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GPS radio occultation with TerraSAR-X and TanDEM-X: sensitivity of lower troposphere sounding to the Open-Loop Doppler model

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Abstract

The Global Positioning System (GPS) radio occultation (RO) technique provides valuable input for numerical weather prediction and is considered as a data source for climate related research. Numerous studies outline the high precision and accuracy of RO atmospheric soundings in the upper troposphere and lower stratosphere. In this altitude region (8–25 km) RO atmospheric soundings are considered to be free of any systematic error. In the tropical (30° S–30° N) Lower (< 8 km) Troposphere (LT), this is not the case; systematic differences with respect to independent data sources exist and are still not completely understood. To date only little attention has been paid to the Open Loop (OL) Doppler model. Here we report on a RO experiment carried out on-board of the twin satellite configuration TerraSAR-X and TanDEM-X which possibly explains to some extent biases in the tropical LT. In two sessions we altered the OL Doppler model aboard TanDEM-X by not more than ±5 Hz with respect to TerraSAR-X and compare collocated atmospheric refractivity profiles. We find a systematic difference in the retrieved refractivity. The bias mainly stems from the tropical LT; there the bias reaches up to ±1 %. Hence, we conclude that the negative bias (several Hz) of the OL Doppler model aboard TerraSAR-X introduces a negative bias (in addition to the negative bias which is primarily caused by critical refraction) in our retrieved refractivity in the tropical LT.

1 Introduction

In a Global Positioning System (GPS) Radio Occultation (RO) event a receiver aboard a Low Earth Orbiting (LEO) satellite records signals transmitted by a GPS satellite setting beyond (or rising above) the horizon. From the raw measurements bending angle and refractivity profiles are derived under the assumption of a spherically layered atmosphere (Kursinski et al., 1997). This RO atmospheric soundings are a valuable input for Numerical Weather Prediction (Kuo et al., 2000; Healy, 2008) and climate related

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research (Ringer and Healy, 2008; Steiner et al., 2009). Following the proof of concept mission GPS/MET (Rocken et al., 1997) a number of satellites were equipped with GPS receivers, such as SAC-C, the six-satellite COSMIC constellation, TerraSAR-X and TanDEM-X (Hajj et al., 2004; Anthes et al., 2008; Beyerle et al., 2011; Zus et al., 2014). All studies outline the high accuracy of RO atmospheric soundings in the Upper Troposphere (UT) and Lower Stratosphere (LS). In this altitude region (8–25 km) RO atmospheric soundings are considered to be free of any systematic error. In particular in the tropical (30° S–30° N) Lower (< 8 km) Troposphere (LT), this is not the case; positive and negative biases with respect to independent data sources exist. Most of the mechanisms which contribute to those systematic errors are well understood. For example, the large negative refractivity bias (several percent) below 3 km is mainly caused by critical refraction (Sokolovskiy, 2003; Ao et al., 2003). Inversion errors caused by geometric optical methods were strongly reduced by radio-holographic methods that solve for multipath propagation (Gorbunov, 2002; Jensen et al., 2003). The remaining inversion errors depend on the length of the signal, additive noise and tunable inversion parameters (Sokolovskiy et al., 2010). Errors caused by Closed Loop (CL) tracking are eliminated by Open Loop (OL) tracking (Sokolovskiy, 2001). However, the OL tracking relies on a OL Doppler model, i.e. a bending angle climatology and the real time navigation solution (for details see below). The question arises whether a slightly different OL Doppler model has a spurious effect on RO atmospheric soundings.

The close proximity of TerraSAR-X and TanDEM-X offers a unique opportunity (the satellites are in a closely controlled formation with distances < 1 km); if the receivers aboard TerraSAR-X and TanDEM-X track the same setting (or rising) GPS satellite the differences in the retrieved atmospheric products measure the precision of the GPS RO technique. We performed such an experiment and confirmed the high precision of atmospheric soundings (Zus et al., 2014). We also showed that if the the OL Doppler model aboard TanDEM-X is biased with respect to TerraSAR-X then the atmospheric soundings are biased as well. While in the previous experiment we altered the OL Doppler model aboard TanDEM-X by as much as ±10 Hz with respect to TerraSAR-

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X in a follow-on experiment we altered the OL Doppler model aboard TanDEM-X by ±5 Hz with respect to TerraSAR-X. This allows us to study the sensitivity of atmospheric soundings to the OL Doppler model.

