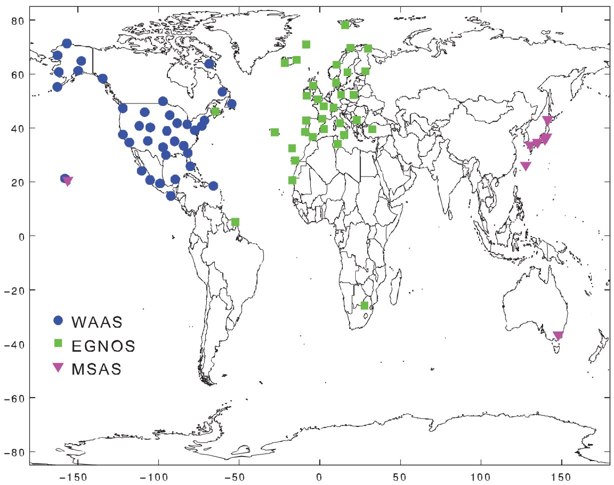
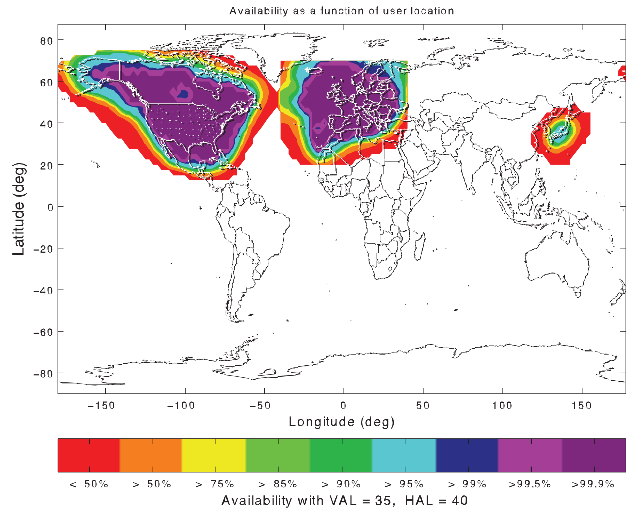


▲ **FIGURE 1** Existing SBAS reference networks, consisting of 38 reference stations for WAAS, 34 for EGNOS, and 8 for MSAS



▲ **FIGURE 2** Simulation results from MAAST for availability of LPV-200 provided by current systems

Future Augmented

Coverage Improvement for Dual-Frequency SBAS

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After reviewing current performance of WAAS, EGNOS, and MSAS, the authors present expected future performance, including the benefits of GPS L5. They evaluate the impact of the Indian GAGAN and Russian SDCM systems on global coverage and examine southward expansions for the original three SBASs. Finally, a look at the impact of a second constellation of navigation satellites and the performance for a user taking advantage of two core constellations.

The Wide Area Augmentation System (WAAS) monitors GPS and provides both differential corrections to improve accuracy and associated confidence bounds to assure integrity. The first satellite-based augmentation system (SBAS), it was commissioned for service in 2003. Japan's MTSAT-based Satellite Augmentation System (MSAS) was commissioned in 2007, and the European Geostationary Navigation Overlay Service (EGNOS) was declared operational in 2009, with safety-of-life service commissioning expected in mid-2010. Two other SBASs are in the developmental stage: India's GPS Aided Geo Augmented Navigation (GAGAN) and Russia's System for Differential Corrections and Monitoring (SDCM) have fielded equipment and plan to become operational in the next few years.

Coming improvements will expand SBAS coverage areas and strengthen their performance. In the near term, these include more monitoring stations and algorithmic enhancements, with incorporation of a second civil signal in a protected aeronautical band and new GNSS constellations in the long term.

An SBAS utilizes a network of precisely surveyed reference receivers, located throughout its coverage region. The information gathered from these reference stations monitors the GNSS satellites and their propagation environment in real time. Availability of SBAS service is a function of two quantities: the arrangement of the pseudorange measurements used to determine the user's position, referred to as geometry; and the quality of each individual measurement, referred to as the confidence bound. Although very small confidence bounds can make up for poor geometries, and strong geometries can overcome large confidence bounds, both values are generally required to be good to obtain high availability.

