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MITRE PRODUCT

An Introduction to WAAS and Its Predicted Performance

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An Introduction to WAAS and its Predicted Performance*

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ABSTRACT

The FAA is developing a Wide-Area Augmentation System (WAAS) to GPS that will broadcast clock, ephemeris, and ionospheric corrections. Aviation user equipment will apply the corrections to GPS measurements and also convert error bounds into the position domain. Flight operations can be conducted using WAAS guidance only when the horizontal, and in some cases also the vertical, position error bound is less than a threshold that depends on the phase of flight. The expected fraction of time that a given flight operation can be conducted is termed its availability. Geomagnetic storms sometimes are accompanied by large spatial and temporal gradients in ionospheric delay that result in an increase in ionospheric and position error bounds, which reduces availability. The paper estimates availability of precision approach operations under various scenarios.

BACKGROUND

The FAA is conducting a phased development of a Wide-Area Augmentation System (WAAS) to augment the Global Positioning System (GPS). WAAS will support en route, terminal, nonprecision approach (NPA), NPA with vertical guidance (NPV), and Category I (CAT I) precision approach (PA) flight operations. WAAS provides the following functions using broadcast signals from geostationary earth orbiting (GEO) communications satellites: 1) extra GPS-like ranging signals; 2) a vector of corrections to the GPS signal-in-space, including components for ionosphere, clock, and ephemeris errors; and 3) an integrity monitoring function to alert users to out-of-tolerance conditions in a timely manner. Phase 1 will be fully operational in September 2000.

The concept of operations of WAAS is described briefly as follows:

1. WAAS Reference Stations (WRSs) are deployed throughout the U.S. to measure pseudoranges and carrier phases on L1 and L2 frequencies from all visible satellites. (A semicodeless technique is used to derive a code measurement on L2.)
2. The WRSs send these measurements to WAAS Master Stations (WMSs), which calculate clock and ephemeris corrections for each GPS satellite, ephemeris information for each GEO, and ionospheric vertical delays on a grid. The grid consists of fixed ionospheric grid points (IGPs) at an altitude of 350 km above the Earth's surface. Grid spacings are 5°x5° between 55S and 55N and are larger beyond this region [1]. A recent proposal is likely to be adopted that adds more IGPs to the grid and would allow 5°x5° spacing between 60S and 60N.
3. In addition to the corrections, the WMSs calculate error bounds for ionospheric corrections called grid ionospheric vertical errors (GIVEs) at each IGP, and also combined error bounds for clock and

* This paper is based on system analysis studies performed for the FAA GPS Product Team (AND-730). This paper reflects the views of the authors. Neither the Federal Aviation Administration nor the Department of Transportation makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein. This work was produced for the U.S. Government under Contract Number DTFA01-93-C-00001 and is subject to Federal Acquisition Regulation Clause 52.227-14, Rights in Data-General, Alt. III (JUN 1987) and Alt. IV (JUN 1987).

ephemeris corrections for each visible satellite, called user differential range errors (UDREs).

4. The WMSs send these corrections and error bounds to the users (aircraft) through GEO communication satellites (e.g., Inmarsat 3) with a data rate of 250 bits/s.
5. User avionics apply these corrections to their pseudoranges in order to improve the accuracy of their position estimates. They also use the UDREs and GIVEs and other information to calculate error bounds on position error called the vertical protection level (VPL) and horizontal protection level (HPL). For the integrity of the system, these protection levels must bound the position errors with probability ≥ 0.9999999 in one hour (for en route through NPA operations) and during one NPV or PA (150 seconds).

Figure 1 shows Phase 1 resources for WAAS. They consist of 25 WRSs, 2 WMSs, 3 Ground Earth Station sites (GESs), and 2 GEOs, in addition to the terrestrial communication network. The two GEOs are Inmarsat 3 (AORW located at 54°W, and POR located at 178°E). Figure 2 shows a simplified procedure of how the WAAS user receiver employs the ionospheric delay corrections and the GIVEs.

WAAS REQUIREMENTS

Table 1 lists a summary of requirements for WAAS for different phases of flights [1,2]. These requirements are in draft for future phases of WAAS. Integrity is the ability of WAAS to provide timely warnings to users when the system should not be used for navigation. More specifically, WAAS integrity requirements are specified in terms of the probability of misleading information in a flight operation. Navigation information is misleading if horizontal position error (HPE)

