12. Satellite Based Augmentation Systems

Todd Walter

Satellite-based augmentation systems (SBASs) are designed to enhance the performance of standard global navigation satellite system (GNSS) positioning. SBASs improve the positioning accuracy by providing corrections for the largest error sources. More importantly, SBASs provide assured confidence bounds on these corrections that allows users to place integrity limits on their position errors. Several systems have been implemented around the world and several more are in development. They have been put into place by civil aviation authorities for the express purpose of enhancing air navigation services. However, SBAS services have been widely adopted by other user communities, as the signals are free of charge and easily integrated into GNSS receivers.

This chapter describes the basic architecture, functions, and application of SBAS. Because the key motivation behind SBAS is integrity, it is essential first to understand the error sources that affect GNSS and how they may vary with time or location. It is then explained how the corrections and confidence intervals are determined and applied by the user. The different SBASs that have been developed around the world are described and how they are developed to the same international standards such that each is interoperable with the others. The performances and services of each system are described. Finally, the evolution of SBAS from its current single-frequency single-constellation form into systems that support multiple-frequencies and multiple-constellations is described.

The goal of this chapter is to explain the motivation for developing SBASs and provide the reader with a working knowledge of how they function and how they may be used to enhance GNSS positioning accuracy and integrity.

12.1 **Aircraft Guidance** 340
12.1.1 Aviation Requirements 340
12.1.2 Traditional Navigational Aids 341
12.1.3 Receiver Autonomous Integrity Monitoring (RAIM) 341
12.1.4 Satellite-Based Augmentation Systems (SBAS) 342

12.2 **GPS Error Sources** 343
12.2.1 Satellite Clock and Ephemeris 344
12.2.2 Ionosphere 344
12.2.3 Troposphere 344
12.2.4 Multipath 345
12.2.5 Other Error Sources 345

12.3 **SBAS Architecture** 345
12.3.1 Reference Stations 345
12.3.2 Master Stations 346
12.3.3 Ground Uplink Stations and Geostationary Satellites 347
12.3.4 Operational Control Centers 349

12.4 **SBAS Integrity** 349
12.4.1 Integrity Certification 349
12.4.2 Threat Models 350
12.4.3 Overbounding 350

12.5 **SBAS User Algorithms** 351
12.5.1 Message Structure 351
12.5.2 Message Application 352
12.5.3 Protection Levels 353

12.6 **Operational and Planned SBAS Systems** 353
12.6.1 Wide Area Augmentation System (WAAS) 353
12.6.2 Multifunction Satellite Augmentation System (MSAS) 356
12.6.3 European Geostationary Navigation Overlay Service (EGNOS) 356
12.6.4 GPS Aided GEO Augmented Navigation (GAGAN) 356
12.6.5 System of Differential Corrections and Monitoring (SDCM) 358
12.6.6 BeiDou Satellite-Based Augmentation System (BDSBAS) 358
12.6.7 Korean Augmentation Satellite System (KASS) 358

12.7 **Evolution of SBAS** 358
12.7.1 Multiple Frequencies 358
12.7.2 Multiple Constellations 359

References 360

12.1 Aircraft Guidance

Satellite navigation is finding ever increasing use in aviation. The utility of satellite navigation is enabled by a variety of augmentation systems. These augmentation systems are independent of the individual satellite constellations and monitor their performance continuously. Most importantly, the augmentations detect faults in real time and warn the pilots within seconds. Such assistance is needed because the constellation ground control system may not detect and report faults for tens of minutes or longer. The fault detection alternatives include aircraft-based augmentation systems (ABASs), ground-based augmentation systems (GBASs), and satellite-based augmentation systems (SBASs). This chapter focuses on SBASs [12.1]. Particular emphasis will be placed on the wide area augmentation system (WAAS, [12.2]), which is the SBAS for North America and was also the first operational SBAS. SBASs have also been developed in Japan, Europe, and India and are being developed in Russia, China, and South Korea.

Currently, SBASs augment the global positioning system (GPS) with the following three services:

- Integrity monitoring to improve safety
- A ranging function to improve availability and continuity
- Differential GPS corrections to improve accuracy.

Thus augmented, GPS meets the performance requirements for most phases of flight, including vertical guidance during airport approach. The first SBAS, WAAS, was commissioned in July 2003. The accuracy of the system rapidly made it an industry standard in GPS receivers. It routinely achieves horizontal accuracies better than 85 cm and vertical accuracies better than 1.2 m 95% of the time [12.3]. SBAS has achieved widespread adoption in nonaviation fields due to its open standard, free provision, and high accuracy [12.4, 5].

12.1.1 Aviation Requirements

Navigation systems used for aviation are judged by four key measures [12.1]:

1. Accuracy: The reported aircraft position must be close to the true position. Accuracy generally characterizes nominal errors and is usually expressed as a 95% confidence number. That is, it is specified as a number $\geq 95\%$ of the nominal position errors. Accuracy is the easiest requirement for SBAS to meet. Integrity, continuity, and availability are all much more difficult to achieve.
2. Integrity: An aviation navigation system must ensure that no position error larger than a maximum tolerable bound is presented to the pilot. All faults that could lead to larger position errors must be flagged within a specified time-to-alert (TTA), and the probability of failing to flag such a fault must be below some small probability per operation, typically between 10^{-5} and 10^{-9} depending on the operation.
3. Continuity: Once an aircraft begins a critical operation, the navigation system must continue to function until the operation is complete. The allowable probability of a navigation system outage during an aircraft approach operation varies from 10^{-5} to 10^{-9} per operation.
4. Availability: The navigation system must be functional and meet the above requirements a large fraction of the time in order to be useful to aircraft. Indeed, aviation requires availabilities better than 99–99.999% of the time. It is both unsafe and uneconomical to send an airplane to an airport only to discover once there that landing guidance is unavailable.

The numerical value for each requirement depends on the aircraft operation and they become more demanding as the aircraft is brought closer to other aircraft or to the ground, e.g., approaching an airport and preparing to land. So-called precision approach operations require vertical position accuracies of a few meters. Airport approach operations have particularly tough requirements for accuracy and integrity. Thus, most SBAS development and characterization effort focuses on this application. Generally, as long as the SBAS can meet the approach requirements, it will also meet the requirements for the other phases of flight.

Vertically guided approach is based on a smooth glide path with a constant rate of descent. This glide path, typically 3°, passes through a *decision height* where the pilot must decide whether or not to complete the landing. Pilots prefer vertically guided approach to the more challenging nonprecision approach. Nonprecision approach is also known as a step-down approach because pilots alternate a sequence of constant altitude segments with vertical step-downs as they approach the airport. This process requires the pilot to change the vertical descent rate of the aircraft at different points along the approach. This increased workload has contributed to a larger number of aircraft accidents. Before augmented GPS, an instrument landing system (ILS) or microwave landing system (MLS), sited at the airport, were the only systems able to provide precision approach. SBAS enables precision approach without any airport-specific equipment. It allows the pilot to use a constant rate of descent down to a decision height of 200 ft above the ground, using a localizer precision with vertical guidance (LPV) procedure [12.6]. This is an important benefit as thousands of smaller airports are not equipped with ILS or MLS.

12.1.2 Traditional Navigational Aids

Traditionally, aviation has relied on radio-navigation signals from ground-based transmitters to determine aircraft position (Chap. 30). These systems are still largely in place and in wide use as the aviation community is very risk averse and slow to change. Typically, aircraft uses the same set of avionics originally installed in the aircraft, without update, for more than 20 years. It can be very difficult and costly to transition away from the existing set of equipment. The main set of navaids currently in use is:

- Distance measuring equipment (DME)
- Very high frequency (VHF) omni-range (VOR)
- The tactical air navigation system (TACAN)
- The ILS.

These are described in more detail below.

A DME consists of a fixed antenna and transmitter–receiver that responds to aircraft interrogations after a fixed delay. As the aircraft knows the amount of the fixed delay, it obtains a true range to the antenna by subtracting the delay from the time between interrogation and response and dividing by 2. Because it also knows the location of the antenna, the aircraft then knows that it is somewhere on a circle at a fixed distance from that location. By querying 2 DMEs or using other information, the aircraft can further refine its position. The typical ranging accuracy of a DME is on the order of hundreds of meters. Each DME can be received to ≈ 150 nmi. The United States (US) Federal Aviation Administration (FAA) maintains ≈ 1100 DMEs in the conterminous United States (CONUS) to ensure nearly complete coverage by multiple DMEs.

A very high frequency (VHF) omnidirectional range (VOR) sends out two signals: one is uniform in all directions and the other is highly directional. By measuring the time between receipt of these messages, the aircraft can obtain a directional angle from the VOR. The typical accuracy of a VOR is less than half a degree. Thus, a co-located VOR and DME can provide an absolute position good to several hundred meters although this uncertainty increases with distance from the navaids. As with DMEs, there are on the order of 1100 VORs within CONUS.

The TACAN system is a military version of a combined VOR/DME system. However, the DME portion of the TACAN signal is available for use to civilians and in the United States, most DMEs are actually TACANs. A VORTAC is a combined VOR and TACAN that meets both military and civilian needs

An ILS consists of two sets of antennas and transmitters, one to provide angular offsets from the runway centerline and the other to provide angular offsets from the desired vertical glide path. The first set, called the localizer, provides horizontal guidance and the second set, called the glideslope, provides vertical guidance. In order to provide guidance to a single runway end, both the localizer and glideslope equipment are required. To serve both ends of a single runway, separate glideslope and localizer installations are required. Depending on the level of calibration, an ILS can safely guide an aircraft to within 200 ft of the ground (Category I) or all the way down to a blind landing (Category III). There are ≈ 1300 ILSs in the United States.

Each of these terrestrial navigational aids requires owned or leased land to occupy, reliable power and communication, maintenance, and constant calibration. Each piece of equipment is flight inspected for accuracy as often as every 2 months. The installation and ongoing support costs to maintain thousands of terrestrial navigational aids are significant. The FAA investigated satellite-based methods for providing guidance in order to reduce the existing navaid infrastructure and overall costs of maintenance.

12.1.3 Receiver Autonomous Integrity Monitoring (RAIM)

The first and most common use of GPS in aviation provides horizontal guidance by utilizing receiver autonomous integrity monitoring (RAIM [12.7]), which is a variety of ABAS, to detect faults. Such RAIM-capable receivers estimate aircraft position and then compute the measurement residual for each satellite. The residuals are the difference between the actual measurement and the expected value that corresponds to the estimated position without using that satellite. This check detects measurement faults, provided there are at least 5 satellites in view with good geometry. RAIM is further capable of isolating measurement faults provided there are at least six satellites in view with very good geometry (Chap. 24).

GPS-based RAIM is the most widely used form of satellite navigation by aviation to date. It only provides horizontal guidance, but does so without any expensive ground infrastructure. Its coverage is global and not subject to limited ground networks or loss of signal due to blockage by terrain. It is also generally far more accurate than VOR/DME/TACAN, and does not require flight inspection to maintain calibration.

RAIM leverages the normally over-specified nature of the GPS position solution, but this method is very sensitive to the state of the GPS constellation. In poor geometries, RAIM quickly becomes unavailable. For this reason, RAIM receivers cannot be the primary navigation aid; they must supplement another navigation aid. In contrast, SBAS-enabled receivers may be the primary navigation system for nonprecision approach because the fault monitoring is done on the ground and communicated to the aircraft. SBAS can provide availability in much worse geometries than RAIM can support.

