Development of Satellite Navigation for Aviation
(FAA Award No. 95-G-005)
Technical Description of Project and Results
Stanford University
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1.0 Introduction

This report describes the key elements and results of Stanford University's contribution to the development of the Wide Area Augmentation System (WAAS) and its underlying technologies. The Wide Area Augmentation System (WAAS) became the first operational space based augmentation system (SBAS) in July 2003. WAAS augments the Global Positioning System (GPS) with the following three services: integrity monitoring to improve safety; a ranging function to improve availability and continuity; and differential GPS corrections to improve accuracy. Thus augmented, GPS has the continuity required for enroute and terminal area flight. It also has the integrity required for vertical guidance during airport approach. WAAS also protects the aviation community from uncertainties in GPS satellite replenishment.

Stanford University played a key role in the early development and prototyping of WAAS. Stanford then became actively involved in implementing WAAS and establishing its initial safety certification. Later, Stanford played a significant role in the improvement of WAAS to the point that today it provides LPV service to 100% of CONUS and more than 95% of Alaska. Stanford has and will continue to play a very active role in the modernization of WAAS to incorporate the future GPS L5 signal and new GNSS constellations such as the European Galileo system.

2.0 1995-1999 Early Development through the NSTB

Before 1995, the Stanford GPS laboratory and its members were active in the initial development of WAAS. The first papers on real-time wide-area differential GPS were produced as part of Dr. Changdon Kee's thesis work under the guidance of Professor Bradford Parkinson. Professor Per Enge was one of the first co-chairs of RTCA SC-159 WG-2 on the development of the WAAS MOPS. In 1993, the FAA asked Stanford to participate in the National Satellite Test Bed (NSTB), the prototype for WAAS. Stanford established three West Coast reference stations and developed their own independent master station software. Towards the end of 1994, Stanford performed the first ever flight tests in which all of the error sources were fully separated and the individual components were all broadcast to the user.

For these reasons the FAA directed the Stanford University GPS laboratory to refine their master station and user avionics algorithms to support further flight testing and prototyping. In early 1995 the performance reliability was improved and many successful landings using the NSTB code were performed (see Figure 2-1). At that time the messages were transmitted to the user via a local VHF link as the geostationary

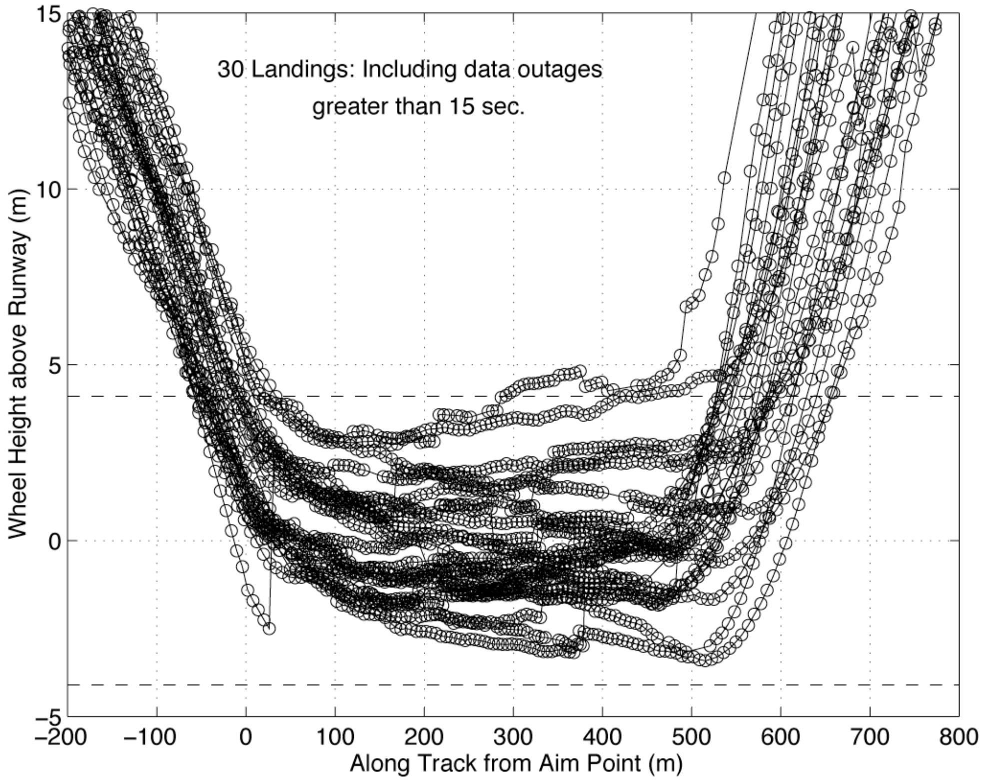

Figure 2-1. *Here the height of the wheels, as calculated by the wide-area differential GPS position solution, is shown versus the surveyed height of the runway for 30 separate landings performed during three different months. These results include periods of data where we had not received any differential correction data for more than 15 seconds. These outages were caused by difficulties with the local data link and are not inherent to the WAAS approach.*

satellites available at the time were at a different frequency from the GPS satellites and difficult to integrate into the system.

Early system accuracy was limited by the lack of redundancy in the NSTB reference stations, data loss in the VHF link, and limitations with the early algorithms. The NSTB algorithms developed by Stanford were deliberately kept simple to ensure that their fault modes could be fully analyzed. Although much more complex algorithms could provide greater accuracy, the simpler algorithms would be required to assure integrity. This approach would eventually find its way into WAAS, as the Corrections Processor (CP) uses uncertified complex algorithms to generate the corrections and the Safety Processor (SP) uses simple certified algorithms to determine the confidence bounds. The Stanford NSTB algorithms were similar to the SP approach.

As part of the ongoing integrity investigations Weighted Receiver Autonomous Integrity Monitoring (WRAIM) was proposed by Stanford as an evolution of previous RAIM techniques. Although originally proposed for vertical guidance to be used in combination with WAAS, the horizontal protection level calculation developed later became a standard implementation for use in non-differentially corrected avionics.

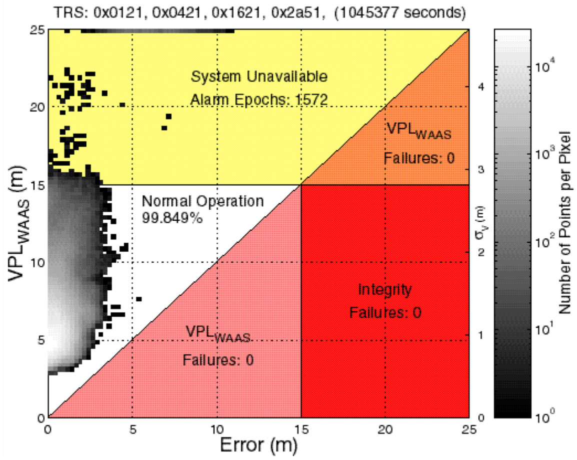

Figure 2-2. *This histogram shows the distribution of the true vertical error and the bound provided by the instantaneous VPL. The system is declared available when the VPL is below the VAL. At the time, the VAL was thought to be between 10 and 20 meters.*

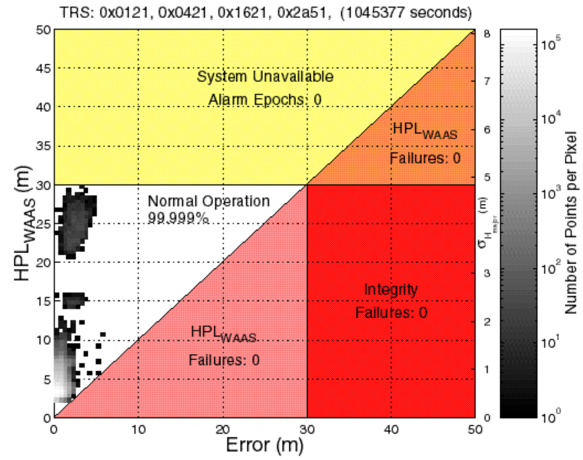

Figure 2-3. *This histogram shows the distribution of the true horizontal error and the bound provided by the instantaneous HPL. The system is declared available when the HPL is below the HAL. At the time, the HAL was thought to be between 30 and 50 meters.*

A critical outcome of prototyping and flight-testing was contribution to the development and validation of the WAAS MOPS. By evaluating different proposed algorithms in the aircraft and in the master station software, Stanford was able to validate many aspects of the WAAS MOPS and recommend changes where they were found deficient. Stanford made numerous recommendations affecting the message formats and content. In particular, improvements were made to the tropospheric correction and bound, ionospheric grid, ionospheric GIVE quantization levels, interpolation algorithms, IGP selection rules, and degradation of older message contents.

