Ray-traced Delays in the Atmosphere for Geodetic VLBI

Armin Hofmeister, Johannes Böhm

Abstract The application of ray-traced slant path delays has the potential to enhance geodetic Very Long Baseline Interferometry (VLBI) analysis through improving the correction of the tropospheric effects on the observations. The utilization of directly estimated ray-traced slant path delays calculated from true meteorological data has the potential to overcome the shortcomings of the commonly used method of indirectly determined slant path delays via zenith delays mapped to the actual observation angle. Within our project RADIATE VLBI (Ray-traced Delays in the Atmosphere for geodetic VLBI) we are developing a new ray-tracing program for application in geodetic VLBI analysis. We introduce our project and present an overview of the current development status of our ray-tracer. In order to verify our results, we compare our ray-traced delays to results of a ray-tracer comparison campaign by Nafisi et al. (2012b), [4]. The RADIATE piecewise-linear solution for the slant total delay calculated from mapping factors at 5° elevation agrees with most of the other ray-tracers, with mean differences below 1 cm and standard deviations below 0.6 cm at the station Tsukuba and mean differences below 2.5 cm and standard deviations below 1 cm at the station Wettzell.

Keywords Ray-tracing, troposphere, VLBI

Department of Geodesy and Geoinformation, Vienna University of Technology, Austria

1 Derivation of Slant Path Delays

The influence of the troposphere is one of the major error sources in space geodetic applications such as Very Long Baseline Interferometry (VLBI) or Global Navigation Satellite Systems (GNSS) (Böhm (2012), [1]). Besides the common way of determining zenith delays and mapping them to the elevation angles, it is possible to use ray-tracing algorithms to directly determine the slant delays for each observation.

The great advantage of this approach is the possibility of using the true meteorological data along the exact ray path of each individual observation to determine the slant total delays, whereas in the standard approach only surface-based data serve as input to calculate zenith hydrostatic delays and the zenith wet delays are only estimated within the VLBI analysis using the wet mapping factors as partial derivatives (Böhm (2012), [1]). Therefore the currently common method to determine the slant delays shows some disadvantages because of its indirect approach through the use of zenith delays and mapping functions.

In the following the ray-tracing technique for application in geodetic VLBI will be discussed.

2 Ray-tracing Technique

In order to determine the slant path delays for geodetic VLBI observations, it is necessary to reconstruct the original signal path for each observation as accurately as possible. For this task different approaches of ray-tracing can be used, some more sophisticated than others, but more detailed methods often lead to increased computation times.

For the signal path determination, information about the state of the atmosphere in the form of pressure, temperature, and humidity is needed. These data are delivered through numerical weather models with certain resolutions in the horizontal and vertical directions. From the information gained by a numerical weather model, the refractivities at the different height levels can be calculated, and with them the signal path can be determined.

After deriving the true signal path of the observation, the slant path delay is calculated again using the refractivities.

3 Project RADIATE VLBI

One main goal of project RADIATE VLBI (Ray-traced Delays in the Atmosphere for geodetic VLBI), funded by the Austrian Science Fund (FWF), is to determine ray-traced delays for all VLBI observations since 1979 (about 5 Mio.) (Böhm (2012), [1]).

Through the development of the new ray-tracer called RADIATE within the project, we want to enhance the processing of VLBI sessions in order to improve the resulting geodetic parameters such as station coordinates and the scale of the terrestrial reference frame or Earth orientation parameters (EOP) (Böhm (2012), [1]).

3.1 Ray-tracer RADIATE

For our RADIATE ray-tracer we use meteorological data from the European Centre for Medium-range Weather Forecasts (ECMWF) in the form of a global numerical weather model (ECMWF pressure level data) with a horizontal resolution of 0.125° x 0.125°, a vertical span of 25 pressure levels, and a time resolution of six hours with epochs at 0h, 6h, 12h, and 18h. Interpolation of the meteorological parameters in the vertical direction is carried out prior to the ray-tracing to establish also a high vertical resolution besides the originally already high horizontal resolution. The temperature is linearly interpolated, and the total pressure and the water vapor pressure are logarithmically interpolated as described by Nafisi et al. (2012a), [3].

