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Article

Comparison of brightness temperatures observed from ground-based microwave radiometers during TUC

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Abstract

The agreement of two ground-based microwave radiometers during the Temperature, hUmidity, and Cloud (TUC) profiling campaign has been evaluated in terms of measured brightness temperature. To account effectively the instruments' specifications, we discuss and estimate an equivalent monochromatic frequency, which significantly reduces the bias introduced by ideal monochromatic modelling. The effect of this equivalent monochromatic frequency can reach 0.4 K and thus we recommend its use in further study involving TUC radiometers. This analysis showed agreement within expectations for three of the four selected pairs of channels, although results are strictly valid in a limited range. As a consequence, the derived products are expected to be of the same quality. However, the inconsistency found in the remaining pair is expected to propagate in the retrieved humidity profiles.

Zusammenfassung

Die Übereinstimmung zweier bodengestützter Mikrowellen-Radiometer während der Temperature hUmidity and Cloud (TUC) Kampagne wurde anhand der gemessenen Helligkeitstemperaturen bewertet. Um die wirklichen Gerätespezifikationen zu bestimmen, diskutieren und schätzen wir eine äquivalente monochromatische Frequenz, welche die durch die ideale monochromatische Modellierung bewirkte Abweichung signifikant reduziert. Der Effekt dieser äquivalenten monochromatischen Frequenz kann 0,4 K erreichen, weshalb wir deren Verwendung in weiteren Studien mit TUC Radiometern empfehlen. Diese Untersuchung ergab Übereinstimmung innerhalb der erwarteten Schranken für drei von vier ausgewählten Paaren von Kanälen, obwohl die Resultate streng genommen nur in einem beschränkten Bereich gültig sind. Deshalb wird erwartet, dass die abgeleiteten Produkte von derselben Qualität sind. Jedoch muss angenommen werden, dass sich die im verbleibenden Paar gefundene Inkonsistenz auf die abgeleiteten Feuchtigkeitsprofile fortpflanzt.

1 Introduction

During the period from November 2003 to February 2004, the Temperature, hUmidity, and Cloud (TUC) profiling campaign (RUFFIEUX et al., 2006) was held at the MeteoSwiss station in Payerne, Switzerland. A variety of active and passive ground-based instruments joined the resident operational suite in the effort of characterizing the atmospheric boundary layer. In this paper, we focus on the two multichannel microwave radiometers (MWRs) that were operated throughout the TUC campaign.

Ground-based microwave radiometry represents a mature technique for the retrieval of atmospheric variables such as integrated water vapour (IWV), integrated liquid water (ILW), and vertical profiles of temperature and water vapour density, as described by WESTWATER (1993). The accuracy of retrievals from ground-based radiometric measurements is well established and often these retrievals are used as a reference for other techniques (REVERCOMB et al., 2003) or as a reliable first guess in integration approaches (BIANCO et al., 2005). On the other hand, the calibration of MWRs needs particular attention, because it can change rapidly and it is likely to drift depending on internal and environmental conditions. A variety of techniques can be used to calibrate MWRs, but usually only a combination of different techniques provides an accurate end-to-end calibration (CIMINI et al., 2005). Any misestimate of the coefficients that enter MWRs calibration will result in inconsistency in the direct measurements, i.e. brightness temperature (T_b), and, in turn, in the retrieved atmospheric quantities. For this reason, the calibration of each MWR and the cross-consistency between independent MWRs need to be checked carefully before any attempt of further study.

Therefore, the aim of this work consists of addressing the TUC MWRs' performance in direct measurements of T_b, to identify possible sources of error in other studies, such as intercomparison of integrated water vapour (MARTIN et al., 2006a), atmospheric profile

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retrievals (CIMINI et al., 2006), atmospheric absorption models validation (HEWISON et al., 2006), and evaluation of integrated techniques (KLAUS et al., 2006). The environmental conditions during TUC were typical of wintertime in a mountain range. Because of differences in beamwidth, location, and angular scanning of the MWRs, and to the variability of cloud liquid water, we decided to limit the analysis to clear sky zenith observations only. This selection significantly reduces the dynamical range of the observed data and allows only limited comparison between the radiometers. However, the sensitivity and the performances of MWR in cold dry conditions are important because of the relevance of MWR measurements in polar and mountain regions.

