GNSS Evolutionary Architecture Study

Phase I - Panel Report

February, 2008

Executive Summary

This Report documents preliminary findings of the Global Navigation Satellite System (GNSS) Evolutionary Architecture Study (GEAS) Panel. The FAA Global Navigation Satellite System (GNSS) Program Office established an expert panel consisting of FAA, DoD, JPL, MITRE, academia, and industry personnel. The Panel developed candidates for an integrity architecture for modernized GNSS that would satisfy en route, terminal, and precision approach operations as low as 200'AGL at 99.0% availability or better and be capable of providing LPV-200 performance worldwide. These architectural alternatives are based on an allocation of civil aviation requirements between space, user, and ground segments and identify conspicuous strengths and weaknesses with respect to technical, cost, schedule, operational, and institutional risks.

Each alternative integrity architecture must address all the presently identified GNSS fault modes (ionosphere, troposphere, satellite clock, navigation message, satellite signal modulation, etc.) In addition, the preferred integrity architecture will be judged against the following criteria:

- Provides 10^{-7} integrity for precision approach operations to 200' above ground level (AGL) worldwide.
- Enables a reasonable path to an autoland capability with 10^{-9} integrity worldwide.
- Is compatible with future civil aviation systems including Next Generation Air Traffic System (NGATS) and Automatic Dependent Surveillance-Broadcast (ADS-B).
- There is no dependency on technologies that may not be available by the completion of the GPS III/OCX schedules.
- Defines User equipment compatible with normal aviation development cycles.

Further corollary objectives of the GEAS effort include:

- Assess capability of modernized GPS to simplify fault detection and provide an alternate broadcast channel.
- Evaluate the integrity architecture for military aviation application.
- Enable a smooth integration of foreign GNSS constellations in the avionics
- Constructive interaction with National effort coordinated by NSSO & RITA to define/refine the GPS III end-state integrity architecture.
- Determine implications associated with WAAS transition from L1/L5 WAAS to the GPS III end-state.

The GEAS Panel identified three architectural concepts as candidates for the integrity assurance design of the future: GNSS Integrity Channel (GIC, shown in Figure 6); Absolute Receiver Autonomous Integrity Monitoring (ARAIM, shown in Figure 7); and

Relative Receiver Autonomous Integrity Monitoring (RRAIM, shown in Figure 8). These candidate architectures all include some level of aircraft monitoring to identify and remove faults before they can be included in the user navigation solution. All three candidates also employ integrity monitoring either on the satellites or on the ground to observe the satellite signals to identify and exclude faults. It's the allocation of the integrity burden on the aircraft versus the aircraft-external monitors that differentiates these architectures; GIC depends primarily on integrity monitors outside of the aircraft, ARAIM places more responsibility on the avionics (hence requires a more robust GPS constellation) and RRAIM shares the integrity burden more equally between the aircraft, the GNSS constellation, and the external monitors.

- GIC would use a combination of ground and space monitoring of the GPS satellites. One possibility would be a worldwide implementation of a dual frequency Space Based Augmentation System (SBAS). Implementation of this integrity architecture could include a regional ground-based monitoring network of GNSS receivers and communication links via geostationary satellites or other means to provide integrity and/or correction messages directly to the users. The GIC is the least demanding candidate architecture with respect to the geometry robustness of the basic GNSS constellation because over-specified navigation solutions are not required by the avionics. However, it is the most demanding in terms of messaging to the user. Integrity alerts must be provided within six seconds of the onset of a hazard.
- In the RRAIM integrity architecture concept, the user aircraft performs positioning and integrity monitoring autonomously, using current satellite measurements and a prior set of measurements validated by the external integrity monitoring. The time-to-alert requirements for these aircraft-external monitors are significantly relaxed relative to the GIC architecture because the previously validated data set that the user aircraft utilizes can age for minutes. RRAIM is implemented by checking the residual of the relative carrier phase position fix over the coasting time. RRAIM is strongly dependent on the aircraft-external monitors to provide the validated data sets used at the beginning of the coasting period. Constellation geometry requirements are more demanding than GIC, but relaxed relative to ARAIM.
- The ARAIM integrity architecture would essentially be an extension and refinement of existing RAIM algorithms. ARAIM would improve on today's RAIM because the large ionospheric errors affecting range measurements would be removed using dual-frequency measurement diversity. ARAIM residuals would be subject to more sensitive thresholds and smaller position errors could be detected without loss of confidence. ARAIM is almost, but not quite, autonomous. External monitoring must exist for all the same faults as GIC but

> there’s a key difference, latency can be significantly increased. The external monitoring will guarantee failure probabilities for the individual satellites are as expected and provide the associated user range accuracies (URAs). ARAIM is the least demanding architecture with respect to bandwidth and latency of the integrity broadcast mechanism to the user. ARAIM is the most demanding of the candidate architectures with respect to constellation geometry and requires good geometry for the subsets created when deleting satellites from the all-in-view set.

These three integrity architectural alternatives span an extremely important trade space, i.e., GNSS constellation strength versus integrity data latency. The GIC paradigm serves well for regional systems; today's SBASs are single frequency GICs that serve CONUS, Europe, and Japan. However, a worldwide GIC is considerably more challenging given the data latencies that would have to be enforced in a worldwide system. The percentage of the globe that has a 99.5% availability of LPV-200 (Vertical Protection Level (VPL) < 35 m, Horizontal Protection level (HPL) < 40 m) for the postulated GPS constellations is shown below.

	GPS Constellation					
Architecture	24 minus 1 SV	24	27 minus 1 SV	27	30 minus 1 SV	30
GIC	86.6%	100%	97.8%	100%	100%	100%
RRAIM (30 sec coasting)	81.2%	99.4%	96.8%	100%	100%	100%
RRAIM (60 sec coasting)	74.4%	98.5%	92.8%	100%	100%	100%
RRAIM (300 sec coasting)	28.0%	76.1%	52.3%	99.6%	93.9%	100%
ARAIM	7.80%	44.7%	30.6%	94.1%	90.5%	100%

Table 1 Summary of Coverage for 99.5% Availability

Note that these three alternatives (GIC, RRAIM and ARAIM) are integrity architectures, *not* system architectures. For example, GPS IIIC may well provide an excellent mechanism to implement one (or more) of these architectures in the 2030 time frame, prior to onset of peak solar ionospheric disturbance cycle in 2033 while new messages utilizing GEOs for the broadcast channel might be a good system to implement one or more of those architectures in the 2020 time frame, prior to next solar cycle peak circa 2022. This phase of the GEAS activity focused primarily on evaluating and comparing the availabilities of the candidate architectural concepts versus the number of satellites deployed in the GPS constellation. Assumptions regarding constellation performance will be refined in the next phase of the GEAS effort.

The GEAS Panel formulated the following Conclusions for the FAA based on findings and results of this Phase of the GEAS effort.

- Next generation GNSS-based avionics can provide vertical guidance to all airports worldwide ***without*** requiring navigation equipment to be located on or near the airport. There are three candidate integrity architectures that could be implemented to provide the requisite integrity performance.
    - GPS III offers the opportunity to design integrity into the ranging signals and minimize the need for integrity augmentations but a full operational capability of this architecture is unlikely before about 2030.
- Avionics should include RRAIM and ARAIM.
    - RRAIM algorithms have the potential to allow TTA requirements to be relaxed for GNSS signal monitoring systems thereby enabling some monitoring architectures that would otherwise be ineffective or very challenging to implement.
    - While ARAIM is demanding with respect to the number of satellites required to support high LPV-200 availability, it is likely to be effective when multiple GNSS constellations are deployed.

Further in depth analyses will still be required to ensure that the candidate integrity architectural concept remains feasible and realizable. The GEAS Panel identified numerous actions for this next phase of activity in order to address three major areas: trade space refinement; integrity performance analysis; and transition strategy. Performance of this work is considered essential in developing the details associated with the integrity architecture and path forward.

The key area of study for the GEAS in the next phase is the development of the transition strategy. As the GEAS develops the details for the final architectural construct, it is crucial to map the path forward from the current infrastructure to this desired endpoint. The actual integration, or degree of integration, of the key aviation functions into the GPS Modernization Program presents significant institutional and organizational challenges that remain to be resolved as part of the ongoing GEAS and GPS III design definition efforts.

This Report contains preliminary technical information only and does not represent official US Government, FAA, or GNSS Program Office positions or policy, except where explicitly stated, quoted, or referenced.

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Section 1 Introduction

Modernized GPS will provide two civil frequencies in aeronautical radio navigation service (ARNS) bands: L1 and L5. This frequency diversity will alleviate the two most significant limitations of the current system: ionosphere induced disturbances and vulnerability to radio frequency interference (RFI). Future aircraft will likely equip using both frequencies to reap these benefits. Additionally, modernized GPS may also enable use of improved fault detection architectures and possibly provide a more convenient channel to broadcast integrity information to the users. The multiplicity of fault monitors used by aviation today could be re-distributed in order to improve performance and/or reduce cost. Today, the Wide Area Augmentation System (WAAS) ground system has nearly total responsibility for detecting fault modes as well as determining integrity for real-time operations in the service volume. With the advent of modernized GPS, the aircraft can then assume more of the assurance burden using onboard integrity monitors. Alternatively, the GPS III ground system(s) and satellites could incorporate some portion of the necessary fault monitors. In addition, GPS satellites of the future could broadcast integrity information to the users and obviate the need for WAAS/SBAS broadcast geostationary satellites utilized today.

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These architectural alternatives are based on an allocation of civil aviation requirements between space, user, and ground segments of the GNSS and identify conspicuous strengths and weaknesses with respect to technical, cost, schedule, operational, and institutional risks. Each alternative integrity architecture must address all the presently identified GNSS fault modes (ionosphere, troposphere, satellite clock, navigation message, satellite signal modulation, etc.) In addition, the preferred integrity architecture will be judged against the following criteria:

- Provides 10^{-7} integrity for precision approach operations to 200' above ground level (AGL) worldwide.
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- There is no dependency on technologies that may not be available by the completion of the GPS III/OCX schedules. In other words, there is no dependency on technologies that may not be available by the completion of the GPS III/OCX schedules.

- Defines User equipment compatible with normal aviation development cycles.

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Section 2 Background

This report focuses on the use of modernized GPS [1], [2], [3] and other new satellite navigation systems to aid the navigation of aircraft approaching airports and preparing to land. Airport approach warrants such a focused treatment because it is the most demanding phase of flight. The requirements associated with the underlying navigation system are quite extraordinary: navigation must be available greater than 99% of the time regardless of the weather; the navigation system must be especially reliable after an aircraft approach has commenced (the probability of a continuity break must be smaller than 8×10^{-6} per 15 seconds for the duration of the aircraft approach); and the navigation system must vigilantly protect against the possibility of misleading information (MI). This protection means that the navigation system must detect any threatening faults or rare-normal events within a few seconds (defined as the Time-To-Alert or TTA). Such faults are hazardous only when they produce undetected navigation errors greater than 10m to 35m (depending on the decision altitude). This performance protection property is called integrity, and the risk of an integrity failure must be less than 10^{-7} to 10^{-9} per approach.

The approach operation is depicted in Figure 1. The procedure can generally be categorized by the lowest decision altitude (DA) enabled by the navigation system. Below this altitude the pilot must have visual observation of the runway environment. Without visual cues the pilot must abort the landing and should proceed to an alternate airport. Lower DAs demand more crew training and more sophisticated navigation

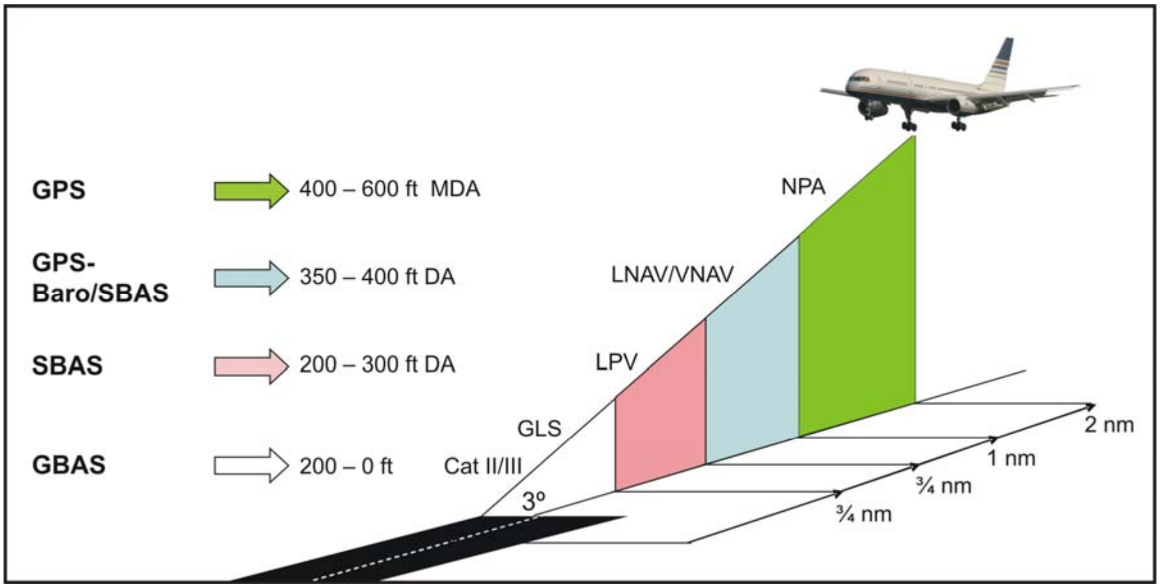

Figure 1 Approach Operational Minimums

equipment on the ground and in the air. However, a lower DA is certainly desirable during periods of inclement weather.

Non-precision approach (lateral navigation (LNAV)) refers to approach procedures where the radio equipment gives lateral guidance only and the vertical information comes from barometric altimetry. A lateral view of a non-precision approach is shown in the top half of Figure 2. As shown, the aircraft is allowed to “drive” at a certain barometric altitude until it reaches a specified distance from the airport. At that distance, it may “dive” to a lower altitude known to be clear of obstacles. These “drive and dive” procedures are not favored by pilots because the resultant workload is quite high and any such distractions are unwelcome during the stressful approach and landing phases of flight. Precise vertical guidance presents a much more manageable workload to the pilot and thus is inherently safer. This contrast is depicted in Figure 2.

