Influence of the horizontal resolution of numerical weather models on ray-traced delays for VLBI analysis

A. Hofmeister, D. Landskron, J. Böhm

Abstract Ray-traced delays offer the opportunity to correct the influences of the troposphere on observations of space geodetic applications such as Very Long Baseline Interferometry (VLBI). As the Numerical Weather Model (NWM) builds the data base for the ray-tracing through providing the needed meteorological data, the selection of an appropriate NWM is of major concern. In this respect also the horizontal resolution of the NWM may have significant impact on the resulting ray-traced slant delays. So, directly on the ray-traced delays the horizontal resolution of the NWM shows an increasing impact with decreasing elevation angle. In case of using horizontal resolutions of either 0.125° x 0.125° or 1° x 1°, real significance in terms of differences in the resulting ray-traced delays is only given at elevation angles smaller than 10°, as the differences start to exceed the cm-level at lower elevations. If the ray-traced delays are applied to the VLBI analysis of the CONT11 campaign, the horizontal resolution of the NWM has in general a very small influence with respect to Baseline Length Repeatability (*BLR*) and Station Coordinate Repeatability (*SCR*). Depending on the general parameterization of the analysis, the influence of the horizontal resolution of the NWM may even be negligible.

Keywords Ray-tracing, Troposphere, Numerical weather model, VLBI

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1 Introduction

The application of ray-tracing for the calculation of tropospheric slant delays serves as a promising alternative for the correction of the influences of the troposphere on the observations of space geodetic techniques such as the Very Long Baseline Interferometry (VLBI). Compared to the standard approach, where the slant delays for the tropospheric correction are determined via estimating zenith delays and applying mapping functions, the ray-tracing approach estimates the slant delays directly for the actual ray paths of the observations.

In order to determine these ray paths and the delays along these paths, meteorological data are needed as main input for the ray-tracing approach. These data are usually taken from a Numerical Weather Model (NWM). Nowadays there are many different NWMs available, which can be used for the ray-tracing. But besides the general selection of a specific NWM it is also necessary to choose its horizontal resolution, which may have significant impact on the resulting ray-traced delays. Concerns why not to use the highest available horizontal resolution of a NWM may be driven by the fact that a higher resolution also means increased amount of data to download and to process per needed epoch of the NWM data.

2 The ray-tracing approach

This chapter gives a short introduction to the ray-tracing method for the application in geodetic VLBI. The calculation of the ray-traced slant delays for each VLBI observation consists of two parts.

The first part is the ray-tracing itself. Here the real signal path is reconstructed within an iterative process using the so-called outgoing elevation angle of the signal, which represents the elevation angle in the vacuum. For this task different approaches exist that in principle differ in complexity and therefore also in accuracy, but basically all of these approaches have in common that they need refractivity values in order to determine the signal path. These refractivity values can be derived from the meteorological data that are provided by the NWM.

In the second part the gained knowledge of the actual signal path is needed as the refractivity values along the reconstructed path are used to calculate the tropospheric slant delay of the observation.

3 Impact of the horizontal resolution of the NWM

On the one hand it is possible that the use of a horizontally higher resolved NWM may lead to improved accuracy of the ray-traced delays, but on the other hand it is certain that a horizontally higher resolved NWM leads to an increased demand for storage space and processing time. If a calculation of ray-traced delays for geodetic VLBI sessions that cover a broad time span is considered, many epochs of NWM data are needed. Thus, using a NWM with a high horizontal resolution leads to high amounts of data that need to be processed. Therefore the research on how the horizontal resolution of the NWM affects the ray-traced delay results should reveal a quantification of the need of a horizontally highly resolved NWM for ray-tracing.

3.1 Methodology of the research

In order to assess the effect of the horizontal resolution of the NWM on the ray-traced delays, we carry out two different main fields of investigation. The first part covers the assessment of the direct effects on the ray-traced delays if the same NWM, but with different horizontal resolutions, is used to calculate the delays. In the second part we apply these differently determined ray-traced delays to the VLBI analysis in order to see the effects on the results with respect to Baseline Length Repeatability (*BLR*) and Station Coordinate Repeatability (SCR).

