Good, Better, Best

Expanding the Wide Area Augmentation System

Timothy R. Schempp

AIR TRAVEL PROMISES to become safer and cheaper thanks to the Wide Area Augmentation System (WAAS). It assists or augments GPS by providing the increased accuracy, availability, continuity, and integrity necessary for aircraft navigation. Unaugmented, or standalone, GPS isn't accurate enough for some types of runway approach procedures. Using geostationary Earth orbit (GEO) communications satellites, WAAS provides corrections to the GPS satellite orbit and clock information in a satellite's navigation message as well as ionospheric delay information. These corrections permit a user's receiver to compute a more accurate position, often to better than 1 meter horizontally and 2 meters vertically, with a 95% confidence.

WAAS also increases the availability and continuity of GPS for aircraft navigation by requiring fewer redundant observations for determining a valid position. Availability is also increased through the provision of the additional GEO ranging signals.

INNOVATION INSIGHTS
with Richard Langley

WAAS also benefits GPS users on the ground.

But perhaps most importantly, WAAS provides the increased integrity needed for a safety-of-life navigation system. Within 6 seconds of a fault detection, an alarm message corrects the error or allows a safe transition to an alternative navigation procedure. The advantages of WAAS for aviation include greater runway capability, reduced separation standards which allow increased capacity in a given airspace without increased risk, more direct enroute flight paths, new precision approach services, reduced and simplified equipment onboard aircraft, and significant government cost savings due to the elimination of maintenance costs associated with older, more expensive ground-based navigation aids.

But WAAS not only benefits GPS users in the sky. Many GPS users on terra firma are making use of the increased accuracy and availability afforded by WAAS. For example, according to the FAA, OnStar has added WAAS capability to the GPS receivers in General Motors 2008 product year vehicles. And even surveyors are making use of the WAAS ranging signals for improving real-time kinematic survey operation.

While WAAS was already a much-valued addition to standalone GPS, significant improvements were made to WAAS over the past three years, including expansion of the reference station network and the commissioning of two new GEOs. 2008 will see even more enhancements. In this month's column, we take a look at WAAS's recent upgrades and take a peek into its future.

"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 10.

The Wide Area Augmentation System (WAAS) enhances the GPS Standard Positioning Service, providing sufficient integrity, accuracy, availability, and continuity for use in commercial aviation. Fielded by the U.S. Federal Aviation Administration (FAA), the system provides enroute through non-precision approach, lateral navigation / vertical navigation (LNAV/VNAV), and localizer performance with vertical guidance (LPV) runway approach capabilities (see the "Navigating Aircraft with GPS and WAAS" sidebar for definitions of these terms).

But WAAS is more than a navigation system for pilots. Most any GPS receiver you buy today is WAAS-enabled, allowing everyone from hikers and bikers to surveyors, farmers, and rescue workers to enjoy the benefits of improved accuracy and integrity in their day-to-day activities. Since WAAS is compliant with the same international standards used to build Japan's MTSAT Satellite-based Augmentation System (MSAS) and Europe's European Geostationary Navigation Overlay Service (EGNOS) along with several other systems under development, a WAAS-enabled GPS receiver will improve the accuracy, integrity, availability, and continuity of GPS for users around the world.

Over the last three years, WAAS has undergone a major expansion, adding reference stations in Alaska, Mexico, and Canada; upgrading processing software; and replacing the legacy geostationary Earth orbit (GEO) satellites with new satellites that are well positioned to give dual-signal coverage to users in North America. Many of these enhancements were fielded in September 2007, resulting in a significant performance improvement for every WAAS user in North America.

