3-1-2 Air Navigation with Global Navigation Satellite Systems and the Ionospheric Effects

**SAKAI Takeyasu, MATSUNAGA Keisuke,
YOSHIHARA Takayuki, and SAITO Susumu**

Global navigation satellite system(GNSS) is now used in air navigation. Ionospheric delay in radio wave propagation is one of the most serious problems in using GNSS. Since not only the accuracy but also the safety is very important in air navigation, augmentation systems are necessary to ensure the safety. SBAS(Satellite-based Augmentation System), which covers a wide area with geostationary satellites, or GBAS(Ground-based Augmentation System) which covers a local area around an airport is among those augmentation systems. They are now partially in operation. Local ionospheric delay gradient is a threat to these systems. Measures to protect users from the threat of the ionospheric gradient prevent the advanced use of GNSS in air navigation. If ionospheric gradients were effectively detected without fail and users were timely notified about it, GNSS would be utilized in a more advanced way in air navigation.

Keywords
Air navigation, Global navigation satellite system, Satellite-based augmentation system, Ground-based augmentation system, Ionospheric anomaly

1 Introduction

In recent years, global navigation satellite systems (GNSS) as typified by the Global Positioning System (GPS) have come into advanced use in the air navigation industry. Ionospheric delays can be a major source of error in GPS usage and how to correct those delays poses a key challenge. Both safety and accuracy are of critical importance to air navigation. Several augmentation systems designed to assure safety have already been developed and put to practical use on a limited scale.

This report discusses the concept of integrity—an essential element of air navigation applications based on a global navigation satellite system—and how to assure integrity. It then introduces the augmentation systems used with global navigation satellite systems and the measures built into those augmentation systems to address ionospheric effects.

2 Ionospheric delays and global navigation satellite systems

GPS is a global navigation satellite system administered by the U.S. The GPS receiver monitors radio signals broadcast from at least four GPS satellites (global navigation satellites) and then measures distances to those satellites, thereby computing the current location of the receiver[1]. The earth's atmosphere between global navigation satellites (e.g., GPS satellites) and ground-based receivers affects radio wave propagation. Plasma present in the ionosphere that forms part of the earth's atmosphere slightly varies the refractive index of radio waves, resulting in the velocity of radio wave propagation in the ionosphere being varied from the velocity of light in the vacuum. Because satellite positioning uses the radio wave propagation time to estimate distance, changes in the velocity of radio wave propagation are directly related to positioning errors. Refractive index n and group refractive index n' in the plasma can be expressed in equations as:

$$n = 1 - \frac{e^2 n_e}{8\pi^2 m_e \varepsilon_0 f^2} \quad (1)$$

$$n' = 1 + \frac{e^2 n_e}{8\pi^2 m_e \varepsilon_0 f^2} \quad (2)$$

where, e denotes the quantum of electric charges, n_e the electron density, me the electron mass, ε_0 the electric constant, and f the frequency. Here, phase velocity v and group velocity v' of radio waves can be expressed in equations as:

$$v = \frac{c}{n} \quad (3)$$

$$v' = \frac{c}{n'} \quad (4)$$

Given the relation $n < 1$, $n' > 1$, the phase of radio waves in the plasma advances while the propagation of information is delayed. Because the propagation time equals the inverse of velocity of propagation integrated between the satellite and receiver, group delay τ caused by ionospheric plasma can be expressed as:

$$\tau = \int_{sat}^{rec} \frac{n'-1}{c} dl \quad (5)$$

This value can be converted to distance as:

$$d = \frac{40.3}{f^2} \int_{sat}^{rec} n_e dl \quad (6)$$

The phase delay may be converted to distance as:

$$\phi = \int_{sat}^{rec} (n-1)\, dl = -\frac{40.3}{f^2} \int_{sat}^{rec} n_e dl \quad (7)$$

where, λ denotes the radio wavelength. Obviously, the group delay distance and phase delay are proportional to the total electron content (TEC) integrated by the electron density between the satellite and receiver, and assume identical absolute values with opposite signs. Because both TEC and frequency are positive values, the phase delay is always negative, so that the phase advances in plasma. This means that the phase of the carrier measured by GPS advances (shortens) while the code pseudo-range lengthens. The total number of 10^{16} electrons per square meter is expressed as 1 TECU. Figure 1 plots the group delays per TECU relative to frequencies, indicating 0.16 m, 0.27 m and 0.29 m at GPS L1 (1.57542 GHz), L2 (1.22760 GHz) and L5 (1.17645 GHz), respectively. The typical TEC during the solar maximum and minimum in spring and autumn in the vicinity of Japan is 70 TECU in the daytime and 15 TECU at nighttime. This corresponds to delays of 11 m, 19 m and 20 m in the daytime and 2.4 m, 4.0 m and 4.4 m at nighttime at frequencies L1, L2 and L5, respectively.

