1.5 System Overview, Recent Developments, and Future Outlook for WAAS and LAAS

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ABSTRACT

Over the past decade, two separate approaches have been developed to augment the Global Positioning System to meet the accuracy, integrity, continuity, and availability needs of civil aviation users. One utilizes a network of reference stations spread across a large area and derives a single set of differential corrections that is relayed to users via GPS-like signals from Geosynchronous (GEO) satellites. It is known as the Wide Area Augmentation System (WAAS) or, more generally, as a Space Based Augmentation System (SBAS). The other utilizes a single reference station within a given airport and provides differential corrections via VHF Data Broadcast (VDB) within a 50-km region around that airport. It is known as the Local Area Augmentation System (LAAS) or, more generally, as a Ground Based Augmentation System (GBAS).

This paper summarizes the history of WAAS and LAAS and provides an overview of the key technical elements of both systems. It provides up-to-date status reports for the fielding of WAAS and LAAS by the U.S. Federal Aviation Administration (FAA) and focuses on the most challenging aspect – verification of the integrity and continuity requirements. It concludes by projecting the future for both systems based on the performance improvements that appear to be possible and the most demanding requirements that WAAS and LAAS may be asked to meet.

1.0 Introduction

When the GPS Standard Positioning Service (SPS) based on L1 C/A code was declared to have reached Initial Operational Capability (IOC) in 1993 [1], it was generally understood that SPS could not meet the requirements of civil aviation users. For one thing, SPS was intentionally degraded by Selective Availability (S/A) such that its ranging accuracy was insufficient for precision approach applications. More importantly, while the GPS Operational Control Segment (OCS) does its best to maintain the performance of GPS, it does not have the mandate to prevent or detect failures at the levels required to meet the continuity or integrity requirements for civil aviation operations [2]. Receiver Autonomous Integrity Monitoring (RAIM) was developed to enhance user integrity, but for a variety of reasons, it cannot be the sole means of providing integrity for civil aviation [3,4].

The use of differential GPS (DGPS) was originally developed as a means of defeating S/A and achieving meter-level accuracy [5]. The combination of DGPS with the concept of a GPS integrity channel (GIC) [6] was the genesis of WAAS as a means to provide both the accuracy and integrity needed for GPS-based aircraft operations [7,8]. LAAS developed as a means to provide higher-accuracy differential corrections and integrity alerts in a local area using a radio data link [9,10]. Early flight tests of prototype WAAS and LAAS systems [11,12] convincingly demonstrated the potential of this technology to replace and expand upon the capabilities of existing ground-based aircraft navigation aids such as VOR/DME and the Instrument Landing System (ILS). As a result, the International Civil Aviation Organization (ICAO) selected GPS as the primary basis for future aircraft navigation and landing systems in 1995 [13].

Since the mid-1990's, the development of WAAS and LAAS has surmounted many technical and organizational hurdles, and both systems are now on the verge of achieving IOC. Section 2.0 of this paper summarizes the civil-aviation requirements that WAAS and LAAS address. Section 3.0 describes the WAAS and LAAS architectures and identifies the key components of both systems. Section 4.0 describes the key technical challenges that must be overcome for WAAS and LAAS to be certified and how they have been successfully addressed. Section 5.0 summarizes the current status of WAAS and LAAS, and Section 6.0 projects the improvements to WAAS and LAAS that are expected to occur in the next few years. Section 7.0 concludes the paper.

2.0 Summary of Civil Aviation Requirements

Requirements for civil aviation operations that will be supported by WAAS and LAAS have been derived from the requirements that apply to existing navigation aids,

