The Advantages of Local Monitoring and VHF Data Broadcast for SBAS

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ABSTRACT

In Space Based Augmentation Systems (SBAS), many reference receivers are placed throughout a large region, and their measurements are combined to create a set of corrections for each ranging satellite as well as for ionosphere delays. These corrections as well as confidence parameters are broadcast to the user via Geostationary satellites. Unfortunately, today's SBAS systems do not necessarily achieve the highest levels of service desired for aviation applications. The U.S. Wide Area Augmentation System (WAAS) is capable of guiding an aircraft to within 250 feet of the ground, just shy of the CAT I decision height of 200 feet and well short of a CAT III autoland operation. The accuracy of WAAS system has been consistently observed to be better than 2 m (95%) throughout the U.S, which is within the accuracy requirements for both CAT I and CAT III operations. However, the error bounds reported by WAAS are several times larger due to the possible impact of unobserved anomalies on WAAS users.

One approach to improving SBAS performance is to add a GBAS-like local monitor at airports for which CAT I or better service is desired. This local monitor could be used to identify times when the SBAS performance is such that it permits these more demanding operations. Because the local monitor is within 10 km of the airplane and the runway, it can detect local error sources that SBAS cannot. This in turn leads to tighter confidence parameters than SBAS can broadcast. Because the local monitor is independent of the broadcast corrections, it is not possible for the local monitor to introduce an actual measurement error. At worst, it could miss an existing SBAS error and fail to provide an integrity warning. However, this would require simultaneous offsetting failures of two independent systems. As such, it may be possible to design the system with less stringent multipath and receiver failure requirements than those that apply to "traditional" GBAS.

Once a local presence at a particular airport is established, the local monitor would broadcast the SBAS corrections and reduced confidence bounds over a local VHF data broadcast designed to fit within the existing GBAS standards. In this way, it is similar to the Australian Ground-based Regional Augmentation System (GRAS) with the addition of local monitoring to provide improved local performance. This paper introduces the Local Area Monitor (LAM) concept, explains how it is envisioned to work, and discusses its advantages and disadvantages relative to the existing SBAS, GBAS, and GRAS means of supporting GNSS-based precision approach.

1.0 Motivation for Local Area Monitoring

The concept of the Space Based Augmentations System (SBAS) has been around since the early 1990's. In SBAS, many reference receivers are placed throughout a large region for which coverage is desired, and their measurements are combined to create a set of corrections for each GNSS satellite in view as well as for ionosphere delays. These corrections as well as confidence parameters on the accuracy are broadcast to the user via Geostationary satellites as data encoded onto additional GNSS ranging signals. Several systems are either well underway or are already commissioned. These include the Wide Area Augmentation System (WAAS) in the United States, the European Geostationary Navigation Overlay Signal (EGNOS) in Europe, the MTSAT Satellite-based Augmentation System (MSAS) in Japan, and the GPS Aided Geostationary-Augmented Navigation (GAGAN) system in India.

Unfortunately, SBASs do not necessarily achieve the highest levels of service desired for aviation applications. WAAS, which achieved Initial Operational Capability (IOC) in July 2003, is capable of guiding an aircraft to within 250 feet of the ground by supporting reasonable (95 – 99%) availability for a Vertical Alert Limit (VAL of 50 meters). While this is a useful service, it falls shy of the CAT I decision height of 200 feet and well short of a CAT III autoland operation. The accuracy of the WAAS system since IOC has observed to be better than 2 m (95%) throughout the U.S, which is within the accuracy requirements for both CAT I and CAT III operations (see [1]). However, the vertical error bounds or "Vertical Performance Levels" (VPLs) reported by WAAS are roughly an order of magnitude larger than this due to the potential impact of rare anomalies that might not be observable to the WAAS reference network within the time to alert (see Figure 3 in Section 3.0). Potential severe ionosphere spatial-decorrelation anomalies are the dominating cause of high protection levels in WAAS (see [2,3]).

Because SBAS system integrity and availability performance is limited by what SBAS cannot see, one means of improving its performance is to add additional monitor stations near airports where tighter VPLs are desired. These monitors could be used to verify that no potentially-unforeseen threats exist within the region surrounding the airports equipped with them (anomalies are rare; thus this will be the case the vast majority of the time). When this "local verification" exists, the local monitor can "re-broadcast" the received SBAS corrections along with confidence parameters that are much tighter than what SBAS can support. Since these improved confidence parameters are only valid close to the monitor, separate corrections and confidence parameters for the local area would be broadcast using the Ground Based Augmentation System (GBAS) VHF Data Broadcast (VDB) standard in a manner similar to that of the Australian Ground-based Regional Augmentation System (GRAS) (see [4]). Using the GBAS VDB standard allows aircraft equipped for GBAS but not SBAS to also utilize the service.

This paper introduces the design of the Local Area Monitor (LAM) and evaluates its advantages and disadvantages. Section 2.0 outlines the basic concept of both the LAM and the related "SBAS repeater" system, and Section 3.0 discusses the potential benefits of LAM as an augmentation of SBAS and as a faster means to achieve CAT I precision approach capability. Section 4.0 describes the range-domain-based LAM architecture, and Section 5.0 shows its projected availability for supporting CAT I precision approaches. Section 6.0 describes the implementation of an "SBAS repeater" system, and Section 7.0 summarizes the paper and explains the next steps in transforming the LAM concept from paper to reality.

2.0 The Local Area Monitor (LAM) Concept

Figure 1 shows the elements of the proposed Local Area Monitor and how they would work together to improve on existing SBAS performance. The LAM equipment added to SBAS includes a local GPS receiver (perhaps with multiple receivers and antennas to improve robustness to individual receiver faults) that receives both GPS and SBAS GEO signals and a VDB transmitter for the broadcast of SBAS corrections (modified to fit into the GBAS ICD format) and modified LAM protection levels in GBAS format (see [5]). The local receiver is responsible for both processing the corrections as an SBAS user would in order to transform SBAS "vector" corrections into the scalar corrections used in GBAS (see Appendix A of [6]). In addition, the local receiver checks the validity of the resulting scalar corrections by comparing them to the local scalar corrections that would be computed by a GBAS ground station following the procedure specified in the FAA Local Area Augmentation System (LAAS) CAT I Specification [7]. This comparison, along with pre-derived models of nominal SBAS accuracy, is used to detect faults and compute the error confidence parameters that are broadcast to nearby aircraft.

