

Modernizing WAAS

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ABSTRACT

The Wide Area Augmentation System (WAAS) became operational on July 10, 2003. Currently this system provides en-route through non-precision approach guidance. Further, the signals are capable of providing vertical guidance to bring an aircraft within 250 feet of the ground. WAAS offers significant benefit to both aviation and non-aviation users. However, the vertical guidance availability is vulnerable to disturbances in the ionosphere and to GPS satellite outages. Fortunately, solutions to these limitations are well underway in the form of GPS modernization and Galileo. GPS modernization will provide two civil frequencies that enable users to directly estimate and remove ionospheric effects. Galileo will provide many additional ranging sources that will make the user more robust to the loss of an individual one.

Naturally, WAAS should also be modernized to take advantage of these new signals. We investigate different methods to incorporate the signals and model their improvement to the aviation user. The best performance comes to a fully modernized user who can incorporate both civil frequencies and both constellations (GPS and Galileo). However, there is still significant benefit to legacy users who can only receive single frequency GPS signals. By upgrading the WAAS Reference Station (WRS) receivers to measure Galileo signals we can double our sampling of the ionosphere. The increased sampling translates into smaller broadcast confidence values on the single frequency ionospheric corrections. These lower values lead to higher availability. Similarly, the L5 signal has better noise properties and can be acquired at a lower elevation angle. This leads less uncertainty in the ionospheric measurements and to smaller confidence values.

Before the modernized GPS and the Galileo constellations are complete, we can take advantage of the first new satellites. Users who can recognize the signals can begin to take advantage of them if proper correction information is broadcast. Legacy users will begin to see confidences improve as the new signals are mixed in with the old.

The airborne noise and multipath confidence factor will grow in importance. Currently, it is the smallest term in the protection level calculation. For a dual frequency user it may become the largest. Efforts are underway to better characterize this airborne environment. The level of service offered by the end state system will depend on the final curve used to bound the error.

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 ensure the integrity. WAAS utilizes a network of precisely surveyed reference receivers, located throughout the United States. The information gathered from these WAAS reference Stations (WRSs) monitors GPS and its propagation environment in real-time [1].

Availability of WAAS 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, it generally requires both values to be good to obtain high availability.

Geometry is determined purely by the locations of the ranging satellites relative to the user. The basic geometry is provided the GPS constellation. Historically it has exceeded expectations and there are currently 29 healthy satellites in orbit when only 21 are nominally guaranteed [2]. However, as satellites are taken off-line in critical orbital slots, the quality of the geometry can degrade significantly. There could be short duration outages, daily at some locations. Since the goal is to provide service more than 99% of the time, this 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.

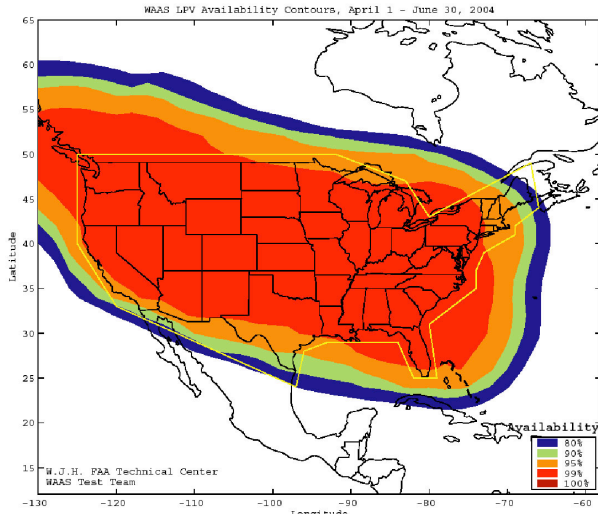


Figure 1. Actual Performance of the WAAS as observed by the FAA William J. Hughes Technical Center [8]. This represents a three month average of LPV availability from April 1-June 30, 2004

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 WAAS, this last error source is the most significant. User's may sample the ionosphere anywhere in the service volume, but WAAS only has measurements from its reference station locations. Thus, there is always the possibility of undetected ionospheric disturbances [3]. This leads 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). WAAS 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 there are two levels of service we are interested in studying: Category I precision approach with