In the next section, details of the MWRs deployed during TUC are given. Section 3 describes the differences we expect to see considering the instruments' technical differences, while section 4 presents the comparison during the TUC campaign. Finally, in section 5, we discuss the results and make recommendations for further studies.

Table 1: Nominal central frequency (f_0), full 3dB bandwidth (B), and calibration accuracy (ε) for TP/WVP-3000 and ASMUWARA channels. Single side-band channels are indicated with a star. The TP/WVP-3000 doubleside filter passes signals within 40–190 MHz of f_0 in each sideband. Values for calibration accuracy are typical for the range of brightness temperatures compared in this analysis.

	TP/WVP-3000			**ASMUWARA**		
#	f_0[GHz]	B[GHz]	ε [K]	f_0[GHz]	B[GHz]	ε [K]
1	22.235	0.15	0.52	18.750	*0.30	1.50
2	23.035	0.15	0.40	22.200	*0.76	1.50
3	23.835	0.15	0.40	23.600	*0.90	1.50
4	26.235	0.15	0.29	31.500	1.10	1.50
5	30.000	0.15	0.21	52.500	*0.59	3.00
6	51.250	0.15	1.06	53.940	*0.12	1.50
7	52.280	0.15	0.89	55.260	*0.52	0.50
8	53.850	0.15	0.38	57.200	*1.30	0.50
9	54.940	0.15	0.24	151.000	4.00	2.00
10	56.660	0.15	0.22			
11	57.290	0.15	0.22			
12	58.800	0.15	0.22			

2 Instrumentation

Two independent MWRs were deployed during TUC; the TP/WVP-3000, owned and operated by UK Met Office, and the All-Sky MUlti WAvelength RAdiometer (ASMUWARA), built and operated by the Institute of Applied Physics (IAP), University of Bern.

2.1 TP/WVP-3000

The TP/WVP-3000 is a 12-channel microwave radiometer built by Radiometrics Corporation, Boulder, CO, USA. The system uses a combination of internal target, noise diode, and tipping curve (HAN and WESTWATER, 2000; CIMINI et al., 2005) to achieve accurate calibration. It is capable of automatic and continuous elevation scan, while it is manually steerable in the horizontal plane. Although an azimuth automatic steering device is commercially available from the manufacturer, this unit is not provided with it. The channels' nominal characteristics, such as central frequency, bandwidth, and absolute accuracy are listed in Table 1. An additional vertical-pointing infrared channel, which we use for cloud screening only, is part of the system. Further information are available in WARE et al. (2003) and HEWISON and GAFFARD (2003).

2.2 ASMUWARA

The ASMUWARA is an unique 9-channel microwave radiometer built by IAP of University of Bern (MARTIN et al., 2006b). The system uses a combination of two external targets and tipping curve to achieve accurate calibration. Due to its rotatable mirror and azimuth drive, ASMUWARA is able to scan both in elevation and azimuth. Thus, ASMUWARA can observe in any direction of the upper hemisphere, all channels simultaneously, including an additional broadband infrared channel. The channels' nominal characteristics are listed in Table 1, while for further details see (MARTIN et al., 2006b, 2006c).

