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Tropospheric Delay Correction in L1-SAIF Augmentation

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ABSTRACT

L1-SAIF (L1 Submeter-class Augmentation with Integrity Function) signal is one of the navigation signals of QZSS (Quasi-Zenith Satellite System), which provides augmentation function for mobile users in Japan. This paper presents the detail of the tropospheric delay correction in L1-SAIF augmentation. L1-SAIF augmentation aims to achieve sub-meter class accuracy and to provide integrity information of the GPS positioning. The structure of L1-SAIF signal is defined to have full compatibility to the SBAS (Satellite Based Augmentation System) L1 signal, and there are some additional messages supporting more sophisticated ionospheric and tropospheric delay corrections in order to improve correction accuracy. Especially, the tropospheric delay correction via satellites is first attempted in L1-SAIF signal. The tropospheric delay correction information is generated at the ground station using the data collected at GEONET (GPS Earth Observation NETwork) stations. The correction message contains the information of the zenith tropospheric delay (ZTD) values at 105 Tropospheric Grid Points (TGP) in the service area. From this message a mobile user can acquire the ZTD value at some neighboring TGPs, and estimate the local ZTD value accurately by using a suitable ZTD model. Only 3 L1-SAIF messages are necessary to provide all of the tropospheric correction information. Several investigations using the actual data observed at many GEONET stations overall Japan have proved that it is possible to achieve the correction accuracy of 13.2mm RMS. The presented correction strategy is actually planned to be implemented in the augmentation system using L1-SAIF signal after strict examinations using long-term data.

KEYWORDS: QZSS, GNSS, Augmentation System, Tropospheric Delay

1. INTRODUCTION

Quasi-Zenith Satellite System (QZSS) is a Japanese satellite navigation system which enhances the availability, accuracy and reliability of GPS signals for users in the region of Japan. Electronic Navigation Research Institute (ENRI) is carrying out the research and development of an augmentation system using QZSS to improve the positioning accuracy and its reliability by an augmentation message named L1-SAIF (L1 Sub-meter class Augmentation with Integrity Function) (Ito *at al.*, 2005). The service area of L1-SAIF is shown in Figure 1. In this augmentation it is aimed to achieve the positioning accuracy of 1m RMS of mobile users. A simulation system has proved the feasibility to achieve the aimed accuracy by introducing a more sophisticated ionospheric delay correction in addition to SBAS (Satellite Based Augmentation System) (Sakai *et al.*, 2006 and 2007), where the error sources, such as ephemeris and clock of GPS satellites, ionospheric delay, and tropospheric delay, have almost the same magnitude. Therefore, it is also expected that it is possible to achieve the more accurate positioning by introducing the tropospheric delay correction.

Some preliminary studies have shown the feasibility to achieve the more accurate correction by introducing the tropospheric delay correction. In these studies, the correction information are generated from the data of the numerical weather prediction (Takeichi et al., 2006) and GPS network analysis (Takeichi et al., 2007), and only 2 or 3 SBAS-type messages are necessary to provide the whole correction information of the L1-SAIF service area. Moreover, it is clarified that these correction method is able to achieve the more accurate correction than that by the tropospheric delay model used in SBAS. This paper presents the tropospheric delay correction strategy in L1-SAIF augmentation developed based on these previous results. The characteristics and the correction concept of the tropospheric delay are briefly introduced, and the detail of the correction information generation and its application to the positioning correction are presented. In all of the evaluation in this paper, the zenith tropospheric delay (ZTD) result of the GPS network analyses using Bernese (AIUB, 2007) are used, where the final ephemeris provided by IGS and the GPS observation data corrected at the GEONET (GPS Earth Observation NETwork) stations (Miyazaki *et al.*, 1998) during the whole year of 2002 are used. There are more than 1200 GEONET stations spread all over the land of Japan as shown in Figure 1, and the ZTD values at about 900 stations are available from the analyses. The accuracy of the ZTD result is estimated better than 10mm RMS.