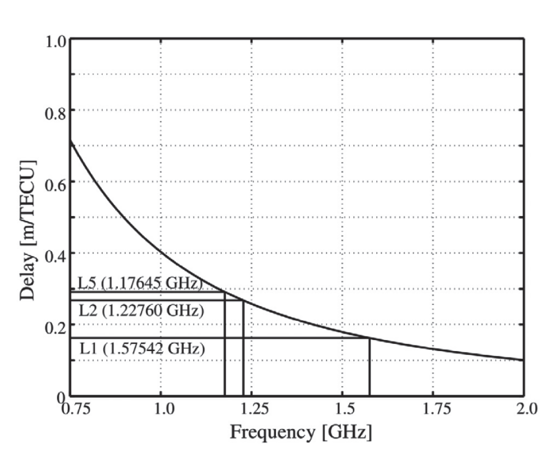

Fig. 1 Group delays per TECU relative to frequencies

3 Impact on GPS and countermeasures

3.1 Impact on GPS

As explained in the foregoing section, the ionospheric delay present in the code pseudorange of a GPS satellite signal is proportional to TEC along the path of radio wave propagation and generally gets larger with a lower-elevation-angle satellite. While ionospheric delays are manifested as range errors on individual GPS satellites, these delays adversely affect the ultimate positioning solution or the accuracy of estimating the observation point coordinate location and receiver clock, as errors. How the range error in the code pseudo-range caused by an ionospheric delay affects these estimates depends on the number of satellites available and satellite location (geometry), but its impact is generally known to worsen positioning accuracy in the vertical direction. Although DOP (dilution of precision) is available as an index to assess the impact of GPS satellite location on the positioning solution by assuming equal range errors present in the pseudo-ranges of GPS satellites, the practical job of assessing a degraded positioning solution in which ionospheric delays are factored should consider that the effects of range errors caused by ionospheric delays are varied among GPS satellites.

In GPS-based precision surveys, ionospheric delays are typically corrected using the carrier phase of two frequencies (L1 and L2). In air navigation applications concerned with real-time processing and safety, the ionospheric correction with carrier phase of L1 and L2 is not directly used, since code pseudo-ranges are mainly used and the L2 band is not globally protected as a navigation band. In some augmentation system implementations, however, the ionospheric correction with the L1 and L2 signals may be used to generate ionospheric delay correction information.

3.2 Correction based on navigation messages

Navigation messages that are broadcast from GPS satellites include GPS satellite orbit information, plus ionospheric correction parameters. As a means of ionospheric delay correction based on navigation messages in the point positioning with code pseudo-ranges, daily variations are approximated on an ionospheric delay model (Klobucher model[2]) derived by adding a constant nighttime ionospheric delay of 5 ns (1.5 m), plus the upper half of a cosine function peaking at 14 hours (local time), to a daytime ionospheric delay. The amplitude and period of the cosine function are each represented in a cubic polynomial of the geomagnetic latitude, and a total of eight coefficients are conveyed by navigation messages. An ionospheric thin-shell model is postulated for calculating ionospheric delays and its point of intersection with the path of GPS radio wave propagation is called an ionospheric pierce point (IPP). Note that the ionospheric delay model introduced above uses the geomagnetic latitude of the IPP of each GPS satellite observed. A lower-elevation satellite tends to post a larger ionospheric delay. This effect is expressed by multiplying each ionospheric delay by an inclination factor that allows for the angle of incidence of GPS radio waves at the IPP.

3.3 Differential correction process

The usefulness of corrections implemented using an ionospheric delay model like the one introduced above generally diminishes as ionospheric delays involved in the observed values deviate farther from the model. As a solution to enhanced positioning accuracy, a differential correction method is used for generating corrections in real time from actual observation data, coupled with transmission to user stations also in real time to boost positioning accuracy. This differential correction process uses GPS reference stations of known locations and calculates range errors involved in the code pseudo-range from the observed values, thereby extracting such inherent common errors as GPS satellite orbit error, GPS satellite clock error, ionospheric delay and tropospheric delay for use as correction information.