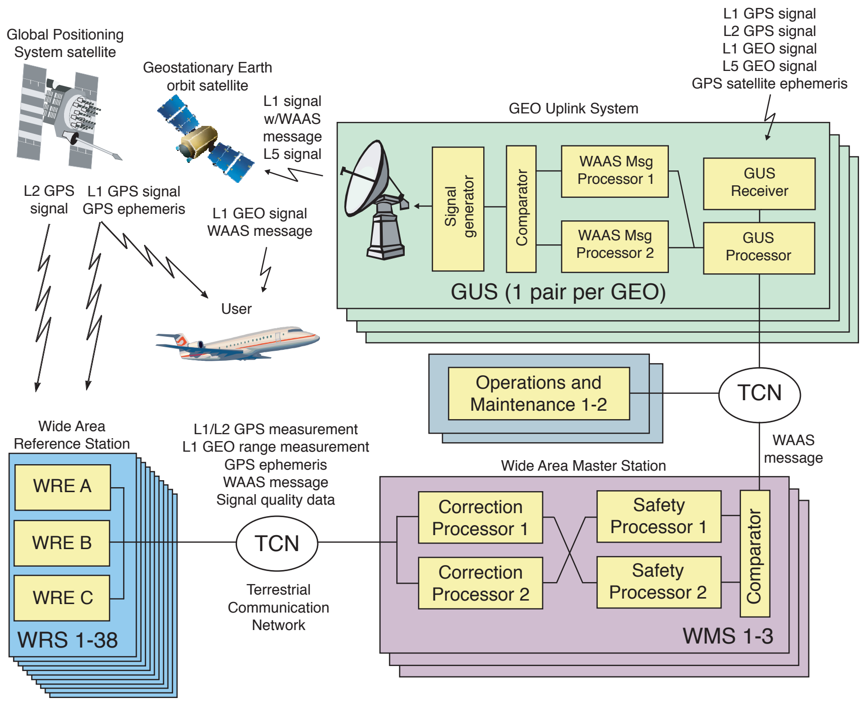
The System

WAAS is a wide-area differential GPS system that processes measurements from reference stations throughout North America to compute ionospheric corrections and satellite orbit and clock corrections (see **FIGURE 1**). GPS measurements are processed by a network of Wide Area Reference Stations (WRSs) located throughout the coterminous United States (CONUS), Alaska, Puerto Rico, Hawaii, Mexico, and Canada. L1 and L2 measurements from the WRSs are used by the Wide Area Master Stations (WMSs) to form WAAS corrections and integrity information. Dual-frequency (L1/L2) measurements are used to calculate ionospheric delays. However, L2 measurements are not usable by aircraft equipment because the L2 signal does not fall in a protected radio frequency band, a requirement for such a safety-of-life service.

Thus, WAAS provides ionospheric corrections for the single-frequency L1 users who cannot adequately correct for ionospheric delay on their own. These corrections are provided in the form of a latitude-longitude grid, hence the term ionospheric grid delays. Users' receivers interpolate the grid delays to obtain corrections for a particular satellite at a particular location. The ionospheric grid points (IGPs) cover North America.

Signal quality data measured by the reference receivers is used in the Safety Processor to detect GPS signal deformation which could result in a hazard similar to the "GPS SV19 failure." That failure occurred in 1993 when the pseudorandom noise code modulation on the satellite's signal became distorted, leading to tracking errors and larger than normal positioning errors.

The assembled WAAS message is output to the GEO Uplink System (GUS). The GUS chooses data from one of the WMSs and uploads the data to a geostationary WAAS satellite, which broadcasts the data to users. The GEOs broadcast both an L1 and L5 signal. Currently, the L5 signal is only used by the GUS itself to calculate ionospheric delay. In the future, when L5 signals are available from GPS satellites, the GEO L5 signal will contain a WAAS message for dual-frequency L1/L5 users.



▲ **FIGURE 1** WAAS architecture

Redundancy. Redundant system components are used to increase system reliability and mitigate hazardous information from a failed piece of hardware. Each of the 38 reference stations has three WAAS Reference Equipment (WRE) units, each with its own co-located antenna, receiver, and data processor. The system actively uses data from two of the WREs at a reference station. Data from the third WRE at each reference station is used during system maintenance or whenever the system detects a WRE failure.