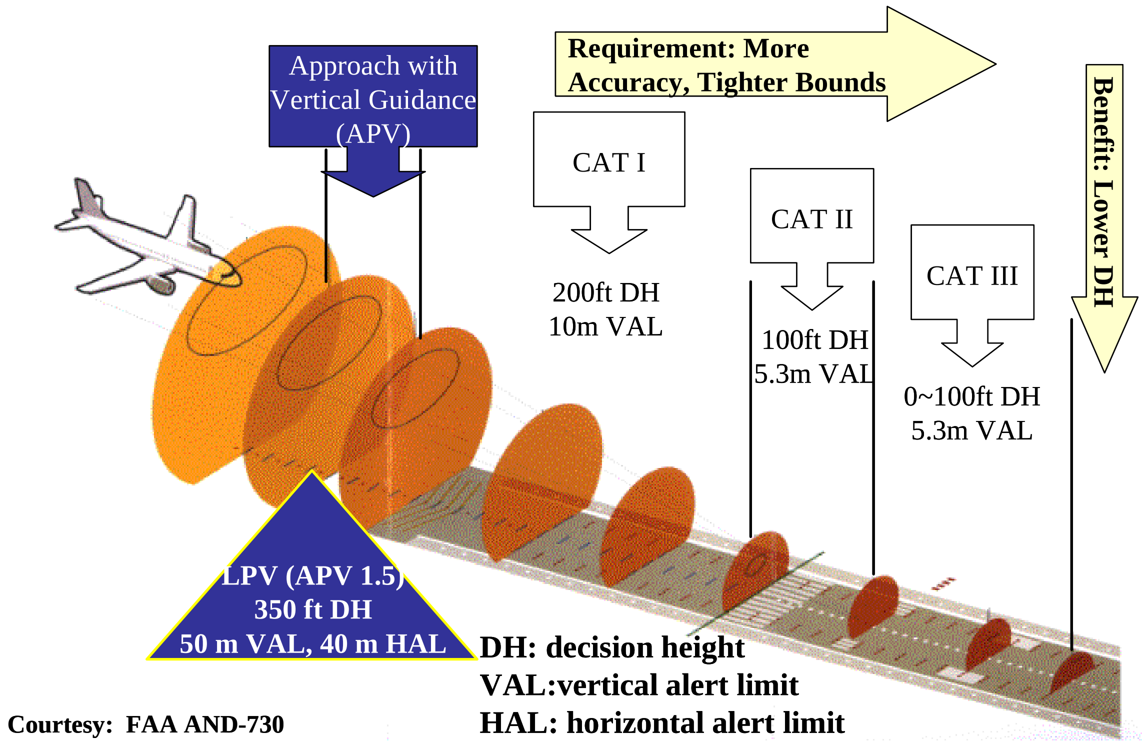

Figure 1: Alert Limit Evolution for Aircraft Precision Approaches

such as ICAO Annex 10 for ILS [14,15]. Detailed listings of these requirements can be found in [4,16]. The key parameters upon which requirements are placed can be defined as follows [17]:

Accuracy: Measure of navigation output deviation from truth, usually expressed as 1σ or 95% (approximately 2σ) error limits.

Integrity: Ability of a system to provide timely warnings when the system should not be used for navigation. **Integrity Risk** is the probability of an undetected hazardous navigation system anomaly.

Continuity: Likelihood that the navigation signal-in-space supports accuracy and integrity requirements for duration of intended operation. **Continuity Risk** is the probability of a detected but unscheduled navigation interruption after initiation of approach.

Availability: Fraction of time navigation system is usable (as determined by compliance with accuracy, integrity, and continuity requirements) before approach is initiated.

These requirements are parameterized in such a way that each aircraft is able to determine, before beginning an operation, whether or not it can proceed. The aircraft does this by computing position-domain **protection levels** based on the GPS satellites in view and approved by WAAS or LAAS, the ranging error standard deviations or "sigmas" broadcast by WAAS or LAAS, and the "*K*-value" multipliers needed to achieve the required integrity and continuity risk probabilities based on a zero-mean Gaussian distribution. WAAS and LAAS requirements are defined such that the integrity requirement always dominates the accuracy requirement; thus verification of integrity also confirms accuracy. Continuity is covered by only including the set of measurements whose probability of remaining usable throughout an operation is below the continuity risk requirement for that operation [18].

The nominal or fault-free (known as "H0" in LAAS) vertical protection level (VPL) is given by:

$$VPL_{H0} = K_{FFMD}\,\sigma_{vert,H0} \quad (1)$$

where $\sigma_{vert,H0}$ is derived by computing the weighted pseudoinverse matrix **S** based on the line-of-sight vectors to the satellites and the range error (after corrections are applied) sigmas broadcast for each approved satellite (see [18,19,20] for the complete algorithm). K_{FFMD} for WAAS vertical positioning is 5.33, corresponding to a 10^{-7} integrity risk requirement [4,16,19]. For LAAS, the majority of this probability is allocated to failure cases, and what is allocated to the fault-free case results in K_{FFMD} = 5.81 for Category I precision approaches with three active reference receivers [4,15,18]. Since the *K*-values are fixed, verifying in real time that the broadcast error sigmas overbound the true error distribution in the tails is a significant technical challenge that is addressed further in Section 4.0 [20,46].

