Evolving WAAS to Serve L1/L5 Users

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ABSTRACT

GPS has launched its first L5 capable satellites and plans to achieve L5 Full Operational Capability (FOC) in the 2019 time frame. L5 is of great interest to the Wide Area Augmentation System (WAAS) and the aviation community, as it will allow aircraft to measure and remove the ionospheric delay affecting each ranging observation. Currently, this error source is the most significant cause of unavailability for WAAS users. Its elimination will result in greater performance and a larger service area under WAAS. However, in order to take advantage of L5, both the aircraft and WAAS will need to be updated. We have previously recommended changes to the airborne protection level calculations to exploit these new signals. In this paper we describe changes that must be made to WAAS to support the new protection level equations and provide dual-frequency service.

INTRODUCTION

WAAS was initially declared operational in 2003 [1] and has had many improvements made to it over the intervening years. It currently achieves excellent coverage over the vast majority of North America, providing corrections to the GPS L1 signal. However, when the ionosphere is disturbed or when the constellation is weak, its availability may be reduced. Using both the L1 and L5 signals in the aircraft will remove the primary dependence on the state of the ionosphere. Removing this largest source of uncertainty allows service to be provided under more conditions than are allowed today. Thus, the use of L1 and L5 together will provide very robust coverage of vertical guidance down to 200 feet throughout North America.

However, the inclusion of L5 introduces some issues that are not fully addressed by the current WAAS system. The L5 signal has to be monitored and its use in the new protection levels must be assured. This paper first looks at the threat space specific to satellite navigation users. It then investigates how the monitoring algorithms must be adapted to address the threat space as it specifically applies to dual frequency use. Some changes are relatively simple such as the effects of satellite clock and ephemeris errors. However, others are more involved. Specifically, signal deformations have potentially far greater impact on the ionosphere-free pseudorange combination. Addressing the signal deformation threats will require greater changes both on the ground and likely in the air. Of, course, throughout this evolution the legacy L1-only WAAS service must be maintained. In addition, the cost of this upgrade is to be minimized and so emphasis will be placed on making minimal changes to existing monitoring in order to both maintain existing service and provide the new dual frequency service.

WAAS THREATS

As described in previous papers [2], threat models describe the anticipated events that a system must protect the user against and conditions during which it must provide reliably safe confidence bounds. Each threat model must describe the specific nature of the threat, its magnitude, and its likelihood. Together, the various threat models must be comprehensive in describing all reasonable conditions under which the system might have difficulty protecting the user. Ultimately the threat models form a major part of the basis for determining if the system design meets its integrity requirement. Each individual threat must be fully mitigated to within its allocation. Only when it can be shown that all threats have been sufficiently addressed can the system be deemed safe.

WAAS was developed primarily to address threats to GPS. However, it also runs the risk of introducing new threats in the absence of any GPS fault. Included in any threat model must be self-induced errors. Some of these errors are universal to any design while others are specific to the implementation. The following is a high level list of generic threats. While it is not fully comprehensive, it does include the most significant categories either for magnitude of effect or likelihood. There are numerous other threats that have a smaller effect, are less likely, or are implementation specific.

High-Level Threat List

- Satellite
    - Clock/ephemeris error
    - Signal deformation
    - Code carrier incoherency
- Ionosphere
    - Local non-planar behavior
        - Well-sampled
        - Undersampled
- Troposphere
- Reference receiver
    - Multipath
    - Thermal noise
    - Antenna bias
    - Survey errors
    - Receiver errors
- Master station
    - SV clock/ephemeris estimation errors
    - Ionospheric estimation errors
    - SV Tgd estimation errors
    - Receiver IFB estimation errors
    - WRS clock estimation errors
    - Communication errors
    - Broadcast errors
- User errors

The following paragraphs provide greater detail for each threat, although the full details depend on implementation and must be decided by the service provider.

SV Clock/Ephemeris Estimation Errors

Satellites suffer from nominal ephemeris and clock errors even when there are no faults in the GPS system [3] [4] [5] [6]. Additionally, the broadcast GPS clock and ephemeris information may contain significant errors in the event of a GPS system fault or erroneous upload. Such faults may create jumps, ramps, or higher order errors in the GPS clock, ephemeris, or both [7] [8] [9] [10] [11]. Such faults may be created by changes in state of the satellite orbit or clock, or simply due to the broadcasting of erroneous information. Either the user or the system may also experience incorrectly decoded ephemeris information.

The User Differential Range Error (UDRE), a term designed to describe residual satellite errors, must be sufficient to overbound the residual errors on the corrected satellite clock and ephemeris.

Signal Deformations

The International Civil Aviation Organization (ICAO) has adopted a threat model to describe the possible signal distortions that may occur on the GPS L1 CA code. These distortions will lead to biases that depend upon the correlator spacing and bandwidth of the observing receivers. Such biases would be transparent to a network of identically configured receivers [12] [13] [14].