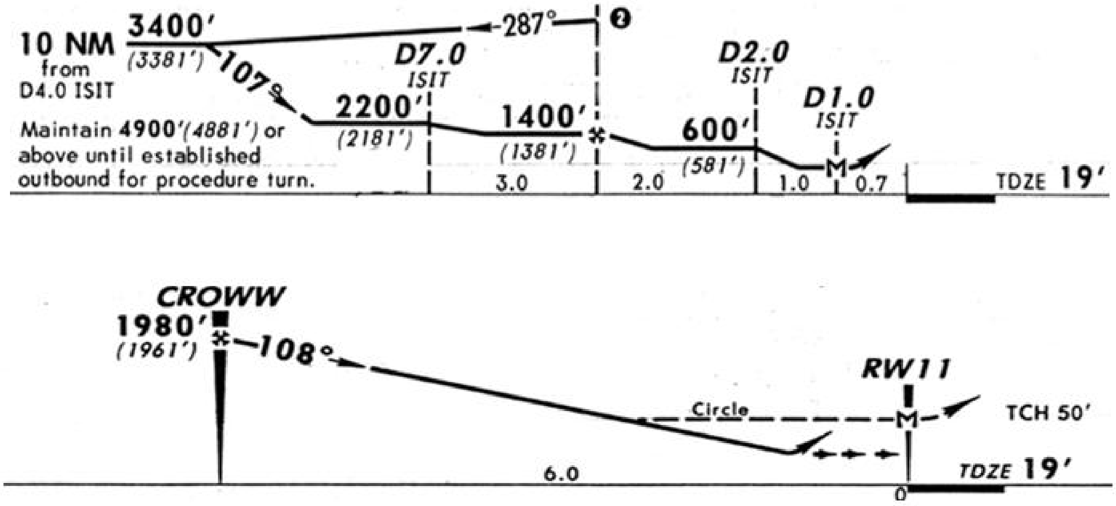

Figure 2 LNAV Approach

Provision of worldwide vertically guided precision approach is the stated goal of the aviation community and the objective for the architecture formulated by the GEAS Panel. The ability to fly an aircraft approach at a decision altitude of 200 feet anywhere in the world regardless of the weather, time of day, and without the use of any dedicated GNSS-equipment at the receiving airfield, provides significant benefits to aviation performance and safety. Moreover, satellite navigation, especially modernized GPS, is the technology enabler that provides smooth vertical guidance necessary to achieve this step towards increased air safety.

GPS was developed by the U.S. Department of Defense (DoD) to provide precise estimates of position, velocity, and time to users worldwide. The DoD approved the basic architecture of the system in 1973, the first satellite was launched in 1978, and the system was declared fully operational in 1995 [4]. A GPS user can typically estimate their location with an accuracy of better than 10 meters and determine time to better than 100 nanoseconds. Today, this capability serves over two hundred million users with a wide variety of applications. Of these, a relatively modest population of approximately two hundred thousand GPS users requires aviation integrity. However, this aviation number grows steadily since every new Airbus, or Boeing and most new General Aviation aircraft, are outfitted with a GPS receiver.

For aircraft navigation, fault detection and isolation is paramount. Faults that may cause misleading information (MI) must be detected and mitigated in real-time. The operation of GPS itself has been very reliable but faults that could cause MI have occurred. Some are man-made while others can be attributed to natural environmental effects.

For example, navigation data broadcast by the GPS satellites occasionally contains significant errors. As shown in Figure 3, the GPS satellites are monitored by a relatively sparse ground control network (Five stations are shown in Figure 3, but eight new stations have been recently added [5]). Measurements at the ground stations are used to determine and project the orbit of the GPS satellites. These orbit projections are then uploaded to the spacecraft and broadcast to the users. Generally, this estimated orbit is usually accurate to within one or two meters of the true orbit [6]. However, the broadcast ephemeris occasionally contains some rather large errors. Between 1999 and 2007, errors greater than 50 meters occurred on 24 different occasions. An outlier occurred on April 10, 2007, when the broadcast ephemeris for Space Vehicle (SV) 54 contained an error of at least 350 meters [7].

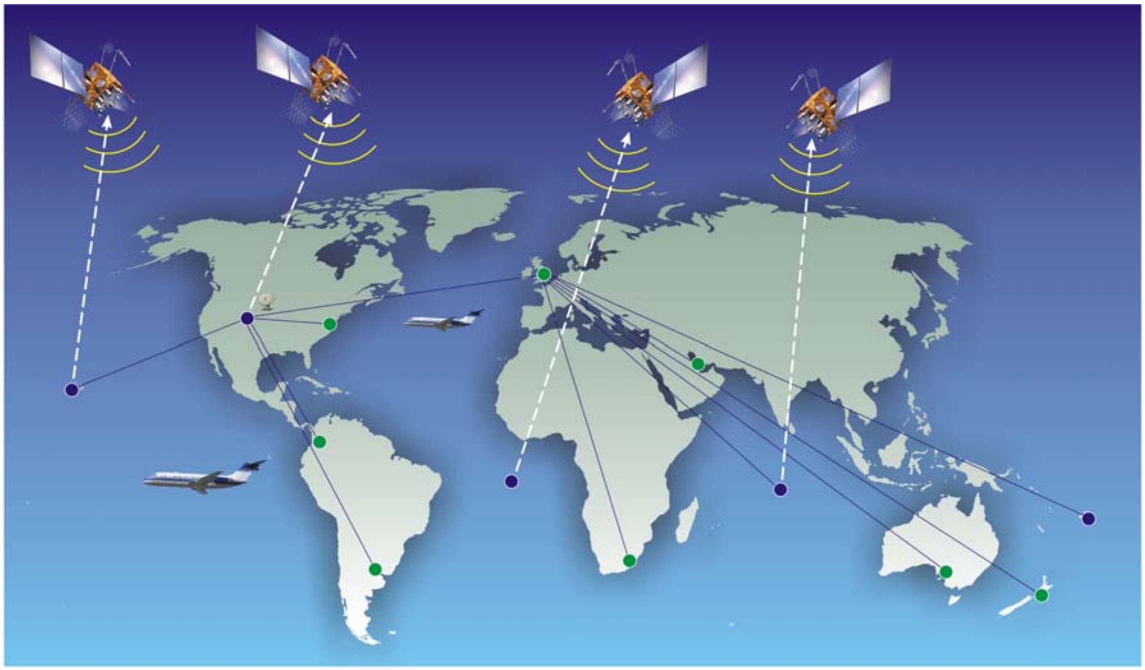

Figure 3 Global Positioning System

The navigation broadcast from each satellite also contains an estimate of the time offset of the onboard atomic clock relative to GPS system time. This time offset is nominally accurate to within nanoseconds. However, large clock runoffs were experienced on SV22 on July 28, 2001; SV27 on May 26, 2003; SV35 on June 11, 2003, and SV23 on January 1, 2004. These events generated range measurement errors of 1000 meters or more [8]. The pseudorange error on SV22 on July 28, 2001, was reported to be 200,000m by some users and 300,000m by others.

In the Fall of 1993 navigation engineers observed that the signal from SV19 was anomalous and caused range measurement errors. Specifically, the falling edge of the digital modulation was not synchronous with the master clock carried by the satellite and was actually occurring approximately 30 nanoseconds 'late'. This lag caused a ranging error of approximately 3 meters that in turn produced position errors of up to 9 meters for certain types of user receivers. This situation was corrected by switching from the active modulation unit to a backup unit available on all GPS satellites [9]. Though such anomalous performance has only been observed once in GPS operational life, it is an excellent example of the challenge associated with ensuring integrity at the required service levels for safety of life systems.

The natural operating environment presents a navigation challenge. While reluctant to call these events *faults*, these rare-normal 'natural' events must be detected with equal certainty. The ionosphere is the most likely source of such rare-normal events. The GPS satellites operate at a nominal altitude of 20,000 km and their signals traverse the ionosphere which occupies the region from roughly 80 km to above 1000 km [10]. Since the GPS signals occupy L-band the ionosphere nominally introduces a delay of a few meters during the day and approximately one meter at night. Nominally, the spatial and temporal variation in this delay is very smooth and readily correctable. However, every solar cycle contains a number of ionospheric storms where the propagation delay is much higher and spatial and temporal gradients exist as well. Datta-Barua lists some 40 significant events in the last solar peak period [11]. Only a handful of these events were considered navigation threats in the United States but *all* such events must be evaluated in real-time in order to provide the requisite system integrity for navigation.

The international civil aviation community has developed two distinct techniques for fault detection: receiver autonomous integrity monitoring (RAIM) and ground based monitoring (SBAS and GBAS). Section 3 briefly describes this first generation of fault detection techniques. It is expected that by 2025 (or 2030) GPS will be modernized and other satellite navigation systems will be available. Most importantly, modernized GPS and other new systems will broadcast signals at two frequencies suitable for aviation navigation use by virtue of their presence in an ARNS band. The current GPS constellation contains only one frequency that can be used in the civilian aircraft, L1. The future GPS frequency diversity will obviate most of the issues associated with ionospheric effects described above. Modernized GPS also enables use of a second generation of fault detection methods and techniques. Candidate architectures with such second generation integrity techniques are introduced in Section 4. Section 5 begins the GEAS Panel analysis of these architectural alternatives by reviewing the target requirements and developing basic error models. Sections 6, 7, and 8 present in depth analyses for the candidate architectures identified by the GEAS Panel. Section 9 provides a quantitative comparison of the availability for each architecture versus constellation strength; Section 10 presents the GEAS Panel conclusions and recommendations while Section 11 defines the necessary Future Work activities for the GEAS Panel.

Section 3 First Generation Integrity Monitoring

Currently two rather distinct approaches provide the real-time fault detection capability needed by aviation. receiver autonomous integrity monitoring (RAIM) is based entirely on measurement redundancy and resides in the aircraft receiver equipment. Some RAIM implementations use barometric altitude information to substitute for a satellite range measurement. Augmentations, primarily Space Based Augmentation System (SBAS) and Ground Based Augmentation System (GBAS) rely on networks of reference receivers at known locations on the ground. Both approaches are briefly described in this section. There are other variations of augmentation system such as Ground-based Regional Augmentation System (GRAS) and Special Category I (SCAT-I), but these are not discussed in the report.

RAIM requires an over-specified navigation solution. Four satellites are required to estimate the four unknown states of the aircraft - latitude, longitude, altitude, and the offset of the receiver clock relative to GPS time [12]. With five satellites, autonomous fault detection may be possible. With six satellites, autonomous fault isolation may then also be possible.

In a typical RAIM implementation [13] the avionics use all satellites in view to form a position and time estimate for the aircraft. The receiver projects this position estimate back onto the line-of-sight vectors to the individual satellites. The differences between the projections and the original pseudorange measurements are used to assess the likelihood of any underlying measurement fault. If only four satellites are available, these measurement residuals are all zero and no fault detection capability is available. With five, or more, satellites a large residual indicates the presence of a faulted satellite somewhere in the mix.

RAIM performance is critically dependent on the satellite constellation geometry. For fault detection, a minimum of five satellites in view is required. However, for fault isolation six satellites are required. The subsets formed by deleting one satellite at a time must also provide sufficient geometry for fault detection capability. RAIM is highly desirable because of its autonomy; minimal external integrity information is required. However, RAIM's ultimate utility to the user may always be limited because good RAIM coverage requires that the basic GNSS be robust with many satellites on orbit. Consequently, in 1995, when GPS achieved full operational capability (FOC) with 24 operational satellites, the FAA could only authorize RAIM-based aircraft to use GPS as a supplemental-means of navigation. This limitation means aircraft still required legacy ground-based navigation equipment on board for periods when RAIM would not be available.

Both GBAS [14] and SBAS [15] are differential GPS augmentation systems. GPS performance is discerned using GPS receivers located at known reference positions. These differential systems compare their reference receiver GPS measurements to those that should exist at their known reference receiver positions. The observed differences are then converted to corrections and error bounds that are broadcast to user aircraft in real-time. The broadcast corrections are applied by the user avionics to improve the accuracy of GPS from several meters to one meter or less while assuring the integrity of the broadcast data.

GBAS is a local area differential GPS system with all reference receivers placed on the property of the airport to be served. The GBAS corrections and error bounds are broadcast to the approaching aircraft using a line-of-sight VHF transmitter that is also located on the airport property. The International Civil Aviation Organization (ICAO) refers to these systems as ground-based because the data link is terrestrial radio [16].

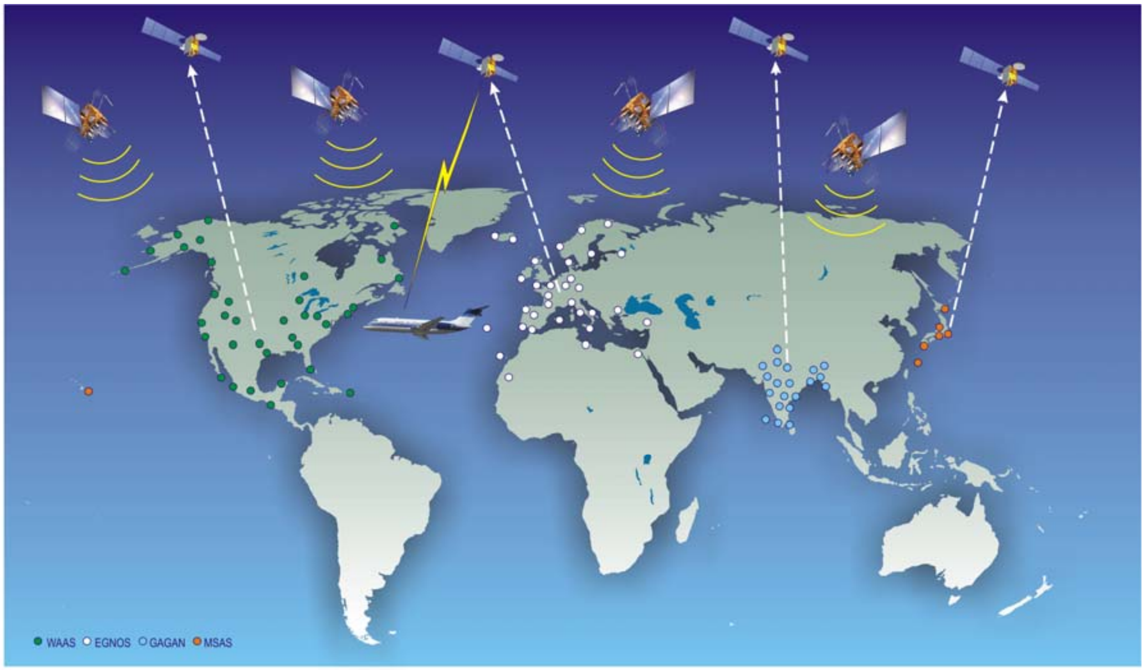

Figure 4 Space Based Augmentation Systems

As shown in Figure 4, SBAS is a wide area differential GPS system. In contrast to GBAS, SBAS reference stations span regional areas and the SBAS develops a four dimensional correction for each satellite. One element of this 4-tuple corrects the satellite clock while the remaining three elements correct the satellite ephemeris (location). SBAS also broadcasts a grid of ionospheric errors for the region spanned by the SBAS ground stations. These ionospheric corrections are only valid across the area spanned by the reference stations. The corrections are broadcast to users via a geostationary satellite with nominal earth field of view coverage. The broadcast signal-in-space (SIS) is similar to the GPS L1 C/A signal and is also synchronized to GPS time. Consequently, the geostationary satellite SIS serves two purposes: a corrections data link and an additional ranging signal suitable for navigation use.

