Theoretical Analysis of the Frequency Allocation of the Hinge Points Around 22.235 GHz

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Introduction

Microwave ground- and satellite-based sensing of atmospheric precipitable water vapor (PWV) is commonly based on the measurement of down/up welling brightness temperature (Tb) in the spectral region around the water vapor rotational line at 22.235 GHz. Besides instrumental accuracy and unknown surface emissivity in the case of downward viewing, the main sources of uncertainty are the presence of liquid water in the antenna beam, the dependence of absorption on the atmospheric thermodynamic profiles and the error resulting from inversion method, including forward modelling error. The contribution from liquid water is usually removed by simultaneous measurements of Tb at another frequency, located in an atmospheric window (i.e., 30-36 GHz). The dependence on atmospheric profile can be limited by choosing the frequency channel near the so called "hinge points." However, the frequency allocation of such points is not exactly determined. Since Westwater (1978), the hinge points around 22.235 GHz have been usually assumed to be at 20.6 GHz, in the low-frequency side, and at 23.8 GHz, in the high-frequency side. More recently, other investigators (Cady-Pereira et al. 2002) have raised questions on the frequency allocation of the second hinge point, proposing 24.7 instead of 23.8 GHz. Because the frequency choice of 24.7 GHz is not in a protected radio frequency band, any move to this frequency should be carefully considered. In this paper we study the frequency location of the hinge points by means of the minimization of PWV retrieval error. We consider three databases of atmospheric thermodynamic sets of profiles (pressure, temperature, humidity) collected in three contrasting environments (arctic, mid-latitude, tropical), and process them with four commonly used microwave absorption models (Liebe et al 1987, 1993; Rosenkranz and Water 1998; Delamer et al. 2002). We added random noise, to simulate instrumental uncertainty, and evaluated different inversion methods for single-channel PWV retrieval. Thus, we show spectra of PWV retrieval uncertainty for typical cases, and we discuss our choice of the frequency location for the hinge points around 22.235 GHz water vapor line.

Datasets and Simulations

From three historical datasets of arctic (5141), mid-latitude (12670) and tropical (1086) radiosonde observations (RAOB), we have computed down-welling brightness temperature in the frequency range around the water vapor line at 22 GHz, using a variety of four radiative forward models (FM). The PWV ranges from 0.05 to 3.5 cm with a mean value of 0.7 cm for the arctic dataset, from 0.2 to 6.0 with 2.1 cm mean at mid-latitudes, while between 2.3 and 7.0 cm with mean 5.0 cm for the tropics dataset. The four models we consider are hereafter referred as LIEBE87 (Liebe and Layton 1997), LIEBE93 (Liebe et al. 1993), ROSEN98 (Rosenkranz and Water 1998) and MONORTM (Cady-Pereira et al. 2002; Delamere et al. 2002). A comparison between these forward models is available in (Cimini et al 2003). From the sets of simulated Tb (19 to 26 GHz, 0.1 GHz spectral resolution, total 71 frequencies for each RAOB), we trained PWV single-frequency statistical regression algorithms of different kind and order (linear in Tb, quadratic in Tb, linear in opacity τ, quadratic in τ) for each model and for each environment. Thus, we have computed PWV using single-frequency retrievals, obtaining a set of 71 values of PWV for each RAOB of each environment and for each regression algorithm. We define the difference between the estimated PWV and the “true” value, measured by RAOB, as the retrieval error (RE). Thus, the RE is a function of the environment ENV, of the forward model FM, of the index of order/kind of regression i, of the frequency index j, and of the RAOB index k:

$$RE_{ENV,FM}(i,j,k) = (PWV_{est}(i,j,k) - PWV_{true}(k))_{ENV,FM}$$

From these values we computed the standard deviation of $RE_{ENV,FM}(i, j, k)$ over the ensemble of realizations k, thus obtaining $\sigma_{ENV,FM}(i, j)$, which represents an estimates of the PWV retrieval uncertainty using the regression method i, trained with Tb at frequency j, simulated with the forward model FM, processing RAOB data from the environment ENV. Note that the regression technique is centred on the mean value of the ensemble, so the retrieval is unbiased and the root mean square is equal to the standard deviation. Figure 1 shows three plots (one for each environment) containing the $\sigma_{ENV,FM}(i, j)$ spectra obtained with linear regression on Tb using the MONORTM forward model. In each subplot are evident two minima, which therefore show the frequency allocation of minima of the PWV retrieval uncertainty. In other words, the frequency corresponding to those minima indicate the best choice, in terms of minimum retrieval error, for PWV estimates by means of single-channel measurements around the 22.2 GHz water vapor line. In the low-frequency side we find a minimum at 20.7-20.8 GHz, while for the high-frequency side the minimum location ranges from 23.6 to 23.8 GHz. Thus, Figure 1 shows that the frequency allocation of these minima depends only slightly (±0.1 GHz) on the environment and so on the main water vapor content. Note that $\sigma_{ENV,FM}(i, j)$ shows also a maximum at 22.2 GHz, because in the vicinity of the center of the line the retrieval uncertainty is higher due to the