12.1.4 Satellite-Based Augmentation Systems (SBAS)

SBAS is capable of assuring better horizontal accuracy than RAIM as well as providing vertical guidance. Therefore, SBAS can safely bring the aircraft closer to the ground with fewer satellites in the sky and with worse observational geometry.

An SBAS utilizes a network of ground monitors to continuously observe the performance of the navigation satellites. As shown in Fig. 12.1, the reference stations send their measurements to master stations that determine differential corrections and corresponding confidence bounds. Each master station processes the measurements and transmits data to an uplink station. The uplink station relays this information to the end users via a geostationary Earth orbit (GEO) satellite. Each SBAS has multiple master stations, uplink stations, and GEOs so that it can reliably survive the failure of any one component. SBAS augments the core constellations with the following three services:

1. *Differential corrections*: SBAS broadcasts differential corrections for each satellite tracked by the ground network. The SBAS also transmits corrections for the effects of ionospheric delay over its region of interest. By applying these corrections to their pseudorange measurements, the user equipment improves its position accuracy.
2. *Integrity monitoring*: SBAS also broadcasts error bounds for each monitored satellite and each ionospheric correction parameter. These error bounds are used to determine the maximum possible airborne position error that may remain after the differential corrections are applied. Error bounds are appreciably more difficult to generate than differential corrections because the probability that the position error bound fails to overbound the true error must be smaller than 10^{-7} per approach. In addition, this information must be updated within 6 s of any unsafe condition.
3. *Ranging*: The SBAS GEO signals are similar to GPS L1 coarse/acquisition (C/A) signals in design and so an SBAS-enabled receiver uses essentially the same hardware as a normal GPS receiver. In addition, the SBAS signals are synchronized to GPS so they can be used for ranging. The additional ranging measurements are added to the suite of GPS ranging signals to improve the time availability and continuity of the position fix.

Each master station generates a grid of corrections for the ionosphere over its coverage region. This grid is 5° by 5° in latitude and longitude between 60° S and

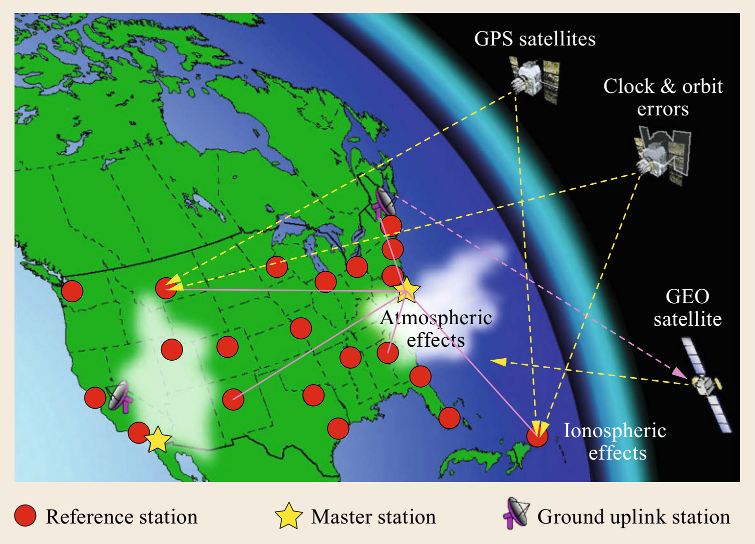


Fig. 12.1 General concept of a satellite-based augmentation system (SBAS)

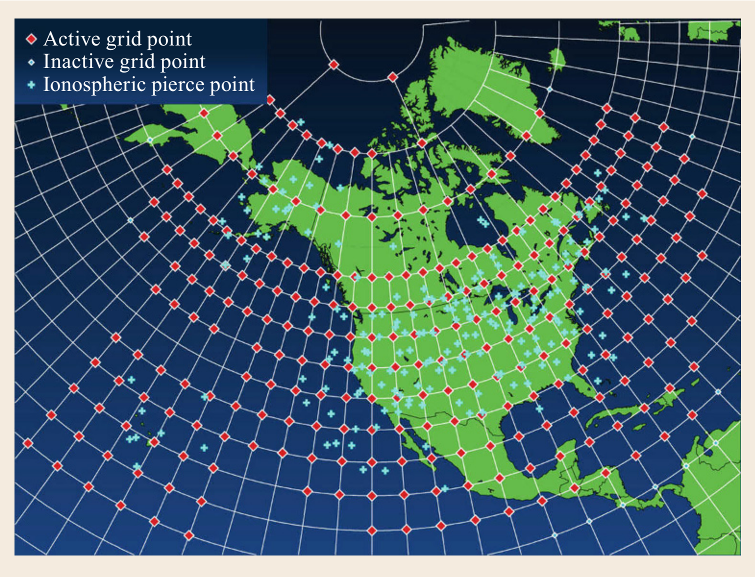


Fig. 12.2 SBAS ionospheric grid over North America

60° N and is less dense over the polar regions [12.8]. As with the stand-alone GPS single frequency ionosphere model, the SBAS ionospheric corrections model the ionosphere as though it were a thin shell existing at 350 km above the surface of the Earth [12.9]. The line of sight between the receiver and the satellite penetrates this layer at a point labeled the ionospheric pierce point (IPP). The user applies the four surrounding grid values to interpolate the ionospheric delay specific to each location of their IPPs. Figure 12.2 shows the SBAS ionospheric grid over North America with the grid points used by wide area augmentation systems (WAASs) indicated by *red diamonds*. Also shown are the IPPs as measured by the reference stations at one particular time.

The master station also generates a vector correction for each GPS satellite in view of the reference network. One element corrects the satellite clock and the other three elements are corrections for the three dimensions of satellite position. These corrections are generated from the pseudorange measurements after the ionospheric contribution has been removed and errors due to the troposphere and multipath have been minimized.

While the processing to generate the ionospheric and satellite specific corrections is sophisticated, the more difficult task is to bound the position errors that will remain after the corrections are applied. The bounds for the residual errors in the ionospheric corrections are called grid ionospheric vertical errors (GIVEs). The GIVE bounds the ionospheric correction for a given point in the grid for a line of sight that passes vertically through that point. Lines-of-sight at other angles get multiplied by a geometric obliquity factor to adjust the delay and confidence values for the longer ray path. The master station also bounds the impact of the satellite-specific error after correction, and these bounds are called user differential range errors (UDREs). They bound the projection of the satellite clock and location errors when projected onto the line-of-sight to the worst-case location in the coverage area.

The master station packs the ionospheric corrections, satellite specific corrections, and associated bounds into the SBAS message stream. This message stream is uplinked to the GEOs. These satellites are essentially bent pipes – they simply shift the uplink signal frequency and broadcast the message to users everywhere in the geostationary footprint.

12.2 GPS Error Sources

GPS signals are affected by many potential sources of error. It is important to understand these error sources and the possible effect they may have on the signal. For integrity, we are primarily interested in the effect they have on ranging accuracy. The errors may cause unmodeled variations in the reception time of the signals and hence the apparent range to the satellite. An SBAS first attempts to correct these errors in order to improve accuracy. Then, to the extent that it cannot fully correct the errors, it must describe to the user how much uncertainty remains on each of their corrected pseudorange measurements. It is therefore essential to understand and describe the physical source and effect of the different error sources. These sources are usually broken into three categories:

- Those originating on the satellite with the generation and broadcast of the signal.
- Those affecting the signal during its propagation from the satellite to the user.
- Those affecting the signal at the receiver and in its immediate vicinity.

The first category includes errors in the described satellite orbit position and clock offset, biases between the signals on different frequencies or between the code and carrier components, deformations of the signals, and look-angle-dependent biases from the satellite antenna. The propagation environment includes the effects of the ionosphere and the troposphere. The final category includes local multipath, receiver noise and tracking errors, and user antenna bias effects. For SBAS, both the errors affecting the reference stations and the users are important. The most significant error sources are described in greater detail below.

12.2.1 Satellite Clock and Ephemeris

Satellites suffer from nominal ephemeris and clock errors (Sect. 3.3.4) even when there are no faults present. These are typically very small for GPS, usually less than a meter in projected error. Occasionally, the broadcast GPS clock and ephemeris information may contain significant errors relative to the true state of the satellite position and clock. Such faults may appear as jumps, ramps, or higher order errors in the GPS clock, ephemeris, or both. These faults may be created by changes in state of the satellite orbit or clock, or simply due to the broadcasting of erroneous information. For example, a clock fault may lead to a sudden change in the timing of the broadcast signal while the position description remains accurate. Another example is an unannounced maneuver where the orbit suddenly changes, but the clock remains accurate. Alternatively, the satellite state may not change, but the navigation data that is broadcast to the user is changed to contain incorrect information. Another possibility is that everything about the satellite is correct, but either the user or the reference station incorrectly decodes the ephemeris information. For GPS, the nominal clock and position errors create projected pseudorange errors that typically have a standard deviation better than 1 m. Faults are rare on GPS, typically occurring no more than twice a year, but may lead to projected errors of several kilometers.

12.2.2 Ionosphere

The ionosphere (Chap. 6) is a complex three-dimensional (3-D) distribution of free electrons primarily distributed between 100 and 1000 km above the surface of Earth [12.9]. It is often modeled as a two-dimensional (2-D) structure occurring in a thin shell at a height of 350 km. The electron distribution varies over the course of the day with a maximum effect in the local afternoon when the Sun's radiation has created the largest number of free electrons, and a minimum effect at night when those same electrons have recombined with the positive ions. There are seasonal changes with the ionosphere as the Earth's magnetic field changes its orientation with respect to the Sun. The Sun also undergoes an ≈ 22 year cycle where it reverses its magnetic field. This leads to an 11 year cycle in the ionosphere with significantly more ionospheric delay and disturbances near the maximum of the cycle than nearer to the minimum.

For nonequatorial regions (roughly $> 25°$ of latitude), the thin shell model is usually a very good model. The ionosphere is easily estimated and bounded over large distances by assuming a linear variation in delay in the east–west and north–south directions. However, periods of disturbance occasionally occur where simple confidence bounds fall significantly short of bounding the true error [12.10, 11]. Additionally, in equatorial regions of the world, the ionosphere often contains significant 3-D structure. Disturbances can occur over very short baselines causing them to be difficult to describe in the limited SBAS message structure. Variations $>$ 20 m of vertical delay over a 50 km baseline have been observed, as have rates of change as large as four vertical meters of delay per minute.

12.2.3 Troposphere

Tropospheric errors (Chap. 6) are typically small compared to ionospheric errors or satellite faults. Historical observations were used to formulate a model and analyze deviations from the assumed model used by SBAS. The assumed model will not exactly match the local climatological conditions. There are unpredictable variations in barometric pressure, temperature, and moisture content. Each of these variations may produce up to a few decimeters of vertical delay error that can map to a few meters of error at very low elevation angles. Typically, the total vertical error is < 10 cm and therefore < 1 m at low elevation [12.12].