The most significant contribution to early MOPS development was the creation of the protection level approach and formulation that determines how integrity is maintained as well as affecting availability and continuity. The previous approach combined 99.9% bounds and neglected to protect against the rare normal fault. Instead, Stanford proposed bounding each error term with a Gaussian and basing the protection level on the square root of the sum of the variances. Research demonstrated that the new approach provided better integrity and still maintained sufficient availability. During this period Stanford created Appendices E (Weighted RAIM), J (Protection Level Formulation), and P (IGP selection rules) of RTCA DO-229. In addition, numerous contributions were made throughout Appendix A (Message Contents and Formats).

The continuing improvements made to the NSTB master station code and avionics allowed investigation into integrity threats affecting the system. Satellite errors such as clock run-off and ephemeris errors were investigated for the potential impact on users and the master station's ability to detect them. A six second outage affecting the Block II satellites was discovered and investigated for its impact on continuity. Stanford developed a means to display accuracy, integrity, and availability on a single chart that

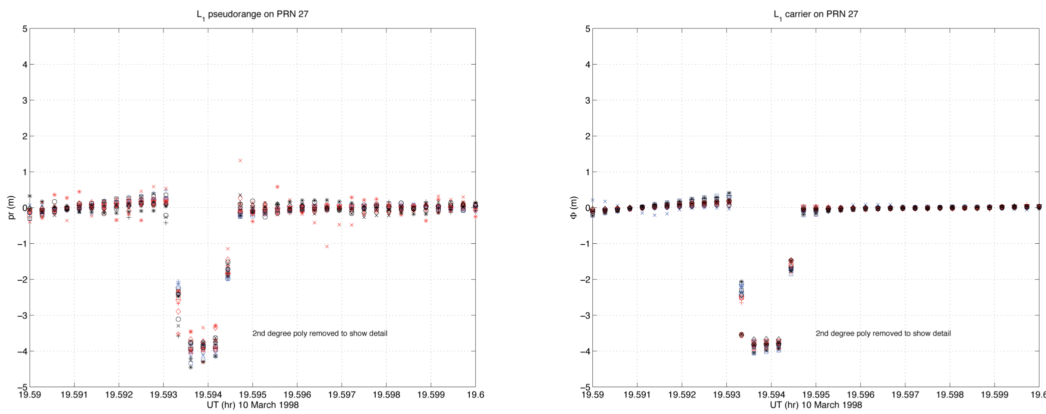

Figure 2-4. *The clock discontinuity on SVN 27 at 19:35:23 UTC 10 March 1998 measured approximately -4 m and lasted between five and six seconds. The right plot shows the effect on pseudorange for several receivers and the left plot shows the effect on carrier phase.*

was used to quickly get a sense of system performance over a given period (see Figure 2-2 and 2-3).

Because the NSTB was continuously monitoring the GPS satellites, new anomalies were observed and investigated. One occurred on March 10, 1998, when the clock on SVN 27 experienced a 4 m shift for a period of 5 seconds (see Figure 2-4). Prior to the NSTB, GPS anomalies that were this small and this short would likely have escaped detection. However, they are a potential source of integrity and continuity faults. With the NSTB master station algorithms performing at sub-meter accuracy levels, errors of this magnitude stood out and were flagged for further evaluation.

In 1998, L1 signals from the geostationary satellites became available, simplifying the airborne GPS/NSTB receiver and allowing for improved GEO ranging. Stanford further refined its GEO orbit estimation and GEO correction accuracy. Testing could now be conducted that would accurately reflect the expected performance of the operational configuration. The NSTB network had been extended to cover Alaska, and in the summer of 1998 Stanford undertook its most ambitious flight test trials.

The data from all of the NSTB reference stations was processed in real time using Stanford algorithms. Analytic models and filters were used to remove or calibrate reference station local errors such as tropospheric delay, multipath, and receiver inter-frequency bias. Every second, state-space filters computed estimates of the three primary errors: satellite clock, vector satellite ephemeris, and vertical ionospheric delay. The estimates and their associated confidences were then packaged in a 250 bps message according to the format defined in the RTCA WAAS MOPS. This 250 bps message was transmitted to the user every second with a total latency of raw GPS measurement to applied correction kept to less than 6 seconds. Meanwhile, information was displayed on the computer screen to assist the operator on the aircraft.

For the Alaska flight tests, the WAAS message stream was sent via ethernet to an Inmarsat uplink station in Santa Paula, California. The message was packed into a Gold-

Figure 2-5. *The test aircraft at Juneau airport and a view of the equipment inside.*

Code modulated carrier that was broadcast at L1 by the POR GEO satellite. Due to antenna/receiver configuration problems, only the Stanford master station and test aircraft could receive the POR signal. Consequently, no ranging capability was incorporated into the GEO signal for this particular set of trials. During one day, scheduling prevented access to the POR GEO. In such a case, the WAAS message stream was sent via modem to the Stanford flight-ops office at the Juneau airport. The message was then transmitted to the test aircraft by a VHF radio link operating at 112.25 MHz.

The test aircraft was a Beechcraft Queen Air operated by Sky Research, Inc. This twin-engine aircraft was outfitted with navigation, attitude, cockpit display, and video recording payloads. The first three payloads were products of ongoing Stanford research projects. To accommodate all of the hardware, three seats were replaced with equipment racks, and a multitude of GPS antennas were installed on the hull of the airplane. Photographs of the test aircraft are shown in Figure 2-5.

Of primary importance was the navigation payload. The computer was an industrial grade PC with a Pentium processor. A NovAtel GPSCard provided raw GPS measurements at 10 Hz as well as the GPS navigation messages. A NovAtel Millenium collected the 250 bps WAAS messages at 1 Hz from the GEO signal. The maximum rate of the Millenium was 4 Hz. Nominally this would be sufficient, but the 10 Hz GPSCard was required for the cockpit display. WAAS corrections were extracted from WAAS message packets. Navigation software developed at Stanford applied the WAAS corrections to the GPS measurements and produced position and velocity solutions at 10 Hz. Information regarding the visible satellites, WAAS status, and position and velocity were sent to the screen. Raw GPS and WAAS data was logged to disk for later processing. A VHF radio modem was also used to receive the WAAS message in the absence of the GEO signal.

The entire flight test campaign took place August 1-12, 1998. The operations were based out of Juneau. The flight plan for each day typically consisted of a set of closed traffic patterns with varying final approach distances, published VFR and IFR approaches, and a precision approach used by Alaska Airlines (the only major passenger carrier in the region). In advance, a tunnel in space was programmed into the flight display computer for each approach. One pilot flew the airplane through the virtual tunnel using the cockpit

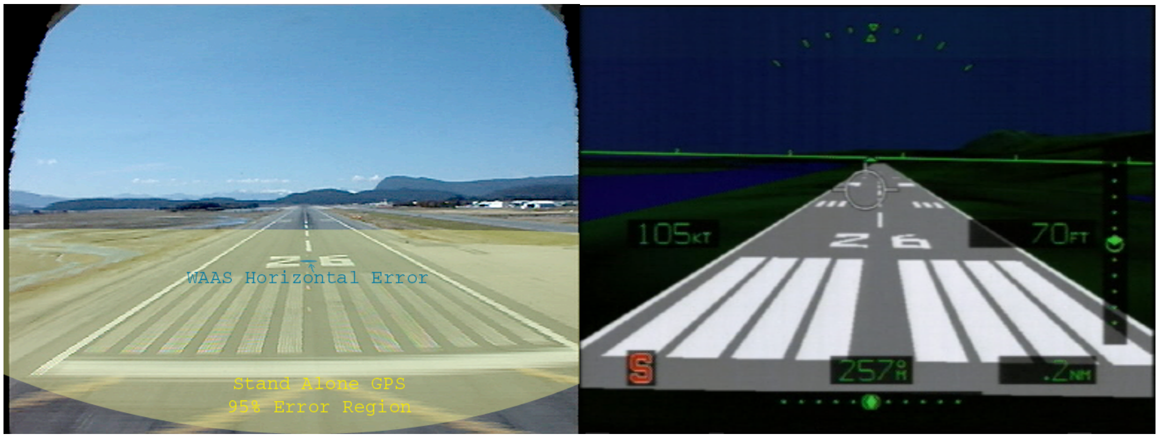

Figure 2-6. *The view out the nose-mounted camera is shown on the left and the view from the real-time cockpit display to the pilot is shown on the right in these synchronized frames.*

display, while the other pilot communicated with air traffic control and kept eyes out the window. In the interest of safety, all test operations were done under visual flight rules. There were four early days of good weather, August 2-5, during which a wide variety of approaches were flown at the Juneau International Airport. On August 8, a flight test was conducted at Sitka, a town approximately 140 km southeast of Juneau. Testing here was significant because an NSTB reference station was located at Sitka. This station was taken out of the real-time processing, and the GPS data was used later to derive carrier-smoothed DGPS truth trajectories of the aircraft. On August 11, another flight test was conducted in Sitka, as well as in Petersburg, roughly 200 km south of Juneau. Overall, 48 approaches were performed and approximately 24 hours of flight time were logged. Because NSTB and WAAS do not require equipment at the airfield, it was very easy to expand the flight testing and move to airfields that were not originally part of the original plan.