Geometry is determined purely by the locations of the ranging satellites relative to the user. Currently the basic geometry is provided by the GPS constellation. Historically it has exceeded commitments, and there are currently 29 healthy satellites in orbit when only 21 are nominally guaranteed. However, as satellites are taken off-line in critical orbital slots, the quality of the geometry can degrade significantly. There could be short duration losses of service daily at some locations. Since the goal is to provide service more than 99.9 percent of the time, these outages can have a dramatic impact. WAAS currently mitigates this concern by adding geostationary satellites with a ranging function virtually identical to the GPS satellites. These satellites are always in view and improve the overall geometry, although they do not eliminate the problem completely.

The confidence bounds relate to the expected error sources on the range measurements. Currently three error sources are corrected via broadcast to the user: satellite clock error, satellite ephemeris error, and delay error due to propagation through the ionosphere. These error sources are described by two confidence bound terms: the user differential range error (UDRE) for the satellite errors, and the grid ionospheric vertical error (GIVE) for the ionospheric errors.

For single-frequency SBAS, this last error source is the most significant. Users may sample the ionosphere anywhere in the service volume, but the SBAS only has measurements from its reference station locations. Thus, there is always the possibility of undetected ionospheric disturbances. This leads to larger confidence bounding terms and lower availability.

The combination of geometry and confidence bounds yields the protection levels (PL). PLs are the real-time confidence bound on the user's position error. To match aviation requirements these are broken into a vertical protection level (VPL) and a horizontal protection level (HPL). Each SBAS guarantees that the user's actual position error will be smaller than these values 99.99999 percent of the time. The PLs are calculated in real-time using stored and broadcast information. They must be compared to the maximum allowed value for a desired operation. The upper bounds are called alert limits (AL) and they are fixed numbers whose values depend on the operation.

In this article we are interested in the localizer performance with vertical guidance (LPV)-200 approach with a VAL of 35 meters and HAL of 40 meters. Currently, LPV aviation approaches can only be accomplished with a WAAS GPS receiver. Performance of an LPV approach allows minimums as low as 200 feet above ground level before a missed approach must be executed. As of January 2010, there were 1,930 published WAAS LPVs, with plans to add 300 per year in the United States.

Because GPS and SBAS generally perform better at horizontal positioning than vertical, the requirement that the VPL be below the VAL is nearly always the limiting constraint for these operations.

Methodology

To determine the global availability and the effect of potential improvements, we used our Matlab Algorithm Availability Simulation Tool (MAAST). This tool uses almanac data to calculate the position of the satellites for each specified epoch. The almanac chosen for this study corresponds to the GPS almanac broadcast on April 8, 2009, when there were 30 healthy satellites. However, PRNs 25 and 32 were removed to simulate a condition with 28 healthy satellites. MAAST also implements the WAAS integrity algorithms to calculate the corresponding UDRE and GIVE values. Finally, it uses these values to implement the airborne algorithms specified in the minimum operational performance standards (MOPS) for SBAS. The MOPS specifies user algorithms for determining the protection levels. For these simulations, the VPL and HPL are calculated about every 5 minutes and every two and a half degrees across the globe.

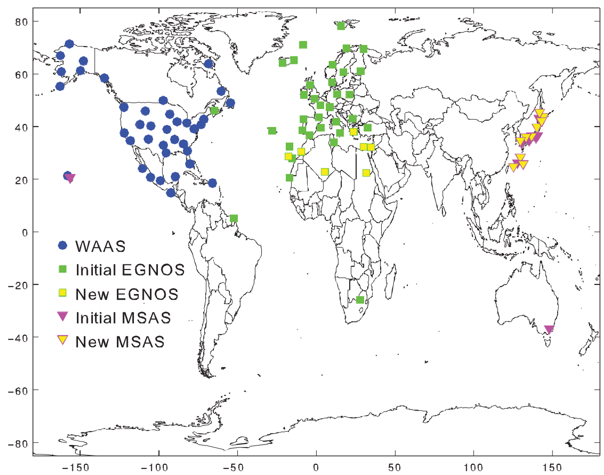
MAAST does a good job of predicting WAAS behavior. It is less accurate when predicting other systems' performance. EGNOS has developed its own monitoring receivers and integrity algorithms and has different criteria for assigning a satellite a particular UDRE value and assigning each ionospheric grid point's (IGP's) GIVE value. Nevertheless, both systems are designed to meet ICAO requirements for integrity, and their performance should be somewhat similar. In observing EGNOS coverage plots and comparing them to MAAST predictions, we do see differences. However, the size of the coverage region and approximate boundaries are reasonably close and provide an idea of performance if not an exact map.