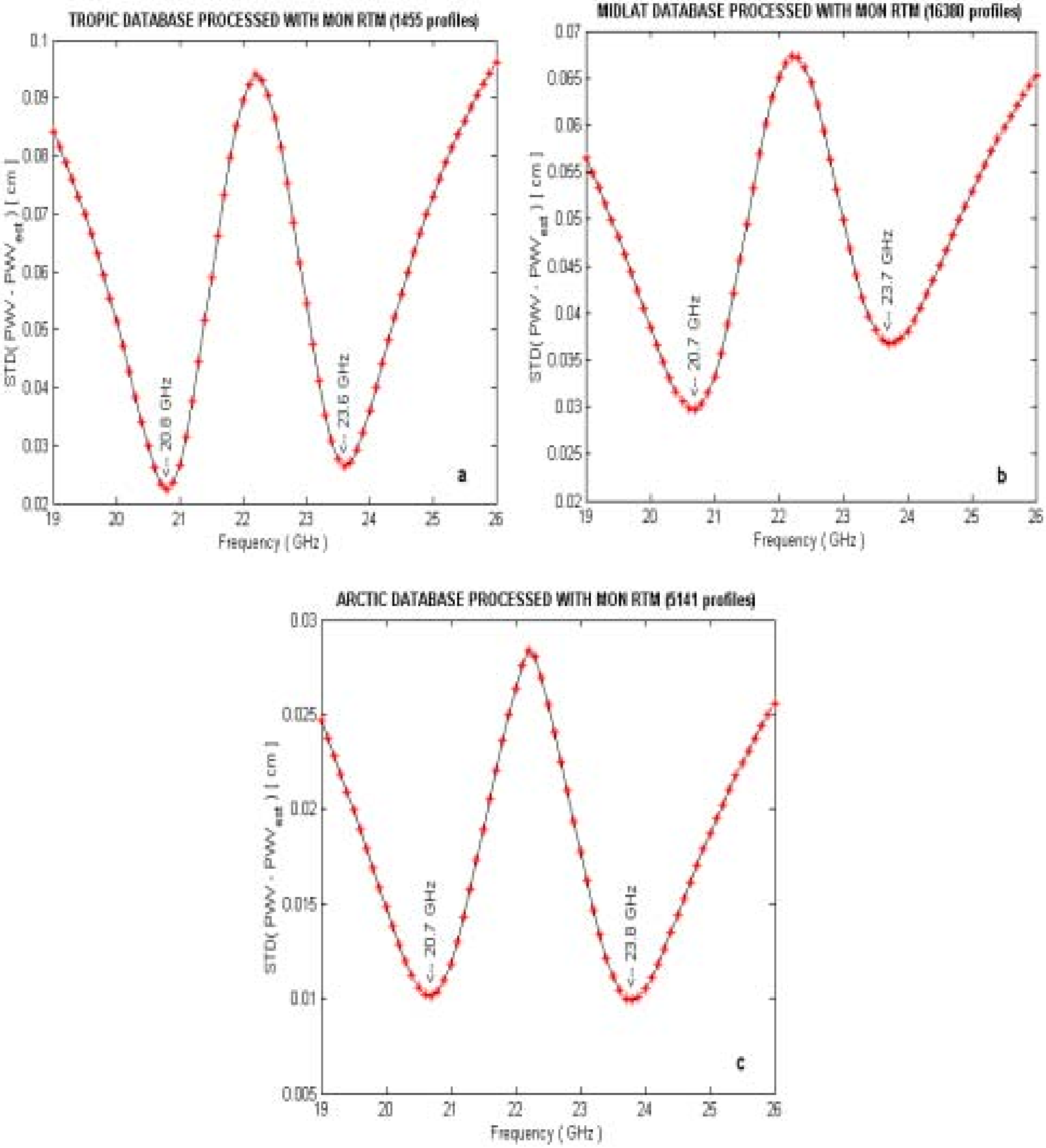

Figure 1. $\sigma_{ENV,FM}$(i, j) for the (a) tropical, (b) mid-latitude, and (c) arctic databases. MONORTM has been deployed to compute simulated Tb. PWV was estimated using linear regression on original synthetic Tb

pressure dependence of the line width. Note that for the three environments the level of retrieval uncertainty varies, due also to the different mean value of PWV. For example, the maximum of $\sigma_{ENV,FM}(i, j)$ at 22.2 GHz reaches 0.10 cm in the tropics, 0.07 at mid-latitudes, while 0.03 in the arctic, which roughly means the 2%, 3%, and 4% of the corresponding dataset's PWV mean value. These results are quite independent from the considered forward model, as we demonstrate in the next sections. To obtain these results, we have considered simulated Tb as they come from forward model computations. This assumes we did not consider the contribution to the retrieval uncertainty coming from the instrumental noise. In reality, Tb measurements by microwave radiometers are associated with a standard uncertainty of about 0.5 K, when tipping curve calibration procedure is applied (Han and Westwater 2000; Cimini et al. 2002). By adding random numbers chosen from a normal distribution with mean zero and standard deviation 0.5 to the computed Tb, we simulated real "noisy" measurements. Then, using the regression coefficients computed from the original datasets, we calculated again the PWV retrievals, this time considering synthetic noisy data. The $\sigma_{ENV,FM}(i, j)$ spectra obtained from noisy data from the tropical, mid-latitude and arctic datasets are shown in Figure 2. Although the shape of $\sigma_{ENV,FM}(i, j)$ is not as smooth as it was for the original data, the trend is the same: a maximum near 22.2 GHz and two minima, divided in the low- and high-frequency sides. Note that the value of $\sigma_{ENV,FM}(i, j)$ near the maximum does not change substantially when synthetic noise is added to original Tb. On the other hand, values far from the line center increase up to twice the original value. This effect is related to the values of signal-to-noise ratio at different frequencies. For the tropical environment we find that the minima are located at 21.0 and 23.6 GHz. For the mid-latitude environment the low-frequency minimum is at 20.9 GHz, while the high-frequency minimum is predicted at 23.5 GHz. For the arctic environment, the level of $\sigma_{ENV,FM}(i, j)$ at the minima increases almost to the level at the maximum, reducing considerably the differences found in Figure 1. Thus, for the arctic environment with 0.5 K Tb uncertainty, the single-channel PWV retrieval uncertainty does not depend much on what frequency is used. Also this effect is due to the value of signal-to-noise ratio, since the PWV mean value is low in the arctic (0.7 cm), and so is the Tb.

Regression Methods and Forward Models

Then, we want to study how sensitive is the frequency allocation of the two minima to the details of the used scheme, such as the regression technique or the forward model.

