Performance Analysis of Korean WADGPS Algorithms with NDGPS Data

Youngsun Yun*, Doyoon Kim*, Chulsoo Pyong* and Changdon Kee**
School of Mechanical & Aerospace Engineering
Seoul National University, Seoul, Korea 151-742

Abstract

To provide more accurate and reliable positioning and timing services to Korean nationwide users, the Ministry of Maritime Affairs and Fisheries of Korea is implementing Korean NDGPS (Nationwide DGPS), which is operational partly. And it also has a plan to construct WADGPS (Wide Area Differential GPS) system using sites and equipments of the NDGPS reference stations. For that, Seoul National University GNSS Laboratory is implementing and testing prototypes of WRS (Wide-area Reference Station) and WMS (Wide-area Master Station).

Until now, because there are not enough installed WRSs to be used for computing wide area correction information, we cannot test algorithms of WMS with the data processed actually in WRSs. Therefore to evaluate the performance of the algorithms, we made a MATLAB program which can process RINEX (Receiver INdependent Exchange) format data with WADGPS algorithm. Using that program which consists of WRS, WMS and USER modules, we processed the data collected at NDGPS reference stations, which are saved in RINEX format. In WRS module, we eliminate the atmospheric delay error from the pseudorange measurement, smooth the measurement by hatch filter and calculate pseudorange corrections for each satellite. WMS module collects the processed data from each reference stations to generate the wide area correction information including estimated satellite ephemeris errors, ionospheric delays at each grid point, UDRE (User Differential Range Error), GIVE (Grid Ionosphere Vertical Error) and so on. In USER part, we use the measurements of reference stations as those of users and estimate the corrected users' positions and protection levels (HPL, VPL).

With the results of estimation, we analyzed the performance of the algorithms. We assured the estimated UDRE /GIVE values and the protection levels bound the corresponding errors effectively. In this research, we can expect the possible performance of WADGPS in Korea, and the developed modules will be useful to implementation and improvement of the algorithms.

Key Word : Korea, WADGPS, NDGPS, Performance

Introduction

GPS provides high-accuracy position solutions for users of various applications. However, using GPS alone cannot provide sufficient accuracy and reliability performances for safety-critical systems such as airborne or maritime navigation system. LADGPS (Local Area Differential GPS) and WADGPS (Wide Area Differential GPS) are concepts of GPS augmentation system to solve

* Researcher
E-mail : einheit@snu.ac.kr, Tel : 02-880-7395 Fax : 02-878-0559
** Associate Professor

this problem, which can provide correction information. WADGPS has larger service coverage with a relatively small number of reference stations, and more reliability. The Ministry of Maritime Affairs and Fisheries (MOMAF) of Korea and Seoul National University GNSS Laboratory (SNUGL) are conducting a project on Korean WADGPS system. To predict the performance of the system, we are implementing a testbed of WADGPS. Since 2003, we have installed 3 WRSs (Wide-area Reference Stations) in the Korean peninsula. After we finish the installation of them so that we can have enough WRSs to generate wide-area correction information, we will test the system in real-time. But at this time, we don't have sufficient reference stations, therefore we processed NDGPS data to determine appropriate algorithms and predict possible performance of the system. WRSs in WADGPS testbed will use the same antenna and GPS receivers with NDGPS stations. So, for data processing in this paper, we used the NDGPS data which are saved as RINEX format every 30 seconds.

In this paper, we introduce the data processing algorithms for the Korean WADGPS. With the results from WADGPS processing, we will discuss the performance focused on accuracy, integrity and availability.

Algorithms

Previously in SNUGL, Kim has analyzed the performance of Korean WADGPS algorithms with simulation and live data processing[1]. However, it was focused on accuracy performance of the system. Yun has improved the simulation program to analyze integrity and availability performance[2]. In this paper, to consider the characteristic of Korean WADGPS network, we adopted Tsai[3] and Chao[4]'s algorithms and modified them to have high integrity performance.

Korean WADGPS Data Processing Procedure

SNUGL has been developing Korean WADGPS data processing program in MATLAB, which consists of 3 modules: WRS, WMS and USER. The functions of each part are shown in Figure 1. RINEX format GPS data are used as input data for WRS module.

WRS uses 'Navigation' data files that have ephemeris data for visible satellites, for estimation of satellite position and clock biases. And with them, it processes 'Observation' data files which provide GPS measurements, including L1/L2 pseudorange, carrier phase and doppler, etc. From the archived data, WRS estimates ionospheric delays at each pierce points and removes estimated error components receiver and satellite clock biases, tropospheric and ionospheric delays, from pseudorange measurements. WRS passes the estimated positions of visible satellites, bias-removed pseudoranges, ionospheric delay estimations with pierce points.