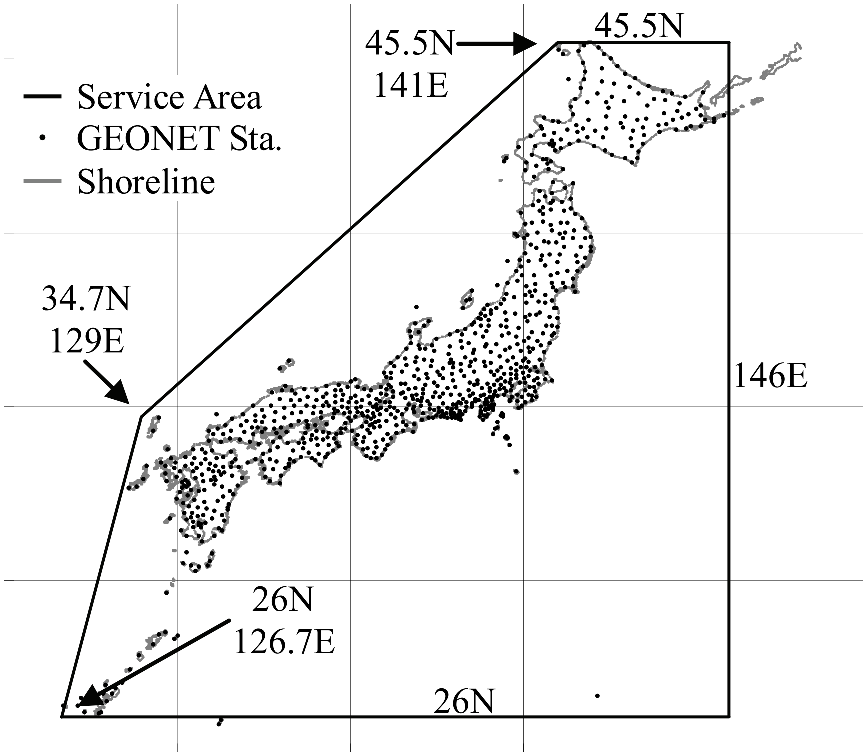

Figure 1. Service Area of L1-SAIF and GEONET Stations

2. OUTLINE OF TROPOSPHERIC DELAY CORRECTION

2.1 Tropospheric Delay

The tropospheric delay is a delay of a GPS signal which occurs in the troposphere. It is generally represented by the ZTD because it is possible to obtain the common delay by multiplying the ZTD by a mapping function (Figure 2). The mapping function is the ratio of the tropospheric delay and ZTD, which is determined only by the elevation of the GPS satellites. For example, the following mapping function $m(El)$ is used in SBAS (RTCA, 2001).

$$m(El) = \frac{1.001}{\sqrt{0.002001 + \sin^2(El)}} \tag{1}$$

where El is the elevation of the GPS satellite. A user can correct the tropospheric delay in all of the receiving signals by the local ZTD. Therefore, a user requires only the local ZTD value, and the correction information should consist of some information to provide it.

The ZTD of a GPS signal is around 2.5m on average (Spilker Jr., 1996). In SBAS the ZTD estimation is carried out using a ZTD model defined in RTCA (2001), which has the accuracy of 74mm RMS in the region of Japan (Takeichi *et al.*, 2006 and 2007). The tropospheric delay in the pseudorange of a lower-elevation satellite becomes longer, and the positioning error becomes about 3 times of the ZTD estimation error on average and larger than some ten times at most (Takeichi *et al.*, 2006 and 2007). Because the tropospheric delay changes very frequently due to the variations of the weather and geographical conditions, the correction information must be detailed both in time and space to realize an accurate ZTD estimation.

2.2 Concept of Tropospheric Delay Correction in L1-SAIF

To enable the tropospheric delay correction of the mobile user, the real-time correction information must always be available at an arbitrary point in the service area. According to the previous study (Takeichi *et al.*, 2007), it is possible to apply the result of the GPS data analyses to generate the tropospheric delay correction message in SBAS and to achieve the correction accuracy better than SBAS tropospheric delay model. Therefore, the tropospheric delay correction in L1-SAIF augmentation is expected to be successfully realized by following this strategy. The basic concept is designed as follows:

(1) The real-time analysis of the ZTDs at 200 GEONET stations through the precise point positioning (Iwabuchi *et al.*, 2006) is carried out at ENRI ground station. The accuracy of this analysis is expected to be around 5mm RMS.

(2) The correction information at about 100 imaginary points in the service area is generated from the analysis result, and the correction message is transmitted to users through QZS (Figure 3 and 4).

(3) A user acquires the correction message through QZSS, and estimate the local ZTD from the correction information to apply the positioning correction (Figure 4).

