Prototype of Satellite-Based Augmentation System and Evaluation of the Ionospheric Correction Algorithms

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BIOGRAPHY

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ABSTRACT

The SBAS, satellite-based augmentation system, is basically the wide-area differential GPS (WADGPS) effective for numerous users within continental service area. For a practical investigation of wide-area augmentation technique, the authors have implemented the prototype system of the SBAS. This prototype generates the complete SBAS messages capable of wide-area differential correction and providing integrity based on the dual frequency observation dataset.

The system has been successfully implemented and tested with the SBAS user receiver simulator. It has achieved positioning accuracy of 0.3 to 0.6 meter in horizontal and 0.4 to 0.8 meter in vertical, respectively, over mainland of Japan during nominal ionospheric conditions with 6 monitor stations located similar to the MSAS. The historical severe ionospheric activities might disturb and degrade the positioning performance to 2 meters and 3 meters for horizontal and vertical, respectively. In all cases, both horizontal and vertical protection levels have never been exceeded by the associate position errors regardless of ionospheric activities.

This kind of prototype system is not only a proof of feasibility of the actual system but also a practical tool to evaluate and compare algorithms inside the MCS. The authors evaluated the current and improved ionospheric correction algorithms in a practical manner using the prototype in offline mode. The proposed algorithm of adaptive switching between the planar and zeroth order fit reduced protection levels down to one third relative to the current baseline so will contribute to improve the availability of the SBAS.

INTRODUCTION

Recently some GPS augmentation systems with nation-wide service coverage have been rapidly developed in Japan. The MTSAT geostationary satellite for the MSAS (MTSAT satellite-based augmentation system) [1], Japanese SBAS, was launched in February 2005 and it is now under the operational test procedures. Additionally QZSS (quasi-zenith satellite system) is planned to be launched in 2008, which will broadcast GPS-compatible ranging signals including the wide-area augmentation (L1-SAIF signal: submeter-class augmentation with integrity function) [2]. MSAS employs geostationary satellite on the basis of the SBAS standard defined by the

ICAO, International Civil Aviation Organization, for civil aviation applications [3][4], while QZSS satellites will be launched on the 24-hour elliptic orbit inclined 45 degrees in order to broadcast signals from high elevation angle supporting urban canyons.

For a practical investigation of wide-area augmentation technique, the authors have implemented the prototype system of the SBAS. Actually this prototype, RTWAD, is computer software running on PC/UNIX which is capable of generating wide-area differential correction and integrity information based on input of the dual frequency observation dataset. The corrections are formatted into the complete 250 bits SBAS messages and output as one message per second. Our prototype system utilizes only code phase measurement on dual frequencies. Preliminary evaluation showed that this prototype system generated fully functional SBAS messages providing positioning accuracy of 0.4 to 0.7 meter in horizontal and 0.6 to 1.0 meter in vertical.

This kind of prototype system is not only a proof of feasibility of the actual system but also a practical tool to evaluate and compare algorithms inside the master control station, or MCS, of the SBAS. It enables direct evaluation of various correction algorithms and parameters in terms of user positioning error in the controlled environment. One can choose the most effective algorithm for the operational system based on the actual data observed during the nominal- and worst-case environment. Because MSAS has no testbed system, such a prototype system should be a powerful tool to evaluate and validate candidate algorithms for improvement of the performance of MSAS.

The ionospheric delay problem is currently the largest concern for MSAS program. In early 2004 the MSAS Technical Review Board of JCAB (Japan Civil Aviation Bureau) established an Ionosphere Working Group for this problem. Supporting such activities, the authors have been investigating the ionospheric effects over Japan to predict and improve the actual performance of MSAS on the ionosphere [5]-[7].

The authors have already evaluated zeroth and quadratic order fit for generation of ionospheric corrections at the IGP and pointed out a problem of the current storm detector algorithm. All of these analyses were based on the ionospheric delay observation, i.e., in the range domain. The primary mission of the SBAS is, however, protecting users from the large error exceeding alert limits; we need evaluation in the position domain to clarify and characterize the current problem of MSAS. Our SBAS prototype system looks suitable for this purpose. The system is capable to generate the actual ionospheric corrections during storm and quiet ionospheric conditions under various versions of algorithm and parameters. We can evaluate them with observations at any user locations in the position domain, and the range domain if necessary.

In this paper the authors will firstly introduce the SBAS prototype system implemented by ENRI. Its function and performance will be briefly described. Next, evaluation of the current ionospheric correction algorithm based on the prototype will be discussed. It will be shown that introducing zeroth order fit would reduce protection levels inducing improvement of the availability of the SBAS.

SBAS PROTOTYPE SYSTEM

The SBAS is basically the wide-area differential GPS (WADGPS) [8] effective for numerous users within continental service area. In order to achieve seamless wide-spread service area independent of the baseline distance between user location and monitor station, the WADGPS provides vector correction information, consisting of corrections such as satellite clock, satellite orbit, ionospheric propagation delay, and tropospheric propagation delay. The conventional differential GPS system like RTCM-SC104 message generates one pseudorange correction for one satellite. Such a correction is dependent upon reference receiver location and valid only for the specific LOS direction. The baseline distance between user receiver and reference station is restricted within a few hundred km, or less than 100 km during storm ionospheric conditions.

In case of vector correction like wide area differential GPS, pseudorange correction is divided into some components representing each error source. User receivers can compute the effective corrections as functions of user location from the vector correction information. For example, satellite clock error is uniform to all users anywhere, while ionospheric density depends upon location with a few hundred km space constant.

Summary of SBAS Signal Specification

The SBAS is a standard wide-area differential GPS system defined in the ICAO SARPs (standards and recommended practices) document [3]. Unlike the other DGPS systems, SBAS has capability as integrity channel for aviation users which provides timely and valid warnings when the system does not work with required navigation performance.

The SBAS provides (i) integrity channel as civil aviation navigation system; (ii) differential correction information to improve positioning accuracy; and (iii) additional ranging source to improve availability. SBAS signal is broadcast on 1575.42 MHz L1 frequency with 1.023 Mcps BPSK spread spectrum modulation by C/A code of

Table 1. Differential correction messages for the SBAS (part).