12.2.4 Multipath

Multipath (Chap. 15) depends upon the environment surrounding the antenna and on the satellite locations. In aircraft, a well-placed antenna may have a very clean environment and the motion of the aircraft usually causes multipath to vary quickly. Thanks to carrier smoothing, the overall aircraft multipath can be reduced to < 25 cm standard deviation for a narrow correlator receiver [12.13]. The reference stations however may be in much more cluttered environments and therefore can experience multipath errors of several meters. Because the reference station antennas are stationary, the period of the multipath can be 10 min or greater. For GPS, multipath also contains a periodic component that repeats over a sidereal day. Thus, severe multipath may be seen repeatedly for several days or longer. However, with two frequencies, the reference stations may use a very long time constant for carrier smoothing and also be able to achieve standard deviations < 25 cm after sufficient smoothing time.

12.2.5 Other Error Sources

The previous sections describe the four most significant error sources, but there are other error sources that usually are not a factor but that potentially could affect performance. One such example is signal distortions on the GPS codes [12.14, 15]. Because the signals are not strictly identical, there will be differences in their measured arrival time that depend upon the correlator spacing and bandwidth of the observing receivers. Such biases would be transparent to a network of identically configured receivers, but could be noticeably different to a user receiver with a different design. There are nominal deformation biases that are always present and may be several decimeters large. There is also concern over possible fault modes that could lead to errors > 10 m.

Another postulated threat is that a satellite may fail to maintain the coherency between the broadcast code and carrier. This fault mode is one that occurs on the satellite and is unrelated to incoherence caused by the ionosphere. This threat causes either a step or a rate of change between the code and carrier broadcast from the satellite. This threat has been observed on the L5 signals of the new Block IIF GPS satellites.

Look-angle-dependent biases in the code and on the carrier phase on both L1 and L2 are present on GPS antennas [12.16]. These biases may be several tens of centimeters. They may result from intrinsic antenna design as well as manufacturing variation. They are known to be present on the satellite antennas, on the reference station antennas, and on the users antennas. A closely related error source is survey error on the reference station antennas which could lead to errors in estimating the satellite corrections.

12.3 SBAS Architecture

As previously mentioned, an SBAS consists of three elements:

- The reference network
- The central processing facility
- The GEOs.

The reference network collects the basic GPS data in real-time and forward it for further analysis. The central processing facility evaluates the data and generates corrections and decisions about integrity. This information is then broadcast to the users via GEOs. These elements and their function are described in the following subsections.

12.3.1 Reference Stations

Each reference station contains independent threads of reference equipment. Each thread consists of an antenna, a dual-frequency GPS receiver, an atomic clock, and redundant communication links. Figure 12.3 shows racks containing three threads of equipment for a WAAS reference station. Redundant threads are included so that hardware faults may be readily detected. The reference receivers are dual frequency. Every sec-

Fig. 12.3 A WAAS reference station (reproduced with permission of the FAA satellite navigation team)

ond they take pseudorange measurements and carrier-phase measurements at the GPS L1 and L2 frequencies. The L1 and L2 frequencies are 1575.42 and 1227.60 MHz, respectively. The atomic clock makes it easier to compare previous measurements to the current ones and to identify outliers. The raw measurements from the reference stations are sent to each master station along redundant communication lines to ensure that each measurement arrives with very high likelihood. Reference stations are spaced $\approx 200\,\mathrm{km}$ or more apart. They are often placed at facilities that can provide security, reliable power (with backup), and reliable communications. No processing is performed at the reference station locations. Instead the raw measurements are all sent to the central locations for processing. The reference station network should have enough redundancy such that the loss of any individual station will not limit availability of the overall service.

12.3.2 Master Stations

An SBAS master station has four main tasks:

- Collect the data
- Formulate the corrections
- Determine the confidence bounds
- Pack the information into messages for broadcast.

The master station will seek to obtain all of the raw GPS data from every thread of every reference station. However, in order to meet the TTA it cannot wait too long for this data to come in. At a certain time it has to move forward and make its determinations with the information that it has for the epoch in question. This process is repeated every second as the master station continuously has to decide what the next message to send should be.

Upon getting the data from the receivers, the master station first performs consistency checks to identify and isolate erroneous data. The data from the parallel threads at each reference station must agree with each other and with previous information. If it does not, the master station must determine which information is incorrect. If it cannot do so, then it must immediately warn the user that the prior correction data may be unsafe. Much more commonly, it is able to identify and remove bad measurements before they are used downstream. Next the data is fed into various filters and estimators. There is a satellite clock and orbit estimator that also estimates reference station clock offsets. There is an estimator for the biases between the L1 and L2 signals that are induced by hardware on the satellites and at the reference stations. Finally, there is an estimator for the ionospheric delay at each of the grid points that the SBAS chooses to correct.

Most importantly, there are safety monitors that determine how much error may be present in the estimates. By correcting GPS with SBAS, one is initially doubling the risk of failure. There are now two very complex systems that can fail instead of just one. The first task for SBAS is self-monitoring to ensure that it does not introduce error. Each reference station contains parallel threads of equipment. Each thread operates independently of the others. As a first layer of screening for errors, the output of each thread is compared against the others. The expected geometry difference is first removed using the surveyed antenna coordinates and the broadcast satellite position. Additionally, the clock difference between each thread must be resolved from measurements. This is performed by combining information from all common satellites over time. If the corrected measurements disagree by too much then they are discarded. If too many measurements are discarded from a particular thread then it is flagged for maintenance. This cross comparison will identify any large receiver/clock failures as well as large multipath errors not common between the antennas. Smaller receiver errors or any common mode error can still escape detection. Later monitors compare the measurements from different reference stations for consistency as well as examine the temporal behavior to try to identify SBAS errors and prevent them from affecting performance. By screening measurements across multiple threads at the first stage, the vast majority of harmful errors are eliminated before they can affect downstream filters.

The monitors continue by characterizing the levels of code noise and multipath remaining on the measurements after error screening and carrier smoothing [12.13]. These screened measurements are used to monitor errors on the satellites and estimated delays due to ionosphere so it is very important to understand and bound the limits of observability. The confidence values associated with each measurement are then propagated through the subsequent monitors so that the monitors may accurately state how much certainty they have in their ability to screen for errors.

The postcorrection satellite clock and ephemeris errors are bounded by the UDREs. The master station looks at the projected clock and ephemeris error throughout the service volume and has to make sure that the UDRE is sufficiently large to protect all users. However, there are other errors that may be present on the satellite. The code and carrier signals may not be completely synchronized. Should this be the case, the measured range to the satellite will vary with the amount of smoothing that has been performed which can change for users depending on time of acquisition and most recent cycle slip. There is also the possibility of variations in the signals shape that can affect the tracking of the signal. All of these possible error sources have to be covered by the UDRE.

Dual frequency measurements are required to generate the ionospheric corrections. The ionosphere is dispersive and so the ionospheric delay at L1 is different from the delay at L2. More specifically, the observed delay is inversely proportional to the frequency squared. The SBAS ground system leverages this relationship to estimate the ionospheric delay at the vertices in the grid. Unfortunately, the avionics directly cannot make use of the L2 signal because it lies in a nonaviation portion of the radio spectrum. The FAA cannot assure its availability. Hence, the ground system estimates the ionospheric delay for the avionics and sends the grid of ionospheric delay estimates to the airborne user. The density of the reference network is determined by the spatial decorrelation of the ionospheric delay [12.17]. Few reference stations are required if the ionosphere is always smooth. If the ionosphere has steep gradients, then a greater number is required. In the future, GNSS satellites will broadcast two signals for civil aviation (L1 and L5). At that time, new avionics will use both frequencies to compute the ionospheric delay in the aircraft because the L5 frequency does fall within a protected aviation band.

The ionospheric delay value at each grid point must be estimated from the individual ionospheric measurements from each reference station [12.18–21]. In addition, the ionospheric correction error at each grid point is bounded by the GIVE. Because the measurements do not coincide with the grid points they must be combined in a way to account for the potential spatial variation of the ionosphere.The GIVEs must account for the measurement errors and the uncertainty in the propagation model. The ionospheric grid points (IGPs) themselves are separated by roughly ≈ 500 km. Therefore, it is not possible to resolve very fine scale structure of the ionosphere. Further the measurements from the reference stations are sparse. The SBAS method for correcting the ionosphere depends on the fact that the ionosphere is generally slowly varying over hundreds of kilometers. The IGP delay algorithm nominally assumes limited variation in latitude and longitude, but must be prepared to identify times when its assumptions are invalid. Sometimes the ionosphere may be in a more disturbed state where the basic SBAS model is not an accurate description. At these times, the algorithm must recognize the problem and increase the confidence bounds accordingly [12.22].

SBAS uses a standard tropospheric model to predict the amount of tropospheric delay that exists on both the reference station and user lines of sight [12.12]. This is a climatological model based on years of primarily North American observations but that has been verified after the fact with data from other parts of the world. It provides values for the barometric pressure, temperature, and other parameters given a latitude and time of year. From these parameters the amount of tropospheric delay can be estimated. This model also provides an upper bound on the error that may be remaining after applying it.

The satellite, ionospheric, and tropospheric corrections can be applied to each reference station measurement to evaluate the combined effect of the corrections for that specific line-of-sight. These errors should combine together in the expected manner. If the total error bound does not appear to properly bound all such measurements then the UDREs and GIVEs may need to be increased. This range domain check is another reasonability test to ensure all of the information is consistent.

As a final check, each reference station thread can evaluate its corrected position solution against the known surveyed location of its antenna. This helps to ensure that all of the corrections are working well together and are adequately bounded. The range domain and position domain tests ensure that all of the corrections combine together correctly. The integrity bounding methodology requires that the errors can be treated as though they are independent. A dependency that leads to a magnification of the errors in the position domain would become more obvious with these evaluations.

Finally, the message processor determines which 250 bit message should be sent for the current epoch and packages it appropriately [12.8, 23]. Usually the messages can follow an expected schedule. However, in the event of an integrity alert, the master station must send a message capable of alerting all affected users. If only a single satellite or IGP is affected, then the messages specific to those confidence bounds need to be sent. However, if many satellites are affected or the SBAS cannot autonomously isolate the faulty data, then more of the SBAS service may need to be alerted as potentially unsafe. Fortunately, such events are exceedingly rare. When alerts are broadcast, they are repeated four times in a row. This is due to the concern that a user receiver may miss an individual message (or even up to three messages). It is important to ensure that the user receives this data when prior information is no longer correct.

12.3.3 Ground Uplink Stations and Geostationary Satellites

Geostationary satellites are an excellent means for disseminating the SBAS messages. An SBAS can cover a large continental-scale region, as does the footprint of a GEO. The GEO signals are made very similar to the GPS L1 C/A and L5 signals, respectively, on those frequencies. Thus, they provide extra ranging measurements for the user. These signals broadcast data at 250 bit/s, which is sufficient to transmit the SBAS corrections and confidences. The signals come from space and are therefore unlikely to be blocked by terrain in open sky environments where aircraft typically operate. The very name for SBAS, *satellite*-based augmentation system, comes from the pairing of the ground system with this satellite-based method of delivery. Figure 12.4 depicts the ANIK-F1R GEO used by WAAS.