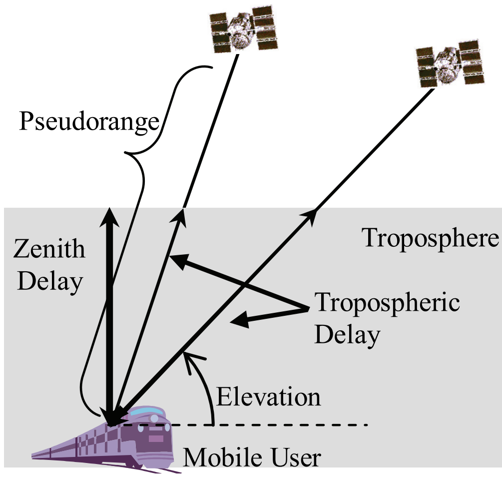

Figure 2. Tropospheric Delay Estimation from ZTD

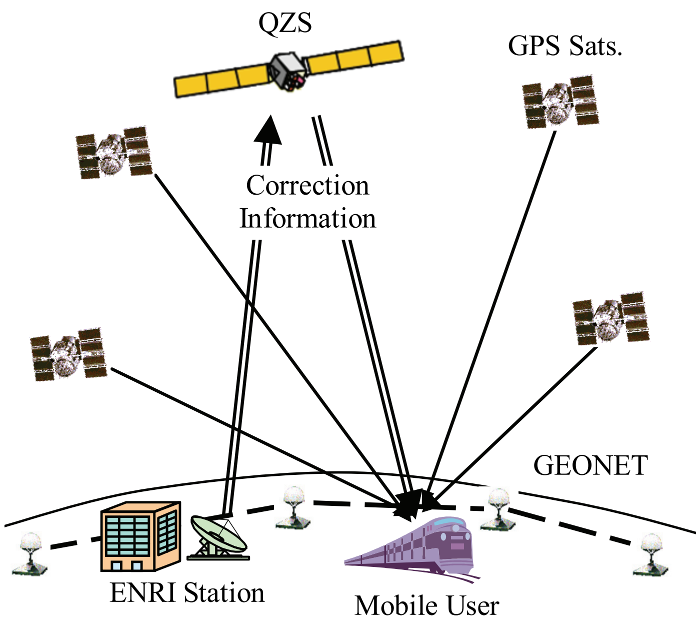

Figure 3. Generation & Transmission of L1-SAIF Message

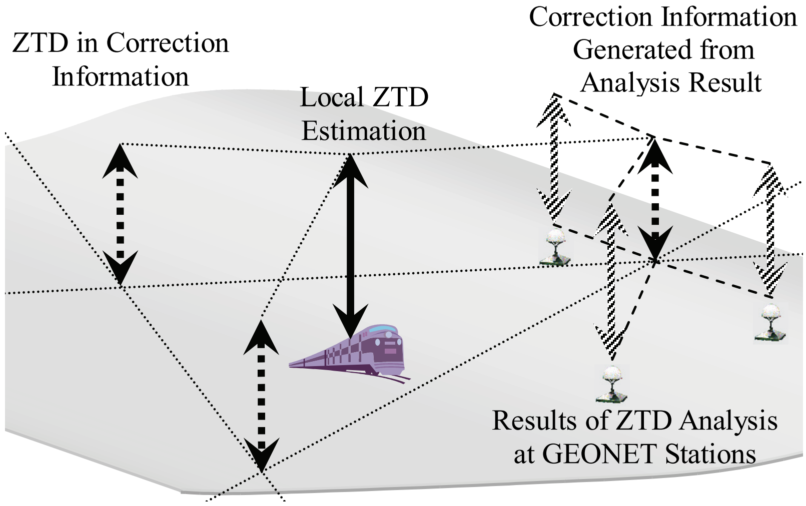

Figure 4. Generation of Correction Information and Estimation of Local ZTD

3. GENERATION OF CORRECTION INFORMATION

3.1 Design of Correction Message

The format of L1-SAIF message is defined to follow that of SBAS, which has 212 bits for the augmentation data and 250 bits in total (RTCA, 2001). L1-SAIF message is transmitted every one second including one of the augmentation messages, and the tropospheric delay correction message is planned to be transmitted about once a minute.

According to the previous studies, a set of 6 bits data is sufficient for the correction information of one point to avoid large accuracy degradation, and the correction information at about 100 points are required to fully cover the L1-SAIF service area. Therefore, a tropospheric delay correction message is determined to have the correction information of 35 points and the rest 2 bits for the message identification. It is also determined that the correction information of 105 points is transmitted by 3 messages. The format of the tropospheric delay correction message is shown in Figure 5.

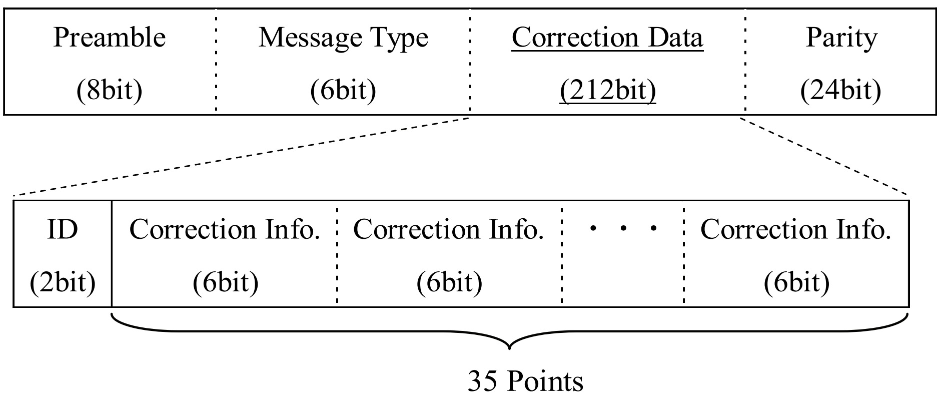

Figure 5. Design of Tropospheric Daly Correction Message

3.2 Tropospheric Grid Point

There is no sufficient capacity to include the information about the location of the points of the correction information. Furthermore, because the removal, transfer and addition of GEONET stations are continuously carried out, it is unsuitable to choose the GEONET stations as the points of the correction information. Therefore, in advance of the beginning of the L1-SAIF operation, the locations of 105 points should be determined in the service area, and all users also should originally have the full of the location information.