In Figure 3 we show the effect of the choice of regression technique for tropical, mid-latitude and arctic datasets processed with MONORTM. We prefer to show results obtained using original data with no synthetic noise, although results are quite similar. For each environment, we have two subplots: the top panel shows the $\sigma_{ENV,FM}(i, j)$ obtained using two different inversion methods, linear regression on Tb and quadratic regression on Tb, as stated in the legend. The bottom panel shows the difference between the two lines, so representing the improvements in retrieval uncertainty using a different order of regression. For the tropics, the improvements brought by using second order regression in Tb show maximum value, of the order of 0.015 cm, around the $\sigma_{ENV,FM}(i, j)$ minima. It is also evident that changing the regression method does not affect dramatically the frequency position of the minima (shown inside squared bracket in the legend). This is true also for the other two environments. Similar considerations apply when using noisy data. As anticipated, we have also implemented linear or

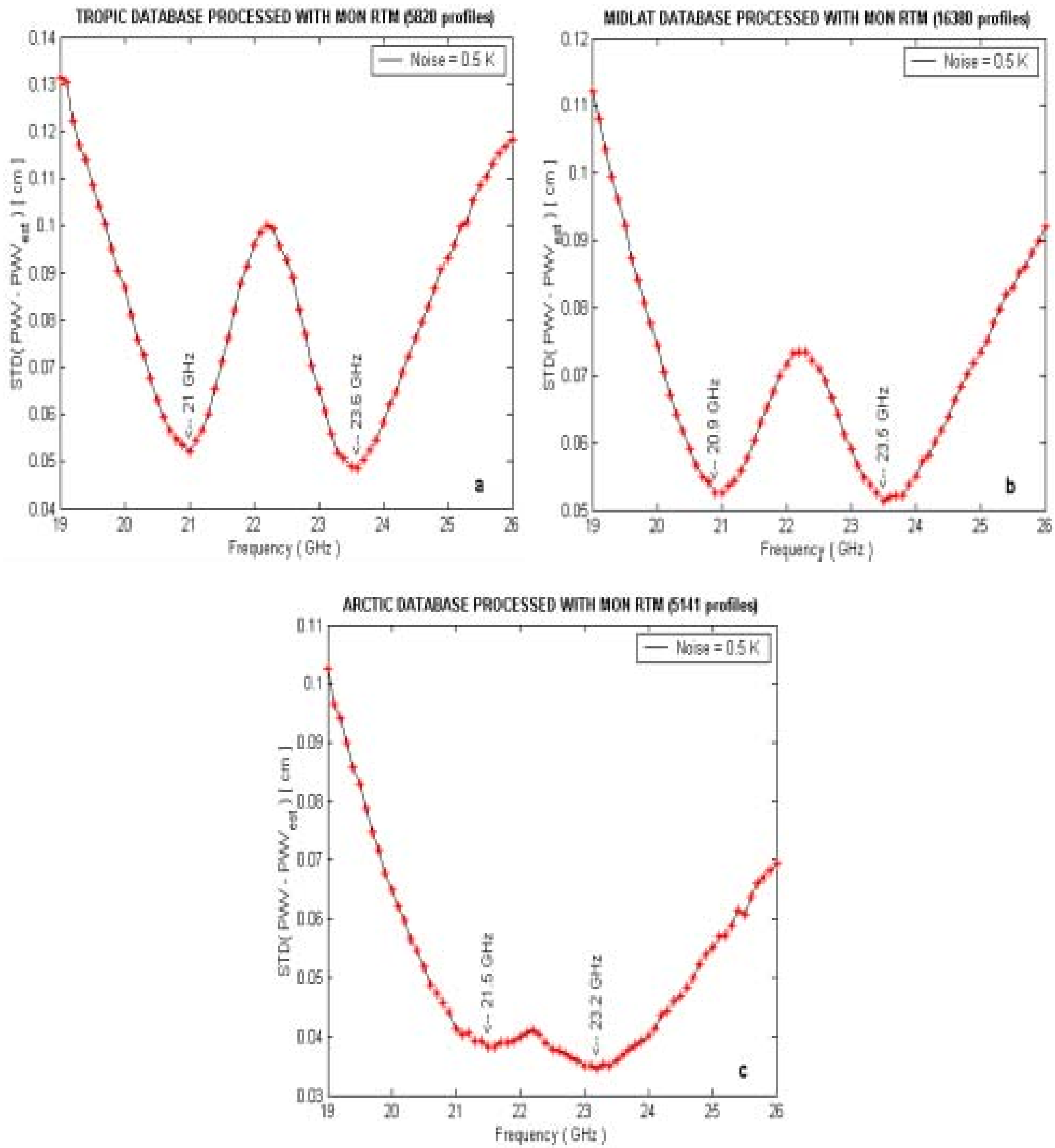

Figure 2. Same as for Figure 1, but using synthetic noisy Tb, obtained by adding random numbers chosen from a normal distribution with mean zero and standard deviation 0.5 to the original Tb.