Message Type	Data Type	For	Contents	Range	Unit	Max Interval [s]
2 to 5	Fast Correction	13 satellites	FC^j $UDREI^j$	±256 m 0 to 15	0.125m -	60 6
6	Integrity	51 satellites	$UDREI^j$	0 to 15	-	6
24	Mixed fast/long-term satellite error correction	6 satellites	FC^j $UDREI^j$	±256 m 0 to 15	0.125m -	60 6
		2 satellites	Δx^j Δy^j Δz^j Δb^j	±32 m ±32 m ±32 m $\pm 2^{-22}$ s	0.125 m 0.125 m 0.125 m 2^{-31} s	120 120 120 120
25	long-term satellite error correction	4 satelites	Δx^j Δy^j Δz^j Δb^j	±32 m ±32 m ±32 m $\pm 2^{-22}$ s	0.125 m 0.125 m 0.125 m 2^{-31} s	120 120 120 120
26	ionospheric delay	15 IGPs	$I_{v,IGPk}$ $GIVEI_k$	0 to 64 m 0 to 15	0.125m -	300 300

PRN 120 to 138. This RF signal specification means SBAS has ranging function similar to GPS. Data modulation is 500 symbols per second, i.e., 10 times faster than GPS with 1/2 coding rate FEC (forward error correction) which improves decoding threshold roughly 5 dB. SBAS message consists of 250 bits and broadcast one message per second. This message stream brings WADGPS corrections and integrity information.

SBAS message contains 8 bits preamble, 6 bits message type ID, and 24 bits CRC. The remaining 212 bits data field is defined with respect to each message type. For example, Message Type 2-5 is fast corrections to satellite clock; Message Type 6 is integrity information; Message Type 25 is long-term corrections to satellite orbit and clock; and Message Type 26 means ionospheric corrections. Table 1 summarizes SBAS messages relating to wide area differential corrections. Note that every corrections are with 0.125 meter quantization and integrity information (UDREI and GIVEI) is represented as 4-bit index value.

User receivers shall apply long-term corrections for j-th satellite as follows:

$$\begin{bmatrix} \tilde{x}^j \\ \tilde{y}^j \\ \tilde{z}^j \end{bmatrix} = \begin{bmatrix} \bar{x}^j + \Delta x^j \\ \bar{y}^j + \Delta y^j \\ \bar{z}^j + \Delta z^j \end{bmatrix}, \quad (1)$$

where $\left(\bar{x}^j, \bar{y}^j, \bar{z}^j\right)$ is satellite position computed from the broadcast ephemeris information. For satellite clock, corrected transmission time is given by:

$$\tilde{t} = t_{SV}^j - \left(\Delta \bar{t}_{SV}^j + \Delta b^j\right), \quad (2)$$

where $\Delta \bar{t}_{SV}^j$ is clock correction based on the broadcast ephemeris (see GPS ICD). The other corrections work with measured pseudorange:

$$\tilde{\rho}^j = \rho^j + FC^j + IC^j + TC^j, \quad (3)$$

where *FC*, *IC*, and *TC* mean fast correction, ionospheric correction, and tropospheric correction, respectively. User receivers shall compute their position with these corrected satellite position, clock and pseudorange.

Message Type 26 contains ionospheric corrections as the vertical delay in meters at 5 by 5 degree latitude and longitude grid points (IGP; ionospheric grid point). User receivers shall perform spatial bilinear interpolation and vertical-slant conversion following the procedure defined by the SARPs to obtain the LOS delay at the corresponding IPP (ionospheric pierce point). For SBAS, tropospheric correction is not broadcast so is computed by pre-defined model.

Integrity function is implemented with 'Protection Level.' The protection level is basically estimation of the possible largest position error at the actual user location. User receivers shall compute HPL (horizontal protection level) and VPL (vertical protection level) based on integrity information broadcast from the SBAS satellite with respect to the geometry of active satellites and compare them with HAL (horizontal alert limit) and VAL (vertical alert limit), respectively. Alert limits is defined for each operation mode; for example, HAL=556m and VAL=N/A for terminal airspace; HAL=40m and VAL=50m for

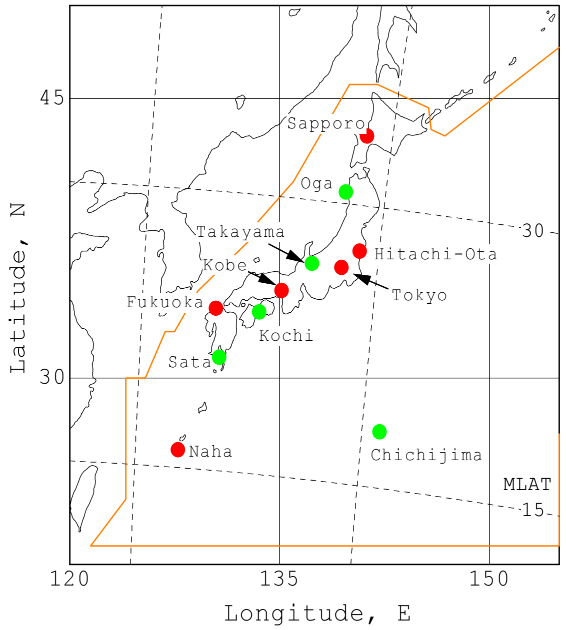

Figure 1. Observation stations for the prototype system. (Red) Monitor stations similar to the MSAS; (Green) User stations for evaluation.

APV-I approach with vertical guidance mode. If either protection level, horizontal or vertical, exceeds the associated alert limit, the SBAS cannot be used for that operation. Each SBAS provider must broadcast the appropriate integrity information (UDREI and GIVEI) so that the probability of occurrance of events that the actual position error exceeding the associated protection level is less than 10^{-7} .