3 Theoretical predictions

As shown in Table 1, apart from the 151 GHz channel, the TP/WVP-3000 and ASMUWARA cover similar spectral ranges, as both instruments were designed for the retrieval of atmospheric IWV, ILW, temperature and humidity profiles. In comparing the measurements from the two MWRs, we need to understand what differences in T_b we expect to see due to the different technical design of TP/WVP-3000 and of ASMUWARA. It is important to note that even for those channels that are almost overlapping (e.g. 22.235/22.2 GHz) we do expect differences in T_b not only because of the slight shift in the nominal central frequency, but also the different bandwidth B. In fact, none of these channels is truly monochromatic; conversely, they receive radiation in a passband (single or double, see Table 1) around the central frequency, whose nominal width is indicated by the 3dB bandwidth B. On the other hand, the effect of frequency stability should be small. In fact, according to the manufacturers, central frequency is stable within 100 kHz; even assuming 1MHz, difference in T_b would be of the order of 0.01 K.

3.1 Equivalent monochromatic frequency

The effect of the finite bandwidth needs to be investigated and taken into account in any application involving the measured brightness temperatures. However, simulations of band-averaged T_b require increased computation resources for a relative small correction (order of 0.1 K). A way to effectively undertake this issue is to define an Equivalent Monochromatic Frequency (EMF), which corresponds to the monochromatic frequency that minimizes the difference with the band-averaged T_b for a representative background dataset. As we demonstrate in this section, the EMF does not always correspond to the nominal central frequency.

In the following we explain how we estimated the EMF for the TUC campaign. First of all, we computed monochromatic T_b at nominal central frequency and also band-averaged T_b from 316 radiosondes launched during the TUC experiment using the specifications in Table 1. The assumption of a rectangular function is just an approximation of the actual shape of the bandpass filter. However, for the considered radiometers, the bandpass filters are quite regular, with sharp edges and no particular slope within the nominal bandwidth, such that deviations from the rectangular approximations are considered of second order. The radiosonde profiles were extrapolated up to 0.1 mb using a reference mid-latitude winter profile. Although the extrapolation contributes sensibly to the modelled T_b, it was found that the choice of reference profile produced negligible differences for the channels used in this study. We used the atmospheric absorption model described in LIEBE and LAYTON (1987), limiting our calculations to zenith observations in clear sky conditions. Although we are aware of the uncertainty underlying the choice of the absorption model, this is a second order effect in this analysis, as we explain in section 3.2. For a detailed study on microwave absorption models, see HEWISON et al. (2006).

From the same set of radiosonde profiles, we computed monochromatic T_b for a set of 40 frequencies (one set for each channel) separated by 5 MHz steps and located in a 200 MHz window centred at the nominal central frequency. Then, for each radiosonde profile and for each channel, we found the frequency corresponding to the minimum difference with respect to the band averaged T_b. The resulting frequency would be one realization of the EMF. Finally, for each channel we estimated the EMF as the frequency corresponding to the maximum of the histogram for the ensemble of these 316 realizations.

The resulting EMF are shown in Table 2 for ASMUWARA and Table 3 for TP/WVP-3000. For the TP/WVP-3000, Table 3 is broadly consistent with a similar study done by HEWISON and GAFFARD (2003) for a different site and climatology. Also, in Table 2 and 3 we show mean and standard deviation of the differences in T_b between nominal central monochromatic, band averaged, and equivalent monochromatic calculations. Thus, Table 2 and 3 contain (in this order): channel number (# chan), nominal central frequency (f_0), the estimated equivalent monochromatic frequency (EMF), mean (ΔT_b) and standard deviation (σT_b) of T_b difference between band-average (ba) and nominal monochromatic centre frequency (mc), and band-average and equivalent monochromatic (em). In any case, the mean T_b difference between ba and mc remains between –0.26 and +0.36 K, the largest values being found at 51 to 54 GHz channels. Thus, for these instruments and environmental conditions, the effect of a finite bandwidth is small, but not negligible. The encouraging result is that the standard deviation is very small, less than 0.1 K, for all but the 22 GHz channels. This means that for most of the channels we could take this effect into account as a mere bias. In conclusion, this analysis indicates that:

– If in our simulations we use monochromatic T_b computed at the nominal centre frequency, we are prone to include an error of the order of 0.1 K (0.36 K in the worst case). Conversely, using EMF

Table 2: Nominal central frequency (f_o), equivalent monochromatic frequency (EMF), T_b mean difference (ΔT_b) and standard deviation (σT_b) for band-average minus nominal monochromatic central frequency (ba-mc) and band-average minus equivalent monochromatic frequency (ba-em) for ASMUWARA channels.

