Atmospheric Delay Reduction Using KARAT for GPS Analysis and Implications for VLBI

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Abstract

We have been developing a state-of-art tool to estimate the atmospheric path delays by ray-tracing through meso-scale analysis (MANAL data) data, which is operationally used for numerical weather prediction by Japan Meteorological Agency (JMA). The tools, which we have named 'KAshima RAytracing Tools (KARAT)', are capable of calculating total slant delays and ray-bending angles considering real atmospheric phenomena. The KARAT can estimate atmospheric slant delays by an analytical 2-D ray-propagation model by Thayer and a 3-D Eikonal solver. We compared PPP solutions using KARAT with that using the Global Mapping Function (GMF) and Vienna Mapping Function 1 (VMF1) for GPS sites of the GEONET (GPS Earth Observation Network System) operated by Geographical Survey Institute (GSI). In our comparison 57 stations of GEONET during the year of 2008 were processed. The KARAT solutions are slightly better than the solutions using VMF1 and GMF with linear gradient model for horizontal and height positions. Our results imply that KARAT is a useful tool for an efficient reduction of atmospheric path delays in radio based space geodetic techniques such as GNSS and VLBI.

1. Introduction

Radio signal delays associated with the neutral atmosphere are one of the major error sources of space geodesy such as GPS, GLONASS, GALILEO, VLBI, In-SAR measurements. The recent geodetic analyses are carried out by applying the modern mapping functions based on the numerical weather analysis fields with horizontal gradient model for the purpose of a better modeling of these propagation delays, thereby improving the repeatability of site coordinates. The Global Mapping Function (GMF)[3], and Vienna Mapping Function 1 (VMF1)[2, 4] have been successfully applied to model the zenith hydrostatic delay in the recent years. In addition, the lateral spatial variation of wet delay is reduced by linear gradient estimation[9, 5]. The anisotropic mapping function is also a powerful tool for removing or calibrating the effects of horizontal variability of atmosphere within GNSS and VLBI analyses. Atmospheric gradients are assumed to have a simple linear form which can be modeled by the anisotropic mapping function. However, it has been suggested that this assumption is not always appropriate in the context of intense mesoscale phenomena such as the passage of a cold front, heavy rainfall, or severe storms. Based on prior work by Ichikawa et al.[8], we have developed a state-of-art tool to obtain atmospheric slant path delays by ray-tracing through the meso-scale analysis data from numerical weather prediction with 10 km horizontal resolution provided by the Japan Meteorological Agency (JMA)[6, 7]. The tool, which we have named 'KAshima RAytracing Tools (KARAT)', is capable of calculating total slant delays and ray-bending angles considering real atmospheric phenomena. Hobiger et al. preliminarily compared precise point positioning (PPP) estimates using KARAT with that using the GMF based on GPS data of GEONET operated by Geographical Survey Institute (GSI)[6]. Under the various atmospheric conditions the results imply that the performance of KARAT is almost equal to the solution which is obtained by applying the GMF with gradients. In our study, we have compared PPP processed position solutions using KARAT with those using state-of-the-art mapping functions in order to evaluate the present KARAT potential for longer time periods. In our comparison 57 stations of GEONET data during the year 2008 were processed.

2. KARAT

The KARAT have been developed at the National Institute of Information and Communications Technology (NICT), Japan and are capable of calculating total slant delays and ray-bending angles.

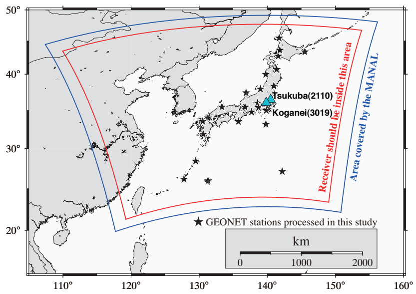

Figure 1. The GEONET stations processed in this study. The boundary of JMA meso-scale analysis (MANAL) data is also shown. The two triangles denote the location of Tsukuba and Koganei GEONET stations, respectively (see Figure 2)

The JMA meso-scale analysis data (which will be called "JMA MANAL data" hereafter) which we used in our study provides temperature, humidity, and pressure values at the surface and at 21 height levels (which vary between several tens of meters and about 31 km), for each node in a 10km by 10 km grid that covers Japan islands, the surrounding ocean and East Asia[13]. The 3-hourly operational products are available from JMA since March, 2006. A linear time interpolation is implemented in KARAT to obtain results at arbitrary epochs which allows also to evaluate temporal changes of estimates. Further details of KARAT are described in Hobiger et al.[6, 7].