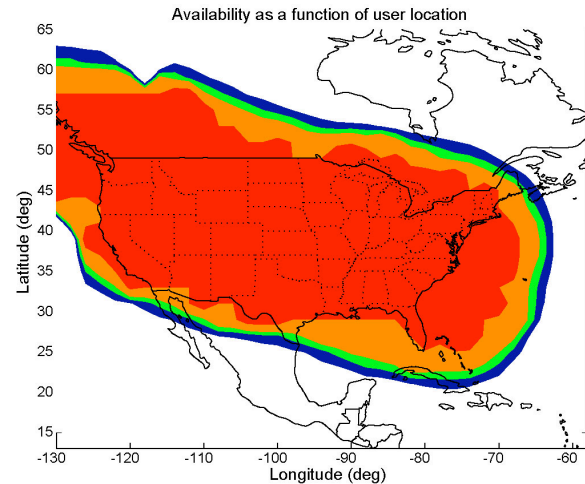


Figure 2. Simulated results from MAAST. This represents a 24-hour average of LPV availability. Although slightly optimistic compared to actual performance, it is very representative.

a Vertical Alert Limit (VAL) of 12 m and a Horizontal Alert Limit (HAL) of 40 m; and the LPV approach with a VAL of 50 m and HAL of 40 m [4] [5]. Because GPS and WAAS 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 two operations. It is generally sufficient to study performance of only the VPL to determine availability.

This paper will present the current performance of WAAS and then study the expected performance for the future. Specifically we will look at the first set of network improvements that are expected to provide Full LPV Performance (FLP) for most of the United States. Next, we will look at the benefit of GPS L5 and how that will improve WAAS performance. Finally, we will examine the impact of Galileo and predict the performance for a user taking advantage of both Global Navigation Satellite Systems (GNSS).

METHODOLOGY

To determine the effect of potential improvements we used our Matlab[®] Algorithm Availability Simulation Tool (MAAST) [6]. This tool uses almanac data to calculate the position of the satellites for each given epoch. It also implements the WAAS integrity algorithms to calculate the corresponding UDRE and GIVE values. Finally, it uses these values to implement the MOPS [7] specified user algorithms for determining the protection levels. The VPL and HPL are calculated every 5 minutes and every

two degrees. Thus, availability can be calculated over a broad geographic region.

MAAST is a deterministic model. Satellite outages, cycle-slips, and other rare events are not modeled. Instead, it assumes that when a satellite is above an elevation mask it can be reliably tracked. The integrity algorithms are largely deterministic and can be implemented in this manner as well. MAAST assumes that all internal consistency checks pass and that no system faults are present. As such, MAAST is slightly optimistic. It does not model the minor faults that occur every day such as delayed acquisition, cycle-slips, satellite outages, etc. Such events are infrequent and thus have lesser impact at the 99% level or lower. However, to model higher availabilities accurately, we would need to include all such events.

As can be seen in Figures 1 and 2, MAAST does a good job of predicting current behavior. While, it is slightly more optimistic and less smooth than the long-term average, it generally identifies the limits of availability to within a few degrees of the correct location. Thus, MAAST provides a reasonable estimate of system performance.

CURRENT SYSTEM STATUS

Currently WAAS is in its Initial Operating Capability (IOC) phase. It consists of 20 WAAS Reference Stations (WRS) in the Conterminous United States (CONUS) plus three in Alaska, one in Hawaii, and one in Puerto Rico for a total of 25. The station locations are shown in Figure 3. There are two WAAS Master Stations (WMS), and two geostationary satellites (GEO). The GEOs are two of the International Maritime Satellites (INMARSAT) I-3 satellites [9]: the Pacific Ocean Region (POR) satellite at 178° E and the Atlantic Ocean Region-West (AOR-W) satellite at 54° W.

As can be seen in Figure 1, availability of LPV service is very high for most of CONUS. However, there are some regions where performance is lower than the 99% minimum target. The Northeast, Southern Florida and Texas, as well as the West Coast all suffer from reduced availability. Figure 4 shows the 99% VPL corresponding to the simulation in Figure 2; that is, regions where the user's VPL is the value indicated by the color (or smaller) 99% of the time. As can be seen the orange region indicating the 50 m (or better) VPL needed for LPV corresponds to the red region in Figure 2 where 99% availability is achieved. Because VPL plots are better for

showing how much margin the system has in meeting its requirements the remainder of the plots in this paper will show 99% VPL levels rather than just availability.