The differential correction process can be broken down into local and wide-area differential correction according to intended use. Local differential correction, useful in the vicinity of reference stations, generates correction information as common error information without distinguishing ionospheric delays from error sources, such as GPS satellite orbit errors and tropospheric delays. Local differential correction tends to yield high accuracy due to its relative technical simplicity, but its correction information characteristically degrades as users are located far away from the reference stations. Wide-area differential correction involves a network of reference stations deployed within the service coverage to break down the range errors involved in these code pseudo-ranges by error source, and thus generates correction information for transmission to the users. For this reason, measurements using the dual-frequency carrier phase of L1 and L2, and the gridding of correction information are typically used with regard to ionospheric delays.

4 GPS for air navigation

4.1 Air navigation and integrity

The usefulness of GPS for aircraft navigation has been recognized from the beginning, but a key challenge was how to assure integrity. Integrity here refers to the ability to guarantee that a navigation system is error-free, and promptly issue a warning in case the system becomes unfit for navigation purposes due to, for example, the failure to provide intended positioning performance. Securing integrity calls for a means of immediately detecting any abnormal signal transmitted from a GPS satellite and reporting it to users.

GPS positioning accuracy is adequate for aircraft navigating en route. However, GPS only has five monitor stations located worldwide, making it insufficient for immediately detecting satellite failures in real time and reporting those failures to users. Moreover, each national government is responsible for providing a means of air navigation (with the Japan Civil Aviation Bureau being responsible in this country), and full-scale dependence on the U.S. navigation system (including the issue of assuring integrity) would prove difficult.

Keen to work out international standards for civil aviation including navigation systems, the International Civil Aviation Organization (ICAO) instituted the Global Navigation Satellite System (GNSS) panel in 1993 to drive its pursuit of global navigation satellite systems. The panel termed a global navigation satellite system that provides performance available for civil air navigation purposes as GNSS, and introduced an international standard known as GNSS Standards and Recommended Practices (SARPs) in November 2001[3]. According to GNSS SARPs, GNSS is defined to encompass ground receivers and ground monitoring facilities, as well as artificial satellites. It is configured of GPS or GLONASS (a core system) with an augmentation system. GNSS SARPs also define the performance requirements to be fulfilled by GNSS.

Three kinds of augmentation systems are defined as follows: (i) SBAS (satellite-based augmentation system), which transmits augmentation signals in wide-area on a continental scale by means of geostationary satellites, (ii) GBAS (ground-based augmentation system), which provides local augmentation on VHF waves targeting areas around airports, and (iii) ABAS (aircraft-based augmentation system), which provides augmentation only with the aid of equipment mounted on-board aircraft. Among these, SBAS and GBAS secure a high degree of integrity by monitoring GPS signals with ground monitor stations, and also transmit correction information to offer high user positioning accuracy. SBAS is equivalent a wide-area differential correction system as mentioned earlier; GBAS is equivalent to a local differential correction system.

ABAS is intended to assure integrity by verifying the consistency of information collected by on-board equipment, such as with the aid of redundant GPS signals, but only works for navigation in the horizontal direction because the system cannot secure adequate integrity for positioning information in the height direction. SBAS and GBAS are discussed below from the perspective of the provider of the means of navigation.

4.2 Integrity assurance scheme

GNSS SARPs define the performance requirement for integrity as the probability of user receiver positioning errors being held within an alert limit or the prompt posting of positioning errors to the user in case user receiver positioning errors exceed the alert limit. In other words, this refers to the probability of events where positioning errors are held below the alert limit not occurring, without being notified to the user. This probability is defined as $1-10^{-7}$ per hour for aircraft en route or $1-2\cdot10^{-7}$ for aircraft approaching and landing on a runway.

The alert limit requirement would vary as a parameter of in-flight airspace, and its value had not been determined in the stages of augmentation system development. For this reason, the confidence limit for user positioning errors occurring in a service volume has been assigned a significance level of 10^{-7} or less on this augmentation system. This confidence limit is called a “protection level,” and the augmentation system transmits information allowing user receivers to calculate the protection level. The augmentation system must ensure that the probability of user positioning errors exceeding the protection level is held below 10^{-7}. Under this framework, when the protection level is below the alert limit, GNSS is assumed functional in the current airspace (Fig. 2). If user positioning errors are likely to exceed the alert limit for some reason, the protection level rises proportionately to exceed the alert limit, thereby allowing for abnormal conditions to be detected and posted to users

