

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

Ryuichi Ichikawa ², Thomas Hobiger ¹, Yasuhiro Koyama ¹, Tetsuro Kondo ²

¹⁾ *Kashima Space Research Center, National Institute of Information and Communications Technology*

²⁾ *National Institute of Information and Communications Technology*

Contact author: *Ryuichi Ichikawa*, e-mail: `richi@nict.go.jp`

Abstract

We have been developing a state-of-the-art tool to estimate the atmospheric path delays by ray-tracing through mesoscale analysis (MANAL) data, which is operationally used for numerical weather prediction by the 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, and In-SAR measurements. The recent geodetic analyses were carried out by applying modern mapping functions based on the numerical weather analysis fields with horizontal gradient model with the purpose of better modeling 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 recent years. In addition, the lateral spatial variation of the 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 the 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-the-art tool to obtain atmospheric slant path delays by ray-tracing through the mesoscale analysis (MANAL) 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 those

using the GMF based on GPS data from 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 we processed 57 stations of GEONET data during the year 2008.

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.

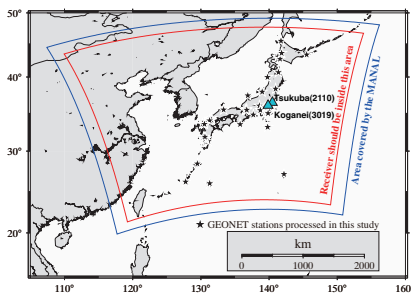


Figure 1. The GEONET stations processed in this study. The boundary of JMA mesoscale analysis data is also shown. The two triangles denote the location of Tsukuba and Koganei GEONET stations, respectively (see Figure 2).

The JMA mesoscale 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 from several tens of meters to about 31 km), for each node in a 10 km by 10 km grid that covers the Japanese islands, the surrounding ocean, and East Asia [13]. The 3-hourly operational products have been 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].

Although the third scheme can include small scale variability of atmosphere in the 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 two more 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 evenly distributed over the Japanese islands, we can investigate effects of various weather conditions on the processing. In addition, we can avoid uncertainties due to the individual difference of equipment in terms 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 were modeled by dry (using the Saastamoinen model [14]) and wet constituents.

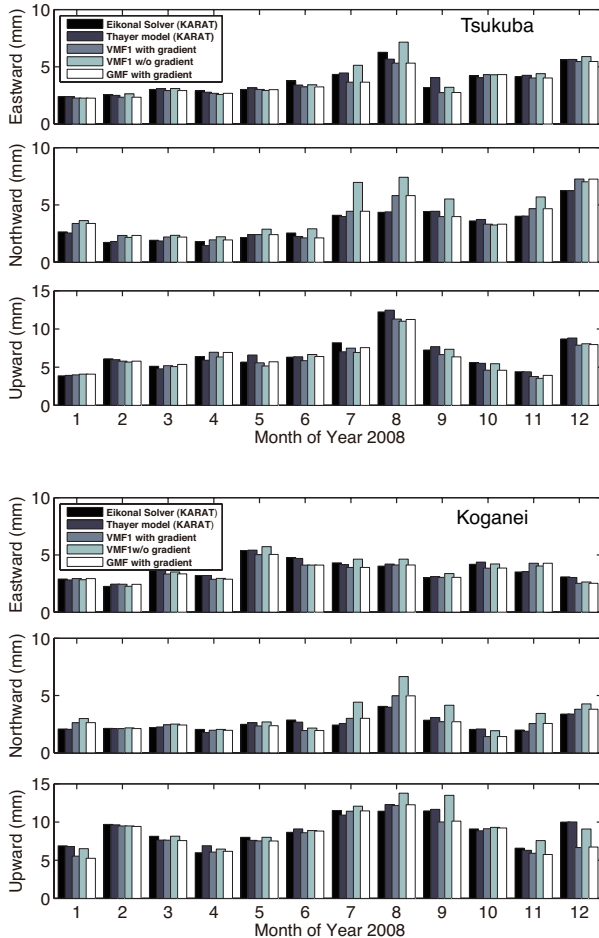


Figure 2. Monthly averaged repeatabilities of station positions at Tsukuba (upper) and Koganei (lower) during 2008.

In this figure five cases of solutions are shown: KARAT solution using Eikonal solver, KARAT solution using the Thayer model, VMF1 solution with gradient, VMF1 solution without gradient, and GMF with gradient. 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 experienced severe heavy rainfall events during August 26–31, 2008. Especially, the total rainfall around Tsukuba was about 300 mm during these six days. The north-south position errors were caused by steep water vapor gradients associated with an EW rain band at 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 the KARAT solutions (both the Eikonal solver and the Thayer model) are much better for the north-south component at both stations during July and

The wet delay 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 downweighting at lower elevation angles was applied. The ocean loading correction based on the 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 the 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 serve as a reference to which the ray-traced solutions can be compared. In our comparison, PPP estimations using the GMF and VMF1 without linear gradients were also performed.

In order to examine the position error magnitude, the monthly averaged daily repeatabilities 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.

August. This suggests that both KARAT solutions are quite competitive with 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.

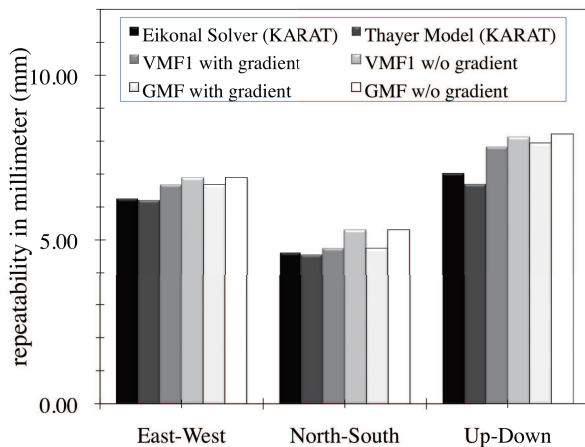


Figure 3. Averaged station position repeatability for 57 GEONET stations shown in Figure 1 for the year 2008.

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 10 km MANAL data is three hours, whereas the PPP processing including gradient estimation was performed with a 300-second interval. Under extreme atmospheric conditions 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 corrections by comparison between precise point positioning (PPP) solutions using the ray-tracing tool KARAT using JMA MANAL data with those using the modern mapping functions based on numerical weather models. In our comparison 57 stations of GEONET during 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 ability 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 is improved (i.e., time and spatial resolution, including new observation data). In spite of the present model imperfection 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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