Stations are connected into the system through the Terrestrial Communications Network (TCN), which is divided into two separate and diverse networks designated Ring 1 and Ring 2. The backbone of each ring consists of high reliability dual T1 circuits with enough capacity to ensure that every message is delivered on each ring even if one leg of the network goes down. Each WMS consists of two correction processors and two safety processors. A hardware comparator performs a bit-by-bit comparison of the output WAAS messages from the two safety (validation) processors. If one or more bits mismatch, the correction and validation component (C&V) faults itself and another C&V automatically takes over. Each GUS receives a WAAS message from each WMS. In the event that a WMS fails to send a message, the GUS switches to a different WMS. A pair of GUS sites is assigned to each GEO satellite. In the event that one GUS site fails or during system maintenance, the other GUS site automatically takes over. The two GEO satellites are positioned such that most users in North America will have dual GEO coverage. In the event of a satellite or uplink failure, users' receivers automatically switch to the other available satellite.

Enhancements

Under the "WAAS Full LPV" contract awarded by the FAA, WAAS is undergoing a series of enhancements designed to improve overall system reliability and extend the LPV service region. These enhancements result in a significant availability improvement in CONUS and Alaska as well as expanding LPV service into Canada and Mexico.

A comparison of performance requirements for the WAAS Initial Operating Capability (IOC) — achieved in 2003 — and the Full LPV Contract is given in **TABLES 1** and **2**. The tables provide availability and accuracy figures for LNAV and LPV approaches. The primary difference between LNAV and LPV is the size of the Horizontal Alarm Limit (HAL) and Vertical Alarm Limit (VAL), which refer to the

TABLE 1. (a) Lateral Navigation (LNAV) and (b) Localizer Performance with Vertical Guidance (LPV) requirements

(a) LNAV Performance	IOC Req.	Full LPV Req.
Availability	99.9%	99.99%
HAL	556 m	556 m
VAL	N/A	N/A
Horiz. 95% accuracy	100 m	36 m
Probability of HMI	10^{-7} per hour	10^{-7} per hour
Time to alarm	10 s	10 s
Coverage	Over 100% of CONUS	Over 100% of CONUS
(b) LPV Performance	**IOC Req.**	**Full LPV Req.**
Availability	95%	99%
HAL	556 m	40 m
VAL	50 m	50 m
95% Accuracy	Vert. 7.6 m Horiz. 7.6 m	Vert . 2.0 m Horiz. 1.5 m
Probability of HMI	10^{-7} per approach	10^{-7} per approach
Time to alarm	6.2 s	6.2 s
Coverage	75% + of CONUS	100% + of CONUS

TABLE 2. WAAS full Localizer Performance with Vertical Guidance (LPV)

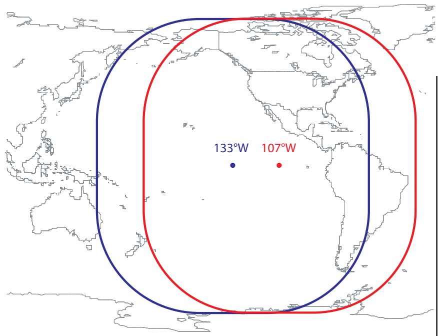
	Requirement	Measured Performance
LPV CONUS 99% availability	100% of CONUS	100% of CONUS
LPV Alaska 95% availability	75% of Alaska	88% of Alaska
LNAV CONUS 99.99% availability	100% of CONUS	100% of CONUS
Vertical accuracy	2.0 m 95% bound	0.95 m 95% bound
Horizontal accuracy	1.5 m 95% bound	0.60 m 95% bound
Time to alarm	6.2 s	6.2 s
Probability of HMI	10^{-7}	0

horizontal and vertical uncertainty needed to perform an approach. The tables also state the requirements on the probability of WAAS providing Hazardously Misleading Information (HMI).

