

Impact of Personal Privacy Devices for WAAS Aviation Users

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ABSTRACT

Personal privacy devices (PPDs) are low-cost jammers to mask GPS signals, so that the location of the host vehicle is not revealed to other parties. Although it is illegal to use PPDs in the United States, they are being used and have caused problems for other GPS users.

This paper investigates the PPD impact on aviation users from the WAAS service perspective. Although PPD jammers on the ground cannot reach airplanes far in the air, PPDs can interfere ground-based WAAS reference stations. We conducted Montel-Carlo simulation on WAAS availability coverage based on real data retrieved from current WAAS reference stations. Our simulation results show that PPD jamming activity has had negligible impact on WAAS service due to redundancy and robustness of large number of WAAS reference stations.

Introduction

Personal privacy devices (PPDs) have raised some concerns in the regime of Global Navigation Satellite Systems (GNSS) [1, 2]. The intention of PPDs is to protect the privacy of the user so that the user's location is not revealed, therefore the user will not be tracked or monitored. Figure 1 lists some examples of PPDs currently for sale on Internet. They are low-cost jamming devices. Most of them plug in the cigarette lighter of cars or trucks and jam the GPS signal. Although the intention of PPDs is to protect a certain user, PPDs actually interfere with all GPS users in the local area [3], potentially aviation users.



Figure 1. PPDs for Sale on Internet

Aviation users rely on Wide Area Augmentation System (WAAS) for accuracy and integrity. WAAS augments GPS by transmitting error correction messages calculated from 38 WAAS reference stations (WRS) on the ground [4]. Figure 2 illustrates WAAS system architecture. Although airplanes flying in the sky are far from the PPD jammers on the ground, PPDs can potentially deteriorate aviation performance by interfering the WAAS reference stations on the ground. It is currently unknown how close an aircraft has to be to a jammer to be impacted, but there is a risk that a PPD right under the approach path could cause a loss of service not modeled in this paper.

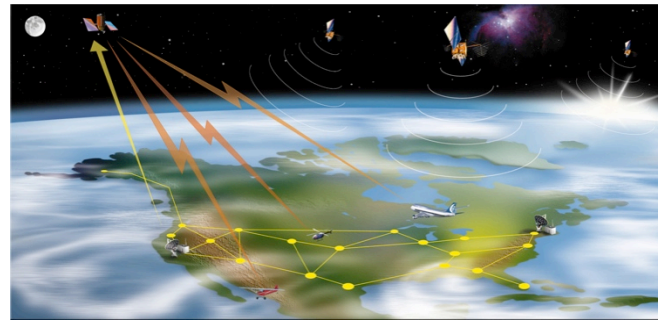


Figure 2. WAAS system illustration [5]

The goal of this paper is to determine the effect of PPD-induced outages on the availability of the WAAS service. We will present quantitative result over CONUS. We conduct Monte Carlo simulation based on real data from WAAS reference stations.

The paper is organized as follows. We will first model PPD behavior based on read data retrieved from 38 ground-based WAAS reference stations. We measure the time duration of each satellite outage due to PPD, and characterize the frequency and likelihood of PPD outages occurred at WAAS reference stations subject to PPD. We then conduct Monte Carlo simulation based on our PPD modeling using the Matlab Algorithm Availability Simulation Tool (MAAST). We show the WAAS availability coverage maps for the expected maximum case and the case 10 times worse, and for current GPS constellation and 24-satellite constellation. Finally, we will conclude the paper.

PPD MODELING BASED ON REAL WRS DATA

The first step for PPD modeling is to obtain real data from WAAS reference stations and analyze the PPD effect for a single WRS. Figure 3 shows the PPD impact for WAAS ZDC reference station at Leesburg, Virginia on April 09 2011 as an example. The x-axis is time over 24-hour period. The y-axis is the signal-to-noise ratio (C/No) for three WAAS Geostationary satellites. Two jamming events were observed. The jammers caused 20 dB degradation for the received signal strength.

