Augmentation Performance of QZSS L1-SAIF Signal

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BIOGRAPHY

Takeyasu Sakai is a Senior Researcher of Electronic Navigation Research Institute, Japan. He received his Dr. Eng. in 2000 from Waseda University. He is currently developing the prototype software of satellite-based augmentation system (SBAS) and also working for design of QZSS augmentation message. He is a member of the MSAS Technical Review Board of JCAB.

Sonosuke Fukushima is a senior researcher at Electronic Navigation Research Institute (ENRI), Japan. He received his M. Eng. in Electronic Engineering from the University of Electro-Communications (UEC). Since 1998 he has been working at ENRI. He is currently working in the field of Ground-Based Augmentation System (GBAS), Airport Pseudolite (APL) and QZSS (Quasi-Zenith Satellite System). Currently, he is also a doctor course student in the Tokyo University of the Marine Science and Technology.

Noboru Takeichi is a Researcher of Electronic Navigation Research Institute (ENRI). He received his Ph.D. in 2002 from the university of Tokyo. After working for Japan Aerospace Exploration Agency he joined ENRI in 2006 and is currently a member of the project team for high-accuracy satellite positioning system.

Ken Ito is engaged in research on a satellite navigation system at ENRI. He is now in charge of highly accurate positioning experiment system using a Quasi-Zenith Satellite.

ABSTRACT

QZSS (quasi-zenith satellite system) is a Japanese satellite navigation program with a regional service coverage planned to be launched in 2009. In order to broadcast radiosignals from high elevation angle into urban canyons, the QZS (quasi-zenith satellite) will be launched into a 24-hour elliptic orbit inclined 45 degrees on which a satellite is kept within a certain range of geographic longitude and stays above Japan at least 8 hours everyday. QZSS will offer both supplement and augmentation signals in order to offer the maximum benefit to users.

QZSS will broadcast GPS augmentation messages on the GPS L1 frequency. For this purpose L1-SAIF (submeter-class augmentation with integrity function) signal has been developed based on SBAS standard because both of them offer similar function to the almost same service area. The target of positioning accuracy with augmentation was set as 1 meter for horizontal. QZSS will also provide the integrity function necessary for safety of mobile users. L1-SAIF augmentation messages are being designed to be upper compatible with SBAS messages; The extended messages are designed to enhance the performance of augmentation system.

Performance analysis of the L1-SAIF augmentation message has been conducted using the prototype SBAS software developed by ENRI. This prototype has capability to simulate L1-SAIF MCS and to generate augmentation message stream which could be used to evaluate the actual position accuracy at any user location. According to the result the target accuracy is likely achievable. The prototype has been operating continuously since April 2006 for long-term test, and so far it is stable and any troubles have never been detected. Furthermore, most recently realtime message generator has been developed and tested with realtime data connection from GEONET observation sites. The prototype is functional and stable even in realtime mode.

INTRODUCTION

Recently some GPS augmentation systems with nation-wide service coverage have been developed in Japan. The MTSAT geostationary satellites for the MSAS (MTSAT satellite-based augmentation system) [1], the Japanese SBAS, were launched in 2005 and 2006, and the MSAS is now undergoing operational test procedures. Additionally, the first QZSS (quasi-zenith satellite system) space vehicle is planned to be launched in 2009, which will broadcast GPS-compatible ranging signals including the wide-area augmentation channel [2][3].

The MSAS has been developed based on the SBAS (satellite-based augmentation system) standard [4] defined by the ICAO (International Civil Aviation Organization) for civil aviation applications. The SBAS basically offers an integrity channel, wide-area differential GPS (WADGPS) service, and addition of a C/A-code ranging signal for users within a continental service area. The frequency and modulation of SBAS signal is same to those of GPS so that the antenna and RF front-end circuit in the receiver could be shared. The SBAS has already been operational in the US since 2003, and one could also receive test signal of EGNOS in Europe and of MSAS in Japan. Now SBAS capable receivers are not expensive in the market.