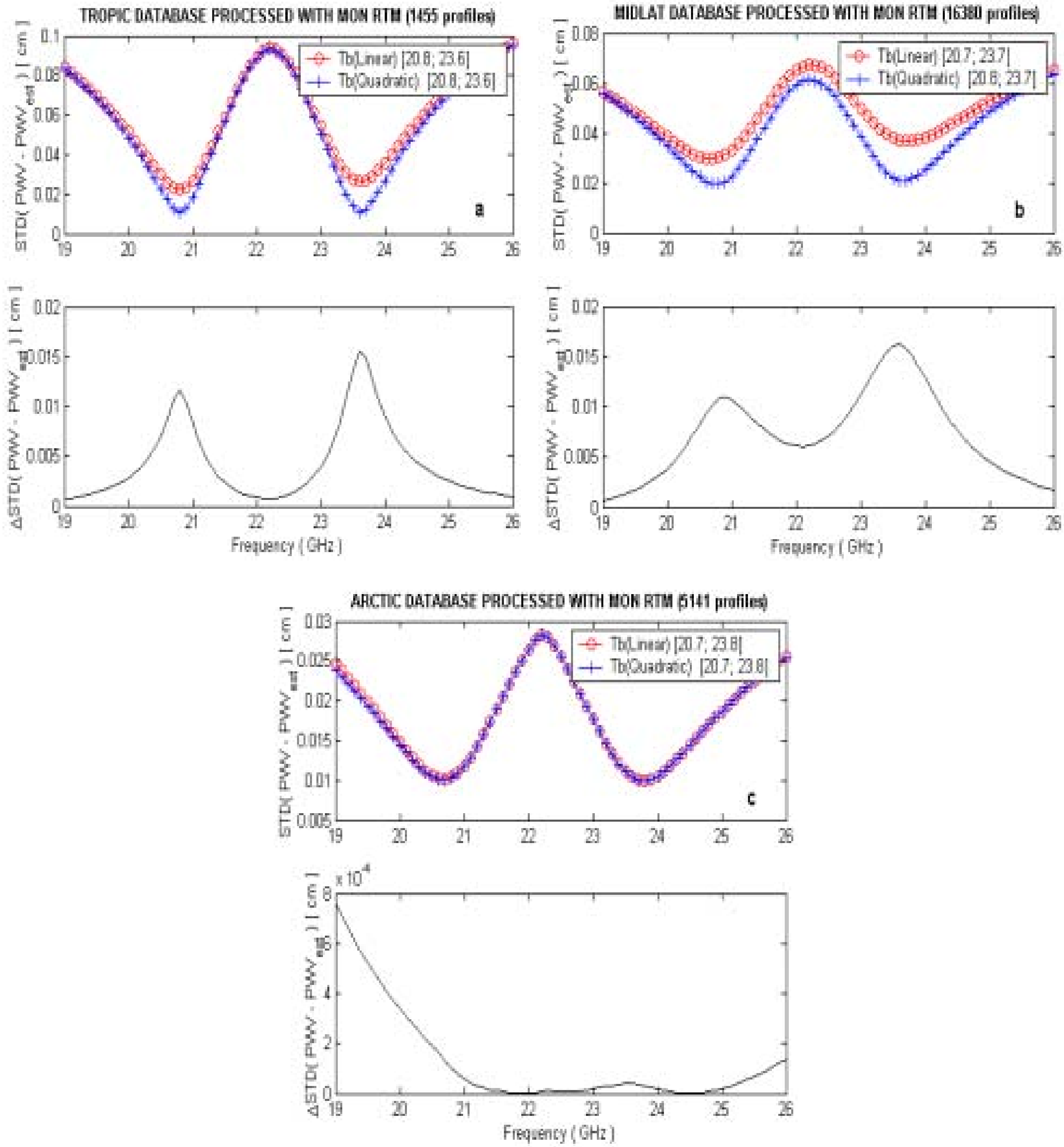

Figure 3. Top panels: $\sigma_{ENV,FM}$(i, j) for the (a) tropical, (b) mid-latitude, and (c) arctic databases processed with MONORTM. PWV is estimated with linear (red) and quadratic (blue) regression on Tb, without adding synthetic noise. Bottom panels: difference in $\sigma_{ENV,FM}$(i, j) when using the two order of regression.

quadratic regression in τ, which we do not show for brevity. However, in all these plots is evident that the frequency allocation of the minima is only slightly dependent (of the order of ±0.1 GHz) on the choice of regression method.