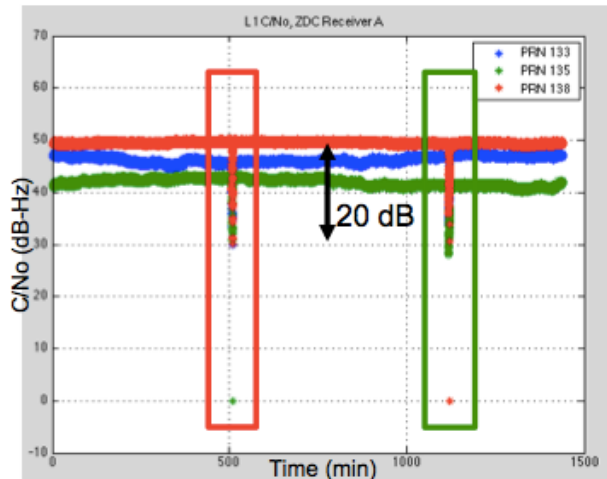


Figure 3. Received WAAS GEO satellite signal-to-noise ratio over 24 hours of ZDC site at Leesburg, Virginia

We take the first jamming event as an example. Figure 4 shows the signal to noise ratio of all the GPS satellites in view. All GPS satellites suffer signal power degradation due to PPD jamming. The duration of the PPD jamming is 60 seconds. Note that the received signal power of satellites at high elevation can be as strong as 55dB-Hz, 20dB higher than the satellites at low elevation. Therefore, satellites at high elevation are more robust to PPD. In general, satellites above 35° elevation can very likely tolerate the PPD degradation. Later in our Monte Carlo simulation, we will simulation the cases where PPD turns off all the satellites and only satellites below 35° elevation.

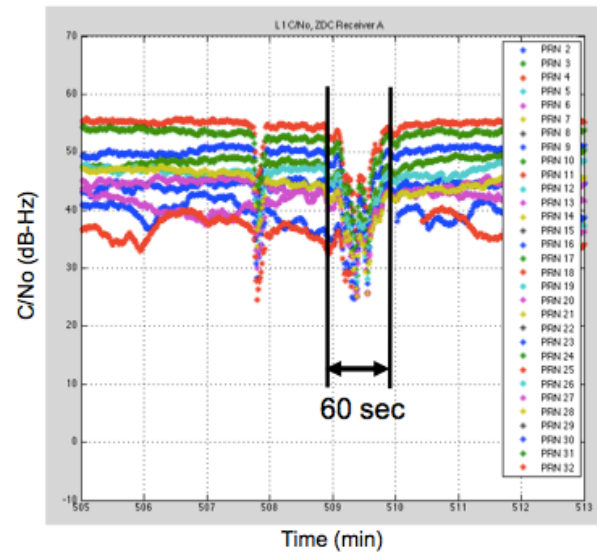


Figure 4. PPD degradation to received signal power of GPS satellites in the first jamming events in Figure 3. The jamming duration is 60 seconds. GPS satellites at high elevation are more robust to PPD jamming because of the signal power margin.

Like the ZDC site, some WRS are very close to traffic, thus is likely to be interfered by PPDs. Figure 5 shows another example of such WRS at Miami, Florida. The WAAS reference station site is 200 meters from a busy high way with 10 lanes on both directions, and only 80 meters to a local road with 8 lanes.

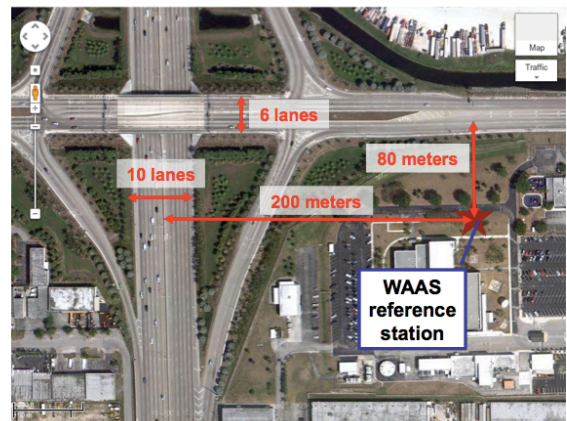


Figure 5. WAAS reference site at Miami, Florida

However, there are also WRS far from likely interference sources. Figure 6 gives an example of WRS at Cold Bay, Alaska. For WRS in such remote areas, PPD should not be a concern.