Figure 4 shows that there is little availability of LPV service in Alaska. Further, although availability was high throughout the CONUS for the last quarter, there have been times when performance was worse. WAAS is currently vulnerable to ionospheric disturbances that aren't well modeled by the MOPS broadcast format [3]. During such events, WAAS is unable to provide vertical guidance and users are left with only horizontal guidance: Non-Precision Approach (NPA) and RNP 0.1 capability. During the last quarter of 2003, two of the largest ionospheric storms ever observed occurred. WAAS maintained full integrity at all times and averaged over the quarter, these storms reduced WAAS availability by about 1% overall [10]. However, each storm lasted for several hours each. Although the overall outage time is not large, operationally it is undesirable to have this vulnerability to ionospheric events. Thus, future WAAS improvements will seek to expand the service region and eliminate outages due to the ionosphere.

FULL LPV PERFORMANCE

The FAA is currently implementing a significant network upgrade to improve the performance of the system. Four new reference stations will be added to Alaska, four new stations will be added to Canada, and five to Mexico, for a total of 38 WRSs. The station locations are shown in Figure 5. These locations have been chosen both to improve coverage in weak spots for the U. S. service volume and to improve performance in Canada and Mexico. Another master station will be added, as well as two new geostationary satellites, one at 107°W and the other at 133° W. These are primarily being implemented to improve continuity. The additional WMS allows full redundancy even if one is in maintenance, while the additional GEOS guarantee redundant coverage throughout the service volume.

The Ionospheric Grid Point (IGP) mask will be expanded around Alaska. The IGP mask limits the boundary of single-frequency service. In order to obtain vertical guidance, the user must have real-time ionospheric corrections. Additional reference stations allow us to both expand the mask and make it denser. The final form of the IGP mask is not yet set, but Figure 5 shows the assumed mask for this paper. Additional IGPs are planned to improve coverage in Canada; however, they

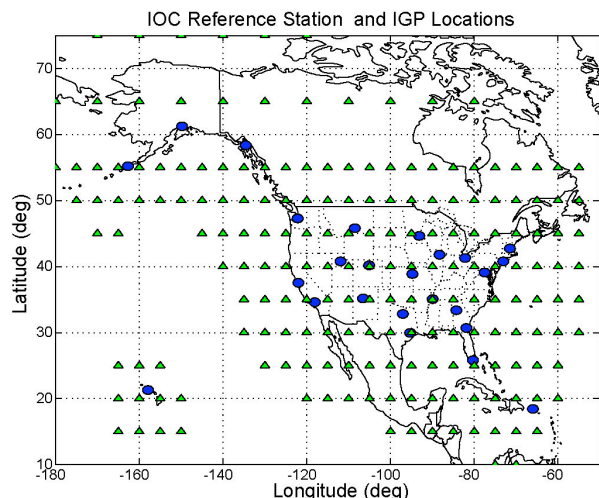


Figure 3. Current WAAS network. The positions of the WRSSs are marked by the blue circles. The green triangles indicate the broadcast Ionospheric Grid Points (IGPs)

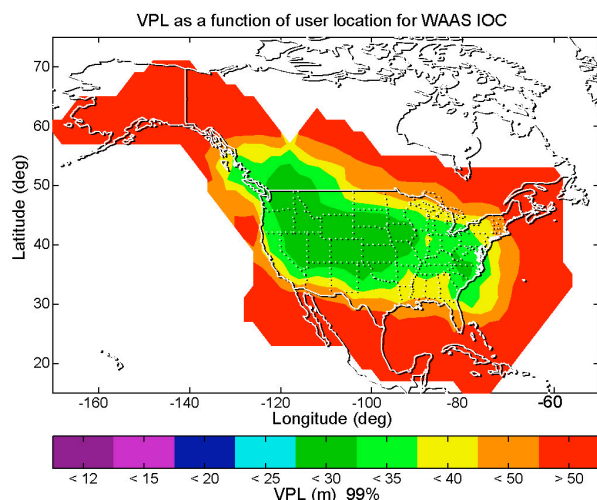


Figure 4. The 99% VPL for IOC WAAS. The orange region marks the boundary of where the VPL is 50 m or below 99% of the time. This corresponds to the red 99% availability region in Figure 2.

are not modeled in this paper, as their exact specification has not yet been determined.