The flight tests provided Stanford with the first opportunity to examine NSTB guidance of an aircraft in Alaska. The Stanford algorithms performed smoothly without interruption and successfully guided the pilot and aircraft through a wide variety of approaches. Performance was demonstrated by comparing the virtual out-the-window cockpit display, which was driven by NSTB, with the actual nose mounted camera picture. This comparison is best done at the runway threshold when marker lines can be used as a reference. Figure 2-6 contains video captures of these two images. Based on measures of this type, NSTB horizontal accuracy was consistently better than 2 m for all landings in Alaska.

Visibility of the GEO satellite proved to be a non-issue. During straight and level flight as well as banked traffic pattern turns the GEO signal was never lost. To test GEO reception in extreme conditions, a series of wing-overs were flown. While correction messages from the GEO experienced short outages, WAAS positioning was sustained through roll angles of up to 45°. A brief 3 second WAAS outage was experienced at a 60° bank away from the GEO. Similar tests were also done off the California coast and the GEO reception did not differ significantly. The main cause is the POR GEO being at 178° West longitude, which is low on the horizon anywhere on the west coast.

Near this same time, Stanford hosted the first ever Interoperability Working Group (IWG) meeting between the FAA, the European Space Agency (the developers of a compatible system in Europe), and the Japanese Civil Aviation Bureau (JCAB who were developing a system in Japan). During this and subsequent meetings it was recognized that interoperability between these system would encourage user adoption. Although all systems had been designed to be compatible with the MOPS, different choices had been made by each system that prevented full interoperability. The IWG was able to resolve these issues and ensure that avionics that worked with WAAS would work equally well with the other systems.

The IWG also explored further cooperation to enhance service when flying from one SBAS to another. Stanford proposed and evaluated several methods to combine information at either the master stations or in the aircraft to enhance performance. These investigations revealed that most of the benefit for operations between SBASs could be obtained by combining pseudoranges at the aircraft without the complexity of exchanging data between the master stations. The MOPS were then updated to enable this level of sharing.

3.0 2000 – 2003 Certification of WAAS

Prior to 2000, NSTB research and WAAS development were kept separate. However, an integrity fault during a pre-approval stage of WAAS caused the FAA to create a new group called the WAAS Integrity Performance Panel (WIPP) to oversee the safety analysis of WAAS. The group was co-chaired by Professor Per Enge and included experts from outside the FAA and their prime contractor, including additional members of the Stanford GPS Laboratory. The group began by examining the architecture of the system and identifying potential weaknesses. The group found that the certified Safety Processor (SP) section of the code required significant modifications to meet the stringent requirements for integrity. The experience gained through the NSTB and the prototype master station software was essential to the ultimate success of the WIPP.

A major effort focused on the GIVE generation. The GIVE is important because the ionosphere is the largest source of uncertainty affecting the user's position accuracy. It was shown that the nominal ionosphere over CONUS is well behaved and easily modeled by the MOPS grid. Figure 3-1 shows the difference in ionospheric measurements as a function of distance between them on a quiet day. A high level of performance would be achievable under quiet conditions. However, conditions were observed that are not well modeled by the grid. Figure 3-2 shows the difference between vertical delays as a function of distance for a disturbed day. Note the difference in scale between the two figures. A definition of irregular behavior was created. This definition was aimed at the WAAS MOPS broadcast mechanism and the internal ionospheric model was formulated to match. A method for identifying irregular behavior was derived and validated. This method conservatively assumes that the ionosphere is always distributed in the worst undetectable manner unless the chi-square statistic exceeds a threshold. When the chi-

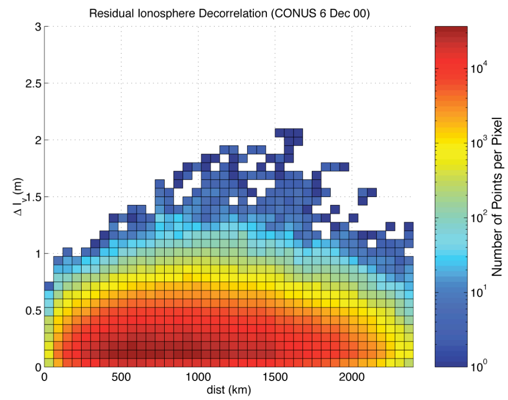

Figure 3-1. *A two dimensional histogram representing the distribution of differential vertical delays, after a planar fit has been removed, versus IPP separation. This data is for a quiet day. The bar at the right indicates the number of counts per square.*

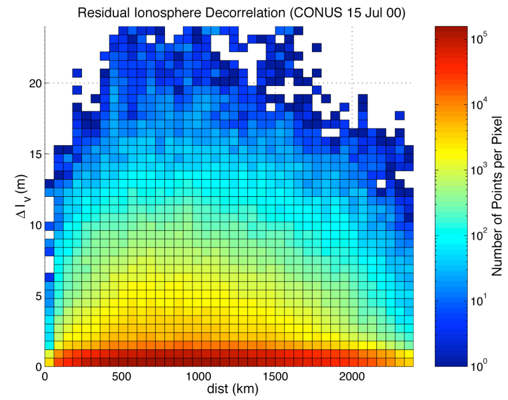

Figure 3-2. *A two dimensional histogram representing the distribution of differential vertical delays, after a planar fit has been removed, versus IPP separation. This data represents a disturbed day.*

square value is larger than the threshold, the bounding variance is increased even further. Thus, integrity is firmly maintained.

It was shown that for quiet days this method is exceedingly conservative. However, on severely disturbed days, the worst-case assumptions were approached and therefore necessary to protect the user. This algorithm preserved integrity even on the worst observed storm days of the current solar cycle. This algorithm was analytically derived before such storms took place and performed as expected when tested during these severe disturbances. A single empirical parameter was determined using data from quiet days. This algorithm was implemented on the operational system and found it to match expectations. In particular, the false alarm rates were better than the requirement for quiet days. By creating a detector that could distinguish between quiet and disturbed days, Stanford was able to provide an algorithm that met integrity but provided high availability on quiet days.

Another key component of the GIVE algorithm is the undersampled threat model. This accounts for the changes in the ionosphere that could occur outside of where the system actually has measurements. This model required careful design to protect against threats that had been actually observed without being so conservative as to deny all availability. This work was closely coordinated with many parties involved. Stanford made many significant contributions including the first version of the threat tool, the formulation of the threat, creation of deprivation schemes to determine the threat, and creation of metrics to characterize the threat.

Boston College had a subcontract from Stanford during this time and they also were key participants in the development of the ionospheric safety analysis and undersampled threat model. Their experience in the theoretical background in ionospheric physics was essential to ensuring that the models developed were consistent with the known physical understanding of the ionosphere. They also obtained and analyzed ionospheric data from

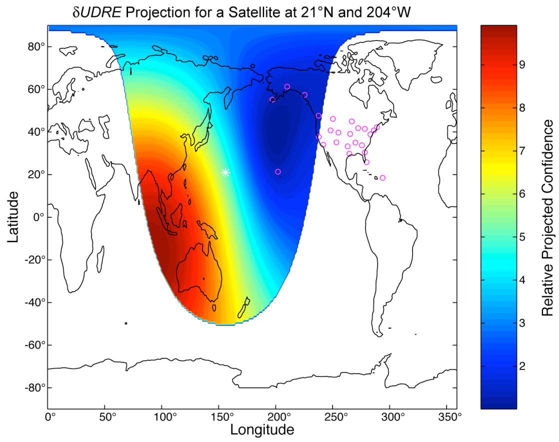

Figure 3-3. *Projected user confidence according to the normalized discretized Covariance matrix.*

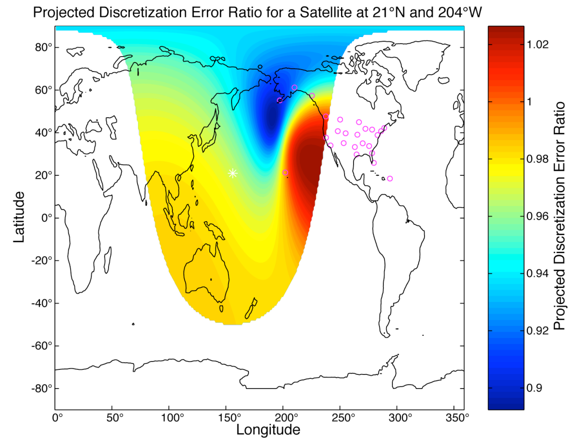

Figure 3-4. *Projected ratio of the full bandwidth covariance divided by the discretized value.*

locations around the world to help refine maximum vertical delay models, maximum ionospheric rate models, and the undersampled threat model.