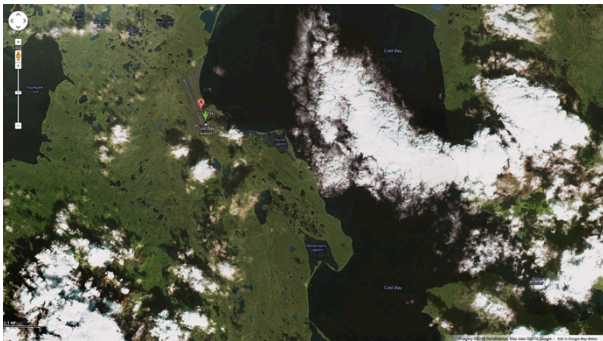


Figure 6. WAAS reference site at Cold Bay, Alaska

Due to the physics of wireless radio signals that PPD transmits, the impact of PPD diminishes over distance. T. Kraus, et al. surveyed popular in-car jammers, and presented the interference diminishing effect of three different PPDs for a few GPS receivers as shown in Figures 7 and 8. The effective PPD radius is about 500 meters. Figure 9 groups all 38 WRS with respect to their distances to nearby high way. The WRS in red rectangle are reference sites within 500 meters of traffic. It is shown that the WAAS reference stations subject to PPD jamming are a small subset of all the WRS.

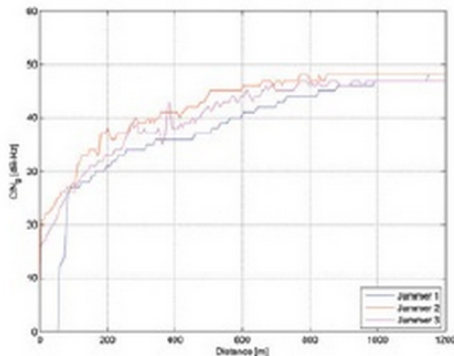


Figure 7. Field test result of a NAVILoc receiver in presence of PPD jammers. PPD degrades received GPS signal-to-noise-ratio (SNR). Such degradation diminishes over distance [5].

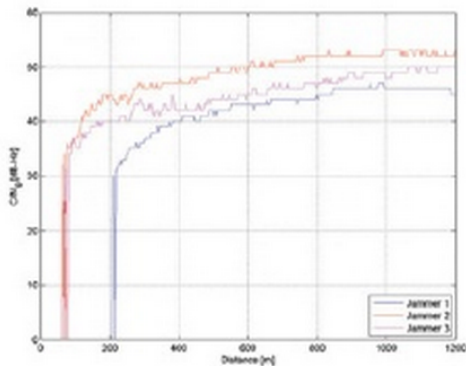


Figure 8. Field test result of a Garmin receiver in presence of PPD jammers [5]. PPD impact radius is about 500 meters.

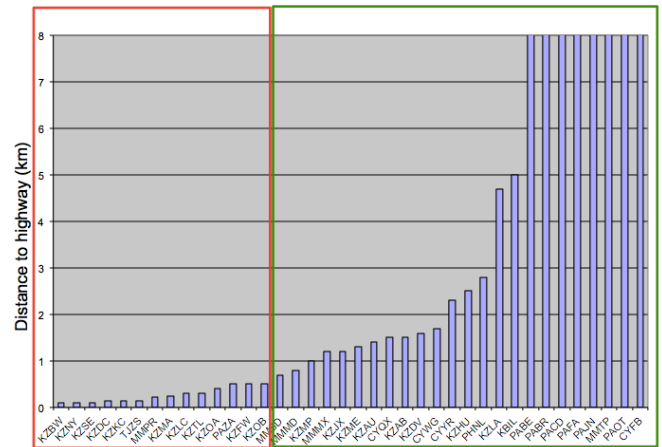


Figure 9. Distance of WRS to Highway. the WAAS reference stations subject to PPD jamming are a small subset of all the WRS.