The intent of the Full LPV Performance (FLP) phase of WAAS is, as its name implies, to provide LPV coverage to all of CONUS and most of Alaska. As can be seen in Figure 6, the addition of the WRSSs and GEOs meet this goal. Now all of CONUS and most of Alaska are well below the required 50 m VAL. No algorithm changes were necessary to achieve it. Although the WRS receivers and antennas will be upgraded, their improvement in performance was not modeled.

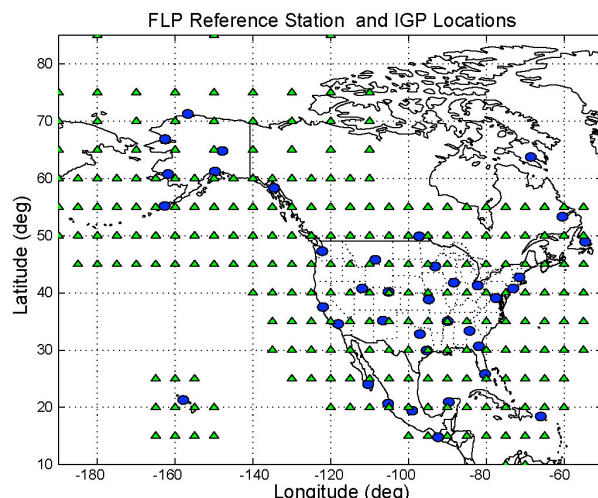


Figure 5. Full LPV Performance (FLP) network. Additional WRSSs are added to Alaska (4), Canada (4), and Mexico (5). The IGPs are expanded near Alaska.

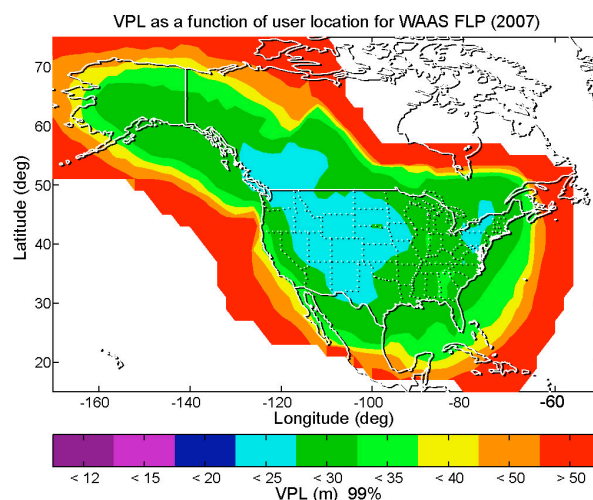


Figure 6. The 99% VPL for FLP WAAS. Now LPV coverage (50 m or below VPL) extends to all of CONUS and most of Alaska. However, the West Coast may still be vulnerable to outages.

Further, having margin against the VAL translates into continuity; the system could tolerate some unmodeled outages and still meet the requirements. Additionally, since the two new GEOs guarantee at least double coverage throughout the service volume, WAAS will be tolerant of the unexpected loss of any single GEO. Thus, FLP is expected to meet both its availability goal and improve system continuity as well.

GPS L5

The GPS constellation will be modernized to meet future military and civil needs [11]. A key new feature that will become available in the next 15 years is a second civil frequency. GPS L5 will be centered at 1176.45 MHz and will be in a protected aviation band [12]. 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.

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 (σ_{flt}), the ionospheric correction (σ_{UIRE}), the airborne code noise and multipath (σ_{air}), and the troposphere (σ_{trop}). The specification for these terms can be found in appendices A and J of the MOPS [7]. The total one-sigma confidence bound for a particular line-of-sight is the root sum square (RSS) of these four terms:

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

Figure 7 shows the size of each of the error bounding terms. The satellite clock and ephemeris term (fast and long-term corrections or flt) is based on the minimum UDRE value of 2.25 m [13]. The User Ionospheric Range Error (UIRE) term is based on the WAAS IOC minimum GIVE value of 3 m [13]. The airborne multipath term follows the Airborne Accuracy Description (AAD-A) defined in [14]. The tropospheric term is defined in