QZSS is a satellite navigation system with a regional service coverage. In order to broadcast radiosignals from high elevation angle into urban canyons, the QZS (quasi-zenith satellite) will be launched into a 24-hour elliptic orbit inclined 45 degrees on which a satellite is kept within a certain range of geographic longitude and stays above Japan at least 8 hours everyday [5]. QZSS will offer both supplement and augmentation signals in order to offer the maximum benefit to users.

GPS augmentation messages will be provided on the GPS L1 frequency. For this purpose L1-SAIF (submeter-class augmentation with integrity function) signal has been developed based on SBAS standard [4] because both of them will offer similar function to the almost same service area. The target of positioning accuracy was set as 1 meter for horizontal. QZSS will provide the integrity function necessary for safety of mobile users, hence integrity mechanism developed for SBAS is attractive.

Before launch of space vehicles, the authors have conducted performance analysis of the L1-SAIF augmentation message. The analysis may be conducted in some ways; Typical one is model-based analysis which gives the average performance. For more reliable analysis of the performance expected in the actual user environment, it is necessary to simulate MCS (master control station) algorithms of the augmentation system. For this purpose, the prototype SBAS developed by ENRI has been used to simulate L1-SAIF MCS.

The prototype was developed originally for investigation of MSAS performance improvement, but of course could be applied to performance analysis of the QZSS L1-SAIF which employs the same technology referred as wide-area augmentation system. It generates the complete SBAS message stream; Using user receiver simulator, user positioning accuracy could be evaluated at any user locations as the augmentation performance of the system.

In this paper the authors will firstly explain L1-SAIF augmentation signal planned to be implemented as a part of the QZSS program. In addition to the current SBAS messages, some new message types will be introduced to enhance augmentation performance. Then the prototype SBAS software is briefly described with some results of simulation of L1-SAIF performance. It will be shown that L1-SAIF has the potential to achieve the target accuracy for users within the service area.

QZSS AUGMENTATION SIGNAL

It is planned that each QZS space vehicle broadcasts both supplement and augmentation signals at L-band frequency. The former means basic ranging signals compatible with GPS L1C/A, L2C, L5, and L1C, while the latter includes L1-SAIF and LEX signals.

QZSS Program Overview

The fundamental mission of QZSS program is to construct and operate the satellite navigation system other than GPS. The service area of QZSS is limited to regional, therefore QZS will be launched into 24-hour geosynchronous elliptic orbit and kept within a certain geographic longitude range. A QZS will stay above Japan at least 8 hours everyday, therefore three satellites are necessary to provide continuous navigation service from high elevation angle. The navigation payload for the mission is being developed as a technical challenge.

On the other hand, QZSS has actually been developed as a preliminary facility of the national location-based service infrastructure. It is required to broadcast GPS-like signals to capture users as many as possible. In addition,

Table 1. Frequency plan of QZS.

Signal	Channel	Frequency	Bandwidth	Min. Power
QZS-L1C	L1CD	1575.42 MHz	24 MHz	–163.5 dBW
	L1CP		24 MHz	–158.4 dBW
QZS-L1-C/A	L1C/A		24 MHz	–158.5 dBW
QZS-L1-SAIF	L1-SAIF		24 MHz	–161.0 dBW
QZS-L2C	L2C	1227.6 MHz	24 MHz	–161.0 dBW
QZS-L5	L5I	1176.45 MHz	25 MHz	–157.9 dBW
	L5Q		25 MHz	–157.9 dBW
QZS-LEX	LEX	1278.75 MHz	42 MHz	–156.0 dBW

an augmentation signal which enhances position accuracy and integrity performance is also attractive to mobile users.