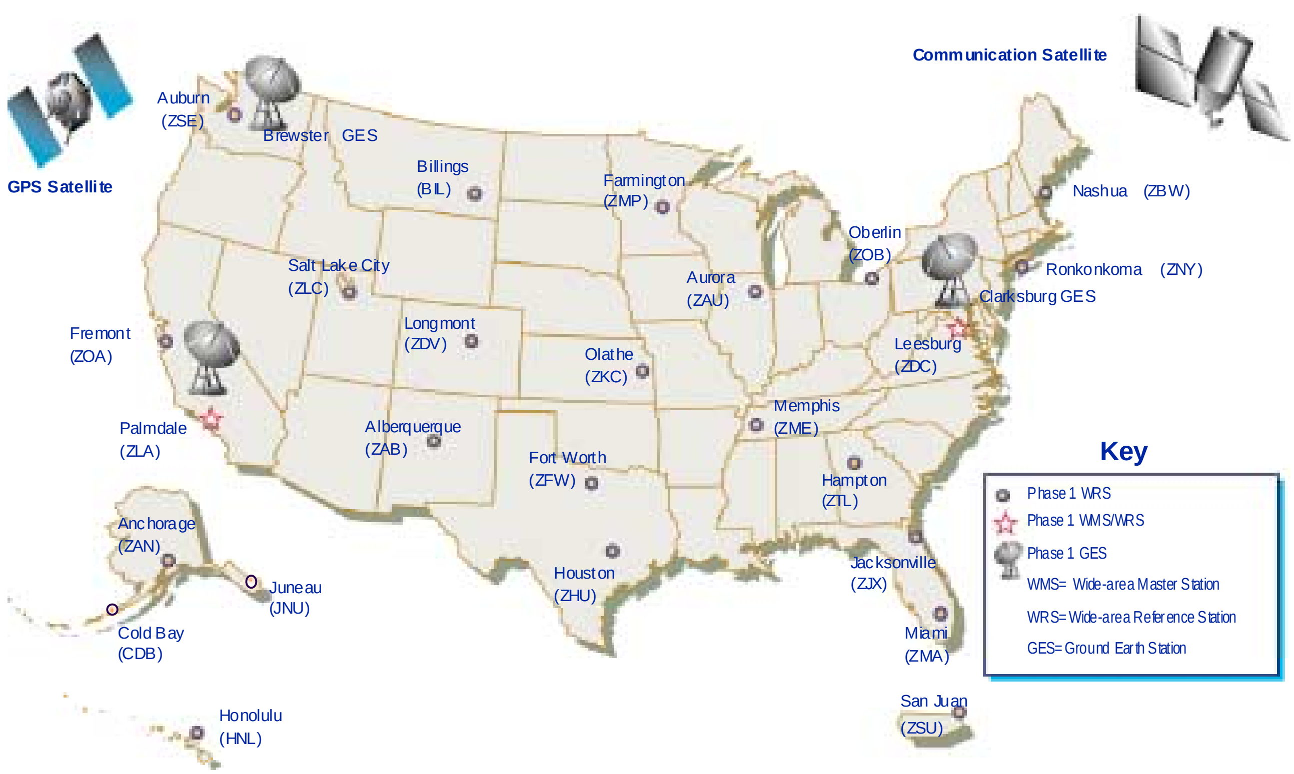

Figure 1. WAAS Phase 1 Resources

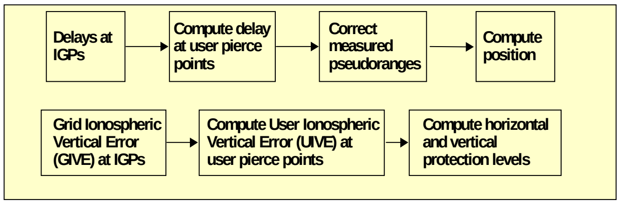

Figure 2. WAAS User Receiver's Ionospheric Function

is larger than HPL in en route, terminal, or NPA. For NPV and precision approach, vertical information is also used for navigation, so misleading information also exists if vertical position error (VPE) is larger than VPL. Integrity requirements are defined as follows:

For PA and NPV:

$\Pr\{VPE \le VPL \text{ and } HPE \le HPL\} \ge 0.9999999$ during one approach.

For enroute, terminal, and NPA:

$\Pr\{HPE \le HPL\} \ge 0.9999999$ during one hour.

Availability is the percentage of time that WAAS services are usable. Availability requirements are defined as follows:

For PA and NPV,

$\Pr\{VPL \le VAL \text{ and } HPL \le HAL\} \ge X$, $(0.95 \le X \le 0.999)$, where X depends on the phase of WAAS.

For en route, terminal, and NPA,

$\Pr\{HPL \le HAL\} \ge Y, (0.999 \le Y \le 0.99999)$, where Y depends on the phase of WAAS.

The definitions of VPL and HPL are given in Appendix J of Reference [1]. Figure 3 shows the notion that VPL must be less than VAL. According to Reference [1], HAL is the radius of a circle in the horizontal plane, with its center being the true position, which describes the region which is required to contain the indicated horizontal position with a probability of $1{-}10^{-7}$ per flight hour for en route to NPA or per approach for NPV and PA. VAL is half the length of a segment on the vertical axis, with its center being the true position, which describes the region which is required to contain the indicated vertical position with a probability of $1{-}10^{-7}$ per flight hour for en route to NPA or per approach for NPV and PA.

Table 1. Summary of WAAS Requirements

Phase of Flight	Integrity	Availability	Alert Limit(s)
En Route Oceanic	$1 - 10^{-7}$/hour	0.999 – 0.99999	HAL = 4 nm
En Route Domestic	$1 - 10^{-7}$/hour	0.999 – 0.99999	HAL = 2 nm
Terminal	$1 - 10^{-7}$/hour	0.999 – 0.99999	HAL = 1 nm
Nonprecision Approach (NPA)	$1 - 10^{-7}$/hour	0.999 – 0.99999	HAL = 0.3 nm
NPA with Vertical Guidance (NPV)	$1 - 10^{-7}$/appch	0.95 – 0.999	VAL = 20 m HAL = 0.3 nm
WAAS Category I	$1 - 10^{-7}$/appch	0.95 – 0.999	VAL = 12 m HAL = 20 - 40 m