The ionospheric algorithms followed the model of defining a threat model and then ensuring that the algorithms mitigated the threats with the required probability. This design criterion was applied to all other threats and algorithms. Prior to the WIPP, threat models had not been created to describe each feared event. The WIPP developed these threat models and then evolved or created anew algorithms to mitigate them. Stanford led the development of the GIVE algorithm, which is the most critical algorithm in WAAS, and was heavily involved in the development of the UDRE, CCC, and RDM monitors.

As part of the development of the UDRE monitor it was recognized that there was a problem with meeting the requirement to bound the error for the worst-case user within the service volume. As a solution, Stanford developed and recommended Message Type 28 containing a relative clock and ephemeris covariance matrix for individual satellites. From this matrix, users can reconstruct their location specific error bound rather than applying the largest bound in the service volume. Figure 3-3 shows the projected increase in UDRE as a function of location for a particular satellite location and reference station network. By transmitting this information to the user, two benefits are achieved: improved availability within the service volume and improved integrity in the region outside. Figure 3-4 shows the difference between the full covariance matrix projection (known to the master station) and the value that fits within the 250-bit message. This difference is addressed by slightly increasing the broadcast UDRE value.

Message Type 28 contains matrices for two satellites per message, and each message is broadcast at the same rate as the long-term corrections (Message Type 25). Message Type 28 was incorporated into WAAS and was adopted by RTCA and the International Civil Aviation Organization (ICAO) for inclusion in the MOPS and the international Standards And Recommended Procedures (SARPS).

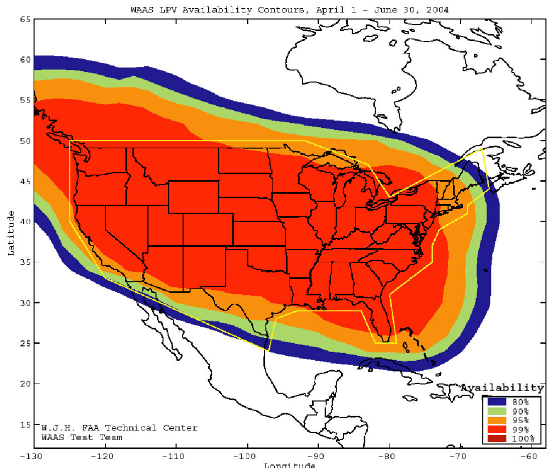

Figure 3-5. *Actual Performance of the WAAS as observed by the FAA William J. Hughes Technical Center. This represents a three month average of LPV availability from April 1-June 30, 2004*

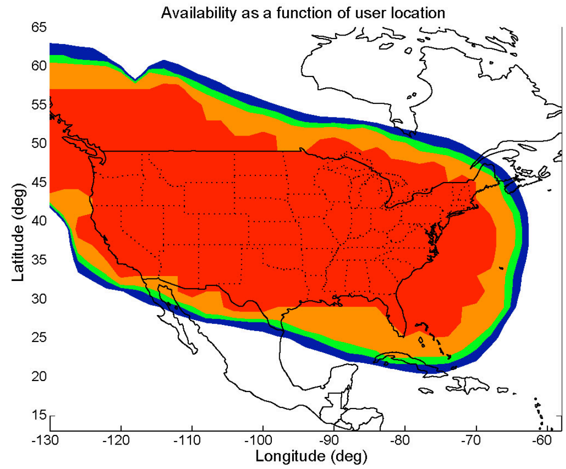

Figure 3-6. *Simulated results from MAAST. This represents a 24-hour average of LPV availability. Although slightly optimistic compared to actual performance, it is very representative.*

Message Type 28 improves both availability inside the service volume and integrity outside the service volume. Its application is relatively simple for the user and optional for the service provider. Reductions in the projected error bound to the user were shown to be between 25% and 35%.

The CCC monitor was developed to protect against a loss of coherency between the code and carrier signals. Stanford also demonstrated that it was effective in mitigating a most likely subset of signal deformation threats. The full signal deformation threat model had been developed earlier by Stanford and adopted by ICAO as part of the SARPS. The most likely subset was a subset of the full ICAO threat model that contained the threats most closely matching the known characteristics of the signal deformation fault observed on SVN-19 in 1993. A more comprehensive monitor that would mitigate the full ICAO threat model was planned and implemented in a later build of the WAAS software.

To facilitate the evaluation of the performance of different candidate algorithms, Stanford developed a MATLAB tool that could conduct SBAS availability analyses. This toolset includes simulation algorithms that are constantly being developed and updated. This tool set is called the MATLAB Availability Analysis Simulation Tool (MAAST). MAAST is a set of functions for use as a fast, accurate, and highly customizable experimental test bed for algorithm development. A user-friendly interface was developed for the tool. It is open source and can be downloaded from the Stanford WAAS web site (http://waas.stanford.edu). MAAST was used extensively to evaluate algorithmic effect on availability during WAAS development and is used by SBAS researchers around the world. Figures 3-5 and 3-6 demonstrate the fidelity of MAAST which can be run in less than an hour.

There are four major components of MAAST: confidence computation, simulation models, outputs, and the graphic user interface. The confidence computation of the toolset calculates UDRE, GIVE, troposphere confidence, and airborne confidence, and uses error estimation algorithms either currently implemented or proposed. Users can readily add and modify the algorithms that they are testing. The simulation models include the user location, WAAS reference station (WRS) location, satellite constellation options, etc. The outputs of the toolset include plots of availability, protection levels, UDRE and GIVE maps and histograms. The graphic user interface of this toolset allows the user to specify different options. It is user configurable and can be customized easily to fulfill research needs.

The most significant contribution during this phase of the program was the final documentation of the safety analysis of the full program against all threats. Stanford co-led the design, structure, and content of this document. The analysis evaluated the Probability of Hazardously Misleading Information (PHMI) and the document was called the PHMI document. Stanford outlined the arguments necessary to validate that each monitor would mitigate its full threat model to the required probability. Further, they provided many of the necessary analyses and arguments to support the safety analysis. Stanford also evaluated the validity of the arguments that they did not create. This document, that is more than 700 pages in length, was produced and validated in the first half of 2002. It represented a large cumulative effort on the part of all members of the WIPP. The PHMI document formed the basis behind the certification of the initial operating capability of WAAS and led to its commissioning in July 2003.

The Wide Area Augmentation System was unlike any previous navigation system fielded by the FAA. Historically, the FAA had implemented relatively simple and distributed systems. Each only affects a small portion of the airspace and each is maintained independently of the others. WAAS, in contrast, is a complex and centralized system that provides guidance to the whole airspace. Consequently, the certification for WAAS had to proceed very cautiously. WAAS was pursued because its benefits are significant. It provides guidance throughout the national airspace. It enables approaches with vertical guidance to nearly 1,600 runway ends in the United States without requiring local navigational aids. It will enable advanced procedures such as curved approaches and departures. Eventually, it will allow greater capacity through smaller separation standards. These and other benefits motivated the effort to create and certify this new type of system. Although the analysis became much more difficult than any previous system, WAAS had to maintain the same or higher level of safety than the prior infrastructure.

Another difference with WAAS is that it is inherently a non-stationary system. It relies on satellites that are constantly in motion and that may change their characteristics. Additionally, the propagation of the satellite signals varies with local conditions. Thus, the system has differing properties over time and space. However, the system requirements apply to each individual approach. In particular, the integrity requirement, that the confidence bound fails to contain the true error in fewer than one in ten million approaches, must apply to all users under all foreseeable operational conditions. A role of the WIPP was to independently assess the safety of WAAS and to recommend system improvements. To accomplish these tasks, the WIPP had to determine how to interpret the integrity requirement for WAAS, develop algorithms to meet this requirement, and ultimately validate them.

Primarily the WIPP quantified the degree to which WAAS mitigated the system vulnerabilities. Over the first two years, the WIPP changed the design of several system components where the system could not satisfactorily demonstrate the required level of integrity. As each threat was addressed, the WIPP built upon what it had learned.

Some of the main lessons that emerged from the WIPP are:

- The aviation integrity requirement of 10^{-7} per approach applies in principle to each and every approach. It is not an ensemble average over all conditions.
- For events where fault modes or rare events are not known, validated threat models are essential both to describe what the system protects against and to quantitatively assess how effectively it provides such protection.
- The system design must be shown to be safe against all fault modes and external threats, addressing the potential for latent faults just beneath the system's ability to detect them. Conventional non-aviation differential systems presume no failures exist until consistency checks fail.
- Analysis must take place primarily in the range or correction domain as opposed to solely in the position domain.
- The small numbers associated with integrity analysis are not intuitive. Careful analysis must take priority over anecdotal evidence.

With WAAS successfully commissioned, the program then turned to improving system performance and planning for future upgrades such as the GPS L5 signal and new GNSS constellations.