WMS gathers all the pre-processed data from each WRS to generate ephemeris and ionospheric delay corrections, and send them to USER module.

USER fixes their positions and estimates position error bounds at every epoch after

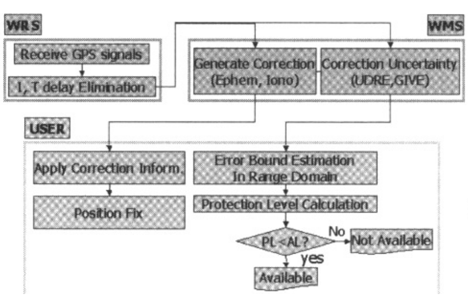

Fig. 1. Data Processing Procedure

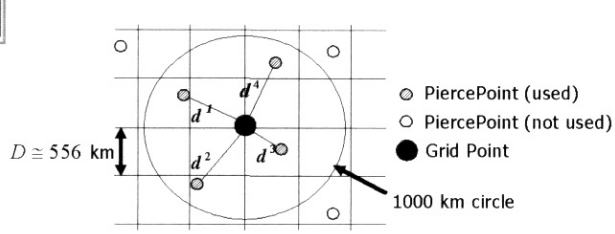

Fig. 2. Generate Ionosphere Correction

application of the corrections from WMS. For data delivery from WRS to WMS and WMS to USER, we used binary files to shorten processing time. Output files from user are saved in ASCII matrix format to make it easy to summarize the results in MATLAB.

Vertical Ionospheric Delay Estimation

With the ionospheric delays processed through appropriate procedures and pierce points from WRS, WMS estimates vertical ionospheric delay at each grid point. The estimation algorithm used in this paper is Chao's weighted least-square estimator. This method uses ionosphere data that have pierce points within 1000km from the target grid point. Because of the constraint of Korean WRS network geometry, some grid points cannot be surrounded by sufficient amount of pierce points. So, this method can be useful in this condition.

Figure 2 shows grid points and pierce points. In this algorithm, we only use the measurements of four pierce points (dashed dots) that are in the circle. We use equation (1) to calculate ionospheric delay at grid point and the weighting function (ω^k) is defined as equation(2).

$$\hat{I}_{Grid,V} = I^{Grid}_{Klob,V} \sum_{k=1}^{K}\left[\left(\frac{I^k_{meas,V}}{I^k_{Klob,V}}\right)\cdot \omega^k\right] \Big/ \sum_{n=1}^{K}\omega^n \tag{1}$$

where,

$\hat{I}_{Grid,V}$: estimated vertical ionospheric delay at the grid point

$I^{Grid}_{Klob,V}$: vertical ionospheric delay at the grid point using broadcasted Klobuchar model parameters

$I^k_{meas,V}$: measured vertical ionospheric delay at the pierce point

$I^k_{Klob,V}$: vertical ionospheric delay at the pierce point using broadcasted Klobuchar model parameters

ω^k : weight for the k-th pierce point

$$\omega^k = \Delta^k/\sigma^k \tag{2}$$

Here, spatial decorrelation factor is defined as equation (3) and we can notice that the weighting factor is in inverse proportion to distance from grid point and standard deviation of measurement.

$$\Delta_k = \exp[-(d^k/2D)^k] \tag{3}$$

Grid Ionospheric Vertical Error(GIVE) Estimation

WMS also should estimate the uncertainty of the estimated vertical ionospheric delay - GIVE (Grid Ionospheric Vertical Error). With Chao's method, we can get the GIVE value easily by equation (4).

$$GIVE = 3.29 \times \sqrt{1/\sum_{n=1}^{K}\omega^n} \tag{4}$$

But, to make GIVE bound ionosphere correction error, WMS validates the calculated GIVE values. WMS use the broadcast ionospheric corrections and GIVE indices. It estimates ionospheric delay at each IPP with the user algorithm as equation (5).

$$\hat{I}_{PP,V} = \sum_{i=1}^{4} W_i(x_{PP}, y_{PP}) \cdot \hat{I}_{Grid,V,i} \tag{5}$$

where,

$\hat{I}_{PP,V}$: vertical ionospheric delay at pierce point, estimated with the broadcast ionospheric correction information