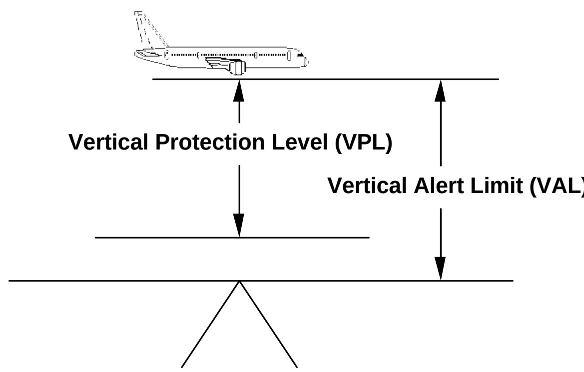

Figure 3. Definition of VPL and VAL

SPACE WEATHER EFFECTS ON WAAS

Severe geomagnetic storms can cause a large temporal rate of change of the ionospheric delay and also a large spatial gradient. WAAS is capable of detecting these changes and updating the broadcast values of the ionospheric delay and the GIVEs more often. Both delay and GIVEs will tend to be larger in the vicinity of a storm.

Navigation for en route through NPA should be unaffected by ionospheric conditions since the HAL is very large; furthermore, WAAS ionospheric corrections will not be used during these phases of flight by avionics meeting only the minimum requirements of Reference [1]. For the NPV and PA phases of flight, the alert limit requirements (VAL and HAL) are much more stringent and therefore require the use of ionospheric corrections.

The maximum ionospheric grid update interval is 5 minutes and is the interval that is normally used. WAAS monitors the spatial gradients and the rate of change of total electron content (TEC) or ionospheric delay. In the vicinity of a storm, WAAS calculates large values of GIVEs at each IGP. These GIVEs are used to calculate bounds on the user's vertical and horizontal position errors. During a period of storms, the grid (or portions of it) will be updated at a faster rate (e.g. ≤ 1 min). The impact of large GIVE values during a storm is to cause VPL to exceed the VAL for precision approach (expected to be set initially at 12 m) in areas affected by the storm. This will disallow precision approach. NPV approaches can continue to be conducted unless the VPL also exceeds the VAL for NPV (expected to be set initially at 20 m or somewhat more). If the VPL exceeds 20 m, then NPVs are disallowed, but NPA can still be conducted. This illustrates the "fail soft" performance offered by WAAS; this performance should be acceptable to the user community when compared to severe weather fronts, snow storms, and tornadoes, when many airports can be closed completely.

The Ap and Kp indices are general global daily measures of geomagnetic activities. These indices do not indicate where the center or the region of a storm is. The following definitions of geomagnetic activities originate from the National Geophysical Data Center (NGDC)/National Oceanic and Atmospheric Administration (NOAA).

A *quiet ionosphere* is said to occur when Ap < 30, a *minor storm* when 30 ≤ Ap < 50, a *major storm* when 50 ≤ Ap < 100, and a *severe storm* when Ap ≥ 100. These storm activities can occur at any time during the day or night and at any time during the solar cycle. A majority of storms occur during the peak of solar cycle. Most storms commence in the afternoon and last a few days. The first phase of a severe storm (first few hours) is the most disturbed time and usually results in a temporal rate of change and spatial gradient of ionospheric delay that are much higher than normal.

It should be noted that not every storm has a major impact on TEC. Mendillo and Klobuchar in their 1974 study [3] examined about 75 storms and found that between 20 to 25 (about 30 percent) of these storms had a major impact on TEC.

The statistics of the Ap index over an 11-year cycle are shown in Figure 4. This figure shows that during 1991, the percentage of Ap index ≥ 100 was 3.425%. This was the largest percentage of severe geomagnetic storm activities over the 11-year cycle. This does not mean that every user would be affected simultaneously by a storm, or for that percentage of time. Only a certain percentage of users are affected by any storm due to the facts that storms do not cover the entire service volume and only a few hours of the storm cause significant changes in TEC.

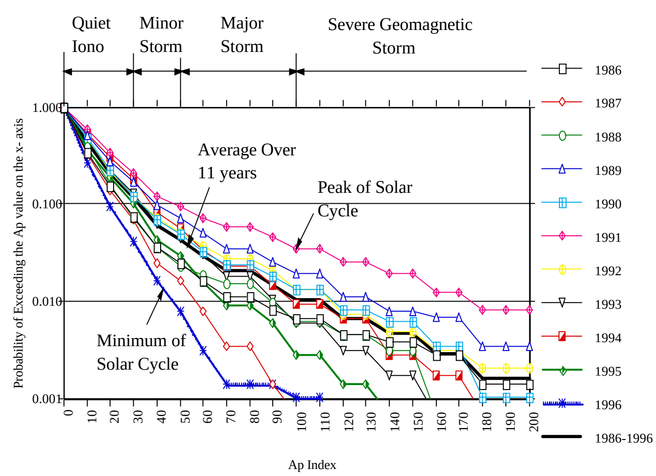

Figure 4. Statistics of the Ap Index over 11-Year Cycle

PREDICTED PERFORMANCE

During the last few years, the FAA Technical Center conducted hundreds of flight tests using the National Satellite Testbed (NSTB), which is an R&D system similar to WAAS. An example of the accuracy results for some of these flight tests for PA is shown in Table 2 [4]. Some of these approaches were conducted at Atlantic City Airport, NJ and the others were at Crows Landing, CA. These occurred between May 31 and June 3, 1994, which is halfway down in the solar cycle. This table shows good results for vertical and lateral accuracy.