The MSAS algorithms are based upon the same algorithms used in earlier versions of WAAS. Therefore, MAAST should be slightly more accurate in modeling its performance. GAGAN uses the same prime contractor as WAAS and therefore similar algorithms may be expected. Less is known about the intended SDCM algorithms and therefore the modeling of this system faces the largest uncertainty. Again, the MAAST predictions should be viewed as indicative rather than precise. Individual availability maps will not be completely correct, but relative performance improvements should be properly indicated.

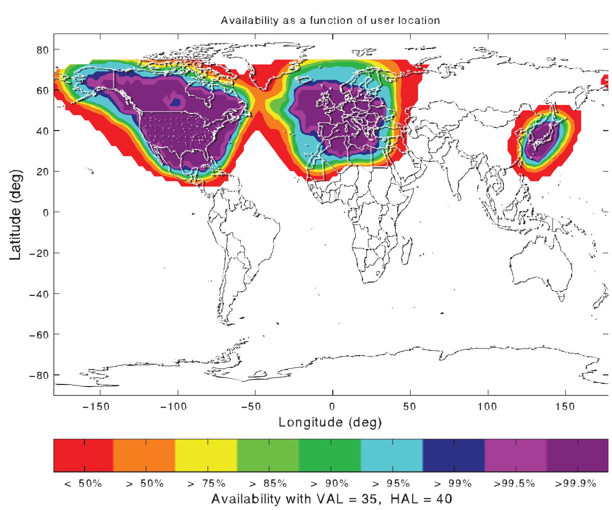
Current Systems Status

Currently WAAS is in its full LPV-200 performance (FLP) phase. It consists of 20 WAAS reference stations (WRS) in the conterminous United States (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. The station locations are shown as blue circles in FIGURE 1. There are three WAAS master stations (WMS) and two geostationary satellites (GEOs). The GEOs are the Intelsat Galaxy XV satellite at 133° W and the Telesat ANIK F1R satellite at 107° W.

As can be seen in FIGURE 2, availability of LPV-200 service is very high for most of North America. In general, this performance meets the goals for the system. However, in some regions performance is lower than the 99 percent minimum target. The West Coast, Alaska, and Southern Mexico all suffer from reduced availability.



▲ **FIGURE 3** Improved SBAS networks.The newly added reference stations are marked by yellow-filled squares for EGNOS and yellow-filled triangles for MSAS.



▲ **FIGURE 4** Improved single-frequency SBAS coverage for the original three SBAS

MSAS is in its initial operating phase. It consists of six ground monitoring stations (GMSs) on the Japanese Islands, one in Australia, and one in Hawaii (magenta triangles in Figure 1). There are two master control stations (MCSs) and two Multifunction Transport Satellite (MTSAT) geostationary satellites at 140° E and 145° E.

Because of the limited network size, the GEO UDREs for MSAS are set to 50 meters and therefore do not benefit vertical guidance. Further, the limited ionospheric observations offer little availability of LPV-200 service as can be seen in Figure 2. 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 LPV-200 operations. Until then, MSAS provides only lateral navigation.

EGNOS is also in its initial operations phase. It consists of 28 ranging and integrity monitoring stations (RIMS) in Europe, one in Turkey, three in Africa, one in North America, and one in South America (green squares in Figure 1). There are four master control centers (MCCs) and two GEOs, the INMARSAT Atlantic Ocean Region-East (AOR-E) satellite at 15.5° W and the ARTEMIS satellite at 21.5° E.

For a variety of reasons, EGNOS has chosen to implement its GEO satellites without a ranging capability. Thus, for our simulations we have set them as data-links only and do not model a ranging capability. EGNOS also currently implements Message Type 27 (MT-27) rather than Message Type 28 (MT-28) as do WAAS and MSAS. MT-27 restricts the use of low UDRE values to a box centered on the European region. Its borders can be discerned in Figure 2. Currently it has little impact on LPV-200 service, but if EGNOS is to expand its coverage, it may become a limiting factor. Availability of LPV-200 service is very high for most of Europe. However, there is a desire to expand coverage to more reliably cover Iceland, Scandinavia, Eastern Europe, and the Mediterranean and South Atlantic regions.