Note that ICAO SBAS defines message contents and format broadcast from the SBAS satellite and position computation procedure for the user receivers. Each SBAS service provider should determine how SBAS MCS generates wide area differential corrections and integrity information at its own responsibility. SBAS is wide area system with the potential capability to support global coverage in terms of message format, but it is not necessary to be actually valid globally; each SBAS works for its service area. From this perspective the generation algorithm of SBAS messages can be localized. For example, each provider may design ionospheric correction algorithm to be suitable for the operational region.

Implementation of Prototype System

For a practical investigation of wide-area augmentation technique, the authors have implemented the prototype system of the SBAS. It is developed for study purpose in the laboratory so would not meet safety requirement for civil aviation navigation facilities. Currently the system is running in offline mode and used for various evaluation activities.

Table 2. Description of observation stations.

GEONET ID	Lat [deg]	Lon [deg]	Hgt [m]	Location
Monitor Stations				
950128	43.0	141.3	205	Sapporo
950214	36.8	140.8	76	Hitachi-Ota
93011	35.9	139.5	63	Tokyo
950356	34.7	135.2	85	Kobe
940087	33.7	130.5	49	Fukuoka
940100	26.1	127.8	128	Naha
User Stations				
940030	40.0	139.8	69	Oga
940058	36.1	137.3	813	Takayama
940083	33.5	133.6	71	Kochi
950491	31.1	130.7	368	Sata
92003	27.1	142.2	209	Chichijima

Our prototype system, RTWAD, consisting of essential components and algorithms of WADGPS is developed based only on the public information already published. It is actually computer software running on PC and UNIX written in C language. It generates wide-area differential corrections and integrity information based on input of the dual frequency observation data set. Currently it is running in offline mode so input observation is given as RINEX files. RINEX observation files are taken from GPS continuous observation network, GEONET, operated by GSI (Geographical Survey Institute, Japan). IGS site ‘mtka’ in Tokyo provides the raw RINEX navigation files because navigation files provided from GEONET are compiled to be used everywhere in Japan.

The augmentation information generated by RTWAD is formatted into the complete 250 bits SBAS message and output as data stream of one message per second. Preambles and CRC are added but FEC is not applied. While the GEONET observations are sampled as 30 seconds interval, RTWAD generates one message per second. RTWAD utilizes only code phase measurement on dual frequencies, without carrier phase measurement.

In order to evaluate augmentation information generated by our prototype system, SBAS user receiver simulator software is also available. This simulator processes SBAS message stream and applies it to RINEX observations. It computes user receiver positions based on the corrected pseudoranges and satellite orbit, and also protection levels. SBAS simulator of course needs only L1 frequency measurement, even performing the standard carrier smoothing.

Table 3. Baseline performance of the prototype system; (Upper) RMS error; (Middle) Max error; (Lower) RMS protection level; Units are in meters.

Period	Iono-sphere	940030		940058		940083		950491		92003		Max δ_v
		Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	
2005 11/14-16	Quiet	0.354 1.695 20.02	0.418 2.517 32.11	0.304 1.487 19.41	0.413 2.123 32.18	0.353 1.902 21.62	0.508 4.452 35.46	0.453 3.302 28.37	0.647 6.158 43.97	1.132 6.266 55.34	1.102 5.958 65.38	2.597
2004 11/8-10	Storm	1.546 7.479 101.3	1.900 11.44 152.7	1.157 7.221 91.61	1.560 9.265 146.0	1.057 6.375 89.76	1.559 12.80 154.0	1.639 21.90 100.6	2.195 23.09 167.7	3.302 26.84 109.5	3.427 38.86 188.6	2.019
2004 7/22-24	Active	0.432 2.318 22.56	0.566 4.455 33.69	0.381 2.867 22.08	0.531 5.451 32.58	0.403 2.468 23.13	0.592 4.240 36.99	0.586 2.143 26.59	0.764 5.509 41.24	0.800 4.487 35.58	1.317 9.225 56.11	1.344
2004 6/22-24	Quiet	0.397 2.047 21.73	0.602 4.717 34.32	0.425 2.634 27.00	0.603 3.466 37.69	0.385 1.757 21.39	0.649 3.782 37.82	0.491 2.415 23.14	0.776 4.574 39.36	0.708 4.507 31.32	1.088 6.595 53.77	1.388
2003 10/29-31	Storm	0.982 5.645 127.7	1.057 6.542 181.6	0.659 5.194 191.0	0.840 6.652 231.3	1.407 14.90 152.5	1.863 12.38 249.5	2.164 29.42 144.0	2.901 36.31 229.7	3.121 15.93 129.4	3.356 21.67 216.9	3.135
MSAS Test Signal												
2005 11/14-16	Quiet	0.381 1.659 25.82	0.631 2.405 40.48	0.502 4.873 32.83	0.728 3.700 46.29	0.637 8.517 37.67	0.881 9.396 50.08	0.640 3.012 44.34	0.730 2.680 56.24	0.982 6.267 85.79	1.014 6.614 123.0	1.520

Performance of Prototype System

At first we evaluated the prototype system in terms of user positioning accuracy. The system has run with datasets for some periods including both stormy and quiet ionospheric conditions, and generated SBAS message streams. Essentially it was able to use any GEONET sites as monitor stations, we used 6 GEONET sites distributed similar to the domestic monitor stations of MSAS; Sapporo, Hitachi-Ota, Tokyo, Kobe, Fukuoka, and Naha, indicated as Red circles in Figure 1.Their locations are not exactly identical to the MSAS stations, but similar enough to know baseline performance comparable with MSAS.

User positioning accuracy was evaluated at 5 GEONET sites, Green circles in Figure 1. Site 92003 (Chichijima) is located outside the network of monitor stations, so works as the sensitive user location in the service area, while others are on or near to the mainland of Japan. Table 2 summarizes description of monitor stations and user stations.

Table 3 illustrates the baseline performance of our prototype system. For quiet ionospheric conditions, the horizontal accuracy was 0.3 to 0.6 meter and the vertical error varied 0.4 to 0.8 meter except Site 92003, both in RMS manner. The ionospheric activities disturbed and degraded the positioning performance to 2 meters and 3 meters for horizontal and vertical, respectively. Note that two ionosheric storm events listed in Table 2 are extremely severe observed only a few times for the last decade.