Table 2. Results of Approaches Conducted at Atlantic City, NJ, and Crows Landing, CA [4]

Aircraft	Vertical μ, σ, $\lvert\mu\rvert + 2\sigma$ (m)	Lateral μ, σ, $\lvert\mu\rvert + 2\sigma$ (m)	Ave VDOP	No. of Approaches
Challenger	2.8, 2.0, 6.8	-0.3, 1.3, 2.9	N/A	39
Convair	2.2, 2.25, 6.7	0.5, 1.3, 3.1	1.7	43
Aero-commander	1.1, 1.95, 5.0	0.7, 1.4, 3.5	1.9	29

N/A = Not available
*Aerocommander sensor accuracy is given at 300 ft instead of 200 ft because many approaches were broken off early due to construction at the end of the runway, while resulted in some loss of data.

Examples of Predicted Results of Ionospheric Errors

Figure 5 shows the Cumulative Distribution Functions (CDFs) of the residual vertical ionospheric error and its 99.9th percentile error bound (GIVE) at Atlantic City, NJ, using 15 days in April 1993. The GIVE algorithm of Reference [5] is used to calculate the bounds. This algorithm is still under development, and it may be a candidate for WAAS future phases. The data is separated into two groups. One group includes quiet, minor, and major storms (Ap < 100), and the other group includes only severe storms (Ap ≥ 100). The first group is called “No Storm” in Figure 5, and the second group is called “Storm.” It is seen from this figure that the residual error and GIVE are much higher for the severe storm case as compared to the “No Storm” case as expected. The values on the x-axis are the tabulated values of GIVE as given in [1, 2]. Also, for a fixed probability value, the error bounds (GIVEs) are much larger than the residual errors.

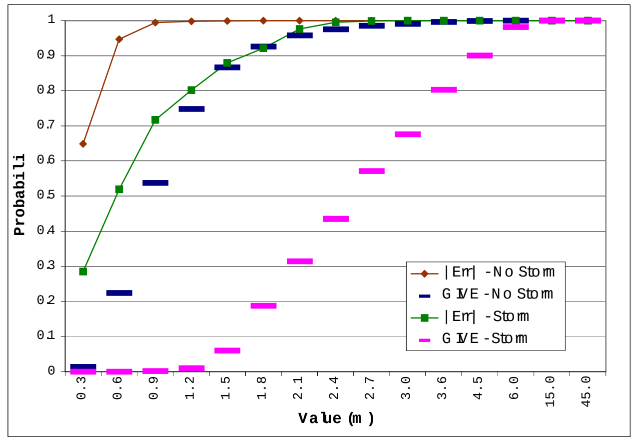

Figure 5. CDF of Vertical Ionospheric Errors and GIVEs [5]

The ionospheric errors and GIVEs are used to calculate the VPE and VPL due to the ionosphere using the formulas in Reference [1]. The CDFs of VPE and VPL are shown in Figure 6.

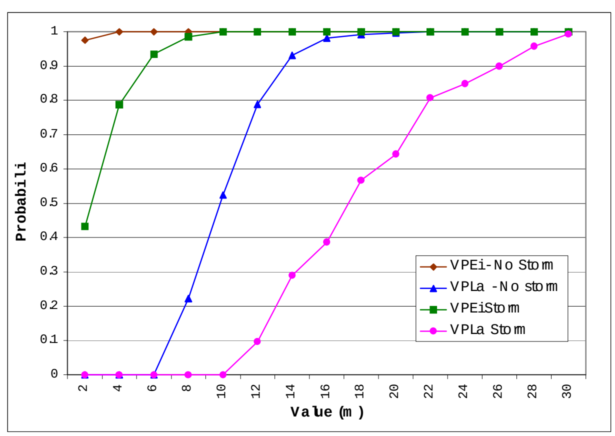

Figure 6. CDF of VPE and VPL [5]

Figure 7 shows a scatter plot between the VPL and the average spatial gradients for all the ionospheric pierce points (IPPs) at and around Atlantic City, NJ, during 15 days in April 1993. This figure shows that, for a quiet ionosphere (i.e., low spatial gradient), there is no significant correlation between VPL and spatial gradient. For an active ionosphere (i.e., average spatial gradient ≥ 0.10 m/100km) there is a trend between both parameters. (In this case, the correlation coefficient is equal to 0.74). This kind of correlation could be very useful to link WAAS performance parameters to the local ionospheric activity rather than the global Ap and Kp indices.