The points of the correction information are located on the land of the service area so that the points form regular triangles, and apexes on the sea are moved toward the shoreline. In addition, some points are added around the large cities. Because the points of the correction information are basically located on triangular grid points, these imaginary points are named TGP (Tropospheric Grid Point). In this TGP arrangement, the distance between an arbitrary location in the service area and its nearest TGP is smaller than 70km, and the average distance between GEONET stations and the nearest TGP is 23.8km. By assigning 105 TGPs equally to 3 correction messages, a user can acquire available correction information at a distance of 50km on average and 200km at most even when only one message is available. All TGPs and their assignment to 3 messages are depicted in Figure 6. The distributions of the distance between GEONET stations and the nearest TGP in both cases where a user receives 3 and 1 message(s) are shown in Figure 7.

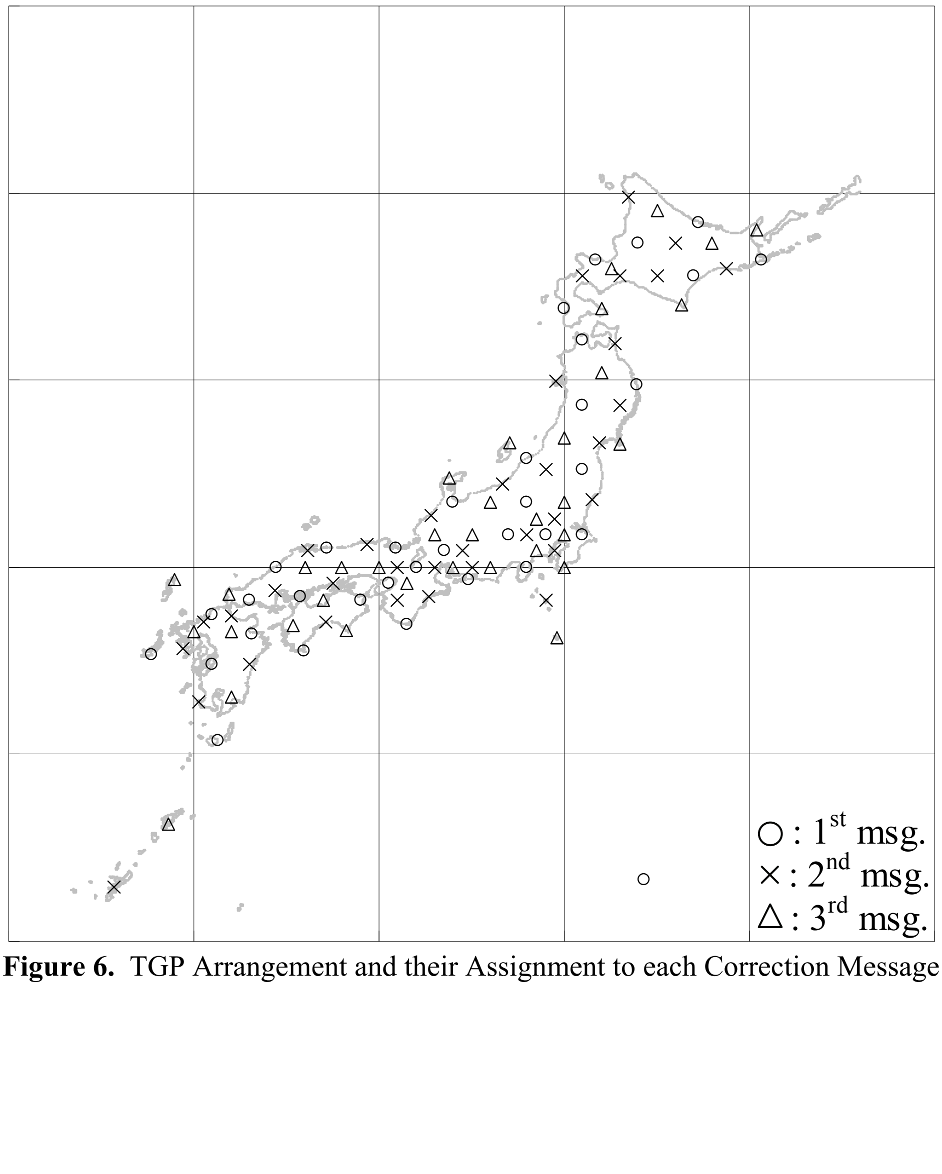

Figure 6. TGP Arrangement and their Assignment to each Correction Message

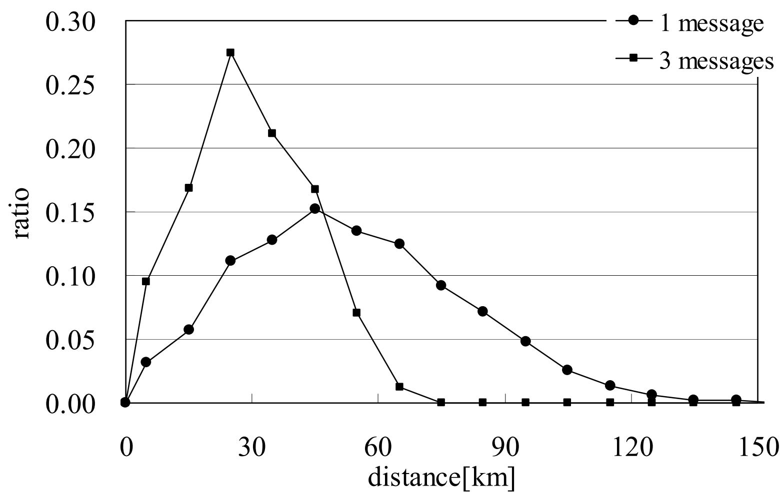

Figure 7. Distribution of Distance between GEONET Stations and Neighboring TGP

3.3 Generation of Correction Information

3.3.1 ZTD estimation at TGP

As the locations of the TGPs are different from those of GEONET stations, the ZTDs at the TGPs must be accurately estimated from the analyses result of the ZTDs at GEONET stations. As mentioned above, the ZTD is strongly affected by the meteorological and geographical conditions. Therefore, it is expected that the behavior of the ZTDs of 2 different points are almost same as long as these points are in almost the same meteorological condition, and it is also expected that the difference of the ZTDs is determined almost by the difference of the geographical conditions. Although a ZTD model, such as SBAS model, cannot express the rapid changes of a ZTD due to the changes of meteorological conditions, it is expected to accurately express the changes due to the variation of geographical conditions. Therefore, it is also expected that the ZTD difference between two points is accurately expressed as a difference of values of some appropriate ZTD model, as long as these points are in almost the same meteorological conditions. This strategy is expected to enable the accurate estimation of the ZTD at a different point. As the accuracy of this estimation naturally depends on the accuracy of the ZTD model, a ZTD model suitable for L1-SAIF service area is newly developed.