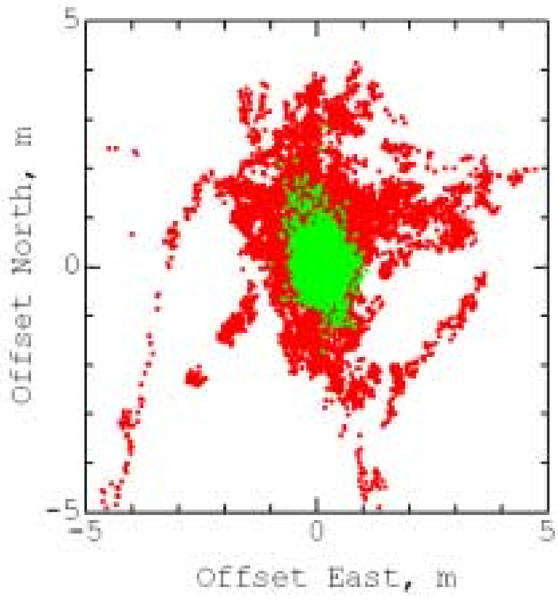

Figure 2. Example of user positioning error at Site 940058 on 22-24 July 2004; (Green) Augmented by the prototype system; (Red) Standalone GPS.

In all cases, SBAS receiver simulators computed horizontal and vertical protection levels as the integrity requirements. Both horizontal and vertical protection

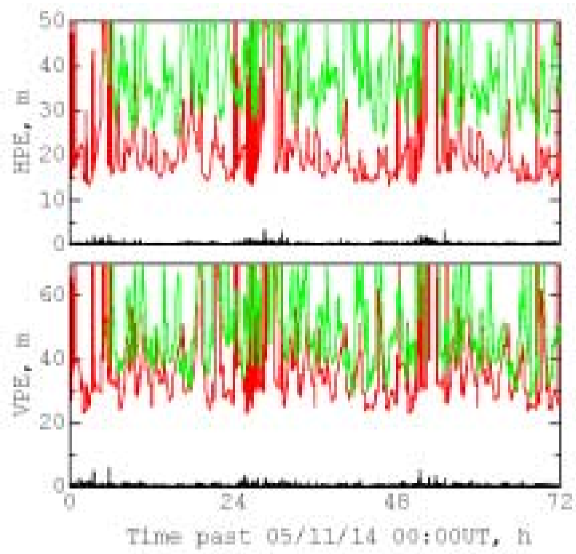

Figure 3. User positioning error and protection levels at Site 950491 during quiet ionosphere; (Black) Actual user error; (Red) Protection levels of the prototype system; (Green) Protection levels of MSAS.

levels have never been exceeded by the associate position errors regardless of ionospheric activities. This means the system provided the complete integrity function protecting users from the large position errors exceeding protection levels. The maximum errors in Table 2 indicate that the large errors sometimes occurred, but they were all within the associate protection levels.

Positioning error was reduced with SBAS messages produced by the prototype system as shown in Figure 2 in comparison with standalone mode GPS. The large biases over 5 meters were eliminated and the error distribution became compact. The horizontal and vertical error were improved from 1.929 and 3.305 meters to 0.381 and 0.531 meter, respectively, all in RMS manner.

Figure 3 shows horizontal and vertical user positioning error at Site 950491 during quiet ionospheric condition on 11/14/05 to 11/16/05. Positioning errors are plotted with Black, sticking to the horizontal axis. Red curves are the protection levels therefore they are protecting users with large margin. They look very conservative but it is difficult to reduce protection levels due to the stringent 10^{-7} integrity requirements.

Verification with MSAS Test Signal

Even MSAS is under operational test, it is sometimes broadcasting test signal. We have received the test signal by NovAtel MiLLennium receiver equipped with SBAS channels at ENRI, Tokyo and decoded it. Test signal was broadcast continuously for three days from 11/14/05 to 11/16/05.

The SBAS user receiver simulator was again used for this evaluation. It processed MSAS messages and computed user position errors in the same way as the previous section. The performance is summarized in the bottom of Table 3. The horizontal and vertical RMS accuracies were 0.4 to 0.7 meter and 0.6 to 0.9 meter, respectively, for this period. Note that this result is based on test signal obtained only for three days with Message Type 0.

Protection levels of MSAS at Site 950491 are also plotted as Green curve in Figure 3. Comparing with output of our prototype system, the protection levels of MSAS were relatively large. This may represent safety margin as the first actual operational system. Anyway MSAS also completely protect users from possible incidental large errors.

Upcoming Plan; Realtime Operation

Up to now our prototype system has been successfully implemented and tested. Currently it is operating in offline mode with past dataset observed and held by GEONET. As the overall performance, 0.3 to 0.6 meter of the horizontal accuracy and 0.4 to 0.8 meter of the vertical accuracy, respectively, both in RMS, were achieved for quiet ionospheric conditions. Even for the historical severe ionospheric storm conditions, the accuracies were degraded to 2 and 3 meters for horizontal and vertical, respectively. The integrity function worked and always kept actual user errors within the associate protection levels.

The next step we are planning is realtime operation. The software for the prototype is basically driven by Kalman filter and operating with causality. Therefore only a little modification will be necessary for realtime operation. ENRI has already installed 6 realtime monitor stations for this purpose and additional one is planned to be installed shortly.

EVALUATION OF IONOSPHERIC CORRECTION ALGORITHMS

One of possible applications of the prototype SBAS is a practical evaluation of the algorithms in the MCS. The authors are responsible to ionospheric problems of MSAS operating in the low magnetic latitude region, so have evaluated ionospheric correction algorithms already proposed in [6] using our prototype system.

Review of the Current Baseline Algorithm

The current baseline algorithm to generate ionospheric corrections for the SBAS is so-called 'Planar Fit' based on a model of planar ionosphere. Here is a review of the baseline algorithm [9]-[11].