Even though GBAS and SBAS developed corrections improve accuracy, their essential purpose is to assure integrity by providing real-time error-bounds. These bounds are called protection levels (PLs) that must overbound the true position error under all conditions and in real-time [17]. The receiver uses the current PL to determine whether a particular operation is safe. If the protection level is smaller than the alert limit (AL) required for a particular operation, then the pilot may fly that procedure. The DAs associated with aircraft approach are shown in Figure 1. As expected, the limits decrease in magnitude as the aircraft gets closer to the ground. If the PL fails to bound the navigation error, then the pilot would be attempting a landing that is not safe and there is insufficient assured integrity to conduct the operation safely. Note however, that the computed bounds (PLs) cannot be too conservative or the capability of the system can not be realized and is overly constrained. Determining the proper balance between capability and assurance is the basic issue associated with safety of life systems.

GBAS and SBAS are much less sensitive than RAIM to the geometric robustness of the basic GNSS constellation since their essential integrity information is derived by comparing the GPS measurements to ground truth. However, these augmentations do require an expensive network of reference receivers and a real-time broadcast to the airborne user. For SBAS, these networks are dense because the ionosphere must be sampled at closely spaced intervals such that sharp gradients can be detected with near certainty [18]. For example, WAAS, the SBAS for the United States, deploys 38 reference stations in North America. Finally, both GBAS and SBAS require a data broadcast mechanism to transmit integrity information to the airborne user. For SBAS, the geostationary satellite must support a bandwidth of 250 bps and the data latency associated with the onset of a failure condition must be no more than a few seconds [19]. For GBAS, the VHF Data Broadcast (VDB) conveys the information related to GPS accuracy, integrity, facility, and the approach at a rate of 31,500 bps.

Section 4 Second Generation Architectures for Aviation Integrity

GPS satellites broadcast the navigation signals in the two bands shown in the top trace of Figure 5. L1 denotes the broadcast at 1575.42 MHz and L2 denotes the broadcast at 1227.60 MHz. As shown, L1 includes a narrowband signal and a wideband signal. The narrowband signal is modulated by a spread-spectrum code, called the C/A code. This code has a modest chipping rate of only 1.023 Mcps so the null-to-null mainlobe spectral occupancy is 2.046 MHz. The wideband signal is modulated by the P(Y) code, which has a chipping rate of 10.23 Mcps so its null-to-null mainlobe spectral occupancy is 20.46 MHz. The C/A code and signal is available to all users and serves as the basis for the vast majority of today's civil applications [20].

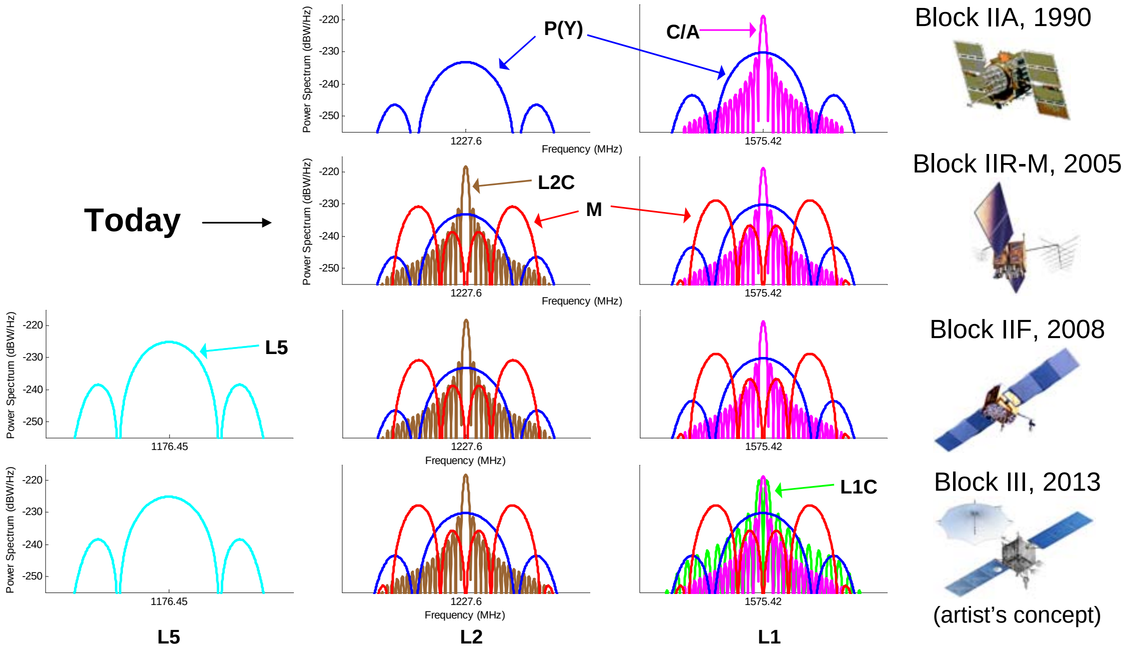

Figure 5 GPS Signal Spectrum

In 2005 the GPS IIR-M satellites began to broadcast the signals shown in the middle trace of Figure 5 [21]. These satellites continue to broadcast the original signals so existing receivers continue to operate. However, there is a new military signal at L1 and L2 and a new civil signal at L2. This new civil signal is useful to the civil community but of little importance to aviation because it does not fall in an Aeronautical Radionavigation Service (ARNS) portion of the spectrum. Civil Aviation organizations require that navigation signals occupy spectrum in ARNS designated bands so there's institutional control over the spectrum to maintain legal protection from RF interference.

At some point in 2009 based on the latest approved GPS Program Enterprise schedule, the GPS IIF satellites will begin to broadcast the signals in a third band called L5 [2]. (L3 and L4, not shown in Figure 5, carry non-navigation information for the military.) L5 is located in an ARNS band and the aviation utility of this new signal is significant since future avionics will be able to eliminate errors due to the ionosphere through use of this signal in conjunction with the L1 C/A signal. The influence of the ionosphere is different at L1 than at L5 so receivers can measure the delays at L1 and L5, compute the difference in delays, use this difference to estimate the full delay on each frequency and then determine an iono-free pseudorange measurement.

The integrity assurance designs of the future will also benefit from the frequency diversity provided by the new GPS signals. Recall that WAAS deploys 38 reference stations to serve North America. This station density is driven by the need to sample and monitor the ionosphere. The integrity architecture of the future will instead be based on airborne calculation of the ionosphere, thus SBAS will need fewer stations to provide improved service to dual frequency users. Current estimates show that expansion of SBAS to provide global coverage for dual frequency users may only require as few as 30 reference stations to provide more robust service. This relief is depicted in Figures 6, 7, and 8, which show potential integrity architectures of the future. They are intended to show sparse monitor networks compared to the dense SBAS monitor network depicted in Figure 4.

Expansion of SBAS may *not* be the most cost effective alternative if the allocation of the integrity workload can be optimized between the aircraft, satellites, and ground systems. In order to assess different alternatives for the integrity allocations, the GEAS Panel developed several potential architectural concepts but ultimately identified three architectural paradigms as candidates for the integrity assurance design of the future. These candidate architectures are: GNSS Integrity Channel (GIC, shown in Figure 6), Absolute Receiver Autonomous Integrity Monitoring (ARAIM, shown in Figure 7), and Relative Receiver Autonomous Integrity Monitoring (RRAIM, shown in Figure 8). All three candidate architectures include some level of aircraft monitoring to identify and remove faults before they can be included in the user navigation solution. All three candidates also employ a ground monitoring network that observes the satellite signals to identify and exclude faults. However, each architecture allocates very different fractions of the integrity burden on the aircraft versus the aircraft-external monitors. GIC allocates most of the responsibility on monitors external to the aircraft so it is similar to SBAS in this respect. ARAIM places most of the responsibility on the avionics so it is similar to

RAIM and requires a more robust GPS constellation. RRAIM shares the integrity burden between the aircraft, the GNSS constellation, and the external monitors so it has features associated with both SBAS and RAIM.

Figure 6 GPS Integrity Channel

The GIC could essentially be a worldwide implementation of a dual frequency SBAS. As mentioned above, the airborne receiver removes the majority of the ionospheric delay using dual frequency measurements while the aircraft-external monitors detect all satellite faults including ephemeris errors, clock runoffs, and anomalous signals. One possibility would be a worldwide implementation of a dual frequency Space Based Augmentation System (SBAS). Implementation of this integrity architecture could include a regional ground-based monitoring network of GNSS receivers and communication links via geostationary satellites or other means to provide integrity and/or correction messages directly to the users. As with SBAS today, the external monitors provide confidence information to the aircraft so the data capacity could be similar to today's SBAS 250 bps. Alternatively, GIC could broadcast just a single URA per satellite, requiring far less channel capacity. However, all integrity-relevant data must be broadcast every six seconds to satisfy the time-to-alert requirement for LPV precision approach. This latency requirement means that for ground-based monitoring the data stream is unlikely to be carried on the GPS satellites themselves, and a separate broadcast channel would be needed to reach the aircraft in time. The most likely broadcast channel mechanism would be geostationary transponders similar to those used for SBAS today. Additionally, the ground network that connects the monitor stations must also provide high capacity and low latency. An alternative method to determine integrity external to the aircraft is to put the integrity monitors on the GPS satellites. The satellites would then directly monitor their own status and alert users or shut off their broadcast signals when integrity could not be assured or a fault detected. Such a capability is under evaluation for inclusion in later stages of the GPS-III Program.

Relative to the other candidate architectures described below, GIC is the most demanding relative to broadcast latencies. However, it is the least demanding candidate architecture with respect to the geometry robustness of the basic GNSS constellation because over-specified navigation solutions are not required by the avionics.

Figure 7 Absolute RAIM

Of the three candidate architectures, ARAIM places the greatest integrity burden on the aircraft and the smallest burden on the GNSS constellation and the external monitors. The ARAIM integrity architecture would essentially be an extension and refinement of existing RAIM algorithms. ARAIM would improve on today's RAIM because the large ionospheric errors affecting range measurements would be removed using dual-frequency measurement diversity. ARAIM residuals would be subject to more sensitive thresholds and smaller position errors could be detected without loss of confidence.

ARAIM is almost, but not quite, autonomous. External monitoring must exist for all the same faults as GIC, however, the latency associated with detection of these faults can be significantly increased. The external monitoring will then guarantee the *a priori* failure probabilities for the individual satellites are as expected and provide the associated user range accuracies (URAs). This information need only be updated approximately every hour so the time-to-alert requirement is satisfied by the fault detection algorithm on the aircraft. The external monitors simply need to ensure that faulted satellites do not stay in the mix for a long time. As such, ARAIM is the least demanding with respect to the bandwidth and latency of the integrity broadcast mechanism to the user. In fact, the ARAIM information could be carried on the GPS satellites themselves with hour long latency. This approach avoids having to maintain constant connection to the user to directly support a six second TTA (such as through the geostationary satellite). However, ARAIM will be the most demanding with respect to satellite geometry. As with RAIM, ARAIM requires good geometry for the subsets created when deleting satellites from the all-in-view set.

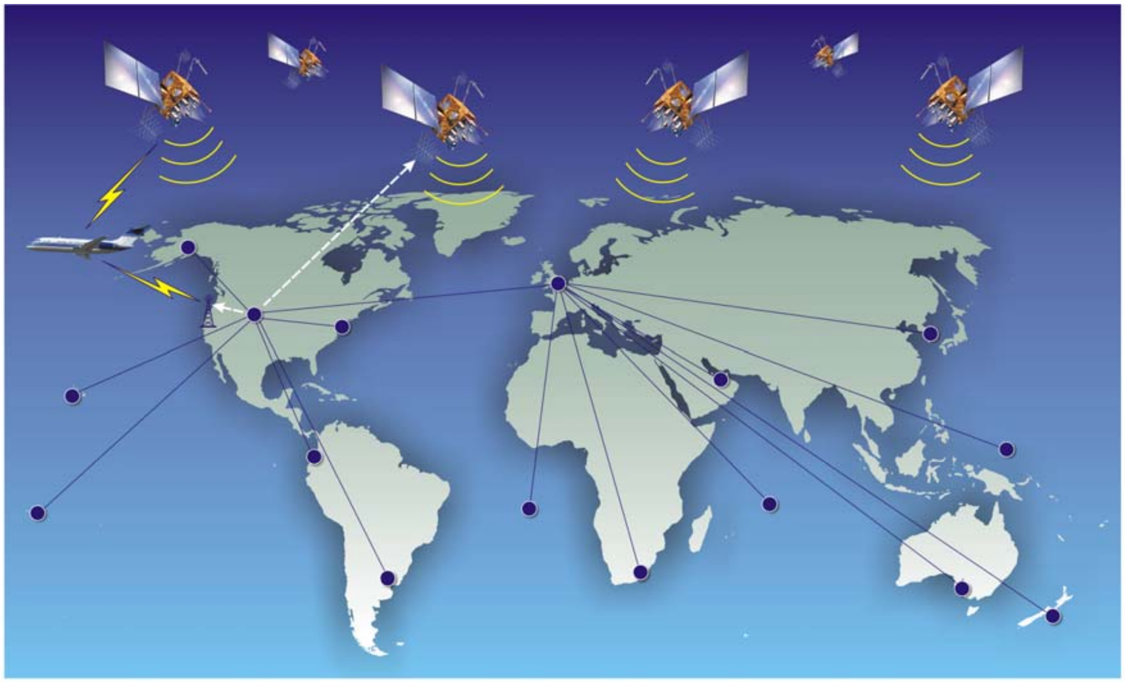

Figure 8 Relative RAIM

In the RRAIM integrity architecture concept, the user aircraft performs positioning and integrity monitoring autonomously, using current satellite measurements and a prior set of measurements validated by the external integrity monitoring. The time-to-alert requirements for the external monitors are significantly relaxed relative to the GIC architecture because the previously validated data set that the user aircraft utilizes can age for tens of seconds or maybe even minutes.