3.3.2 ZTD model

The ZTD model used in SBAS is developed to agree with the average behavior of the ZTD on the whole earth, and it does not always express properly the ZTD around the region of Japan. Therefore, a ZTD model is newly formulated so that it properly expresses the meteorological characteristics around Japan. In the following, this ZTD model is named “ENRI model.”

To set up ENRI model the result of the ZTD analyses are applied, and the average behavior is characterized by season, latitude, and the height above sea level. As a result, it is found that the ZTD variations due to latitude hardly depend on season or height above sea level and those due to height above sea level hardly depend on latitude. Finally, ENRI model is obtained as follows:

$$ZTD_{average} = 2454.9 + 96.8\sin\left(\frac{2\pi}{365.25}(doy - 119.1)\right) + 27.9\sin\left(\frac{4\pi}{365.25}(doy + 10.8)\right) \quad (2)$$

$$ZTD_{latitude} = -6.48\phi + 235.9 \quad (3)$$

$$ZTD_{height} = H \times \left(-0.309 + 0.0227\sin\left(\frac{2\pi}{365.25}(doy + 62.7)\right) - 0.0071\sin\left(\frac{4\pi}{365.25}(doy + 12.6)\right)\right) \quad (4)$$

$$ZTD_{ENRI} = ZTD_{average} + ZTD_{latitude} + ZTD_{height} \quad (5)$$

where doy is the day of year, H [m] is the height above sea level, ϕ [degree] is the latitude, and the unit of ZTD is [mm]. This function is available only in the L1-SAIF service area, where $26^o \leq \phi \leq 51^o$. In the above equation, $ZTD_{average}$, $ZTD_{latitude}$ and ZTD_{height} represent the average variations due to seasonal changes, the changes due to the latitude, and the changes due to the height above sea level, respectively.

For example, the ZTD behavior of ENRI model, SBAS model, and the result of Bernese analyses for 1 year at GEONET station 93019 (Koganei, suburb of Tokyo) are summarized in Figure 8. Although the actual ZTD behaves very frequently, its average behavior seems to be expressed by ENRI model better than SBAS model. According to the evaluation using Bernese result, the accuracy of ENRI model is 52mm RMS, which is better than 74mm RMS of SBAS model.

