height. However, the use of the higher noise level reduces the agreement in terms of RMS difference in the lower 1.5 km. One possibility to improve this might be the use of different noise levels for the different channels. This exercise with real data shows that for statistical retrievals it is very import to take the bias errors properly into account as has already been shown in a simulation study [12].

IV. CONCLUSIONS

For the first time an excellent all weather capability of low boundary layer temperature retrievals could be demonstrated for a microwave radiometer which at the same time is able to perform LWP and tropospheric humidity and temperature observations. This can be achieved by adding angular information (down to 5° elevation) at multiple frequencies to the standard zenith observations. A precondition is that the radiometer points over a homogeneous surface because of the strong variability of energy fluxes close to the surface. Comparisons with a 99 m mast show that these observations

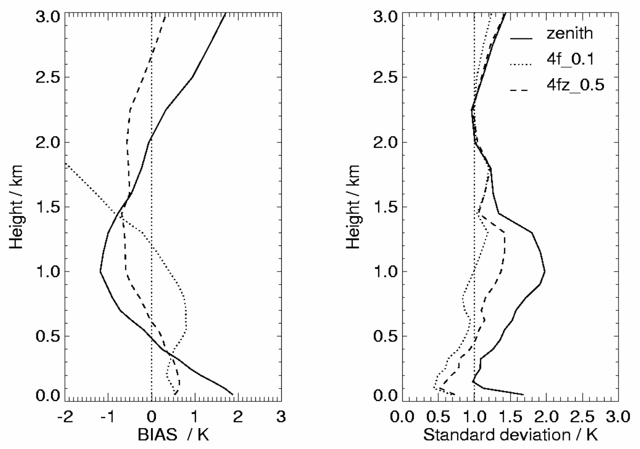

Fig. 9. Comparison of HATPRO retrievals with 80 corresponding radiosoundings from Lindenberg (observation period A and B) in terms of BIAS and RMS difference. Retrievals were performed using zenith observations only (solid), using the angular information at the four most opaque frequencies (4v_0.1) and by further adding the zenith observation by the more transparent channels (4vz_0.5).

allow an accurate detection of inversions and show a comparable quality of the retrieved temperatures to those of radiosoundings.

In order to retrieve a consistent temperature profile with the highest accuracy throughout the troposphere different statistical algorithms were developed. All algorithms including angular information achieved an improved performance in the lowest 1.5 km with a RMS difference less than 1 K to radiosoundings. The best performance throughout the troposphere was achieved when the four most opaque frequencies were used with their angular information and the three more transparent channels were added with their zenith measurement only. For higher altitudes a strong sensitivity to the noise level in the training data set was found which resulted in unacceptable bias errors. In order to further improve the accuracy a more complex bias analysis of brightness temperatures needs to be performed. Furthermore, a better information combination might be achieved by a physical retrieval algorithm.

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REFERENCES

[1] E. R. Westwater, S. Crewell, C. Mätzler, "A Review of Surface-based Microwave and Millimeter wave Radiometric Remote Sensing of the Troposphere", *Radio Science Bulletin of URSI*, RSB-310, pp. 59-80, ISSN 1024-4530, September 2004.

[2] J. Güldner and D. Spänkuch, "Remote Sensing of the Thermodynamic State of the Atmospheric Boundary Layer by Ground-Based Microwave Radiometry," *Journal of Atmospheric and Oceanic Technology*, vol. 18, pp. 925-933, 2001.

[3] J. C. Liljegren, S. A. Boukabara, K. Cady-Pereira, and S. Clough, "The Effect of the Half-Width of the 22-GHz Water Vapor Line on Retrievals of Temperature and Water vapor Profiles with a Twelve-Channel Microwave Radiometer", *IEEE Trans. Geosci. Reomote Sens.,* vol. 43, pp. 1102-1108, 2005.

[4] S. Crewell, H. Czekala, U. Löhnert, C. Simmer, Th. Rose, R. Zimmermann, and R. Zimmermann, "Microwave Radiometer for Cloud Carthography: A 22-Channel Ground-Based Microwave Radiometer for Atmospheric Research," *Radio Science*, 36, pp. 621-638, 2001.

[5] E. N. Kadygrov and D. R. Pick, "The Potential Performance of an Angular Scanning Single Channel Microwave Radiometer and some Comparisons with in Situ Observations," *Meteorological Applications,* vol. 5, pp. 393-404,1998.

[6] M. W. Rotach, E. N. Kadygrov, V. E. Kadygrov, and E. A. Miller, **"**The turbulence structure and exchange processes in an Alpine Valley: The Riviera project," *Bulletin of the American Meteorological Society* (in press).

[7] E. R. Westwater, Y. Han, V. G. Irisov, V. Leuskiy, E. N. Kadygrov, and S. A. Viazankin, "Remote Sensing of Boundary-Layer Temperature Profiles by a Scanning 5-mm Microwave Radiometer and RASS: Comparison Experiment," *Journal of Atmospheric and Oceanic Technology*, vol. 16, pp. 805-8187, 1999.

[8] M. P. Cadeddu, G. E. Peckham, and C. Gaffard, "The vertical resolution of ground-based microwave radiometers analyzed through a multiresolution wavelet technique," *IEEE Trans. Geosci. Remote Sensing*, vol. 40, pp. 531-540, 2002.

[9] Th. Rose, S. Crewell, U. Löhnert, and C. Simmer, "A network suitable microwave radiometer for operational monitoring of the cloudy atmosphere", *Atmos. Res*., vol. 75, pp. 183-200, 2005.

[10] U. Görsdorf, F. Beyrich, H. Dier, and U. Leiterer, "Composite wind and temperature profiles obtained from a complex of in-situ and remote sensing measurement systems for the forcing of a boundary layer model," *Theor. Appl. Climatol*., vol. 73, pp. 97–105, 2002.

[11] U. Löhnert, and S. Crewell, "Accuracy of cloud liquid water path from ground-based microwave radiometry. Part I: Dependency on cloud model statistics and precipitation". *Radio Sci*., vol. 38, 8041, doi:10.1029/2002RS002654.

[12] S. Crewell, and U. Löhnert, "Accuracy of Cloud Liquid Water Path from Ground-Based Microwave Radiometry. Part II. Sensor Accuracy and Synergy," *Radio Science*, vol. 38, 2003:, 8042, doi:10.1029/2002RS002634.

[13] P.W. Rosenkranz, "Water Vapor Microwave Continuum Absorption: A Comparison of Measurements and Models," *Radio Science,* vol. 33**,** pp. 919-928, 1998.

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