$\hat{I}_{Grid,\,V,\,i}$: broadcast vertical ionospheric delay at i-th grid point

$W_i(x_{PP},\, y_{PP})$: weighting factor of a pierce point whose location is $(x_{PP},\, y_{PP})$

And WMS also has measured vertical ionospheric delay at each pierce point, so it can get differences of estimated and measured ionospheric delays as equation (6).

$$e_V = \hat{I}_{PP,\,V} - I^{Meas}_{PP,\,V} \tag{6}$$

Where,

$I^{Meas}_{PP,\,V}$: measured vertical ionospheric delay at pierce point

WMS regards the differences as ionospheric correction errors and if they exceed estimated UIRE (User Ionospheric Range Error) from the broadcast GIVE index values, GIVE values are dumped up to cover the correction errors.

Because Korean WADGPS network doesn't have enough IPPs to cover all over the service area, we increase all the GIVE indices to make system conservative, if any ionospheric correction error is above UIRE. This method can cause large UIRE due to noisy measurements or interfrequency biases, but it can guarantee integrity performance. Further researched will be done to make this better in the future.

$$\left| \hat{I}_{PP,\,V}(t) - I^{Meas}_{PP,\,V}(t) \right| > UIVE \tag{7}$$

Figure 3 is a sample plot of estimated vertical ionospheric correction values and Figure 4 is about estimated GIVE indices.

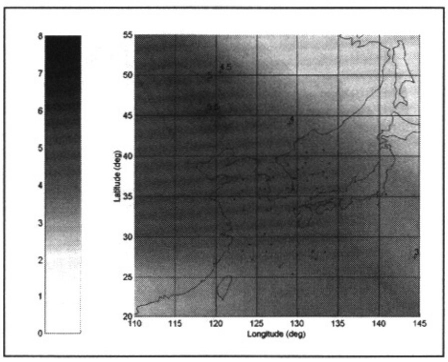

Fig. 3. Estimated Ionospheric Correction

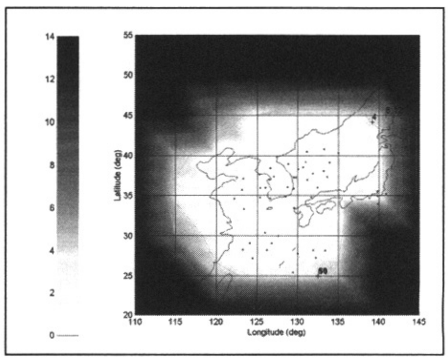

Fig. 4. Estimated GIVE Indices

Ephemeris Error Estimation

To estimate ephemeris errors (satellite position errors and clock biases), we need to eliminate all the other biases from pseudoranges. Pseudorange measurement after elimination of ionospheric and tropospheric delays can be expressed as the following equation (8).

$$\begin{aligned} \rho_{ij} &= \boldsymbol{D}_{ij} \cdot \boldsymbol{e}_{ij} - b_j + B_i + n_{ij} \\ &= [(\boldsymbol{R}_j + \delta\boldsymbol{R}_j) - \boldsymbol{S}_i] \cdot \boldsymbol{e}_{ij} - b_j + B_i + \nu_{ij} \end{aligned} \tag{8}$$

where,

ρ_{ij} : measured pseudorange at i-th WRS from jth satellite

$\boldsymbol{D}_{ij}$: range vector from i-th WRS to j-th satellite

$\boldsymbol{e}_{ij}$: unit vector from i-th WRS to j-th satellite

R_j : j-th satellite location calculated from GPS message

δR_j : ephemeris error vector of j-th satellite

S_i : known i-th monitor station location

b_j : j-th satellite clock offset

B_i : i-th WRS clock offset

ν_{ij} : measurement noise including mi.smodelling of ionosphere and troposphere

In the equation, the unknown variables X can be defined for all the WRSs ($i = 1, 2, \cdots, n$) and GPS satellites ($j = 1, 2, \cdots, n$) as follows.

$$x = [\delta R^T \quad b^T \quad B^T]^T \tag{9}$$

where,

$$\delta R = [\delta R_1^T \ \ \delta R_2^T \ \cdots \ \delta R_m^T]^T, \quad b = [b_1 \ \ b_2 \ \cdots \ b_m]^T, \quad B = [B_1 \ \ B_2 \ \cdots \ B_m]^T$$

If we gather all the measurement equations (8) for all the WRSs and GPS satellites, and rearrange them, we can obtain a matrix equation as follows.

$$z = H X + \nu \tag{10}$$

H and z can be constructed by simple computation. Using the equation (10), we can estimate satellite position errors and clock offsets with weighted least square method or minimum variance estimator. WLS is very sensitive estimation method to noise and geometry. Korean WRS network area is very small compared with distance between WRSs and GPS satellites. It may cause large DOP for ephemeris error estimation. So in this condition of system, MV is much more robust and appropriate than WLS. The left plot of Figure 5 is estimated ephemeris correction from WLS and pseudorange residual which has to be corrected by the correction. It shows that the correction is very noisy and biased, but in the case of MV (the right plot) it goes along with the residuals. Therefore minimum variance method was used in this paper.