In Sect. 2 we provide an overview of our data analysis. In Sect. 3 we compare collocated TerraSAR-X and TanDEM-X refractivity profiles to study the sensitivity with respect to the OL Doppler model. Section 4 summarizes the results.

2 Data analysis

Here we provide an overview of the processing chain leading from GPS RO measurements to refractivity profiles. For details on GFZ's processing system POCS-X (Potsdam Occultation Software) the reader is referred to Beyerle et al. (2011). In the first processing step the L1 and L2 atmospheric excess phase between the GPS and LEO satellite are derived from dual frequency phase measurements. In this step we distinguish phase measurements from CL and OL tracking mode (the processing of the latter will be described in more detail hereinafter). Auxiliary input data, i.e., precise satellite orbits, clocks and navigation data bits, are provided by GFZ. In the second processing step the L1 and L2 atmospheric excess phase profiles are inverted to L1 and L2 bending angle profiles and linearly combined to an ionospheric corrected bending angle profile. The bending angle profile is transformed to a refractivity profile (Abel inversion). This refractivity profile is assigned to a single Tangent Point (TP) (geographical location), represents the output of the processing chain and the input to the statistical comparisons.

In a setting RO event (rising RO events are not considered in this study) the receiver starts CL tracking at a Straight Line Tangent Point Altitude (SLTA) of 120 km and switches to OL tracking at a SLTA of −15 km. In the CL tracking mode the receiver outputs total phase samples while in the OL tracking mode the receiver outputs Numerically-Controlled Oscillator (NCO) phase samples ϕ_n^{NCO} along with in- and quadrature-phase correlation sum samples $\hat{I}_n = I_n/D_n$ and $\hat{Q}_n = Q_n/D_n$ respectively.

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Here, the subscript n denotes sample number, I_n and Q_n denote the demodulated in-phase and quadrature-phase correlation sum samples and $D_n = \pm 1$ denote the navigation data bits. In post-processing the total phase sample ϕ_n is constructed according to Beyerle et al. (2011)

$$\phi_n = \phi_n^{\mathrm{NCO}} + \delta\phi_n \quad (1)$$

The residual phase sample $\delta\phi_n$ is determined through application of the four-quadrant inverse tangent to demodulated in- and quadrature-phase correlation sum samples

$$\delta\phi_n = \mathrm{atan2}(Q_n, I_n) + c_n \quad (2)$$

The term c_n unwraps the residual phase

$$c_n = \begin{cases} c_{n-1} + 2\pi : & \mathrm{atan2}(Q_n, I_n) - \mathrm{atan2}(Q_{n-1}, I_{n-1}) < -\pi \\ c_{n-1} - 2\pi : & \mathrm{atan2}(Q_n, I_n) - \mathrm{atan2}(Q_{n-1}, I_{n-1}) > +\pi \\ c_{n-1} : & \text{otherwise} \end{cases} \quad (3)$$

with $c_1 = 0$. The residual phase extraction requires demodulated in- and quadrature-phase samples. Thus, knowledge of the navigation data bits is presupposed. GFZ established a global network of ground-based GPS receivers for that purpose (Beyerle et al., 2009).

The NCO phase is calculated onboard utilizing an OL Doppler model, which is based on a bending angle climatology and the real time navigation solution (Ao et al., 2009). In theory, the total phase is independent of the chosen OL Doppler model provided that the difference between the true Doppler and the chosen OL Doppler model remains below the Nyquist frequency (half of the sampling frequency) of 25 Hz (Sokolovskiy, 2001). The true atmospheric Doppler is unknown. Fortunately, the atmospheric Doppler

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is not very sensitive to the variety of atmospheric conditions that exist (Ao et al., 2009). Therefore, the current OL Doppler model, which to our understanding is the same onboard of SAC-C, TerraSAR-X and TanDEM-X, is assumed to be accurate enough to prevent spurious systematic errors in retrieved atmospheric soundings. To best of our knowledge no RO experiment exists that confirms this assumption. A recent RO experiment Zus et al. (2014) shows that the retrieved refractivity depends on the chosen OL Doppler model. However, it is not clear if this is of practical relevance because the OL Doppler model was altered by as much as ±10 Hz and no evidence is given that the OL Doppler model is actually biased. A quick look on Fig. 6 in Beyerle et al. (2011) suggests that the OL Doppler model is indeed biased by several Hz. Hence, in a follow on RO experiment we altered the OL Doppler model aboard TanDEM-X by a few Hz with respect to TerraSAR-X, compare retrieved collocated refractivity profiles and take a closer look on the current OL Doppler model aboard TerraSAR-X.