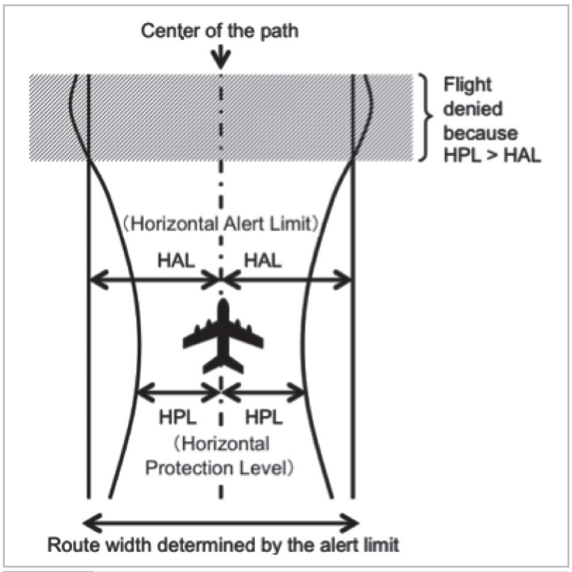

Fig.2 Protection level and alert limit

If the protection level calculated by a user receiver for a given airspace exceeds the alert limit, then GNSS is made unavailable in that airspace. Accordingly, a lower protection level setting would make a navigation system easier (more accessible) to use (more available), but this entails a tradeoff with the integrity requirement for meeting the user positioning error-protection level relation.

4.3 Integrity threats

A certain level of hardware reliability is required to assure integrity, but the availability of error-free information to users assumes essential importance. If a system is shut down due to inadequate hardware reliability, system continuity would suffer, not integrity. From the standpoint of integrity, it would be better to shut down the system instead of delivering invalid information to users as far as efficiency is concerned. The kind of invalid information that threatens integrity or could produce a user positioning error exceeding the protection level is called “hazardous misleading information (HMI).”

The user positioning error-protection level relation discussed above must always be met at any point whatsoever in a service area. This means that the integrity requirement must be met in even the worst case among multiple cases, rather than being met by the collective average of all those cases. A very high level of integrity is sought (10^7 hours = 1,141 years), which virtually inhibits the occurrence of user positioning errors beyond the protection level. In the practical process of authenticating SBAS or GBAS as a navigation system, it is necessary to ensure that user positioning errors do not exceed the protection level and are kept sufficiently small.

Assuring integrity entails the work of assessing the probability and size of HMI relative to each individual positioning error, and taking relevant measures as appropriate. Even error sources that can cause positioning errors would not translate into HMI when easily detectable by a ground station. Moreover, even hardly detectable error sources would be of no concern if only leading to minor positioning errors. Easily detectable errors sources are typified by GPS satellite clock and orbit errors; hardly detectable ones involve tropospheric propagation delays.

Each individual factor identified to translate into HMI is called a “threat.” Measures must be taken to prevent each individual threat from resulting in HMI. Among these measures, the “monitoring” process is designed to suit the characteristics of a given threat and be implemented within SBAS or GBAS. When threats are detected by monitoring, actions are invoked, such as increasing the protection level, to prevent threats from resulting in HMI.

The upper panel of Fig. 3 shows a conceptual image of the probability distributions of GNSS positioning errors. Normal distributions (marked green) in the middle designate positioning errors that may result from various factors; the spike in distributions apart from normal distributions represents lower-frequency events that could invoke major errors. Correctable events are marked blue; uncorrectable events are marked red. As can be seen from the lower part of the diagram, SBAS and GBAS apply correction information to make normal distributions appear more compact, while delivering valid integrity information to eliminate any threats that could definitely resulting in HMI, thereby protecting the users.

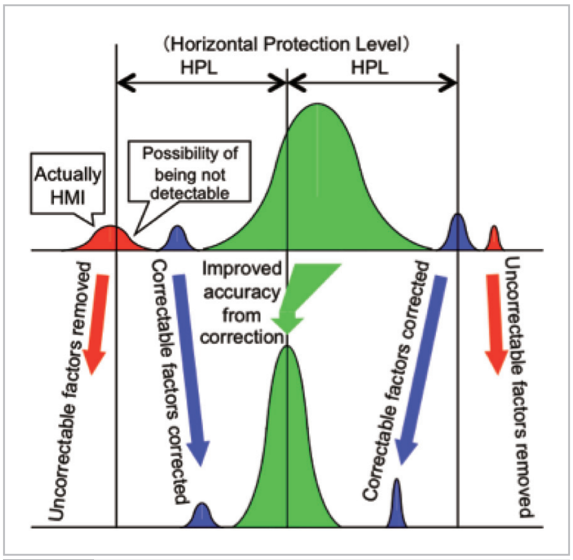

Fig.3 Concept of positioning error distribution
(Upper) GNSS without augmentation
(Lower) Effect of the augmentation system

4.4 Ionospheric storm effect

The most serious of all prevailing integrity threats is the effect from propagation delays associated with ionospheric storms. Although ionospheric storms may not occur frequently, they occur at other than a negligible level. Ground monitor stations do not necessarily detect ionospheric storms as they occur, with such storms being manifested as major user positioning errors that could result in an HMI event where the user positioning error exceeds the protection level.