The aircraft uses carrier smoothed code measurements that have been validated by the ground monitors and projects these measurements forward in time by adding the difference between current and past carrier phase measurements. These projected range measurements are used to generate position fixes in real-time. Simultaneously, the integrity of these position fixes is ensured by RRAIM which protects against any failures that occur after the last externally validated data set. In its most basic form, RRAIM is implemented by checking the least squares residual of the relative carrier phase position fix over the coasting time. RRAIM only uses the very precise carrier phase measurements for projection so extremely tight detection thresholds can be set without incurring penalties associated with high false alarm rates, ultimately leading to high levels of RRAIM availability.

RRAIM is strongly dependent on the aircraft-external monitors to provide the validated data sets used at the beginning of the coasting period. RRAIM requires that the pseudorange position solution from the recent past be valid and requires redundancy in the ranging signals from multiple satellites to cross-check that faults do not become significant in the intervening time. RRAIM uses the low noise carrier measurements rather than the noisier code phase measurement so the constellation geometry requirements are relaxed relative to ARAIM. The RRAIM latency requirements are intermediate relative to GIC and ARAIM. The required capacity is probably commensurate with the excess capacity available from the geostationary satellites used today for SBAS. However, the capacity could likely be made compatible with the bandwidth that would be available from the GPS satellites of the future. The latency requirement may be difficult to satisfy for ground-based monitoring using GPS satellites to transmit messages unless the crosslink data transmission capability is implemented. Although this may be possible using an increased number of automated GPS upload stations. The crosslink capability will also allow the reduction of the age of the broadcast data. In turn, this capability will improve the overall accuracy and may be necessary to achieve the required accuracy to support a high availability of ARAIM.

Section 5 Requirements, Error Sources and Overbounding

As stated earlier, the GEAS objective is to develop an architectural solution(s) to provide a worldwide vertical guided approach capability to an altitude as low as 200 feet. One such capability is provided through LPV-200 procedures. The key requirements will be outlined in this section and include accuracy, integrity, time-to-alert, continuity, and availability. While there are requirements on both vertical and horizontal positioning, the vertical positioning requirements are much more difficult to satisfy so the GEAS evaluation focused exclusively on the vertical positioning requirements.

The accuracy requirement is expressed at the 95th percentile. In the vertical positioning domain this value must be below 4m for each user aircraft. As the requirement only extends to 95%, the rare event tails of the error distributions do not impact the evaluation of this criterion. Comparatively small biases and sigma values can then be used modeling these errors as Gaussian.

Another formulation for the accuracy requirement is known as the Effective Monitor Threshold (EMT). The EMT performance requirement means that a fault must be detected at least 50% of the time when an error is present that creates a vertical positioning error equal to the EMT. Larger errors must be detected with even greater probability. In the GEAS Panel deliberations EMT was set at 15m. This requirement ensures that the user navigation system accuracy, even in the presence of a fault, will guide the airplane to within the desired touchdown region on the runway.

The WAAS FRD states the integrity requirement as the probability of Misleading Information (MI) being less than or equal to 2×10^{-7} per approach. MI is defined as any undetected event where the actual position error is greater than the dynamically calculated upper bound (known as the Vertical Protection Level, or VPL) for more than a specific time (Time-To-Alert). Further, the VPL must also remain below a static Vertical Alert Limit (VAL) to ensure that the aircraft be kept safely away from obstacles. For LPV-200, the VAL is 35m. The requirement that VPL remain below the VAL is the dominant limitation to performance.

The two accuracy requirements and the integrity requirement limit the distribution of Vertical Positioning Errors (VPEs). Implicit in the EMT requirement is the assumption or assertion that faults are rare events, i.e., typically occurs less frequently than one in 100,000 approaches. Thus the VPE distribution is restricted at 95% (4m), 99.999% (15m), and 99.99999% (35m).

Should a fault occur such that the Vertical Positioning Error (VPE) is greater than the VPL, the user must be alerted within the Time-To-Alert (TTA). For LPV-200, the TTA requirement is 6.2 seconds. Note that this requirement applies to the entire system, ground and air. In the RRAIM and ARAIM candidates the aircraft avionics is capable of alerting the pilot well within this TTA so the latency requirement on the ground system component can be extended for these architectures.

A continuity requirement applies to the probability of an interruption in approach service. The average probability of an interruption in approach must be less than 8×10^{-6} per 15-second interval unless the interruption was announced sufficiently in advance, e.g., via a Notice to Airmen (NOTAM).

Availability is the fraction of time that service is supported (i.e., the PLs are below their ALs and the expected accuracy and continuity are within their requirements). For the system to be useful, it must be available at least 99% of the time at any location where LPV-200 service is authorized [16]. For scheduled service, the system may need to be available for even greater percentages of time (between 99.9% and 99.999%).

All the candidate architectures identified by the GEAS Panel rely on dual frequency ranging measurements. The L1 and L5 signals are combined in a way to eliminate the first-order ionosphere induced measurement error [22]. The iono-free range measurement dual frequency combination magnifies the impact of measurement and multipath induced error. The resulting measurement uncertainty for the j^{th} satellite is described as normally distributed with zero mean and variance,

$$\sigma^2_{j,DF\_air} = \left(\frac{f_1^2}{f_1^2 - f_5^2} \right)^2 \sigma^2_{L1,j,air} + \left(\frac{f_5^2}{f_1^2 - f_5^2} \right)^2 \sigma^2_{L5,j,air} \tag{1}$$

where f_1 and f_5 are the L1 and L5 frequencies, respectively, and $\sigma^2_{L1,j,air}$ and $\sigma^2_{L5,j,air}$ are the multipath and noise error variances affecting the individual measurements. This dual frequency term replaces the σ_{air} and σ_{UIRE} terms of Appendix J of the SBAS Minimum Operational Performance Standards MOPS [19]. The specific model for $\sigma^2_{L1,j,air}$ may also be found in this appendix. Although the performance of L5 for noise and multipath is expected to be better than that of L1, the Panel assumed the same airborne model for the L5 frequency. σ^2_{j,DF_air} is a deterministic function of the elevation of the satellite.

An integrity term will be broadcast to the user to overbound the errors in the satellite's clock and ephemeris. For GIC and RRAIM this bound must protect to a fraction of the overall integrity budget as in SBAS. For ARAIM, however, the aircraft has the capability to detect absolute errors on its own so the broadcast bound can be less stringent.

The user will also calculate the overbound for unmodeled tropospheric effects. The tropospheric model and uncertainty used by the GEAS Panel are identical to those specified in Appendix A of the SBAS MOPS [19]. The error is defined to be normally distributed with variance specified by $\sigma^2_{j,tropo}$ and this variance is also a function of the elevation of the satellite. The three error components are assumed independent so the variance of the j^{th} line of sight for the smoothed pseudorange measurements are described as

$$\sigma^2_{j,p} = \sigma^2_{j,clk\_eph} + \sigma^2_{j,DF\_air} + \sigma^2_{j,tropo} \tag{2}$$

In addition to a variance term, there is a broadcast bias term per satellite used to bound errors that may appear random but affect users in the same way repeatedly. Examples of such biases are antenna biases [23] or nominal signal deformations [24] [25]. These error sources affect a particular geometry identically each time it is encountered. Further, this term is used to account for non-Gaussian behavior in the above error terms through a technique known as paired bounding [26]. Thus, a maximum bias term, $b_{j,\,max}$, is broadcast to bound the effect of this type of error source.

Section 6 GNSS Integrity Channel Architecture

Conceptually, the easiest architectural alternative is to extend the existing SBAS service provided by the WAAS to include global coverage. WAAS currently has 38 reference stations in the United States, Canada, and Mexico and provides LPV-200 service to much of North America [27] [28]. WAAS uses both the L1 and L2 GPS signals and needs its dense reference station network in order to estimate and bound the ionosphere induced error. If WAAS users were to use both L1 and L5 signals, coverage would expand dramatically. However, there is a limit to the practical extent of this architectural paradigm since the communication networks to the reference stations are already near the limit of supporting the six-second TTA. An extended worldwide network will likely result in too large a communication network latency to support the TTA of 6.2 seconds.

Additionally, WAAS uses geostationary satellites to broadcast its information to its users. At least four optimally placed GEOs would then be required to provide near-global redundant coverage and still the polar regions would not be well covered. While a single global network could conceptually provide worldwide LPV-200 service, transmitting the information to the user in a cost effective way that supports the required TTA is not trivial and may preclude any practical implementation of this architectural approach.

One variant on this alternative would be to expand each region of the world separately. WAAS could be expanded to cover North and South America; EGNOS to cover Europe and Africa; MSAS and GAGAN to cover Asia, Oceana, Australia, and possibly the Middle East. It is certainly likely that this path will develop naturally. The disadvantage with this approach is the inherent dependency on other regions to support the stated GEAS goals for worldwide GNSS.

Another variant with this alternative is to allocate most of the integrity decision determination capability on the GPS satellites themselves. This approach would readily comply with the rapid TTA for those faults that can effectively be monitored onboard the space vehicles but there is a concern that ephemeris errors may not be detectable with this approach. However, it is likely that ephemeris errors are sufficiently slow in developing that a ground monitoring network would have sufficient time to detect them before they became large enough to present a hazard to the user. This architectural variant contains more uncertainty than the other candidates because effective spacecraft monitors have not yet been thoroughly developed for each fault mode. There is an inherent risk in this approach that during the detailed threat analysis activity a rapidly developing fault could be identified that would be impractical for the satellite to detect. It is therefore essential to conduct this threat analysis early in the development path if this architecture is to be pursued further.

Regardless of the exact implementation, these GIC approaches share the common feature that integrity is supplied to the aircraft in similar fashion as it is today for SBAS. Therefore, redundant satellite geometry is not required and the aircraft can operate with only four satellites in view. All these GIC methods thus use the same VPL equation, it is the SBAS VPL equation with the addition of the explicit bias term

$$VPL_{GIC} = K(P_{HMI})\sqrt{\sum_{i=1}^{n}(S_{u,i}^{p}\sigma_{i,p})^{2}} + \sum_{i=1}^{n}|S_{u,i}^{p}|b_{i,\max}, \tag{3}$$

where $S_{u,i}^{p}$ is the vertical component of the projection matrix corresponding to satellite i as defined in Appendix J of the SBAS MOPS [19], $K(P_{HMI}) = Q^{-1}(1 - P_{HMI}/2)$, and Q is the cumulative distribution function of a Gaussian random variable with zero mean and unit variance.

Section 7 RRAIM Architecture

The GEAS Panel identified a novel airborne navigation integrity approach based on relative receiver autonomous integrity monitoring (RRAIM) [29] [30] [31] that would be a viable candidate for the world-wide GNSS. In this concept, the user aircraft can perform positioning and punctual integrity monitoring (i.e., within the Time-To-Alert) autonomously with current satellite measurements and a prior set of measurements that have been validated by some combination of ground and spacecraft monitoring (GIC). No additional broadcast data beyond that already provided by GIC is needed. In the RRAIM approach the TTA requirement for the GIC ground and spacecraft integrity systems to detect failures quickly is significantly reduced because the previously validated data set that the user aircraft applies can be tens of seconds, and perhaps even several minutes, old. This relaxed TTA will enable the ground integrity monitoring network to have a relaxed latency requirement that will facilitate expansion to global coverage. The use of both carrier smoothed code and raw carrier phase measurements in the RRAIM architecture results in higher availability for geometrically weaker constellations than is provided by traditional “Absolute” RAIM (ARAIM) architectures that are based solely on the use of carrier smoothed code.

The RRAIM architecture works as follows. The user aircraft receives satellite ranging measurements (dual frequency code and carrier), along with corrections and integrity information generated by ground and/or satellite integrity monitoring. The aircraft stores past measurements for a given time duration, called the “coasting time,” to a point where ground/satellite integrity monitor detections and notifications are guaranteed to have been received by the aircraft. The specific duration of such storage is still a parameter under study because it influences the performance requirements both for RRAIM and the ground/space monitors (time-to-alert, in particular) as well as the type of GIC distribution channel needed.

The aircraft uses carrier smoothed code measurements validated by the GIC ground/satellite integrity monitors and projects these measurements forward in time by adding the difference between current and past carrier phase measurements. These projected range measurements are then used to generate position fixes in real-time. Simultaneously, the integrity of these position fixes is assured by RRAIM. In its most basic form, RRAIM can be implemented by checking the least squares residual of the relative carrier phase position fix over the coasting time. Tight detection thresholds can be set without incurring high false alarm rates because only carrier phase measurements are used in the RRAIM function. This feature ultimately leads to high levels of RRAIM availability. The RRAIM detection function acts specifically to capture faults that have occurred during the coasting interval since prior faults are detected by the GIC. More specifically, the detection function need only capture faults that affect the carrier phase. Code signal deformation and code-carrier divergence faults during the coasting interval are irrelevant because only carrier phase measurements from the coasting interval are used for positioning. The detection function is specifically needed to detect satellite clock anomalies whose onset occurs during the coasting time. It is worth noting that satellite orbit ephemeris faults can also be detected using RRAIM but this is unlikely to be necessary since the aircraft can always use that last ephemeris validated by the GIC. RRAIM can also be used to detect ephemeris faults such as those resulting from unannounced maneuvers.

