# Coverage Improvement for Dual Frequency SBAS

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**ABSTRACT**

In the next few years GPS will start broadcasting civil signals suitable for aviation use on both the L1 and L5 frequencies. In addition, Galileo and other constellations will offer an even greater number of dual frequency ranging measurements. The Wide Area Augmentation System (WAAS) and the other Satellite Based Augmentation Systems (SBASs) can also be updated to exploit these new signals. Such updates offer a variety of improvements over existing single frequency systems. These dual frequency systems will be fully robust against ionospheric gradients that currently limit vertical guidance during severe ionospheric disturbances. Further, they offer improved resistance against interference as operations can proceed when aircraft lose access to one frequency or the other. However, the largest benefit to a user taking advantage of both frequencies is that their availability can extend much farther away from the reference station network. The uncertainty in the ionospheric behavior at the user is essentially eliminated, allowing this increase in coverage.

Importantly, this availability can be extended into equatorial areas where the current single-frequency, two-dimensional grid can be a very poor fit to actual behavior. Thus, availability to these regions can be reliably provided for the first time. This paper examines the coverage that will be offered by SBAS systems when they upgrade to dual-frequency operation. It will examine the coverage offered to the user through the combined coverage of existing and planned systems. Further, we will examine how, with small extensions in their reference station networks, nearly global coverage of LPV-200 service may be achieved.

Finally, we will present the improvement to coverage that can be provided by also integrating additional constellations into the SBAS coverage. Additional ranging signals dramatically improve the users geometry, even further extending coverage from reference station networks.

**INTRODUCTION**

The Wide Area Augmentation System (WAAS) monitors the Global Positioning System (GPS) and provides both differential corrections to improve the accuracy and associated confidence bounds to assure the integrity. It was the first of the Satellite Based Augmentation Systems (SBASs) and was commissioned for service in 2003 [1]. The Japanese system MTSAT-based Satellite Augmentation System (MSAS) followed next and was commissioned in 2007 [2]. The European system, European Geostationary Navigation Overlay Service (EGNOS) [3] was declared operational in 2009, but has not yet been commissioned for safety-of-life service. That commissioning is expected to occur in mid-2010. Two other SBASs are in the developmental stage. The Indian system, GPS Aided Geo Augmented Navigation (GAGAN) [4], and the Russian SBAS, System for Differential Corrections and Monitoring (SDCM) [5], have fielded equipment and are planning to become operational in the next few years.

These SBASs are also planning improvements to expand their coverage areas and strengthen their performance. These include near-term improvements such as additional monitoring stations and algorithmic enhancements. There will also be longer-term improvements such as the incorporation of a second civil signal in a protected aeronautical band and the addition of new GNSS constellations.

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 [6]. 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 [7]. 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% 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 [8]. This leads to larger confidence bounding terms and lower availability.

The combination of geometry and confidence bounds yields the Protection Levels (PL). Protection Levels 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% 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 paper we are interested in the LPV-200 approach with a VAL of 35 m and HAL of 40 m [9] [10]. 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.

This paper will present the current performance of WAAS, EGNOS, and MSAS. Then we will study expected performance for the future. Specifically we will look first at the set of network improvements that could expand LPV-200 performance around Europe and Japan. Next, we will look at the benefit of GPS L5 and how it will improve SBAS performance. Then we will add in the GAGAN and SDCM systems to evaluate their impact on global coverage and also examine southward expansions for the original three SBASs. Finally, we will examine the impact of a second constellation of navigation satellites and evaluate the performance for a user taking advantage of two core constellations.

## METHODOLOGY

To determine the global availability and the effect of potential improvements we used our Matlab® Algorithm Availability Simulation Tool (MAAST) [11]. 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) [12] 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.