Using planar model, the vertical ionospheric delay at an IGP is estimated by:

$$\left[\hat{a}_0 \quad \hat{a}_1 \quad \hat{a}_2\right]^{\mathrm{T}} = \left(G^{\mathrm{T}} \cdot W \cdot G\right)^{-1} \cdot G^{\mathrm{T}} \cdot W \cdot \mathbf{I}_{\mathbf{v,IPP}}, \qquad (1)$$

where G is $N \times 3$ design matrix which describes the geometry of IPPs, and W^{-1} is the covariance matrix of the observation dataset, $\mathbf{I}_{\mathbf{v,IPP}}$. $\hat{I}_{v,IGP} = \hat{a}_0$ is the resulted estimation.

Integrity is the most important requirement for SBAS, so the bounding information of corrected pseudoranges is broadcast to users. For ionospheric corrections, the MCS broadcasts GIVE value for this purpose. The current algorithm computes GIVE values based on the formal variance of the least square fit with the assumption that the distribution of residual errors is normal, so it needs to determine whether each IGP is in storm condition or not. The 'storm' condition means the distribution of residual errors is possibly not normal.

The formal variance of the least square fit of Eqn. (1) is given by:

$$\hat{\sigma}^2_{\hat{I}_{v,IGP}} = \left[\left(G \cdot W \cdot G^{\mathrm{T}}\right)^{-1}\right]_{1,1}, \qquad (2)$$

and the variance around the IGP is:

$$\hat{\sigma}^2_{\hat{I}_v}(\Delta\phi, \Delta\lambda) = \begin{bmatrix} 1 \\ \Delta\phi \\ \Delta\lambda \end{bmatrix}^{\mathrm{T}} \left[\left(G \cdot W \cdot G^{\mathrm{T}}\right)^{-1}\right]_{1,1} \begin{bmatrix} 1 \\ \Delta\phi \\ \Delta\lambda \end{bmatrix}. \qquad (3)$$

Because IGP interval is 5 degrees, the maximum of the variance with respect to the IGP can be described as:

$$\hat{\sigma}^2_{\hat{I}_v,\max} = \max\begin{pmatrix} \hat{\sigma}^2_{\hat{I}_v}(-2.5,-2.5), & \hat{\sigma}^2_{\hat{I}_v}(-2.5,2.5) \\ \hat{\sigma}^2_{\hat{I}_v}(2.5,-2.5), & \hat{\sigma}^2_{\hat{I}_v}(2.5,2.5) \end{pmatrix}, \qquad (4)$$

so, GIVE value should be computed based on:

$$\hat{\sigma}^2_{bound,IGP} = \frac{\chi^2_{1-P_{FA}}}{\chi^2_{P_{MD}}} \cdot \left(\hat{\sigma}^2_{\hat{I}_v,\max} + \sigma^2_{decorr}\right), \qquad (5)$$

where a coefficient outside blankets is so-called inflation factor, and σ_{decorr} denotes inherent uncertainty of the ionosphere plane. $\chi^2_p(n-3)$ is the thresholds for chi-square statistics as a function of the degree of freedom (the number of observations minus the number of unknowns). The bounding information computed by Eqn. (5) is converted into 4-bit index of GIVEI; user receivers shall compute protection levels with $\sigma_{GIVE,IGP}$ indicated by GIVEI which is always equal to or greater than $\hat{\sigma}_{bound,IGP}$ derived from Eqn. (5).

According to procedure to compute protection levels in user receivers defined by SARPs [3], the actual correction error (residual) must be bounded by $5.33\sigma_{UIVE}$ anywhere and anytime (UIVE denoting user ionospheric vertical error is the ionospheric error bound at the IPP linearly interpolated from GIVEs at four or three IGPs). Now we can define the normalized residual error as:

$$\delta_v = \Delta I_v / \sigma_{UIVE} = \left(I_v - \hat{I}_v\right) / \sigma_{UIVE}, \qquad (6)$$

where I_v is the actual vertical ionospheric delay at user location, and $\hat{I}_v$ is the ionospheric correction provided by SBAS message, i.e., bilinear interpolation of vertical delays at the surrounding IGPs. Clearly it gives an example that integrity of the system cannot be maintained if this normalized residual error exceeds 5.33 at somewhere in the service area.

The current storm detector determines whether an IGP is in storm condition or not based on the chi-square statistics of the observations,

$$\chi^2 = \left(\hat{\mathrm{I}}_{\mathrm{v,IPP}} - \mathrm{I}_{\mathrm{v,IPP}}\right)^{\mathrm{T}} \cdot W \cdot \left(\hat{\mathrm{I}}_{\mathrm{v,IPP}} - \mathrm{I}_{\mathrm{v,IPP}}\right), \qquad (7)$$

compared with the threshold, $\chi^2_{1-P_{FA}}(n-3)$. If chi-square statistics is larger than this threshold, the IGP is determined to be in storm condition and the associate GIVE value is set to the maximum in order to protect users from a possible large error.

Baseline Algorithm and Problem

Table 3 showed the baseline performance of our prototype system. As the baseline algorithm, ionospheric corrections are generated by planar fit described as Eqn. (1)-(5) with standard storm detector algorithm in Eqn. (7). The parameters determining the number of IPPs used for fit were Nmax=30 and Nmin=10.

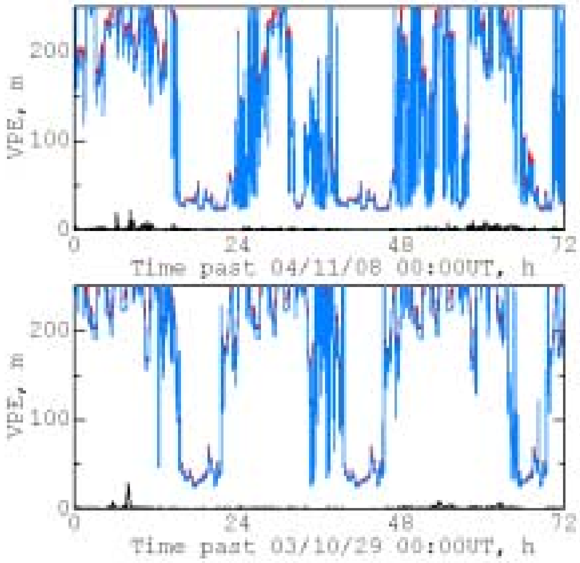

Figure 4. Vertical Protection Levels at Site 950491 during storm ionospheric condition; (Black) Actual user error; (Red) VPL; (Blue) Ionospheric component of VPL.