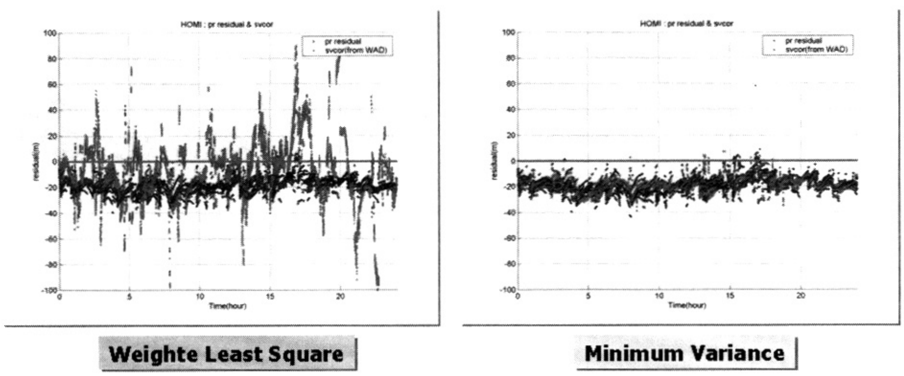

Fig. 5. Pseudorange Residual(Blue) & Estimated Ephemeris Correction(Red) from WLS(left) and MV(right)

User Differential Range Error (UDRE) Estimation

WMS estimates the uncertainty of ephemeris and satellite clock correction - UDRE (User Differential Range Error). UDRE for each visible satellite is calculated as the following equations.

$$P_{UDRE} = R + H \hat{P} H^T \tag{11}$$

where,

$\boldsymbol{R}$: measurements covariance

$\boldsymbol{H}$: observation matrix, from WRSs to SV

$\hat{\boldsymbol{P}}$: covariance of the estimated ephemeris and clock error

$$\sigma^2_{UDRE} = \left(\sum_{i=1}^{i=M} \frac{1}{\boldsymbol{P}_{UDRE,\, ii}} \right)^{-1} \tag{12}$$

where,

$\boldsymbol{P}_{UDRE,\, ii}$: i-th diagonal elements of $\boldsymbol{P}_{UDRE}$

Then, for broadcast, WMS calculates the UDRE value for each visible satellite.

$$UDRE = \sigma_{UDRE} \times 3.29 \tag{13}$$

And to make UDRE conservative, we used similar feedback method to UIVE. The differences between pseudorange residuals and corrections are blue dots in Figure 6, which are almost below 2 meters. And the estimated UDRE values are covering the correction errors fully.

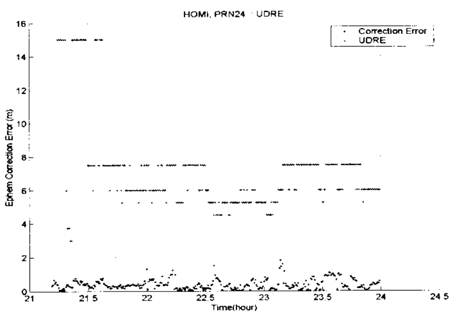

Fig. 6. Correction Error(Blue) & UDRE(Red)

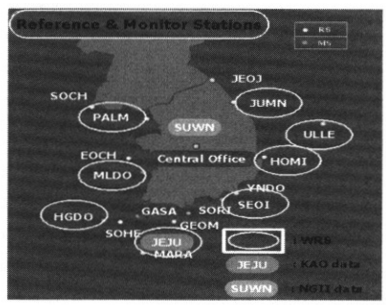

Fig. 7. Korean NDGPS Reference Stations

Results and Analysis

NDGPS Data Used in Data Processing

Korean NDGPS has 11 reference stations and 5 monitoring stations (Figure 7). Among them, 7 reference stations were chosen as WRSs and 1 reference station of KAO (Korea Astronomy Observatory) was added to the WRS network.