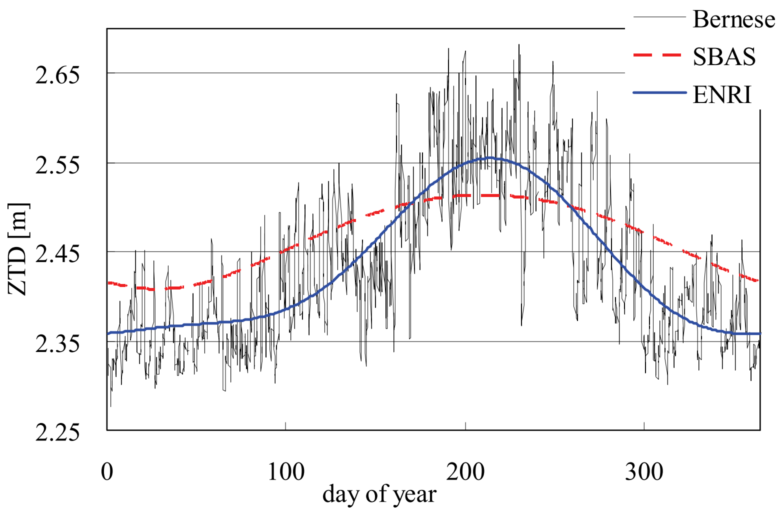

Figure 8. ZTD Behavior

3.3.3 Generation algorithm

By using ENRI model it is possible to estimate the ZTD at a TGP from the ZTD analysis result at neighboring GEONET stations. In the previous studies, it has been ascertained that the behaviors of the ZTDs of different two points within the distance below 70km are similar enough to avoid the large increase of the estimation error (Takeichi *et al.*, 2006 and 2007). Therefore, the ZTD at a TGP is estimated from the ZTDs at GEONET stations within 70km. As it is also important to properly consider the local weather condition, the ZTDs at up to 3 neighboring GEONET stations are used. When 2 or 3 GEONET stations are available within 70km, one optimum ZTD is estimated as a weighted average.

The detail of the correction of the ZTD difference and the weighed average are as follows:
1) Correction of ZTD Difference due to Height Difference

$$ZTD_{TGP} \equiv ZTD_{GEONET} + ZTD_{TGP}^{ENRI} - ZTD_{GEONET}^{ENRI} \tag{6}$$

where ZTD_{TGP} is the ZTD at the TGP to estimate, ZTD_{GEONET} is the result of the ZTD analysis at a GEONET station, ZTD_{TGP}^{ENRI} and ZTD_{GEONET}^{ENRI} are the ENRI model at the TGP and the GEONET station, respectively.
2) Weighted Average
From several investigations, the following weighing function $w_{TGP}(x)$ is formed, where x [km] is the distance between TGP and the referring GEONET station. This function means the inverse of the variance [mm^2]. Through the weighted average shown as Equation (8), the ZTD of the TGP is estimated as ZTD_{TGP}^{I}.

$$w_{TGP}(x) = 1/(0.17x + 7.8)^2 \tag{7}$$

$$ZTD_{TGP}^{I} = \frac{\sum w_{TGP}(x_n) ZTD_{TGP}^{n}}{\sum w_{TGP}(x_n)} \tag{8}$$

Finally, to minimize the data amount of the correction information, ±320mm of the difference between the estimated ZTD and ENRI model at each TGP is digitized by 6bits, and included into the correction message. The value included in the correction message $ZTD_{TGP}^{Message}$ is given as follows:

$$ZTD_{TGP}^{Message} = ZTD_{TGP}^{I} - ZTD_{TGP}^{ENRI} \tag{9}$$

It is also possible to simply obtain the same correction value $ZTD_{TGP}^{Message}$ by the following equation:

$$ZTD_{TGP}^{Message} = \frac{\sum w_{TGP}(x_n)\left(ZTD_{GEONET} - ZTD_{GEONET}^{ENRI}\right)}{\sum w_{TGP}(x_n)} \tag{10}$$

3.4 Accuracy Evaluation

To ascertain the effectiveness of the above-mentioned estimation strategy, the estimation accuracy is evaluated using the ZTD analysis result. In the evaluation a GEONET station is regarded as a TGP, and the estimated ZTD and the result of ZTD analysis are compared. As a result of the evaluation using all available GEONET stations, the accuracy of the estimated ZTD is 12.0mm RMS on average. For example, the error history at GEONET station 93019 (Koganei) is shown in Figure 9, where the monthly average and variance of the error are also shown as squares and triangles. In this case, 3 GEONET stations, 93013 (Omiya), 93016 (Adachi) and 93032 (Yokohama), are used for the estimation, which are in 29~34km from 93019. The accuracy of this case is 7.0mm RMS. In Figure 9, gradual changes of the monthly average and variance are seen. Throughout the year, the average keeps a small value in spite of the large dispersion of the error, which shows the validity of this presented estimation method. From June to September, the humidity is generally high and severe weather, such as typhoons and torrential downpour, frequently occurs in the region of Japan. These situations degrade the accuracy of ENRI model, and the variance becomes larger in this season. These characteristics are mutual to all stations.

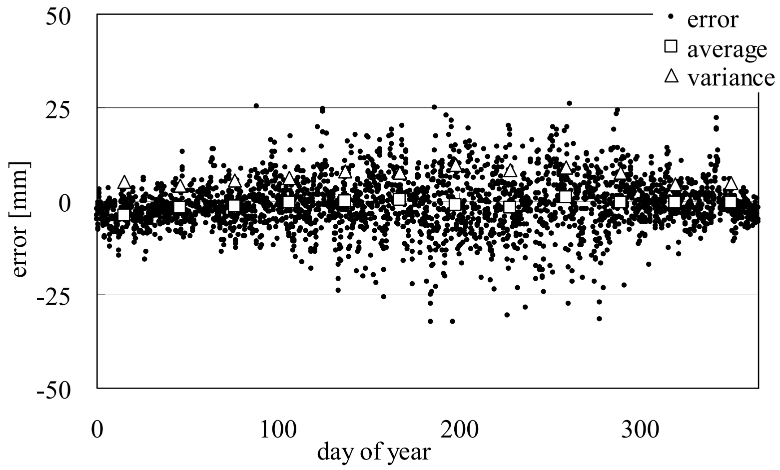

Figure 9. Behavior of Estimation Error at TGP (GEONET93019)