3.2 Data for the research

As observational data input for the ray-tracing and the VLBI analysis we use the CONT11 campaign of the International VLBI Service for Geodesy and Astrometry (IVS), covering 15 days of continuous VLBI observations.

As meteorological data input for the ray-tracing we utilize the operational NWM from the European Centre for Medium-Range Weather Forecasts (ECMWF). This global NWM delivers the meteorological data via 25 pressure levels with a temporal resolution of 6 hours. For our research we use two different horizontal resolutions of the NWM: 0.125° x 0.125° and 1° x 1°.

For the calculation of the ray-traced delays we utilize our program RADIATE, which is developed within project RADIATE VLBI (Ray-traced Delays in the Atmosphere for geodetic VLBI), funded by the Austrian Science Fund (FWF). Within the processing the vertical resolution of the NWM is increased by interpolation at discrete height levels. As ray-tracing method the piecewise-linear approach is used. In order to receive the delay for each observation at the exact observation time, a linear interpolation of the delays calculated at the two adjacent epochs of the NWM, that directly surround the observation time, is carried out. More detailed information on the ray-tracing program RADIATE can be found in Hofmeister and Böhm (2014).

Now, with the use of the program RADIATE ray-traced delays for the CONT11 observations of all participating stations are calculated twice. Once using the NWM(0.125°) with a horizontal resolution of 0.125° x 0.125° and once using the NWM(1°) with a horizontal resolution of 1° x 1°. These two sets of ray-traced delays, which will be called RD(0.125°) and RD(1°) from now on, are used for the following comparisons.

3.3 Direct effect on the ray-traced delays

For assessing the impact of the different horizontal resolutions directly on the ray-traced delays, a comparison of the differences in the domain of the Slant Total Delay (STD) is carried out. Besides the comparison of the direct STD differences (ΔSTD), also the

ΔSTD_{mf} are compared, which denote the differences in the STD calculated from the mapping factors (mf). Equations (1) to (3) show the formalism of the calculations. ZTD refers to the Zenith Total Delay. The subscripts describe the ray-tracing solution, i.e. the horizontal resolution of the NWM used for its calculation. The calculation of the ΔSTD_{mf} using the mf together with the $ZTD_{RD(0.125°)}$ as the reference ZTD leads to a kind of scaled result compared to the ΔSTD.

$$\Delta STD = STD_{RD(0.125°)} - STD_{RD(1°)} \tag{1}$$

$$\Delta STD_{mf} = STD_{RD(0.125°)} - mf_{RD(1°)} \cdot ZTD_{RD(0.125°)} \tag{2}$$

with

$$mf_{RD(1°)} = \frac{STD_{RD(1°)}}{ZTD_{RD(1°)}} \tag{3}$$

Figure 1 shows the ΔSTD and Figure 2 shows the ΔSTD_{mf} for the station KOKEE.

Concerning the results of ΔSTD for all CONT11 stations, the differences for elevation angles larger than 10° reach up to only a few cm for the majority of stations and remain mainly at a level of 1-2 cm. At elevation angles smaller than 10° the differences rise significantly and can even reach a few dm at 1° elevation as we have seen in our studies with simulated observations. The general size of the differences is mainly caused by the differences in the wet delay.

Looking at the domain of STD_{mf}, again for all CONT11 stations, the differences in general are, as expected, scaled in the sense of reduced compared to the ΔSTD. So, only very small differences of mostly below 1 cm are visible at elevation angles larger than 10°. At smaller elevation angles the differences start to rise and some outliers can be found. A few stations, but especially KOKEE (see Figure 2) and TSUKUB32, show a kind of special behaviour. At these stations the ΔSTD_{mf} are significantly increased at low elevations compared to the quite small and homogeneous differences at higher elevations.