KARAT can estimate atmospheric slant delays by three different calculation schemes. These are (1) a piece-wise linear propagation, (2) an analytical 2-D ray-propagation model by Thayer[16], and (3) a 3-D Eikonal solver [7].

Though the third scheme can include small scale variability of atmosphere in horizontal, it has a significant disadvantage due to the massive computational load. In this paper we discuss estimations using the second and the third schemes since we would like to focus on the both sophisticated methods.

3. Precise Point Positioning Results for GEONET Stations

In order to compare KARAT processing and modern mapping functions we analyzed data sets of GEONET, which is a nationwide GPS network operated by GSI. In our comparison 57 stations from GEONET of the year 2008 were considered for processing. We chose the stations which were not affected by crustal deformations caused by seismic activities. Figure 1 shows the locations of the selected stations in our study. Since these stations are distributed over the whole Japan islands evenly, we can investigate effects of various weather conditions on the processing. In addition, we can avoid uncertainties due to the individual difference of equipments in term of the same type of antenna-receiver set in GEONET.

At first, precise point positioning (PPP) estimates covering the whole period shown above were obtained for all sites using GPSTOOLS[15]. The troposphere delays have been modeled by dry (using the Saastamoinen model[14]) and wet constituents.

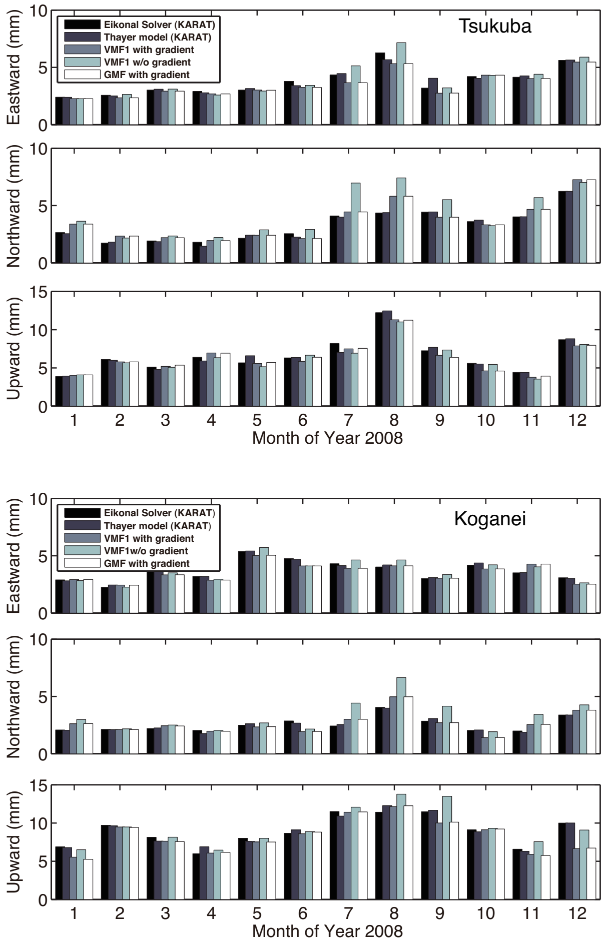

Figure 2. Monthly averaged repeatabilities of station positions at Tsukuba (upper) and Koganei (lower) during year of 2008.

The latter one was estimated as unknown parameters using the GMF and VMF1 together with linear gradients[5]. Process noise values of zenith delays and linear gradients were set to 0.1 mm and 0.01 mm, respectively. The elevation cutoff angle was set to 10° and down-weighting at lower elevation angles was applied. The ocean loading correction based on NAO.99b model was applied[10] and no atmospheric loading was applied. The a-priori hydrostatic zenith delays were computed from the Saastamoinen model[14] based on standard atmosphere values with station height correction.