SBAS and GBAS provide protection against this problem by assuming the continuing presence of ionospheric disturbances in generating integrity information, and also by factoring a sufficient margin into the protection level to discourage users from using a possibly hazardous satellite. The worst case of ionospheric storms is always assumed based on past records of ionospheric observation data. Moreover, monitors are installed to be able to deal with HMI conditions they have been observed in the past.

Because these precautions are taken, the protection level tends to rise, leaving room for improvement concerning availability. One cause of degraded availability is monitor stations located too sparsely in preparation for a worst case scenario, given their inability to identify normal conditions other than ionospheric storms. Given the insight into the status of ionospheric storms from the standpoint of space weather, a normal protection level free from concern over anticipated ionospheric storms could possibly be drastically lowered for improvement.

5 Actual augmentation systems

5.1 SBAS (MSAS)

5.1.1 How SBAS works

SBAS broadcasts GNSS augmentation information from geostationary satellites to broad sets of users. SBAS consists of ground equipment, geostationary satellites and user receivers.

Normally, multiple ground monitor stations are distributed at intervals of about several hundred kilometers to collect data with receivers enabled for dual-frequency signals originating from a GNSS core system. Satellite-specific orbit/clock errors and ionospheric delays are estimated from the data collected, and integrity information, SBAS satellite ranging data and correction information are generated, which are then uplinked to an SBAS satellite.

SBAS signals have the same frequency and C/A code modulation as GPS-L1, and are assigned pseudo-random noise (PRN) numbers from 120 to 138. This allows signals originating from the SBAS satellite to be used as GPS-like ranging signals. Augmentation information is broadcast at 250 bps, with each message consisting of 250 bits (preamble (8), message type ID (6), data area (212) and CRC (cyclic redundancy check) code (24)).

User receivers use the augmentation information received from the SBAS satellite to work out positioning and integrity information. Tropospheric errors are calculated within the receivers using a model.

5.1.2 SBAS ionospheric correction

SBASs now in service or under development target single-frequency aviation user receivers and users who conduct positioning calculations based on the pseudo-ranges of the GNSS core satellites and SBAS satellites. The methodology is formulated as an ICAO international standard[3].

SBAS is intended for users in a wide area, with ionospheric delay information being broadcast as values at 5˚ x 5˚ ionospheric grid points (IGPs) of geographic longitude and latitude. (At latitude higher than 55˚, the IGP layout varies.) The following types of SBAS messages relevant to ionospheric correction are broadcast:

Type 18: IGP service status flag
Type 26: IGP vertical delay estimate (@L1)
(0 to 63.875 m, 0.125 m unit)
and post-correction vertical error
(residual) variance (index)
Type 10: Time degradation parameters

User receivers calculate ionospheric delays and residual variances by assuming the ionosphere as being a thin shell at an altitude of 350 km. First, the longitude and latitude of the ionospheric pierce point (IPP) of satellite signals received by users from each satellite are calculated. The vertical delays/residual variances at the surrounding IGPs in the longitude/latitude plane are then subjected to bilinear interpolation for calculating values at IPP, which are then multiplied by an inclination factor according to satellite elevation angle for working out the ranging correction/residual variance values. The residual variance is further multiplied by a time degradation factor or other factor to perform positioning and calculate the protection level based on satellite location as described in Section **4.2**.

Each SBAS message has a maximum update time and a user availability time defined as provider service requirements. Table 1 lists the requirements for ionospheric correction messages.

Table 1 *Maximum update times and availability times of SBAS ionospheric correction messages*

Message Type	Maximum update interval [sec]	Time-out interval [sec]	
		En-route to non-precision approach	Precision approach
18	300	1,200	1,200
26	300	600	600
10	120	360	240

How to generate SBAS messages is left to the discretion of each SBAS service provider, but system implementation/verification must be done so as to meet the integrity requirements defined in Section **4**.

5.1.3 Current status of SBAS

SBASs now in service (2009) include MSAS (in Japan) [4], WAAS (in the U.S.) and EGNOS (in Europe), while GAGAN (India) is under development. Figure 4 shows an example of the deployment of MSAS ground stations, along with surrounding IGP and IPP distributions.