Near-Term Improvements

EGNOS is fielding additional reference stations in the Canary Islands, Northern Africa, and the Middle East. In the longer term, MT-28 is being considered as a replacement for MT-27. In our modeling we added seven new RIMS, shown in **FIGURE 3**, and implemented MT-28. We also improved the ionospheric mask by including additional IGPs. We did not update GEO locations nor did we model ranging capability that could further enhance performance. By comparing **FIGURE 4** to Figure 2 improvements can be seen, in particular expanded LPV-200 operation to the south.

The future of MSAS improvements is less certain, with no firm commitments for major service enhancements. We have chosen to model fairly aggressive enhancements based upon studies made by the Electronic Navigation Research Institute in Japan. We have added 10 new reference stations in Japan and made the ionospheric threat model less conservative, in line with current WAAS algorithms. Together, these improvements offer good vertical guidance coverage over Japan.

These improvements extend coverage in the vicinity of the reference station networks, but are unable to push availability much beyond. This is primarily due to the limitations of the ionospheric corrections. Because strong gradients can exist outside of the viewing area of the network, tight confidences cannot be provided to those regions.

SBASs model the ionosphere as a thin 2-dimensional shell 350 kilometers above Earth. This works well for quiet mid-latitude and polar ionosphere. However, equatorial ionosphere often has significant vertical structure that is not well replicated by the SBAS message. The resulting confidence bounds are then too large to reliably provide LPV-200 capability. No certified algorithm capable of bounding the equatorial ionosphere is known to the authors. Instead, it is recommended that SBASs in equatorial areas wait for the forthcoming L5 signal to provide vertical guidance in their regions.

GPS L5

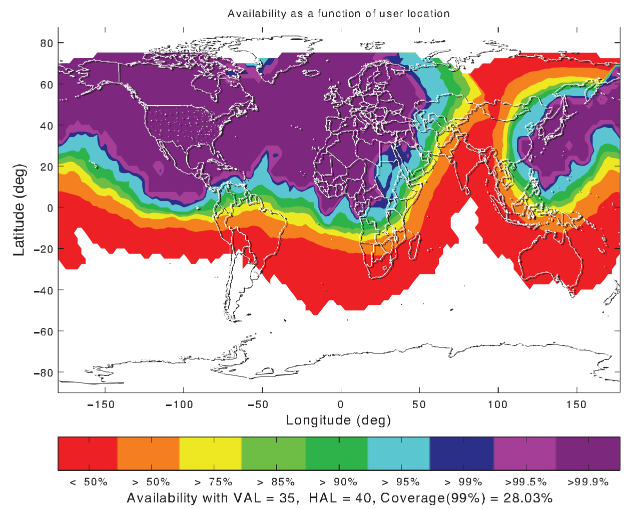
The next GPS satellite to be launched will contain a new civil signal, L5, centered at 1176.45 MHz and in a protected aviation band. As such, it will be approved for use on aircraft. When the L5 signal is used in combination with L1, the ionospheric delay for each line-of-sight can be directly estimated. This will dramatically lower the uncertainty of the pseudorange measurement. Thus, if the SBAS is upgraded to provide corrections appropriate for an L1/L5 user and the user similarly upgrades his or her avionics, SBAS service can be dramatically improved.

Another important advantage of the second civil frequency is its relative immunity to ionospheric storms. Because the users are now directly eliminating the amount of delay they actually experience, they are no longer affected by shortcomings in the MOPS ionospheric model. The weaker effect of scintillation may have some impact; however, we do not expect to lose vertical guidance altogether. Furthermore, the availability of two civil frequencies offers protection against unintentional interference. If either L1 or L5 is jammed, the user still has access to guidance on the available frequency.

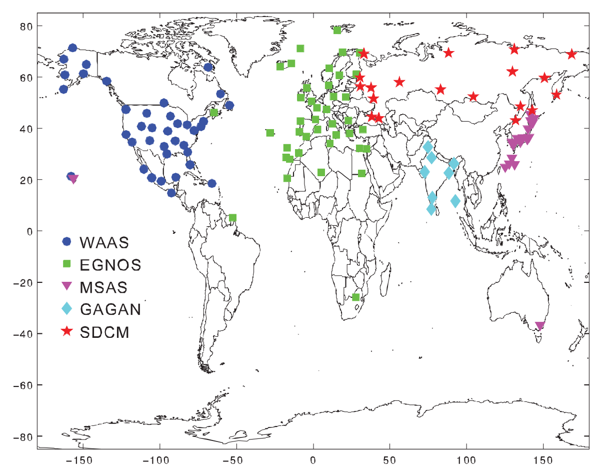
At the moment there is no MOPS for an L1/L5 user, so any ground or user algorithms will have to be speculative. We propose basing future L1/L5 algorithms on the existing L1-only algorithms. Instead of using L1-only pseudorange measurements, the user forms the ionosphere-free combination. For the confidence term representing the total pseudorange error on a line-of-sight, the ionospheric correction terms and airborne multipath terms are replaced with a single value representing airborne noise and multipath for the ionosphere-free combination.