3 Results and discussion

We analyze setting occultation pairs for two periods in 2012; 11 to 15 December and 18 to 22 December. In these time periods we altered the OL Doppler model aboard TanDEM-X by ±5 Hz with respect to TerraSAR-X. In the time periods we obtain 753 and 720 occultation pairs respectively with horizontal TP differences < 1 km.

The mean and SD between TanDEM-X and TerraSAR-X refractivity as a function of the altitude is shown in the Fig. 1. The upper (lower) left panel shows the statistic for the time period where the OL Doppler model is altered by + (−) 5 Hz. In the UT (at altitudes above 8 km) excellent agreement is found; the SD is about 0.15 % and the mean deviation is negligible. This finding is in good agreement with our previous study (Zus et al., 2014) and stresses the high precision of the GPS RO technique in the UT. In the LT (at altitudes below 8 km) the increase in the SD is not unexpected since we obtain a similar increase in the SD if the same OL Doppler model is used (Zus et al., 2014). However, the systematic difference in the OL Doppler model introduces a mean deviation which reaches ±0.3 %. This bias mainly stems from the tropics (the latitude band 30° S–30° N) as can be seen from the upper (lower) right panel. There the bias reaches up to ±1 %. The retrieved refractivity at high latitudes is hardly affected by the systematic difference in the OL Doppler model. In essence, a bias in the OL Doppler model of ±5 Hz introduces a bias of up to ±1 % in the retrieved refractivity in the tropical LT. By taking into account the result of our previous study (Zus et al., 2014), i.e., a bias in the OL Doppler model of ±10 Hz introduces a bias of ±2 % in the retrieved refractivity in the tropical LT, we conclude that the fractional refractivity bias in the tropical LT reaches about 1/5 of the OL Doppler model bias.

A possible explanation for the observed behaviour is that the shift of the OL Doppler model causes a change in the reconstructed total phase and subsequently the retrieved refractivity because the deviation between the modified OL Doppler model and the true atmospheric Doppler exceeds the Nyquist frequency of 25 Hz. In addition RO simulation studies (Beyerle et al., 2006) show that for weak signal amplitudes the residual Doppler (the time derivative of the residual phase Eq. 2) starts to get randomly distributed around the OL Doppler model. Therefore, if the OL Doppler model is biased, the retrieved refractivity is biased as well. The mean and SD between TanDEM-X and TerraSAR-X Doppler (the time derivative of the total phase) as a function of the Signal to Noise Ratio (SNR) for our RO experiment is shown in Fig. 2. The upper (lower) left panel shows the statistic for the time period where the OL Doppler model is altered by + (−) 5 Hz. For the noise level, which is about 10 V/V, the average Doppler difference is ±5 Hz since the OL Doppler models deviate by ±5 Hz. The average Doppler difference at the noise level is not regarded as problematic. However, already for SNRs below about 40 V/V the average Doppler difference shows a tendency towards the Doppler model off-set. The fact that the refractivity bias arises mainly in the tropics can be explained by taking into account that this is this geographical region where large signal bending and therefore signal defocusing occurs. In particular phase and amplitude samples from SLTA regions characterized by strong signal attenuation (attributed to large bending as the signal traverses sharp refractivity layers) contribute to the bias.

A simple ad-hoc procedure to counteract the OL Doppler bias in post-processing appears feasible: identify SLTA regions (at least two consecutively samples) where the SNR reaches a threshold of say 30 V/V and shift the total Doppler by the same magnitude as the OL Doppler bias but with opposite sign. The modified total Doppler is integrated over time to obtain the corrected total phase. This corrected total phase and the SNR are input to further processing. The corresponding mean and SD between TanDEM-X and TerraSAR-X refractivity as a function of the altitude is shown in the Fig. 3. The upper (lower) panel shows the statistic for the time period where the OL Doppler model is altered by + (−) 5 Hz. It can be seen that the ad-hoc procedure mitigates the biases visible in Fig. 1. Clearly, the rudimentary nature of this ad-hoc procedure does not warrent its use in practice.