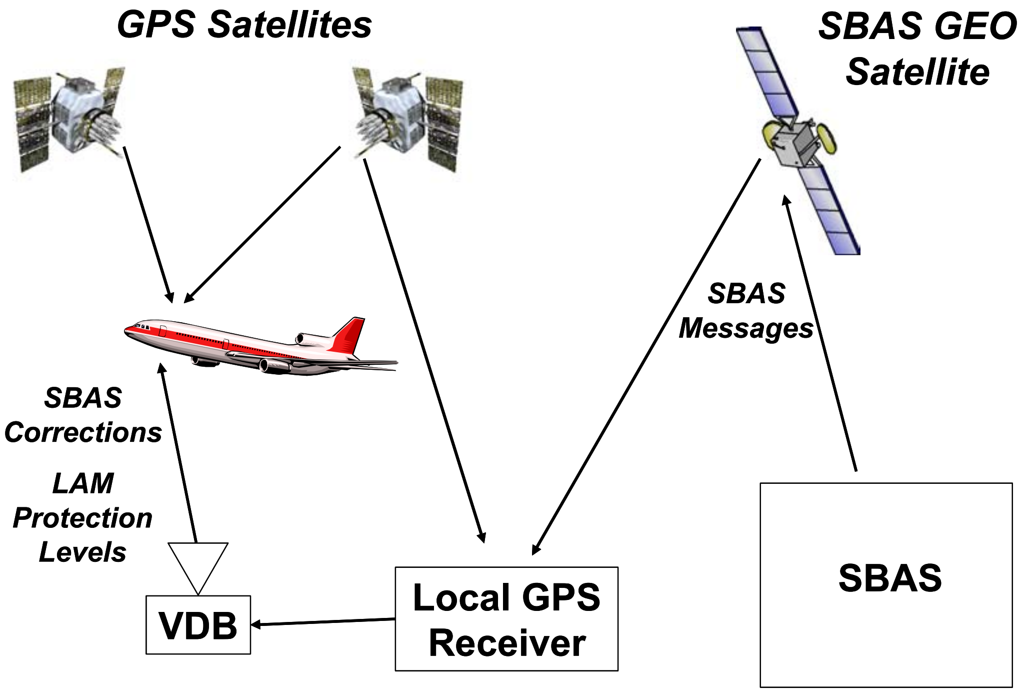

Figure 1: Local Area Monitor (LAM) Concept Diagram

As noted above, the reduced confidence parameters in the LAM messages are only valid within a certain distance of the local monitor. The GBAS ICD format includes a "D_{max}" parameter that defines the maximum distance from the GBAS reference point (in this case, the location of the local receiver antenna) for which the broadcast corrections and confidence parameters can be used [5]. Also note that the architecture in Figure 1 is somewhat limited by the latency that exists due to the use of SBAS GEO messages to receive corrections. This latency could be removed by installing direct data connections from SBAS to each local receiver, but the added cost likely outweighs the benefit of reducing latency (this issue is still under study).

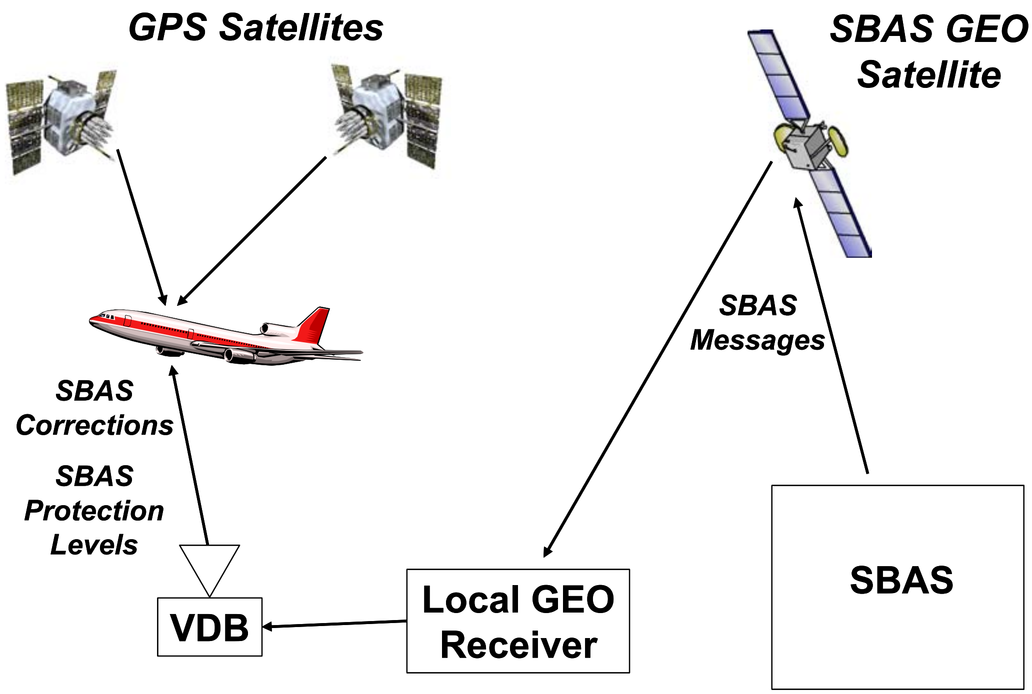

Figure 2: SBAS Repeater Concept Diagram

Figure 2 shows a concept similar to LAM in which the local receiver does no monitoring. Instead, its sole purpose is to receive SBAS corrections via GEO and re-broadcast them in GBAS format with little change. Because this local receiver does no monitoring of the SBAS corrections, it has no basis to reduce the broadcast SBAS confidence intervals – it simply provides SBAS-level service to nearby users equipped to receive GBAS VDB messages. This variant is known as the "SBAS repeater", and it is the one that is the most similar to the Australian GRAS. While the primary motion of fielding SBAS repeaters instead of LAM systems would be to expand SBAS coverage to users that are only equipped for GBAS, it also serves as a backup mode to the LAM concept in Figure 1 by being able to support SBAS performance when local GPS measurements are excluded due to faults within the local receiver [8]. Of course, if the local receiver fails entirely, and switchover to a redundant local receiver is not possible, both LAM and SBAS-repeater services would be unavailable until at least one local receiver is working.