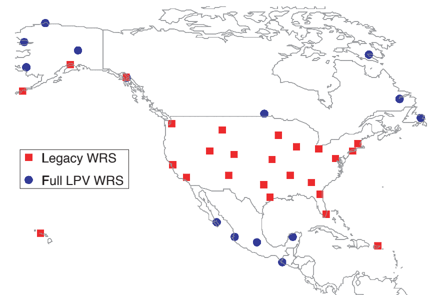
WAAS must meet its integrity requirements anywhere a receiver can perform a WAAS-user position solution. Integrity is ensured by users computing Horizontal and Vertical Protection Limits (HPL and VPL). The HPL and VPL are overbounded estimates of the potential errors in positions computed using WAAS. To ensure integrity, the HPL and VPL must bound user position errors with a probability confidence level of 99.99999%. HPL and VPL are computed by using the overbounding variances of the residual errors, including the User Differential Range Error (UDRE) and the Grid Ionospheric Vertical Error (GIVE), after applying WAAS corrections. Users take and adjust these variances with their local position and combine them with the receiver bounding variances to compute the VPL and the HPL. The HPL and VPL have to be below set (HAL and VAL) thresholds to perform a particular type of WAAS-assisted approach. This includes operations in regions outside U.S. national airspace. The LPV service volume is naturally limited by the coverage of the ionospheric corrections (because LPV users must apply these corrections). The WAAS integrity requirements are met everywhere within the GEO footprints.

New Satellites. In July 2007, two GEO satellites replaced the legacy IOC Inmarsat Atlantic Ocean Region West (AOR-W) and Pacific Ocean Region (POR) GEO satellites. Pseudorandom noise code (PRN) 135 is assigned to the Galaxy 15 satellite (FAA designator Central Region West or CRW) operated by Intelsat and positioned at 133°W. PRN 138 is assigned to the Anik F1R satellite (FAA designator Central Region East or CRE) operated by Telesat (formerly Telesat Canada) and positioned at 107°W. The new satellites will provide superior ranging capabilities compared to the IOC GEO satellites and ensure that all WAAS users have dual GEO coverage (a significant reliability improvement). **FIGURE 2** shows the footprints of the two GEO satellites.

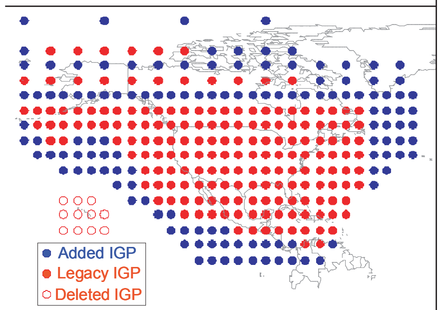
New Stations. In June 2006, an additional Master Station was integrated into the system. The additional Master Station ensures that WAAS will always have at least two Master Stations operational even when one Master Station is down for routine maintenance or upgrades.



▲ **FIGURE 2** WAAS GEO satellite footprints



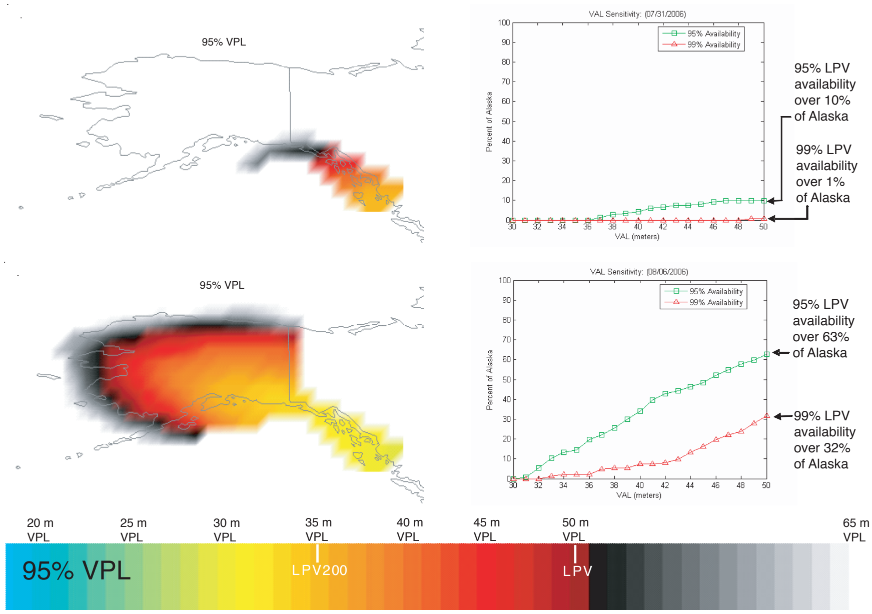
▲ **FIGURE 3** Legacy and 13 additional WAAS reference stations



▲ **FIGURE 4** Updated ionospheric grid-point locations

All reference stations in the system have been upgraded to use a new GPS receiver that provides detailed information about GPS signal quality for use in an enhanced signal-quality monitoring algorithm.