Above the ECMWF-supported pressure levels, a model of a standard atmosphere is used to extend the data up to 84 km.

RADIATE is currently capable of three different 2D ray-tracing approaches, forcing the ray to stay within a vertical plane of constant azimuth:

1. <u>Piecewise-linear method:</u>
   A fast, but less sophisticated approach. This method will be further referred to as RADIATE pwl.

2. <u>Refined piecewise-linear method:</u>
   A kind of improved version of the piecewise-linear approach designed for ray-tracing with lower vertical resolution. The refractivities along the signal path are determined in a refined way. This method will be further referred to as RADIATE ref. pwl.

3. <u>Thayer method:</u>
   A more sophisticated approach since curved ray-traces are introduced for enhanced reconstruction of the true signal path. This method will be further referred to as RADIATE Thayer.

For detailed information on the ray-tracing methods 2 and 3 please refer to the paper of Hobiger et al. (2008), [2].

In order to estimate the slant delays at the actual VLBI observation time, linear interpolation between the delays calculated at the two sequent epochs of meteorological data directly surrounding the observation is done.

3.2 Future Goals for RADIATE VLBI

It is planned to additionally set up a 3D ray-tracing approach, where the ray paths are not limited to a certain azimuthally fixed vertical plane.

Furthermore, ray-tracing for (near) real-time applications of geodetic VLBI such as the IVS Intensive sessions is planned to be realized within the project (Böhm (2012), [1]).

The program code will be converted from MATLAB® to FORTRAN or C.

4 Comparison of Different Ray-tracers

In order to verify the RADIATE ray-tracer and its results from the different ray-tracing approaches, we have carried out a comparison of the determined zenith and slant delays to results of a past comparison campaign, described in Nafisi et al. (2012b), [4], where ray-tracers of five institutions took part. Table 1 gives a brief overview of the ray-tracing packages from the institutions that were part of the past comparison campaign.

4.1 Data for the Comparison

For comparing the RADIATE results, ray-tracing has been done using the same data sets (numerical weather models and geoid undulations) as for most of the participants in the past comparison campaign. This means that ray-tracing has been carried out for the stations Tsukuba (Tsukub32) at 12 August 2008, 0 UTC and Wettzell at 1 January 2008, 0 UTC using regional ECMWF numerical weather models with a horizontal extent of 20° x 20° and a resolution of 0.1° x 0.1° containing 25 pressure levels. Slant delays have been determined for a fixed elevation of 5° at full azimuthal coverage using a step width of 2°. Since the artificial observations are set exactly to the epochs of the numerical weather models, no time interpolation of the calculated delays has been necessary in order to match the observation times (Nafisi et al. (2012b), [4]).

There is one important difference in the input data used by the ray-tracers GFZ and Horizon concerning the utilized numerical weather model. Those two ray-tracers used the ECMWF-native model level data containing 91 model levels, whereas all other ray-tracers used the ECMWF-pressure level data containing 25 pressure levels (Nafisi et al. (2012b), [4]).

Please refer to Nafisi et al. (2012b), [4] for more details on the data sets and calculation settings used in the past comparison campaign.

4.2 Results

Looking only at the different RADIATE results for the zenith total delays (ZTD), shown as a difference plot to the RADIATE pwl results for the stations Tsukuba and Wettzell in Figure 1, it can be seen that all three different ray-tracing approaches yield the same results. This is because the three different ray path determination approaches do not influence the zenith delays, and therefore differences should only occur in the slant delays.

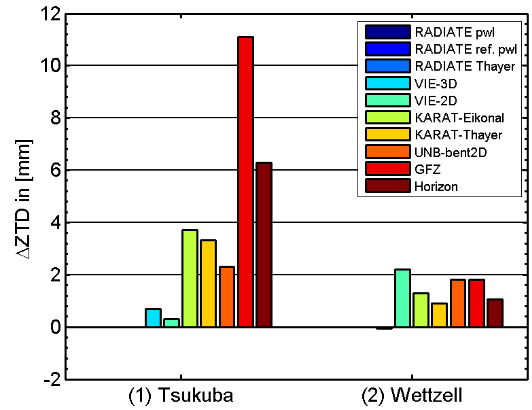

Fig. 1 Differences in zenith total delay (ZTD) [ZTD from a specific ray tracer minus ZTD from RADIATE pwl]. The reference ZTD taken from RADIATE pwl has the following absolute values: (1) Tsukuba: 2.5716 m, (2) Wettzell: 2.2057 m. Please refer to the Web version of the Proceedings to see the original color-coded version of this figure.