As was shown in [13], MAAST does a good job of predicting the behavior of WAAS. However, it is less accurate when predicting the performance of other systems. EGNOS has developed their own monitoring receivers and integrity algorithms. Consequently, they have 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 therefore performance of the systems 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

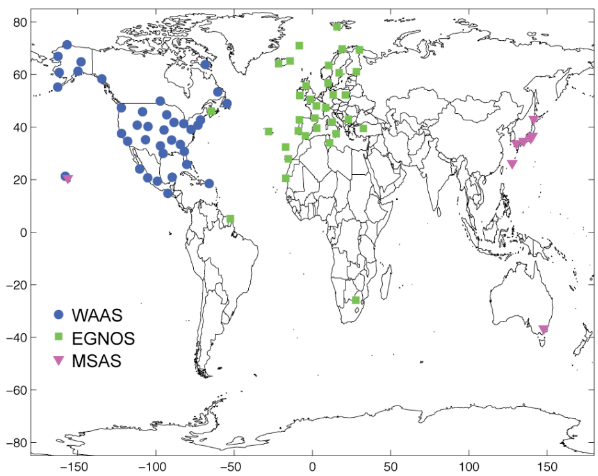


**Figure 1.** *Existing SBAS reference networks, consisting of 38 reference stations for WAAS, 34 for EGNOS, and 8 for MSAS.*

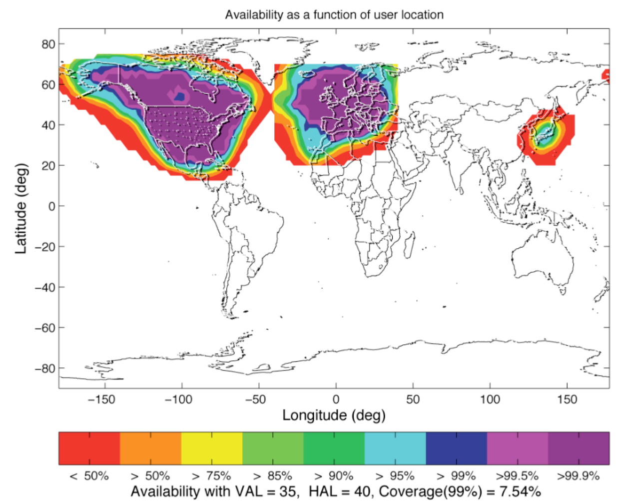


**Figure 2.** *Simulation results from MAAST for availability of LPV-200 provided by currents systems.*

therefore 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 is also using 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.

## STATUS OF CURRENT SYSTEMS

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. WAAS was commissioned for service in July 2003 and many improvements have been made to the system since [1].

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, there are some regions where performance is lower than the 99% minimum target. The West Coast, Alaska, and Southern Mexico all suffer from reduced availability.

MSAS is in its initial operating phase. It 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. The station locations are shown as 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. MSAS was commissioned for service in September 2007 [2].

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 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, in addition to one in Turkey, three in Africa, one in North America, and one in South America for a total of 34. The station locations are shown as green squares in Figure 1. There are four Master Control Centers (MCCs) and uses two GEOs. The GEOs are the INMARSAT Atlantic Ocean Region-East (AOR-E)

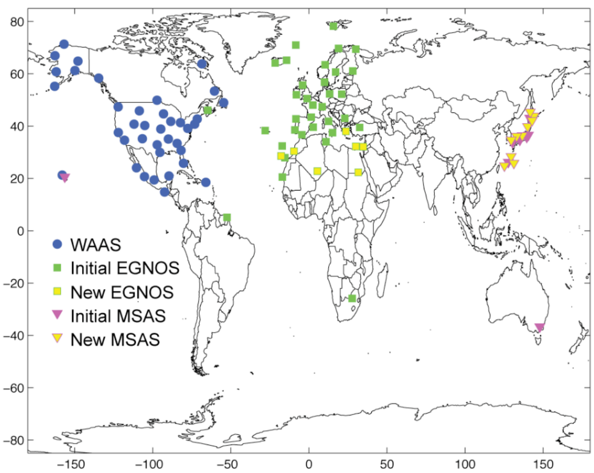


**Figure 3.** *Improved SBAS networks. The newly added reference stations are marked by yellow filled squares for EGNOS and yellow filled triangles for MSAS.*

satellite at 15.5° W and the ARTEMIS satellite at 21.5° E [3]. EGNOS was declared operation in October 2009, but has not yet been certified for safety-of-life service. This final approval is expected to occur in mid 2010.