Section 7.1 RRAIM Navigation Algorithms

In all the GEAS Panel candidate architectures positioning is based on the use of ionosphere-free, carrier-smoothed pseudoranges. For RRAIM specifically, range corrections generated and validated by a GIC are also applied. To accommodate the potentially significant latency, *T*, introduced by the GIC processing and messaging, the resulting (GIC-corrected, ionosphere-free, and carrier-smoothed) pseudoranges, *p*, are projected to the current time using punctual and past ionosphere-free carrier phase measurements, ϕ, as follows:

$$\hat{p}_t = p_{t-T} + \Delta\phi_{t,t-T} \,. \tag{4}$$

In Equation (4), $\Delta\phi_{t,t-T}$ is $\phi_t - \phi_{t-T}$, the difference in carrier phase measurements between time *t* and *t–T*, and these are expressed directly in distance rather than angular units. The projected range measurement is related to the true range, *r*, between the user and the satellite by

$$\hat{p}_t = r_t + \tau_t + \delta p_{t-T} + \delta\Delta\phi_{t,t-T} \,, \tag{5}$$

where τ is the receiver clock bias, δp_{t-T} is the error in p_{t-T}, and $\delta\Delta\phi_{t,t-T}$ is the error in $\Delta\phi_{t,t-T}$.

Section 7.1.1 RRAIM Error Models

As in the GIC architecture, the error term, δp_{t-T}, is the sum of three sources found in Equation (2): (a) carrier-smoothed code receiver noise and multipath, (b) residual troposphere error, and (c) residual error in the GIC-generated range correction (accounting for satellite clock and orbit errors). The standard deviation, σ_p, is a function of time, *t–T*, because the satellite elevation varies with time.

The error term, $\delta\Delta\phi_{t,t-T}$, in Equation (5) is also the sum of three sources: (d) the change in carrier phase receiver noise and multipath over time interval *T*, (e) the change in tropospheric error over the time interval, and (f) the satellite clock drift over the time interval. Error source (d) can be modeled as a zero-mean, normally distributed variable with standard deviation $\sigma_{\Delta(n+mp)}$. Receiver noise is well modeled as a white process, so its contribution to $\sigma_{\Delta(n+mp)}$ is not a function of *T*. However, multipath noise is colored so time-differencing results in a contribution to $\sigma_{\Delta(n+mp)}$ that will vary with *T* but will become constant as *T* exceeds the multipath time constant (which is typically less than 20 sec for a moving aircraft). In this study, the GEAS Panel assumed a conservative constant value of $\sigma_{\Delta(n+mp)}$ = 6cm for all values of *T*. Error source (e) accounts for the effect of troposphere spatial variation experienced by a moving aircraft. This effect is modeled as a zero mean normal distribution with standard deviation $\sigma_{\Delta trop}$. Based on analysis of troposphere spatial decorrelation measurement data by van Graas [32] [33], and assuming nominal aircraft speed of 180 kt (0.092 km/s) during final approach, the standard deviation is empirically modeled as the following function of *T* and satellite elevation, *E*:

$$\sigma_{\Delta trop} = \left[1.22\frac{\text{cm}}{\text{km}} + 0.41\frac{\text{cm}}{\text{km}} \times \frac{90\,\text{deg} - E}{85\,\text{deg}}\right] \times 0.092\,\text{km/s} \times T \qquad (6)$$

with upper limits on $\sigma_{\Delta trop}$ as a function of elevation as defined in Table 2.

EL (deg)	5-10	10-20	20-30	30-40	40-90
$\sigma_{\Delta trop}$ (cm)	40	20	14	10	8

Table 2: Upper Limit on $\sigma_{\Delta trop}$ as a Function of Elevation

The satellite clock drift error (f) over time interval *T* can be modeled as zero-mean and normally distributed with a standard deviation of

$$\sigma_{\Delta clk} = 0.085\frac{\text{cm}}{\text{s}} \times T\,. \qquad (7)$$

This is an empirical model that is consistent with GPS measurement data collected and processed by van Graas [32]. The three random error components of $\delta\Delta\phi_{t,t-T}$ are independent so the variance of $\delta\Delta\phi_{t,t-T}$ is

$$\sigma^2_{\Delta\phi} = \sigma^2_{\Delta(n+mp)} + \sigma^2_{\Delta trop} + \sigma^2_{\Delta clk} \qquad (8)$$

The error covariance matrices associated with δp_{t-T} and $\delta\Delta\phi_{t,t-T}$ for *n* satellites in view are $\mathbf{R}_{\delta\mathbf{p}} = \text{diag}(\sigma^2_{p,1}, \ldots, \sigma^2_{p,n})$ and $\mathbf{R}_{\delta\Delta\phi} = \text{diag}(\sigma^2_{\Delta\phi,1}, \ldots, \sigma^2_{\Delta\phi,n})$, respectively. Recall that the elements within each of these diagonal matrices are different from each other because the elevations of the individual satellites will differ. In addition, the elements of the matrix $\mathbf{R}_{\delta\Delta\phi}$ are functions of the coasting time *T*. The total error associated with the projected ranging measurements, $\hat{p}_t$, in Equation (5) for *n* satellites is then described by the covariance matrix $\mathbf{R}_{\delta\hat{\mathbf{p}}} = \mathbf{R}_{\delta\mathbf{p}} + \mathbf{R}_{\delta\Delta\phi}$ and an unknown bias vector $\boldsymbol{\beta}$, whose elements are bounded in magnitude by $b_{i,\max}$, where *i* is the satellite index.

Section 7.1.2 RRAIM Positioning

The GPS observation equation for positioning with *n* satellites is

$$\begin{bmatrix} \hat{p}_{t,1} \\ \vdots \\ \hat{p}_{t,n} \end{bmatrix} = \mathbf{G} \begin{bmatrix} \mathbf{x_t} \\ \tau_t \end{bmatrix} + \begin{bmatrix} \delta\hat{p}_{t,1} \\ \vdots \\ \delta\hat{p}_{t,n} \end{bmatrix} + \boldsymbol{\beta}, \tag{9}$$

where

$$\mathbf{G} = \begin{bmatrix} \mathbf{a}_{\mathbf{t},1}^{\mathrm{T}} & -1 \\ \vdots & \vdots \\ \mathbf{a}_{\mathbf{t},\mathbf{n}}^{\mathrm{T}} & -1 \end{bmatrix}, \tag{10}$$

$\mathbf{a}_{\mathbf{t,i}}^{T}$ is the unit line-of-sight vector from the aircraft to satellite *i*, $\mathbf{x_t}$ is the 3×1 position vector for the aircraft, and $\delta\hat{p}_{t,i} = \delta p_{t-T} + \delta\Delta\phi_{t,t-T}$, which for *n* satellites is normally distributed with zero mean and covariance, $\mathbf{R}_{\delta\hat{\mathbf{p}}}$. When $n \geq 4$, the least squares solution to (9) can be obtained. In this case the weighted pseudoinverse is

$$\mathbf{S^p} = (\mathbf{G}^T \mathbf{R}_{\delta\hat{\mathbf{p}}}^{-1} \mathbf{G})^{-1} \mathbf{G}^T \mathbf{R}_{\delta\hat{\mathbf{p}}}^{-1} \tag{11}$$

and the resulting state estimate error covariance matrix is

$$\mathbf{R_{pos}} = (\mathbf{G}^T \mathbf{R}_{\delta\hat{\mathbf{p}}}^{-1} \mathbf{G})^{-1}. \tag{12}$$

The variance, σ_u^2, of the local vertical component of position estimate error can be extracted from this covariance matrix. In addition, the effect in the position domain of the bias vector, $\boldsymbol{\beta}$, is bounded by

$$b_u = \sum_{i=1}^{n} | S_{u,i}^{p} | \times b_{i,\max}, \tag{13}$$

where $S_{u,i}^{p}$ is the element of the projection matrix $\mathbf{S^p}$ that corresponds to the vertical position component and satellite *i*.

Section 7.1.3 RRAIM Fault Detection

GPS satellite faults that occur prior to $t-T$ are subject to the detection functions provided by the GIC. These functions are specifically designed to ensure that the required integrity risk (P_{HMI}) is achieved at the time of monitor output. Information from the GIC integrity monitors is applicable at the aircraft at time $t-T$. The values of the residual bias magnitude bound, $b_{i,\max}$, and standard deviations, σ_j, are parameters that describe the distribution of these post-GIC-monitored ranging errors. However, punctual positioning at time *t* is needed to navigate the aircraft so it is also necessary to ensure the integrity of the carrier phase measurement, $\Delta\phi_{t,t-T}$, which is used in the range projection Equation (4). The integrity of the carrier phase measurement is accomplished using the RRAIM fault detection algorithm described below. (Note that the RRAIM can be implemented using solution separation method as well).

Under fault-free coasting (*FFC*) conditions, the vertical position error, e_u, is bounded by a VPL corresponding to the following distribution:

$$e_u \mid FFC \sim N(b_u, \sigma_u) \tag{14}$$

To model the effect of a measurement fault during coasting (*FDC*) on a given satellite *j*, we introduce the $n\times1$ column vector, $\mathbf{q_j}$, whose elements are all zero except the *j*th, which has a value of one. Given a failure of magnitude *f* on satellite *j*, the vertical position error is bounded by the distribution

$$e_u \mid FDC \sim N(b_u + f_u, \sigma_u), \tag{15}$$

where

$$f_u = \mathbf{S^p_{u,:}}\,\mathbf{q_j}\, f\,. \tag{16}$$

In the RRAIM architecture, detection of such failures is performed using only the time differenced carrier phase measurements, $\Delta\phi_{t,t-T}$. For *n* satellites, these measurements are related to the time differenced change in position, $\mathbf{\Delta x_{t,t-T}}$, and clock, $\Delta\tau_{t,t-T}$, by

$$\begin{bmatrix} \Delta\phi_{t,t-T,1} \\ \vdots \\ \Delta\phi_{t,t-T,n} \end{bmatrix} = \mathbf{G}\begin{bmatrix} \mathbf{\Delta x_{t,t-T}} \\ \Delta\tau_{t,t-T} \end{bmatrix} + \begin{bmatrix} \delta\Delta\phi_{t,t-T,1} \\ \vdots \\ \delta\Delta\phi_{t,t-T,n} \end{bmatrix} + \mathbf{\Delta G}\begin{bmatrix} \boldsymbol{\delta}\mathbf{\hat{x}_{t-T}} \\ \delta\hat{\tau}_{t-T} \end{bmatrix}, \tag{17}$$

where $\mathbf{\Delta G}$ is the change in the observation matrix **G** due to satellite line-of-sight motion between *t* and *t–T*, and $\boldsymbol{\delta}\mathbf{\hat{x}_{t-T}}$ and $\delta\hat{\tau}_{t-T}$ are the errors in the prior knowledge of the position and receiver clock at *t–T*. The last two terms on the right hand side of (17) are zero mean normally distributed errors with covariance matrix

$$\mathbf{R_d} = \mathbf{R_{\delta\Delta\phi}} + \mathbf{\Delta G}(\mathbf{G}^T\mathbf{R^{-1}_{\delta p}}\mathbf{G})^{-1}\mathbf{\Delta G}^T\,. \tag{18}$$

The weighted pseudoinverse of **G** associated with (17) and (18) is

$$\mathbf{S^d} = (\mathbf{G}^T\mathbf{R_d^{-1}}\mathbf{G})^{-1}\mathbf{G}^T\mathbf{R_d^{-1}}\,. \tag{19}$$

Defining for simplicity of notation $\mathbf{\Delta\Phi} = \begin{bmatrix} \Delta\phi_{t,t-T,1} & \cdots & \Delta\phi_{t,t-T,n} \end{bmatrix}^{\mathrm{T}}$, the weighted least-squares residual vector is

$$\boldsymbol{\delta}\mathbf{r} = (\mathbf{I} - \mathbf{S}^{\mathbf{d}})\Delta\boldsymbol{\Phi} . \tag{20}$$

It is shown in [34] that under fault free conditions (i.e., *FFC* for the RRAIM architecture), that

$$z = \boldsymbol{\delta}\mathbf{r}^T \mathbf{R}_{\mathbf{d}}^{-1} \boldsymbol{\delta}\mathbf{r} = \Delta\boldsymbol{\Phi}^T \mathbf{R}_{\mathbf{d}}^{-1} (\mathbf{I} - \mathbf{S}^{\mathbf{d}})\Delta\boldsymbol{\Phi} \tag{21}$$

is χ^2 distributed with *n*–4 degrees of freedom.

A fault detection threshold, *D*, on test statistic, *z*, is then defined to ensure a fault-free alarm probability that complies with the continuity risk requirement (4×10^{-6}/15 sec which is one half of the total requirement for LPV-200). When a fault occurs during coasting (i.e., *FDC*) the fault vector, $\mathbf{q}_{\mathbf{j}} f$, is present in the time differenced measurement, $\Delta\boldsymbol{\Phi}$, and in this case *z* is *non-centrally* χ^2 distributed with *n*–4 degrees of freedom and non-centrality parameter, $\lambda_{d,j} f^2$:

$$z \sim \chi^2(n-4, \lambda_{d,j} f^2) \tag{22}$$

where $\lambda_{d,j} = \mathbf{q}_{\mathbf{j}}^T \mathbf{R}_{\mathbf{d}}^{-1} (\mathbf{I} - \mathbf{S}^{\mathbf{d}}) \mathbf{q}_{\mathbf{j}}$.