As a result, QZSS is planned to broadcast both supplement and augmentation signals. The former consists of GPS civilian signals, i.e., L1C/A, L2C, L5, and L1C with minimum modifications. Employing the L1C signal in advance even to GPS, QZSS would provide the cutting-edge navigation signal environment within the service area. Of course the necessary coordination with GPS JPO to broadcast these signals has been in progress. The frequency plan of QZSS is summarized in Table 1. The detail specification is defined by IS-QZSS document [5] to be issued by JAXA, Japan Aerospace Exploration Agency.

L1-SAIF is one of QZSS augmentation signals. The ENRI, Electronic Navigation Research Institute, has been developing signal design for L1-SAIF which is compatible with SBAS signal. Additionally QZS will broadcast experimental ranging signal called LEX on frequency band identical with Galileo E6. The LEX provides 2 kbps data channel for various augmentation experiments.

JAXA is responsible for developing the QZSS space segment, i.e., QZS, and deploying ground facilities including MCS and regional tracking stations. The first QZS space vehicle will be launched in 2009 according to the latest plan.

Augmentation message stream broadcast on L1-SAIF will be generated by the facility installed in the ENRI. The messages are uploaded to QZS via JAXA MCS, then broadcast to users within the service area with modulation identical to the SBAS. L1-SAIF signal has been developed based on SBAS standard [4] because both of them will offer similar function to the almost same service area. The target of positioning accuracy was set as 1 meter RMS. QZSS will provide the integrity function necessary for safety of mobile users, so integrity mechanism developed for SBAS is attractive.

Overview of QZSS L1-SAIF Signal

The structure of QZSS L1-SAIF signal is being defined to have full compatibility to the SBAS L1 signal. The signal frequency is identical with GPS/SBAS L1 (1575.42 MHz). 1.023 Mcps BPSK modulation is employed with right-hand circular polarization The generator of pseudorandom noise code for spreading spectrum is the same with GPS gold code; PRN numbers from 183 to 187 are allocated to QZSS L1-SAIF (See Table 2).

The data rate is 250 bits per second with 1/2 rate FEC encoding, and a message consists of 250 bits, so QZS will

Table 2. PRN assignment for QZS L1 frequency.

PRN	Signal	Satellite
183 to 187	L1-SAIF	QZS #1-5
188 to 192	L1-SAIF	NSC
193 to 197	L1 C/A	QZS #1-5
198 to 202	L1 C/A	NSC

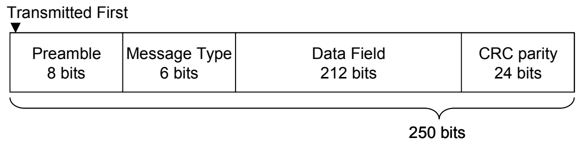

Figure 1. L1-SAIF message structure.

transmit one message per second. The message contents are upper compatible to the SBAS. The only difference from the SBAS signal other than message definitions is Doppler and power variation due to elliptic orbit [5]. Correction to the relativistic effects should also be applied.

Each L1-SAIF message consists of 250 bits, which divided into (1) 8 bits fixed preamble pattern; (2) 6 bits message type ID; (3) 212 bits data field; (4) 24 bits CRC parity, like the SBAS message. Figure 1 summarizes L1-SAIF message format. MSB is transmitted first in each field. Note that FEC encoding is applied to the 250 bits raw message so that preamble pattern could not be used to capture the beginning of message unless FEC is decoded.

Message types 0 to 28, 62, and 63 are assigned compatible with SBAS. QZS will not transmit message types 9 and 17 because these messages contain information dependent upon GEO orbit. Type 12, SBAS network time, and Type 27, SBAS service message, are also not used. Other SBAS-compatible messages are formatted to be identical with SBAS specification; There is no change of message format for these messages.

Extended messages are assigned as message types 52 to 60 as shown in Table 3. Types 52 to 55 are considered to used for atmospheric corrections; Type 56 contains intersignal bias corrections; Types 57 to 59 are assigned to QZS ephemeris and almanac; and Type 60 is for announcement of regional information such as system maintenance schedule.