In general, the influence of the horizontal resolution of the NWM directly on the ray-traced delay is increasing with decreasing elevation angle. Nevertheless, a really significant effect is only given at low elevations.

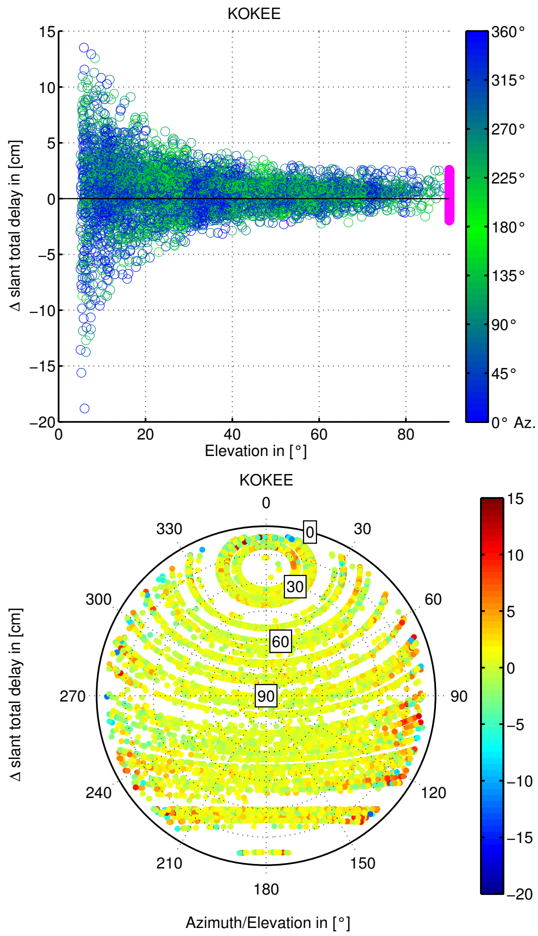

Fig. 1 ΔSTD for the station KOKEE. Upper plot: ΔSTD w.r.t. to the elevation angles, the respective azimuths are shown via colour-coding. Lower plot: skyplot of the observations with colour-coded ΔSTD. Please refer to the web version of the proceedings to see the plots in colour.

3.4 Effect on VLBI analysis results

In order to assess the influence of the horizontal resolution of the NWM on the VLBI results, the ray-traced delays RD(0.125°) and RD(1°) are applied to the VLBI analysis of CONT11. As parameters for the quantification of the impact on the VLBI results, the weighted BLR and the weighted SCR are used. The weights for the calculation of the BLR are the inverse formal baseline length errors. These are derived using the covariances of the baseline-forming stations. For the SCR the weights are calculated using the inverse formal coordinate errors. The VLBI analysis is carried out with the