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) [14] 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 has several system improvements under development and more are planned. Already additional reference stations are being fielded in the Canary Islands, Northern Africa, and the Middle East [3]. 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

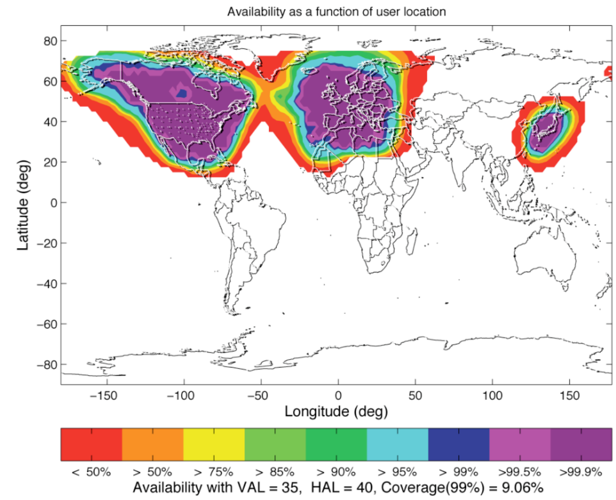


**Figure 4.** *Improved single frequency SBAS coverage for the original three SBAS*

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. Many studies have been made, but as of yet there are 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 (ENRI) in Japan. We have added ten new reference stations in Japan. We have also made the ionospheric threat model less conservative, in line with current WAAS algorithms. Together, these improvements offer good vertical guidance coverage over Japan as can be seen in Figure 4.

It can be seen that 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. Thus the only option to provide service to an L1-only user is to expand the reference network into the desired region. However, this approach is limited by the message structure of SBAS.

SBASs model the ionosphere as a thin 2-dimensional shell 350 km 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. GPS L5 will be centered at 1176.45 MHz and will be in a protected aviation band [15]. As such, it will be approved for navigation. 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 their avionics, SBAS service can be dramatically improved.

Another important advantage of the second civil frequency is its relative immunity to ionospheric storms. 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. The weaker effect of scintillation [16] may have some impact, however, we do not expect to lose vertical guidance altogether [17]. 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. However, we do suggest a few improvements that address some challenges that were experienced in developing the initial systems.

For a single frequency user, each line-of-sight has four confidence terms that are summed together to obtain the total confidence. These terms correspond to: the satellite clock and ephemeris corrections ($\sigma_{flt}$), the ionospheric correction ($\sigma_{UIRE}$), the airborne code noise and multipath ($\sigma_{air}$), and the troposphere ($\sigma_{trop}$). The specification for these terms can be found in Appendices A and J of the single frequency SBAS MOPS [12]. The total one-sigma confidence bound for a particular line-of-sight is the root sum square (RSS) of these four terms:

$$\sigma_{tot}^2 = \sigma_{flt}^2 + \sigma_{UIRE}^2 + \sigma_{air}^2 + \sigma_{trop}^2 \quad (1)$$

When a user has access to two civil frequencies, they can remove the ionospheric effects by forming the iono-free combination of the two pseudoranges:

$$\begin{aligned} PR_{iono-free} &= \frac{f_1^2 PR_1 - f_5^2 PR_5}{f_1^2 - f_5^2} \\ \sigma_{iono-free}^2 &= \left( \frac{f_1^2}{f_1^2 - f_5^2} \right)^2 \sigma_1^2 + \left( \frac{f_5^2}{f_1^2 - f_5^2} \right)^2 \sigma_5^2 \end{aligned} \quad (2)$$

where $f_1$ and $f_5$ are the L1 and L5 frequencies (1575.42 MHz and 1176.45 MHz) respectively. If $\sigma_1$ and $\sigma_5$ are comparable then the iono-free combination has roughly three times as much noise as either single frequency term, but is substantially smaller than $\sigma_{UIRE}$. Furthermore, satellites do not need a grid correction to be used, thus satellites farther from the network and IGP mask can be incorporated into the position solution. The dual frequency confidence bound for a single satellite is then given by

$$\sigma_{tot\_if}^2 = \sigma_{flt}^2 + \sigma_{iono\_free}^2 + \sigma_{trop}^2 \quad (3)$$

where $\sigma_{air}$ is used in place of $\sigma_1$ and $\sigma_5$ in (2).