We have also analysed in greater detail the effects caused by using different forward models. In particular we computed the difference in $\sigma_{ENV,FM}(i, j)$ when using linear regression in Tb simulated with LIEBE97, ROSEN98, and MONORTM, with respect to LIEBE87. In Figure 4, we show results for the three environments, obtained from the original data. Near the center of the line, LIEBE93 and ROSEN98 give the best (i.e., smallest) retrieval uncertainty. For the tropical and mid-latitude datasets, three (L87, L93, ROS) out of four models show similar results around 20.6 and 23.8 GHz, while the remaining (MON) stays higher. Nevertheless, the difference in $\sigma_{ENV,FM}(i, j)$ caused by the choice of forward model is bracket between ±0.006 cm (~0.1% of the PWV mean value). On the other hand, for the arctic environment the largest uncertainty is given by ROSEN98, instead of MONORTM, and differences in $\sigma_{ENV,FM}(i, j)$ caused by the choice of forward model are bracket between ±0.002 cm (~0.3% of the PWV mean value). Thus, we can conclude that although the choice of forward model leads to an uncertainty of the order of few millimetres for PWV retrievals (Cimini et al 2003), it does not influence strongly the study of $\sigma_{ENV,FM}(i, j)$.

Summary and Conclusions

From our analysis of the retrieval error RE and the retrieval uncertainty $\sigma_{ENV,FM}(i, j)$ of ground-based single-channel estimates of PWV, based on three historical databases of radiosondes launched at different latitudes, and on the computation of synthetic brightness temperature Tb, we obtained the following results.

Retrieval error analysis: Single-channel PWV retrieval error does depend on the used frequency. The retrieval uncertainty spectrum shows a maximum in the center of the line and two minima, whose frequency allocation depends on the choice of the environment (by means of PWV mean value), of the instrumental noise, of the regression method and of the forward model.

Environment: Although the level of $\sigma_{ENV,FM}(i, j)$ changes significantly among the three datasets, the frequency allocation of the minima is only slightly dependent on the choice of the environment (differences of the order of 0.1 GHz).

Instrumental noise: Adding synthetic instrumental noise to the original data changes substantially the shape of $\sigma_{ENV,FM}(i, j)$, although the trend remains similar. The frequency location of the minima are subject to a displacement towards the center of the line of the order of few tenths of GHz.

Regression method: The retrieval uncertainty values and the frequency allocation of the minima do depend on the choice of regression method, although not dramatically (differences of the order of 0.01 cm for retrieval uncertainty and 0.1 GHz for frequency allocation).