3.0 Advantages and Limitations of Local Area Monitoring

In Section 1.0, several advantages of LAM from the SBAS point of view were mentioned. LAM addresses the limitations of SBAS observability that lead to high protection levels by adding observations in the vicinity of airports where lower protection levels (and thus support of CAT I precision approaches) is desired. At the same time, since LAM has no impact on the SBAS corrections themselves (it merely translates them into scalar corrections at its location), the LAM introduces no added integrity risk to SBAS. From a monitoring point of view, the worst thing that could happen would be an anomalous SBAS error below the SBAS VPL (but above the 10-meter VAL for CAT I approaches) that is not detected by the LAM due to a simultaneous and independent LAM failure that "cancels out" the SBAS error. Short of this exceedingly-improbable event, the LAM improves local SBAS observability (and thus lowers SBAS protection levels) without any other penalty to SBAS.

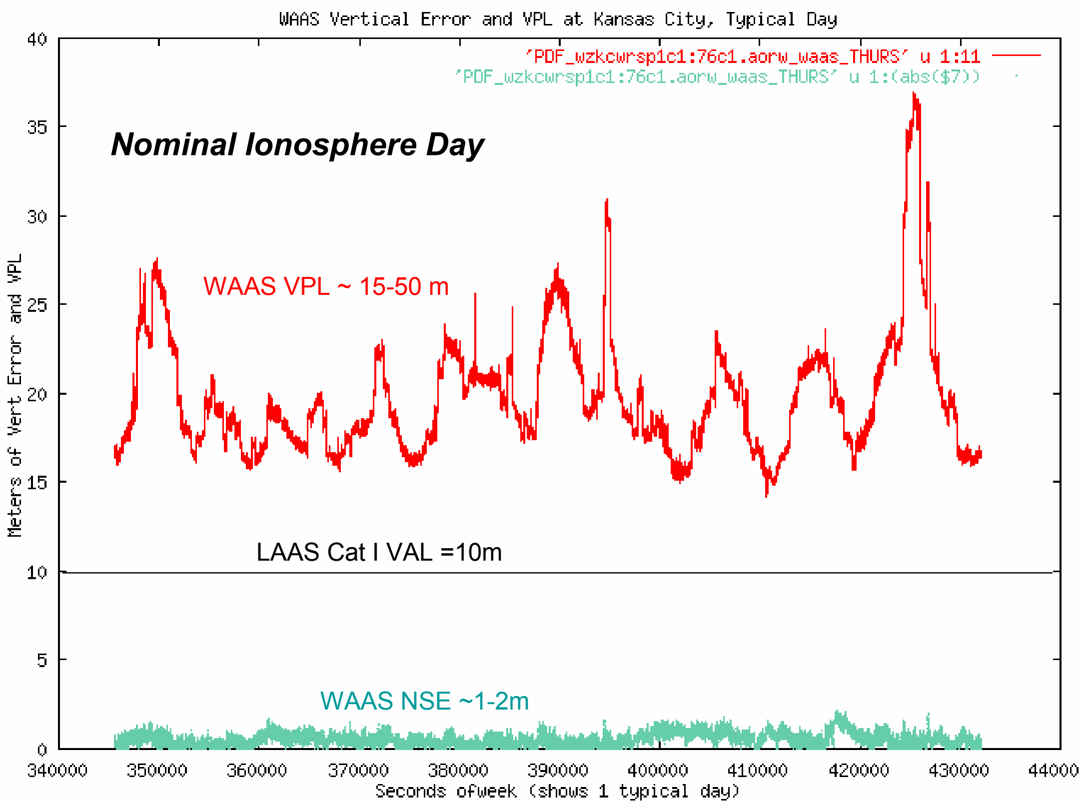

Figure 3: WAAS Vertical Position Accuracy and Protection Levels on a Typical Day [1]

LAM also offers advantages relative to the current plan to achieve CAT I precision approach by installing GBAS sites at individual airports. GBAS requires three or more ground reference receivers with fully-certified hardware and software (since these receivers directly generate the corrections broadcast to users). To gain the full benefit from these receivers, intricate dipole/helibowl Multipath Limiting Antennas (MLAs) will be fielded to minimize ground-reflection multipath errors to the maximum degree possible (see [10]). The same does not apply to LAM. Because LAM accuracy is generally limited by the nominal accuracy of SBAS (see Figure 3, from [1], for an example of WAAS accuracy and VPL on a typical, nominal-ionosphere day), the additional accuracy of MLA's is less advantageous. Instead, simpler and cheaper choke-ring (GAD-B-Class – see [11]) antennas should suffice, and this will greatly simplify LAM airport siting. In addition, because the LAM receivers are monitoring already-certified SBAS corrections, it is likely that the LAM receivers and software will not require the same degree of certification as do GBAS reference receivers. While this has not yet been confirmed, it is quite possible that, on a per-airport basis, CAT-I-capable LAM will be significantly cheaper and easier to install than CAT I GBAS and would be ready for service sooner as well.