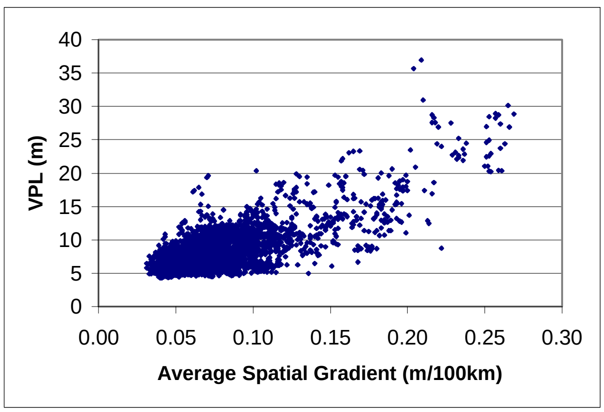

Figure 7. Scatter Plot of VPL vs. Average Spatial Gradient

Examples of Predicted WAAS Availability

Phase 1 WAAS will have 25 WRSs in the U.S. Future phases plan additional WRSs, although their location and number have not yet been determined. Figure 8 depicts a possible future configuration of WRSs beyond Phase 1 that consists of the 25 U.S. WRSs, plus 8 more in Canada and 3 in Mexico. Future phases of WAAS will also probably include additional GEOs.

Availability is affected by the number and location of GEOs and WRSs, solar activity, algorithms that correct for and bound the ionospheric delay errors, and monitoring alert limit thresholds.

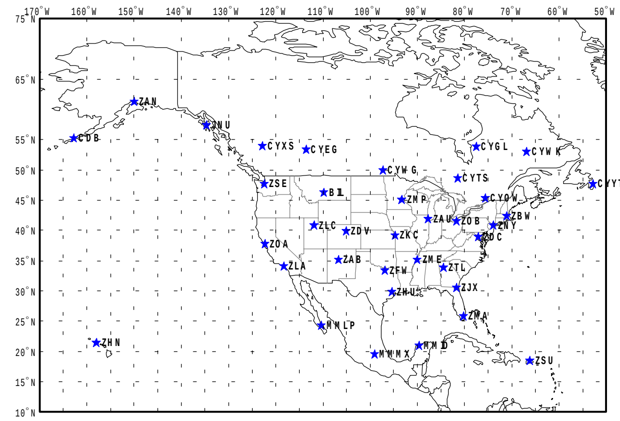

Figure 8. Possible Future Configuration of WRSs

In order to illustrate these effects on availability, four comparisons have been constructed using the Satellite-based Worldwide Availability Tool (SWAT) described in Reference [6]. These comparisons show the effects on availability by changing one element at a time and are described below. In all of these cases, the UDRE value is assumed to be 2.0 m, which is a slightly conservative value that is considered to be typical for early phases of WAAS. Smaller values of UDRE (e.g., 1.5 m) have been identified as achievable with a fully implemented WAAS. Since the analysis focuses on relative performance of different cases, a smaller value of UDRE will not change the conclusions of this paper.

Comparison 1: Increasing WAAS resources
An increase in WAAS resources can result from adding WRSs and GEOs. Additional WRSs extend the service area. Additional GEOs improve the redundancy of the system and increase the chances of receiving WAAS messages. Figure 9 illustrates the availabilty of the system with 25 WRSs and 2 GEOs. Figure 10 shows the effects of adding 11 WRSs and 1 GEO. Figure 10 illustrates an

improvement in availability resulting from the increased WAAS resources.

Comparison 2: Improving Ionospheric Algorithms
An improvement in ionospheric algorithms can extend availability at the edges of coverage. Figure 11 shows the availability projected with Phase 1 WAAS ionospheric algorithms, while Figure 10 illustrates the effects of a newer algorithm under development [5]. The Phase 1 algorithm requires that there be at least 1 IPP sequence in at least 3 grid squares surrounding an IGP. The newer algorithm has a less stringent requirement. Figure 10 illustrates the increased availability especially around the edge of coverage.

Comparison 3: Relaxing Requirements for New Phases of Flight
When the rigorous requirements of a precision approach are not required, a relaxation in the horizontal and/or vertical precision requirements increases the probability the requirements can be met. Figure 12 shows the effects of a VAL requirement of 12 m (CAT I PA), compared to the results of a VAL requirement of 20 m (NPV) as shown in Figure 10. There are small increases in availability in the southeast region.

Comparison 4: Effects of Severe Ionospheric Conditions
As discussed previously, ionospheric storms increase errors on the ionospheric grid, and the increased GIVEs decrease the probability that horizontal and vertical protection levels can remain below their alert limits. Figure 12 shows the availability during a period when the Ap index was below 100. The effects on availability during a severe storm (Ap > 100) can be seen in Figure 13, which shows a significant loss of availability throughout large parts of the service area.

These conditions are summarized in Table 3.

Table 3. Summary of Availability Comparisons

Comparison Number	Description	Relevant Figure No.
1	Increasing WAAS Resources	9/10
2	Improving Ionospheric Algorithms	11/10
3	Relaxing Requirements for New Phases of Flight	12/10
4	Effects of Severe Ionospheric Conditions	12/13