Compared to the other ray-tracers, the agreement of the zenith total delay is quite good for the station Wettzell (see right part of Figure 1) with differences up to a maximum of about 2 mm. Looking at the results for the station Tsukuba (see left part of Figure 1), increased differences can be seen. As stated earlier, GFZ and Horizon used a different numerical weather model for their calculations, which obviously results in significant differences in the determined zenith total delay. This is mainly because of the wet part of the zenith delay, as the different numerical weather model apparently shows the largest difference in this part. Also the other ray-tracers have slightly increased differences to the RADIATE zenith delays of up to 4 mm, but most of them are still on a quite low level, yielding a fine agreement.

For some ray-tracers also the zenith hydrostatic delays determined from the equation by Saastamoinen (1972), [5] are presented in Nafisi et al. (2012b), [4]. Compared to the RADIATE results (see Figure 2), we

Table 1 Ray-tracing packages of the five institutions that participated in the past comparison campaign described by Nafisi et al. (2012b), [4].

Ray-tracing package	Method	Institution	Developers
GFZ	2D	GFZ (German Research Centre for Geosciences)	Florian Zus and Jens Wickert
Horizon	Eikonal (2D)	GRGS (Groupe de Recherche de Géodésie Spatiale)	Pascal Gegout
KARAT	Thayer (2D) and Eikonal (3D)	NICT (National Institute of Information and Communications Technology)	Thomas Hobiger and Ryuichi Ichikawa
UNB-bent	2D and 3D	UNB (University of New Brunswick)	Landon Urquhart, Marcelo Santos, Felipe Nievinski
VIE	2D and 3D	Vienna University of Technology	Vahab Nafisi, Johannes Böhm, Dudy D. Wijaya

can again see a good agreement of the RADIATE solutions with the other ray-tracers. Once more the difference to the GFZ ray-tracer is significantly larger, probably again due to the different numerical weather model from which the total pressure at the surface has been retrieved, which is needed for calculating the zenith hydrostatic delay when using the equation by Saastamoinen (1972), [5]. The differences of the RADIATE results to the other ray-tracers are mainly around 0.1 mm at both stations Tsukuba and Wettzell, if the GFZ solution is neglected.

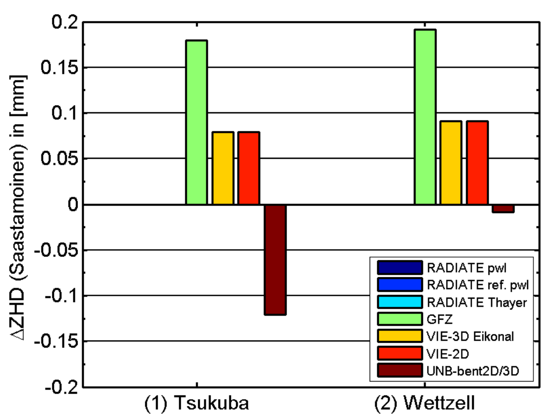

Fig. 2 Differences in zenith hydrostatic delay determined from the equation by Saastamoinen (1972), [5] [ZHD (Saastamoinen) from a specific ray tracer minus ZHD (Saastamoinen) from RADIATE pwl]. The reference ZHD (Saastamoinen) taken from RADIATE pwl has the following absolute values: (1) Tsukuba: 2.2948 m, (2) Wettzell: 2.1662 m. Please refer to the Web version of the Proceedings to see the original color-coded version of this figure.

If we look at the slant total delays (STD) for the station Tsukuba in Figure 3, it is again obvious that the RADIATE results agree quite well with the other ray-tracers except for GFZ and Horizon due to the previously described reason. Especially when just the trends of the slant total delays are taken into account, the RADIATE results match with the other ray-tracers, if the results of GFZ and Horizon are not considered. The RADIATE pwl approach agrees with the other ray-tracers with mean differences below 4 cm and standard deviations of the differences below 0.6 cm.