Wide-Area Differential GPS (WADGPS)

L1-SAIF signal offers the better accuracy to users by employing wide-area differential GPS (WADGPS) technique [6] 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

Table 3. Message types of L1-SAIF.

Type	Contents	Compa-tibility	Status	Type	Contents	Compa-tibility	Status
0	Test mode	SBAS	Fixed	26	Ionospheric delay & GIVE	SBAS	Fixed
1	PRN mask	SBAS	Fixed	27	SBAS service message	Unused	Fixed
2-5	Fast correction & UDRE	SBAS	Fixed	28	Clock-ephemeris covariance	SBAS	Fixed
6	UDRE	SBAS	Fixed	52-55	Atmospheric correction	New	TBD
7	Degradation factor for FC	SBAS	Fixed	56	Intersignal bias	New	Tentative
9	GEO ephemeris	Unused	Fixed	57	QZS ephemeris	New	TBD
10	Degradation parameter	SBAS	Fixed	58	QZS ephemeris	New	Tentative
12	SBAS network time	Unused	Fixed	59	QZS almanac	New	TBD
17	GEO almanac	Unused	Fixed	60	Regional information	New	TBD
18	IGP mask	SBAS	Fixed	61	Reserved	New	Tentative
24	Fast & long-term corrections	SBAS	Fixed	62	Reserved	SBAS	Fixed
25	Long-term correction	SBAS	Fixed	63	Null message	SBAS	Fixed

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.

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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 [4]. 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 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 4 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:

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

Table 4. 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

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:

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

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

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

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

Table 5. L1-SAIF Messaging Capacity.

Message	Type	Messages Required for Constellation	Interval [s]	Messages per min
Fast Correction	2 to 5	3	10	18
Long-Term Correction	25	4	60	4
Ionosphere	26	2	60	2
Troposphere	54 and 55	3	60	3
QZS Ephemeris	58	1	30	2
FC Degradation	7	1	60	1
Degradation Parameter	10	1	60	1
PRN Mask	1	1	60	1
IGP Mask	18	2	60	2
C-E Covariance	28	10	60	10
Total				44
Margin for Other Messages				16

operation mode; for example, HAL=556m and VAL=N/A for terminal airspace; HAL=40m and VAL=50m for 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.

Applying SBAS Messages to L1-SAIF Augmentation

L1-SAIF augmentation messages are designed to be upper compatible with SBAS messages. SBAS messages are employed just as they are except GEO- and SBAS-dependent messages (Message Types 9, 12, 17, and 27). This approach offers the maximum compatibility with SBAS which lowers the cost for modification of receiver software.

It was concerned, however, that the corrections are basically quantized with resolution of 0.125 meter for the most messages of SBAS even our target was 1 meter RMS. To consider this problem, the performance analysis, described in the next section, was conducted and it was shown that submeter-class accuracy could be achieved even with 0.125 meter quantization. Actually reducing quantization resolution did not result in the better accuracy.

On the basis of this result, L1-SAIF messages are, so far, being defined as shown in Table 3. For corrections to clock and ephemeris error, fast and long-term correction messages of SBAS are adequately functional. The ionospheric correction algorithm of SBAS with thin-shell assumption and 350 km shell height is enough for submeter-class augmentation unless severe ionospheric storm conditions which occur a few times per year. Also, taking care of such a condition, L1-SAIF may offer additional atmospheric correction messages as Types 52 to 55. Troposheric delay correction may be applied if necessary.

Type 56 intersignal bias correction message is prepared to make corrections applicable to several signals, such as L2C, L5, and L1C because broadcast corrections are generated based on only L1C/A signal.

Types 57 and 58 QZS ephemeris provide the orbit parameters of QZS itself to enable computing the position of phase center of the space vehicle at time of signal transmission. Type 59 QZS almanac consists of coarse parameters of QZSS space segment for signal acquisition.