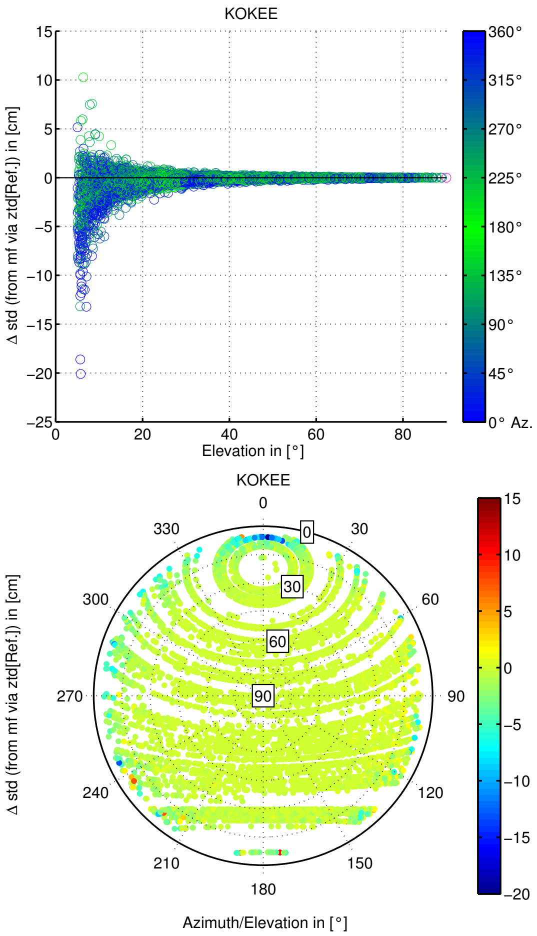

Fig. 2 ΔSTD_{mf} for the station KOKEE. Upper plot: ΔSTD_{mf} w.r.t. to the elevation angles, the respective azimuths are shown via colour-coding. Lower plot: skyplot of the observations with colour-coded ΔSTD_{mf}. Please refer to the web version of the proceedings to see the plots in colour.

software VieVS (Böhm et al., 2012) using two different parameterizations:

1. Ray-tracing only
   - Ray-traced slant delays used as a priori input.
   - No estimation of Zenith Wet Delays (ZWD) or tropospheric gradients.
2. Ray-tracing, est. ZWD 1h, est. gradients 6h
   - Ray-traced slant delays used as a priori input.
   - Estimation of ZWD every hour with a relative constraint of 1.5 cm after 1 hour.
   - Estimation of tropospheric North- and East-gradients every 6 hours with a relative constraint of 0.05 cm after 6 hours for both.

In the analysis of CONT11 the stations WARK12M and ZELENCHK are not considered.

The following comparisons investigate the differences Δ in BLR and SCR resulting from the use of the ray-traced delays RD(0.125°) or RD(1°) in the VLBI analysis. Equations (4) and (5) show how the Δ are calculated. Each subscript describes which ray-tracing solution has been applied to the analysis.

$$\Delta BLR = BLR_{RD(0.125^\circ)} - BLR_{RD(1^\circ)} \quad (4)$$

$$\Delta SCR = SCR_{RD(0.125^\circ)} - SCR_{RD(1^\circ)} \quad (5)$$

The ΔBLR and ΔSCR derived from the analysis with parameterization 1 can be seen in Figure 3. The BLR differs on average only by -0.5 mm. No clear trend of an improvement can be derived in case the horizontally higher resolved NWM(0.125°) has been used for the delay calculation, as only 34 of the 66 baselines are improved. The baselines formed by the station KOKEE are influenced the most on average. The ΔSCR are at a very low mm-level. The stations KOKEE, TSUKUB32 and YEBES40M show increased Δ in the up-direction. This effect may come from their significantly increased ΔSTD_{mf} at low elevations, described in Section 3.3. Interestingly, this effect is inverse for the station TSUKUB32. The North-components seem to be improved by the usage of the horizontally higher resolved NWM(0.125°), but concerning the small amounts, this trend is not really significant.

Figure 4 shows the ΔBLR and ΔSCR derived from the analysis with parameterization 2. The BLR differs on average only by +0.2 mm. There is no clear trend for the impact of the horizontal resolution of the NWM derivable. For the most baselines the ΔBLR is in between ±1 mm. The baselines for the station KOKEE are again influenced the most on average, but this time oppositely compared to the results of the first analysis parameterization. Also in the domain of the SCR no trend for the impact of the horizontal resolution of the NWM can be derived. Parameterization 2 reduces the Δ in the North- and East-direction to sub-mm-level. Only the Δ in the up-direction is again a bit increased at some stations. In general, the impact on the SCR is too small to be significant.