Still, the question is whether in the tropics the (default) OL Doppler model aboard TerraSAR-X is biased by several Hz with respect to truth. If this is the case, then the retrieved refractivity is biased as well. Ground truth is not accessible. However, we argue that if SNR is sufficiently high the average OL Doppler miss-modeling (the residual Doppler with opposite sign) is a good proxy for the OL Doppler model bias. Figure 4 shows the average OL Doppler miss-modeling as a function of the SLTA for the tropics. Clearly, at a SLTA of −150 km the average OL Doppler miss-modeling is meaningless because on average the signal amplitude decreases to noise level. However, at SLTAs larger −150 km the average OL Doppler miss-modeling tends to be negatively biased. Hence we conclude that the retrieved refractivity in the tropical LT is negatively biased as well. From the average OL Doppler miss-modeling and our rule of thumb we estimate that this bias reaches about −0.5 %. Also shown is the average OL Doppler miss-modelling as a function of the SLTA for periods where the OL Doppler model aboard TanDEM-X is altered by ±5 Hz (red and blue line). Now, the average OL Doppler miss-modelling exhibits a positive (negative) bias. Likewise, we conclude that the retrieved refractivity in the tropical LT is positively (negatively) biased.

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4 Conclusions

In two sessions we altered the OL Doppler model aboard TanDEM-X by ±5 Hz with respect to TerraSAR-X and compare collocated atmospheric refractivity profiles. We find a systematic difference which stems from the tropical LT; there the bias reaches up to ±1 %. Hence, we conclude that the negative bias of the OL Doppler model (several Hz) aboard TerraSAR-X introduces an additional negative refractivity bias (reaching about −0.5 %) in the tropical LT. To mitigate this phenomena we propose to consider a presumably more accurate on-board OL Doppler model in current (future) GPS RO missions. This can be achieved by utilizing a more accurate latitude dependent bending angle climatology. Note, that the current bending angle climatology is based on the average of a large number of SAC-C bending angle profiles (Ao et al., 2009). In addition, increasing the sampling frequency from 50 to 100 Hz will make the RO atmospheric soundings less susceptible to the remaining OL Doppler model bias (Beyerle et al., 2011).

It is important to note that in this study we considered setting occultations only. Rising occultations differ from setting occultations insofar as the NCO phase is calculated onboard utilizing an OL delay model (Ao et al., 2009). From Fig. 8 in Ao et al. (2009) we estimate that the time derivative of the OL delay model is about 5 Hz larger than the OL Doppler model. Therefore, for rising occultations we anticipate a positive refractivity bias (reaching about +0.5 %) in the tropical LT. A detailed analysis is left for a future study.

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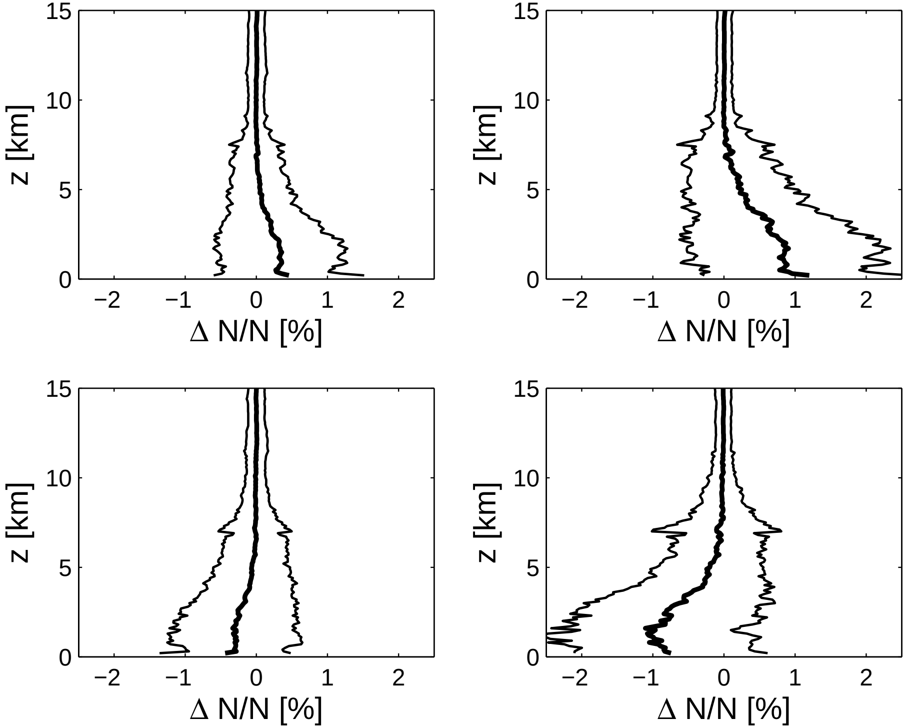