Type 60 regional information may enables broadcasting any text message in flexible format to notify users a kind of regional information, such as QZSS maintenance schedule or national disaster information.

According to an investigation with the prototype SBAS described later, message interval for sub-meter class augmentation is expected as Table 5. It is necessary to broadcast 44 messages per minute to achieve the basic performance. The L1-SAIF still have capacity of broadcasting the other 16 messages every minute usable for the advanced atmospheric corrections and regional information.

Note that so far all L1-SAIF messages are tentative and subject to change. IS-QZSS [5] will define the messages in detail.

PERFORMANCE ANALYSIS

Performance analysis of the augmentation system may be conducted in some ways. Typical way is model-based analysis; At first construct appropriate model of ranging accuracy and then project it into position domain. This method is quite simple and gives average performance, however this is very rough estimate and does not reflect MCS algorithms.

For more reliable analysis of the actual performance, we need to simulate MCS algorithms; For example, generating augmentation message enables evaluation of the actual user error; This approach would be a kind of so-called error-based analysis. Here the authors employ the latter approach. Actually ENRI has developed prototype SBAS software applicable to this purpose [7][8].

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

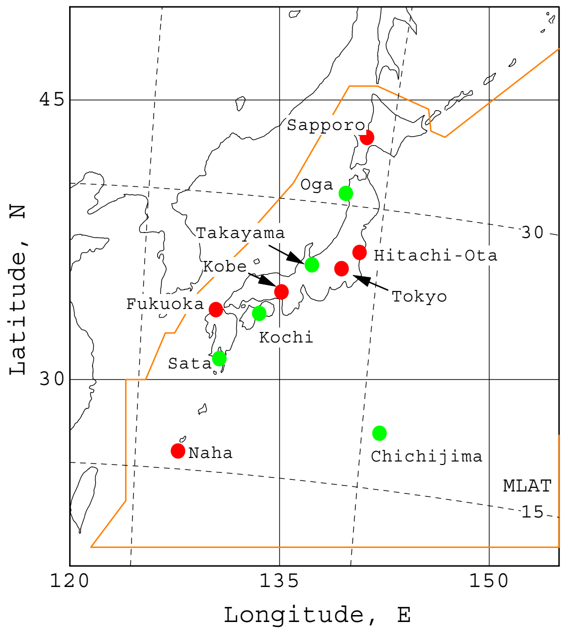

Figure 2. Observation stations for the prototype system. (Red) Monitor stations similar to the MSAS; (Green) User stations for evaluation.

Table 6. 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

civil aviation navigation facilities. The system was tested in offline mode and used for various evaluation activities.

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

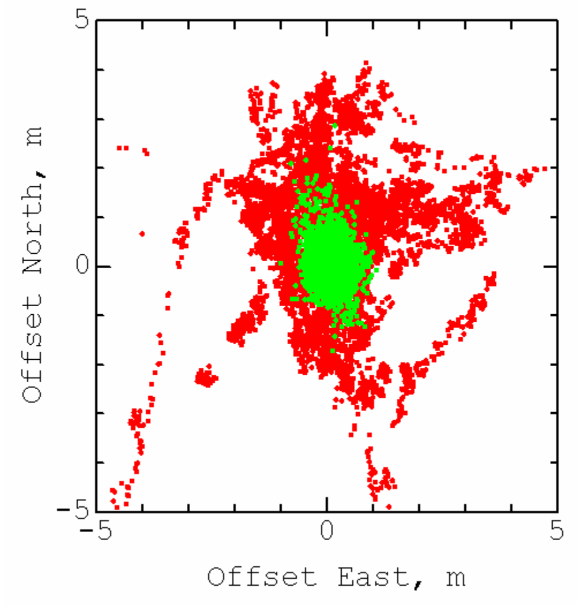

Figure 3. Example of user positioning error at Site 940058 on 22-24 July 2004; (Green) Augmented by the prototype; (Red) Standalone GPS.