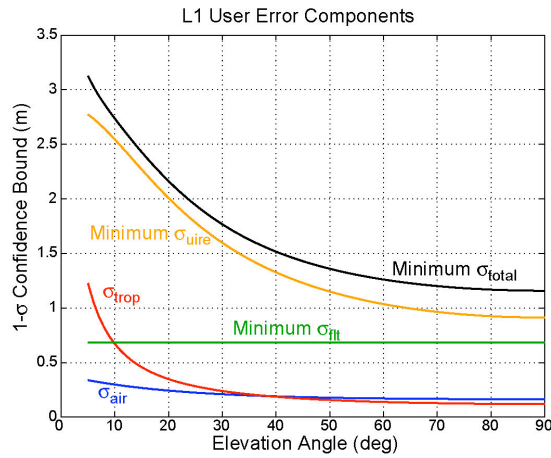


Figure 7. The four components of the single frequency user error bound are shown here as a function of elevation angle.

Appendix A of the MOPS [7]. In practice, σ_{UIRE} and σ_{flt} will be much larger than the other terms due to larger broadcast GIVE and UDRE values (and the influence of message types 7, 10, and 28). The black line shows the minimum possible one-sigma bound value for each pseudorange measurement.

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:

$$PR_{iono-free} = \frac{f_1^2 PR_1 - f_5^2 PR_5}{f_1^2 - f_5^2} \quad (2)$$

$$\sigma_{iono-free}^2 = \left(\frac{f_1^2}{f_1^2 - f_5^2} \right)^2 \sigma_1^2 + \left(\frac{f_5^2}{f_1^2 - f_5^2} \right)^2 \sigma_5^2$$

Where f_1 and f_5 are the L1 and L5 frequencies (1575.42 MHz and 1176.45 MHz) respectively. If σ_1 and σ_5 are comparable then the iono-free combination has roughly three times as much noise as either single frequency term. This is the penalty paid for removing the ionospheric error. However, this is still a good trade as can be seen in Figure 8. The iono-free term replaces the combination of the airborne code noise and multipath term and the ionospheric term. The resultant is roughly 3 times the size of σ_{air} , but is substantially smaller than σ_{UIRE} . The total minimum dual frequency error bound is roughly half the minimum single frequency bound. In practice the improvement is even better as the single frequency ionospheric term is almost always much larger than the minimum value.

The improvement in performance for a dual frequency

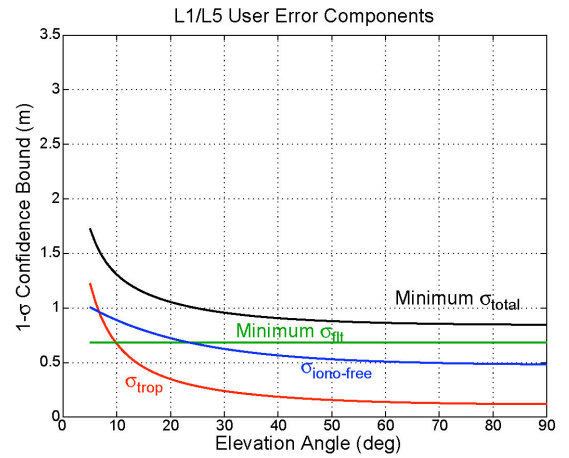


Figure 8. The three components of the dual frequency user error bound are shown here as a function of elevation angle.