GPS measurements of the NDGPS stations are archived in RINEX format every 30 seconds. And they are provided through website for authorized researchers who want to use them[5]. We downloaded the 24-hour RINEX data of July 14th in 2003. And to simulate an inland user, NGII (National Geographic Information Institute) data of 'SUWN' were used.

User Performances

We processed 1 NGII data and 3 NDGPS data. The WADGPS user can correct ionospheric delays and ephemeris errors by broadcast WADGPS corrections.

HPL-HE, VPL-VE plots for user 'SUWN' are shown in this chapter. Here, HE and VE mean horizontal and vertical errors respectively, and PL is the protection level which means uncertainty bound of the estimated position solution. We used LPV requirements in this performance analysis. LPV (Lateral Precision with Vertical Guidance) is a new approach procedure with vertical guidance used by FAA and it is the counterpart of APV-I in international community. It does not require any equipment beyond standard WAAS or SBAS equipment.

Figure 8 shows HPL-HE plot and VPL-VE for a WAD user. Each rectangular bound represents HAL (40m for LPV) and VAL(50m for LPV, 20m for APV-II). We can see that there is no point at which position error is larger than protection level. It means that probability of HMI (Hazardous Misleading Information) is zero, or PL bounds errors perfectly. But there are some points that have large PLs (>40m for HPL, >50m for VPL), which means the system lost availability. But the LPV availability of the USERs are all over 99%, which meets the requirement 95%.

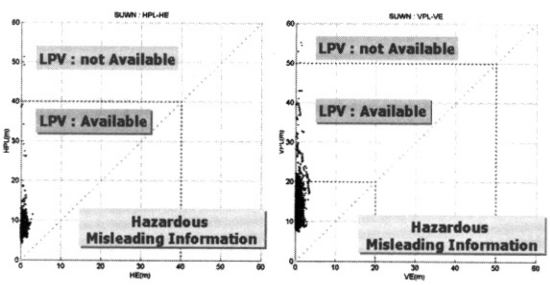

Fig. 8. HPL-HE & VPL-VE

Table 1. Summary of User Performances

	SUWN	MLDO	SEOI	JUMN
95% HE (LPV, m)	1.48	1.16	1.44	1.09
95% VE (LPV, m)	2.00	1.65	1.69	1.40
Avail. LPV (%)	99.55	99.62	99.69	99.72
Avail. APV-II (%)	90.83	93.37	92.32	97.20
Integrity (%)	100	100	100	100

For 4 users (1 NGII + 3 NDGPS), we summarized performances. Table 1 shows 95% horizontal and vertical position error in LPV operation, percentage of LPV and APV-II instantaneous availability, and integrity. Integrity means the percentage of epochs at which there are no misleading information (Protection Level < Position Error). At all USERs, accuracy meets the LPV requirement (7.6m). And all users have LPV availability above 95% and 100% integrity.

Conclusions

To implement Korean WADGPS testbed, we need to know which algorithm will be appropriate to each estimation, how we have to process raw measurements, what kind of problems will be occurred in data processing procedures and etc. To get solutions for them, we implemented a WADGPS data processing program, which can process data saved in RINEX format. Korean WADGPS network is expected to have small coverage, so we used appropriate algorithms in that case. With the program, we processed data from Korean NDGPS reference stations and through the results, we evaluated performance of each virtual users. All the users have good accuracy, integrity and availability performances, which can meet LPV requirements. To evaluate the performance statistically with sufficient amount of samples, continuous monitoring of the system is necessary.

Acknowledgement

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References

1. D. Kim, C. Kee, Development &Performance Analysis of Korean WADGPS Positioning

Algorithm, The 9th GNSS Workshop - International Symposium on GPS/GNSS, Wuhan, China, November, 2002.

2. C. Kee, Y. Yun, D. Kim, Simulation - based Performance Analysis of SBAS in Korea: Accuracy & Availability, Proceedings of ION GNSS 2003, Portland, CA, September 2003.

3. Y. Tsai, Wide Area Differential Operation of the Global Positioning System: Ephemeris and Clock Algorithms, A Stanford University Ph.D. Dissertation, August 1999.

4. Y. Chao, Real time implementation of the wide area augmentation system for the global positioning system with an emphasis on ionospheric modeling, A Stanford University Ph.D. Dissertation, 1997.

5. Korean NDGPS website, http://www.ndgps.go.kr

6. RTCA Special Committee159 Working Group 2, Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, RTCA Document Number DO-229C, 2001.