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.

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

Table 7. Baseline performance of the prototype system; (Upper) RMS error; (Lower) Max error; Units are in meters.

Period	Iono-sphere	940030 Oga		940058 Takayama		940083 Kochi		950491 Sata		92003 Chichijima	
		Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver
Prototype											
2005 11/14-16	Quiet	0.354 1.695	0.418 2.517	0.304 1.487	0.413 2.123	0.353 1.902	0.508 4.452	0.453 3.302	0.647 6.158	1.132 6.266	1.102 5.958
2004 11/8-10	Storm	1.546 7.479	1.900 11.44	1.157 7.221	1.560 9.265	1.057 6.375	1.559 12.80	1.639 21.90	2.195 23.09	3.302 26.84	3.427 38.86
2004 7/22-24	Active	0.432 2.318	0.566 4.455	0.381 2.867	0.531 5.451	0.403 2.468	0.592 4.240	0.586 2.143	0.764 5.509	0.800 4.487	1.317 9.225
2004 6/22-24	Quiet	0.397 2.047	0.602 4.717	0.425 2.634	0.603 3.466	0.385 1.757	0.649 3.782	0.491 2.415	0.776 4.574	0.708 4.507	1.088 6.595
2003 10/29-31	Storm	0.982 5.645	1.057 6.542	0.659 5.194	0.840 6.652	1.407 14.90	1.863 12.38	2.164 29.42	2.901 36.31	3.121 15.93	3.356 21.67
MSAS											
2005 11/14-16	Quiet	0.381 1.659	0.631 2.405	0.502 4.873	0.728 3.700	0.637 8.517	0.881 9.396	0.640 3.012	0.730 2.680	0.982 6.267	1.014 6.614

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 2. 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 5 summarizes description of monitor stations and user stations.

Table 7 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 ionospheric storm events listed in Table 7 are extremely severe observed only a few times for the last decade. So far, the prototype employs 'Planar Fit' algorithm [9], same as WAAS and MSAS, for ionospheric correction.

In all cases, SBAS receiver simulators computed horizontal and vertical protection levels as the integrity requirements. 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 exceeding protection levels. The maximum errors in Table 7 indicate that the large errors sometimes occurred, but they were all within the associate protection levels.

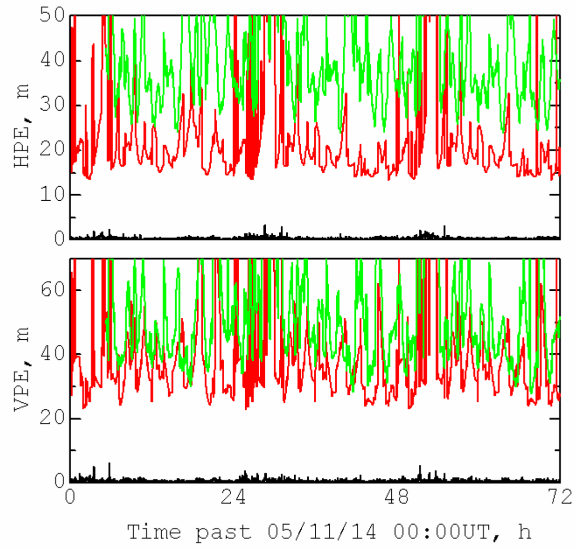

Figure 4. User positioning error and protection levels at Site 950491 during quiet ionosphere; (Black) Actual user error; (Red) Protection levels of the prototype system; (Green) Protection levels of MSAS.