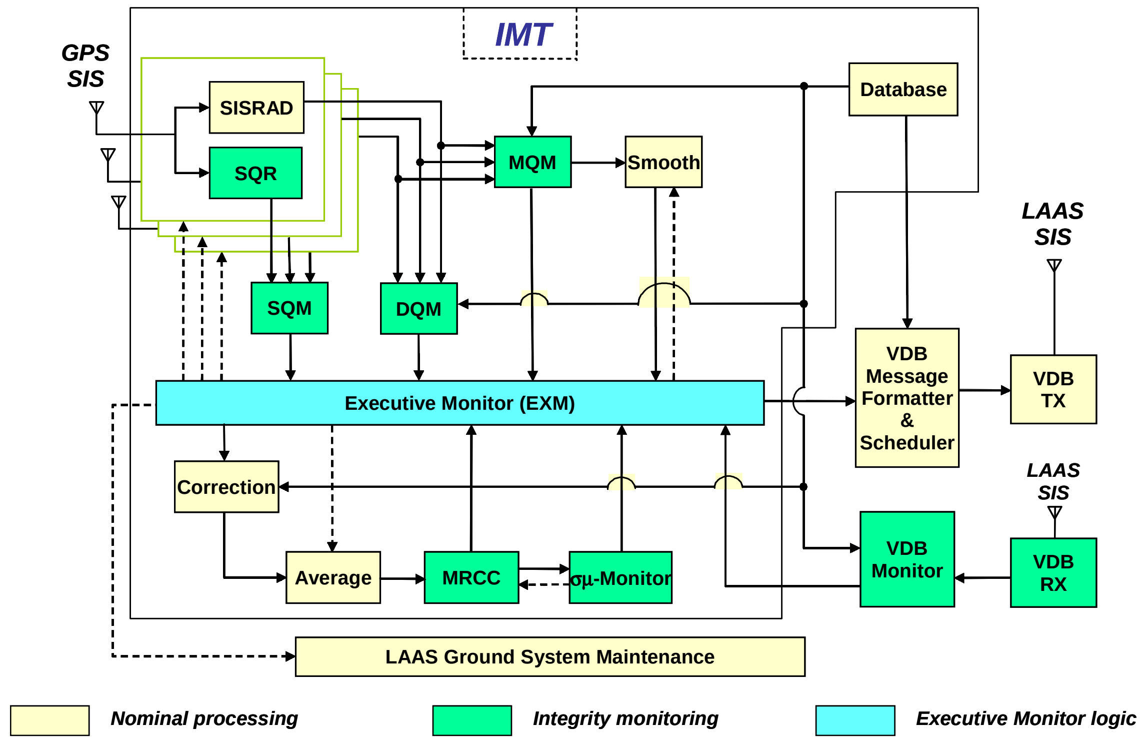

Figure 2: LAAS Integrity Monitor Testbed (IMT) Functional Block Diagram

The protection levels computed by users are compared to **alert limits** in each position axis of interest to determine whether the system meets the integrity and continuity requirements for a given operation [4,15,16]. These values are set based on the maximum safe excursions from nominal flight paths based on the presence of nearby obstructions. Figure 1 shows how these alert limits decrease as the aircraft gets closer to the runway and to obstacles on the ground [21]. Because GPS satellite geometries are least favorable in the vertical direction, and because obstacles are more threatening in the vertical direction, the vertical alert limit (VAL) is the driving requirement (i.e., meeting the VAL requirement for a given operation insures that the corresponding HAL or LAL requirements are met in practically all cases). The initial phase of WAAS is capable of providing acceptable availability for approaches down to the “APV 1.5” or “LPV” level shown in Figure 1, which has a decision height (lowest height at which WAAS guidance is sufficient) of about 350 feet above ground level and a VAL of 50 meters. Early LAAS installations will support approaches down to Category I decision height of 200 feet (10 – 12 meter VAL).

3.0 WAAS and LAAS Architecture Overview

The most fundamental system element for both WAAS and LAAS is the reference station, comprising one or more reference receivers connected to antennas at fixed locations known (pre-surveyed) to within 1 – 2 cm. These reference receivers provide continuous measurements for all GPS satellites in view so that differential corrections can be formed. They typically have multiple receivers and antennas to provide the required availability and continuity and to allow failures of individual reference receivers can be detected and excluded before they corrupt the differential corrections.

Figure 2 shows a functional block diagram for the Stanford University LAAS ground facility (LGF) prototype known as the Integrity Monitor Testbed (IMT). The functions shown in yellow boxes are those required to calculate DGPS corrections [22,23]. These algorithms are well known and comprise perhaps 10% of the IMT software. The functions shown in green boxes are groupings of integrity monitor algorithms that are designed to detect different failure modes as follows:

SQM (Signal Quality Monitoring): Detects satellite signal deformation, low signal power, and code-carrier divergence;

DQM (Data Quality Monitoring): Detects anomalies in satellite navigation data (ephemeris and clock data);

MQM (Measurement Quality Monitoring): Detects step, ramp, and acceleration errors in reference receiver measurements (may be due to satellite or receiver faults);

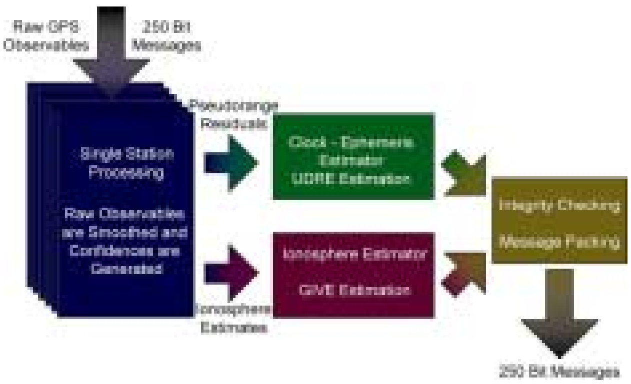

Figure 3: Wide-Area Master Station Functions

MRCC (Multiple Receiver Consistency Check): Computes B-values that compare measurements across reference receivers and uses them to detect reference receiver failures; and

σμ-monitor (Sigma-Mean Monitor): Collects B-values over time and uses them to detect violations of the broadcast pseudorange correction error sigma (σ_{pr_gnd}) and assumed mean of zero.

The IMT implementation of these functions is described in more detail in [23,46].

The remaining 30 – 40% of the code is dedicated to **Executive Monitoring** (EXM), which collects the outputs from each monitor and determines which measurements, if any, are flawed and must be excluded from the set used to compute the differential corrections sent to users. EXM in the IMT is primarily based on Boolean logic. For example, monitor alerts (generated when a test statistic exceeds its pre-set acceptability threshold) on multiple satellites tracked on a single reference receiver, all measurements on that receiver are considered to be faulty unless more than one of the flagged satellites is also flagged on one of the other reference receivers. If this latter event occurs, no clear diagnosis of a reference receiver or satellite failure can be made, and the IMT must temporarily shut down (in this case, broadcast empty correction messages indicating that no satellites can be safely used) [22,23].