Thirteen additional reference stations (see **FIGURE 3**) have been installed to improve availability in CONUS, Alaska, Mexico, and Canada. The four Alaskan stations were cut over into the system in August 2006 and the Mexican and Canadian stations in September 2007. To take advantage of the new reference stations, the ionospheric grid mask has been expanded to cover all of North America (see **FIGURE 4**). **FIGURE 5** shows the availability improvement realized when the Alaskan reference stations were integrated into the system. The performance in Alaska is described by two plots. The first (left) graph shows a 95% bound on the VPL. A red color at a particular location indicates that the VPL is less than or equal to 50 meters during 95% of the day. When the VPL is less than 50 meters and the HPL is less than 40 meters, a user can perform an LPV approach with a 250-foot decision height (see the "Navigating Aircraft with GPS and WAAS" sidebar for an explanation of decision height). Since the VPL is almost always larger than the HPL, the VPL alone is a good indicator of system performance. The second graph shows the percent of the CONUS and Alaska region, which achieves various VPLs for 95% and 99% of the day.



▲ **FIGURE 5** Performance improvement in Alaska from additional reference stations

WAAS Shadows

Whenever possible, each release of new capabilities is integrated into the system without interrupting WAAS service. Raytheon has developed a sophisticated set of five WAAS "Shadow Systems" which mimic the fielded system and allow a thorough end-to-end test of all software, hardware, and cut-over procedures. The shadow systems are capable of linking together reference stations, master stations, and GEO uplink stations. Network traffic from the operational WAAS is fed into Raytheon's facility in Fullerton, California, where it is filtered and processed as if it went through a fielded master station. The actual output WAAS message is internally looped back into the system and inserted into the WRS data as if the messages were broadcast from a live GEO satellite. Each shadow system along with the fielded system is monitored with a set of automated tools that look at