In addition to the distance of WRS to traffic, Figure 10 shows the median weekly Radio Frequency Interference longer than 30 seconds detected by the Automatic Gain Control (AGC) of WAAS reference receivers. The data are retrieved from all 38 WRS from Nov. 27, 2011 to Mar 10, 2012 [6, 7]. According to Figure 10, the site of ZMA has the most number of median detectable RFI events. This is consistent with the fact that ZMA site is close to traffic as shown in Figure 5.

Among all the detectable RFI events, only a small portion (less than 10%) actually causes satellite outages.

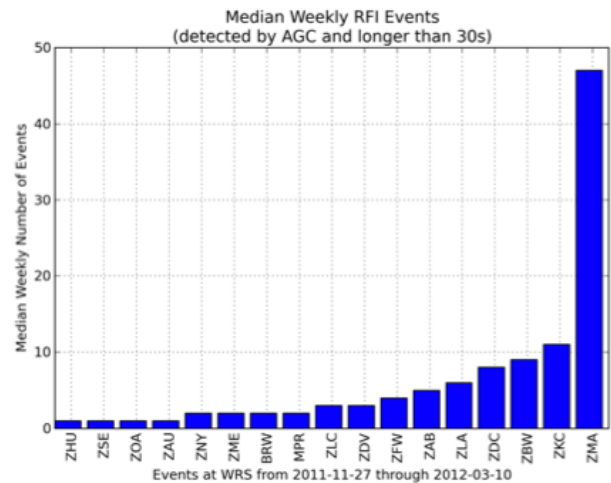


Figure 10. Median weekly Radio Frequency Interference (RFI) longer than 30 seconds detected by the Automatic Gain Control (AGC) of WAAS reference receivers [6, 7].

MONTE CARLO SIMULATION SETTINGS

Based on our understanding of PPD impact on WRS, we identify 16 at-risk reference stations. We conduct Monte Carlo simulation to analyze PPD impact on WAAS availability coverage. The settings of our Monte Carlo simulation are the following. We set 10 outages at randomly selected times between 4AM to 6PM local time spread across 10 randomly selected at-risk stations. Given the current PPD level, this is a very conservative setting. We believe it reflects the expected maximum. The mean time between outages is equivalent to 38 hours. The duration of each outage is 60 second. We ran our simulation analysis over 24 hours in one-minute intervals.

The simulation is based on the Matlab Algorithm Availability Simulation Tool (MAAST) developed by the GPS Laboratory at Stanford University [8]. The following pieces of codes have been added to the MAAST.

We introduced new “reset times” to restart the Code Noise and Multipath (CNMP) smoothing to the end of the outage time as shown in Figure 11.

We added CNMP curve for WAAS geostationary satellite instead of always assuming floor value. We also added reset times prior to current day as shown in Figure 12.

We added the option that only satellites below a certain angle will lose lock. With this function, we can simulate the case in which C/No for higher satellites may remain sufficient to maintain visibility.

We then modified the codes so that WRS antenna mask angles are programmable. They can vary by station.