As explained in the foregoing section, SBAS is dedicated to providing a broad range of services, but remains vulnerable to constrained performance in low-geomagnetic-latitude regions of intense ionospheric activity due to the delivery of ionospheric correction information such as the values of IGP at 5° latitude, as well as the update rate (600-second message validity). Consequently, SBAS encounters difficulty in offering a high level of integrity ($1-10^{-7}$) while minimizing the protection level in the presence of small spatial/temporal changes in ionospheric delays or spatially small disturbances such as plasma bubbles for the deployment of ground stations.

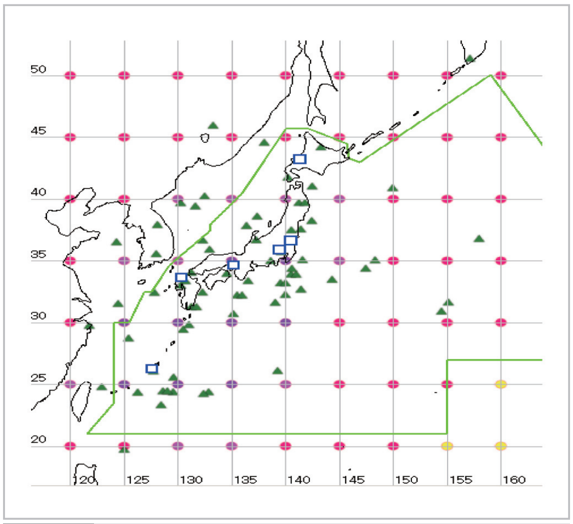

Fig.4 *MSAS ground station layout, IGP location, and examples of IPP distributions*
□ denotes an MSAS ground station (at Sapporo, Hitachi-Ota, Tokorozawa, Kobe, Fukuoka and Naha, with the stations at Hitachi-Ota and Kobe serving as geostationary satellite uplink stations). ● denotes a 5°x 5° longitude/latitude ionospheric grid point (IGP). ▲ denotes the IPP of a GPS satellite monitored by a ground station at a given time (at altitude of 350 km).

Enhanced SBAS ionospheric correction performance should benefit from efforts to explore system capabilities tailored to initial detection and prediction, including the development of ionospheric models useful under the conditions outlined above, deploying ground stations based on those models, and detecting and handling disturbance phenomena.

5.2 GBAS

5.2.1 How GBAS works

A landing guidance system based on a single-frequency differential GPS positioning principle, GBAS is intended for use in the vicinity of an airport (with a minimum coverage requirement of approx. 40 km). Each GBAS has three to four GPS reference stations (GBAS reference stations) deployed on the premises of an airport to generate information on correcting common errors (e.g., GPS orbit errors and ionospheric delays present in code pseudo-ranges of GPS satellite signals, residual error parameters by error source for determining the reliability of positioning solutions calculated by aircraft), and then broadcasting all such information to aircraft on the VHF band (108 to 118 MHz) as augmentation messages like those listed in Table 2 (VHF Data Broadcast (VDB)). Each aircraft performs a positioning process based on the correction information, and calculates the protec-

Table 2 *Contents of augmentation messages generated by GBAS*

Message Type	Contents
1	Differential correction information and more
2	Reference station layout, integrity information (e.g., ionospheric delay, tropospheric delay) and more
4	Final approach path information and more
5	Satellite availability information and more

tion level from residual error parameters to assess in real time whether it is held within tolerances to determine the reliability of its positioning solution.

Pseudo-range errors that may exist at both GBAS reference stations and aircraft to an equivalent extent include GPS satellite orbit errors, satellite clock offsets, ionospheric delays and tropospheric delays. GBAS removes most of these common errors. Other possible errors such as receiver clock errors, receiver noise and multipath errors are reduced by averaging the multiple sources of GPS received data from GBAS reference stations located more than 100 m apart to generate more accurate and reliable augmentation information.

The possible range of guidance supported by landing guidance systems to enable the precision approach of aircraft is specified by ICAO regarding visibility, landing system performance and other factors, and with landing system requirements defined for three levels of the approach and landing phases (Categories I to III)[3]. Category I, for example, supports the initial stage of landing system requirements. Landing systems falling in Category I should provide precision guidance up to a height of about 60 m (200 ft.)—the so-called decision height (DH)—at which the pilot decides whether to land or not.