The Kalman-filter estimation interval was set to 300 s, without overlapping data from consecutive days. The daily position estimates from these solutions act a reference to which the ray-traced solutions can be compared. In our comparison, PPP estimations using the GMF and VMF1 without linear gradient were also performed.

In order to examine the position error magnitude the monthly averaged daily repetabilities for each coordinate component at both stations are displayed in Figure 2. We determined repeatability as the standard deviation of the position solutions with respect to a linear regression.

In this figure five cases of solutions (i.e. KARAT solution using Eikonal solver, KARAT solution using the Thayer model, VMF1 solution with gradient, VMF1 solution without gradient, GMF with gradient) are shown. The results of VMF1 without gradient reveal the largest repeatability value for all components at both stations during the summer season (July, August, and September), as one would expect.

Tsukuba and Koganei have undergone severe heavy rainfall event during August 26-31, 2008. Especially, the total rainfall around Tsukuba was about 300 mm during these 6 days. The north-south position errors were caused by steep water vapor gradient associated with an EW rain band which lies around both stations. Such large position errors are partly reduced using the modern mapping functions with gradient model as shown in Figure 2.

On the other hand, the results of KARAT solutions (both the Eikonal solver and the Thayer model) are much better for the north-south component at the both station during the July and

August. These suggest that the both KARAT solutions are quite competitive to the modern mapping functions with gradient model. Figure 3. shows the averaged repeatabilities for all 57 stations. In this figure the results for each coordinate component for all six solutions (i.e. Eikonal solver, Thayer model, VMF1 with gradient, VMF1 without gradient, GMF with gradient, and GMF without gradient) are represented.

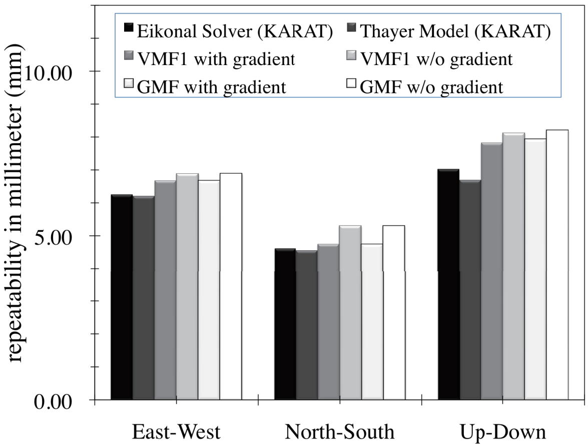

Figure 3. Averaged repeatability of station position during year of 2008 for 57 GEONET stations shown in Figure 1

It indicates that both KARAT solutions are slightly better than the modern mapping functions with gradient solution. However, there are no significant differences between the Eikonal solver and the Thayer model.

One has to consider that the time-resolution of the JMA 10km MANAL data is three hours, whereas the PPP processing including gradient estimation was performed for 300 seconds interval. Under the extreme atmospheric condition such as a severe rainfall event the three hour time spacing and the 10 km horizontal resolution of the JMA MANAL data may not be always sufficiently accurate to reduce atmospheric path delay effects.

4. Summary

We have assessed the performance of ray-traced atmospheric delay correction by comparison between the precise point positioning (PPP) solutions using the ray-tracing tool 'KARAT' through the JMA MANAL data with those using the modern mapping functions based on numerical weather models. In our comparison 57 stations of GEONET during the year of 2008 were processed. The KARAT solutions are slightly better than the solutions using VMF1 and GMF with a linear gradient model for both horizontal and height positions. On the other hand, there were no significant differences between the two KARAT solutions, i.e. Eikonal solver and Thayer model. We need further investigations to evaluate the capability of KARAT to reduce atmospheric path delays under various topographic and meteorological regimes. One advantage of KARAT is that the reduction of atmospheric path delay will become more accurate each time the numerical weather model are improved (i.e. time and spatial resolution, including new observation data). In spite of the present model imperfectness and coarse time resolution, we think that KARAT will help to support station position determination by improving the numerical stability due to a reduction of unknown parameters.

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