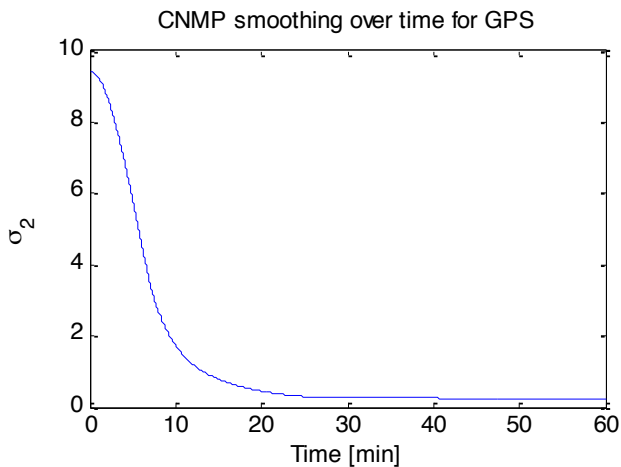


Figure 11. CNMP smoothing for GPS satellites

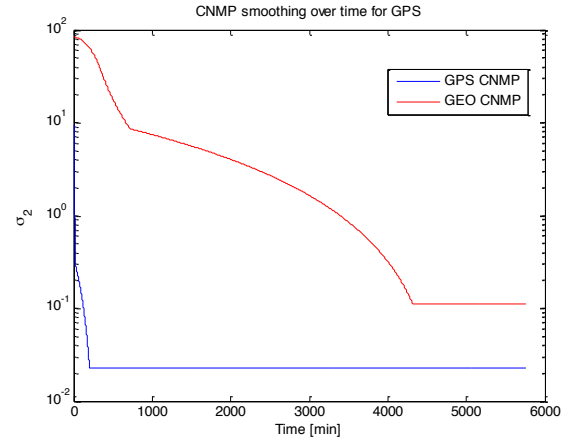


Figure 12. CNMP smoothing for GPS and WAAS GEO satellites

SIMULATION RESULTS

Figure 13 shows WAAS availability coverage over CONUS with no PPD interference. The Vertical Alert Level (VAL) is set to be 35 meters. The Horizontal Alert Level (VHL) is 40 meters. The availability result is based on the current GPS Constellation with the almanac data extracted on May 20, 2012. Note that the coverage for 95% availability is calculated over the whole rectangular area. Therefore it is 54.41% in this case, rather than a number close to 100% if it was calculated over CONUS area. The availability coverage in Figure 13 provides a baseline for PPD impact analysis.

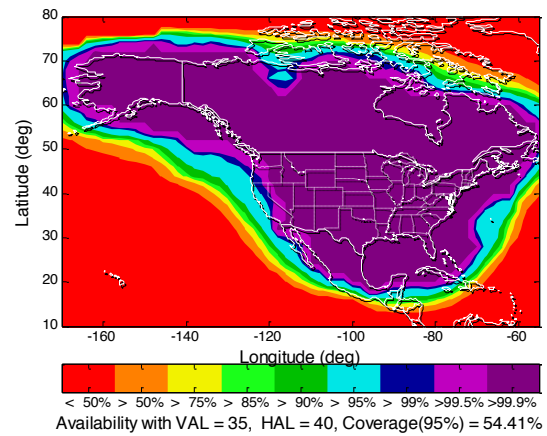


Figure 13. WAAS availability coverage for current constellation, baseline No PPD Case

Figure 14 shows the average WAAS availability coverage with PPDs causing 10 outages randomly selected from 16 at-risk stations at randomly selected times between 4AM to 6PM local time. The WAAS coverage for 95% availability is 54.3% over the rectangular area. In other words, the WAAS availability coverage of 10 outages is 99.78% of no outage case.

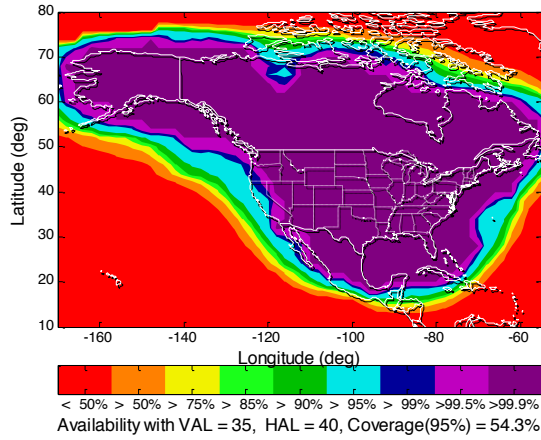


Figure 14. Average availability coverage for 10 outages in 24 hours for current constellation, all satellites experience outages

Since satellites at high elevation are more robust against interference due to their high received signal power, we simulated the case in which only satellites lower than 35° are out. The result is shown in Figure 15. The WAAS coverage for 95% availability is 99.85% of the baseline no outage case.