The positioning principle of GBAS allows the system to deliver significantly high accuracy and its performance has long been verified. In the meantime, integrity (i.e., measure of assuring the validity of generated correction information) has loomed as a key challenge. Category I, for example, defines the probability of not entering a hazardous state due to invalid correction information as being $1-2 \cdot 10^{-7}$ per approach, thereby dictating an extremely high level of reliability. For this and other reasons, mitigation algorithms have been developed for both risk extraction and assessment as needed. In the U.S., preparations are now underway to launch GBAS Category I service. Enhanced ground and on-board equipment may eventually allow GBAS to support operations up to Category III, thus enabling precision guidance down to a height of 0 m.

5.2.2 GBAS ionospheric delays

Because GBAS ionospheric delays exist almost to an equal extent in the psuedo-range data received by both GBAS reference stations and aircraft, most have been thought removable. But GBAS implements a smoothing process for the code-pseudo range called "carrier smoothing" (using a time constant of 100 seconds) to cut multipath errors present in the code-pseudo range based on the carrier phase of the GPS signal. As expressed in Equations (6) and (7), ionospheric delays involved in the code pseudo-range and carrier phase have the same magnitude but opposite polarities, and ionospheric delay contained in the code pseudo-range and that contained in the carrier phase up to 100 seconds before are matters of concern[5]. Therefore, if a spatial gradient of an ionospheric delay (hereinafter "ionospheric gradient") is encountered as an aircraft lands after making the final approach from a point several ten kilometers apart from a GBAS reference station as shown in Fig. 5, it will affect GPS satellites passing over that region.

The ionospheric gradient (dI/dx) is normally expressed as a rate of ionospheric delay change for each horizontal kilometer, and indicated in mm/km units. Assuming that the

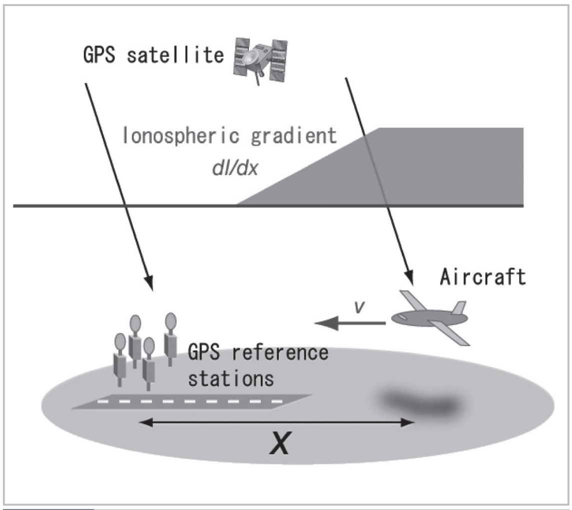

Fig.5 GBAS and ionospheric delay spatial gradient

ionospheric gradient does not change over time and disregarding GPS satellite behavior, maximum δI of range errors in the satellite's line of sight (slant) direction as corrected by GBAS and derived from the ionospheric gradient can be generally expressed in Equation (8) as:

$$\delta I \cong \frac{dI}{dx}(x + 2\tau v) \qquad (8)$$

where, x denotes the separation between the GBAS reference station and aircraft. The first term on the right side designates a range error similar to typical differential GPS resulting from a spatial change in the ionospheric delay; the second term designates the effect of carrier smoothing. In the U.S., GBAS safety design is implemented based on the settings of an ionospheric gradient maximum of 425 mm/km and a horizontal distance of 6 km from a GBAS reference station to the decision height (DH). The range error maximum estimated at DH by solving Equation (8)—with smoothing time constant τ of 100 s and aircraft velocity v of 0.070 km s^{-1} assigned—is calculated to be about 8.5 m [6]. Complications involving adverse conditions such as fewer GPS satellites are generally known to worsen the ultimate positioning solution. As a result, some actual vertical errors are found to exceed a vertical warning limit of 10 m at DH, despite a vertical protection level not exceeding 10 m, and thus suggest the need to employ methods of countering GBAS integrity threats and mitigating risks [7].

5.2.3 Ionospheric risk assessment and mitigation

In the U.S., the ionospheric gradients (called "storm enhanced density" or SED) resulting from magnetic storms have been modeled as an ionospheric front and three parameters (ionospheric gradient magnitude, slope width, and velocity) have been isolated and delimited to build an ionospheric threat model. As a result, the U.S. has adopted possible ionospheric gradient maximums of 425 mm/km and 375 mm/km for high-elevation and low-elevation GPS satellites, respectively [8]. These values are based on ionospheric gradients associated with SED observations made in North America on November 20, 2003.