4. APPLICATION OF CORRECTION INFORMATION

4.1 Application Algorithm of Correction Information

A user estimates the local ZTD from the acquired correction information. In this case the user estimates the local ZTD from the correction information using ENRI model. By the TGP arrangement shown in Figure 6, a user at an arbitrary location in the service area can acquire the correction information within the distance of 70km if 3 correction messages are available. Even when only one message is available, the user can obtain the correction information at a TGP within 50km on average and 200km at most. To properly consider the local weather condition, the correction information up to 3 TGPs is applied for the estimation. The estimation strategy is basically the same as Equations (6)~(8). As the correction information originally contains the difference between the estimated ZTD and ENRI model at TGPs, a user can obtain the local ZTD as the sum of the local ENRI model and the value in the correction information. The sequence of the local ZTD estimation is summarized in Equations (11)~(13). It also provides the same local ZTD by obtaining the weighed average of the values in the correction information first, and adding it to the local ENRI model next as shown in Equation (13).

The sequence of the local ZTD estimation is as follows:
1) Correction of ZTD Difference due to Height Difference

$$ZTD_{USER} \equiv ZTD_{TGP}^{Message} + ZTD_{USER}^{ENRI} \tag{11}$$

where ZTD_{USER} and ZTD_{USER}^{ENRI} are the local ZTD to estimate and ENRI model at the user's position, respectively.
2) Weighted Average
The weighing function $w_{USER}(x)$, which has the same form as Equation (7), is available, where the parameters are changed to fit the inverse of the estimation error variance. Through the weighted average the user can finally obtain the local ZTD as ZTD_{USER}^{I}.

$$w_{USER}(x) = 1/(0.08x + 12.0)^2 \tag{12}$$

$$ZTD_{USER}^{I} = \frac{\sum w_{USER}(x_n) ZTD_{USER}^{n}}{\sum w_{USER}(x_n)} = \frac{\sum w_{USER}(x_n) ZTD_{TGP}^{Message,n}}{\sum w_{USER}(x_n)} + ZTD_{USER}^{ENRI} \tag{13}$$

4.2 Accuracy Evaluation

The accuracy of the user's local ZTD estimation is evaluated using the result of ZTD analysis, where a GEONET station is regarded as a user, and its local ZTD is estimated using the correction information at neighboring TGPs. As a result, the average estimation accuracy is 13.2mm RMS. The accuracy is slightly worse than that of the ZTD estimation at TGPs because the estimation error doubly increases. In addition, it is also confirmed that a user can obtain the local ZTD value of 23.8mm RMS accuracy even when only one correction message is available, which is still better than those realized by using SBAS model or the numerical weather mapping information. Figure 10 depicts the distributions of the estimation accuracy in both cases where a user receives 3 and 1 message(s) and the error of numerical weather mapping (NWP) and SBAS model (Takeichi *et al.*, 2006 and 2007). As one example, the history of the estimation error at GEONET 93019 (Koganei) is shown in Figure 11, where the ZTD at GEONET 93019 is estimated from the correction values at neighboring 3 TGPs, which are in the range from 17km to 39km, and the accuracy is 9.1mm RMS. The dispersion of the error becomes larger than that shown in Figure 9, which is because of the repeat of the estimation.