4.0 2004 – 2009 Enhancement of WAAS and Future Evolution

With WAAS successfully commissioned, Stanford turned its attention to improving system performance, preparing for the eventual incorporation of the GPS L5 and Galileo signals, and evaluating new candidate architectures to use satellite navigation. The coverage area of the initial implementation of WAAS was not as large as desired. In addition, the integrity changes required by the WIPP increased the user protection levels to where aircraft could only come to within 250 feet to the ground instead of the desired 200-foot minimums. Therefore, second and third generation safety monitors were planned to rapidly improve system performance.

Again Stanford led the development of the ionospheric algorithms. As these algorithms were the largest contributor to the protection levels, they had the greatest potential to improve performance through reductions in the GIVEs. Stanford developed the safe implementation of algorithms that would utilize real-time estimates of the chi-square values to lower the current estimate of ionospheric variability. Additionally, Stanford

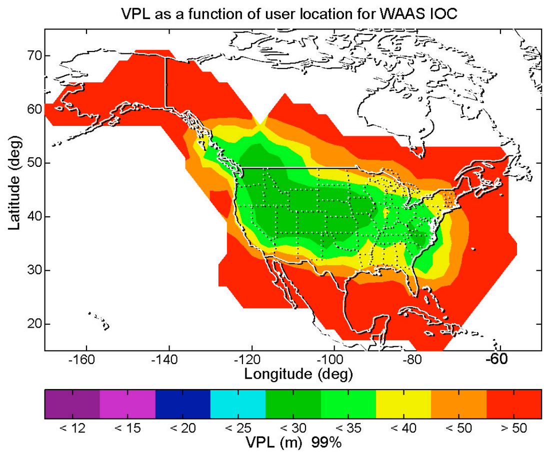

Figure 4-1. *The 99% VPL for initial WAAS. The orange region marks the boundary of where the VPL is 50 m or below 99% of the time.*

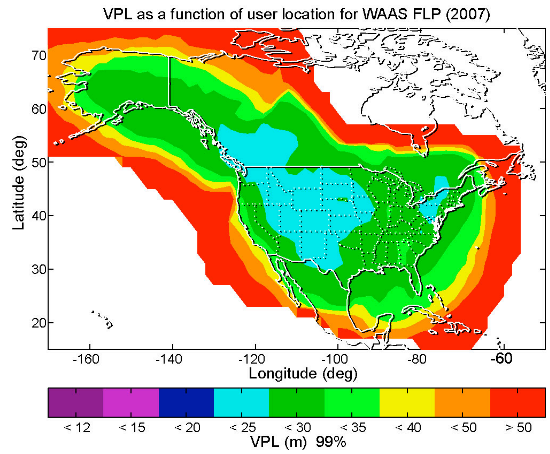

Figure 4-2. *The 99% VPL for WAAS in 2007. Now LPV-200 coverage (35 m or below VPL) extends to nearly all of CONUS and most of Alaska. However, the West Coast is still vulnerable to outages.*

determined new deprivation schemes for the undersampled threat that led to large reductions in the threat model.

In October and November of 2003, two of the largest ever observed ionospheric storms took place. WAAS successfully maintained integrity during these events, but subsequent analysis demonstrated that ionospheric behavior could be worse than had been previously believed. Stanford was a major part of a collaborative effort to investigate the physics and behavior of the ionosphere during these storms. This effort further developed the extreme storm detector for WAAS. When tripped, this monitor will increase all GIVEs to 45 m for at least 8 hours. This has the effect of removing vertical guidance service while retaining horizontal guidance for WAAS users. However, it will guarantee safety during even the worst of anticipated future ionospheric disturbances while improving performance during non-disturbed periods. Since the ionosphere over the United States is not disturbed more than 99.8% of the time, this has the benefit of significant improvement to WAAS availability and coverage.

Stanford also applied a technique called Kriging to ionospheric estimation and demonstrated that it could offer improved performance during mildly disturbed conditions. The rigorous analysis that accompanied Kriging allowed other improvements to be properly analyzed and included in the operational system. Together these improvements significantly lowered the GIVE values both at the center of CONUS and at the edges of coverage. At the same time, the algorithm was shown to provide the required margin of safety.

The FAA determined that with a modest reduction to the Alert Limits, a 200-foot operational minimum could be achieved. The improvements to the GIVEs provided good coverage for this new 200-foot service called LPV-200. The introduction of LPV-200 allowed WAAS to meet its originally stated goal for service provision. The addition of new reference stations in Alaska, Canada, and Mexico allowed WAAS to extend its coverage area beyond its originally stated goals. Figures 4-1 and 4-2 show the MAAST predicted availability for the initial implementation of WAAS and the version available in late 2007. The actual availability closely matched these predictions.

The extension into new areas required scrutiny of the ionospheric behavior at both high and low latitudes. The contributions of both Boston College and Stanford were essential to demonstrating the safety of the WAAS ionospheric algorithms in these expanded regions. Data from these areas during the previous ionospheric solar maximum was obtained and analyzed. Ionospheric threats were evaluated compared to the assumptions built into the WAAS algorithms. It was found that for Southern Mexico the ionospheric behavior could become significantly worse. Therefore, IGPs below a certain line are not permitted to have GIVE values below 15 m. This preserves the performance of the more northerly grid points and yields excellent availability for Northern Mexico, CONUS, Canada, and Alaska.

A deferred action from the initial implementation of WAAS was the inclusion of a monitor that would protect against the full ICAO signal deformation threat model. New receivers were fielded that could make measurements at multiple spacings of the correlation peak. Stanford was entirely responsible for the design and analysis of this new algorithm. The new SQM monitor collects the raw correlation values from all reference stations and separates satellite signal variations from receiver biases to form a series of metrics that evaluate the relative behavior of all of the satellites in view. If a particular satellite has characteristics too different from the other satellites, its UDRE will be raised. A careful analysis links the observability that the network has at a given instant to the potential threat in the ICAO model. UDREs for satellites that are poorly observed may need to be increased as satellites rise and set over the network. However, it has been shown that the SQM monitor has negligible impact on availability while fully mitigating the full threat model.

While investigating signal deformations, it was observed by several researchers that the signals are not all nominally ideal. Each satellite has small deformations that cause small nearly constant differences between receivers. The magnitude of the difference depends upon the receiver filters and tracking loop implementation. Across the allowed user space in the MOPS, ranging differences as large as a meter or so were possible. Further, it was noticed that the signals of the geostationary satellites were even more different from the GPS satellite than they were from each other. Therefore, Stanford recommended and evaluated changes to the allowed user space to reduce the potential impact of these nominal deformations. Stanford created Appendix T for the WAAS MOPS and a receiver evaluation tool to ensure that receiver manufacturer designs would not excessively exacerbate the signal differences.

Appendix T models the differences in the geostationary and GPS satellite signals and evaluates the influence of the user’s filters and tracking loop implementation. The error must be less than 50 cm. Together with changes in the allowed user space, the worst affected receiver designs were eliminated from contention. Stanford had to coordinate with receiver manufacturers to determine what information could be exchanged without

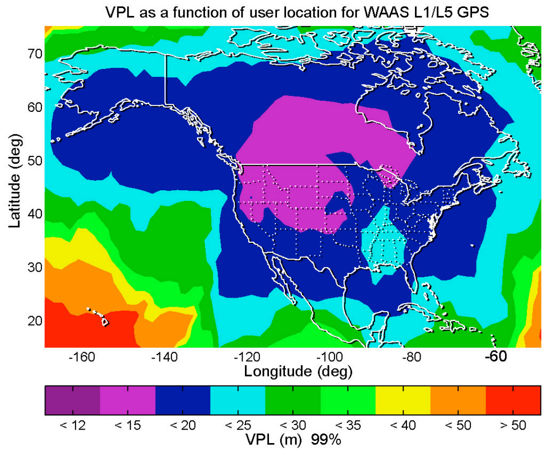

Figure 4-3. *The 99% VPL for a dual-frequency user using the current WAAS network.*

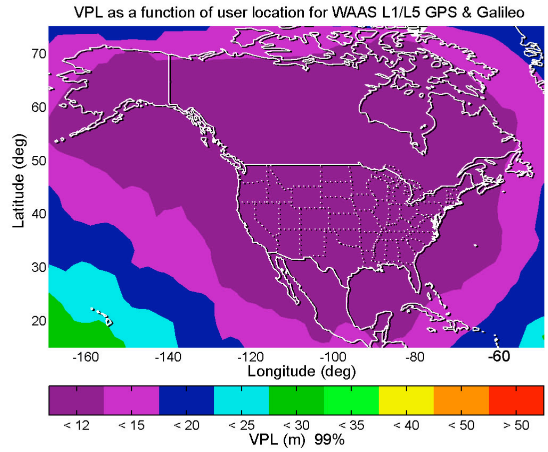

Figure 4-4. *The 99% VPL for a user with access to dual-frequency GPS and Galileo satellites.*

compromising their intellectual property and what tests they would accept. Further, it was necessary to ensure that none of the existing designs would be precluded from operation. These changes reduced the potential impact of signal deformations on the user community resulting in an increase in availability for WAAS and LAAS.