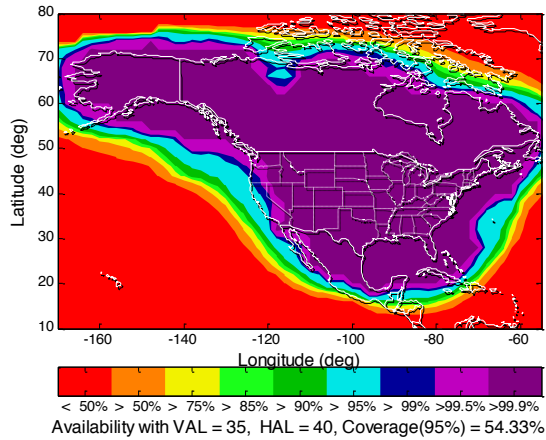


Figure 15. Average availability coverage for 10 outages in 24 hours for current constellation, only satellites below 35° suffer outages

In addition to the expected maximum of current PPD level, we also simulated the situation even 10 times worse in case the number of PPD increases in the future. That is, PPDs causing 100 outages randomly selected from 16 at-risk stations at randomly selected times between 4AM to 6PM local time. Figures 16 and 17 shows the WAAS availability coverage. Figure 16 assumes that all satellites experience outages, while only satellites below 35° suffer outages in Figure 17. The WAAS availability coverage is 99.58% and 99.72% of the baseline on PPD case respectively.

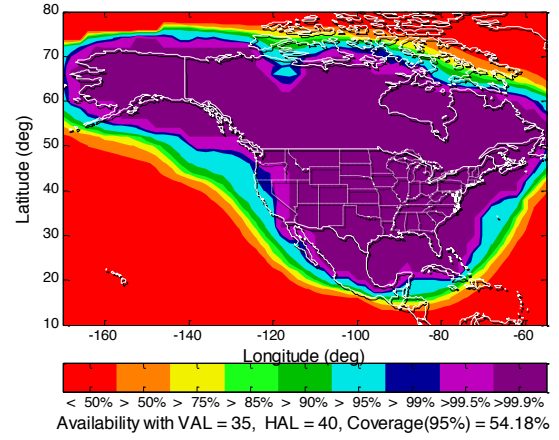


Figure 16. Average availability coverage for 100 outages in 24 hours for current constellation, all satellites experience outages

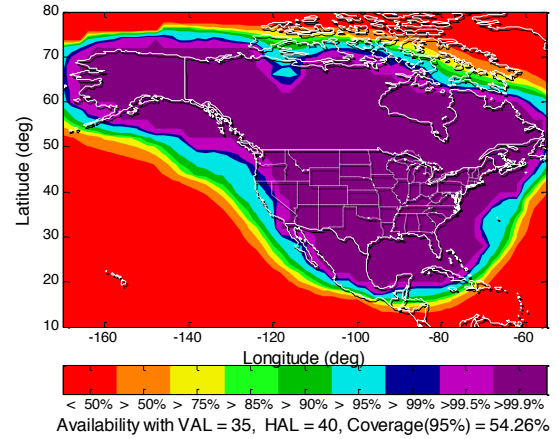


Figure 17. Average availability coverage for 100 outages in 24 hours for current constellation, only satellites below 35° suffer outages

The simulation result for WAAS availability coverage under PPD interference is summarized in Table 1. The numbers are normalized with respect to the case with no PPD.