While LAM can only improve upon existing SBAS performance, it does have two significant limitations when compared to CAT I GBAS. The first is that, while GBAS can be fielded anywhere, LAM must be fielded within existing SBAS coverage. While this is a significant constraint at present, it will become less and less so with time as additional SBAS networks are fielded and certified (Figure 4 shows the combined coverage of the most-mature SBAS networks: WAAS, EGNOS, and MSAS). The second limitation is that LAM, being limited by SBAS accuracy, will not achieve the same CAT I availability as would GBAS,

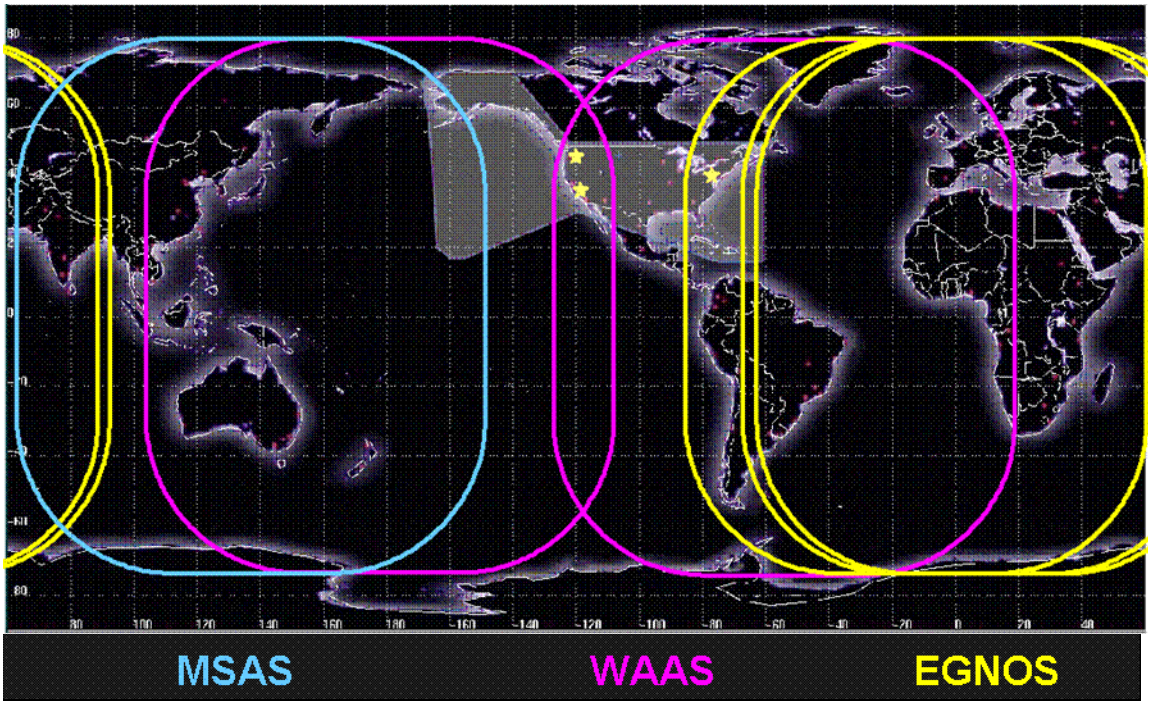

Figure 4: Global Extent of SBAS Coverage

particularly an MLA-equipped GBAS. These limitations, along with the fact that CAT II/III service is needed from augmented GNSS in the future, make it clear that LAM is not a replacement for GBAS. Instead, if fielded, LAM would serve as a stepping-stone toward a future CAT II/III-capable GBAS. In countries well-covered by SBAS, LAM may replace CAT I GBAS as this intermediate step if the advantages discussed above make it possible to achieve acceptable CAT I availability significantly sooner and cheaper than CAT I GBAS.

4.0 Range-Domain Implementation of Local Area Monitoring

Two different but complementary approaches to LAM have been proposed [9,24]. The approach described in this paper (from [9]) compares SBAS corrections (converted into scalar corrections for the LAM location as described in Appendix A of [6]) to GBAS corrections (computed as described in [7]) for each satellite in view of the LAM as follows:

$$\hat{\delta} = W - L \tag{1}$$

where W is the scalar SBAS correction for a given satellite, and L is the corresponding LAAS correction (after the LAM receiver clock bias has been removed as per [7]). If the LAM measurement were perfect, this equation would express the LAM user range error as a bias due to the error in SBAS. The LAM receiver also has local measurement error (albeit smaller than typical SBAS error) that must also be taken into account. A vertical protection level equation for LAM users thus includes both error contributions as follows (see [9] for details):

$$\mathrm{VPL}_{LAM} = K_{bnd}\sqrt{\sum_{i=1}^{N} S_{v,i}^{2}\sigma_{tot,i}^{2}} + \left|\sum_{i=1}^{N} S_{v,i}\hat{\delta}_{i}\right| \tag{2}$$

where the first right-hand-side term expresses the impact of nominal LAM errors at a K_{bnd}-sigma level (K_{bnd} is based on the sub-allocated rare-event probability for which this VPL applies), and the second right-hand-side term expresses the bias-error impact of the measured difference between SBAS and LAM corrections. In both terms, the third row of the geometry translation matrix S (or S_v) is used to convert range error into vertical position error over all N usable satellites. The local range measurement error standard deviation (σ_{tot}) is an RSS of LAM measurement error, (presumed) user measurement error, and ionosphere and troposphere spatial decorrelation errors:

$$\sigma_{tot} = \sqrt{\sigma_L^2 + \sigma_{air}^2 + \sigma_{iono}^2 + \sigma_{trop}^2} \tag{3}$$

This model of the LAM protection level must be converted to fit within the existing GBAS ICD message fields in such a way that user protection levels computed according to GBAS standards exceeds the "true" LAM protection level from (2) [5,12]. A detailed method for doing this is developed in [9]. The key change is a modified equation for the value of σ_{pr_gnd} broadcast by the LAM (see equation (16) in [9]) and the broadcast of $\hat{\delta}$ values in the GBAS "B-values". The result is that the GBAS VPL_{H1} calculated by users in accordance with the LAAS MOPS [12] matches the desired VPL_{LAM} in (2). A desirable side effect of the translation in [9] is that the user-computed VPL_{H0} typically exceeds VPL_{H1} and thus has the most influence on user availability. By varying a "free parameter" in the translation, the number of healthy GBAS reference receivers (M), the degree to which VPL_{H0} exceeds VPL_{H1} can be controlled, as shown in Figure 5. The red line in Figure 5 corresponds to VPL_{LAM} from (2) based on just under one day of data compiled at the LAAS Test Prototype at the FAA Technical Center in Atlantic City, NJ [13]. This line essentially matches the user-computed VPL_{H1}. The green line represents the user-computed VPL_{H0} when M = 2 (the lowest possible value) is broadcast. With M = 2, VPL_{H0} almost always exceeds the best possible current VPL estimate given by VPL_{LAM}, but there are several times when it is below VPL_{LAM} and thus poses slightly higher-than-desired continuity risk. Increasing M to 4 actually increases VPL_{H0} further (unlike in GBAS) and creates the blue line in Figure 5, which always exceeds VPL_{LAM} and does so with greater margin. This margin represents "continuity margin", meaning that it makes users more robust to sudden increases in VPL_{LAM} brought on by SBAS failures or LAM failures (either would increase $\hat{\delta}$ from (1)). It is anticipated that SBAS failures will set a lower bound on LAM continuity, but increasing M gives the LAM some control over continuity risk in excess of that dictated by SBAS.