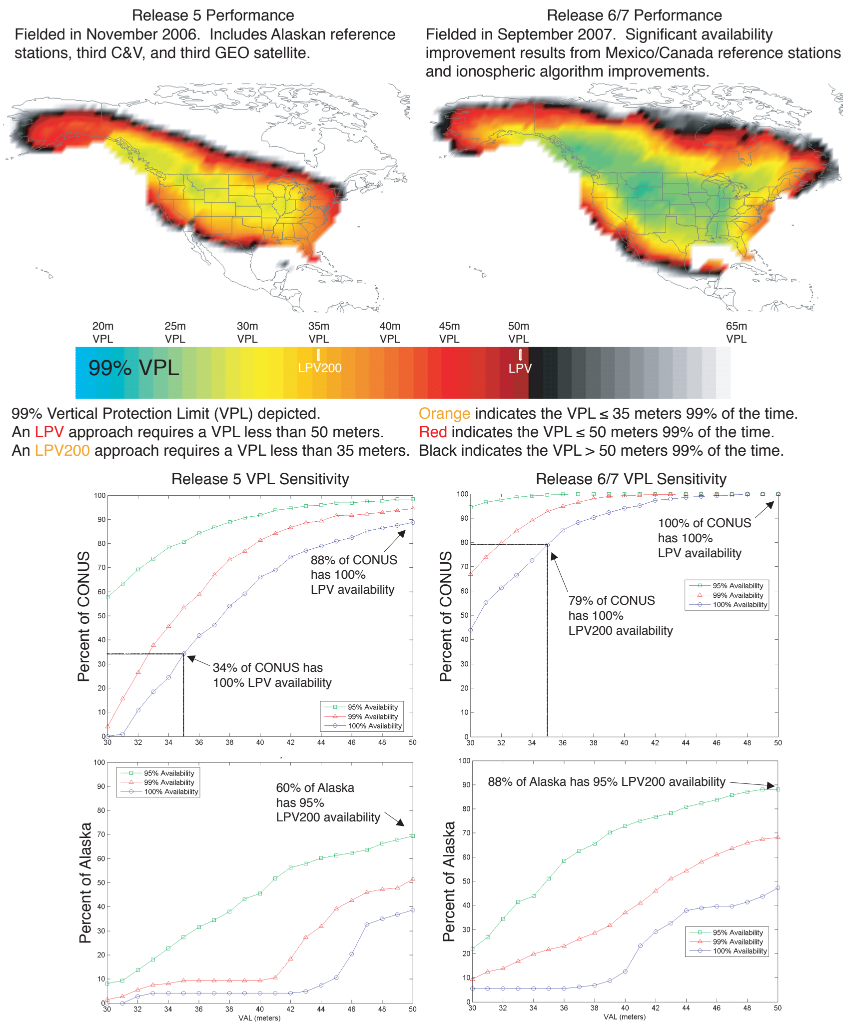
Navigating Aircraft with GPS and WAAS

Before the advent of GPS, a common procedure for aircraft navigating from point A to point B was to fly over navigation beacons in a doglegged sequence of route segments. With GPS in place, direct "straight line" routes from A to B could be planned and flown. Such navigation procedures are known as area navigation or RNAV. Unaugmented GPS is capable of providing RNAV enroute and terminal navigation to position an aircraft in the vicinity of an airport.

For landing, an aircraft's electronics switches to approach navigation. Traditionally, approaches are classified as either precision or nonprecision, depending on the accuracy and capabilities of the navigational aids used. Precision approaches use both lateral (course) and vertical (glide slope) guidance to a decision height. If the required visual references, such as the approach lights or the runway environment, are not in view at this height, the pilot must fly a "missed approach," which is a specified, controlled routing away from the runway.

Nonprecision approaches provide lateral course guidance only, using a "minimum descent height." This height is defined as the height below which an aircraft must not descend until visual reference has been established, typically between 250 and 500 feet (aviation operations in the U.S. and elsewhere normally use imperial units), depending on the particular airport. Unaugmented GPS is capable of providing a non-precision approach, now referred to as lateral navigation (LNAV). On an LNAV approach, the pilot flies the final approach using lateral guidance, but when the aircraft reaches the final approach fix, the pilot descends to a minimum descent height using the barometric altimeter. WAAS provides the additional capability for aircraft to use GPS for vertical navigation (VNAV), hence the ability to fly LNAV/VNAV approaches. LNAV/VNAV is an approach in which a vertical glide slope guides the aircraft to a distance of about 3800 feet before the runway threshold at an average decision height of 350 feet.

WAAS permits aircraft to fly to even lower minimum decision heights using Localizer Performance with Vertical Guidance (LPV). An LPV approach use lateral guidance from WAAS and vertical guidance provided by either the barometric altimeter or WAAS. An LPV approach enables descent to 200–250 feet above the runway, and can only be flown with a WAAS receiver. An LPV approach with a 200-foot decision height is sometimes called an LPV200 approach. LPV approaches are operationally equivalent to the legacy Instrument Landing System Category I approaches but do not require any navigation infrastructure to be installed at the runway. In November 2007, a total of 964 published LPV approach procedures and 1224 LNAV/VNAV approach procedures were available for use in the United States.



▲ **FIGURE 6** WAAS performance summary for Release 5 (November 2006) and Release 6/7 (September 2007) as determined using shadow test systems

every aspect of system performance.

To facilitate testing new reference stations, data from Alaska, Mexico, and Canada were sent to Raytheon's facilities many months before the new reference stations were cut over into the operational system. This allowed the data from the reference stations to be tested without any impact on the operational system.

Any time a shadow system disagrees with the operational system or abnormal system behavior is observed, an anomaly is entered into a database and tracked until it is resolved. A WAAS build has generally been tested for four or more months on a shadow system prior to fielding. Test engineers practice all cutover procedures on the shadow systems prior to fielding a change. This rigorous testing methodology ensures that there will be no surprises when a release goes to the field. Each release is fielded without interrupting WAAS service.