The GEOs in use today are simple transponders. They listen for an analog signal at one frequency, translate it to the correct L-band frequency, and retransmit it toward Earth with minimum latency. The pseudorandom noise (PRN) code, messages, and timing are all generated on the ground. The signals are controlled through a closed-loop system that makes it appear as though they originated on the spacecraft [12.24]. The satellite effectively redirects the signal from the ground uplink station (GUS) back down toward the ground. The only change made by the satellite is from the uplink frequency to the correct downlink frequency. This approach is used because the transponder payloads are lighter and less expensive than the full navigation payloads on GPS satellites.

The GUS consists of a computer to receive messages from the multiple master stations, an atomic clock to provide a stable frequency reference, a signal generator to create the signal to uplink to the GEO, a receiver to monitor the GEO downlink signal, a GPS receiver to ensure the GEO is synchronized to GPS time, and a controller to steer the uplinked signal. Figure 12.5 shows the large antenna at the GUS in Napa valley, California, used by WAAS to uplink the signal to its GEO at 133° W. The ground uplink signal is most commonly $> 3\,\mathrm{GHz}$. The computer must decide which message to send the next epoch. This will be based upon which master stations it has received messages from and which ones it has sent in the past. Typically, it will continuously send messages from the same master station. However, if communication to that station is interrupted, or if it is commanded to switch to another master station, then it will switch. If it receives no valid messages then it can either send an empty message or initiate an alert sequence.

The generated signal is very similar to a GPS L1 C/A code signal. The main differences are that the center frequency is well above the L1 band and the data bits are switched at 500 sps (symbols per second). The message is encoded onto the signal and it is beamed up to the GEO. The GEO receives this signal and downconverts it to L1 and broadcasts it back down to Earth. The signal is received at the GUS and the center frequency and timing of the chips on the uplink signal are adjusted to make it appear as though the downlink signal was generated on the GEO in synchronization with the GPS satellites.

The GEO signals are generally less accurate than the GPS signals. The transponders for some GEOs have a narrower bandwidth. This difference creates a loss of precision and some signal distortion. By generating

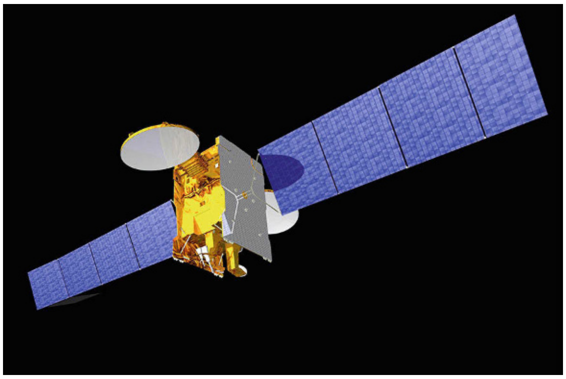


Fig. 12.4 The ANIK-F1R GEO used by WAAS (reproduced with permission of the the FAA satellite navigation team)

Fig. 12.5 A WAAS geostationary uplink station (reproduced with permission of the FAA satellite navigation team)

the signal on the ground some of the uplink path errors (e.g., ionosphere, troposphere) cannot be fully removed and therefore affect the downlink accuracy. Further, because the GEOs move very slowly in the sky, carrier smoothing does not reduce the multipath error on the ground at a static location, such as the reference receivers, very effectively. This increased error leads to less accurate orbit and clock estimation and larger uncertainty in bounding the error. Aircraft motion does cause enough variation for carrier smoothing to be effective in the aircraft.

12.3.4 Operational Control Centers

Figure 12.6 shows one of the two operational control centers for WAAS that has three master stations, one of which is located at this center. From this center, the operators can monitor the status and performance of WAAS. The operators schedule maintenance and upgrades of the various components at the reference, master, and uplink stations. This control center also monitors weather, air traffic, and the traditional navigational aids. The operators interact with other systems in the national airspace to ensure all are well integrated. The different systems are managed together to ensure that any routine maintenance can be optimally scheduled and unplanned disruptions are properly communicated. The control center also produces notices to inform users of changes to the system performance [12.25] and interact with operators of GPS.

Fig. 12.6 A WAAS operational control center (reproduced with permission of the FAA satellite navigation team)

12.4 SBAS Integrity

Augmentation systems for aviation are very different from conventional differential GPS services. They are supplementing and ultimately replacing existing navigational aids whose safety has been demonstrated over many years of operational experience. Consequently, the safety of an augmentation system must be proven before it is put into service.

The integrity requirement is that the positioning error must be no greater than the positioning confidence bound, known as the protection level. This requirement is specified with a TTA and with a probability. The TTA requirement means that if the position error exceeds the protection level, the user must be informed within a very short period (6 s for the most demanding SBAS operation). Once a fault has occurred, the position error must fall below the protection level or the pilot must be informed that the system is unsafe to use within 6 s. The probability requirement is that no more than one in ten million operations may suffer an unannounced position error exceeding the protection level for > 6 s. SBAS provides differential corrections and confidence bounds to the user. The correction confidence bounds are used, together with the geometry of satellites tracked by the user, to calculate the protection level. In order to use the calculated position for navigation, the protection level must be small enough to support the operation. The user only has real-time access to the protection level and does not know the true position error. Integrity is not maintained if the user has been told that the error in position is small enough to support the operation, but in fact, it is not. The majority of the effort in establishing an SBAS is in ensuring and demonstrating that these integrity requirements are met.

12.4.1 Integrity Certification

Certification is the process by which a provider ensures that the service it is providing meets the requirements. Certification involves analysis, testing, and documentation. Some of the important aspects of aviation integrity certification are [12.26]:

1. The aviation integrity requirement of 10^{-7} per approach applies to each and every operation. It is not an average over all conditions. The probability also applies to the worst allowed conditions.
2. Validated threat models are essential both to describe what the system protects against and to quantitatively assess how effectively it provides such protection.

3. The system design must be shown to be safe against all fault modes and external threats, including the potential for latent faults just beneath the system's ability to detect.
4. The small numbers associated with integrity analysis are not intuitive. Careful analysis must take priority over anecdotal evidence.

Because the requirement applies to all operations, threats and error conditions must be evaluated under worst allowable conditions. For example, if a user is allowed to operate under the maximum of the 11 year solar cycle, ionospheric errors must be modeled under this worst-case time. They cannot be an average of the high and low points of the solar cycle. Threat models are the means to capturing and describing the various errors that can occur and will be described in the next section. These models must describe both observed and anticipated threats and must treat them quantitatively.

12.4.2 Threat Models

Threat models describe the anticipated events against which the system must protect the user. The threat model must describe the specific nature of the threat, its magnitude, and its likelihood. Together, the various threat models must be comprehensive in describing all reasonable conditions under which the system might have difficulty protecting the user. Ultimately the threat models form a major part of the basis for determining if the system design meets its integrity requirement. Each individual threat must be fully mitigated to within its allocation. Only when it can be shown that each threat has been sufficiently addressed can the system be deemed safe. Quantitative assessment as opposed to a qualitative assessment is essential to establishing 10^{-7} integrity. SBAS works by analyzing specific failure modes and identifying which may be present and to what likelihood. Each potential failure mode must be ruled out within the limits of the system observability. If a failure mode is positively identified as being present in the system, or cannot be eliminated due to measurement noise, then the user must be notified within 6 s of it adversely affecting their position estimate.

SBAS is primarily thought of as addressing existing threats to GPS. However, it runs the risk of introducing threats in the absence of any GPS fault. By necessity, it is a complex system of hardware and software. Included in any threat model must be self-induced errors. Some of these errors are universal to any design while others are specific to the implementation. For example, the software design assurance of WAAS reference receivers is such that they cannot be trusted to be mistake free. Reference receiver software faults became a unique threat that had to be mitigated through downstream integrity monitoring.

12.4.3 Overbounding

Each individual error source has some probability distribution associated with it. This distribution describes the likelihood of encountering a certain error value. Ideally, smaller errors are more likely than larger errors. Generally, this is true for most error sources. The central region of most error sources can be well described by a Gaussian distribution. That is, most errors are clustered about a mean (usually near zero) and the likelihood of being farther away from the mean falls off according to the well-known Gaussian model. This is often a consequence of the central-limit theorem, which states that distributions tend to approach Gaussian as more independent random variables are combined.

Unfortunately, the tails of observed error distributions rarely look Gaussian. Two competing effects tend to modify their behavior. The first is clipping. Because there are many cross-comparisons and reasonability checks within SBAS, the larger errors tend to be removed. Thus, for a truly Gaussian process, outlier removal would lead to fewer large errors than would otherwise be expected. The second, and more dominant effect is mixing. The error sources are rarely stationary. Thus, some of the time the error might be Gaussian with a certain mean and sigma and at other times it will have a different distribution. Because we do not necessarily have the ability to identify which condition is present at which time, different conditions will be aggregated into a single distribution. Such mixing may result from a change in the nominal conditions or from the introduction of a fault mode. Mixing generally leads to broader tails or large errors being more likely than otherwise expected.

Mixing causes additional problems. If the error processes were stationary, it would be possible to collect as large a data set as practical and then conservatively extrapolate the tail behavior using a Gaussian or other model. However, because the distribution changes over time, it is more difficult to predict the future performance based on the past behavior. Furthermore, mixing leads to more complicated distributions whose tails are more difficult to extrapolate.

Overbounding is the concept that an actual distribution can be conservatively described by a simple, usually Gaussian, model [12.27]. The overbounding distribution predicts that large errors are at least as likely to occur as they are for the true distribution. Even though the true distribution may not be completely known, there needs to be a practical way to represent it for analysis. Usually this involves a fair amount of conservatism. A true distribution that is made up of a mix of zero-mean Gaussian distributions, could be overbounded by its constituent with the largest standard deviation. Thus, a real distribution that has a sigma value ranging between 1 and 2 m will be represented as though it were always 2 m (or perhaps 2.5 m for added protection). Through various overbounding theorems, the overbound also describes how to combine the error with other terms that have been overbounded [12.27–29]. That is, SBAS will individually overbound the error for each satellite and each IGP. The GIVEs and UDREs broadcast by the SBASs describe overbounds of the actual error distributions affecting the corrections. The overbounding theorems allow users to combine these values to overbound the position errors by calculating the protection levels.

12.5 SBAS User Algorithms

The SBAS Minimum Operational Performance Standards (MOPS) are an internationally agreed upon document [12.8] that describes the method by which an SBAS transmits its differential GPS corrections and integrity information to users. The information is transmitted in 250 bit messages. These messages must be decoded and interpreted every second. The corrections are distributed across several individual messages. The corrections for individual satellites must be combined with receiver measurements and other local information to form the navigation solution and protection levels. The user must reconstruct and apply all of this information correctly. The MOPS ensures that all SBAS service providers encode their information in a compatible manner. The aviation receivers then know what to expect and will work with each of the different SBASs.

12.5.1 Message Structure

The broadcast message structure has 500 sps. These contain forward error correction to significantly reduce the risk of lost or misidentified bits [12.30]. The symbols go through a decoding process to produce 250 bit/s messages. There are two symbols for every message bit. The messages come once per second and contain 212 bit of correction data. Eight additional bits are used for acquisition and synchronization, 6 more bits to identify the message type and the remaining 24 bit designated for parity to protect against the use of corrupted data. Complementary message types must be stored and connected to the other individual components to form a single correction and confidence bound per satellite.