The key distinction between WAAS and LAAS is that, whereas LAAS performs all calculations and monitoring needed for a given airport at that airport, WAAS wide-area reference stations (WRSs) perform relatively simple measurement screening and then transmit their surviving measurements via dedicated land-lines to the Wide-Area Master Station (WMS), of which there are two in CONUS. Figure 3 shows a flow diagram of the WMS functions. After smoothing the raw observables passed on by the WRSs, the WMS performs one process to compute clock ephemeris corrections and a separate one to compute ionospheric corrections. In both cases, the WMS is able to utilize its multi-WRS observability to

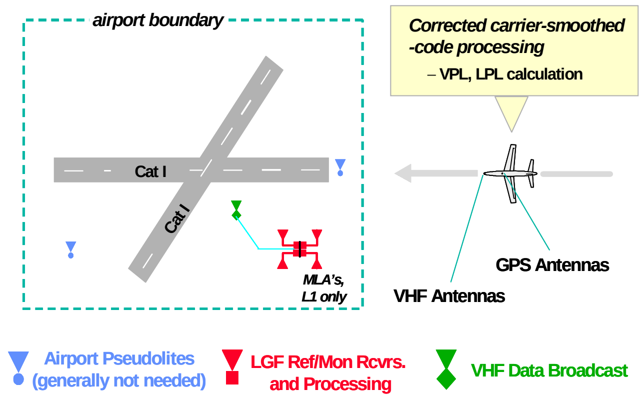

Figure 4: Category I LAAS Architecture Elements

calculate and broadcast real-time 99.9% (3.29 σ) bounds on the errors in both sets of corrections [8]. These are known as **User Differential Range Error** (UDRE) and **Grid Ionospheric Vertical Error** (GIVE) [19], and they are used to compute user range error sigmas for each satellite that go into the calculation of $\sigma_{vert,H0}$ and VPL_{H0} from (1). Integrity monitoring occurs in each of these functions in tandem with the nominal calculations, and additional monitoring of the clock/ephemeris and ionosphere outputs occurs in the final box, right before the 250-bps WAAS correction messages are generated. These "back-end" monitors may alter or exclude these outputs before they go into the corrections.

As noted before, each LAAS airport site is self-contained. Figure 4 shows a diagram of the LAAS elements needed for Category I precision approach service at each airport. The LGF transmits differential corrections, other relevant parameters, and approach-path definition data to approaching aircraft via a high-data-rate VHF Data Broadcast (VDB) using the ILS Localizer frequencies (108.025 – 117.950 MHz with 25 kHz separation between adjacent channels) and a Time Division Multiple Access (TDMA) structure that provides 8 time slots per 0.5-second epoch per channel. Each LGF site is allocated as many as 2 of these 8 for its use [22]. The VDB is designed to reliably cover a region within 23 n.mi. of the VDB transmit antenna location [22]. Definitions of each of the messages broadcast by the VDB are contained in [24], and a detailed technical analysis of VDB performance is provided in [25].

Figure 4 also shows airport pseudolites (APL's) as a possible LAAS availability augmentation. APLs transmit GPS-like pseudorandom code signals at or near L1 and thereby improves overall ranging geometry and user availability (improved geometry reduces the value of $\sigma_{vert,H0}$ in (1)). However, APLs place additional requirements on aircraft receivers and present significant implementation challenges, particularly with respect to not overwhelming GPS satellite signals (the "near-far" problem) and interfering with non-participating GPS users in the vicinity of the airport [26].

In order to achieve coverage over very large areas, WAAS uplinks its 250-bps correction messages to geosynchronous (GEO) satellites that encode the WAAS corrections onto L1 C/A code (using PRNs distinct from those used by GPS satellites) and transmit that code to users. A detailed explanation of the WAAS correction message formats can be found in [8,19]. GEO signals provide WAAS users with additional ranging measurements and thus enhance availability in a manner similar to APLs. However, the limited data-rate means that some information that LAAS broadcasts to users (such as approach-path data) must instead be carried within aircraft databases. Also, the limited accuracy and multipath mitigation that can be achieved from today's "bent-pipe" GEO ranging satellites means that the range error sigmas for GEO satellites are much higher than those for GPS satellites or APLs [27]. In addition, since receiving GEO messages is required to maintain WAAS service, users need to receive signals from more than one GEO to meet a strict (per every approach, as opposed to average loss rate) continuity requirement.

Since WAAS and LAAS are fundamentally similar systems that will be used to support similar civil aviation operations, it is instructive to compare their strengths and weaknesses. WAAS has three primary advantages over LAAS:

(1) The continental-wide coverage that is provided by a single set of differential corrections;

(2) The ability of a widely-distributed and highly-redundant WRS network to compute independent GPS satellite ephemeris solutions and separate them from satellite clock corrections, which makes WAAS practically invulnerable to GPS navigation data failures within the region of primary WAAS coverage; and

(3) The use of GEO ranging signals to augment GPS satellite geometries and enhance user availability.

On the other hand, LAAS has the following advantages:

(1) The need to cover only a limited region around each airport makes LAAS corrections significantly more accurate within that region as well as being less sensitive to atmospheric anomalies;

(2) The reliability and high-data-rate of the LAAS VDB, which provides all data needed for approaches to a given airport and makes use of existing ILS localizer receivers on aircraft [28]; and

(3) The (future) capability to place APLs at airports that have higher availability requirements.