In addition to protecting against observed SBAS errors and rare-event LAM measurement errors, the LAM (using SBAS information) must protect against space-segment (satellite) faults and abnormal ionosphere spatial decorrelation. Here is a summary of how the LAM being developed by the FAA (and using WAAS) is expected to handle each of the fault modes in the GBAS threat model, approximately ordered by increasing difficulty:

1) Low Signal Power: Because WAAS is not required to monitor signal power levels to the degree that LAAS is, the LAM will need its own signal-power monitor and will use the C/N_0 monitor already proposed for the LAAS Ground Facility (LGF) (see [14]). Because low signal power failures are not immediately hazardous (unless other failures occur simultaneously), the level of certification required of this added LAM monitor should not be unduly demanding.

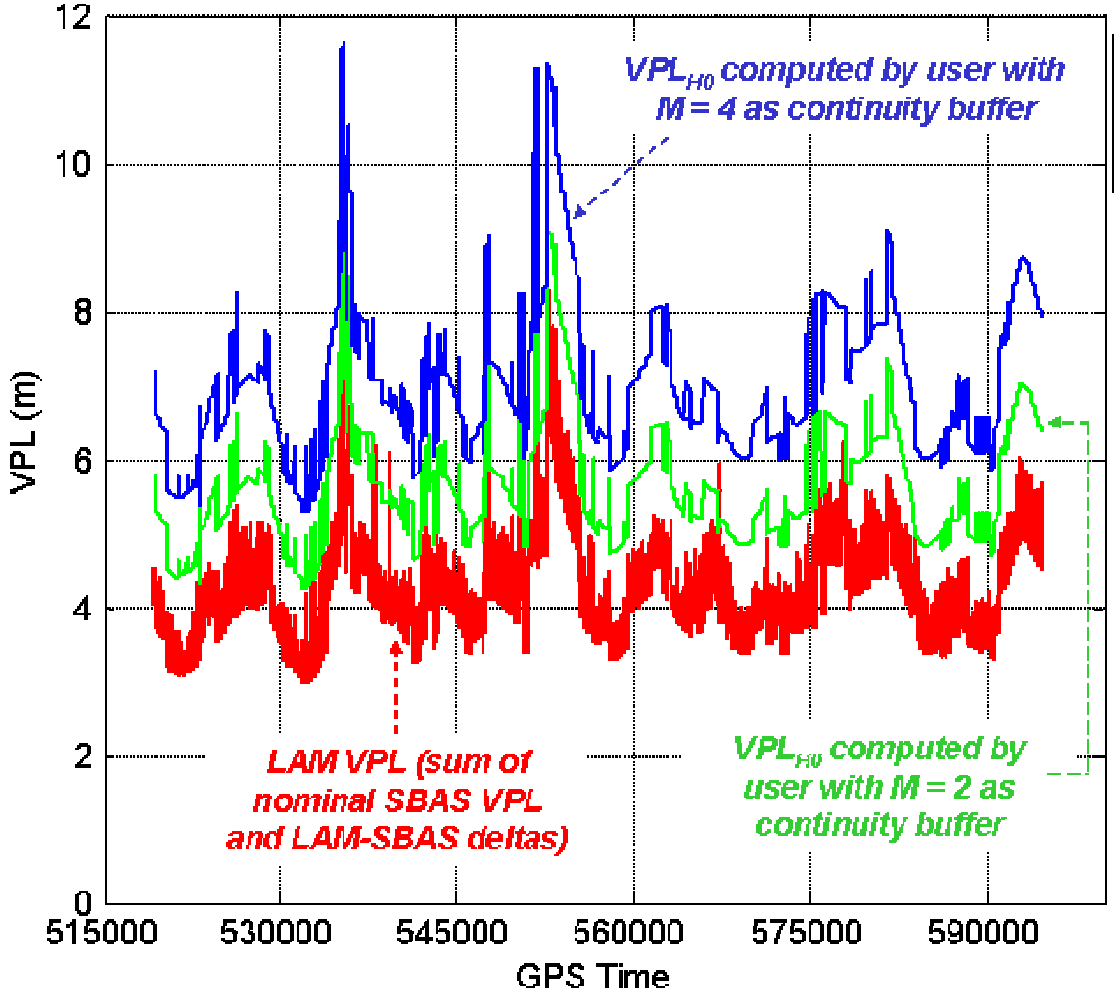

Figure 5: LAM VPL and Bounding User VPL_{H0} as Function of Continuity Buffer

2) Satellite Code-Carrier Divergence: WAAS monitoring of this failure mode is both sufficient and timely enough to support LAM operations; thus no additional LAM monitoring is needed to mitigate it. The LAM may include LGF-like code-carrier divergence monitoring (see [14]), but this would be to improve the LAM response time to potential ionosphere anomalies (see item 6 below).

3) Excess Acceleration: WAAS will detect excess range-measurement acceleration, but at a level that is much higher than what LAAS is required to detect. However, the impact of this failure on the accuracy of WAAS corrections (due to the WAAS corrections being several seconds old) will appear in the $\hat{\delta}$ statistic from (1) because LAM measurements will respond immediately to this failure. If it turns out that $\hat{\delta}$ does not respond sufficiently or quickly enough, the carrier-phase step/ramp acceleration failure monitor in the LGF (see [14]) could also be added to the LAM. However, in this case, the LAM monitor would be integrity-critical, so its software will likely require "Class B" certification.

4) Satellite Ephemeris Failure: For LAM sites within the WAAS coverage region, WAAS observability and monitoring of satellite ephemeris failures is more than sufficient to mitigate any potential hazard to LAM. Analysis to fully validate this assertion is ongoing, and care needs to be taken regarding the possibility of a switch from healthy to erroneous ephemeris data at one of the normal 2-hour navigation data update times to ensure that LAM does not prematurely declare the new (and erroneous) data to be valid.