The SBAS messaging system contains the following elements:

- *Satellite corrections*: The SBAS broadcasts fast-corrections for satellite clock errors that may vary quickly in time. A fast-correction message corrects up to 13 satellite clock offsets and is sent every 6 s. Clock offset rates of change are obtained by differencing sequential fast correction offsets. The SBAS also sends corrections for slowly varying satellite location and clock errors. The corrections consist of Δx, Δy, and Δz satellite locations (and possibly velocities) plus delta clock (and possibly delta clock rate). These long-term corrections are sent approximately every 2 min. Each long-term correction message corrects either two or four satellites depending on whether the rate of change information is also included.
- *Ionospheric corrections*: The SBAS broadcasts a grid of ionospheric corrections. Each ionospheric correction message updates the vertical delay estimate at up to 15 ionospheric grid points and is broadcast once every 5 min.
- *Confidence bounds*: In addition to the corrections, confidence bounds on the remaining errors are also broadcast. The UDREs must be sent every 6 s while the GIVEs are only updated every 5 min. These bounds are essential to maintain the integrity and TTA of the system. The UDREs are included in the fast-correction messages and the GIVEs are included with the ionospheric correction messages. In addition, there are messages that can provide the full 4×4 covariance matrix information for the clock/ephemeris error for each satellite. If broadcast, these matrices are sent every 2 min in messages that update two satellites. The covariance matrices are sent in a message labeled as message type 28 and are often referred to as message type 28 (MT28) parameters [12.31]. An alternate message can define regions where the UDRE values are to be increased. This regional information is sent in message type 27 and labeled as MT27 parameters. A system will either use MT28 or MT27 but never both as they both serve similar purposes but via different means.
- *Degradation parameters*: The potential error in the corrections increases over time. Parameters are broadcast to model these effects. The users apply

these degradations as their corrections age. They are particularly important in maintaining integrity and availability when a user misses the most recent correction.

- *Masks*: The PRN mask is used to designate which satellite belongs to which slot in the fast-correction messages. A mask is used to assign slots so that satellite identifications need not be sent with every fast correction. A similar ionospheric mask is used to associate each slot in the ionospheric correction message with a geographic grid point location. The use of masks reduces the required throughput because the masks are sent infrequently. They also inform the user as to which satellites and which IGPs are corrected by the specific SBAS.
- *Geostationary navigation message*: In contrast to the GPS satellites, the current SBAS satellites are geostationary. Consequently, their location (ephemeris) does not need to be updated as frequently. Nor do they require as large a dynamic range as the geostationary orbit is restricted to a limited region about the equator. These messages broadcast the absolute position (x, y, and z in an Earth centered Earth fixed (ECEF) reference frame), as well as the velocity and acceleration values. The absolute clock and clock rate are also included in this message, as well as the reference time, and an issue of data. This message is broadcast every 2 min.
- *Preamble*: In order to allow the receiver to find the start of the 250 bit message an 8 bit preamble is included at the beginning of every message. There are three unique preambles that repeat in a fixed sequence. By searching for this specific bit pattern, a receiver can synchronize itself with the SBAS data signal.
- *Parity*: For data integrity, the SBAS must use a much stronger error detection algorithm than the six parity bits used in the GPS navigation message. Nonetheless, the overhead for error detection is reduced because the parity bits apply to longer messages than for GPS. The 24 bit cyclic redundancy check (CRC) ensures that the message the user applies is the one intended. Any bits corrupted in transmission are detected before they can create erroneous information.
- *Forward error correction*: Forward error correction is used so that the SBAS can send significantly more data than the 50 bit/s carried in the GPS navigation message. The chosen code for SBAS is a rate 1/2 convolutional code with a constraint length of 7.

The currently used SBAS messages are listed in Table 12.1.

12.5.2 Message Application

The user requires one long-term and two fast corrections for each satellite that it uses [12.23]. The two fast-corrections are differenced to determine the rate of change of the fast clock term. This rate is used with the most recent fast-correction to determine the fast clock value for the current time. The fast clock correction is added to the long-term clock correction to obtain the full clock correction. The orbit corrections are also taken from the long-term correction and added to the orbital location broadcast in the navigation message received directly from the GPS satellite. The UDRE is taken from the fast-correction and increased depending on how long ago the fast correction was received. If MT28 is used, the parameters are used to determine a scaled covariance matrix. This matrix, together with the normalized four-dimensional (4-D) line-of-sight vector, is used to determine a multiplier for the UDRE. Generally, when the user is close to the reference station locations, this scaling factor will be smaller. If the user is far from the reference stations, then this factor may significantly increase its product

Table 12.1 SBAS message types

Type	Contents
0	Do not use for safety applications (WAAS testing)
1	PRN mask assignments, set up to 51 of 212 bit
2–5	Fast pseudorange corrections and UDREs
6	Integrity information, UDREs (multiple satellite alert)
7	Fast correction degradation factor
8	Reserved for future messages
9	GEO navigation message (X, Y, Z, time, etc.)
10	Degradation parameters
11	Reserved for future messages
12	WAAS network time/Coordinated Universal Time (UTC) offset parameters
13–16	Reserved for future messages
17	GEO satellite almanacs
18	Ionospheric grid point masks
19–23	Reserved for future messages
24	Mixed fast/long-term satellite corrections
25	Long-term satellite corrections
26	Ionospheric delay estimates and GIVEs
27	WAAS service message
28	Clock-epemeris covariance matrix message
29–61	Reserved for future messages
62	Internal test message
63	Null message

with the UDRE. If MT27 is used, then the UDRE will be multiplied by those parameters depending on the user's location. As with MT28, the UDRE is generally multiplied by a larger term if the user is farther from the reference stations. This product, which also will include degradation terms, is expressed as a one-sigma value and referred to as the fast and long-term correction bound or s_{flt},

Satellite corrections and confidences are all that are required for less precise lateral navigation. The user can apply the simple single-frequency ionosphere model broadcast by GPS and determine horizontal positions bounded to within a fraction 1 nmi. However, to obtain precise vertical guidance, the user must also apply the SBAS ionospheric corrections.

For each of their IPPs, the user must identify the surrounding IGPs and obtain ionospheric delays for each. It requires a minimum of three enclosing IGPs, but ideally the four defining a rectangle about the IPP are all available. The user then applies a bi-linear interpolation of the surrounding delay values to obtain the vertical delay estimate at the IPP. It applies the same interpolation to obtain the user ionospheric vertical error (UIVE) bound from the surrounding GIVEs. These are converted from vertical to slant by applying the obliquity factor. The resulting confidence term is now called the user ionospheric range error (UIRE). The delay value is subtracted from the pseudorange measurement to that satellite with the corresponding IPP. The user also subtracts the MOPS-specified tropospheric model delay estimate from each line-of-sight to fully correct the range error.

12.5.3 Protection Levels

The basic notion of the protection level equations is that the error sources are approximately Gaussian and that a Gaussian model is sufficiently accurate to be able to conservatively describe the positioning errors. Four error terms are used to describe satellite clock and ephemeris errors (σ_{flt}), ionospheric delay errors (σ_{UIRE}), tropospheric delay errors (σ_{tropo}), and airborne receiver and multipath errors (σ_{air}). The conservative variances of these terms are combined to form a conservative variance for the individual pseudorange error.

$$\sigma_i^2 = \sigma_{\text{flt},i}^2 + \sigma_{\text{UIRE},i}^2 + \sigma_{\text{tropo},i}^2 + \sigma_{\text{air},i}^2 \tag{12.1}$$

This pseudorange variance is inverted and placed on the diagonal elements of the weighting matrix, **W**, and combined with the geometry matrix, **G**, to form the covariance of the position estimate.

$$\left(\mathbf{G}^{\top}\mathbf{W}\mathbf{G}\right)^{-1} \tag{12.2}$$

Here the geometry matrix is expressed in a local east, north, up reference frame. The third diagonal element represents the conservative estimate of the error variance in the vertical direction. Since the vertical protection level (VPL) is intended to bound 99.99999% of errors it is set to the equivalent Gaussian tail value of 5.33. Thus, the final VPL for L1-only SBAS is given by

$$\text{VPL} = 5.33\sqrt{\left[\left(\mathbf{G}^{\top}\mathbf{W}\mathbf{G}\right)^{-1}\right]_{3,3}}\,. \tag{12.3}$$

12.6 Operational and Planned SBAS Systems

Four SBASs have been implemented around the world and at least three more are under development. The operational systems are all compatible with the MOPS and with existing certified SBAS receivers, but they are not identical. They have been developed specifically for their own regions and sometimes faced unique challenges. However, despite any differences SBAS receivers will work equally well with any of these systems and should be able to seamlessly transition from one to any other.

12.6.1 Wide Area Augmentation System (WAAS)

The WAAS has been fully operational for safety-of-life services since July 2003 [12.2]. It consists of 20 WAAS reference stations (WRS) in the CONUS, in addition to seven in Alaska, one in Hawaii, one in Puerto Rico, four in Canada, and five in Mexico for a total of 38. There are 3 WAAS master stations (WMS) and 3 geostationary satellites (GEOs). The GEOs are the Intelsat Galaxy XV satellite at 133° W (PRN 135), the Telesat ANIK F1R satellite at 107° W (PRN 138), and the Inmarsat-4 F3 at 98° W (PRN 133). WAAS is also in the process of procuring replacement GEOs including the SATMEX-9 which will become active in 2017 and be located at 117° W (PRN 131). A full list of all SBAS GEOs can be found in Table 12.2.

Figure 12.7 shows the reference station networks for all of the current and some of the developing SBASs. As can be seen, there is good sampling around the northern hemisphere. WAAS provides excellent coverage for lateral navigation.