Case	Coverage (all out)	Coverage (below 35° out)
No PPD	100%	100%
10 outages	99.78%	99.85%
100 outages	99.58%	99.72%

Table 1. Summary of WAAS availability coverage with PPDs causing 10 and 100 outages for the current constellation. The percentage is normalized with respect to the no-PPD case.

According to Table 1, the PPD impact on WAAS availability coverage is negligible. Figure 19 shows all 38 WRS. The red dots are stations proximate to traffic and subject to PPD outages; the blue dots are stations far from traffic and thus not subject to PPD outages. For WAAS availability coverage, edge stations in square areas matters the most. It happens that among these more critical stations, most of them are not subject to PPD outages. Moreover, the large number of WRS results in redundancy and robustness in the WAAS system. This explains why the PPD impact on WAAS availability is so negligible.

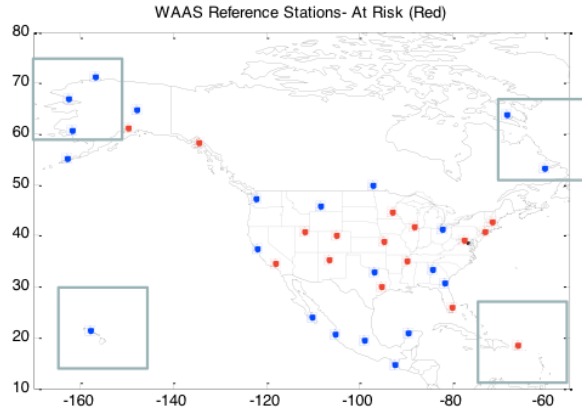


Figure 18. WAAS reference stations. The red dots are stations subject to PPD outages; the blue dots are stations not subject to PPD outages. Edge stations in square areas contribute most to WAAS availability coverage. Most edge stations are not subject to PPD outage

Figures 13-17 are based on the current GPS constellation. Next, we ran the simulation for 24-satellite constellation, since that's the minimum requirement of the GPS constellation. The WAAS availability coverage results are shown in Figures 19-23. The summary of the results for 24-satellite constellation is listed in Table 2. Even for the 24-satellite constellation, the PPD impact on WAAS availability coverage is still minimal. For the case of 10 outages, the availability coverage is still 99.31% and 99.63% for all satellites out and only satellites lower than 35° out, respectively. For the case 10 times worse than the expected maximum PPD level (100 outages), the availability coverage loss is still less than 1.55% compared to the no-PPD case.

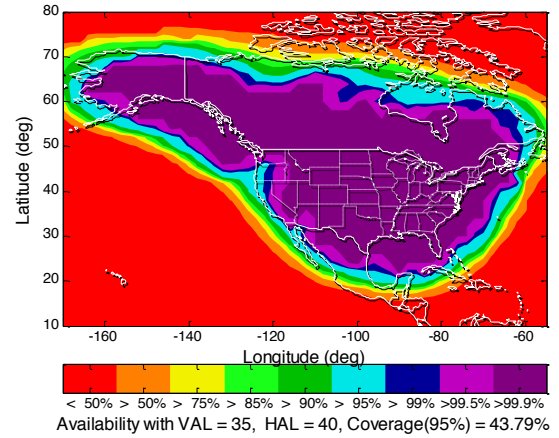


Figure 19. WAAS availability coverage for 24-satellite constellation, baseline No PPD Case

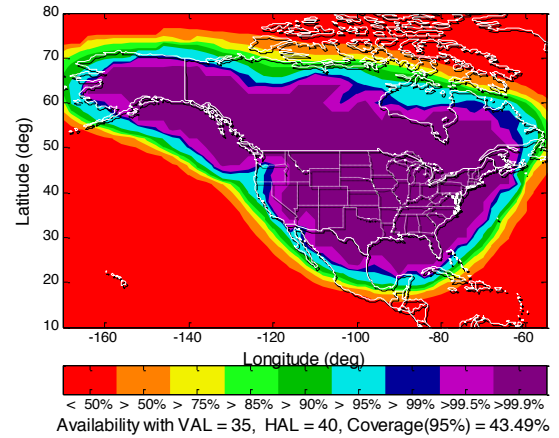


Figure 20. Average availability coverage for 10 outages in 24 hours for 24-satellite constellation, all satellites experience outages