Because WAAS and LAAS have complementary strengths, they fit well together in the future national airspace system. WAAS will support all existing enroute and terminal-area civil aviation operations as well as precision approaches down to the "LPV" (present) and "APV-2" or "GLS" (near future) minima, and LAAS will

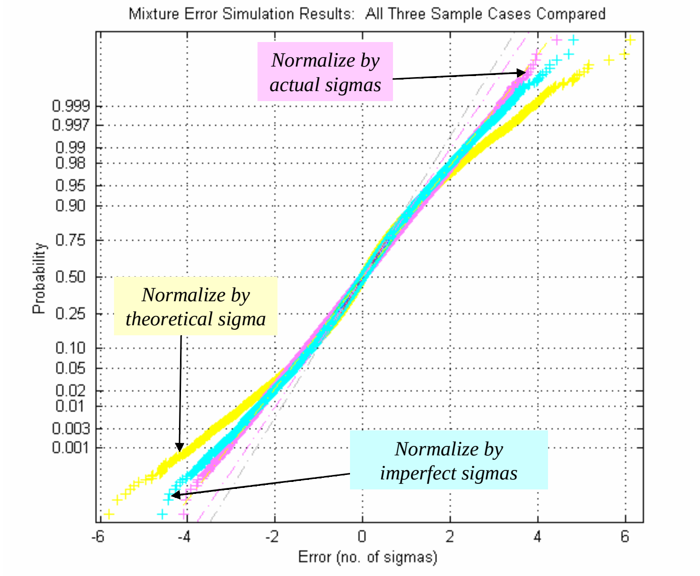

Figure 5: Impact of "Mixing" on Gaussian Samples

cover precision approaches down to Category I (present) and Category II/III (near future) minima, as shown in Figure 1 [29].

In addition, WAAS and LAAS can support each other in real-time. LGF sites that receive WAAS GEO ranging signals will be required to provide corrections for them (thus improving user availability) and to make use of the clock/ephemeris corrections in LAAS ephemeris monitoring (since WAAS can observe ephemeris faults more precisely than LAAS can) [22,30]. Once LGF sites are fielded in sufficient numbers, they may be used as passive WAAS monitors by checking WAAS-based position solutions generated by the LGF reference receivers against the known locations of their antennas.

4.0 Key Technical Challenges to WAAS and LAAS Certification

During the development of WAAS and LAAS, many technical difficulties with specific hardware and software components and their interactions have been addressed and resolved. These include quantifying and limiting the impact of multipath on WAAS and LAAS reference receiver antennas [9,31], designing the WAAS GEO message uplink-downlink process to fit within the time-to-alert required for precision approaches [32], and optimizing the LAAS VDB to provide optimal coverage with minimal co-channel and non-LAAS-user interference [25].

However, the most fundamental challenge to certifying WAAS and LAAS for civil aviation is demonstrating that the integrity and continuity requirements are met for every authorized approach. The per-operation integrity risk requirement of 10^{-7} or lower noted in Section 2.0 is very difficult to conclusively verify in the presence of a wide variety of failure modes that are not fully understood.

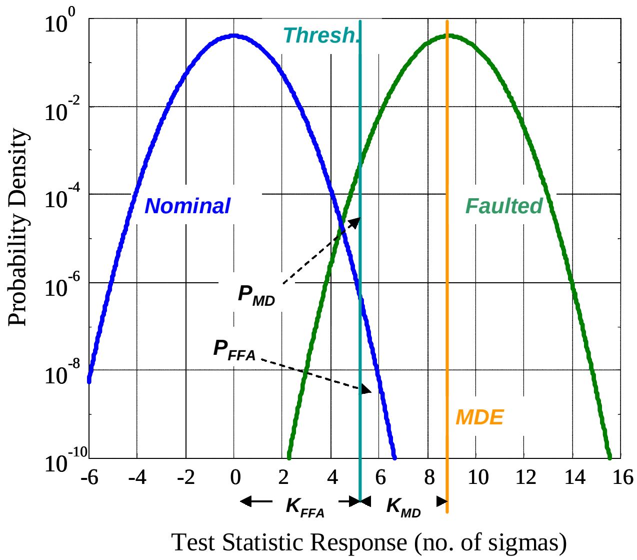

Figure 6: Threshold and MDE Definitions

Many of these failure modes are inherent to GPS and are outside the direct control of the FAA. In addition, it is difficult to verify that nominal WAAS and LAAS performance is overbounded by a zero-mean Gaussian distribution with the broadcast sigma at the 10^{-7} level.

Taking the latter issue first, Figure 5 shows the results of a simulation that mirrors what is observed in LGF data [33]. In this simulation, random samples are generated from zero-mean Gaussian distributions of varying standard deviations from 0.1 – 0.2 m [34]. The combined set of samples is then plotted with Gaussian-probability axes such that a perfect Gaussian would appear as a straight line. Three cases were plotted based on various degrees of knowledge of the actual sigma variation when the results were normalized to represent a single distribution. Normalization by the measured sample standard deviation over all samples shows the greatest deviation from "normality" in the tails. This deviation is due to the well-known effect of "mixing" Gaussian samples with different standard deviations into a single dataset [35]. With improved knowledge of the degree to which the sigmas vary within the larger dataset, improved normalization leads to less inflation, but some uncorrected mixing will always exist in practice because "nominal" conditions generally include a wide range of error sources and distributions. In addition to mixing, several other issues complicate error bounding, including the statistical uncertainty inherent in error sigma and correlation estimates from data and the difficulty of demonstrating error bounding with theoretical models [36,37].