Figure 12.8 shows the lateral navigation coverage provided by WAAS, as well as the Japanese and European SBASs. It can be seen that all of North America

Table 12.2 SBAS GEOs (after [12.32], courtesy of the US Air Force)

PRN	SBAS	Satellite	Location
120	European Geostationary Navigation Overlay Service (EGNOS)	INMARSAT 3F2	15.5° W
121	EGNOS	INMARSAT 3F5	25° E
122	Unallocated		
123	EGNOS	ASTRA 5B	31.5° E
124	EGNOS	Reserved	
125	System for Differential Correction and Monitoring (SDCM)	Luch-5A	16° W
126	EGNOS	INMARSAT 4F2	25° E
127	GPS Aided GEO Augmented Navigation (GAGAN)	GSAT-8	55° E
128	GAGAN	GSAT-10	83° E
129	Multi-function Satellite Augmentation System (MSAS)	MTSAT-1R (or –2)	140° E
130	Unallocated		–
131	WAAS	Satmex 9	117° W
132	Unallocated		
133	WAAS	INMARSAT 4F3	98° W
134	Unallocated		
135	WAAS	Intelsat Galaxy XV	133° W
136	EGNOS	ASTRA 4B	5° E
137	MSAS	MTSAT-2 (or -1R)	145° E
138	WAAS	ANIK-F1R	107.3° W
139	GAGAN	GSAT-15	93.5° E
140	SDCM	Luch-5B	95° E
141	SDCM	Luch-4	167° E
142–158	Unallocated		

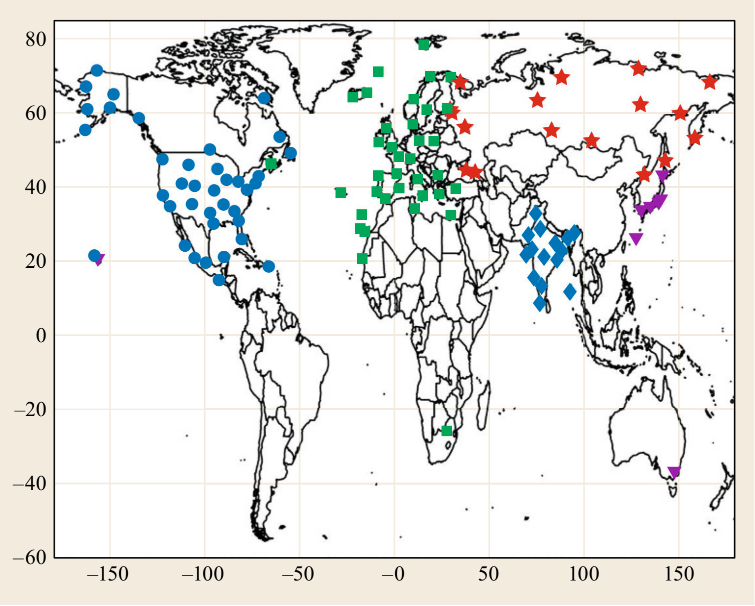


Fig. 12.7 Reference station networks of WAAS (*dark blue circles*), EGNOS (*green squares*), SDCM (*red asterisks*), and GAGAN (*blue diamonds*)

and part of South America can rely on WAAS to navigate to and from any airport of choice. The edges of GEO footprints can be seen in the north of this figure as visibility to at least one of the GEOs is a requirement to get SBAS service. Vertical guidance requires the precise ionospheric corrections of the grid and therefore is restricted to a much tighter region around the reference stations.

Figure 12.9 shows the vertical guidance coverage area for the same three SBASs. It can be seen that WAAS covers CONUS, Alaska, and much of Canada and Mexico. Figure 12.10 shows the vertical coverage

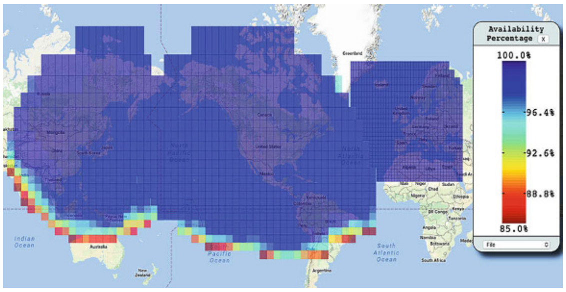


Fig. 12.8 Lateral navigation coverage for WAAS, MSAS, and EGNOS (after [12.33], reproduced with permission of the William J. Hughes FAA Technical Center)

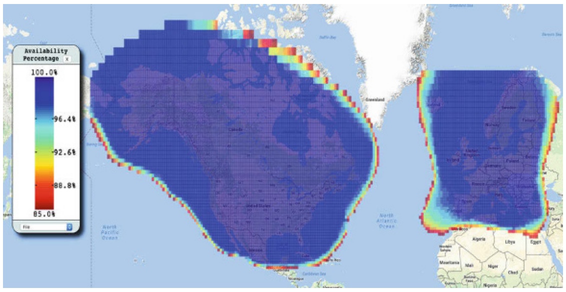
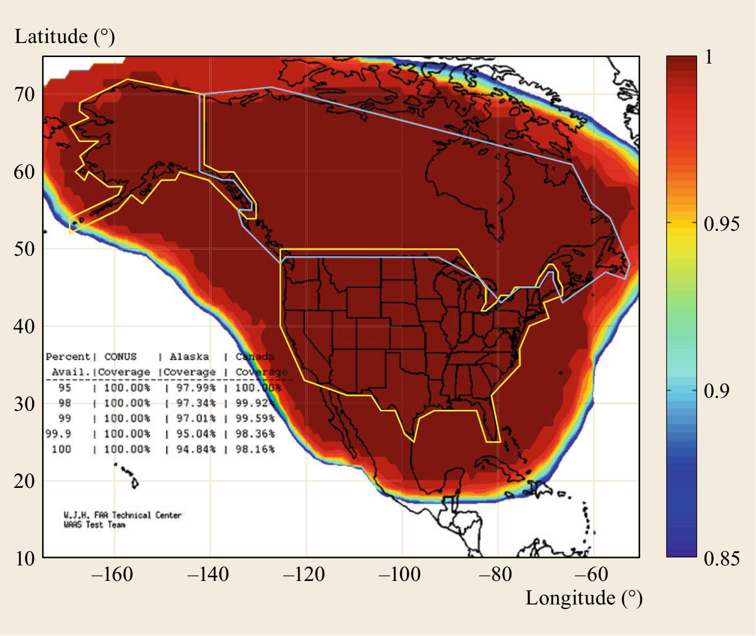


Fig. 12.9 Vertical navigation coverage for WAAS and EGNOS (after [12.33], reproduced with permission of the William J. Hughes FAA Technical Center)

area in greater detail and also tabulates the percentage of each region that achieves a certain level of availability. On the day shown in Fig. 12.10, 100% of CONUS has 100% availability, while 95.04% of Alaska has 99.9% or better availability.

Accuracy is very good when using WAAS. Horizontal accuracy is ≈ 0.75 m 95% in CONUS. This number can be compared to 3.2 m for uncorrected GPS under moderate ionospheric conditions. Under more severe ionospheric conditions the GPS positioning errors can be noticeably worse, but the WAAS corrected accuracy only worsens slightly. For example, in 2003 during a worse solar maximum period, uncorrected horizontal accuracy was 4.8 m 95% while WAAS corrected accuracy was 0.88 m. Horizontal accuracy in Alaska is also ≈ 0.75 m 95% but it is slightly worse in Mexico (≈ 0.90 m) and Canada (≈ 1.0 m). Vertical accuracy for WAAS is ≈ 1.1 m 95% in CONUS compared to 7.6 m for uncorrected GPS. In Alaska, vertical accuracy is ≈ 1.3 m 95%. Again, somewhat worse 95% vertical performance is seen in Mexico (≈ 2.0 m) and Canada (≈ 1.5 m).

WAAS was fielded because its advantages relative to conventional navaids were enormous. It has made precision vertical guidance available throughout the majority of North America. No local airport infrastructure is required for this service. Already more than 80 000 WAAS-enabled aviation receivers have been sold. More than 3500 vertically guided approaches have been commissioned. This is nearly three times as many as provided by ILS. WAAS allows users to access more than 2000 airports that had no previous instrument



Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	100.00%	97.99%	100.00%
98	100.00%	97.34%	99.92%
99	100.00%	97.01%	99.59%
99.9	100.00%	95.04%	98.36%
100	100.00%	94.84%	98.16%

Fig. 12.10 Detailed vertical navigation coverage for WAAS on 19 March 2015 (after [12.33], reproduced with permission of the William J. Hughes FAA Technical Center)

approach. It is also widely used in nonaviation applications [12.34].

Agriculture uses SBAS to more accurately position vehicles and reduce fertilizer and pesticide use. Maritime uses SBAS to guide ships more accurately in poor visibility conditions. SBAS is incorporated into nearly every cell phone as the GEOs are widely visible, the correction data is freely provided, and the system accuracy is greatly improved.

12.6.2 Multifunction Satellite Augmentation System (MSAS)

The multifunction satellite augmentation system (MSAS) consists of six ground monitoring stations (GMSs) on the Japanese islands, in addition to one in Australia, and one in Hawaii for a total of eight [12.35, 36]. The station locations are shown as magenta triangles in Fig. 12.7. There are two master control stations (MCSs) and two multifunction transport satellite (MTSAT) GEOs at 140° E and 145° E. MSAS was commissioned for safety-of-life service in September 2007.

Due to the limited network size, the GEO UDREs for MSAS are set to 50 m and therefore do not benefit vertical guidance. Further the limited ionospheric observations offer little availability of vertical service. As a result vertically guided operations have not yet been authorized based upon MSAS. The Japanese civil aviation bureau (JCAB) has studied performance improvements that could allow it to provide vertically guided operations. Until then, MSAS provides only lateral guidance. Like WAAS, lateral guidance is available for quite a large region around and away from the reference stations.

12.6.3 European Geostationary Navigation Overlay Service (EGNOS)

The European geostationary navigation overlay service (EGNOS) consists of 39 ranging and integrity monitoring stations (RIMSs) in Europe, Africa, and North America [12.37–39]. The station locations are shown as green squares in Fig. 12.7. EGNOS has four master control centers (MCCs) and six navigation land Earth stations (NLESs) that control their three GEOs. The two operational GEOs are the Imarsat-3 F2 satellite at 15.5° W (PRN 120) and the Inmarsat-4 F2 satellite at 25° E (PRN 126). There is an additional GEO, Astra 4B at 5° E (PRN 136), that is under test and will become operational in 2015. Astra 5B is being procured for operation at 31.5° E (PRN 123) beginning in 2016. EGNOS was declared operational in October 2009, and was certified for safety-of-life service in March 2011.

EGNOS also has very good accuracy. It achieves 1.2 m 95% horizontal and 1.8 m 95% vertical accuracy over Europe. For a variety of reasons EGNOS has chosen to implement its GEO satellites without a ranging capability. They are only providing differential corrections and integrity information. It is possible that future GEOs will include ranging.

EGNOS currently implements message type 27 (MT27) rather than message type 28 (MT28) as used by WAAS, MSAS, and the SBAS in India. MT27 restricts the use of small UDRE values to a box centered on the European region (from 20° N to 70° N and 40° W to 40° E). The edges of this MT27 box can be clearly seen in Figs. 12.8 and 12.9. MT27 limits lateral navigation service more so than does MT28, but there is still excellent horizontal coverage in and around Europe. Availability of vertical guidance is very high for most of Europe as shown in Fig. 12.9. Figure 12.11 provides a more detailed view of the availability of vertical guidance over Europe. Over 175 vertical approaches have already been implemented that serve over 100 airports and hundreds more are under development.

EGNOS was developed with a greater emphasis on multimodal support [12.40]. The other SBASs were implemented by their local civil aviation authorities (CAAs) and are therefore originally designed to support aviation needs. They do in fact support all modes of transportation, however, aviation is their only mandate. EGNOS has a mandate also to support other modes of transport such as maritime, rail, and automotive. EGNOS was also originally designed to incorporate the Russian global navigation satellite system (GLONASS). Although GLONASS is not used for its safety-of-life service, GLONASS is still monitored and its measurements are available for other purposes. EGNOS makes it data and corrections available through its EGNOS data access service (EDAS). EDAS provides near real-time access to the RIMS measurements and the broadcast messages. Thus, EGNOS is available to users who do not have visibility to any of its GEOs [12.5, 41].