5) Signal Deformation: Detection of code signal deformation is more challenging for LAM (and for LAAS) because it affects receivers differently depending on their front-end filtering (and resulting bandwidth) and their code correlator-chip spacing. The GBAS standards allow for a range of user receiver designs that cannot all be matched by the design of the LAM receiver (see [12]). Therefore, the $\hat{\delta}$ statistic from (1) cannot protect all user receivers in the allowed space. Equipping the LAM with LGF-like multiple-correlator signal-deformation monitors (e.g., see [15]) would dramatically increase the complexity, cost, and certification requirements of LAM and remove its advantages with respect to LAAS. Therefore, the U.S. LAM will rely on WAAS signal deformation monitoring, which will come on-line in the next major WAAS upgrade scheduled for 2008 [17] (in the meantime, LAM would be limited to what today's WAAS can detect [16]). Preliminary analysis has confirmed that the upcoming WAAS signal deformation monitoring upgrade will detect all steady-state (i.e., pre-existing on a given satellite) signal deformation failures before WAAS approves the satellite and before LAM could be affected. However, detection of transient signal deformation (suddenly occurring on a satellite already approved by WAAS) presents a time-to-alert issue because of the time needed for WAAS to detect it and because of the 3-second latency before users (including LAM sites) are alerted (see [18]). This transient-failure-response issue requires further study, which is ongoing.

6) Ionosphere Spatial Decorrelation: LAM vulnerability to extreme ionosphere spatial gradients is tied up with the ongoing study of the threat that these gradients pose to LAAS and to GBAS in general (see [19, 20, 21]). Preliminary analysis indicates that the ionosphere anomaly threat to LAM is no worse than the threat to LAAS [23], so the ongoing work intended to mitigate this risk for LAAS is directly relevant to LAM as well. Because LAM has access to WAAS Grid Ionosphere Vertical Error (GIVE) values, and these values indicate the presence of an ionosphere storm detected by the WAAS ionosphere storm detector [2, 22], LAM has a major advantage over LAAS (at least if LAAS does not have similar access to WAAS GIVEs) in getting early warning that large spatial gradients are possible. If needed, some of the monitors proposed for the LGF, such as the code-carrier divergence monitor, can be easily implemented in LAM (albeit at extra certification cost).

5.0 Potential CAT I Availability of Local Area Monitoring

Given reasonable SBAS and LAM measurement accuracy models and presuming that the failure modes discussed in Section 4.0 can all be mitigated, it is possible to approximately predict the CAT I precision approach availability that could be achieved via LAM. An analysis of LAM availability (the percentage of the time that the user-computed LAM VPL with $M = 4$ is below an 8 – 12 meter VAL for CAT I) for 20 CONUS airport locations using the 24-satellite RTCA WAAS MOPS almanac for GPS [6], including historically-observed probabilistic weighting of GPS satellite outages down to 4 satellites out, has been conducted. One day of (repeatable) GPS geometries was simulated over 5-minute intervals, and a 7.0-degree elevation mask angle was used at each user location [9]. Standard GBAS ground accuracy designator (GAD) models were used [12, 25], and two models of nominal WAAS accuracy (proposed in [24]) were considered: a "moderate" model with $\sigma_{WAAS} = 0.26\ OF$ (meters), and a more conservative "severe" WAAS error model with $\sigma_{WAAS} = 0.39\ OF$ (meters). In both cases, OF represents the ionosphere obliquity factor that relates zenith

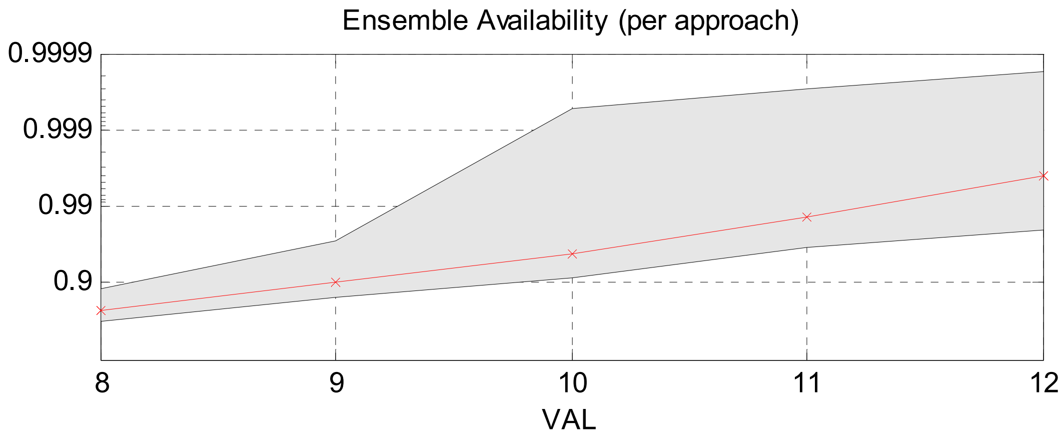

Figure 6: Baseline LAM Availability Projection (One GAD-B-Class Antenna)

ionosphere delay to actual "slant" delay observed at a given elevation angle [6], which ranges from 1 at zenith (90 degrees elevation) to just over 3 at 5 degrees elevation. Finally, a limit of 6 "critical satellites", or satellites whose individual loss would cause VPL to exceed VAL unexpectedly and thus lead to loss of continuity, was enforced as per the LAAS MOPS [12]. This limit is not needed to protect LAM continuity, because LAM continuity will almost certainly be limited by that of SBAS, but it is a constraint LAM users originally equipped for GBAS may apply anyway.