The purpose of the integrity monitor algorithms described in Section 3.0 is to detect and exclude faults and other anomalies before they become hazardous to users so that the nominal protection level given by VPL_{H0} in (1) covers all remaining error sources. In practice, however, this cannot be done perfectly. The detection

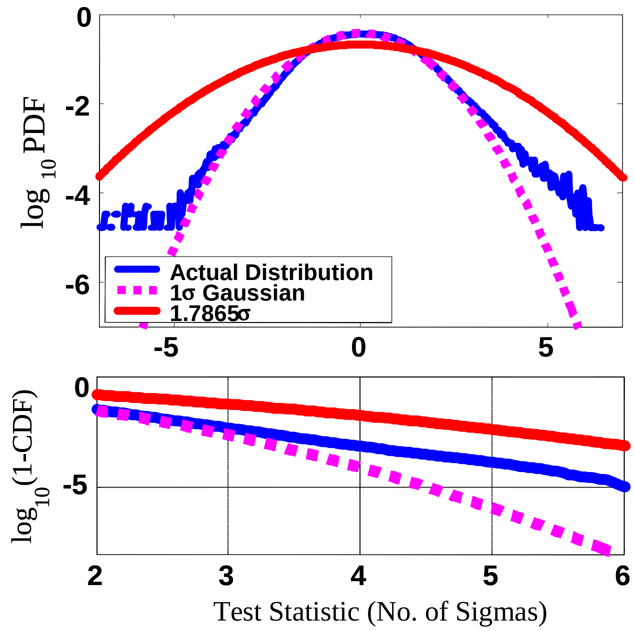

Figure 7: σ_{test} Inflation for MQM Ramp Test

thresholds for these monitors must be high enough to insure that, under fault-free conditions, the threshold is very rarely violated (this is to insure that the continuity requirement is met). A fault whose mean impact on the test statistic is to push it to the threshold value thus will be detected with a probability of 0.5 (noise is equally likely to push the statistic above or below the threshold), which is insufficient. The error that will be detected with a missed-detection probability (P_{MD}) sufficiently low to meet the integrity risk requirement is one whose mean impact on the test statistic is known as the Minimum Detectable Error (MDE) and is defined as [23,38]:

$$MDE \;=\; T \;+\; K_{MD}\, I_{test}\, \sigma_{\text{test}} \tag{2}$$

where T is the detection threshold, K_{MD} is the K-value multiplier needed to give the required P_{MD} from a one-sided zero-mean Gaussian distribution of unit variance, σ_{test} is the actual test statistic sample variance under nominal conditions, and I_{test} is the inflation factor needed for the assumed zero-mean Gaussian distribution to bound the actual test statistic distribution at and beyond P_{MD}. Typically, the threshold T is derived from [23]:

$$T \;=\; K_{FFD}\, I_{test}\, \sigma_{\text{test}} \tag{3}$$

where K_{FFD} is analogous to K_{MD} but is based on the allocated probability of fault-free detection from the continuity requirement. MDE can thus be simplified to:

$$MDE \;=\; (K_{FFD} + K_{MD}\,)\, I_{test}\, \sigma_{\text{test}} \tag{4}$$

Figure 6 shows a graphical illustration of the definition of the threshold and MDE, and Figure 7 shows the distribution of nominal test statistics for an example IMT monitor (in this case, the MQM carrier-phase ramp error test) [39].

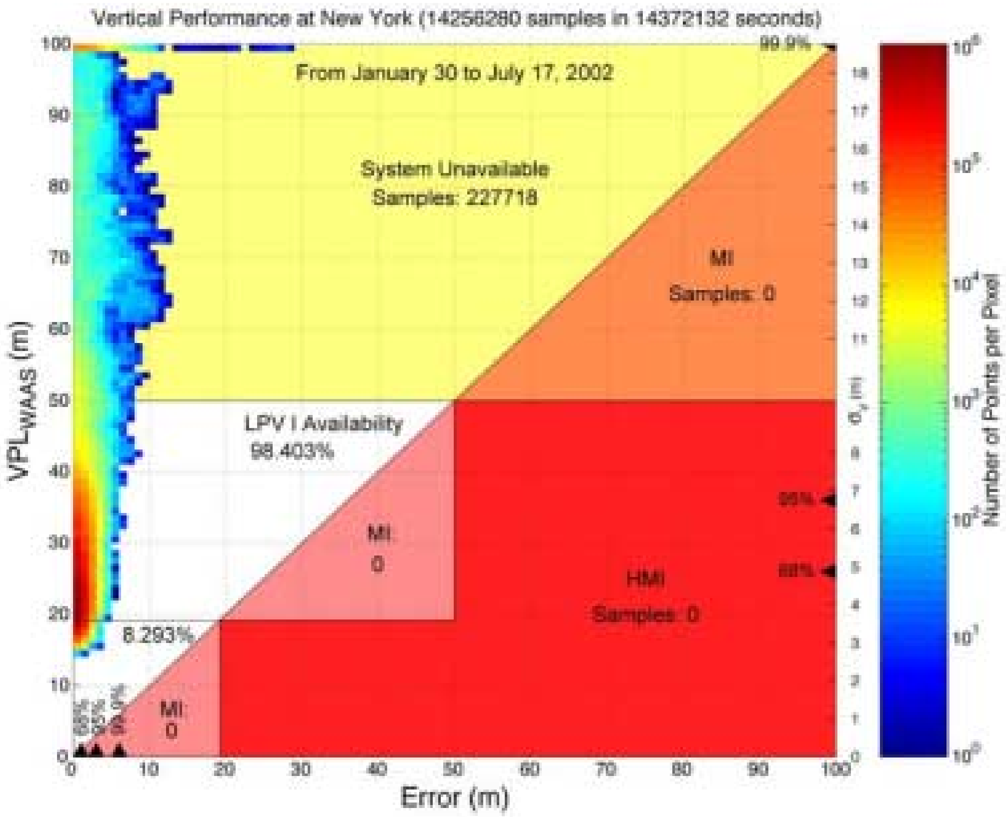

Figure 8: WAAS Vertical Accuracy and Integrity at Queens, New York WRS Site

The MDE for each identified system failure mode can be converted into the range-error domain, de-weighted by its assumed prior probability of occurrence, and compared to the implied range-domain error bound from VPL_{H0} in (1) [40,41,45]. If VPL_{H0} exceeds the bound that applies for a given failure mode (after integrity monitoring), then this failure mode has been acceptably mitigated. If not, two options exist:

(1) Devise a new protection level equation to evaluate the potential impact of that failure mode in real time; or

(2) Inflate the broadcast sigma inputs to VPL_{H0} by the amount needed for VPL_{H0} to exceed the bound implied by the failure mode in question.