In September 2007, a series of algorithm improvements were implemented in the system that significantly improve availability by lowering the HPL and VPL. The development of these improvements was a joint effort among the members of the WAAS Integrity Performance Panel (WIPP). The WIPP is a group of experts assembled by the FAA to provide technical oversight on the development of the WAAS algorithms. The WIPP is composed of members from Stanford University, Jet Propulsion Laboratory, Mitre Corporation, Zeta Associates, and Raytheon.

The most significant of these enhancements affect the computation of the ionospheric corrections and integrity bounds. The WAAS GIVE monitor computes the ionospheric delay corrections at the WAAS grid points. Along with the correction, an integrity bound (GIVE) is calculated. The accuracy of the correction affects the accuracy of the user's position solution. The size of the GIVE impacts system availability. Large GIVEs result in large HPLs and VPLs. When the HPL or VPL exceeds the HAL or VAL at a particular location, the service becomes unavailable. If this happens during an approach, the pilot must execute a missed-approach procedure.

The GIVE monitor computes ionospheric delay estimates at a particular grid point by fitting a plane to delay measurements at the ionospheric pierce points surrounding the grid point as observed by WRSs. (A pierce point is the location of the intercept of a satellite-receiver ray path with a thin shell representation of the actual ionosphere.) The uncertainty in the fit is a function of the geometry of the pierce points, the measurement noise, and the nominal planar fit decorrelation observed during quiet ionospheric conditions. The planar model is tightly coupled with the WAAS irregularity detector, which performs a "goodness of fit" test and inflates the GIVE to 45 meters when a threshold is exceeded. A 45-meter GIVE is not useful to LPV users, so in most cases trips of the irregularity detector cause a loss of availability. To protect users from conditions when the irregularity detector is "near tripping," the uncertainty in the planar fit is multiplied by an additional inflation factor.

The irregularity detector does an excellent job of testing the planarity of the ionosphere in regions with lots of pierce points. However, many satellite geometries exist where an ionospheric storm may not be sampled by WAAS but may be sampled by a user. The WAAS undersampled threat model inflates the GIVE when the ionospheric grid point is not well sampled.

The model is generated from a conservative analysis of the worst ionospheric storms witnessed during a solar maximum period (near the peak of the approximately 11-year sunspot cycle). The irregularity detector is an integral part of the model. When the irregularity detector trips, the data is pruned out of the model. Without the irregularity detector, the model would be significantly worse. A more detailed description of the undersampled threat model along with its values is given in a research paper authored by JPL's Lawrence Sparks and colleagues (see Further Reading).

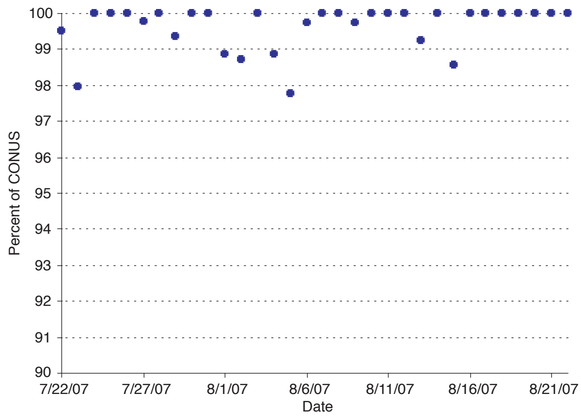
Stormy (Space) Weather

In October and November 2003, a series of intense ionospheric storms adversely affected single-frequency GPS users all over the world. WAAS was operational during these storms and, as expected, the ionospheric storm detector disabled LPV operations throughout CONUS. A thorough analysis of the storm concluded that these conservative measures were justified and WAAS users were protected from the effects of the storm. (See the paper by Habereder et al. listed in Further Reading for more details).

The WAAS integrity requirement must be met in all regions where a user can perform an LPV approach. Along the edge of coverage, it is possible for ionospheric effects to trickle in that have not been well sampled by the reference stations. During extreme storms, these effects can be significantly worse than previously observed. To address this concern, WAAS has added an "extreme storm detector." The extreme storm detector will detect extreme ionospheric storms and disable availability everywhere in the WAAS service region. The detector has been carefully tuned to only trip during significant ionospheric disturbances like those in October and November 2003 and July 2000. Such events are rare and do not seriously affect the overall availability and continuity of the system.