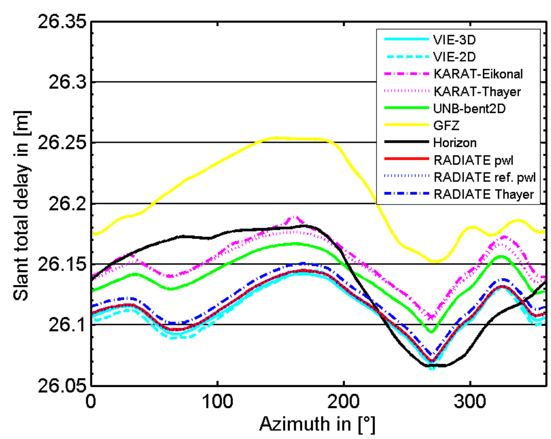

Fig. 3 Slant total delays calculated by different ray-tracers for Tsukuba (Tsukub32) at 5° elevation for 12 August 2008, 0 UTC. Please refer to the Web version of the Proceedings to see the original color-coded version of this figure.

Also for the station Wettzell, the RADIATE ray-tracing approaches deliver slant total delays fitting very well, as RADIATE pwl has mean differences below 2.5 cm and standard deviations of the differences below 1 cm, if the GFZ and Horizon solutions are not considered.

Due to the usage of a high vertical resolution after the interpolation of the original ECMWF numerical weather model, the results of RADIATE pwl and RADIATE ref. pwl are almost the same, as the refined approach only has an advantage if reduced vertical resolution is used.

In the case of the slant total delays (STD) calculated from the total mapping factors (TMF) of the different ray-tracers using the zenith total delay (ZTD) from RADIATE pwl (see Equation 1), the agreement between the RADIATE results and the other ray-tracers is even better for station Tsukuba (see Figure 4), with mean differences of below 1 cm and standard deviations of the differences below 0.6 cm, not considering the results of GFZ and Horizon.

$$STD = TMF * ZTD \tag{1}$$

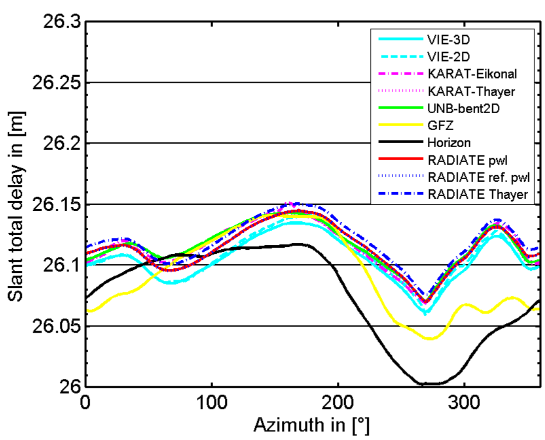

Fig. 4 Slant total delays (STD) calculated from the total mapping factors (TMF) of different ray-tracers for Tsukuba (Tsukub32) at 5° elevation for 12 August 2008, 0 UTC. The STD is calculated with the TMF of the different ray-tracers and the zenith total delay (ZTD) of RADIATE pwl (2.5716 m). Please refer to the Web version of the Proceedings to see the original color-coded version of this figure.

The general agreement of the slant total delays calculated from the total mapping factors for the station Wettzell stays the same compared to the directly computed slant total delays, yielding for the RADIATE pwl approach mean differences below 2.5 cm and standard deviations of the differences below 1 cm, again not taking the results of GFZ and Horizon into account.

5 Conclusions

The comparison showed a good overall agreement of the RADIATE results with the other ray-tracers. Especially with respect to the slant total delays calculated from the total mapping factors for both stations Tsukuba and Wettzell, our results have a fine conformity with all other ray-tracers where direct comparison is possible through the use of the same numerical weather model.

Further investigation into the zenith total delay differences, particularly for the station Tsukuba, may reveal some starting points for quality enhancement of the RADIATE ray-tracer.

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