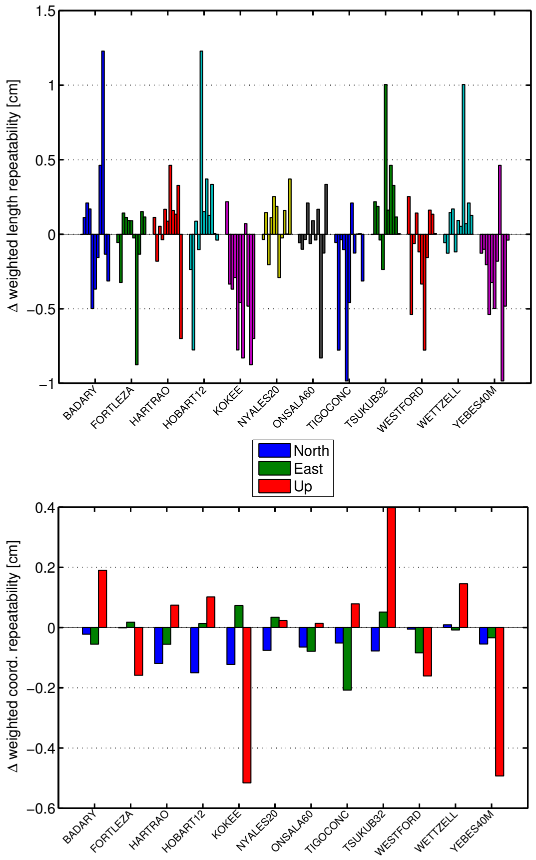

Fig. 3 Δ in analysis results from parameterization 1. Upper plot: Δ of weighted *BLR* for each station sorted by mean baseline length. Lower plot: Δ of weighted SCR. Negative Δ indicate that the horizontally higher resolved NWM(0.125°) would improve the solution. Please refer to the web version for coloured plots.

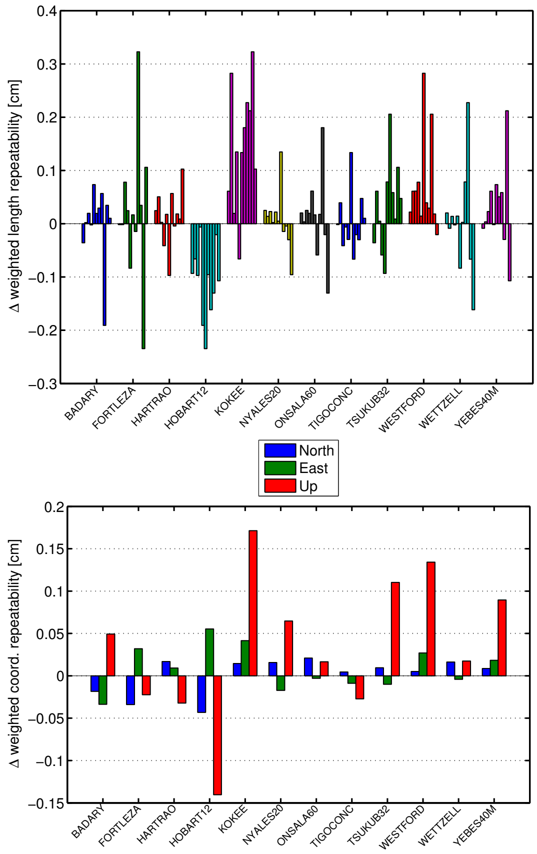

Fig. 4 Δ in analysis results from parameterization 2. Upper plot: Δ of weighted *BLR* for each station sorted by mean baseline length. Lower plot: Δ of weighted SCR. Negative Δ indicate that the horizontally higher resolved NWM(0.125°) would improve the solution. Please refer to the web version for coloured plots.

4 Conclusions

The impact of the horizontal resolution of the NWM directly on the ray-traced delays is increasing with decreasing elevation angle, but a really significant influence is only given at small elevation angles. If the ray-traced delays are applied to the VLBI analysis, there is only a quite small impact as seen with respect to *BLR* and SCR and no clear trend of an improvement can be derived in case of using a horizontally higher resolved NWM. Furthermore the size of the influence is depending on the parameterization of the VLBI analysis. If ZWD and tropospheric gradients are estimated in the analysis, the influence of the horizontal resolution of the NWM, as investigated here for resolutions of 0.125° x 0.125° and 1° x 1°, is negligible.

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