On the ionospheric threat model, a GBAS reference station may detect ionospheric gradients as sharp time-related changes in an ionospheric delay. Called "CCD monitoring," this method of detection uses time-related changes in CCD (code-carrier divergence), which is derived by subtracting the pseudorange associated with the carrier phase from the code pseudo-range, by leveraging the fact that the code pseudo-range and carrier phase have virtually the same magnitude but opposite polarities [9].

A situation may arise, however, where an ionospheric front has yet to reach a reference station or no error has been detected at a GBAS reference station in sync with IPP velocity, resulting in only aircraft being affected by ionospheric gradient error. To address this possible situation, a method called "geometry screening" has been employed in the U.S. According to this method, conceivable range errors are postulated by assuming that ionospheric gradient errors not detectable by a GBAS reference station always exist on the aircraft, and a subset of GPS satellites that could bring unallowable positioning errors is identified on the ground, so that information with deliberately exaggerated residual errors will be broadcast to prevent the protection level from being used beyond the alert limit when an aircraft attempts positioning calculations in that mix of GPS satellites [8].

In Japan, observations of any ionospheric gradients in excess of several hundred mm/km like those observed in the U.S. have yet to be reported, but the concept of GBAS ionospheric risk assessment should allow for the significant plasma bubbles frequently observed in low-geomagnetic-latitude regions, as well as SED. Two ionospheric fronts varying in polarity arise from a single plasma bubble; two or more plasma bubbles generate far more such fronts. Therefore, a perspective of review different from that of assessing vertical error impact using SED should be worthwhile. In addition, the frequency of plasma bubble occurrence is found characteristically higher compared with that of SED.

With these matters taken into consideration, Electronic Navigation Research Institute is building an ionospheric threat model suitable for Japan, as well as probing and developing mitigation methods. It is also exploring the possibilities of ionospheric storm field monitoring, whereby GPS receiving stations are installed at the end of each runway or elsewhere (apart from a GBAS reference station) to detect spatial ionospheric gradient errors in the runway direction, in addition to detecting abnormal time-related changes in ionospheric delays by using CCD monitoring and eliminating those subsets of GPS satellites that could bring about major positioning errors, by the geometry screening method. Any GBAS integrity risks designed to be held within tolerances via these monitoring and mitigation methods should require verification, but any necessary ionospheric storm field monitoring should entail GBAS installation, increased operational constraints, extra costs and other needs. This is because not all ionospheric anomalies are detectable by a ground reference station. This weakness might well be diffused given the availability of space (ionosphere) weather information that both efficiently and unfailingly contributes to the detection of ionospheric gradients.

6 Conclusions

Recent years have witnessed rapid advances in the pace of utilizing GPS-based navigation systems in the air navigation industry, but how to correct ionospheric delays poses a key challenge relative to GPS usage. Both safe and accurate GPS-based navigation systems are of such critical concern to air navigation that these systems place emphasis on assuring integrity. Moreover, because air navigation is meant to address practical needs, it must be available at any time and accessible to anybody. Hence, these two conflicting requirements must be fulfilled to the extent that safety can be maintained.

SBAS and GBAS utilize different methods of generating differential correction information and integrity information for delivery to aviation users, in order to provide accurate and safe aircraft guidance. Under the circumstances, the local gradients of ionospheric delays are the toughest of all sources of error to control when threatening safety. SBAS and GBAS have measures in place to protect to aviation users against the threats of ionospheric gradients, including securing safety margins to meet relevant international standards and setting system design/operational limits. These measures, however, in turn impede the pace of more advanced GPS utilization.

Developing an ionospheric information system capable of detecting ionospheric gradients both efficiently and unfailingly, and releasing it on a timely basis could definitely help facilitate more advanced GPS utilization in air navigation applications.

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***SAKAI Takeyasu**, Dr. Eng.*
Chief Researcher, Communication, Navigation, and Surveillance Department, Electronic Navigation Research Institute
Satellite Navigation

MATSUNAGA Keisuke
Senior Researcher, Communication, Navigation, and Surveillance Department, Electronic Navigation Research Institute
Satellite Navigation

***YOSHIHARA Takayuki**, Ph.D.*
Senior Researcher, Communication, Navigation, and Surveillance Department, Electronic Navigation Research Institute
Satellite Navigation

***SAITO Susumu**, Ph.D.*
Senior Researcher, Communication, Navigation, and Surveillance Department, Electronic Navigation Research Institute
Aeronomy, Satellite Navigation