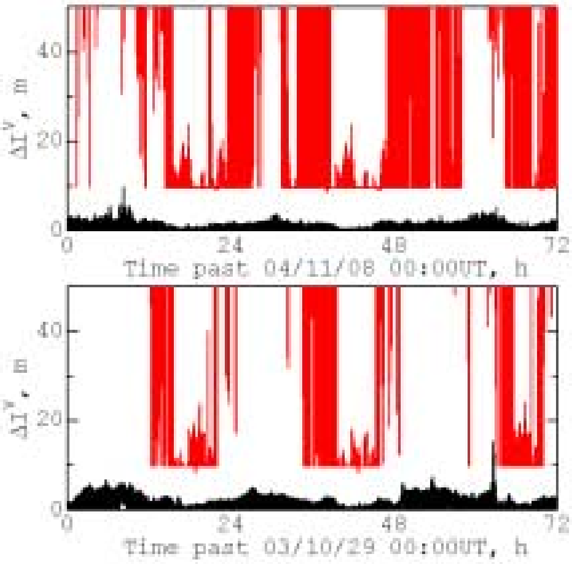

Figure 5. Observed vertical ionospheric residual error at Site 950491 during storm ionosphere; (Black) Actual residual error; (Red) 5.33 UIVE.

According to Table 3, protection levels increase much during ionospheric storm condition. RMS VPL was over 100 meters everywhere even while the largest vertical positioning error was up to 36 meters at the southern locations. If protection levels are reduced down to the levels of the largest position errors, the system could deliver APV-I operation capability anytime anywhere and also APV-II capability to most of Japan. The SBAS could not provide APV operations unless protection levels are reduced enough less than alert limits, even if the positioning accuracy were greatly improved. It is not necessary, so far, to improve accuracy; reducing protection levels is the most important and urgent problem for the current SBAS architecture.

Figure 4 illustrates VPL and ionospheric component of VPL during storm ionosphere. VPL grows large daytime, but decreases to the levels of quiet ionospheric condition (also see Figure 3) in nighttime. This implies that VPL is affected largely by the ionosphere. In fact, seeing ionospheric component of VPL (Blue curve), it is clear that most of VPL was come from ionosphere and effects of other components (UDRE and troposphere) are little. It is necessary to reduce ionospheric component of VPL, i.e. GIVE (grid ionospheric vertical error), to achieve smaller VPL for better system availability.

Ionosphere is the dominant term in computation of Protection Levels, while Table 3 indicates the actual largest error is much smaller than protection levels. Let us see relationship between vertical ionospheric correction residuals and UIVE (user ionospheric vertical error) shown in Figure 5. 5.33 UIVE overbounds the actual residuals with a large margin regardless of the magnitude of the actual residuals. Note that these examples are observed during the historical severe magnetic storm conditions. There is no doubt that overbounding the actual residuals is the fundamental purpose of UIVE, but such margin looks too conservative and in fact sacrifice the system availability.

UIVE is provided as shown in Figure 6 without the storm detector algorithm. Comparing Figures 5 and 6, the large UIVE is resulted in by trip of storm detector. It is important that the actual ionospheric residual exceeded 5.33 UIVE only once (at 03/10/31 14:40:00, lower right in Figure 6) even there is no storm detector. The storm detector certainly protects users from possible large ionospheric residual exceeding 5.33 UIVE, however there were only a few effective true alerts even during storm ionospheric conditions and the others are all false alerts.

Introduction of Zeroth Order Fit

The ionospheric storm detector described in Eqn. (7) caused a lot of false alert conditions lowering system availability. To avoid such a problem there are two possible ways:

(i) Develop an alternative safety mechanism instead of the storm detector;

(ii) Develop a method to compute GIVE values instead of setting to the maximum when storm detector trips.

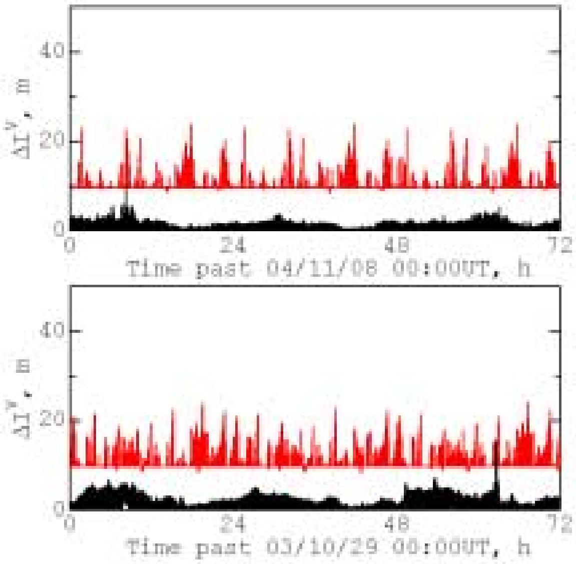

Figure 6. UIVE without the storm detector algorithm. Compare with Figure 5.