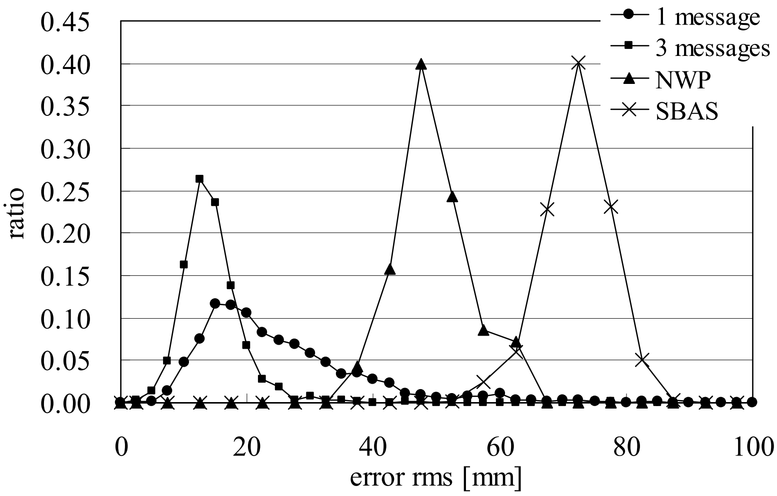

Figure 10. Distribution of Correction Accuracy

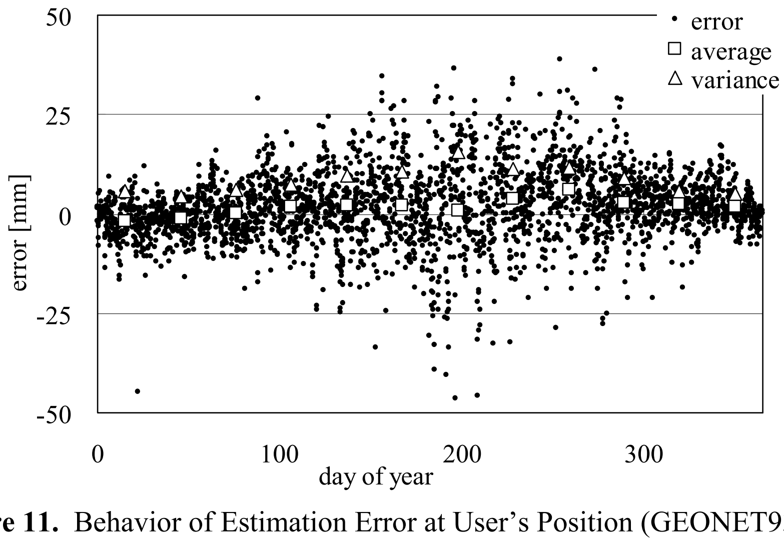

Figure 11. Behavior of Estimation Error at User's Position (GEONET93019)

5. ZTD ESTIMATION ACCURACY

The accuracy of the ZTD estimation at the TGP σ_{TGP}^2 and the user σ_{USER}^2 are evaluated through the comparison between the estimated ZTD and the result of the ZTD analysis. Therefore, the error variance of the ZTD estimation at the TGP σ_{TGP}^2 and the user σ_{USER}^2 in the previous sections are approximately given as follows:

$$\sigma_{TGP}^2 = 2\sigma_{sol}^2 + \sigma_{est}^2 \tag{14}$$

$$\sigma_{USER}^2 = 2\sigma_{sol}^2 + 2\sigma_{est}^2 \tag{15}$$

where σ_{sol}^2 and σ_{est}^2 are the error variances of the ZTD analysis result and the estimation, respectively. From the evaluation result $\sigma_{TGP}^2 = 12.0^2\,\text{mm}^2$ and $\sigma_{USER}^2 = 13.2^2\,\text{mm}^2$, the errors are approximately estimated as $\sigma_{est}^2 = 5.5^2\,\text{mm}^2$ and $\sigma_{sol}^2 = 7.5^2\,\text{mm}^2$. In the actual operation, the digitization error σ_{digi}^2 is also included, and the user's estimation error is approximately given as follows:

$$\sigma_{USER}^2 = \sigma_{sol}^2 + 2\sigma_{est}^2 + \sigma_{digi}^2 \tag{16}$$

As the ZTD product of the precise point positioning analysis and the digitization error are expected to be about $\sigma_{sol}^2 = 5^2\,\text{mm}^2$ and $\sigma_{digi}^2 = 10^2/12\,\text{mm}^2$, respectively, the user's estimation error through the presented strategy is expected to be about 10mm RMS as the following equation indicates.

$$\sigma_{USER}^2 = \sigma_{sol}^2 + 2\sigma_{est}^2 + \sigma_{digi}^2 = 9.7^2\,\text{mm}^2 \tag{17}$$

6. CONCLUSIONS

This paper presents a strategy of the tropospheric delay correction in L1-SAIF augmentation. Because this augmentation system aims to achieve the accurate positioning correction of the mobile users, the correction strategy must be always available at an arbitrary point in the augmentation service area. To satisfy this requirement a method to estimate the ZTD accurately at a different location is proposed, where a ZTD model is applied to compensate the difference of the ZTD between two locations due to the difference of the geographical conditions. An original ZTD model named ENRI model is newly formulated to be suitable for L1-SAIF service area, and the effectiveness of the proposed method is clearly proved through the evaluations using actual data.

To realize the tropospheric delay correction in L1-SAIF based on this estimation method, 105 TGPs are determined to fully cover the land in L1-SAIF service area, and the correction information at TGPs are formed from the result of the ZTD analysis. A user can estimate the local ZTD using the correction information at neighboring TGPs and ENRI model. In this way, a user at an arbitrary location in the service area can always estimate the local ZTD value for positioning correction. Only 3 messages are necessary to transmit the total correction information to the users, and moreover, the better correction accuracy than the current methods, such as SBAS model, is achieved even when only one message is available.

To guarantee the effectiveness of the presented strategy, the more detailed evaluations using the longer-term data are indispensable. In addition, it is still possible to optimize the arrangement of TGPs and the parameters of ENRI model and the weighing functions. After these investigations, the presented strategy is implemented into L1-SAIF augmentation.

It is also possible to apply the presented strategy in an arbitrary area by placing the sufficient GPS observation stations so densely that an arbitrary point in the service area can be in almost the same meteorological condition as one of the stations so that the variations of ZTDs at the point and the station are similar to each other. The required number of the stations is determined by the geographical features and the scale of meteorological phenomena, and it is possible to realize the presented tropospheric delay correction method with small number of stations in flat area.

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