Chan	$\mathbf{f_o}$	**EMF**	**ba-mc**		**ba-em**	
#	[GHz]	[GHz]	ΔT_b	σT_b	ΔT_b	σT_b
			[K]	[K]	[K]	[K]
1	18.750	18.755	0.006	0.002	–0.004	0.002
2	22.200	22.125	–0.202	0.184	0.000	0.004
3	23.600	23.605	–0.026	0.012	0.000	0.006
4	31.500	31.525	0.010	0.001	0.000	0.001
5	52.500	52.495	–0.264	0.047	0.199	0.043
6	53.940	53.940	0.025	0.004	0.025	0.004
7	55.260	55.215	–0.159	0.010	–0.001	0.010
8	57.200	57.165	–0.011	0.017	0.000	0.002
9	151.000	151.060	0.076	0.016	0.000	0.002

Table 3: The same as Table 2 but for TP/WVP-3000 channels.

Chan	$\mathbf{f_o}$	**EMF**	**ba-mc**		**ba-em**	
#	[GHz]	[GHz]	ΔT_b	σT_b	ΔT_b	σT_b
			[K]	[K]	[K]	[K]
1	22.235	22.205	–0.144	0.289	–0.004	0.004
2	23.035	23.040	–0.021	0.009	–0.001	0.006
3	23.835	23.835	–0.000	0.001	0.000	0.001
4	26.235	26.230	0.004	0.001	0.002	0.002
5	30.000	30.005	0.001	0.000	0.000	0.000
6	51.250	51.255	0.139	0.005	–0.005	0.003
7	52.280	52.285	0.360	0.013	–0.099	0.014
8	53.850	53.855	0.348	0.047	0.056	0.052
9	54.940	54.935	–0.032	0.008	0.006	0.016
10	56.660	56.655	–0.003	0.002	0.001	0.001
11	57.290	57.285	–0.001	0.001	0.000	0.001
12	58.800	58.800	0.001	0.001	0.000	0.000

should eliminate this error. However, for all but one channels this error appears to be a mere bias. Thus, a bias-correction to T_b at nominal monochromatic centre frequency should work as well.

– At 22.2 GHz, where the error is more sensitive to the atmospheric state (water vapour), σT_b is of the order of 0.2–0.3 K. If we do not use the band-average or EMF for T_b simulations, we add an error with about 0.2 K mean and 0.2–0.3 K standard deviation. Conversely, using the EMF, we should remove this additional error completely.

Finally, it is important to clarify that these values of EMF are by no means general. The values we present in Tables 2 and 3 are representative for the radiometers deployed during TUC and for the environmental conditions experienced during the campaign (RUFFIEUX et al., 2006). On the other hand, the derived EMFs are valuable for speeding up forward model computations and have been used in the studies related to MWRs that followed the TUC experiment (CIMINI et al., 2006; HEWISON et al., 2006; MARTIN et al., 2006a).

3.2 Selection of channel pairs

When comparing T_b measured by independent MWRs with different characteristics, there is a need to estimate the expected differences. This can be achieved by processing a representative set of atmospheric profiles of thermodynamic variables with a radiative transfer model. In order to keep our T_b comparison independent of atmospheric absorption model, we decided to select a subset of TP/WVP-3000 and ASMUWARA channels for which the gas absorption uncertainty, associated with model parameterization (HEWISON et al., 2006), is a second order effect. In other words, we select pairs of channels that are so close in frequency that any difference in T_b would be roughly the same for any given absorption model. This assumption has been validated within 0.05 K standard deviation (std) for the pairs of channels listed in Table 4.

Table 4: Nominal central frequency (GHz) for selected pairs of channels. Uncertainties due to atmospheric absorption models contribute negligibly to the intercomparison of these channels pairs.