Section 7.1.4 Vertical Protection Levels

The Vertical Protection Level (*VPL*) for the RRAIM architecture is defined as the bound on undetected vertical position error (e_u) that is consistent with the maximum allowable integrity risk: $P_{HMI} = 10^{-7}$. Mathematically this definition may be expressed as follows:

$$P\left\{ \left(|e_u| > VPL \right) \cap \left(z < D \right) \right\} = P_{HMI} . \tag{23}$$

Under the two mutually exclusive and exhaustive events, *FFC* and *FDC*, Equation (23), may be expanded as

$$\begin{aligned} &P\left\{ \left(|e_u| > VPL \right) \cap \left(z < D \right) \middle| FFC \right\} P_{FFC} + \\ &\qquad P\left\{ \left(|e_u| > VPL \right) \cap \left(z < D \right) \middle| FDC \right\} P_{FDC} = P_{HMI} . \end{aligned} \tag{24}$$

The random parts of e_u and *z* are independent, so

$$\begin{aligned} &P\left\{ \left(|e_u| > VPL \mid FFC \right) \right\} P\left\{ \left(z < D \mid FFC \right) \right\} P_{FFC} + \\ &\qquad P\left\{ \left(|e_u| > VPL \mid FDC \right) \right\} P\left\{ \left(z < D \mid FDC \right) \right\} P_{FDC} = P_{HMI} . \end{aligned} \tag{25}$$

The probability of satellite failure is assumed to be 10^{-5}/hour, so

$$P\{FDC\} = (10^{-5} / SV / \text{hour}) \cdot n \cdot T . \tag{26}$$

Therefore, for coasting times (*T*) less than one hour, we can conservatively assume that

$$P\left\{ \left(|\delta r| < D \mid FFC \right) \right\} P\{FFC\} \approx 1 . \tag{27}$$

Therefore Equation (25) can be simplified as

$$\begin{aligned} &P\left\{ \left(| e_u | > VPL \;\middle|\; FFC \right) \right\} \; + \\ &\qquad P\left\{ \left(| e_u | > VPL \;\middle|\; FDC \right) \right\} \; P\left\{ \left(z < D \;\middle|\; FDC \right) \right\} \; P_{FDC} \;=\; P_{HMI} . \end{aligned} \tag{28}$$

Because the distributions for all the probabilities in Equation (28) are known, in principle it is possible to iteratively solve for *VPL*. However, another more practical option is to budget the total integrity risk, P_{HMI}, between the two terms in (28):

$$P\left\{ \left(| e_u | > VPL_{FFC} \;\middle|\; FFC \right) \right\} \;= \alpha \, P_{HMI} . \tag{29}$$

$$P\left\{ \left(| e_u | > VPL_{FDC} \;\middle|\; FDC \right) \right\} \; P\left\{ \left(z < D \;\middle|\; FDC \right) \right\} \; P_{FDC} \;=\; (1-\alpha) \, P_{HMI} . \tag{30}$$

For equal division of integrity risk between the two events $\alpha = 0.5$. However, it is also possible to select α to maximize system availability by choosing $\alpha < 0.5$, thereby allocating more of the allowable integrity risk to the faulted (*FDC*) case.

Therefore, using Equations (29) and (14), the vertical protection level under the hypothesis of fault-free coasting is

$$VPL_{FFC} = K(\alpha P_{HMI})\sigma_u + b_u \, , \tag{31}$$

where the function *K* is defined as in Equation (3). Note that VPL_{FFC} differs from VPL_{GIC} only by the parameter α and the fact that σ_u accounts for the increased position error due to carrier phase coasting over time interval *T*.

The vertical protection level under the hypothesis of fault during coasting can be obtained using the defining Equation (30), Equation (26) which defines the prior probability of a fault during coasting, and Equations (15), (16), and (22), which describe the effect of a fault of magnitude *f* on satellite *j* on the position error and the test statistic. To explicitly define VPL_{FDC}, consider an arbitrary satellite *j* and find the failure magnitude for that satellite, $f_{HMI,j}$, such that

$$\mathrm{X}^2(n-4, \; \lambda_{d,j} \, f_{HMI,j}^2, D) = (1-\alpha) \, P_{HMI} \, , \tag{32}$$

where X^2 is the non-central χ^2 cumulative distribution function evaluated at the threshold *D*. The arguments $n-4$ and $\lambda_{d,j} \, f_{HMI,j}^2$ are the degrees of freedom and the non-centrality parameter, respectively. The vertical protection level for such a failure on satellite *j* is then

$$VPL_{FDC,j} = b_u + \mathbf{S}^{\mathbf{p}}_{\mathbf{u,:}} \, \mathbf{q_j} \, f_{HMI,j} + K((1-\alpha)P_{HMI} \, / \, P_{FDC}) \times \sigma_{u,j} \, , \tag{33}$$

where P_{FDC} is a function of the coasting interval as defined in Equation (26). Assuming the failure occurs on the worst case satellite, the protection level is

$$VPL_{FDC} = \max_{1 \le j \le n} (VPL_{FDC,j}) \, . \tag{34}$$

The final *VPL* for the RRAIM architecture is then bounded by:

$$VPL_{RRAIM} = \max\left(VPL_{FFC}, VPL_{FDC}\right). \tag{35}$$

Section 8 ARAIM

Of the architectures considered in this study, ARAIM presents the least demanding ground monitoring TTA requirement since all faults would first be detected on the user aircraft. The role of ground/space monitoring would be isolation and prevention of multiple failures (SVs flagged as 'bad' by ground/space would not be used by ARAIM). However, ground/space monitoring is still essential to maintain the *a priori* failure rate used by ARAIM. It is important to note that what is identified as a failure for precision LPV-200 approach is substantially more stringent than what is used in today's RAIM schemes that provide only non-precision approach. For ARAIM, a failure is against a URA value of order 0.75m. Clearly, any fault that creates a five sigma or greater error (> 3.75m) can create HMI. However, smaller faults can also cause HMI if they occur with greater frequency than predicted by Gaussian statistics. Thus, too many satellites with 2m faults could also create HMI. The failure *a priori* rate, detection, and removal by the GPS Operational Control Segment (OCS) is well established against threats of tens of meters in magnitude. However, there is much less experience with the performance of the constellation with regard to meter level threats and monitoring against these smaller threats needs to be implemented in the ground integrity monitoring network in order to support precision LPV-200 approach.

Another advantage of ARAIM is that the broadcast bounds from the ground/space segment only need to be valid to a less stringent P_{HMI} level because the aircraft can perform its own absolute integrity validation. Rather than the ground/space segment achieving 10^{-7} per approach on its own, the combination of the two can achieve this level. Thus, the requirement on the ground/space side can be relaxed to 10^{-5} per approach and the corresponding overbound broadcast to the user can be smaller. Perhaps it can be significantly smaller as the truly rare event faults will be initially detected by the aircraft. To model the implication of such a reduction, the bias and variance values used in simulation for ARAIM will be the values in Equation (46) divided by 1.5.

Ideally this integrity monitoring functionality would be integrated into a future upgrade of the GPS operational control centers (OCX). At a minimum, the provision of integrity could be co-located with the monitoring, control, and provision of accuracy functionality and share the same monitoring stations. This would allow an efficient use of resources and a direct path into the satellites to broadcast the integrity parameters. However, GPS serves many communities, most of whom are interested in high accuracy and availability rather than integrity. For this reason, it may be desirable to keep some separation of these functionalities.

Due to the much longer allowable TTA for ground/space monitoring, one hour or longer, the ARAIM broadcast capacity requirements are lower than in the other candidate architectures. For this reason the integrity information can readily be broadcast using the GPS satellites. An hour TTA easily supports having the messages wait in a long queue before being broadcast under the planned L5 navigation stream. Of course, messages should be repeated without update more frequently to enable rapid user initialization.

Section 8.1 Algorithm-VPL Equations

There are two algorithms used to evaluate the Absolute RAIM option. A full description of the algorithm can be found in [35] and [36]. The formulation for both methods are similar with only a minor differences. The following equations are based on Multiple Hypothesis Solution Separation algorithm modified to optimize the vertical protection level while meeting the P_{HMI} requirement.

Section 8.1.1 VPL Equations

The Multiple Hypothesis Solution Separation (MHSS) algorithm considers both faulted and unfaulted modes (satellite errors) and computes a VPL for each mode. Each mode is assigned a portion of the total integrity budget (such that the sum matches the total). The final user VPL is then the maximum over the VPLs for each mode. The VPL for a mode is given by:

$$^{(j)}\mathrm{VPL}_{\mathrm{ARAIM}} = K\left(\frac{^{(j)}P_{alloc}}{P_{a\ priori}}\right) \times {}^{(j)}\sigma_U + \sum_{i=1}^{n} \left| {}^{(j)}S_{U,i}^{p} \right| \times b_{i,\max} + {}^{(j)}SS(\boldsymbol{\varepsilon})\,. \tag{36}$$

The ARAIM VPL is given by:

$$\mathrm{VPL}_{\mathrm{ARAIM}} = \max_{j=0,N}\left[{}^{(j)}\mathrm{VPL}_{\mathrm{ARAIM}}\right], \tag{37}$$

where (*j*) denotes the mode: (0) for all-in-view, (1) for first SV removed, etc.. *K*(*P*) computes the tail distance for an inverse two sided CDF of a normal distribution. σ_U and $S_{U,i}$ are calculated from geometry (**G**) and weighting ($\mathbf{W} = \mathbf{R}_{\boldsymbol{\delta}\mathbf{p}}^{-1}$) matrices corresponding to the overbound of the error.

$$\begin{gathered} {}^{(j)}\sigma_U = \sqrt{\left({}^{(j)}\mathbf{G}^{\mathrm{T}} \cdot {}^{(j)}\mathbf{W} \cdot {}^{(j)}\mathbf{G}\right)^{-1}_{3,3}} \\ {}^{(j)}\mathbf{S}^{p} = \left({}^{(j)}\mathbf{G}^{\mathrm{T}} \cdot {}^{(j)}\mathbf{W} \cdot {}^{(j)}\mathbf{G}\right)^{-1} \cdot {}^{(j)}\mathbf{G}^{\mathrm{T}} \cdot {}^{(j)}\mathbf{W} \end{gathered} \tag{38}$$

$b_{i,\max}$ bounds the bias term, and *SS*(**ε**) is the solution separation term as a function of the errors (**ε**).

The integrity allocation is taken out of the total budget. First, we subtract the probability of the higher order modes which are not evaluated and the constellation fault probability (P_{Const}) from the HMI budget (P_{HMI}= 10^{-7} approach). That then leaves:

$$P_{alloc}^{total} = P_{HMI} - P_{Const} \tag{39}$$

The last term is set to 1.3×10^{-8} /approach to account for common model faults that affect multiple satellites, multiple independent satellite failures and failure of the constellation as a whole. Give each mode an integrity sub-allocation, ${}^{(j)}P_{alloc}$, such that:

$$\sum_{j=0}^{n} {}^{(j)}P_{alloc} = P_{alloc}^{total} \tag{40}$$

$P_{a\ priori}$ is the *a priori* probability of the fault here set to 10^{-5}. For $j > 0$ this is the *a priori* probability of a satellite failure. For $j = 0$ the *a priori* probability is approximated by 1.

An upper bound for the Solution Separation term can be estimated for prediction and is related to the continuity allocation of P_{cont}= 4×10^{-6} (half of the total allocation) which is split equally between all n fault modes. The vertical solution separation term of the j^{th} mode is equal to:

$${}^{(j)}SS(\boldsymbol{\varepsilon}) = \left|\left({}^{(j)}\mathbf{S}^{p}\cdot\boldsymbol{\varepsilon} - {}^{(0)}\mathbf{S}^{p}\cdot\boldsymbol{\varepsilon}\right)_{3}\right| \tag{41}$$

The expected variance of this separation is conservatively represented by:

$$\left[\left({}^{(j)}\mathbf{S}^{p} - {}^{(0)}\mathbf{S}^{p}\right)\cdot\mathbf{R}_{nom}\cdot\left({}^{(j)}\mathbf{S}^{p} - {}^{(0)}\mathbf{S}^{p}\right)^{\mathrm{T}}\right]_{3,3} \tag{42}$$

The nominal bias is given by:

$$B_{nom} = \sum_{i=1}^{n}\left|\left({}^{(j)}S_{U,i}^{p} - {}^{(0)}S_{U,i}^{p}\right)\right|\times b_{i,nom}, \tag{43}$$

where the nominal bias is taken to be smaller than the overbounding term used for integrity. Set b_{nom} to 10 cm (a representative value that needs validation). A column of zeros corresponding to the one missing satellite is added to ${}^{(j)}\mathbf{S}^{p}$ to make it the same size as ${}^{(0)}\mathbf{S}^{p}$. $\mathbf{R}_{nom}$ is the nominal covariance matrix of the measurement errors. For prediction, the SS term can then be written as:

$${}^{(j)}SS = K\left(\frac{P_{cont}}{n}\right) * \sqrt{\left[\left({}^{(j)}\mathbf{S}^{p} - {}^{(0)}\mathbf{S}^{p}\right)\cdot\mathbf{R}_{nom}\cdot\left({}^{(j)}\mathbf{S}^{p} - {}^{(0)}\mathbf{S}^{p}\right)^{\mathrm{T}}\right]_{3,3}} + B_{nom} \tag{44}$$

For the purpose of this study, half of the continuity budget is allocated to the VPL ($P_{cont} = 4\times10^{-6}$). The integrity allocation is optimized to minimize the predicted VPL. This is done by determining the allocation such that all the terms, ${}^{(j)}\mathrm{VPL}_{\mathrm{ARAIM}}$, are equal [35].

Section 8.1.2 Accuracy

95% accuracy is computed assuming that the satellites are all in the nominal mode:

$$\text{Predicted Accuracy} = 2 \times \sqrt{\left[{}^{(0)}\mathbf{S}^{p} \cdot \mathbf{R}_{nom} \cdot {}^{(0)}\mathbf{S}^{p\mathrm{T}} \right]_{3,3}} + \sqrt{\sum_{i=1}^{n} \left({}^{(0)}S_{U,i}^{p} \times b_{i,nom} \right)^{2}} \qquad (45)$$

The accuracy requirement is that the predicted accuracy be less than 4m. However, it was found that the pseudorange accuracy models when converted to position domain yield dramatically larger predicted errors than are actually observed. Consequently, the accuracy modeling technique is being re-evaluated and is not enforced on each geometry in the current evaluation.

Section 8.1.3 Effective Monitor Threshold

This requirement is met by requiring that all solution separation terms be below the required EMT (15m). This implementation insures that when a failure is present, an alarm will be raised before the error grows larger than 15 meters 50% of the time.

Section 9 Preliminary Results

The performance of the architectural constructs was evaluated by using a set of MATLAB scripts based on Matlab Algorithm Availability Simulation Tools (MAAST) [37], MITRE availability model, and IIT availability model to compute the predicted VPLs (3), (35), and (37) for the set of users distributed over the world during one day. Table 2 shows these results.