For discussion of confidence terms for single-frequency users, related equations, and VPL, see the website version of this article at *www.gpsworld.com/dualsbas*.

The improvement in performance for a dual-frequency user can be seen in **FIGURE 5**. The coverage is significantly expanded. Now each region is robustly covered with large margins surrounding their intended service regions. However, coverage is still limited to the areas around these first three SBASs.



▲ **FIGURE 5** Potential dual-frequency coverage of the first three SBASs including network improvements



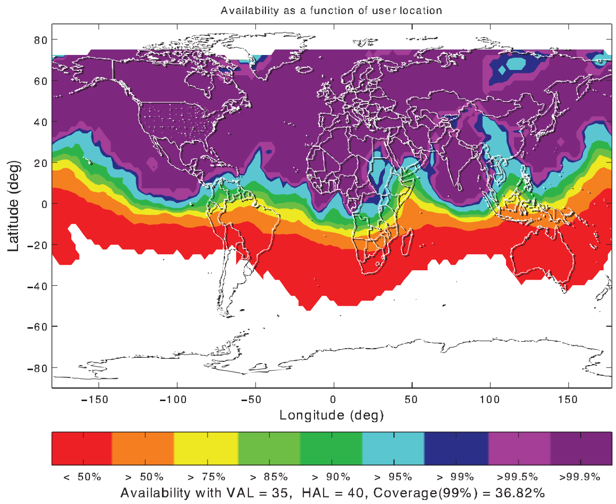
▲ **FIGURE 6** The networks of five SBAS systems. In addition to the reference stations from Figure 3, the eight Indian stations are shown as blue diamonds and the 19 Russian stations are shown as red stars.

GAGAN and SDCM

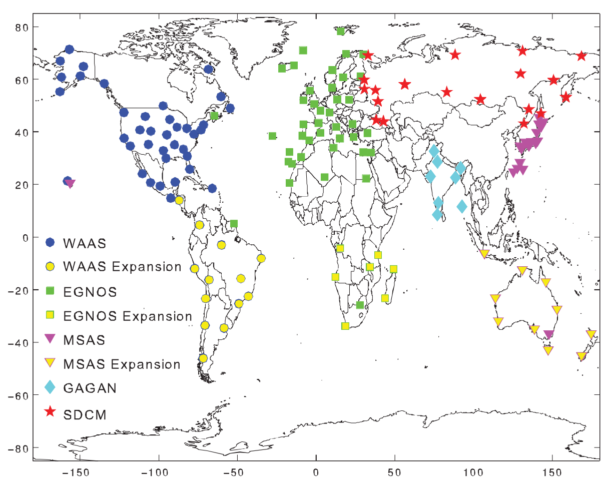
Two additional SBASs are currently under development that will extend coverage to more regions. India is developing GAGAN. Currently it has eight Indian reference stations (INRES) all in India (blue diamonds in **FIGURE 6**). There is one Indian master control center (INMCC), and plans to use the GSAT-4 as its initial GEO. The GSAT-4 is planned for launch in 2010 and will be located near 82° E. The geomagnetic equator passes through India and it therefore faces the full impact of equatorial ionosphere. The advent of L5 will allow GAGAN to obtain high LPV-200 availability that is unlikely to be achievable for single-frequency users.

Russia is developing SDCM. It now has nine operational measuring points (MPs) and has plans for at least 10 more locations, all in Russia (red stars in Figure 6). There are also plans to use three GEOs: Luch-5a planned for launch in 2010 and to be located near 16° W, Luch-5b planned for launch in 2011 and to be located near 95° E, and Luch-4 planned for launch in 2013 and to be located near 167° E.