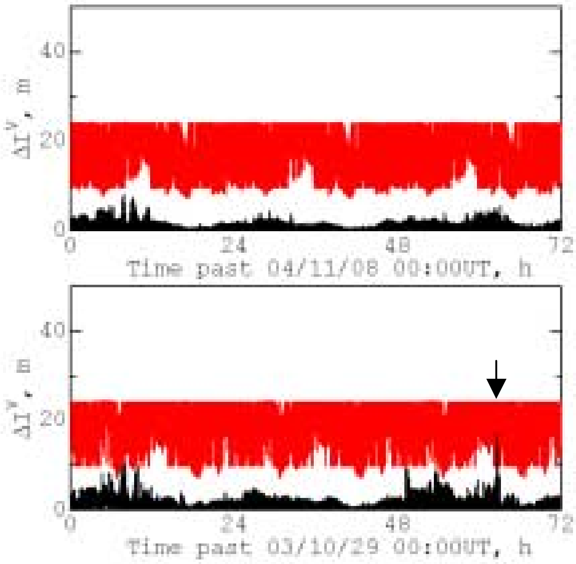

Figure 7. Vertical ionospheric residual error and UIVE produced by the zeroth order fit; (Black) Actual residual error; (Red) 5.33 UIVE. Note that the large residual at 03/10/31 14:40:00, indicated by the black arrow, is also bounded within 4.823 UIVE.

The authors have already proposed both algorithms. An overbounding algorithm based on geometry monitor concept was described in [7] as method (i); and the zeroth order fit [6] is also available as method (ii). Here we have tried the zeroth order fit, the latter method, as follows.

According to the standard storm detector algorithm [9], GIVE will be set to the maximum (GIVE=45m; GIVEI=14) if chi-square statistics exceeded the threshold for the associate IGP. Chi-square statistics is computed by Eqn. (7) therefore large chi-square means planar model is not applicable to the associate IGP because the distribution of fit residuals from the plane is no longer the normal.

It is still possible to apply any ionosphere models other than planar even if chi-square test determined planar model is not applicable. There are many possible algorithms; one way is decreasing the order of fit. It is quite reasonable to decrease the order of estimation, or to reduce the number of unknown parameters to be estimated, is quite reasonable when the observation is noisy or the exact model is unknown. We have little knowledge on the physical structure of stormy ionosphere so far, then increasing the order is not recommended for such a condition.

We employ the zeroth order fit when the storm detector trips or the number of IPP is insufficient. Even for the zeroth order, the above procedure for generating Ionospheric corrections in Eqn. (1) to (5) needs no modifications. Note that the design matrix G becomes $N \times 1$. In order to increase availability of ionospheric corrections, parameters determining the number of IPPs for fit are set to $N_{\max} = 10, N_{\min} = 5$.

At first, the zeroth order fit algorithm without the storm detector was implemented in our prototype system and evaluated during storm ionospheric conditions. No adaptive algorithms are implemented at this step; the zeroth order fit always applied. Table 4 summarizes resulted performance. Comparing with Table 3, RMS

Table 4. Performance by the zeroth order fit; (Upper) RMS error; (Middle) Max error; (Lower) RMS Protection Level; Units are in meters.

Period	Iono-sphere	940030		940058		940083		950491		92003		Max δ_v
		Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	
2004 11/8-10	Storm	1.520 8.653 30.93	1.657 9.725 49.36	0.957 7.435 25.60	1.455 11.24 43.28	0.961 6.713 28.53	1.495 12.77 48.00	1.443 9.788 35.71	2.062 11.34 58.89	2.929 18.76 44.31	3.086 20.81 75.37	2.940
2003 10/29-31	Storm	0.916 4.047 35.04	1.164 6.826 55.02	0.528 5.242 33.09	0.701 6.269 52.63	1.107 11.56 43.63	1.428 11.56 68.06	1.773 14.74 45.22	2.239 19.56 70.62	3.420 15.82 46.35	3.531 17.53 80.89	4.823

Table 5 Performance of the adaptive algorithm; (Upper) RMS error; (Middle) Max error; (Lower) RMS Protection Level; Units are in meters.

Period	Iono-sphere	940030		940058		940083		950491		92003		Max
		Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	δ_v
2005 11/14-16	Quiet	0.360 2.130 19.50	0.421 2.517 31.49	0.305 1.723 18.75	0.414 2.344 31.64	0.339 1.377 19.10	0.510 4.631 33.79	0.468 4.160 21.22	0.643 3.748 37.18	1.219 5.763 51.10	1.184 6.175 59.34	2.597
2004 11/8-10	Storm	1.507 8.343 27.31	1.662 9.697 41.83	0.953 7.457 22.93	1.449 11.28 37.36	0.973 6.641 24.69	1.482 13.08 41.05	1.430 9.505 29.73	2.035 11.30 48.65	2.987 18.69 38.26	3.184 32.01 65.21	2.940
2004 7/22-24	Active	0.431 2.318 33.27	0.561 4.684 40.77	0.381 2.867 32.05	0.533 5.451 39.22	0.396 1.998 35.51	0.589 3.766 42.17	0.581 2.152 37.30	0.772 4.359 44.16	0.823 3.243 52.28	1.352 11.85 62.42	1.665
2004 6/22-24	Quiet	0.396 2.197 32.90	0.602 4.775 39.72	0.424 2.634 35.61	0.600 3.550 43.30	0.384 1.757 36.01	0.645 3.930 42.04	0.490 2.415 37.74	0.771 4.755 44.34	0.708 2.771 51.92	1.078 6.790 60.40	1.388
2003 10/29-31	Storm	0.916 4.047 32.73	1.194 6.918 48.88	0.532 5.219 31.32	0.689 4.938 47.87	1.138 11.81 40.14	1.456 10.00 61.95	1.788 14.74 41.13	2.256 19.56 64.01	3.453 15.56 44.01	3.513 18.06 73.00	4.823

position accuracies are slightly improved, and, more importantly, protection levels are reduced down to one third relative to the current algorithm.

Figure 7 illustrates relationship between the actual vertical ionospheric delay and UIVE produced by the zeroth order fit. The largest normalized residuals of ionospheric corrections, δ_v, were 2.940 and 4.823, both less than 5.33, for two periods of November 2004 and October 2003, respectively. The large residual at 03/10/31 14:40:00, indicated by the black arrow, is also bounded within 4.823 UIVE. This means that the ionospheric correction residuals are protected enough by UIVE even during the most severe storm condition and no additional mechanism like the storm detector is necessary for the zeroth order fit.

Adaptive Algorithm

The zeroth order fit has capability of keeping the actual ionospheric correction residuals within 5.33 UIVE so it does not need additional algorithm like the storm detector. The zeroth order fit means actually simple weighted average so this is robust estimation.