Availability was calculated as the fraction of time that the requirements are met. Users were placed on a five-degree by five-degree grid around the world from -70 to 70 degrees (2088 locations). Geometries were evaluated every minute for a full 24-hour period (1440 epochs). Coverage was calculated as the fraction of the users that meet a 99.5% availability goal. To account for the fact that grid spacing becomes closer at higher latitudes, each user grid contribution to coverage was weighted by the cosine of the latitude. Table 2 contains results indicating the fraction of the globe between -70 and +70 degrees latitude where users would enjoy 99.5% availability of LPV-200 service. The availability calculations are based on specific satellite constellations in combination with assumed numerical models for the error bounds.

Several satellite configurations were evaluated and Table 2 contains coverage results for three different six-plane GPS constellations optimized for 24 [38], 27, and 30 satellites [39]. This Table includes the cases with all satellites available and the cases where one satellite has been removed from operation. The latter cases were used to investigate the vulnerability of the performance of each architectural candidate to satellite outages. To that end, the removed satellite was selected so as to ensure that its removal would have a large impact on the coverage results (without however going to the extent of ensuring maximal impact).

In general, the clock/ephemeris and maximum bias values will be functions of the ground networks and algorithms. For this analysis, a simpler estimate of performance was obtained by using constant values that are considered to be close to the expected values obtainable for well-observed regions. The following values were assumed:

$$\sigma_{j,clk\_eph} = 0.75m,\ b_{j,\max} = 1.125m\,. \tag{46}$$

These values are based on performance of the satellites best observed by WAAS today and possible contributions of nominal deformations and antenna biases [40] [23] [24].

VPL, EMT, and accuracy were computed for each time and location using the algorithms specified above. Note however, that Table 2 only contains results of VPL criteria

satisfaction as the accuracy models have not yet been fully verified. For the RRAIM architecture, coasting times of *T* = 30, 60 and 300 seconds are included.
As shown in Table 2 performance for the GIC is very good for all constellations considered. The 24-satellite constellation is near the lower limit for performance, however, as even a single satellite outage can cause large regions to suffer some outage periods. Notice also that the 27-satellite constellation also has some vulnerability although the availability outages only affect a very small subset of users. It is very interesting to note that the 26-satellite constellation arranged sub-optimally actually performs worse than the optimal 24-satellite constellation despite having two more satellites. This performance paradigm holds for the other two architectures as well. The key observation here is that it is not simply a matter of the number of healthy satellites in the constellation, their orbital location in relation to one another is also very important. A single outage can create a gap in coverage in weak or poorly formulated geometry constellations.

As expected, ARAIM performance is more sensitive to the constellation geometric quality. ARAIM does not achieve high values for the current 24 satellite optimized constellation and requires a constellation optimized for 27 or 30 satellites in order to provide acceptable performance. For this geometric dependency perspective RRAIM performance is much closer to the GIC performance. The additional fault screening causes a small loss in coverage but overall performs well for all three constellations. As with ARAIM, RRAIM also benefits from having a stronger constellation. The percentage of the globe that has a 99.5% availability of LPV-200 (Vertical Protection Level (VPL) < 35 m, Horizontal Protection level (HPL) < 40 m) for the postulated GPS constellations is shown below.

	Constellation					
Architecture	24 minus 1 SV	24	27 minus 1 SV	27	30 minus 1 SV	30
GIC	86.6%	100%	97.8%	100%	100%	100%
RRAIM with 30 s coasting	81.2%	99.4%	96.8%	100%	100%	100%
RRAIM with 60 s coasting	74.4%	98.5%	92.8%	100%	100%	100%
RRAIM with 300 s coasting	28.0%	76.1%	52.3%	99.6%	93.9%	100%
ARAIM	7.80%	44.7%	30.6%	94.1%	90.5%	100%

Table 3: Summary of Coverage for 99.5% Availability

Note that these three alternatives (GIC, RRAIM and ARAIM) are integrity architectures, not system architectures. For example, GPS IIIC may well provide an excellent mechanism to implement one (or more) of these architectures in the 2030 time frame, prior to onset of peak solar ionospheric disturbance cycle in 2033 while new messages utilizing GEOs for the broadcast channel might be a good system to implement one or more of those architectures in the 2020 time frame, prior to next solar cycle peak circa 2022. This phase of the GEAS activity focused primarily on evaluating and comparing the availabilities of the candidate architectural concepts versus the number of satellites deployed in the GPS constellation. Assumptions regarding constellation performance will be refined in the next phase of the GEAS effort

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Section 10 Conclusions/Recommendations

The GEAS effort identified an interesting and important trade space. On one extreme, the GNSS Integrity Channel (GIC) places the integrity burden on the monitors external to the user aircraft. These monitors may be located on the ground as done with today's SBAS. Possibly, some of these integrity monitors could be located on the GNSS satellites themselves. In either event, the monitors are responsible for detecting clock runoffs, ephemeris errors in the navigation message, and signal distortions due to faults in the satellite modulation or RF chain. With GIC, the airborne user receiver assumes that the received signal-in-space is free of these potential difficulties. As shown in Table 2, GIC provides high coverage and availability even when the underlying GNSS constellation is quite weak, geometrically. The increase in cost and complexity for GIC is in the inclusion of a data broadcast and ground monitor system that can send alerts to the aircraft within 6.2 seconds or less.

At the other extreme, Absolute Receiver Autonomous Integrity Monitoring (ARAIM) places nearly all of integrity burden on the user aircraft. GNSS measurement redundancy is used to detect the clock runoffs, ephemeris failures, and signal distortions. The external monitors ensure that ‘bad’ satellites are identified and effectively removed from the GNSS constellation within one or two hours. The external monitors may also communicate more realistic *a priori* failure probabilities for satellites that are either recently launched or late in life. Since ARAIM is based on measurement redundancy it requires a geometrically strong GNSS constellation. Indeed, Table 2 results indicate that 30 satellites are required for 100% coverage. Conversely, the integrity data broadcast need not be fast, data latencies can be on the order of one hour. This ‘relaxed’ latency enables the use of the GNSS satellites themselves for the integrity broadcast.

Relative Receiver Autonomous Integrity Monitoring (RRAIM) occupies the central portion of the trade space. As with ARAIM, measurement redundancy is integral to the approach but here measurement residuals difference the change in position and the carrier phase measurements. This shifts the fault detection criteria from absolute range to the change in range. Fast occurring faults can readily be detected in the aircraft and the external monitors are only responsible for slow onset faults. This may be the most elegant operating point in the trade space. The precision of carrier phase measurements is used to relax the requirements on the GNSS constellation. Results are shown in Table 2 for 100% coverage with 27 satellites. Further, the integrity broadcast can tolerate latencies of minutes, in contrast to seconds for GIC or hours for ARAIM alternatives.

These three alternatives span an extremely important trade space - GNSS constellation strength versus integrity data latency. The GIC can serve well for regional systems;

today's SBAS are single frequency GICs that serve CONUS, Europe, Japan, and the rest of Asia-Pacific region. However, a worldwide GIC is considerably more challenging based on the allowable data latencies that would have to be enforced in a world-wide system.

The next generation of GNSS-based avionics can provide vertical guidance (to support LPV-200) to all qualifying airports worldwide without requiring any navigation equipment to be located on or near the airport. GPS III offers the opportunity to design integrity into the ranging signals and minimize the need for integrity augmentations but a full operational capability for this architecture is unlikely before the 2030 timeframe. The next generation of GNSS based avionics should include both RRAIM and ARAIM capabilities. RRAIM algorithms have the potential to allow TTA requirements to be relaxed for GNSS signal monitoring systems thereby enabling some monitoring architectures that would otherwise be ineffective or very challenging to implement. While ARAIM is demanding with respect to the number of satellites required to support high LPV-200 availability, it is likely to be effective when multiple GNSS constellations are deployed. Initially RRAIM would be implemented utilizing the excess message capacity in current SBAS SISs broadcast by geostationary satellites. In other words, new message types could be defined and multiplexed into today's SBAS data stream. ARAIM would transition online as the underlying GNSS constellations grew in number and geometric robustness. ARAIM would provide vertical guidance as the GPS constellation expands to more than 30 satellites. Alternatively, ARAIM could await the completion and validation of any of the new GNSS constellations from Europe, Russia, or China. Once these constellations prove themselves, then the SBAS satellites could eventually be retired after completion of a suitable user transition time. If these new constellations do not materialize then the SBAS satellites would continue to broadcast the integrity data. For either scenario, dual frequency GNSS and a new integrity augmentation will enable vertical guidance and the associated step forward in aviation safety. It is also envisioned that standards will be defined for one avionics upgrade that will not only support the GEAS integrity architecture but also automatic dependent surveillance-broadcast (ADS-B) and cockpit display of traffic information (CDTI).

Section 11 Future Work

This report details the initial work of the GEAS. In its initial year, the GEAS Panel has developed and examined three specific architectural concepts to provide worldwide LPV-200 service. The basic requirements and performance for each architecture were developed and compared to investigate the design trade space among time-to-alert, ground infrastructure, and constellation geometric robustness.

Further in depth analysis is still required to ensure that the recommended architectural concept remains feasible and realizable. The GEAS Panel identified numerous actions for this next phase of activity spanning several years in order to address three major areas: trade space refinement; integrity performance analysis; and transition strategy. Performance of this work is considered essential to developing the details associated with the recommended architecture and path forward. One of the most important areas of study for the GEAS in the next phase is the development of the transition strategy. As the GEAS Panel develops the details for the final architectural construct, it is crucial to map out the path forward from the current infrastructure to this desired endpoint. The actual integration, or degree of integration, of the key aviation functions into the GPS Modernization Program presents significant institutional and organizational challenges that remain to be resolved as part of the ongoing GEAS and GPS III design definition efforts.

Section 11.1 Trade Space Refinement

Satellite Clock and Ephemeris Errors -- The magnitude of residual errors that remain on the GPS satellite pseudorange due to clock and ephemeris errors is a primary driver for availability. This error is described by the URA term for GPS while in WAAS this error is described by the UDRE. Although both terms are meant to describe the same error they are very different in their accounting for TTA and integrity requirements. The candidate architectures also impose different requirements on these parameters. The GEAS Panel will continue to investigate these dependencies and determine methods for providing bounds that satisfy the specific requirements for each architecture. The requirements for GIC are essentially identical to WAAS so the UDRE monitor is a natural starting point for investigating the performance versus ground network spatial configuration. For RRAIM and ARAIM the TTA is relaxed. The Panel will investigate how this relief may be translated into tighter confidence bounds while still meeting overall integrity requirements.

In addition to characterizing the nominal satellite clock and ephemeris errors, ground monitoring must detect the clock and ephemeris failures. Protection against such failure modes dominates the broadcast UDRE term for WAAS. RRAIM and ARAIM enable the aircraft to detect such failures as well. However, a crucial part of each algorithm is that these types of failures are rare occurrences. For the RAIM techniques associated with TSO C-129, the failures of concern are of order 100 meters or larger. It is easy to observe such failures and determine their rarity. For vertical guidance, failures of interest will be on order of meters so a new characterization of the rarity of these much smaller errors will be required along with the development of the overbounding term. As with existing RAIM, the likelihood of larger errors will need to be of order 10^{-5} per satellite per hour or less. The GEAS Panel will investigate meeting and validating this requirement in conjunction with the evaluation of the ground monitor network and algorithms.

Ground Algorithms and Network to Detect Satellite Faults -- For ground-based monitoring, the ground algorithms and network design have a major influence on availability, therefore, the GEAS will leverage its GPS and WAAS experience to develop a more optimal UDRE type algorithm. The minimum number of stations and their global distribution will be investigated to determine the network that still meets redundancy requirements. The effects of multipath and antenna bias on the measurement quality will also be investigated. Ultimately these error sources will limit confidence in determination of the satellite clock and ephemeris errors. The antenna bias terms in particular are a concern as they may cause consistent errors that then need to be treated accordingly in development of the bounding. Further, the ground monitoring must effectively account for interfrequency biases in both the monitoring receivers and the GPS satellites. Better characterization of the ground monitor performance and ultimately satellite confidence parameters is a critical task in determining availability of the different architectures. Finally, the definition of the algorithm(s) suitable for signal deformation monitoring needs to be developed. The GEAS will continue to work with the GPS Wing on the signal specifications and with RTCA and ICAO on the user space to track and minimize these biases. Whatever portion of the threat space that cannot be mitigated will then be taken into account in the user protection level calculation.

Satellite Based Algorithms to Detect Satellite Faults -- Monitoring of the satellites can take place on the ground as is done in today's WAAS and LAAS or it may be accomplished on the satellite. The Panel will continue to evaluate this trade by evaluating the mitigations required in either location versus the expected threats. Important considerations will be observability, TTA, feasibility, and cost/level of effort. It may be that the optimal solution will place monitors in both locations. The GEAS will analyze how this placement affects the specific architectures, both for performance and cost. As with ground monitors, the space based approach will also need to address signal deformation. The signals produced onboard will never be ‘perfect’ so it is essential to determine the impact of these nominal deformations. The magnitude of the error will be a function of the satellite specifications and the range of allowed user receiver designs. Together these will create maximum allowable biases on the ranging signals that must be included in the protection level equations.

Optimization of the Broadcast Channel -- Another important area of future investigation is the method of broadcast corrections and integrity information to the user. GPS uses the satellites themselves to provide necessary updates while WAAS uses a geostationary satellite to transmit its information and LAAS uses a terrestrial VHF link to communicate to its users. All these methods will be explored in greater detail to determine the relative merits for use within each architecture and application. Using GPS as the channel is attractive but provides the least capacity and highest latency. The GEAS will investigate whether GPS cross-link data communication is required to achieve the desired latency and accuracy. Terrestrial links offer high capacity and low latency but also limited coverage. The geostationary satellites do have good capacity and excellent coverage but are quite expensive to operate. The GEAS will investigate what information to send and the trade-off between message bandwidth and performance. We need to better detail the trades among message bandwidth, latency, and performance as well as further investigate integration with each architectural concept.