In order to extend the coverage of SBASs around the world, Stanford continued its participation in the IWG and met with scientists and civil aviation authorities from around the world to understand potential issues with implementing SBAS under different ionospheric conditions. Stanford hosted a workshop with representatives from Brazil and twice visited India to meet with their representatives. As part of this effort, Stanford and Boston College collected data from South America and analyzed the effect of the ionosphere on GPS signals there. Equatorial ionosphere behaves very differently than mid-latitude ionosphere. This effort discovered that the thin-shell ionospheric grid used by the MOPS is not well suited for the equatorial region. There, nearly every day is a disturbed day. Thus, significant changes to the estimation routines and the WAAS MOPS would be required to provide high availability for single frequency users in this region. Instead, it was recommended that these systems initially be developed for lateral navigation only and then when the GPS L5 signal becomes available have the users remove the ionospheric delays directly using the appropriate combination of the frequencies.

To this end, Stanford and Boston College also investigated scintillation effects to determine ionospheric effects on future dual frequency users. Scintillation studies are still ongoing as little adequate data is available from the previous solar maximum. However, recent work by Stanford indicates that if aviation receivers are able to reacquire signals quickly after a deep fade caused by scintillation and reintroduce the satellite's measurements back into the position solution update within one to two seconds, the overall impact of scintillation may not be as severe as previously feared. Thus, dual frequency operation appears to be a viable solution for providing SBAS coverage of vertical navigation throughout the world.

The GPS constellation will be modernized to meet future military and civil needs. A key new feature that will become available in the next 10 years is a second civil frequency. GPS L5 will be centered at 1176.45 MHz and will be in a protected aviation band. 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. Figure 4-3 shows the MAAST prediction for vertical performance for dual frequency WAAS users with the current network.

In addition to GPS modernization, there are plans to launch an independent European navigational satellite system called Galileo. Galileo is envisioned as being very similar to GPS in that each satellite provides ranging signals at or near the L1 and L5 frequencies with very similar modulations. It is envisioned that Galileo satellites will provide a service that is fully interoperable with the GPS civil signals. Thus, one can approximately model Galileo satellites as being equivalent to GPS satellites in different orbits. It is expected 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. Figure 4-4 shows the MAAST prediction for vertical performance for dual frequency GPS and Galileo WAAS users.

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.

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 ionospheric delay directly. Further, two frequencies offers protection against unintentional interference. If either frequency is lost, the user may revert to single frequency LPV-200. 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-200 coverage and providing improved continuity.

Thus, future single frequency users will experience high availability of LPV-200 service while dual frequency users will achieve Category I performance. We expect the upgraded WAAS to provide Category I service to all dual frequency users within the service volume. Additionally, it can provide LPV-200 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).

Stanford hosted and led a strategic planning meeting for the upgrade of WAAS to include L5. This meeting examined the potential upgrade paths and recommended a primary path with back-up strategy in case of GPS L5 launch delays. This plan is still in progress as the next generation receivers are being procured and the terrestrial communication links are being upgraded. Stanford is also leading the effort for the development of the L5 user MOPS that will specify what information will be broadcast to the users and how it will all be combined to form position estimates and protection levels.

In 2006, Stanford was asked to form and co-chair the GPS Evolutionary Architecture Study (GEAS) to look into future architectures to provide global aviation service. The GEAS determined that Time-to-Alert (TTA) will be one of the more difficult challenges for any global monitoring approach. The GEAS has focused on two classes of architecture: one where the integrity assurance is entirely external to the aircraft, and one where the aircraft exploits redundant signals to meet the TTA requirement. In the first class, integrity messages are broadcast to the airplane within the TTA. For the analysis, all such architectures that achieve this are labeled GPS Integrity Channels (GICs). The key feature of a GIC is that the signals arriving at the aircraft contain integrity information that meets the TTA on their own. The aircraft does not perform a separate evaluation requiring redundant signals.

The other general architecture still has integrity information arriving at the aircraft. However, this information arrives outside of the TTA requirement. The aircraft must make its own integrity determination using this delayed information combined with its current measurements. The GEAS looked at two methods, each of which transfers some of the TTA responsibility onto the aircraft. The first method is called Relative RAIM (RRAIM). It uses precise carrier phase measurements to propagate older code based position solutions forward in time. The veracity of the propagation is checked using RAIM on the very low noise carrier phase measurements. In this way, the overall TTA can be less than a second, but the ground is given tens of seconds to minutes to identify the fault.

The second method is Absolute RAIM (ARAIM). This is more similar to existing FDE techniques except that the requirements must be made much more precise in order to support smaller alert limits. Again, the aircraft is able to raise a flag within seconds of receiving faulty data. The ground is allowed to take an hour or longer to identify the fault and remove it from future consideration. The protection level equations for both methods have been proposed and developed with Stanford leading an effort looking at ARAIM. In addition to the errors considered in previous protection level equations, the two new methods include explicit bias terms to improve the handling of nominal biases and non-Gaussian error sources.

A critical parameter in the performance of these approaches is the strength of the constellation. The performance of each approach was evaluated for constellations optimized for 24, 27, and 30 satellites. Further, their performance was evaluated under conditions of satellite outages. RRAIM can perform very well with fewer satellites.

	Satellite constellation	Satellite constellation	Satellite constellation	Satellite constellation	Satellite constellation	Satellite constellation
Architecture	**24 minus significant SV**	**24**	**27 minus significant SV**	**27**	**30 minus significant SV**	**30**
GIC	**Limited**	**100%**	**High**	**100%**	**100%**	**100%**
RRAIM short latency	**Limited**	**High**	**High**	**100%**	**100%**	**100%**
RRAIM long latency	**Limited**	**Limited**	**Limited**	**High**	**High**	**100%**
ARAIM	**Poor**	**Poor**	**Poor**	**High**	**High**	**100%**

Table 4-1. *The fraction of the earth that achieves 99.5% availability or better for the different architectures as a function of constellation is indicated in this table. Three constellations, optimized for 24, 27, and 30 satellites, were considered in the study. To further investigate sensitivity to the satellite geometry, a satellite was removed from each constellation that had a significant impact on availability. As can be seen in this table, the GIC architectures operate well with 24 or more satellite constellations. ARAIM requires many more satellites to achieve the same performance. RRAIM sits in between. For short times, it is comparable to GIC, for longer times it is closer to ARAIM. All are vulnerable to outages. It is interesting to note that a constellation optimized for 27, but missing an important satellite, performs worse than the constellation optimized for 24 despite having more satellites. Thus, it is not simply a question of the number of ranging sources. Their distribution is also very important.*

ARAIM, on the other hand, is ideal for including Galileo or other satellite constellations. Both of the methods show great promise for providing global vertical guidance.

The preliminary conclusions of the first phase of GEAS were that it is possible to gain some relief against the six-second TTA requirement through the use of RAIM. However, this relief comes at a cost. The number of satellites needed to support high availability RAIM is greater than for a GIC architecture (see Table 4-1). While GIC provides high availability with the current constellation, either of the RAIM solutions will require more satellites. RRAIM with short latency can come close to GIC performance and only requires a few more satellites. RRAIM with long latency and ARAIM both require something approaching 30 satellites to achieve very high availability.

Of course, it is not just a matter of the number of satellites. The current constellation has 32 satellites. However, they are not optimally arranged and several may be marked unhealthy at a given time. This constellation matches the one optimized for 24 satellites and the extra eight are merely redundant to certain positions. To truly take advantage of the extra satellites, we would need them more optimally placed for the larger number. As can be seen in Table 4-1, 26 satellites sub-optimally arranged perform worse than 24 optimally placed.

In 2007, the FAA asked Stanford to participate in the evaluation of integrity to be provided on the next generation of GPS satellites. Stanford started working with the Air Force's GPS-Wing to join their Positioning Signal Integrity and Continuity Analysis (PSICA) team. As part of this team, Stanford evaluated the threats that originate in either the GPS ground or space segment and how best to characterize and bound them.

Stanford participated in the analysis of the specified requirements for the contractors who would develop these two segments and identified several areas that needed improvement. Many of these areas were related to lessons learned while developing WAAS.

The specifications were deficient in the areas of signal deformations, integrity bounding of the ranging signals, and combination of the bounding information to form the protection level. In combination with the GEAS, Stanford recommended new protection level formulas that built upon those used by WAAS. Specific improvements included explicit bias terms to handle the small biases present in the system as well as non-Gaussian behavior of the different errors. The protection level equations can be optimized for availability depending on the actual characteristics of the errors.