FIGURE 7 shows the combined dual-frequency coverage of all five systems, WAAS, EGNOS, MSAS, GAGAN, and SDCM. The vast majority of land masses in the northern hemisphere are now well covered by at least one of the SBASs. Figures 6 and 7 clearly highlight that the majority of development has occurred



▲ **FIGURE 7** The combined dual-frequency availability of the five SBASs



▲ **FIGURE 8** Networks of the five SBAS systems including hypothetical expansions into the southern hemisphere

in the northern hemisphere. In fact, only two reference stations have been placed below the Equator.

Southern Hemisphere

If SBAS is to provide a global solution, its coverage must extend into the southern hemisphere. There have been many discussions with representatives of countries in the southern hemisphere. Further, the United States has had testbed receivers in South America for nearly 15 years. Europe has fielded receivers in Africa. Australia investigated its own variant of SBAS called the Ground-based Regional Augmentation System (GRAS). However, we are not aware of concrete plans for development in this hemisphere.

We anticipate that discussions will eventually evolve into firm plans and that either independent SBASs will be developed in these regions or existing SBASs will expand their networks southward. We have chosen to assume that WAAS, EGNOS, and MSAS will expand their networks to extend LPV-200 coverage to the southern portion of their GEO footprints. This is but one of many possible scenarios. The proposed expansion shown in **FIGURE 8** is not based on any plans, but is based on the notion that civil aviation authorities will want to obtain global coverage. The assumed new southern reference stations are shown as yellow-filled circles for WAAS in South America, yellow-filled squares for EGNOS in southern Africa, and yellow-filled triangles for MSAS in and around Australia. Advantages of dual frequency allow us to have much less dense networks for the expansions, in addition to allowing LPV-200 capability to be obtained in equatorial areas.

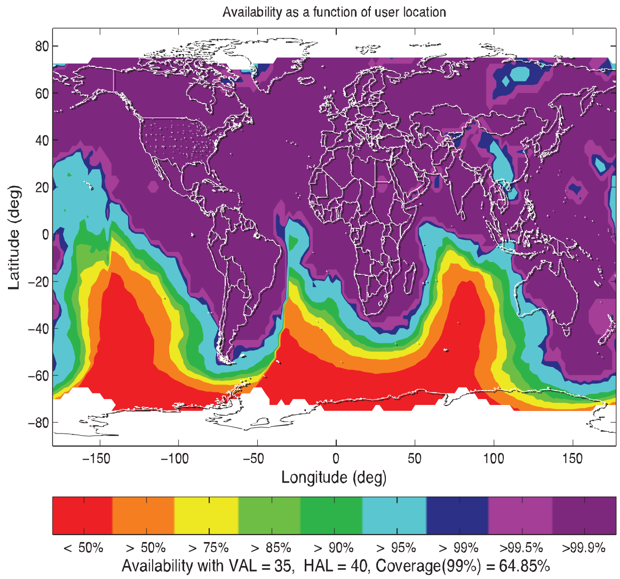
FIGURE 9 shows the combined dual-frequency coverage for these SBASs with the expanded network. Now nearly all land masses have good LPV-200 coverage. Note that we have not attempted to optimize these networks to assure coverage to all land masses, not have we tried to find the minimum number of stations that offer this capability.

Added Core Constellations

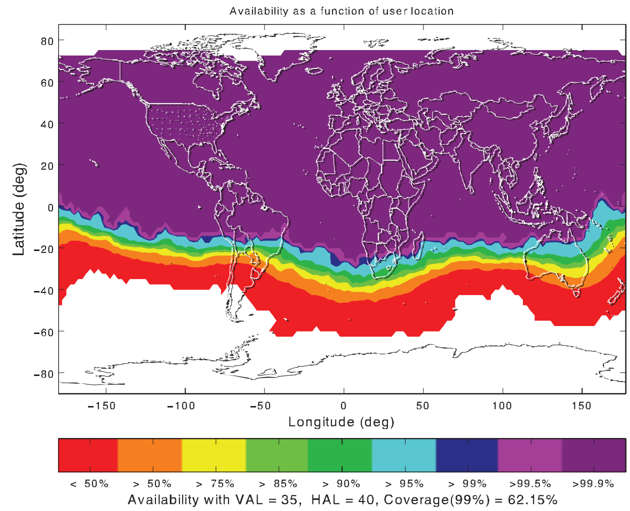
Galileo is envisioned as compatible with GPS in that each satellite provides ranging using signals covering the L1 and L5 frequencies with similar modulations. Although the final specifications are not yet set, it is envisioned that Galileo satellites will provide a service that is fully interoperable with the GPS civil signals. Thus, we can approximately model Galileo satellites as being equivalent to GPS satellites in different orbits. In parallel, China is developing the COMPASS system whose signals are also planned to be compatible with GPS.