12.6.4 GPS Aided GEO Augmented Navigation (GAGAN)

India is developing the GPS-aided GEO augmented navigation (GAGAN) system [12.42, 43]. Currently it has 15 Indian reference stations (INRES) all in India. The station locations are shown as blue diamonds in Fig. 12.7. There are two Indian master control cen-

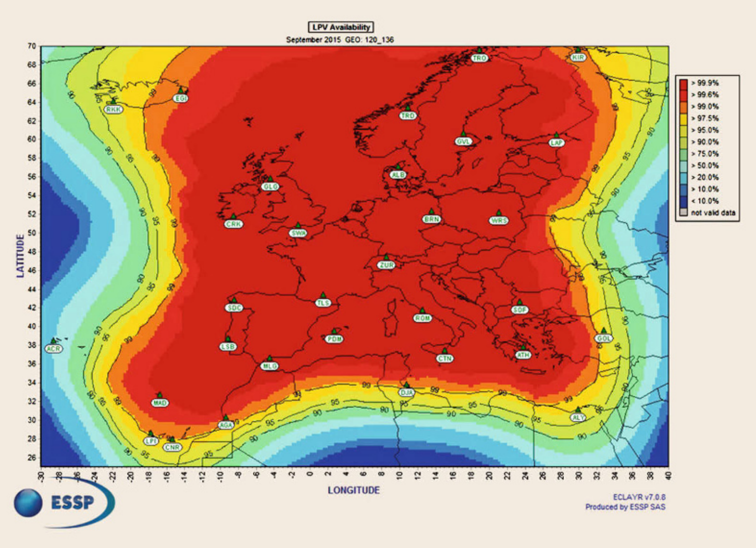


Fig. 12.11 Detailed vertical navigation coverage for EGNOS in September 2015 (after [12.39], reproduced with permission by the European satellite services provider (ESSP))

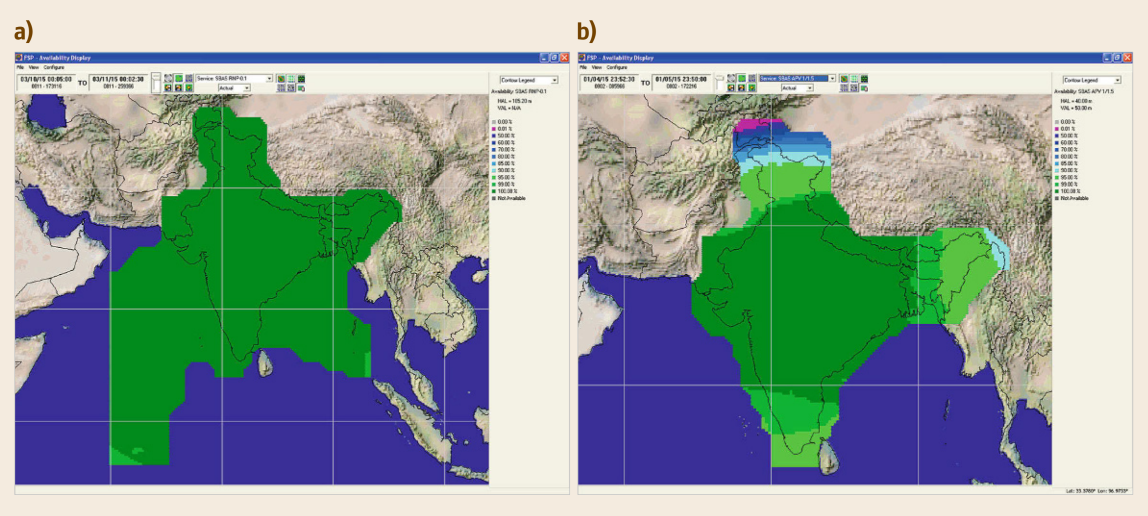


Fig. 12.12 (a) Lateral navigation coverage for GAGAN, **(b)** vertical navigation coverage for GAGAN (after [12.42], reproduced with permission by the Airports Authority of India)

ters (INMCCs), and three Indian navigation land uplink stations (INLUSs) to control its GEOs. GAGAN uses GSAT-8 at 55° E (PRN 128) and GSAT-10 at 83° E (PRN 127) as its GEOs. GSAT-15 at 93.5° E (PRN 139) is currently being deployed and will be launched in 2015.

The geomagnetic equator passes through India and GAGAN therefore faces the full impact of the equatorial ionosphere. During peak ionospheric activity, vertical guidance is not always available. Within the equatorial region, post-sunset hours are frequently beset by large depletions and scintillation. The depletions create large gradients in the ionospheric delay that cannot be easily modeled by the SBAS thin-shell grid. Scintillations interrupt tracking to the satellite signals. Fortunately lateral navigation is less susceptible to these issues as service can be provided even with larger ionospheric delay uncertainty and fewer satellites in view. Figure 12.12a shows lateral availability within the Indian airspace.

Vertical guidance does require small ionospheric delay uncertainty and very good geometry. Thus, many evenings suffer a loss of service, especially during solar maximum periods. The current solar cycle reached its maximum in 2014. Figure 12.12b shows vertical availability on a very good day. The advent of L5 will allow GAGAN to obtain high LPV-200 availability throughout all periods of the solar cycle. GAGAN was certified for lateral only service, which begun in February 2014. The vertical guidance service was certified in April of 2015.

The equatorial ionosphere also causes accuracy to be somewhat worse for GAGAN compared to the other SBASs located in mid-latitude. GAGAN achieves 2.3 m 95% horizontal and 3.7 m 95% vertical accuracy over India.

12.6.5 System of Differential Corrections and Monitoring (SDCM)

Russia is developing its system of differential corrections and monitoring (SDCM [12.44]). Currently SDCM has 19 prototype measuring points (MPs) in Russia and four prototype stations are available outside of Russia. The Russian station locations are shown as red stars in Fig. 12.7. There are also plans to use three GEOs: Luch-5A is at 16° W (PRN 125), Luch-5B at 95° E (PRN 140), and Luch-4 at 167° E (PRN 141). SDCM intends to add 27 additional MPs within Russia and three more outside of Russia. SDCM is still in its development phase with initial service expected in 2016 and fully certified service in 2019. SDCM further intends to augment both GPS and GLONASS. The SDCM prototype achieves 1 m 95% horizontal and 1.5 m 95% vertical accuracy over Russia.

12.6.6 BeiDou Satellite-Based Augmentation System (BDSBAS)

China's satellite navigation system is called Beidou. It includes SBAS-like terms in its navigation message, but these are not backward compatible with existing SBAS receivers. The level of safety associated with these terms is not yet known. A mask and 18 parameters labeled as UDREs are included in one of its subframe messages. An ionospheric grid is also defined over China and delay values and parameters labeled GIVEs are included in other subframes. China has recently announced that it intends to also provide an SBAS service that is compatible with the International Civil Aviation Organization (ICAO) standard to be called BeiDou satellite-based augmentation system (BDSBAS [12.45]). It currently has 20 prototype ground stations in China with plans to ultimately have 30 stations within China and 20 more stations in surrounding areas. GEOs are planned for 80° E, 110° E, and 140° E. The ICAO compatible service is expected to be available around 2020.

12.6.7 Korean Augmentation Satellite System (KASS)

The Republic of Korea has also announced its intention to develop its own SBAS [12.46]. This SBAS will consist of five or more reference stations, two central processing facilities, four GUSs and two GEOs. KASS is in the early development stage with a plan to have preliminary service by 2020.

12.7 Evolution of SBAS

Recently launched GPS satellites have two civil signals at protected aviation frequencies. When both signals are operational, they will allow users to measure the ionosphere directly instead of relying on the SBAS grid for corrections. The uncertainty of the users' direct ionospheric measurements will be much smaller than the broadcast SBAS confidence. Additionally, users can make these measurements anywhere, not just near reference stations. As a result, the service level will improve and the region of coverage will expand much farther from the SBAS networks. Further, additional constellations of navigation satellites are being fielded. The number of useful ranging sources for the user will soon dramatically increase. SBASs will be updated to take advantage of these improvements as they become available [12.47, 48]. The user will experience better availability for existing services and new, even more demanding, services will likely become available.

12.7.1 Multiple Frequencies

The GPS satellites now being launched contain a new civil aviation signal. L5 is centered at 1176.45 MHz and is in a protected aviation band. As such, it will be approved for navigation when it becomes fully operational. When the L5 signal is used in combination with L1, the ionospheric delay for each line-of-sight can be directly estimated and removed. Removing the ionospheric delay will dramatically lower the uncertainty of the pseudorange measurement. Thus, if the SBAS is upgraded to provide satellite clock corrections appropriate for an L1/L5 user and the user similarly upgrades their avionics, SBAS service can be dramatically expanded beyond the current grid of corrections [12.49].

Another important advantage of the second civil frequency is its relative immunity to ionospheric disturbances that are not well modeled by the MOPS grid. Because the user is now directly eliminating the amount of delay they actually experience, they are no longer affected by shortcomings in the MOPS ionospheric model. Thus, a dual frequency user would also have good availability in equatorial areas, even during peak solar activity. The weaker effect of scintillation may have some impact, however, we do not expect to lose vertical guidance altogether, at least not over large areas and for many hours [12.50]. Furthermore, the availability of two civil frequencies offers some protection against unintentional interference. If either L1 or L5 is jammed, the user still has access to guidance on the remaining frequency.

At the moment, the MOPS for an L1/L5 user are at the very early stage of development, so any ground or user improvements are still speculative. When a user has access to two civil frequencies, they can remove the ionospheric effects by forming the ionosphere-free combination of the two pseudoranges

$$
\begin{aligned}
p_{\text{iono\_free}} &= \frac{f_1^2 p_1 - f_5^2 p_5}{f_1^2 - f_5^2}\,,\\
\sigma^2_{\text{iono\_free}} &= \left(\frac{f_1^2}{f_1^2 - f_5^2}\right)^2 \sigma_1^2 + \left(\frac{f_5^2}{f_1^2 - f_5^2}\right)^2 \sigma_5^2\,, \qquad (12.4)
\end{aligned}
$$

where f_1 and f_5 are the L1 and L5 frequencies (1575.42 and 1176.45 MHz), respectively. If σ_1 and σ_5 are comparable then the ionosphere-free combination has roughly three times as much noise as either single frequency term, but is still substantially smaller than σ_{UIRE}. Furthermore, satellites do not need a grid correction to be used, thus satellites farther from the network and the IGP mask can be incorporated into the position solution. The dual frequency confidence bound for a single satellite is then given by

$$
\sigma^2_{\text{tot\_if},i} + \sigma^2_{\text{flt},i} + \sigma^2_{\text{iono\_free},i} + \sigma^2_{\text{trop},i}\,, \qquad (12.5)
$$

where σ_{air} is used in place of σ_1 and σ_5 in (12.4). The VPL term otherwise takes the same form as is used in today's L1-only system. However, now (12.5) is used in place of (12.1) to compute the uncertainty for each line of sight.

Several of the SBAS providers are evaluating plans to offer an L1/L5 service that makes use of these modernized signals. This upgrade will also be accompanied by the inclusion of other constellations as described below.

12.7.2 Multiple Constellations

In addition to GPS L5 development, there are several independent navigation satellite systems being developed with comparable civil frequencies [12.51]. Galileo is being developed by the European Union and is envisioned as being compatible with GPS in which each satellite provides ranging using signals covering the L1 and L5 frequencies with similar modulations. Although the system is still being deployed, it is envisioned that Galileo satellites will provide a service that is fully interoperable with the GPS civil signals.