Current Performance and Future

The recent enhancements significantly improve WAAS availability everywhere in North America. A summary of the system performance is given in **FIGURE 6** and in Table 2. The map graphics show a 99% bound on the VPL. A red color at a particular location indicates that the VPL is less than or equal to 50 meters during 99% of the day. Orange means that the VPL is less than 35 meters 99% of the day, which indicates that an LPV200 approach is available 99% of the day. The second graph shows the percent of the CONUS and Alaska region, which achieves various VPLs during 95, 99, and 100% of the day.



▲ **FIGURE 7** Thirty-one days of shadow test results showing the percent of CONUS achieving 100% LPV availability

Although the results indicated show the performance for a particular day (August 22, 2007 — measured from the shadow test system running Release 6/7) , extensive testing over the past several months has shown that WAAS will have outstanding LPV availability over all of CONUS and Alaska. An analysis of 31 continuous days (July 22 to August 22, 2007) of availability data collected from the shadow system showed that more than 98% of CONUS achieved 100% LPV availability each day (see **FIGURE 7**).

Further availability improvements are planned for a release towards the last quarter of 2008. These enhancements include implementation of the enhanced signal quality monitor, expanded ionospheric grid-point coverage in the Alaska region, and several other software improvements that will further improve coverage in Mexico. Analysis to date shows WAAS will meet all of its performance goals (listed in Tables 1 and 2) with margin by the end of 2008 offering LPV service to most of North America and LPV200 service to most of CONUS.

TIMOTHY SCHEMPP is an engineering fellow with Raytheon Company in Fullerton, California. He holds a master's degree in applied mathematics from California State University, Fullerton, and is currently the technical director for the Wide Area Augmentation System project.

FURTHER READING

■ Development of WAAS

"The NSTB: A Stepping Stone to WAAS" by Andrew Hansen in *GPS World,* Vol. 9, No. 6, June 1998, pp. 73–77.

■ WAAS Standards

Minimum Operational Performance Standards for Global Positioning/ Wide Area Augmentation System Airborne Equipment, RTCA/DO-229D, prepared by SC-159, RTCA Inc., Washington, D.C., December 13, 2006.

■ FAA WAAS Monitoring Web Site

William J. Hughes Technical Center WAAS Test Team: www.nstb.tc.faa.gov

■ GPS Signal Waveform Distortion

"Impact of Evil Waveforms on GBAS Performance" by C. Macabiau and E. Chatre in *Proceedings of PLANS 2000, IEEE Position, Location and Navigation Symposium,* San Diego, California, March 13–16, 2000, pp. 22–29.

"Robust Signal Quality Monitoring and Detection of Evil Waveforms" by R.E. Phelts, D.M. Akos, and P. Enge in *Proceedings of ION GPS-2000, the 13th International Technical Meeting of the Satellite Division of The Institute of Navigation,* Salt Lake City, Utah, September 19–22, 2000, pp. 1180–1190.

■ Solar Effects on GPS

"GPS, the Ionosphere, and the Solar Maximum" by R.B. Langley in *GPS World,* Vol. 11, No. 7, July 2000, pp. 44–49.

■ Ionospheric Threat Model

"Extreme Ionospheric Storms and Their Impact on WAAS" by L. Sparks, A. Komjathy, and A.J. Mannucci in *Proceedings of IES2005, the 11th International Ionospheric Effects Symposium,* Alexandria, Virginia, May 3–5, 2005, paper A105.

■ WAAS Performance During Ionospheric Storms

"Current WAAS Performance and Expected Full Operational Capability Performance," by H. Habereder, T. Schempp, and M. Bailey in *Proceedings of European Navigation Conference GNSS 2004,* Rotterdam, May 16–19, 2004.

■ GPS Aircraft Navigation

"Aircraft Landings: The GPS Approach" by G. Dewar in *GPS World,* Vol. 10, No. 6, June 1999, pp. 68–74.