Stanford recommended a specific method for monitoring conformity of the signals to the required performance to maintain integrity. This method cleanly separates the errors that are due to the ground and space segments of GPS from all other error sources. It addresses errors on each individual satellite as well as the convolved error across multiple satellites. Most importantly the evaluations are unambiguous in their formation and explicitly state how to interpret event probabilities. These evaluations are now being implemented by Stanford and other GEAS members to determine their actual performance. Once refined and finalized they may be applied to other constellations to evaluate their performance as well. These tests are closely linked to the protection level formulations and each may be modified to optimize availability.

The end result of this period was to improve WAAS performance dramatically to offer LPV-200 throughout most of CONUS and Alaska and to prepare for the eventual transition to GPS L5. These evaluations apply throughout the whole globe and not just North America. In addition, new architectures have been evaluated to determine the critical benefits and limitations of using Galileo and a safety certified GPS III constellation in the future. Several alternate architectures have been evaluated and their key performance parameters identified.

5.0 Operational Benefits

Stanford also investigated the benefit of integrating WAAS positioning with attitude, terrain models, and other information to create accurate three-dimensional displays for the pilot. These displays describe the environment in a much more intuitive fashion and could integrate the information on multiple existing displays into one easily understood representation. These displays were implemented in real-time and were flown on the same flight tests that were used to evaluate the performance of the NSTB. Figure 5-1 shows conventional instrument displays on the left and an early form of the 3-D display on the right.

Design of the display was a compromise between including enough information for the pilot to perform the flying task and preventing excess clutter. The Tunnel-in-the-Sky display, shown in Figure 5-1, was designed to aid aircrews by providing an "out the window" view of the world, allowing the horizon, runway, and desired flight path to be seen even in instrument flying conditions. The display presented an artificial horizon along with numerical readouts of groundspeed, heading, and altitude. Raw horizontal and vertical deviation information was displayed on scales similar to the familiar localizer and glideslope needles. The perspective field of view was 40 deg horizontal by 50 deg vertical, with the approach and missed approach paths depicted as a series of 100-m wide by 60-m tall "hoops" spaced at 200-m intervals. Trajectories were stored as sequences of segments with constant turn radii (including straight segments) and constant climb gradients (including constant-altitude flight or descents).

Enhancing aircrew situational awareness has become recognized as a critical element in the reduction of overall aircraft accident rates. Even highly trained crews of well-equipped transport aircraft occasionally lose awareness of the aircraft's position relative to terrain or the desired flight path. Synthesis of this "big picture" is sometimes referred to as "situational awareness" - an understanding of where the aircraft is relative to important features such as desired flight path, terrain, and traffic. Improved display concepts have been investigated as a means of enhancing awareness of position, flight

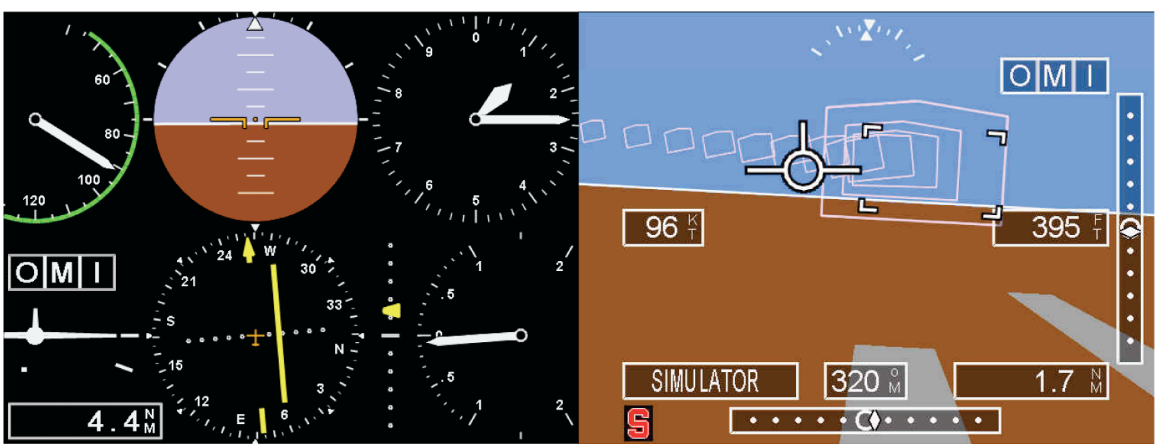

Figure 5-1. *A conventional set of instrument displays is shown on the left and the more intuitive 3-D display on the right.*

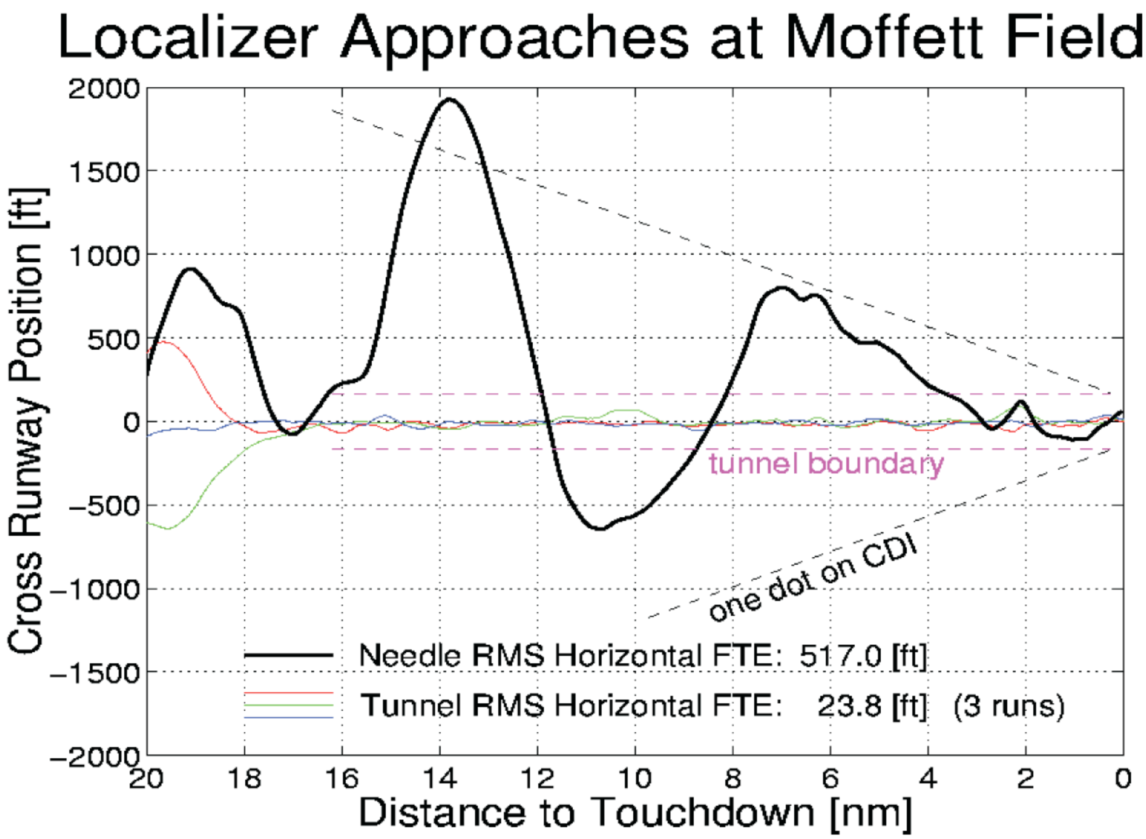

Figure 5-2. *Hand-flown approaches into Moffett Field are shown in black using the conventional ILS needle flown very accurately and the others using the tunnel to provide guidance to the pilot.*

path, and terrain in three dimensions. The prototype system was developed to explore the real-world implications of the Tunnel-in-the-Sky display concept. A series of tunnel "overlay approaches" was designed on top of existing published instrument procedures to demonstrate advantages for non-precision approaches, closely spaced parallel approaches, and noise abatement. Results indicated an order of magnitude reduction in cumulative flight technical error on approach. The flight tests also showed that Tunnel-in-the-Sky displays could improve aircrew situational awareness and operational flexibility during these flight operations.

Early work focused on Tunnel-in-the-Sky presentations to the pilot to provide guidance for many different kinds of paths and reduce Flight Technical Error (FTE) of the hand-flown aircraft. Studies also included effects of situational awareness and pilot workload using the perspective display and conventional instruments. It was demonstrated that FTE could be dramatically reduced with the perspective display. In Figure 5-2 it can be seen that in one instance, the tunnel reduced FTE from 517 ft down to 23.8 ft.