In parallel, China is developing the BeiDou system whose signals are also planned to be compatible with GPS. Initially BeiDou has a B1 signal near L1 at 1561.098 MHz and another open signal, B2, at 1207.14 MHz. Beidou plans to provide signals at the L1 and L5 frequencies sometime after 2020 [12.52]. However, there is some uncertainty about the timeframe and exact nature of these new signals. Unfortunately, this uncertainty makes it difficult to develop the standards needed to create certified avionics. Offering signals precisely at L1 and at L5 does allow for the most convenient integration of BeiDou. However, signals at nearby frequencies could also be accommodated provided they are in aviation frequency bands.

The Russian GLONASS system has been operational for many years. Its current openly available signals are broadcast using different frequencies rather than different codes to distinguish the satellites. These frequencies range from ≈ 1598–1605 MHz (near L1) and another open signal approximately between 1243 and 1249 MHz. There are modernization plans to broadcast signals at L1 and L5 that are more in alignment with the other constellations. It is not yet known when these new signals would be available.

EGNOS plans to correct both GPS and Galileo on both their L1 and L5 signals. SDCM is planning to augment both GPS and GLONASS. BDSBAS intends to augment both GPS and BeiDou. As these constellations mature and their signal offerings become better known, other SBASs may also choose to augment them. The additional signals essentially ensure that the user always has good geometry. With just GPS, one or more satellite outages can lead to a loss of vertical guidance service. However, with two or more constellations, service is tolerant to many satellite outages. Inclusion of multiple constellations into SBAS ensures continuity of service even if the constellations choose to maintain fewer satellites overall in the future. They also allow for the possibility of supporting even more demanding operations.

References

12.1 International Standards and Recommended Practices (SARPS), Annex 10 – Aeronautical Telecommunications (ICAO, Radio Navigation Aids 2006)

12.2 D. Lawrence, D. Bunce, N.G. Mathur, C.E. Sigler: Wide Area Augmentation System (WAAS) – Program status, ION GNSS 2007, Fort Worth (ION, Virginia 2007) pp. 892–899

12.3 Archive List of WAAS and SPS PAN Reports (Federal Aviation Administration, 2001–2016) http://www.nstb.tc.faa.gov/DisplayArchive.htm

12.4 E. Gakstatter: Using high-performance L1 GPS receivers w/WAAS for mapping/surveying, Proc. Stanf. Cent. PNT Symp. (2011)

12.5 K. Ali, M. Pini, F. Dovis: Measured performance of the application of EGNOS in the road traffic sector, GPS Solutions **16**(2), 135–145 (2012)

12.6 H. Cabler, B. DeCleene: LPV: New, improved WAAS instrument approach, ION GPS 2002, Portland (ION, Virginia 2002) pp. 1013–1021

12.7 R.G. Brown: A baseline RAIM scheme and a note on the equivalence of three RAIM methods, Navigation **39**(3), 301–316 (1992)

12.8 Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment (RTCA, Washington DC 2013)

12.9 J.A. Klobuchar: Ionospheric effects on GPS. In: *Global Positioning System: Theory and Applications*, Vol. 1, ed. by B.W. Parkinson, J.J. Spilker (AIAA, Washington DC 1996), pp. 485–515, Chap. 12

12.10 L. Sparks, X. Pi, A.J. Mannucci, T. Walter, J. Blanch, A. Hansen, P. Enge, E. Altshuler, R. Fries: The WAAS ionospheric threat model, Proc. Beac. Satell. Symp., Boston (2001)

12.11 A. Komjathy, L. Sparks, A.J. Mannucci, A. Coster: The ionospheric impact of the October 2003 storm event on wide area augmentation system, GPS Solutions **9**(1), 41–50 (2005)

12.12 J.P. Collins, R.B. Langley: The residual tropospheric propagation delay: How bad can it get?, ION GPS 1998, Nashville (ION, Virginia 1998) pp. 729–738

12.13 K. Shallberg, P. Shloss, E. Altshuler, L. Tahmazyan: WAAS measurement processing, reducing the effects of multipath, ION GPS 2001, Salt Lake City (ION, Virginia 2001) pp. 2334–2340

12.14 R.E. Phelts, T. Walter, P. Enge: Characterizing nominal analog signal deformation on GNSS signals, ION GNSS 2009, Savannah (ION, Virginia 2009) pp. 1343–1350

12.15 C. Macabiau, C. Milner, A. Chabory, N. Suard, C. Rodriguez, M. Mabilleau, J. Vuillaume, S. Hegron: Nominal bias analysis for ARAIM user, ION ITM 2015, Dana Point (ION, Virginia 2015) pp. 713–732

12.16 K. Shallberg, J. Grabowski: Considerations for characterizing antenna induced range errors, ION GPS 2002, Portland (ION, Virginia 2002) pp. 809–815

12.17 S. Rajagopal, T. Walter, S. Datta-Barua, J. Blanch, T. Sakai: Correlation structure of the equatorial ionosphere, ION NTM 2004, San Diego (ION, Virginia 2004) pp. 542–550

12.18 T. Walter, A. Hansen, J. Blanch, P. Enge, T. Mannucci, X. Pi, L. Sparks, B. Iijima, B. El-Arini, R. Lejeune, M. Hagen, E. Altshuler, R. Fries, A. Chu: Robust detection of ionospheric irregularities, Navigation **48**(2), 89–100 (2001)

12.19 J. Blanch: Using Kriging to Bound Satellite Ranging Errors due to the Ionosphere, Ph.D. Thesis (Stanford Univ., Stanford 2003)

12.20 L. Sparks, J. Blanch, N. Pandya: Estimating ionospheric delay using kriging: 1. Methodology, Radio Sci. **46**(RS0D21), 1–13 (2011)

12.21 L. Sparks, J. Blanch, N. Pandya: Estimating ionospheric delay using kriging: 2. Impact on satellite-based augmentation system availability, Radio Sci. **46**(RS0D22), 1–12 (2011)

12.22 T. Walter, S. Rajagopal, S. Datta-Barua, J. Blanch: Protecting against unsampled ionospheric threats, Proc. Beac. Satell. Symp., Trieste (2004)

12.23 T. Walter: WAAS MOPS: Practical examples, ION NTM 1999, San Diego (ION, Virginia 1999) pp. 283–293

12.24 M. Grewal, P.-H. Hsu, T.W. Plummer: A new algorithm for WAAS GEO Uplink Subsystem (GUS) clock steering, ION GPS/GNSS 2003, Portland (ION, Virginia 2003) pp. 2712–2719

12.25 J. Vázquez, M.A. Sánchez, J. Cegarra, P.D. Tejera, P. Gómez Martínez: The EGNOS NOTAM proposals service: Towards full ICAO compliance, ION GNSS+ 2013, Nashville (ION, Virginia 2013) pp. 301–315

12.26 T. Walter, P. Enge, B. DeCleene: Integrity lessons from the WIPP, ION NTM 2003, Anaheim (ION, Virginia 2003) pp. 183–194

12.27 B. DeCleene: Defining pseudorange integrity – overbounding, ION GPS 2000, Salt Lake City (ION, Virginia 2000) pp. 1916–1924

12.28 J. Rife, S. Pullen, B. Pervan, P. Enge: Paired overbounding and application to GPS augmentation, Proc. PLANS 2004, Monterey (2004) pp. 439–446

12.29 T. Walter, J. Blanch, J. Rife: Treatment of biased error distributions in SBAS, J. Glob. Position. Syst. **3**(1/2), 265–272 (2004)

12.30 P. Enge: AAS messaging system: Data rate, capacity, and forward error correction, Navigation **44**(1), 63–76 (1997)

12.31 T. Walter, A. Hansen, P. Enge: Message type 28, ION NTM 2001, Long Beach (ION, Virginia 2001) pp. 522–532

12.32 L1 C/A PRN Code Assignments (US Air Force, Los Angeles Air Force Base 2016) http://www.losangeles.af.mil/About-Us/Fact-Sheets/Article/734549/gps-prn-assignment

12.33 FAA: http://www.nstb.tc.faa.gov/

12.34 A. Heßelbarth, L. Wanninger: SBAS orbit and satellite clock corrections for precise point positioning, GPS Solutions **17**(4), 465–473 (2013)

12.35 H. Manabe: Status of MSAS: MTSAT satellite-based augmentation system, ION GNSS 2008, Savannah (ION, Virginia 2008) pp. 1032–1059

12.36 T. Sakai, H. Tashiro: MSAS status, ION GNSS+ 2013, Nashville (ION, Virginia 2013) pp. 2343–2360

12.37 P. Feuillet: EGNOS program status, ION GNSS 2012, Nashville (ION, Virginia 2012) pp. 1017–1033

12.38 D. Thomas: EGNOS V2 program update, ION GNSS+ 2013, Nashville (ION, Virginia 2013) pp. 2327–2342

12.39 Monthly Performance Reports (European Satellite Services Provider, 2011–2016) https://egnos-user-support.essp-sas.eu/new_egnos_ops/content/monthly-performance-reports

12.40 J. Ventura-Traveset, D. Flament (Eds.): *EGNOS – The European Geostationary Navigation Overlay System – A Cornerstone of Galileo*, *ESA SP-1303* (ESA, Noordwijk 2006)

12.41 R. Chen, F. Toran-Marti, J. Ventura-Traveset: Access to the EGNOS signal in space over mobile-IP, GPS Solutions **7**(1), 16–22 (2003)

12.42 GAGAN (Airports Authority of India, 2013) http://www.aai.aero/public_notices/aaisite_test/faq_gagan.jsp

12.43 India: GAGAN Implementation and Certification in India, 49th Conf. Dir. Gen. Civ. Aviat. Asia Pac. Reg. (ICAO, New Delhi 2012), http://www.icao.int/APAC/Meetings/2012_DGCA/

12.44 S. Karutin: SDCM Program Status, ION GNSS 2012, Nashville, TN 17–21 Sep 2012 (ION, Virginia 2012) 1034–1044

12.45 W. Song, J. Shen: China – Development of BeiDou Navigation Satellite System (BDS) – A program update, Proc. ION Pacific PNT, Honolulu (ION, Virginia 2015) pp. 208–236

12.46 Y. Yun: Influence of reference station distribution on the Korean SBAS performance, Proc. ION Pacific PNT, Honolulu (ION, Virginia 2015) pp. 964–969

12.47 S.S. Jan, W. Chan, T. Walter: ATLAB algorithm availability simulation tool, GPS Solutions **13**(4), 327–332 (2009)

12.48 T. Walter, J. Blanch, R.E. Phelts, P. Enge: Volving WAAS to serve L1/L5 users, Navigation **59**(4), 317–327 (2012)

12.49 T. Walter, P. Enge: Modernizing WAAS, ION GPS 2004, Long Beach (ION, Virginia 2004) pp. 1683–1690

12.50 R.S. Conker, M.B. El Arini, C.J. Hegarty, T. Hsiao: Modeling the effects of ionospheric scintillation on GPS/satellite based augmentation system availability, Radio Sci. **38**(1), 1–23 (2003)

12.51 C.J. Hegarty, E. Chatre: Evolution of the global navigation satellite system (GNSS), Proc. IEEE **96**(12), 1902–1917 (2008)

12.52 Z. Yao: BeiDou next generation signal design and expected performance, Int. Tech. Symp. Navig. Timing (ENAC, Toulouse 2015)