Figure 1. The mean and SD between TanDEM-X and TerraSAR-X refractivity as a function of the altitude. The upper (lower) panel corresponds to the case where the OL Doppler model aboard TanDEM-X is altered by + (−) 5 Hz with respect to TerraSAR-X (11 to 15 December and 18 to 22 December in 2012 respectively). The left panels show the global statistics. The right panels show the statistics in the tropics (latitude band 30° S–30° N).

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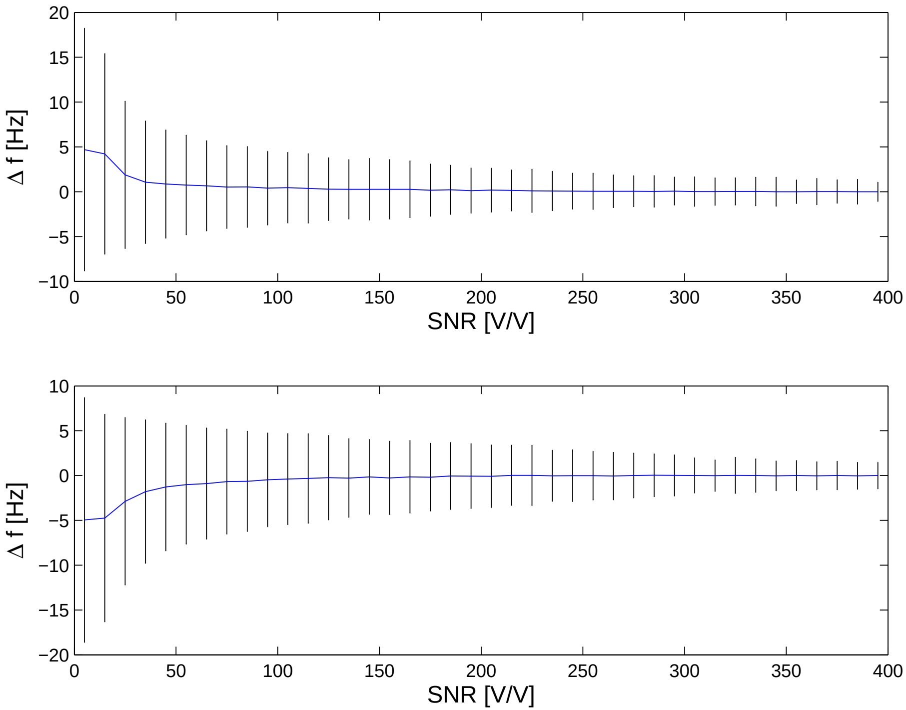

Figure 2. The mean and SD between TanDEM-X and TerraSAR-X Doppler as a function of the SNR. The blue line indicates the mean deviation and error bars indicate the SD. The upper (lower) panel corresponds to the time period we the Doppler model aboard TanDEM-X is altered by + (−) 5 Hz with respect to TerraSAR-X (11 to 15 December and 18 to 22 December in 2012 respectively). For details refer to the text.