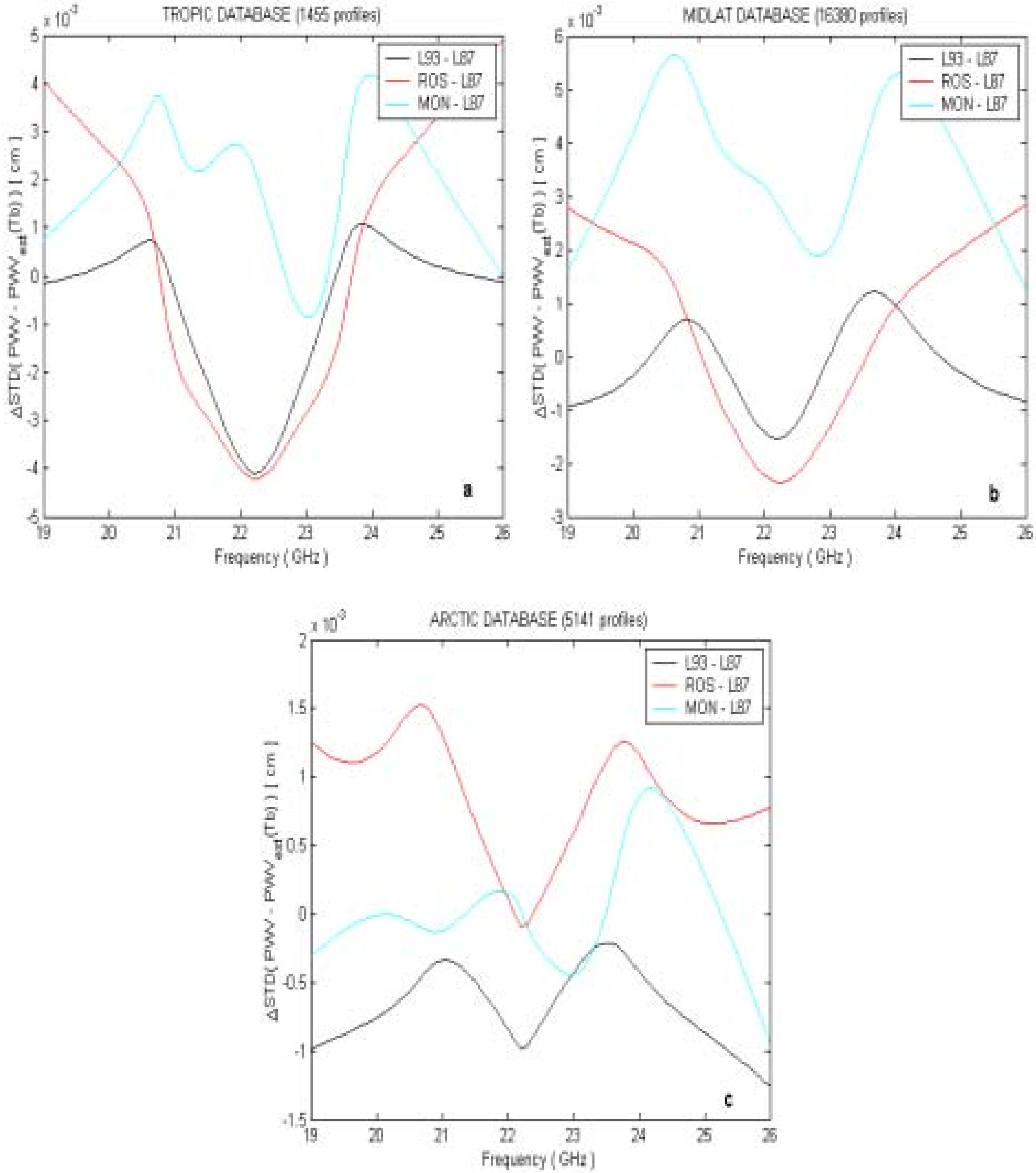

Figure 4. Differences in$\sigma_{ENV,FM}$(i, j) obtained using a variety of forward models for the three environments ([a] tropical; [b] mid-latitude; [c] arctic). Lines represent the difference between $\sigma_{ENV,FM}$(i, j) as obtained with L93, ROS, and MON, with respect to the one obtained with L87.

Forward model: The difference in $\sigma_{ENV,FM}(i, j)$ caused by the choice of forward model is bracket between ±0.006 cm, which corresponds to less than 1% of the mean value of PWV. The frequency allocation of the minima is only slightly dependent on the choice of forward model (differences of the order of 0.1 GHz).

Thus, we can conclude that the frequency locations of the two minima for single-channel PWV retrieval uncertainty range between 20.7 and 21.0 GHz in the low-frequency side, while between 23.5 and 23.8 GHz in the high-frequency side (not considering the particular case of noisy arctic dataset in Figure 2). These results seem to validate the frequency allocation of the so-called hinge points around the water vapor rotational line at 22.235 GHz suggested by Westwater (1978). Considering also that 23.8 GHz falls in a protected radio frequency band, our results do not recommend to move the high-frequency hinge point location to 24.7 GHz.

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