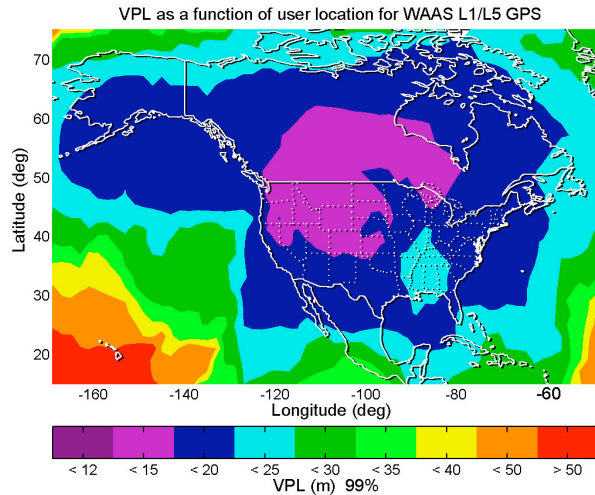


Figure 9. The 99% VPL for a dual-frequency user with the WAAS FLP network

user can be seen in Figure 9. The VPLs are dramatically lowered everywhere. In addition, because the user no longer needs the IGP grid, vertical guidance can be provided much farther away from the reference stations than for the single frequency case. The most important advantage of the second civil frequency, however, is its relative immunity to ionospheric storms. Because the user is now directly eliminating the amount of delay they actually experience, we are no longer affected by shortcomings in the WAAS MOPS ionospheric model. We will no longer have a loss of availability due to ionospheric storms. Although the much weaker effect of scintillation [15] may have some impact, 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 LPV performance on the available frequency.

Unfortunately GPS L5 does not provide Category I (Cat-I) performance (12 m VAL) by itself. To achieve that, an additional improvement must be made. From Figure 8 it is obvious that the UDRE is now the dominant term in the confidence bounding. Effort should focus on reducing the UDRE first, then trying to lower the iono-free term. Assuming both can be reduced by nearly 50%, then Cat-I performance should be nearly reached for the dual-frequency user. However, Figure 9 shows a region in the Southeastern part of the U.S. that has a VPL of 25 m due to poor geometrical coverage. Thus, even if the reductions could be made, this region would be close to (or over) the VAL. Thus, with outages and other minor failures, there would not appear to be sufficient margin to

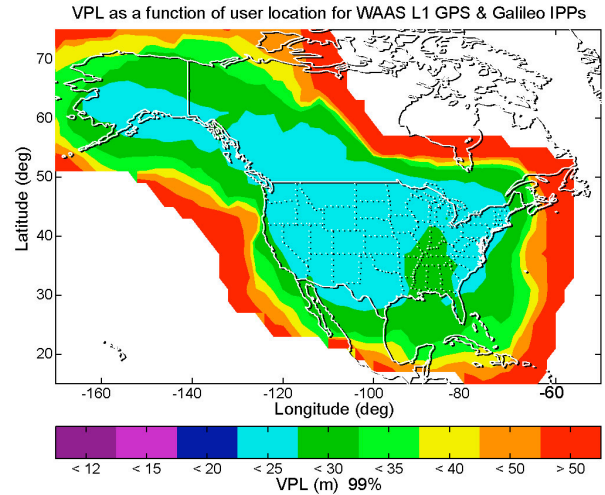


Figure 10. A single frequency legacy GPS-only user would still benefit from Galileo as the extra ionospheric measurements at the WRSs lower the broadcast GIVEs.

guarantee continuity. Although Dual frequency GPS may be able to achieve Cat-I it will take a substantial improvement to the WAAS algorithms.

GALILEO

In addition to GPS modernization, there are plans to launch an independent European navigational satellite system called Galileo [16]. Galileo is envisioned as being very similar to GPS in that each satellite provides ranging using signals at the L1 and L5 frequencies with very 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 [17]. We envision that WAAS will broadcast satellite clock and ephemeris corrections for both GPS and Galileo. These corrections remove any difference in the reference times or coordinate frames between the two systems.

The addition of 30 extra ranging sources will obviously have tremendous benefit for all civil GNSS users. The geometry will be much better, and with nearly 60 orbiting satellites, the loss of one or two should not make a significant difference. Thus, both availability and continuity will be much improved with the advent of Galileo.

Less obviously, legacy L1 GPS-only users may also benefit from Galileo. If WAAS upgrades the receivers in

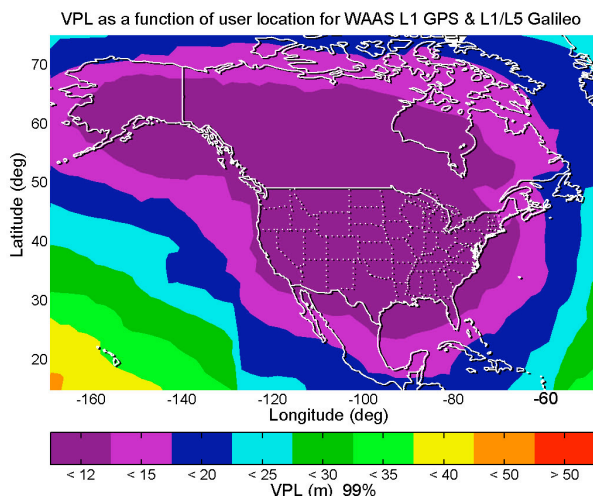


Figure 11. The 99% VPL for a user with access to dual-frequency Galileo satellites and L1 only GPS satellites.