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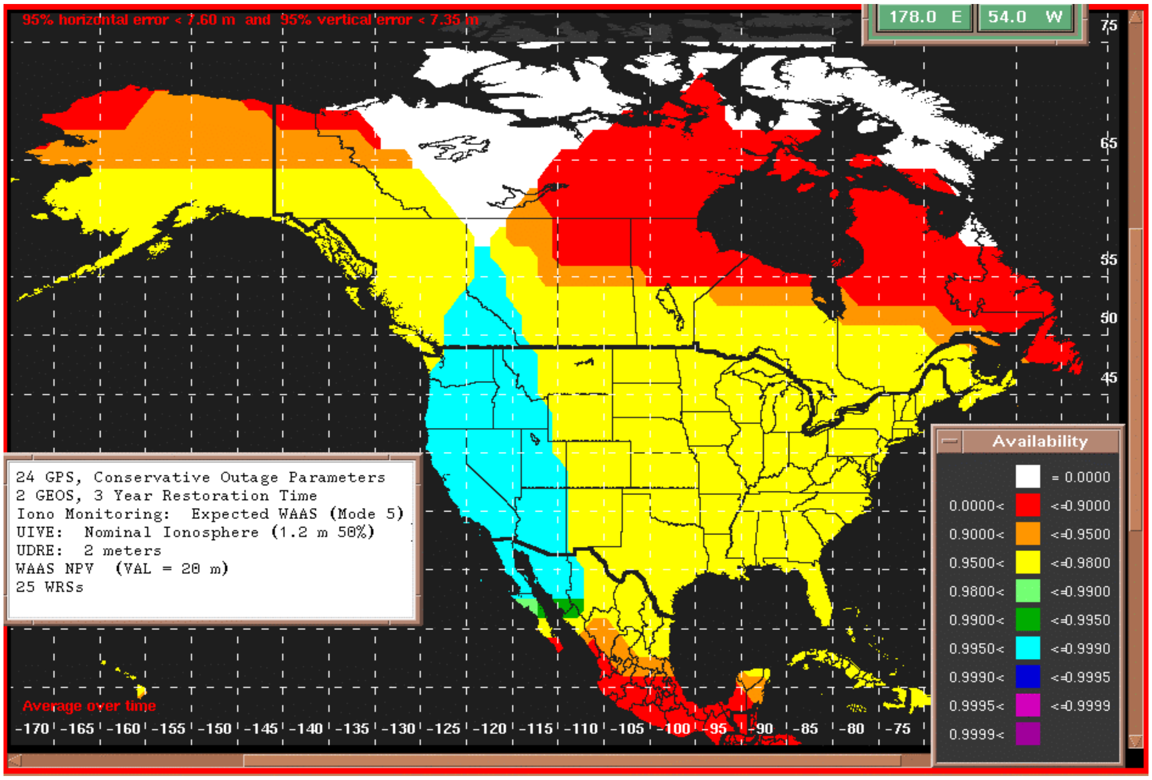

Figure 9. Average Daily Availability
(No storm, UIVE=1.2m, VAL=20m, 25 WRSs, 2 GEOs, new iono algorithm)

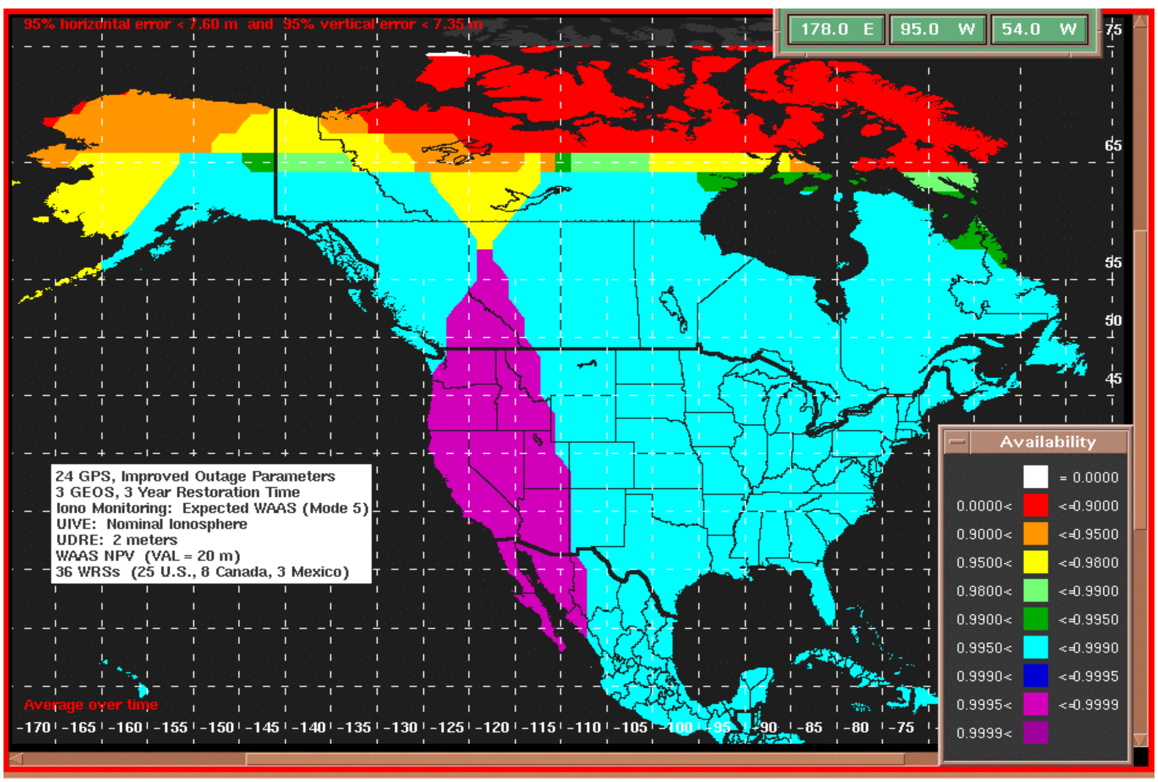

Figure 10. Average Daily Availability
(No storm, UIVE=1.2m, VAL=20m, 36 WRSs, 3 GEOs, new iono algorithm)