	TP/WVP-3000	**ASMUWARA**
Pair #1	22.235	22.200
Pair #2	23.835	23.600
Pair #3	30.000	31.500
Pair #4	52.280	52.500
Pair #5	53.850	53.940
Pair #6	57.290	57.200

For each pair in Table 4, we have computed T_b difference (TP/WVP-3000 minus ASMUWARA) using the band-averaged T_b simulated from the set of TUC radiosondes introduced before. Of these T_b differences, the mean values, standard deviations, and slopes of linear fit as function of the T_b corresponding to the TP/WVP-3000 channel of the pair, are shown in Table 5 and will be discussed in the next section.

4 Empirical comparison

During the TUC campaign, the two MWRs ran continuously for about two months. Overall, the collected data are of high quality, although unfortunately 3 of the 21 available channels experienced major problems. In fact, due to malfunction of the local oscillator, the four ASMUWARA channels in the oxygen band suffered from excess noise resulting in calibration difficulties, making three of them (52.50, 53.940, and 55.260 GHz) unusable. Two of these three channels would have been considered in the T_b comparison, as shown in Table 4 (pairs # 4 and 5). For this reason, our analysis is limited to the remaining four pairs.

In Figure 1, we show a 24-hour time series of T_b measured by TP/WVP-3000 and ASMUWARA at comparing channels. It is evident that TP/WVP-3000 and ASMUWARA measurements are strongly correlated and describe the same diurnal structure both in the water vapour and in the temperature variation. In particular, the maximum in water vapour content, indicated by low frequency channels in the early hours of the day, corresponds to the minimum surface temperature, as indicated by the 57 GHz channels, while the opposite happens right after noon UTC. More on the meteorological situation of this particular day is given in RUFFIEUX et al. (2006).

Note that some of the differences in T_b shown in Figure 1 are actually expected, due to different channels' specifications. Thus, in the following we explain how we compared measurements with expectations. First, we divided the entire TUC period into 5-minute bins and computed the averaged value of T_b measured at zenith for each channel of the two MWRs. Then, we limited our dataset to clear sky conditions, using the readings from the IR sensor mounted on the TP/WVP-3000. This screening reduced the dataset to about 40 % of its original size. For the simulations, we used the band-averaged T_b computed from the set of TUC radiosondes. Finally, we show the results in Figure 2, where each panel corresponds to a pair of Table 4 (excluding pairs with corrupted channels). For each panel, the vertical axis shows the difference in T_b between paired channels (TP/WVP-3000 minus ASMUWARA), while the horizontal axis shows the T_b corresponding to the TP/WVP-3000 channel of the pair. Black dots indicate simulations, grey

Table 5: Slope of linear fit (SLP), mean (AVE), and standard deviation (STD) of T_b difference as simulated and measured at paired channels. Numbers after ± indicate 95 % confidence interval.

	SLP [K/K]		**AVE [K]**		**STD [K]**	
Chan.	simul	meas	simul	meas	simul	meas
22 GHz	0.01±0.00	0.11±0.00	0.19±0.01	1.86±0.02	0.08	0.86
23 GHz	–0.07±0.00	–0.01±0.00	–0.85±0.04	–0.21±0.01	0.35	0.57
30 GHz	0.06±0.00	0.14±0.01	–0.38±0.01	0.01±0.01	0.10	0.58
57 GHz	–0.00±0.00	0.04±0.01	0.04±0.01	–0.32±0.04	0.05	0.71