Figure 6 shows the resulting projection of baseline availability in which the "moderate" WAAS error model is used and a single LAM receiver uses a GAD-B-class choke-ring antenna (additional LAM receivers may be present, but only one contributes to the calculation of $\hat{\delta}$ in (1)). The upper and lower lines represent the best and worst availability at individual locations across the 20 CONUS user locations simulated, and the range of availability between these extremes is gray-shaded, with the red line representing the mean availability over all 20 locations. Because the mean availability in this case is well below the desired minimum availability of 0.99 for a 10-meter VAL (the current CAT I GBAS requirement), some improvement is needed. Note that, in this case, overall or "ensemble" continuity risk over all available GPS geometries is approximately 10^{-5} per 15 sec for a 10-meter VAL (3×10^{-7} per 15 seconds for a 12-meter VAL), while the "specific" continuity risk, meaning the loss-of continuity probability for the "worst" available geometry, is about 10^{-4} per 15 sec for a 10-meter VAL. These numbers do not include loss-of-continuity due to WAAS failures or false alerts, which are expected to occur at a rate of about 1×10^{-4} to 5×10^{-4} per 15 seconds based on estimates made from data in WAAS PAN reports 8 – 11 [1]. Since continuity risk due to WAAS failures equals or exceeds continuity risk due to LAM in this analysis, there is no particular need to improve LAM continuity unless future WAAS improvements make LAM continuity the dominant factor in overall continuity loss.

One means of improving LAM performance is simply to field multiple local receivers, as LAAS does. Figure 7 shows the potential LAM availability if two GAD-B-class antennas are used to generate the $\hat{\delta}$ statistic (i.e., measurements of two GAD-B-class antennas are averaged, reducing overall error by roughly $(2)^{-0.5}$ and resulting in the GAD-B2 error curve in [25]). In this example, the mean availability increases significantly to just over 0.99 for a 10-meter VAL. While this mean result falls well short of the expected mean availability of CAT I LAAS, it may be acceptable from an operational point of view. In

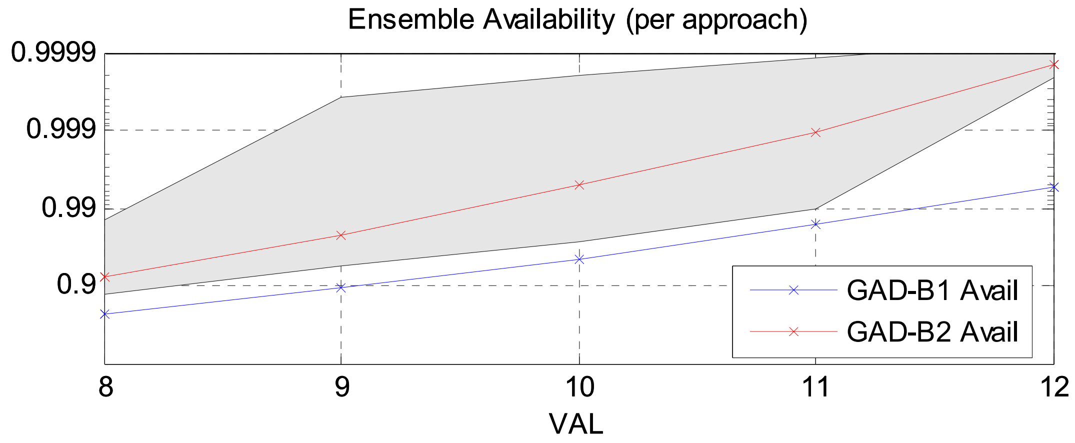

Figure 7: LAM Availability Projection with Two GAD-B-Class Antennas

addition, the maximum availability jumps to above 0.999 at a VAL of 9 meters as opposed to 10 meters.

Figure 8 shows the impact of a different (and less expensive) change to the baseline (GAD-B1) system: broadcasting $M = 2$ instead of $M = 4$, which trades reduced continuity (due to the VPL_{H0} margin over VPL_{LAM} being reduced – see Figure 5) for improved availability. The resulting availability improvement is substantial and is very similar to that of the GAD-B2 case in Figure 7. In Figure 8, the mean availability is just slightly worse than that of Figure 7, and the range between minimum and maximum availability is slightly smaller. However, specific continuity risk is much worse than the baseline case or the GAD-B2 case: 0.003 per 15 seconds. Ensemble continuity is also significantly worse (3×10^{-4} per 15 seconds for a 10-meter VAL and 3×10^{-6} per 15 seconds for a 12-meter VAL).

Because the level of continuity loss for the $M = 2$ case in Figure 8 probably exceeds that of SBAS, $M = 2$ is not likely to be implemented. The compromise case of $M = 3$ (particularly combined with GAD-B2) is likely a much better choice. Additional availability results are shown in [9], and work continues to find the most cost-effective LAM design.

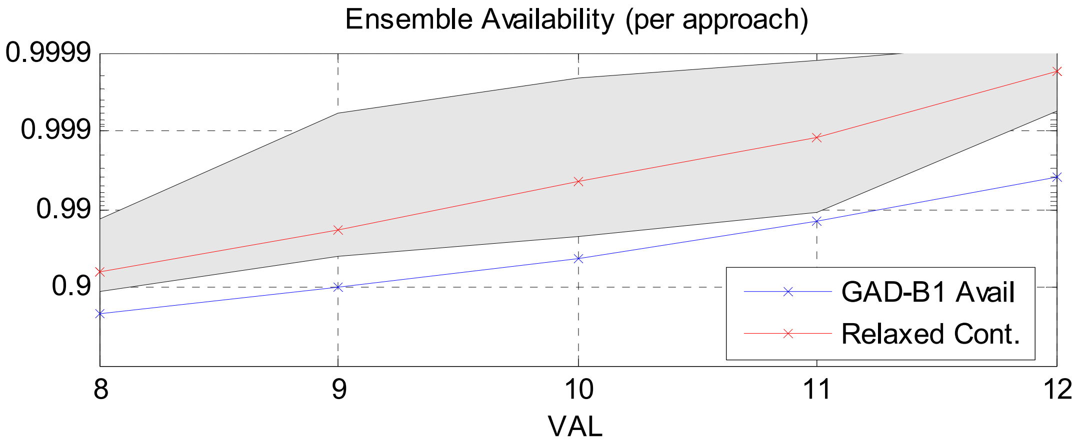

Figure 8: LAM Availability Projection with $M = 2$ (One GAD-B-Class Antenna)

6.0 SBAS Repeater Implementation

As described in Section 2.0 and shown in Figure 2, the SBAS repeater is a LAM without local monitoring, either by design (to eliminate the requirement that local receivers monitor GPS measurements) or as a backup mode to LAM which is used when LAM rejects all local GPS measurements (due to some failure or combination of failures within the LAM) but is still able to receive and decode SBAS corrections with the required integrity. The lack of local monitoring of GPS measurements means that SBAS performance cannot be improved upon, but providing SBAS-level performance to GBAS-equipped users is still of value because the 50-meter VAL that WAAS supports for LPV operations supports precision approaches down to a 250-foot decision height (compared to 200 feet for CAT I). In addition, by broadcasting Final Approach Segment (FAS) data in the GBAS Type 4 Message (see [5]), the SBAS repeater provides approach-specific information for the airport equipped with it to all nearby GBAS-capable aircraft.