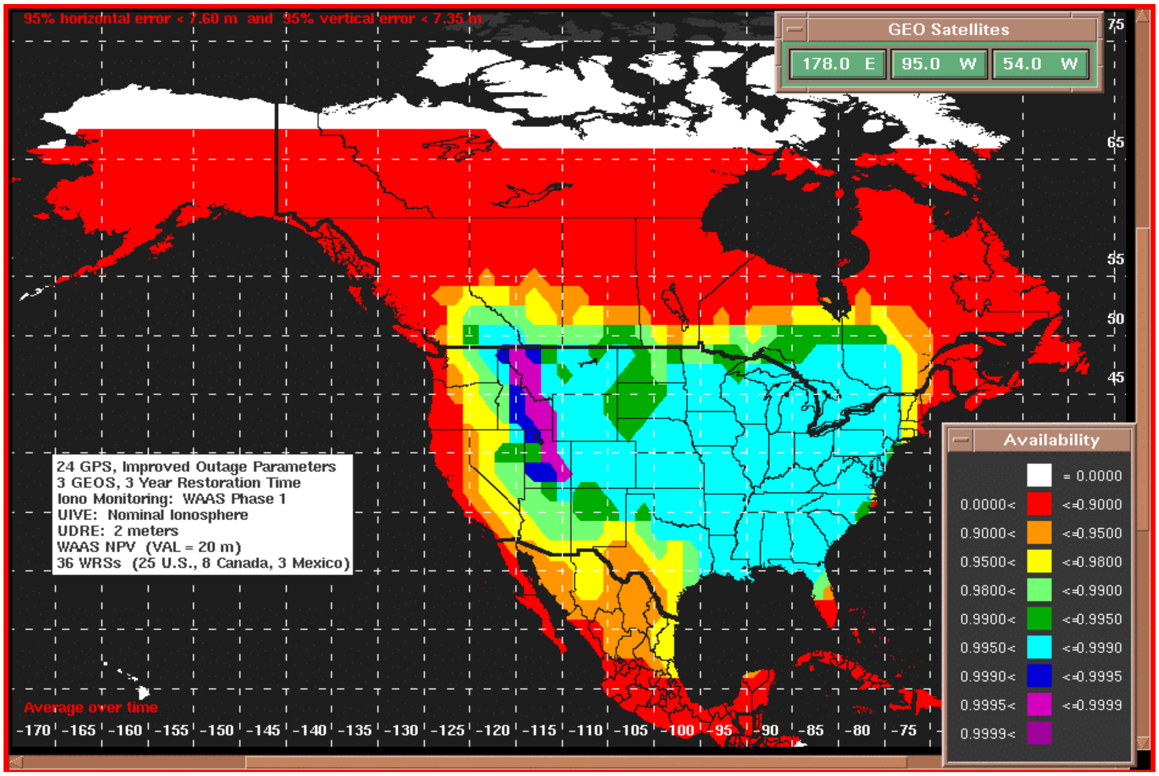

Figure 11. Average Daily Availability
(No storm, UIVE=1.2m, VAL=20m, 36 WRSs, 3 GEOs, Phase 1 iono algorithm)