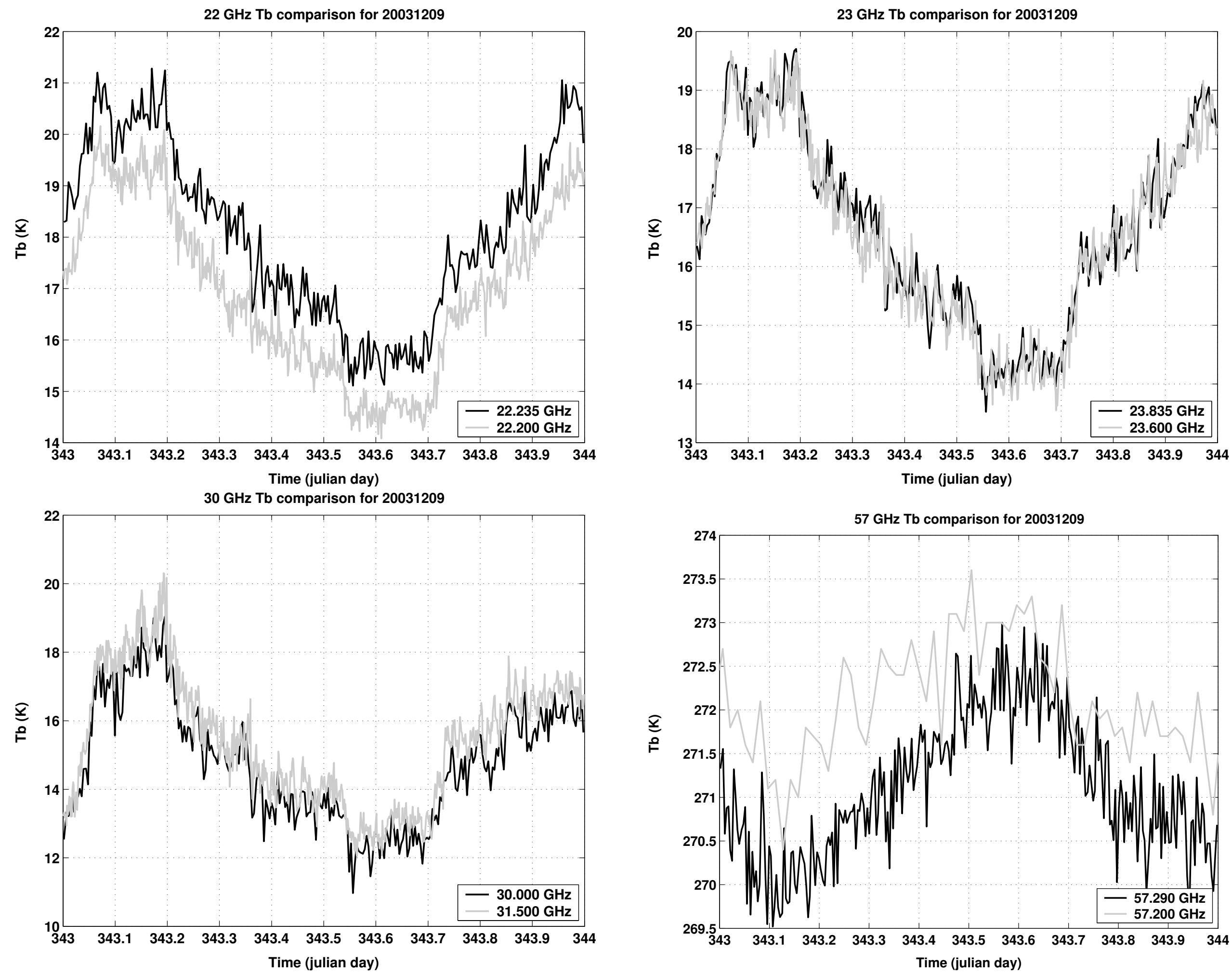

Figure 1: 24-hour time series (2003/12/09) of T_b measured at paired channels. Top: 22 and 23 GHz. Bottom: 30 and 57 GHz.

dots indicate measurements, while black and grey solid lines indicate the linear fits performed on simulations and measurements, respectively. The slope of the linear fit, the expected mean, and the standard deviation of the differences in T_b, both for measurements and simulations, are shown in Table 5. From this table, we can conclude that:

– The slopes from measured data are within 0.1 the theoretical expected values. Despite the tipping curve method being used for both instruments, the largest discrepancies were found in the water vapour channels, especially in the 22 GHz pair.
– Differences between expected and measured bias (i.e. between column 4 and 5 in Table 5) range from 0.36 to 1.67 K. Again, largest discrepancy is found in the 22 GHz pair. Excluding this pair, the main differences stay within 0.64 K. However, it is important to note that the discrepancies in slope between simulated and measured pairs would cause larger differences in presence of higher T_bs. For example, for T_b=60 K at 23 GHz, the difference would rise up to 3 K, which is clearly unacceptable.
– The standard deviations are comparable with the expectations, considering 0.3 K noise level for

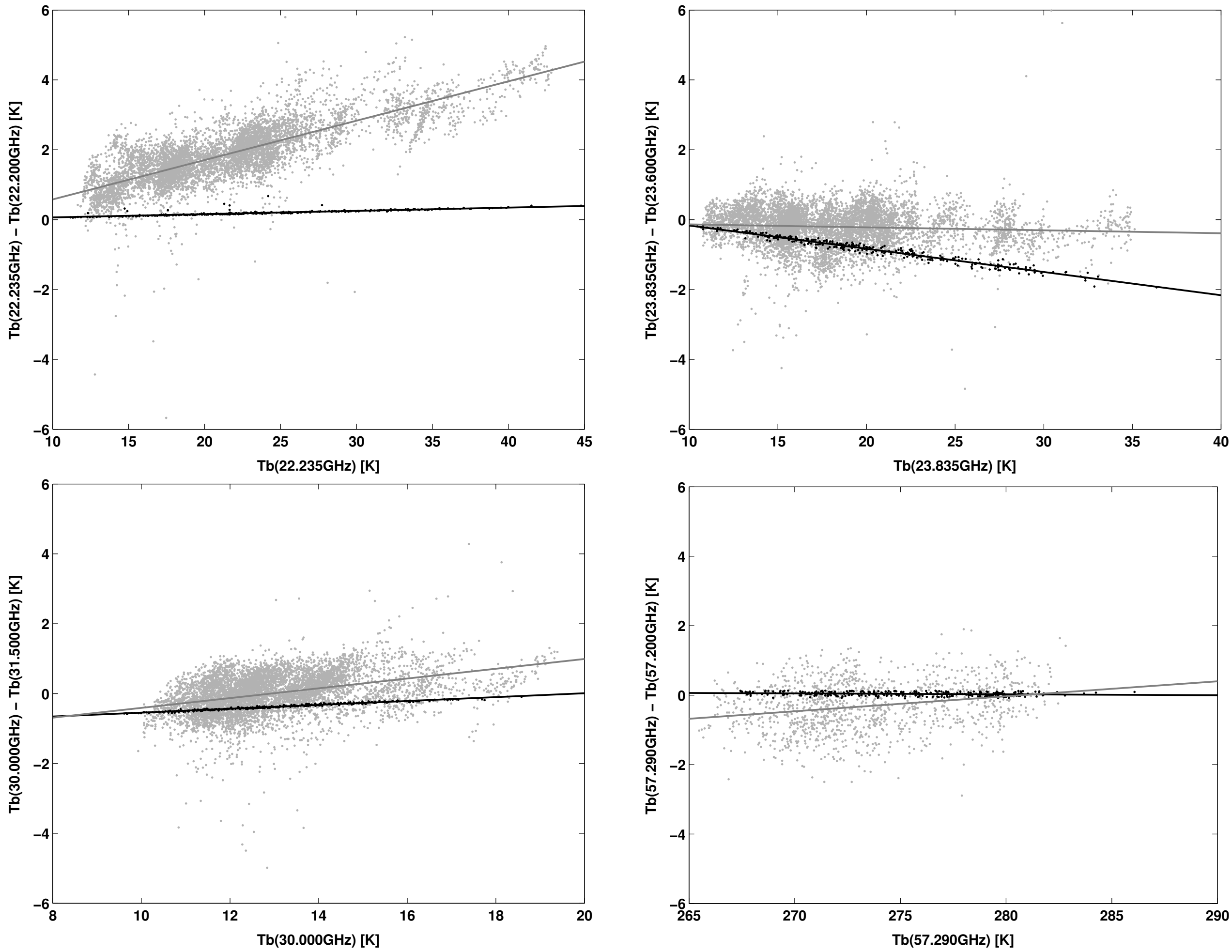

Figure 2: Scatter plot of T_b difference (TP/WVP-3000 minus ASMUWARA) against TP/WVP-3000 T_b, as simulated and measured at paired channels. Top: 22 and 23 GHz. Bottom: 30 and 57 GHz.

each channel. Thus, the comparison is mostly driven by the mean difference. More precisely, in term of root mean square (rms) differences, the 23 and 30 GHz pairs are within the expectations, the 57 GHz pair is 0.15 K over, while 22 GHz pair exceeds the expectations by 0.42 K. Concerning the latter, Figure 2 clearly shows that the resulting main difference does not come from a constant bias, but rather from the difference in slope; as the T_b of the scene increases, the difference between the two channels of the pair gets unacceptably large.

The discrepancies in slope found between measured and simulated pairs are probably related to uncertainties in the estimate of the MWR gain. To add more insight, we could compare measurements with an independent source, as for example simulations computed from simultaneous radiosondes. Unfortunately, the uncertainty associated with the absorption model used for the simulations is usually of the same order of the differences we find here. However, simulations performed using a variety of absorption models seem to agree substantially better with TP/WVP-3000 than with ASMUWARA, regardless of the absorption model (HEWISON et al., 2006).

5 Conclusions and recommendations