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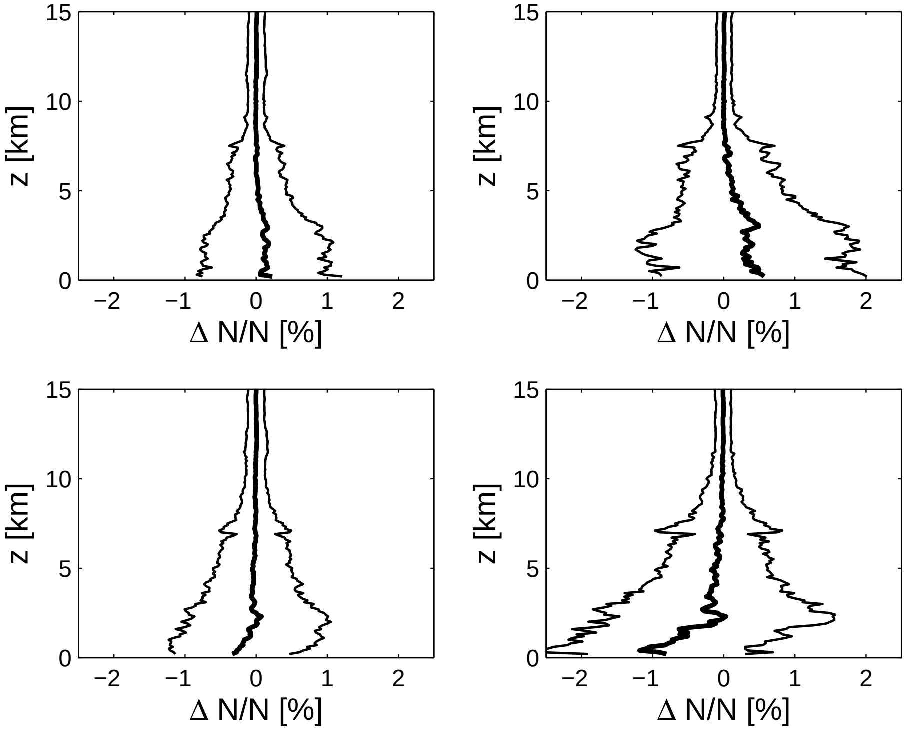

Figure 3. The mean and SD between TanDEM-X and TerraSAR-X refractivity as a function of the altitude. The upper (lower) panel corresponds to the case where the OL Doppler model aboard TanDEM-X is altered by + (–) 5 Hz with respect to TerraSAR-X (11 to 15 December and 18 to 22 December in 2012 respectively). The left panels show the global statistics. The right panels show the statistics in the tropics (latitude band 30° S–30° N). In post-processing an ad-hoc procedure is applied to counteract the OL Doppler model offset (for details refer to the text).

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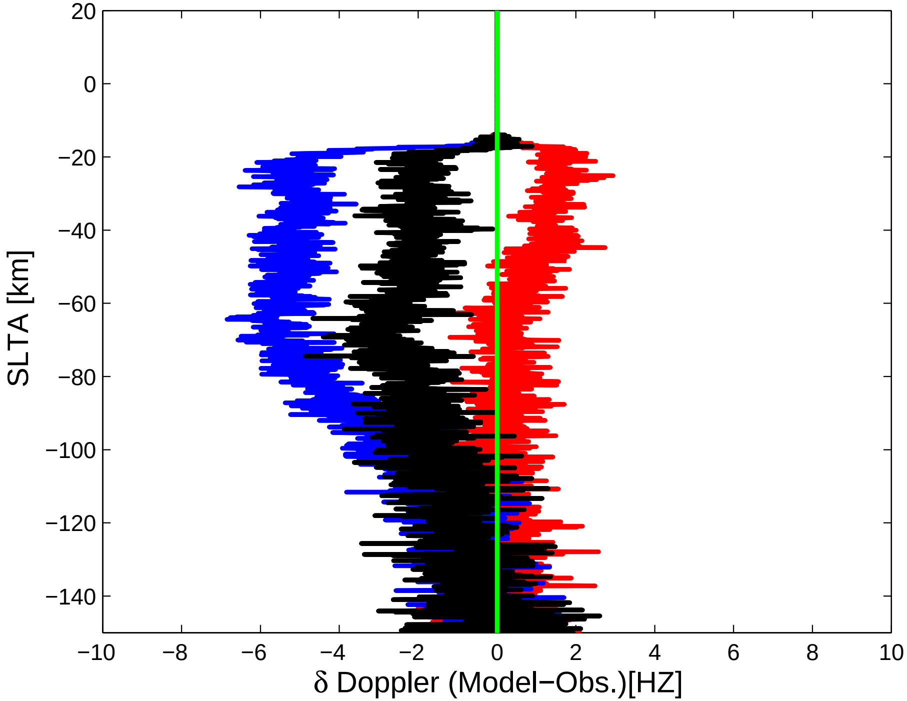

Figure 4. Average OL Doppler miss-modelling as a function of the SLTA in the tropics (latitude band 30° S–30° N). The black line corresponds to TerraSAR-X utilizing the default OL Doppler model (8 to 9 December in 2012). The red (blue) line corresponds to TanDEM-X where the default OL Doppler model is altered by + (−) 5 Hz (11 to 12 December and 19 to 20 December in 2012 respectively).

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