Positioning error was reduced with SBAS messages produced by the prototype system as shown in Figure 3 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 4 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

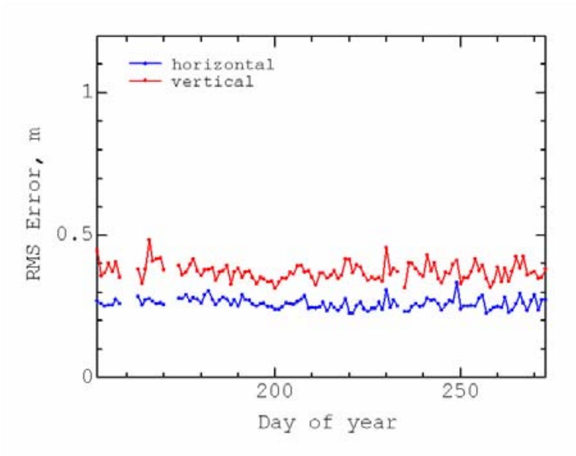

Figure 5. Position accuracy at Site 93011 Kawagoe, near Tokyo, for 4 months from 6/1/06 to 9/30/06.

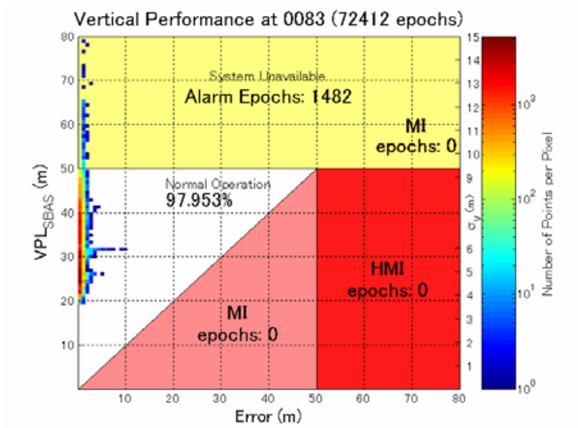

Figure 6. Integrity chart at Site 940083 Kochi, for 30 days from 4/20/06 to 5/19/06. Pairs of the vertical protection level and the associate user position error are plotted as a colored histogram; each plot means the number of points.

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 undergoing operational test, it has been broadcasting test signal. We have received the test signal by NovAtel MiLLennium OEM-3 receiver equipped with SBAS channels at ENRI, Tokyo. 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 7. 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 4. 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.

CONTINUOUS AND REALTIME OPERATION

The prototype has been operated continuously since April 2006 in order to verify the performance of the prototype for long-term [8]. Furthermore recently realtime message generator has been developed which enables the prototype operates in realtime.

Continuous Daily Operation

The prototype has been operated continuously since April 2006 at daily basis with standard configuration of monitor stations and standard filter parameters. Standard configuration means 6 monitor stations distributed similar to the MSAS, and 'Planar Fit' ionospheric correction algorithm.

GPS pseudorange observables are provided from GEONET as daily files. The prototype processes observable input a few days later due to latency of data collection. Generated message stream is also stored as daily files. The performance of generated augmentation message is evaluated with GEONET stations at 40 locations covering the whole Japan for testing integrity.

Figure 5 shows the position accuracy at site 93011 Kawagoe, near Tokyo, for 4 months. The result is promising; The horizontal and vertical accuracy are 0.3 to 0.5 meter. The prototype has been operating stably and did not require any manual operation except reloading data files due to electric power outage.

Figure 6 illustrates an integrity chart for 30 days. The protection levels have never exceeded by user position error, therefore an integrity function of the prototype works completely.

The prototype has still been operating continuously. Generated augmentation messages are stored and disclosed at: http://www.enri.go.jp/sat/pro/data/ppwad . The message archive here is also usable as a source of post-processing wide-area differential correction. The format of augmentation message is identical with

Table 8. Realtime performance of the prototype system; (Upper) RMS error; (Lower) Max error; Units are in meters.