Constellation Dependence -- Continued focus and emphasis will be placed on evaluating the effect of constellation robustness because the strength of the constellation is such a design and architecture driving parameter. Initially three constellations were evaluated together with a single significant satellite outage. Future work will include identification of other important satellite outage conditions and encompass other likely GPS constellation configurations. Table 2 includes the cases with all satellites available and the cases where one satellite has been removed from operation. Evaluation of performance with two satellites are removed will be performed to further investigate the vulnerability of the performance of each architectural candidate to satellite outages. The sensitivity of each candidate architecture will continue to be evaluated as well as possible algorithm mitigations. Additionally, the GEAS will evaluate the benefits of the combination of GPS and other core constellations such as Galileo. Although, the primary focus is to provide a basic capability independent of other constellations, it is highly desirable to leverage additional capability enabled by other constellations. This is an important consideration in the development of the architectures. The timing of the availability of constellations and capability is another important consideration. As these estimates are updated the GEAS must factor this timing into its overall strategy as necessary.

Cost Benefit Analysis -- The GEAS has identified three promising architectures and initiated a trade study among them. However, there is still much work to be performed to develop the details associated with each architecture in order to validate the expected *benefits*. Additionally, these details are required to identify the level of effort required to actually implement the architectures. Additionally, remaining technical risks will be identified for each. These outcomes will be used to inform a cost to benefit trade analysis that will be essential to identifying a recommended architecture. Coordination must continue among the GEAS member organizations to ensure that these long-term efforts are fruitful.

Section 11.2 Integrity Performance Analyses

Fault Trees and P (HMI) Analyses -- As these architectural concepts are refined, detailed fault tree analyses will be created to evaluate the integrity and continuity for each architecture. Further, as each algorithm supporting these architectures is further refined, it will be documented in a manner consistent with the algorithm description documents used on WAAS and LAAS. This approach then enables a transparent review process to assure that any comparison evaluations are properly performed and done on an equal footing. Finally, preliminary P(HMI) methodologies will be prepared. This is an essential step associated with determining the comparative level of effort required to certify the architectural concept.

Validation With Data -- The various methodologies developed by the GEAS for these architectures will need to be tested using real data. The evaluation will be done using the current suite of GPS signals and will need to incorporate L5 as that signal becomes available from the GPS IIF satellites in 2009 through 2012. While these signals are extraordinarily helpful, they will only enable testing at the pseudorange level. In order to evaluate performance in the position domain L1 & L2 data will be used. WAAS has collected an extensive amount of dual frequency data for North America. Sparse worldwide data is also available for use from other sources. The ground algorithms under evaluation will be tested and validated with these data sets. The FAA Technical Center also has available dual-frequency flight test data that will be used to validate the airborne algorithms already developed by the GEAS.

Section 11.3 Transition

Strategy Formulation -- One of the most important areas of study for the GEAS in the next phase is the development of the transition strategy. As the GEAS develops the details for the final architectural construct, it is crucial to map out the path for how to go from the current infrastructure, to this desired endpoint. It is critical that that the GEAS does not impede the current increased use of satellite navigation currently underway. Ideally, the eventual implemented architecture would maximize use of the existing user base. We must investigate paths that encourage the current uptake of L1-only GPS, WAAS, and LAAS and ultimately provide even further capability when there's a full constellation of L5 satellites. The GEAS final architecture must be compatible with existing users and support them as part of a reversionary mode should L5 not be available. The GEAS will develop specific requirements associated with reversionary mode to support LPV operations as part of the definition of transition to L1 and L5 operations. The transition from L1 to L1 & L5 is the most important consideration in choosing our recommended architecture and must be evaluated carefully in the upcoming years. The transition strategy must address global certification/acceptance and geopolitical issues associated with liability as an influence on transition planning.

To the extent allowed in such an unclassified setting, the Panel will also assess the preferred architecture with respect to military aviation use and identify any issues that require more detailed study by military analysts.

Collaboration With RTCA, EUROCAE, and Other Service Providers -- One means to ensure a successful transition is to continue our efforts to communicate with the user community. Therefore, the GEAS must continue to interact with RTCA and EUROCAE to update them on our progress and solicit their feedback. Both these forums provide excellent interaction between service providers, equipment manufacturers, and representatives of the user community. In addition, there must be continued coordination with other service providers (Galileo, Compass, GLONAAS, EGNOS, MSAS, GAGAN) to ensure that the GEAS efforts are compatible with their future plans as well. Initial feedback has already been obtained from user groups that have indicated preference that avionics supporting ADS-B should also be capable of utilizing the GEAS architecture. Only one avionics upgrade should be required to realize this objective.

Supporting Category II and III Operations -- In the longer term, the GEAS will investigate combining dual frequency GNSS with other sensors. Integration with a precise clock and/or inertial sensors, may provide better continuity performance, by providing resistance to interference and scintillation. Altimeters (barometric, radar, or laser) add an additional measurement and provide relief against constellation weakness, but at the cost of complexity. The GEAS will investigate these trades to determine if they have merit and warrant more detailed investigations. A long-term goal of the GEAS is the provision of Cat II/III capability worldwide. It is highly desirable that the final architecture offer an upgrade path to support this goal. The requirements on Cat II/III are very stringent and will be very challenging to meet. The GEAS must investigate the implications of these requirements and understand how the recommended architectures contribute to satisfaction of these needs.

GPS Modernization -- The key GPS III integrity related 'features' or attributes envisioned by the Panel need refinement and the mechanism for realization, or resolution, of these items will need to be factored into the GEAS architectural development. GPS Modernization should provide sufficient design, analyses, and testing so that the residual risk of a GPS integrity failure will be acceptable. The GWing has captured this intent in the GPS III requirements specifications and the FAA expects to actively participate in the GPS III Program throughout its life cycle so there's reasonable probability of success and likelihood of ultimate FAA concurrence with the results. The listing below is not all inclusive but is indicative of the type and extent of coordination with the USAF that will be necessary to actually execute the GEAS integrity architectural vision.

- Monitoring of key parameters at both low threshold levels and higher levels so there is redundancy to the monitoring. The inherent high signal to noise ratio internal to the SV could then render the traditional missed-detection/false-alarm tradeoff moot, i.e., both can be set to 6 sigma or more.
- Onboard clock monitor will effectively eliminate the most likely failure mode GPS has exhibited.
- SVs *might* be able to share info over the cross-links to provide independent sources of data.
- There will be overlap between some form of SBAS/GIC/RRAIM/ARAIM and GPS IIIC so there will be redundant integrity capability for an unknown period of time.
- Some aspects/algorithms/elements of the SBAS/GIC could be merged into the Control Segment, perhaps providing dissimilar redundancy within the CS.
- GWing/2SOPS will be able to gather actual performance data on the SVs during the constellation build-up to 27 or 30 GPS IIIC SVs.

Section 12 References

[1] McDonald, K. D. and Hegarty, C., "Post-Modernization GPS Performance Capabilities," Proceedings of ION Annual Meeting, San Diego, CA, 2000.

[2] Van Dierendonck, A. J., Hegarty, C., Scales, W., and Ericson, S., "Signal Specification for the Future GPS Civil Signal at L5," Proceedings of ION annual Meeting, San Diego, CA, 2000.

[3] Hegarty, C. and Chatre E., "Evolution of the Global Navigation Satellite System (GNSS)," in preparation for Proceedings of IEEE

[4] Parkinson., B., W., "Introduction and Heritage of NAVSTAR, the Global Positioning System," Chapter 1 in Global Positioning System: Theory and Applications Vol. I, AIAA, 1996.

[5] Creel, T., Dorsey, A. J., Mendicki, P. J., Little, J., Mach, R. G., and Renfro, B. A., "Summary of Accuracy Improvements From the GPS Legacy Accuracy Improvement Initiative (L-AII)," Proceedings of ION GNSS, Fort Worth, TX, 2007

[6] Warren, D. L. M., and Raquet, J. F., "Broadcast vs. Precise GPS Ephemerides: a Historical Perspective," GPS Solutions, Volume 7, Number 3, December, 2003

[7] Gratton, L., Pramanik, R., Tang, H., and Pervan, B., "Ephemeris Failure Rate Analysis and its Impact on Category I LAAS Integrity," Proceedings of ION GNSS 2007, Fort Worth, TX, September, 2007.

[8] FAA Technical Center, "Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report," Report #42 April 1 – June 30, 2003. Available at http://www.nstb.tc.faa.gov/REPORTS/PAN42_0703.pdf

[9] Edgar, C., Czopek, F., and Barker, B., "A Cooperative Anomaly Resolution on PRN-19," Proceedings of ION GPS, Nashville, TN, 1999.

[10] Klobuchar, J. A., "Ionospheric Effects on GPS," Chapter 12 in Global Positioning System: Theory and Applications Vol. I, AIAA, 1996.

[11] Datta-Barua, S., "Ionospheric Threats to the Integrity of Airborne GPS Users," Stanford University Ph.D. Thesis, 2007

[12] Misra, P. and Enge, P., "Global Positioning System Signals, Measurements, and Performance," Ganga-Jamuna Press, 2006.

[13] Brown, R. G., "Receiver Autonomous Integrity Monitoring," Chapter 5 in Global Positioning System: Theory and Applications Vol. II, AIAA, 1996.

[14] Enge, P., "Local Area Augmentation of GPS for the Precision Approach of Aircraft," in Proceedings of the IEEE, Vol. 87 No. 1, pp 111-132, 1999.

[15] Walter, T. and El-Arini, M. B. editors, "Selected Papers on Satellite Based Augmentation Systems," ION Redbook Volume VI, 1999.

[16] ICAO Standard and Recommended Procedures (SARPS) Annex 10

[17] DeCleene, B., “Defining Pseudorange Integrity – Overbounding,” Proceedings of ION GPS 2000, Salt Lake City, Utah, 2000.

[18] Walter, T. et al., “Robust Detection of Ionospheric Irregularities,” in Proceedings of ION GPS-2000, Salt Lake City, UT, September 2000.

[19] RTCA, “Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment,” RTCA publication DO-229D, 2006.

[20] Spilker, J. J., “GPS Signal Structure and Theoretical Performance,” Chapter 3 in Global Positioning System: Theory and Applications Vol. I, AIAA, 1996.

[21] Fontana, R. D., Cheung, W., Novak, P. M., and Stansell, T. A., “The New L2 Civil Signal,” Proceedings of ION GPS, Salt Lake City, UT, 2001.

[22] McGraw G. A. and Young R. S. Y., “Dual Frequency Smoothing DGPS Performance Evaluation Studies,” Proceedings of the National Technical Meeting of the ION, San Diego, CA, 2005.

[23] Shallberg, K. and Grabowski, J., “Considerations for Characterizing Antenna Induced Range Errors,” Proceedings of ION GNSS 2002, Portland, OR, 2002.

[24] Mitelman, A. M., Phelts, R. E., Akos, D. M., Pullen S. P., and Enge, P. K., “Signal Deformations on Nominally Healthy GPS Satellites,” Proceedings of the National Technical Meeting of the ION, San Diego, CA, 2004.

[25] Phelts, R. E., Walter, T., Enge, P., Akos, D. M., Shallberg, K., and Morrissey, T., “Range Biases on the WAAS Geostationary Satellites,” Proceedings of the ION National Technical Meeting, San Diego, California, 2004.

[26] Rife, J., Pullen, S., Pervan, B., and Enge, P. “Paired Overbounding and Application to GPS Augmentation” Proceedings of the IEEE Position Location and Navigation Symposium, Monterey, CA, April 2004.

[27] Walter, T. and Enge, P., “The Wide Area Augmentation System,” Chapter 4.1 in “EGNOS the European Geostationary Navigation Overlay System – A Cornerstone of Galileo,” ESA Publication SP-1303, 2006.

[28] Lawrence, D., Bunce, D., Mathur, N. G., and Sigler, E., “Wide Area Augmentation System (WAAS) - Program Status,” Proceedings of ION GNSS, Fort Worth, TX, 2007

[29] Heo, M., Pervan, B., Pullen, S., Gautier, J., Enge, P., Gebre-Egziabher, D., “Autonomous Fault Detection with Carrier Phase DGPS for Shipboard Landing Navigation,” *NAVIGATION: Journal of The Institute of Navigation*, Vol. 51, No. 3, Fall 2004.

[30] Gratton, L., and Pervan, B., “Algorithms for Airborne Ionospheric Front Detection in LAAS Using Carrier Phase and INS Measurements,” Proceedings of the Institute of Navigation National Technical Meeting, San Diego, CA, January 24-26, 2005.

[31] Gratton, L., and Pervan, B., "Airborne and Ground Monitors for Ionospheric Front Detection for the Local Area Augmentation System Using Carrier Phase Measurements," Proceedings of the 18th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS-2005), Long Beach, CA, September 13-16, 2005.
[32] van Graas, F. and Soloviev, A., "Coasting with Relative Carrier Phase RAIM," Briefing to GEAS Panel, Palo Alto, CA, February 21-22, 2007.
[33] Huang, J. and van Graas, F. "Comparison of Tropospheric Decorrelation Errors in the Presence of Severe Weather Conditions in Different Areas and Over Different Baseline Lengths," Proceedings of the 19th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS-2006), Fort Worth, TX, September 26-29, 2006.
[34] Walter, T. and Enge, P., "Weighted RAIM for Precision Approach," in Proceedings of ION GPS-95, Palm Springs, CA, September, 1995.
[35] Blanch, J., Ene, A., Walter, T., Enge, P. "An Optimized Multiple Solution Separation RAIM Algorithm for Vertical Guidance". Proceedings of the ION GNSS 2007, Fort Worth, TX, September 2007.
[36] Lee, Y.C. and McLaughlin, M. P., "Feasibility Analysis of RAIM to Provide LPV 200 Approaches with Future GPS," in proceedings of ION GNSS-2007, Forth Worth, TX, September 2007
[37] Jan, S.S., Chan, W., Walter, T., and Enge, P., "MATLAB Simulation Toolset for SBAS Service Volume Analysis", Proceedings of ION GPS-2001, Salt Lake City, UT, September 2001.
[38] GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE PERFORMANCE STANDARD, 2001 available at http://www.navcen.uscg.gov/gps/geninfo/2001SPSPerformanceStandardFINAL.pdf.
[39] Karl Kovach, Private Communication.
[40] Walter, T., Blanch, J., and Enge, P., "L5 Satellite Based Augmentation Systems Protection Level Equations" Proceedings of the International GNSS Conference, Sydney, 2007.