In this paper we have analysed the agreement in direct measurements between two independent MWRs deployed during the TUC experiment. We have discussed in detail the theoretical differences we shall expect from these instruments, due to the different channel specifications. The results showed that the effect of a finite bandwidth is small, but not negligible. If we do not take into consideration the finite bandwidth, we are prone to include an error of the order of a few tenths of Kelvin (0.1 to 0.36 K). A simple bias correction would work at all but 22 GHz channels, where a residual 0.3 K rms would remain. On the other hand, using the values we have estimated for EMF, the finite bandwidth effect is reduced to less than 0.1 K.

The comparison of simultaneous T_b observations from similar channels was reduced to four pairs only due to malfunction of an ASMUWARA local oscillator, which made three channels unusable. For the remaining pairs, 23, 30 and 57 GHz showed main differences within the expected accuracy and can be considered cross-validated, while 22 GHz showed a bias of about 1.6 K. Note that the previous statements are valid only for the range under analysis. In fact, significant (4 to 10 %) slope discrepancies were found between simulated and measured pairs, which suggest larger differences in presence of higher T_bs.

Any inconsistency found in the direct measurements is likely to propagate in the retrieval. For example, given 1.7 K/mm as a rough estimate of IWV sensitivity at 22.2 GHz, the bias found in this pair would lead to 1 mm (or 1 kg/m_2) bias in retrieved IWV. This is unacceptably large compared to the agreement found between radiometers and radiosondes during TUC, order of 0.1 mm (MARTIN et al., 2006a), although it is clearly an overestimate because it is based on a single channel retrieval.

In conclusion, our analysis produced the following recommendations to the user of TUC data. First, the two MWRs showed agreement within the specifications for three out of four pairs considered in this study. However, we found discrepancies related to the gain estimate, especially at 22.2 GHz, that could potentially result in larger differences in presence of higher T_bs. As a consequence, for the range spanned during clear-sky, derived products are expected to be of the same quality, although retrievals based on the ASMUWARA 22.2 GHz channel may show a dry bias. Second, we recommend that the estimated values of the equivalent monochromatic frequency are used for any further study involving MWRs simulations, measurements, and retrievals, as in fact already adopted in HEWISON et al. (2006), MARTIN et al. (2006a), and CIMINI et al. (2006).

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