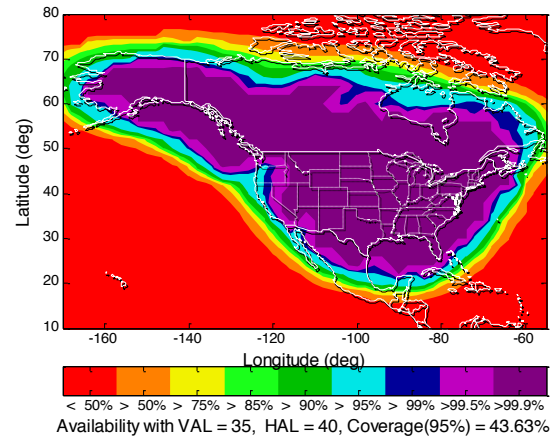


Figure 21. Average availability coverage for 10 outages in 24 hours for 24-satellite constellation, only satellites below 35° suffer outages

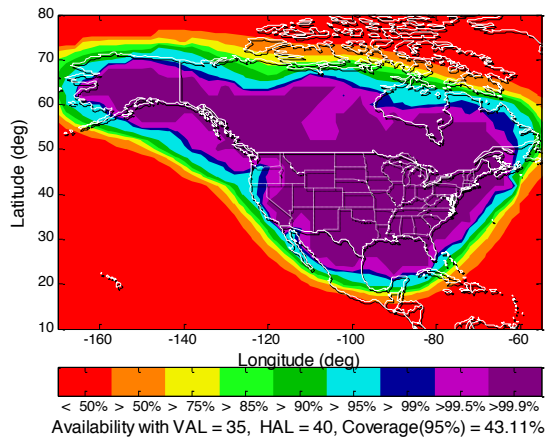


Figure 22. Average availability coverage for 100 outages in 24 hours for 24-satellite constellation, all satellites experience outages

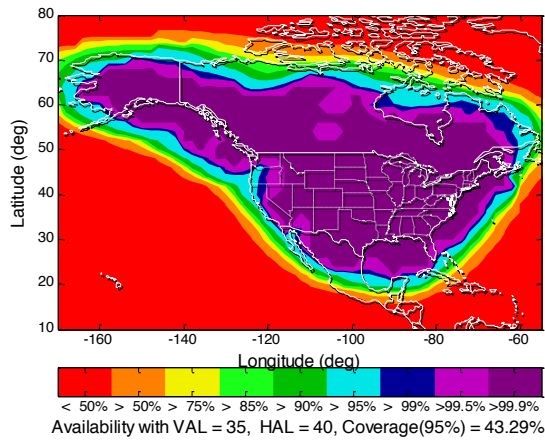


Figure 23. Average availability coverage for 100 outages in 24 hours for 24-satellite constellation, only satellites below 35° suffer outages

Case	Coverage (all out)	Coverage (below 35° out)
No PPD	100%	100%
10 outages	99.31%	99.63%
100 outages	98.45%	98.85%

Table 2. Summary of WAAS availability coverage with PPDs causing 10 and 100 outages for 24-satellite constellation. The percentage is normalized with respect to the no-PPD case.

CONCLUSION

This paper investigates the PPD impact on aviation users from WAAS service perspective. We modeled current PPD interference level based on real data retrieved from current WAAS reference stations. We then conducted

Montel-Carlo simulation for the expected maximum of current observed PPD level and the case 10 times worse.

For both cases, PPD jamming activity has had negligible impact on WAAS performance. PPD rates of occurrence must increase orders of magnitude to significantly affect performance. As long as edge stations remain at low risk for interference, WAAS availability should remain high.

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