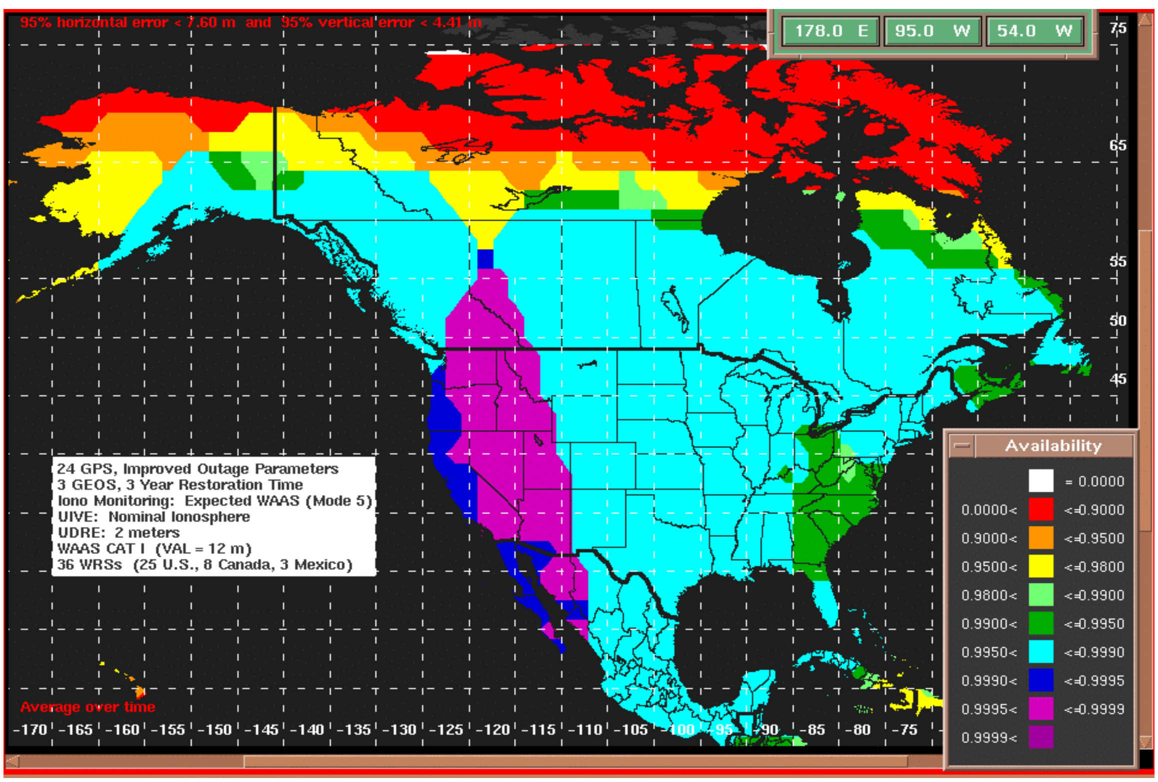

Figure 12. Average Daily Availability
(No storm, UIVE=1.2m, VAL=12m, 36 WRSs, 3 GEOs, new iono algorithm)

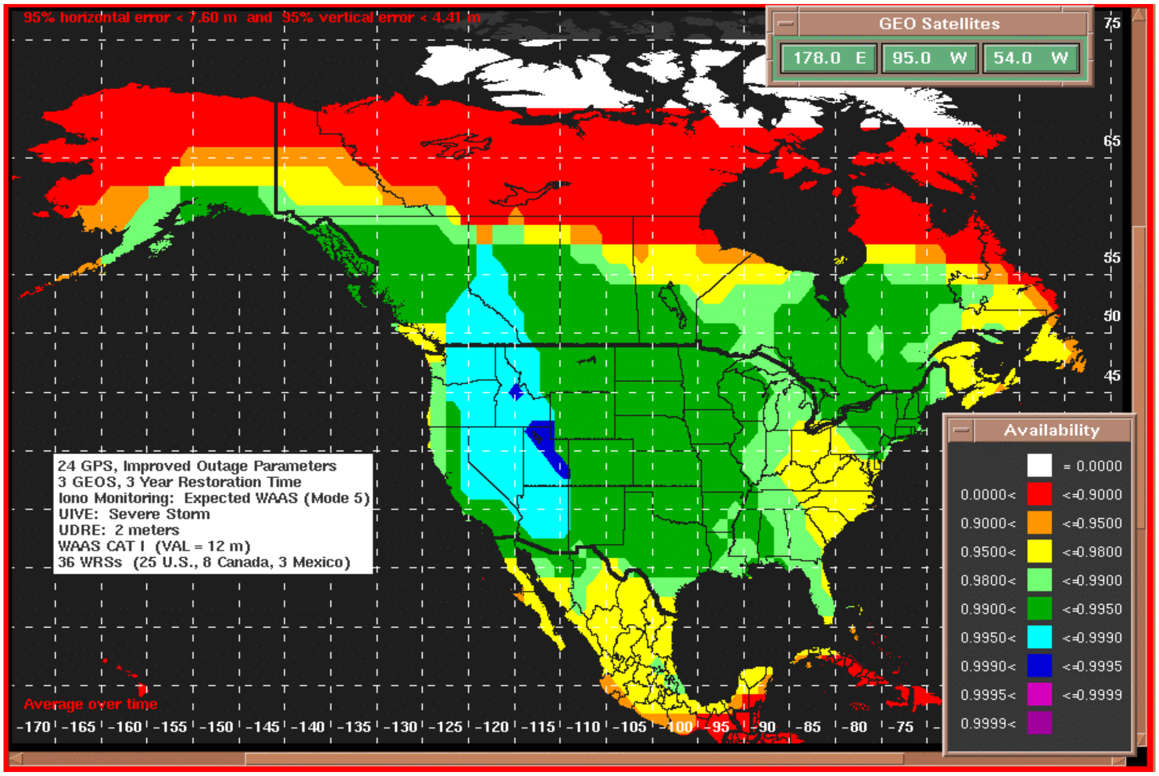

Figure 13. Average Daily Availability
(Storm, UIVE=3.0m, VAL=12m, 36 WRSs, 3 GEOs, new iono algorithm)

Glossary

CAASD	Center for Advanced Aviation System Development
CAT	Category
CDF	cumulative distribution function
FAA	Federal Aviation Administration
GEO	geostationary earth orbiting (communications satellite)
GES	ground earth station (site)
GIVE	grid ionospheric vertical error
GPS	Global Positioning System
HAL	horizontal alert limit
HPE	horizontal position error
HPL	horizontal protection level
IGP	ionospheric grid points
ION	Institute of Navigation
IPP	ionospheric pierce point
L1	L-band frequency 1575.42 MHz
L2	L-band frequency 1227.6 MHz
L-band	L-band frequency
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NPA	nonprecision approach
NPV	NPA with vertical guidance
NSTB	National Satellite Testbed
PA	precision approach
R&D	Research and Development
SWAT	Satellite-based Worldwide Availability Tool
TEC	total electron content
UDRE	user differential range error
UIVE	user ionospheric vertical error
VAL	vertical alert limit
VDOP	vertical dilution of precision
VPE	vertical position error
VPL	vertical protection level

WAAS Wide-Area Augmentation System
WMS WAAS Master Station
WRS WAAS Reference Station