Period	System	940030 Oga		940058 Takayama		940083 Kochi		950491 Sata		92003 Chichijima	
		Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver	Hor	Ver
2007 1/13-16	Prototype	0.582 5.395	0.726 5.707	0.484 4.713	0.609 5.140	0.612 4.584	0.717 4.904	0.995 8.042	1.217 9.260	1.244 11.59	1.850 13.23
	MSAS	0.663 2.504	0.938 5.061	0.643 3.284	0.976 5.250	0.726 6.267	1.197 6.958	0.805 4.651	1.203 5.112	1.156 4.672	1.494 11.41
	GPS Standalone	2.266 7.902	2.608 7.992	1.415 7.059	2.431 10.47	1.695 6.400	2.716 9.657	1.929 7.241	2.494 8.351	2.166 8.439	2.085 6.624

NovAtel's $FRMA record for OEM-3 receivers. SBAS user receiver simulator software is also provided at the same location.

Realtime Operation Trial

The realtime message generator has been developed by ENRI to process realtime observable data stream in addition to RINEX observation files. Up to now realtime data stream outputs from NovAtel OEM-3, Trimble 4000 series, and JAVAD receivers are supported.

The prototype takes receiver data stream via TCP/IP socket connection, then generates augmentation message to be broadcast a few seconds later. This means the prototype generates a bit future message because there is a certain latency due to message relay through MCS, uplink station, and QZS on the orbit.

Most recently realtime operation trial has been conducted with realtime connection to GEONET observation sites. Again the standard configuration of 6 monitor stations was employed. Japan Association of Surveyors has provided realtime data stream to the ENRI through IP-VPN datalink.

Figure 7 shows user position error distribution at Site 940083 Kochi on 1/13/07 to 1/16/07 with and without the augmentation message stream generated by the prototype in realtime mode. The augmentation message is functional and stable even in realtime. Table 8 summarizes the position accuracies at user locations same as Table 7.

CONCLUDING REMARKS

The authors firstly described L1-SAIF signal planned as a part of Japanese QZSS program. L1-SAIF which offers wide-area augmentation to GPS for users within the service area will be broadcast by the QZS. ENRI is responsible for development of L1-SAIF augmentation message.

The prototype SBAS developed by ENRI has been used as a simulator of L1-SAIF MCS. Using this tool the performance of L1-SAIF is evaluated and shown that the

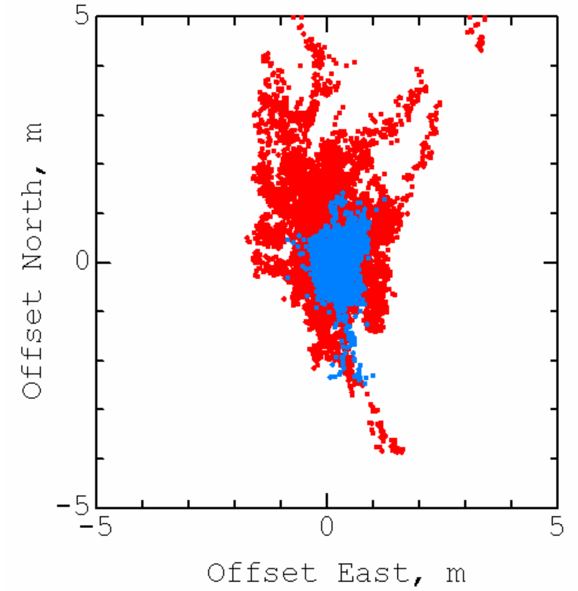

Figure 7. Sample user positioning error at Site 940058 Takayama on 13-16 Jan. 2007; (Blue) Augmented by the prototype in realtime mode; (Red) Standalone GPS.

target accuracy of 1 meter for horizontal is likely achievable. The prototype has been operating continuously since April 2006 for long-term test, and so far it is stable and any troubles have never been detected. Furthermore, most recently realtime message generator has been developed and tested with realtime data connection from GEONET observation sites. The prototype is functional and stable even in realtime mode.

The augmentation message stream generated by the prototype SBAS operating continuously is stored and disclosed at: http://www.enri.go.jp/sat/pro/data/ppwad . SBAS user receiver simulator software is also provided.

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