the WRSs to monitor Galileo satellites, then there will be roughly twice as many measurements of the ionosphere from which to create the single-frequency ionospheric corrections. This will reduce undersampling concerns and result in smaller GIVEs. Thus, even if WAAS did not broadcast Galileo corrections, the system can still improve its performance. Figure 10 shows the 99% VPL for this case and compared to Figure 6 there is quite an improvement. Although both provide LPV service throughout the service volume, the addition of the Galileo ionospheric measurements results in considerably more margin against the VAL. This will result in better continuity for the user.

The larger benefit comes to dual frequency users. By simultaneously tightening the confidence bound (as shown in Figure 8) and strengthening the geometry, now VPLs can be reduced below the Cat-I VAL of 12 m. Figure 11 shows a case where Galileo is fully deployed, but GPS has yet to launch its dual frequency satellites. Despite the fact that half the satellites are single frequency, the improvement in geometry in this scenario provides Cat-I level service though much of CONUS and Alaska.

The final case studied is the desired Final Operating Capability (FOC) phase of WAAS available in 2017 (or so). Here we have two full constellations of dual frequency satellites. Figure 12 shows the resulting 99% VPL contours. Now we have full Cat-I availability throughout CONUS and the majority of Alaska. The addition of WRSs away from CONUS would further expand the Cat-I coverage region.

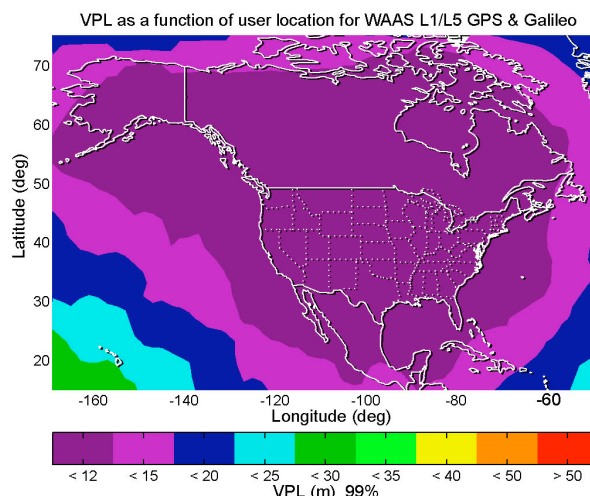


Figure 12. The 99% VPL for a user with access to dual-frequency GPS and Galileo satellites.

CONCLUSIONS

We have analyzed the expected availability for several future scenarios. This analysis was based on our Matlab[®] simulation tool, which we showed that although slightly optimistic, was able to accurately estimate actual system performance. The first round of network improvements will have the desired effect of providing LPV service throughout CONUS and to most of Alaska. Unfortunately, the single frequency system will continue to be vulnerable to outages caused by ionospheric disturbances. Such outages cause less than a 1% reduction in the long-term availability, however they do persist for several hours. Fortunately, horizontal guidance (RNP 0.1) is available throughout such events.

The addition of the L5 signal to GPS will also make vertical guidance immune to ionospheric disturbances, as the user will be able to measure their own effect directly. Further, two frequencies offers protection against unintentional interference. If either frequency is lost, the user may revert to single frequency LPV. However, although GPS L5 dramatically improves performance, it will have a difficult time reaching Category I performance unless coupled with another significant improvement. The UDRE algorithm will need to be substantially improved over the current IOC performance.

Galileo will provide enormous benefit, as the extra ranging sources coupled with dual frequency measurements are able to provide Category-I level performance. Galileo even benefits legacy L1 GPS-only

users extending the region of LPV coverage and providing improved continuity.

Thus, single frequency users will experience high availability of LPV service while dual frequency users will achieve Cat-I performance. We expect FOC WAAS to provide Category I service to all dual frequency users within the service volume. Additionally, it will provide LPV service to any single frequency user, whether they are a legacy user or someone who has lost access to L1 or L5 due to Radio Frequency Interference (RFI).

ACKNOWLEDGMENTS

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