As the authors previously reported, the zeroth order fit can be performed in case that the number of IPPs is insufficient in order to improve availability of the ionospheric corrections as well as when the storm detector trips [6]. Here we introduce an adaptive algorithm as follows;

1. Apply the standard planar fit with the storm detector;
2. If storm detector does not trip, employ resulted correction and GIVE;

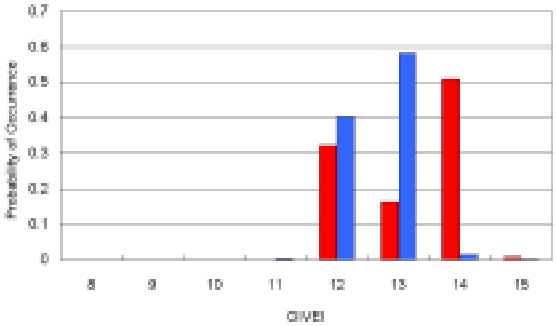

Figure 8. Distribution of GIVEI during storm iono-spheric condition in November 2004; (Red) Baseline algorithm; (Blue) Adaptive algorithm reduced the maximum GIVEI=14.

3. Otherwise, or the number of IPPs is insufficient for the standard planar fit, perform the zeroth order fit.

Clearly this algorithm would reduce the maximum GIVEI events (GIVEI=14) because the zeroth order fit possibly produces lower GIVEI when the storm detector trips. Figure 8 compares the distribution of GIVEI produced during a storm event in November 2004. By using the adaptive algorithm GIVEI were reduced to 13 which means $\sigma_{GIVE,IGP}$ = 4.559 m for most of IGPs, while the baseline algorithm produced the maximum GIVEI=14 relating to $\sigma_{GIVE,IGP}$ = 13.68 m for 50% of IGPs.

Figure 9 shows an example of vertical protection levels produced by the adaptive algorithm during storm ionospheric conditions. Comparing with Figure 4, VPL were reduced down to one third relative to the current

Table 6 Availability for APV-I operation; (Upper) Baseline algorithm; (Lower) Adaptive algorithm.

Period	Ionosphere	940030	940058	940083	950491	92003
2004 11/8-10	Storm	37.1 % 77.6 %	36.9 % 86.8 %	39.1 % 81.6 %	38.3 % 68.7 %	25.7 % 33.8 %
2003 10/29-31	Storm	28.4 % 59.0 %	25.9 % 62.1 %	15.8 % 34.9 %	19.9 % 33.9 %	14.0 % 18.7 %

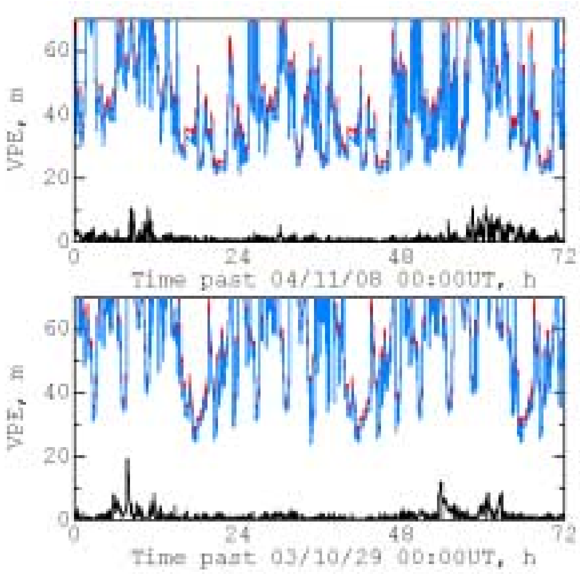

Figure 9. Vertical Protection Levels at Site 950491 during storm ionospheric condition by the adaptive algorithm; (Black) Actual user error; (Red) VPL; (Blue) Ionospheric component of VPL. Compare with Figure 4 with care about the vertical axes.

baseline. This means the adaptive algorithm will contribute to improve the availability of the SBAS

In fact, the adaptive algorithm achieved the performance shown in Table 5. Like the performance of the zeroth order fit, RMS position accuracies are slightly improved and protection levels are reduced down to one third relative to the baseline algorithm. The protection levels are further improved from the zeroth order fit, with sacrifice of slight degradation of positioning accuracies. The largest normalized residual of ionospheric corrections were within 5.33 for every period including the historical severe storm conditions.

Table 6 compares availability of the SBAS for APV-I operation which requires HAL=40m and VAL=50m between two algorithms. The proposed adaptive algorithm improves availability to 60-80% over mainland of Japan. However, it is still necessary to further reduce protection levels for operations in the southern part of Japan.

CONCLUDING REMARKS

The authors firstly reported the performance of the prototype system of SBAS successfully implemented and tested by ENRI. It generated the complete SBAS message stream and evaluated with the SBAS receiver simulator. For quiet ionospheric conditions, the horizontal accuracy was 0.3 to 0.6 meter and the vertical error varied 0.4 to 0.8 meter, both in RMS manner. The historical severe ionospheric activities might disturb and degraded the positioning performance to 2 meters and 3 meters for horizontal and vertical, respectively.

In all cases, both horizontal and vertical protection levels have never been exceeded by the associate position errors regardless of ionospheric activities. This means the system provided the complete integrity function protecting users from the large position errors inducing integrity break.

As an application of this prototype system, the authors evaluated the current and improved ionospheric correction algorithms in a practical manner. It is operational problem that protection levels tend to grow large based on productions of the current algorithm. It was shown that the proposed algorithm of adaptive switching between the planar and zeroth order fit reduced protection levels down to one third relative to the current baseline algorithm. The availability of APV-I operation was improved to 60-80% over mainland of Japan for storm ionospheric conditions.

The prototype system is useful tool for this kind of evaluation of the algorithms inside MCS of the SBAS. Further analysis will be performed using the prototype towards APV-II operations. There is also a plan to operate the prototype system in online mode with realtime monitor stations being installed.

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