For the VPL we propose adding nominal bias terms to handle observed signal biases [18] [19] and non-Gaussian behavior of the underlying error terms [20]. By including these terms it is possible to reduce the net impact of these biases on the user [21]. Further, we propose tailoring the VPL equation to the most significant remaining threat to the user: single satellite fault modes. The L1-only VPL equation is appropriate for threats that affect many signals simultaneously as may happen with the ionosphere or troposphere. However, with the user directly eliminating ionospheric effects, the most significant threats come from satellite fault modes. As these faults are rare, they are unlikely to affect more than one ranging measurement at a time. Therefore, a VPL can be constructed to explicitly account for such a threat. We recommend that the dual frequency VPL take the following form:

$$\begin{aligned} VPL_{H_0} &= K_{HMI} \sqrt{\sum_{i=1}^{N} s_{3,i}^2 \sigma_{ff,i}^2} + \sum_{i=1}^{N} \left| s_{3,i} bias_{nom,i} \right| \\ VPL_{H_1} &= K_{fault} \sqrt{\sum_{i=1}^{N} s_{3,i}^2 \sigma_{ff,i}^2} + \sum_{i=1}^{N} \left| s_{3,i} bias_{nom,i} \right| \\ &\quad + \max_i \left| s_{3,i} bias_{fault,i} \right| \\ VPL &= \max\left[ VPL_{H_0}, VPL_{H_1} \right] \end{aligned} \quad (4)$$

where $K_{HMI}$ is the Gaussian tail factor corresponding to the probability of Hazardously Misleading Information, $s_{3,i}$ is the projection of the pseudorange error onto the vertical position estimate, $\sigma_{ff}$ is the fault free overbounding sigma, $bias_{nom}$ is the nominal bias bound, $K_{fault}$ is the Gaussian tail factor accounting for the probability of fault, and $bias_{fault}$ is a bound on the magnitude of all satellite faults. The $H_0$ condition corresponds to the most likely condition of no faults present. The $H_1$ condition corresponds to the unlikely event of a fault on the dominant satellite. The final VPL is the maximum across both conditions.

Because the faulted bias term covers the satellite faults the fault-free sigma term, $\sigma_{ff}$, can be much smaller than the current total value (1), or the dual frequency version (3). Further, since the probability of fault is small, $K_{fault}$ can be much smaller than $K_{HMI}$. The net result is that the proposed VPL is smaller than the existing VPL for the same conditions.

To model L1/L5 availability we chose the following parameters:

- $K_{HMI} = 5.33$
- $K_{fault} = 2.33$
- $\sigma_{ff}^2 = (\sigma_{flt} / 3)^2 + \sigma_{iono\_free}^2 + \sigma_{trop}^2$
- $bias_{nom} = 0.5$ m
- $bias_{fault} = 5.33 \times \sigma_{flt}$

Other values follow the single frequency MOPS specifications as normally implemented by MAAST.

Given these parameters, the $H_1$ hypothesis nearly always dominates the VPL calculation. We have used a nominal weighting scheme to optimize for accuracy. It is possible

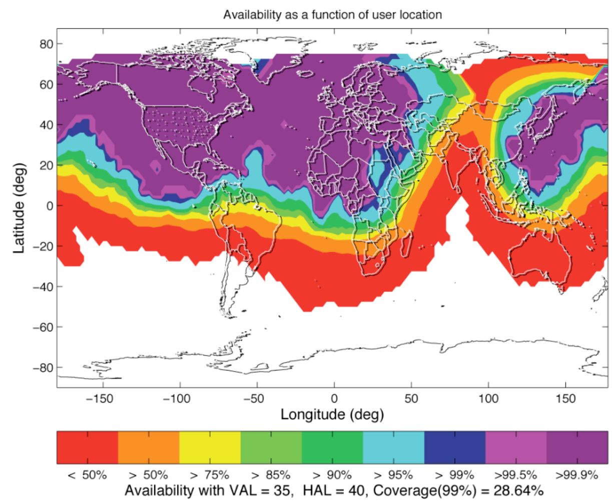


**Figure 5.** *Potential dual frequency coverage of the first three SBASs including network improvements.*

to deweight the dominant satellite to improve availability. We will be looking at practical methods for determining more optimal weighting for the VPL given in (4). However, there is a concern that such optimizations could harm accuracy. The potential benefits vs. risks will be studied.