Later work added terrain information cues to help the pilot recognize and avoid the surrounding terrain. Additionally, complex curved paths were created and presented to the pilot as a highway-in-the-sky. These were tested in Alaska in conjunction with the NSTB tests. The complex paths were generated ahead of time and displayed to the pilot in real-time. The enhanced situational awareness provided by the perspective display

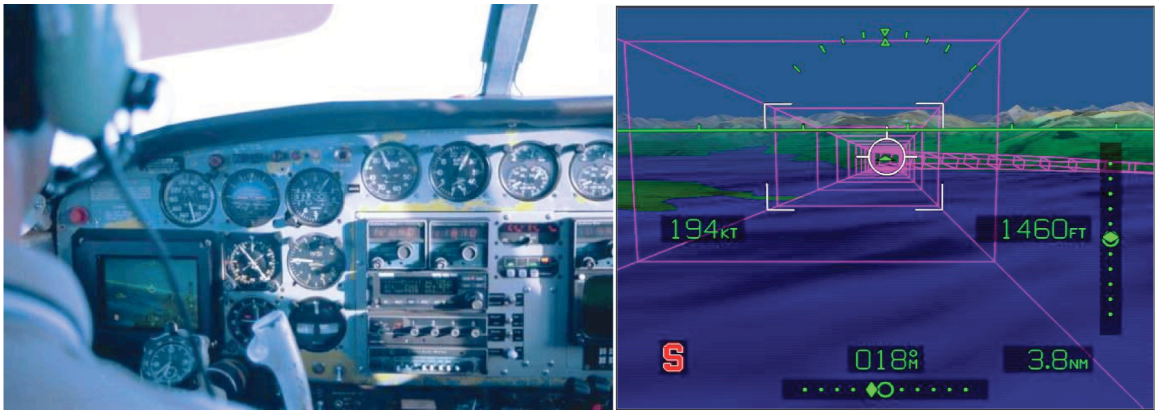

Figure 5-3. *The perspective display was put in the lower left corner of the pilot's visual field. On the right is a screen capture of the image displayed to the pilot showing terrain and the desired flight path.*

concerning the proximity of terrain was evaluated as was the pilots workload and impressions of flying the curved paths. The system evolved during this and later flight testing to improve the effectiveness of the presentation. The test platform was flexible enough to allow changes to be made very quickly and adjust the flight paths as the aircraft was going around to re-enter the highway. Thus, impressions of terrain proximity could be taken into account to move the path further away if desired. Additionally, good weather allowed more flight testing than expected. Thus, it was possible to go to other airports and test more situations. Again, the flexibility of the test platform allowed the downloading of the terrain database while in Alaska and the development of the flight paths. Figure 5-3 shows the display in front of the pilot and a screen capture of the display while following one of the complex procedures.

Subsequent work focused on adding information about nearby aircraft to the display as well. Several applications were investigated, ranging from traffic avoidance to closely spaced parallel approaches to runway incursion avoidance. The display of traffic on the perspective display can be challenging. The display only provides a forward-looking view and thus is not ideal for displaying traffic to the side or behind the aircraft. Therefore, other methods for alerting the pilot to traffic of interest were investigated. This work required an ADS-B air-to-air data-link that at the time was in the experimental stages. Stanford was able to obtain two prototype ADS-B boxes and access to a second flight test aircraft. The applications selected for traffic awareness were closely spaced parallel approaches and runway incursion. Here, an alerting mechanism was selected to color the runway red when another aircraft showed intent of occupying the same runway as the test aircraft.

Another alerting mechanism was to also show a top-down view for parallel approach indicating the position of one's own ship and of the aircraft approaching the parallel runway. Here, an incursion region was highlighted indicating the most hazardous position for the other aircraft. It was discovered that providing information on the other aircraft's roll angle provided the earliest useful indication of a possible incursion. Flight tests were conducted with an aircraft and a van for runway incursion and two aircraft for parallel approach.

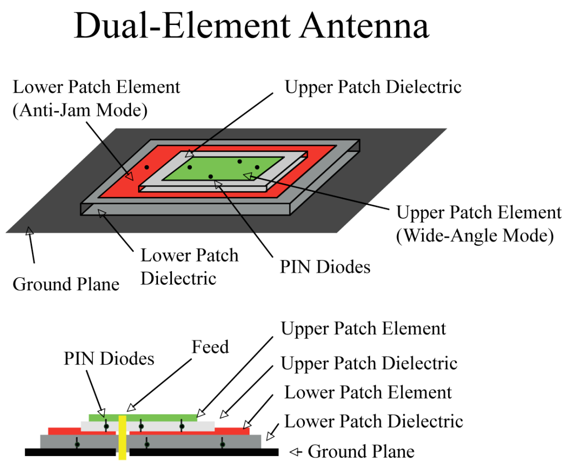

Figure 5-4. *The design of the Dual patch antenna.*

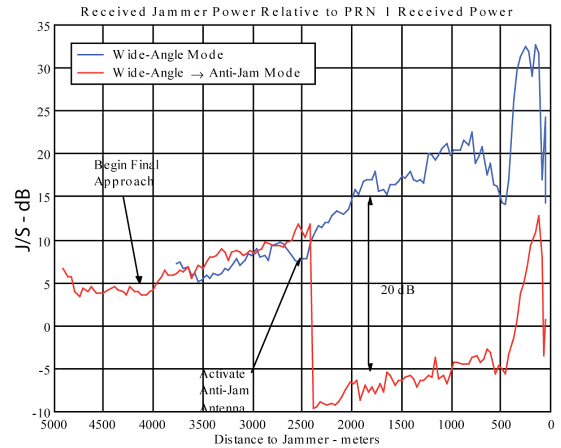

Figure 5-5. *Evaluation of the Jammer to Signal ratio during flight test with a simulated pseudolite jammer.*

Also investigated was including the possible location of wake-vortices on the perspective display. A wake vortex propagation model was generated and incorporated into the display. These wakes would be displayed behind other aircraft as increasingly sized boxes that contained the possible vortices. These boxes persisted for some minutes until one could safely assume they had dissipated. This display was flight tested using two small aircraft. Smoke generators were used to identify the actual wakes and the quality of the display was compared to this reference. It was found that the vortex model and perspective display very accurately identified the area that contained the actual wake vortices.

An ongoing concern with the use of GPS in aircraft is the threat of interference. To mitigate this threat, Stanford designed a novel dual-patch reconfigurable anti-jam GPS antenna for airborne applications. The anti-jam antenna employs two modes of operation. A wide-angle mode is selected for GPS navigation when no radio frequency interference (RFI) is present. If interference is detected, the antenna may be placed in anti-jam mode. The anti-jam mode rejects ground-based RFI, while enhancing signals from high elevation satellites. Since the anti-jam mode reduces the signal strengths of low elevation satellites, use of the wide-angle mode is recommended when no interference is present. Mode switching was accomplished by means of a DC control signal on the feedline. This antenna does not require an external processing unit, typically used with adaptive anti-jam arrays. A smart GPS receiver that is able to detect the presence of RFI may perform switching manually or automatically. This antenna is only slightly larger than conventional aviation GPS patch antennas, and may replace existing antennas with no modification to the fuselage.

The dual-patch anti-jam antenna was built and tested in flight (see Figures 5-4 and 5-5). To simulate a ground based jamming signal, a pulsed pseudolite transmitter was placed at the approach end of the runway. The test aircraft, a Cessna Caravan, flew numerous low approaches over the pseudolite. The signal strengths of the pseudolite and all visible GPS satellites were recorded during these approaches. With the anti-jam mode selected, the antenna suppressed the ground-based simulated jammer by 15 dB, compared to the wide-angle mode. The flight test data also showed that the anti-jam mode improves the J/S ratio by 20 dB for high elevation satellites.

6.0 Summary

Stanford has played a critical role in the development, certification, and evolution of WAAS. An independent prototype was developed by the Stanford GPS laboratory that enabled development of key algorithms that would ultimately influence the operational design of the system. The prototype was also used to develop and validate important elements of the WAAS MOPS that defines the interface between the ground and the aircraft. Chief among these was the protection level equation that specifies how integrity is maintained for all combinations of data.

Stanford led the overall effort to make the system certifiable and led the development of many of the most important integrity monitoring algorithms. These algorithms balanced the requirements of providing integrity at the 10^{-7} level with providing high availability. Stanford and Raytheon led the documentation of the safety analysis that demonstrated that WAAS met its integrity requirement. The PHMI document was a major component of the certification of WAAS.

Stanford also played a critical role in improving WAAS beyond its original implementation to ultimately provide full coverage to CONUS and nearly all of Alaska. In addition, the improvements allowed WAAS to meet its original requirement of providing operations with vertical guidance down to 200 feet. Stanford has prepared for the eventual modernization of the GPS constellation and fielding of other satellite navigation constellations. WAAS will be upgraded to include the new signals and alternate architectures have been investigated to provide coverage throughout the globe.

This report merely highlights some of the contribution Stanford has made toward ensuring that aviation users take maximum benefit from satellite navigation. A great deal more work was actually performed. The following list of publications provides many more topics and details.

Citations of Publications Supported by WAAS
(*Chronological Order with Internet Links*)

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3 citations reported by Googlescholar.com

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