Because the SBAS repeater system is the closest match to the Australian GRAS (see [4]), the proposed GBAS SARPS ICD modifications for GRAS (which are still in draft form) are the best way to broadcast SBAS-repeater information. The proposed GRAS modifications to the GBAS ICD are designed to make the older GBAS ICD better fit with the performance capabilities of GRAS (and also SBAS). For example, the largest VAL that can be broadcast using the LAAS ICD protocol is 25.4 meters (see [5]). The proposed GRAS modifications make it possible to broadcast a VAL of 50 meters, which GRAS and SBAS can support.

While the GRAS modifications are ideally-suited to the SBAS repeater concept, it is likely that the SBAS repeater will be needed to support aircraft equipped with existing GBAS equipment that has not been upgraded to also support GRAS. Since the existing LAAS ICD cannot support a VAL of 50 meters, the best option appears to be to broadcast an “artificial” VAL of 25 meters while also broadcasting one-half of the actual non-zero sigma values generated from the SBAS User Differential Range Error (UDRE) and GIVE values [8]. In other words, the SBAS repeater “pretends” that it is supporting an operation with a 25-meter VAL while telling users that its true sigmas are half of what they actually are. This is sufficient to represent LPV operations within the context of satellite navigation, but for aircraft that combine SatNav-based measurements with other sensors, the lower sigmas might give an over-optimistic projection. While this possibility requires further study, it is not likely to be a problem for two reasons. First, it has been well-established by [1] that, outside of rare anomaly conditions, WAAS errors are much smaller than is represented by WAAS VPL values. Second, users equipped with GBAS will not know that the SBAS repeater has halved its broadcast sigmas, and they will combine half-sigmas from the ground with the full airborne sigma value. Since, ideally, the airborne sigma should be halved as well, using the full airborne sigma value adds conservatism to this approach compared to the better model of LPV operations supported by the GRAS ICD modification. As a result, the SBAS-repeater concept should be able to provide LPV capability to GBAS-equipped users even if they are not equipped to handle the upcoming ICD modification for GRAS.

7.0 Summary and Ongoing Work

In this paper, the concept of Local Area Monitoring (LAM) as a means to improve existing SBAS performance has been described. By installing a local GNSS/GEO receiver at a given airport within SBAS coverage, SBAS corrections can be received and converted into

GBAS format for VDB transmission to nearby GBAS-equipped users. The monitoring conducted within the local receiver and processor verifies that, under nominal conditions, error bounds on SBAS corrections within 30 – 60 km of the LAM site are much tighter than what SBAS broadcasts. The result is a means of enhancing SBAS within the vicinity of an airport such that a 10-meter VAL (typical for CAT I precision approaches) can be achieved with an availability of 0.99 or higher. The key difference between LAM and GBAS is that LAM monitors and passes along SBAS corrections, whereas GBAS must generate and self-monitor its own corrections. Therefore, it is likely that LAM hardware and certification requirements will be much easier to meet than those for GBAS, making it possible to field CAT I GNSS capability (in areas covered by SBAS) before CAT I GBAS will be ready.

Ongoing work on the LAM is focusing on developing a real-time LAM prototype based on the FAA Technical Center LAAS Test Prototype or LTP [13]. At least two LAM concepts will be tested. One is the range-domain-monitoring approach outlined in Section 4.0 of this paper and described further in [9]. The other is a related approach proposed by MITRE/CAASD (see [11,24]) that compares SBAS and LAM measurements in the vertical position domain (i.e., after SBAS and LAM range-domain corrections have been separately applied and converted into vertical positions). This position-domain approach requires significant additional complexity because it must produce a VPL that bounds all possible user position geometries (sets of usable GNSS satellites) with resulting VPLs below VAL. However, the theory of both approaches is quite similar, and we expect that both approaches will prove to be workable (and give acceptable performance) when implemented in the LTP. The LTP-based LAM prototype is expected to begin operating in September 2005.

In addition, a significant amount of work remains to determine whether LAM can acceptably mitigate the failure modes discussed in Section 4.0 (if not, LAM will require additional local monitoring algorithms, which adds to LAM cost and complexity). Of these anomalies, satellite signal deformation and ionosphere spatial decorrelation are likely to be the most troublesome. Existing SBAS signal deformation simulations are being modified to determine how soon LAM would be alerted to possible sudden, “transient” failures. In the U.S., LAM will not achieve full mitigation of signal deformation threats until WAAS is upgraded to include signal deformation monitoring. As for ionosphere decorrelation, the ongoing research for GBAS described in [19,20,21] must be completed before the ability of LAM to mitigate this threat is fully understood. There is good reason to believe that LAM is less vulnerable to ionosphere decorrelation than is GBAS without SBAS information, and this will be verified by ionosphere threat simulations tailored to LAM using the tools already developed for GBAS.

One principle that has been demonstrated in our work on LAM is the degree to which SBAS and GBAS can work together to improve performance beyond what either can achieve separately. While it is necessary to make GBAS work with acceptable performance where no SBAS coverage exists, Figure 4 suggests that SBAS coverage will eventually exist in most populated areas of the world. Based on the degree to which SBAS makes LAM simpler and cheaper than GBAS, GBAS should also be designed to take full advantage of SBAS information where possible in order to improve availability, reduce equipage and certification requirements, or both. In the meantime, LAM may serve as the bridge between today’s SBAS capability and a future GBAS with SBAS support that achieves very high availability for CAT II/III precision approaches and landings.

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