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

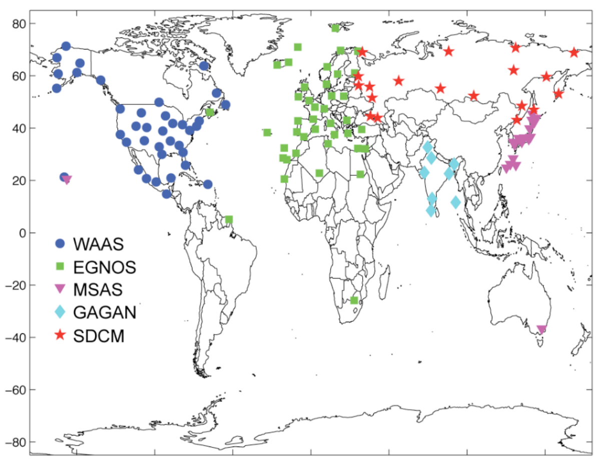


**Figure 6.** *The networks of five SBAS systems are shown. In addition to the reference stations from Figure 3, the 8 Indian stations are shown as blue diamonds and the 19 Russian stations are shown as red stars.*

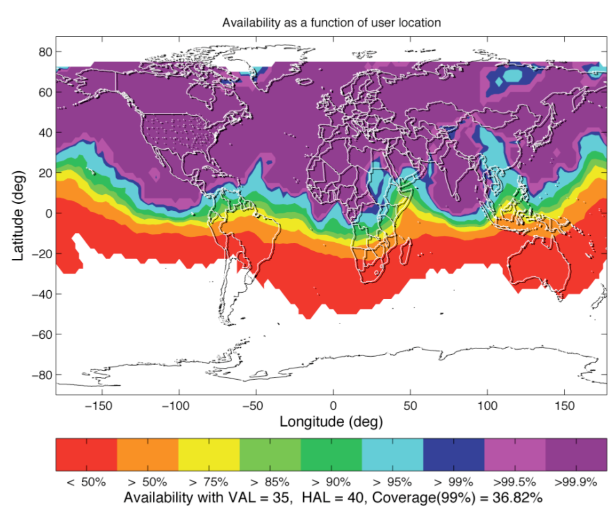


**Figure 7.** *The combined dual frequency availability of the five SBASs is shown.*

## 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. The station locations are shown as blue diamonds in Figure 6. There is one Indian Master Control Center (INMCC), and plans to use the GSAT-4 as its initial GEO [4]. 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. Currently it has nine operational measuring points (MPs) and has plans for at least ten more locations, all in Russia. The station locations are shown as 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 [5].

Figure 7 shows the combined dual frequency coverage of all five systems, WAAS, EGNOS, MSAS, GAGAN, and SDCM. As can be seen, the vast majority of landmasses 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 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 be extended into the southern hemisphere. There have been many discussions with representatives of countries in the Southern Hemisphere. Further, the US has had testbed receivers in South America for nearly fifteen years. Europe has fielded receivers in Africa. Australia investigated its own variant of SBAS called the Ground-based Regional Augmentation System (GRAS) [22]. 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.