The Russian GLONASS system has been operational for many years. However, its current signal structure makes it less suited for incorporation into avionics. There are modernization plans to broadcast L1 signals that are more in alignment with the other constellations. Thus it, too, may one day be incorporated into SBAS. We believe that SBASs will someday broadcast satellite clock and ephemeris corrections for GPS and one or more other core constellations. These corrections will remove any difference in the reference times or coordinate frames between the two systems, allowing the corrected signals to be considered fully interchangeable.

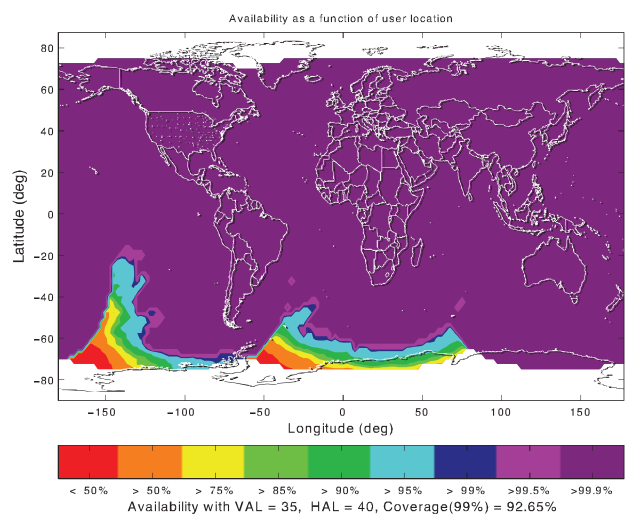
Adding 24 or more extra ranging sources will have tremendous benefit for all civil GNSS users. The user's geometry would be very robust to the loss of one or two satellites. Adding one or more core constellations has the potential to significantly improve SBAS coverage. We chose to model the addition of one constellation, by combining the almanac we used for GPS with one that had been proposed for Galileo. For these scenarios, MAAST is modeling 55 medium earth orbiting navigation satellites in addition to the GEOS used by each SBAS. Because the orbital repeat period is approximately 10 sidereal days for Galileo, the simulated time step and total run time were each



▲ **FIGURE 9** The combined dual-frequency availability of the SBASs with the southern hemisphere stations



▲ **FIGURE 10** The combined dual-frequency, LPV-200 coverage of the five SBAS systems with both GPS and Galileo



▲ **FIGURE 11** Combined dual-frequency LPV-200 coverage, SBASs with GPS and Galileo and the southern hemisphere stations

increased by a factor of ten.

FIGURE 10 shows the improved coverage when the reference stations shown in Figure 6 are used. The additional satellites fill in many potential coverage gaps and now, compared to Figure 7, the SBASs all have even more reliable coverage well beyond their reference networks. Indeed, the Northern Hemisphere is now essentially fully covered. **FIGURE 11** shows the results when the expanded networks of Figure 8 are incorporated. Compared to Figure 9, the southern hemisphere is much more reliably covered. The remaining gaps could easily be filled in with just a few more reference stations if full global coverage were desired.

Conclusions

For single-frequency SBAS the coverage is limited to areas very close to the monitoring station network. However, each region can obtain very good LPV-200 coverage within their desired service area. The addition of GPS L5 makes vertical guidance largely immune to ionospheric disturbances, and permits SBAS coverage to extend into equatorial areas. Independence from the ionospheric grid also allows service to extend farther away from the core network regions. When new Indian and Russian systems are commissioned, a very large fraction of the northern hemisphere will have LPV-200 coverage.

With dual frequency, LPV-200 coverage can be established with comparatively sparse networks in South America, Africa, and around Australia. Additional dual-frequency core constellations such as Galileo, Compass, or GLONASS could greatly expand coverage to well outside the original reference network regions. As GNSS capability is improved and expanded, we anticipate that SBAS coverage may one day provide nearly global LPV-200 or better service capability.

Acknowledgments

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