LAAS has generally chosen Option (1) and, as a result, has defined separate anomaly protection level equations for single-reference-receiver failures (VPL_{H1}) and satellite ephemeris failures (VPL_e) [18,42]. The VPL that applies at any given time (and is compared to VAL) is the maximum of VPL_{H0}, VPL_{H1} VPL_e [18]. Quantification of these protection levels depends upon the assumed **threat models** and **prior probabilities** for each failure mode. For example, a detailed threat model for satellite signal deformation failures (otherwise known as "evil waveforms") has been developed using the one observed example, the detection of the SV 19 fault in 1993, as the starting point [22,38]. Similarly, models have been developed for ephemeris failures [30,42] and ionospheric spatial irregularities originally noticed in WAAS data [43]. Uncertainty in both these threat models and the associated prior probabilities dictates that the assumptions made for them be conservative until sufficient data is observed to justify more realistic values.

WAAS, on the other hand, has only defined VPL_{H0} and thus must inflate the broadcast UDRE and GIVE to cover all failure modes whose MDE in the range-error domain would not otherwise be covered by VPL_{H0} [19,20]. This impacts the broadcast UDRE and GIVE values directly – they are driven by the MDEs of the monitors that are used to validate them, which are themselves driven by the conservative underlying assumptions made regarding ionospheric behavior [44]. The resulting GIVE values tend to be the dominant contributor to VPL_{H0} in practice.

The need to inflate the inputs to VPL_{H0} to cover all fault conditions below MDE contributes to the result shown in Figure 8, which plots measured vertical position errors at the Queens, New York WRS site on the *x*-axis against the values of VPL_{H0} computed there over the first half of 2002 on the *y*-axis. The 99.9% bound on actual vertical errors from this plot appears to be about 7 meters, but typical VPL_{H0} values are far higher than would be expected given this level of nominal performance. This suggests that significant improvements in WAAS (and

LAAS) performance can be achieved if bases can be found to improve monitor performance and justify less-conservative assumptions. This is discussed further in Section 6.0.

5.0 Current Status of WAAS and LAAS

The IOC date for "Phase 1" WAAS has been delayed by the need to resolve a series of technical issues with the original WAAS architecture. To address these issues, the FAA formed the WAAS Integrity Performance Panel (WIPP) to combine the insights of the prime contractor, Raytheon, and several groups supporting the WAAS Program Office, including Stanford, University, Ohio University, Zeta Associates, MITRE/CAASD, AMTI, and the Jet Propulsion Laboratory [47]. The WIPP and its activities were approved by an Independent Review Board in early 2001 [48]. The WIPP changed the WAAS correction and integrity algorithms to better protect integrity. One consequence of this was the increased conservatism of the algorithms that combine to set the broadcast UDRE and GIVE values, which contributes to the overall conservatism noted in the results of Figure 8. Once the WIPP-mandated changes were implemented, WAAS passed its 60-day stability test in September of 2002. "Phase 1" WAAS is now very close to achieving IOC and should do so by the end of July 2003 [49].

During the years in which WAAS was procured, LAAS remained a research and development program with limited resources. This effort led to solutions for problems similar to those encountered by the WIPP in advance of LAAS procurement. These solutions were developed and coordinated by the LAAS Key Technical Advisors (KTAs) supporting the LAAS Program Office, and they were codified in the LGF Specification for operations up to and including Category I precision approaches [22]. In late April 2002, the FAA LAAS Program Office issued a request for offers to provide 10 Limited Rate of Initial Production (LRIP) LGF systems to equip 6 active airports and 4 FAA-support installations, with options for an additional 15 – 40 LGF systems per year over the five subsequent years. The FAA is expected to announce an LRIP contract award imminently (as of mid-October 2002). LRIP system deliveries are expected to occur in 2004, with LAAS IOC following by the end of 2004 or soon thereafter [50].

6.0 Ongoing Research and Future Promise

As discussed previously, the Phase-1 WAAS system and the existing LGF specification and procurement effort are capable of meeting civil aviation requirements up to and including LPV or APV 1.5 for WAAS and Category I precision approach for LAAS (see Figure 1). Both systems have the capability to improve upon user availability for these applications and to meet the requirements for more-demanding approaches (APV 2 or GLS for WAAS, Category II/III for LAAS). Achieving this requires a combination of additional system elements, improved algorithms, and additional data to support less-conservative assumptions. In addition to supporting validation and certification of the existing WAAS and LAAS, research at Stanford University and elsewhere is focused on developing and demonstrating these improvements.

Several near-term equipment enhancements to Phase-1 WAAS are planned under the title of "Pre-Planned Product Improvements," including additional WRS sites in CONUS and Alaska and the procurement or leasing of one additional GEO satellite to provide dual-GEO visibility to all CONUS users. The current schedule is for this new GEO to be on-orbit by the end of 2005 and for Final Operational Capability (FOC) for operations up to and including LPV by the end 2007 [49]. In addition, improvements to the ionosphere algorithms that determine the GIVE values are being pursued [51,52]. Evolution to a "Phase-2" WAAS that is capable of meeting APV-2 and (perhaps) Category I approach requirements is expected to follow. Since this degree of improvement will almost certainly require use of the L5 civil signal, Phase 2 IOC is not projected to occur until satellites transmitting the L5 civil signal predominate in the GPS constellation, which is expected to occur in the first half of the next decade [21,49].