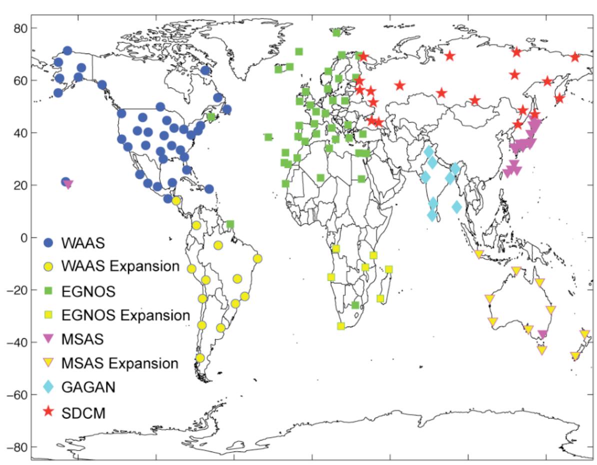


**Figure 8.** *The networks of the five SBAS systems including hypothetical expansions into the southern hemisphere.*

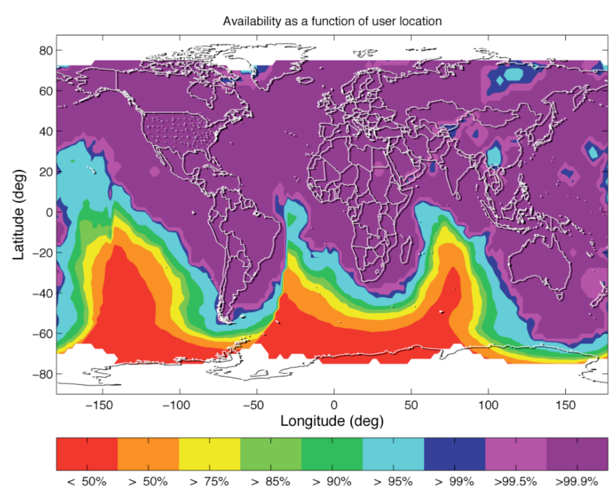


**Figure 9.** *The combined dual frequency availability of the SBASs with the southern hemisphere stations is shown.*

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

## ADDITIONAL CORE CONSTELLATIONS

In addition to GPS L5 development, there are plans to build independent navigational satellite systems with comparable civil frequencies. Galileo is being developed by the European Union and is envisioned as being 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 [23]. In parallel, China is developing the COMPASS system whose signals are also planned to be compatible with GPS [15].

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.

The addition of 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 [23]. 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 ten sidereal days for Galileo, the simulated time step and total run time were each 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 the addition of just a few more reference stations if full global coverage were desired.

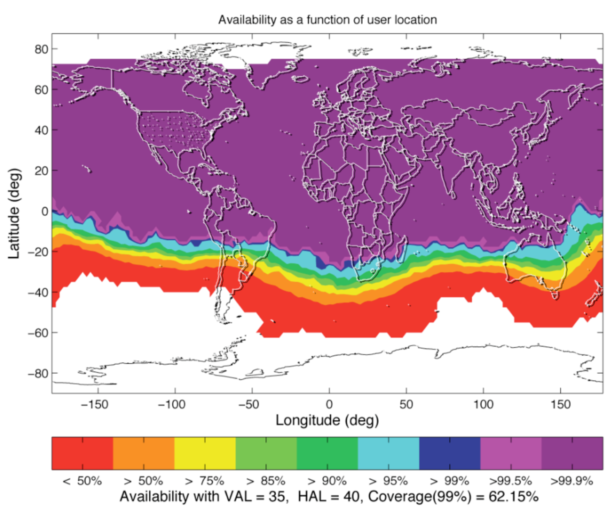


**Figure 10.** *The combined dual-frequency, LPV-200 coverage of the five SBAS systems with both GPS and Galileo.*

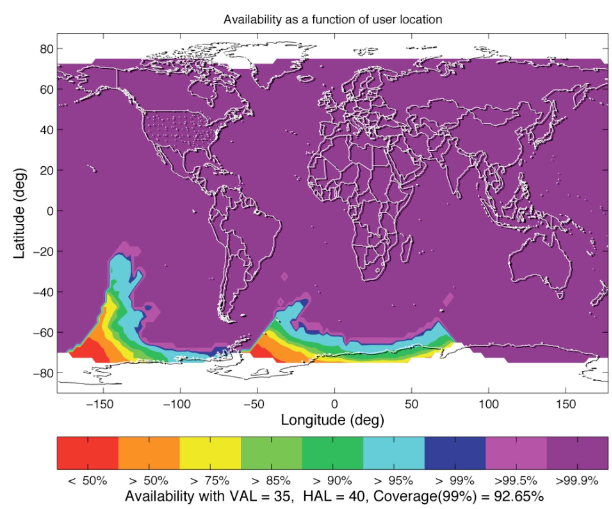


**Figure 11.** *The combined dual-frequency LPV-200 coverage of the SBASs with GPS and Galileo and the southern hemisphere stations.*

## CONCLUSIONS

We have analyzed the expected global SBAS coverage for several possible future scenarios. We have seen that 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 the L5 signal to GPS makes vertical guidance largely immune to ionospheric disturbances, and also 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. India and Russia are actively developing their own SBASs. When these new systems are commissioned for service a very large fraction of the Northern Hemisphere will have LPV-200 coverage.

Although, the systems that are currently operational or that are under development are all located in the Northern Hemisphere, there is great interest extending service to the Southern Hemisphere. Testbeds and prototype systems have been developed and we expect to see stronger commitments in the future. We have demonstrated that with dual frequency, LPV-200 coverage can be established with comparatively sparse networks in South America, Africa, and around Australia.

Finally, we demonstrated that additional dual frequency core constellations such as Galileo, Compass, or GLONASS could greatly expand coverage to well outside the original reference network regions. Today's SBASs are just the first step towards much more widespread service. As GNSS capability is improved and expanded, we expect that SBAS service provision will similarly improve. We anticipate that SBAS coverage may one day provide nearly global LPV-200 or better service capability.

## ACKNOWLEDGMENTS

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