Similarly, several complementary approaches are being pursued to make LAAS capable of supporting Category II/III precision approaches, landings, and rollouts. One proposed addition is a Position Domain Monitor (PDM) separate from the existing LGF reference receivers that performs independent checks of the position accuracy of the corrections generated by the LGF in real-time, similar to the similar "back-end" check in WAAS. Techniques for optimizing the integrity and continuity benefits of the PDM are discussed in [53,54]. If the PDM antenna is positioned sufficiently far away (at least 0.5 – 1 km) from the centroid of the LGF reference receiver antennas, the PDM can also perform "long-baseline" carrier-phase ephemeris monitoring that can detect failures that are otherwise unobservable to the LGF [42,58]. Additional incremental improvements to the existing LGF integrity monitor algorithms are described in [54].

We currently expect that, given these LGF improvements, it will be possible to reach IOC for Cat. II/III LAAS in the latter half of this decade, before L5 is widely broadcast by GPS satellites. The speed with which a Category II/III LGF consensus architecture and specification can be developed depends heavily on the ongoing RTCA and ICAO process of refining the Category II/III LAAS system requirements in [15]. For example, the Category II/III VAL was derived to be 5.3 m in [15], but subsequent work has demonstrated that it could be made substantially higher (and thus easier to meet with high availability) without affecting the safety of Category II/III operations [55]. However, as with Phase 2

WAAS, Category II/III LAAS FOC is likely to be delayed until the L5 civil signal is widely available.

In addition to the failure modes discussed previously, intentional or unintentional radio frequency interference (RFI) to GPS signals is of great concern because of the very tight continuity requirements placed on civil aviation applications. Even if integrity is never threatened (if it were, the existing WAAS and LAAS monitors would almost certainly detect it), repeated loss-of-service due to RFI cannot be tolerated [56]. Future WAAS and LAAS upgrades will include increased robustness to RFI via increased GPS signal power (as a near-term result of GPS modernization), the use of L5 and possibly L2 civil signals, and integration of airborne GPS receivers with inertial instruments.

One promising aspect of WAAS and LAAS development is the degree to which WAAS and LAAS are being pursued outside the U.S. Nations or regions pursuing WAAS or SBAS-like systems include Europe, Japan, China, India, and Australia and have attracted considerable interest in Korea and South America. LAAS is being actively pursued in Europe and Asia. Europeans and Asians have taken a leading role in some aspects of WAAS and LAAS technology, such as pseudolites and future GEO ranging satellite concepts (e.g., see [57]). International acceptance of WAAS and LAAS and international agreement on SBAS and GBAS standards is critical to providing the full benefit of WAAS and LAAS to civil aviation worldwide.

7.0 Conclusions

WAAS and LAAS are the products of a long train of developments in GPS and differential GPS technology, particularly with regard to reference and master station algorithms, data link message and transmission system design, and integrity algorithms and safety modeling. The last of these is the most challenging because of the relatively high degree of uncertainty regarding the nature and probability of GPS and WAAS/LAAS failure modes.

The key to WAAS and LAAS integrity assessment is the definition of protection levels to express position error bounds at defined integrity risk probabilities. These protection levels bound rare-event errors due to nominal conditions (H0) and, where necessary, specific fault conditions. WAAS and LAAS users compute protection levels in real-time and compare them to defined alert limits for particular operations to obtain an indication as to whether or not the operation is safe. The key to improving WAAS and LAAS performance is developing improved algorithms, making additional measurements, or finding justifications for relaxing over-conservative assumptions built into WAAS and LAAS integrity assessment. These contribute to reducing vertical protection levels for given GPS satellite geometries and thus allowing WAAS and LAAS to (a) support operations with tighter alert limits, and (b) enhance the availability of existing operations.

The technologies and integrity-assessment methods developed for WAAS and LAAS are not only beneficial to civil aviation. As the very high nominal accuracy and availability of GPS SPS and DGPS becomes used in more and more civil applications, uses with safety-of-life criticality (including marine, railroad, and intelligent highway applications) are likely to become common. The integrity algorithms developed for WAAS and LAAS can be easily adapted to these other applications and provide a road-map for certification of these operations. If this occurs, WAAS and LAAS will have made a very important and widespread contribution to the future worldwide usefulness of GPS and GNSS technologies.

BIOGRAPHIES

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ACKNOWLEDGMENTS

The authors would like to thank Brad Parkinson, Dave Powell, Clark Cohen, Changdon Kee, Boris Pervan, A.J. Van Dierendonck, Pratap Misra, Dan Hanlon, Leo

Eldredge, Steve Hodges, J.C. Johns, Deane Bunce, Ray Swider, Ron Braff, Bruce DeCleene, Barbara Clark, Victor Wullschleger, Tim Murphy, Ted Urda, and Frank Van Graas for their help during our years of WAAS and LAAS development. Peggy Brister was very helpful in reviewing the original draft of this paper. The advice and interest of many other people in the Stanford GPS research group is appreciated, as is funding support from the FAA WAAS Program Office (AND-730) and LAAS Program Office (AND-710). The opinions discussed here are those of the authors and do not necessarily represent those of the FAA or other affiliated agencies.

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