The UDRE must be sufficient to overbound errors caused by signal deformation.

Code-Carrier Incoherency

Another threat is that a satellite may fail to maintain the coherency between the broadcast code and carrier. This fault mode occurs on the satellite and is unrelated to incoherence caused by the ionosphere. This threat causes either a step or a rate of change between the code and carrier broadcast from the satellite. This threat has never been observed on the GPS L1 signals, but has been observed on WAAS geostationary signals and on the GPS L5 signal [15] [16].

The UDRE must be sufficient to overbound errors caused by code-carrier incoherency.

Ionosphere and Ionospheric Estimation Errors

The majority of the time, mid-latitude ionosphere is easily estimated and bounded using a simple local planar fit. However, periods of disturbance occasionally occur where simple confidence bounds fall significantly short of bounding the true error [17]. Additionally, in other regions of the world, particularly equatorial regions, the ionosphere often cannot be adequately described by this simple model [18] [19]. Some of these disturbances can occur over very short baselines causing them to be difficult to describe even with higher order models. Gradients larger than three meters of vertical delay over a ten-kilometer baseline have been observed, even at mid-latitude [20] [21].

The broadcast ionospheric grid format specified in the Minimum Operational Performance Standards (MOPS) [22] also limits accuracy and integrity. The simple two-dimensional model and assumed obliquity factor may not always provide an accurate conversion between slant and vertical ionosphere. There will also be instances where the five-degree grid is too coarse to adequately describe the structure of the surrounding ionosphere.

There are times and locations where the ionosphere is very difficult to model. This problem may be compounded by poor observability [23] [24]. Ionospheric Pierce Point (IPP) placement may be such that it fails to sample important ionospheric structures. This may result from the intrinsic layout of the reference stations and satellites, or from data loss through station, satellite, or communication outages. As a result, certain ionospheric features that invalidate the assumed model can escape detection.

Finally, because the ionosphere is not a static medium there may be large temporal gradients in addition to spatial gradients. Rates of change as large as four vertical meters per minute have been observed at mid-latitudes [20].

The Grid Ionospheric Vertical Error (GIVE), a term designed to describe residual ionospheric estimation errors, must account for inadequacies of the assumed ionospheric model, restrictions of the grid, and limitations of observability. The GIVE must be sufficient to protect against the worst possible ionospheric disturbance that may be present in that region given the IPP distribution. Additionally, since each ionospheric correction does not time out until after ten minutes, the GIVE and the Old But Active Data (OBAD) terms [22] must protect against any changes in the ionosphere that can occur over that time scale. Because the physics of the ionosphere are incompletely understood, the most practical ionospheric threat models are heavily data driven and contain a large amount of conservatism.

Tropospheric Errors

Tropospheric errors are typically small compared to ionospheric errors or satellite faults. Historical observations were used to formulate a model and analyze deviations from that model [25]. A very conservative bound was applied to the distribution of those deviations. The model and bound are described in the MOPS [22]. These errors may affect the user both directly through their local troposphere, and indirectly through errors at the reference stations that may propagate into satellite clock and ephemeris estimates. The user protects against the direct effect using the specified formulas.

WAAS must ensure that the UDRE adequately protects against the propagated tropospheric errors and their effect on satellite clock and ephemeris estimates. Of particular concern are the statistical properties of these error sources. These errors may be correlated for long periods, and will produce correlated errors across all satellites at a reference station and each receiver at the reference station.

Multipath and Thermal Noise

Multipath is the most significant measurement error source. It limits the ability to estimate the satellite and ionospheric errors. It depends upon the environment surrounding the antenna and the satellite trajectories. While many receiver tracking techniques can limit its magnitude, its period can be tens of minutes or greater [26] [27]. Additionally, it contains a periodic component that repeats over a sidereal day. Thus, severe multipath may be seen repeatedly for several days or longer.

Since all measurements that form the corrections and the UDREs and GIVEs are affected by multipath, great care must be used to bound not only its maximum extent but its other statistical characteristics as well (non-gaussian, non-white, periodic, etc.). There is potential for correlation between measurements and between antennas at a single reference site. Additionally the local environment may change either due to meteorological conditions (snow, rain, ice), or physical changes (new objects or structures placed nearby).

If carrier smoothing is used to mitigate multipath then robust cycle slip detection is essential. Half integer cycle slips have been observed on many different types of receivers. In one case, several half cycle slips were observed in the same direction each several minutes apart resulting in a several meter error. Cycle slip detection must be able to reliably catch unfortunate combinations of L1 and L2 or L5 half and full integer cycle slips in order to achieve an unbiased result.

Antenna Bias

Look-angle dependent biases in the code phase on both frequencies are present on reference station and GPS satellite antennas [28] [29]. These biases may be several tens of centimeters. In the case of at least one reference station antenna, they did not become smaller at higher elevation angle. These biases are observable in an anechoic chamber, but more difficult to characterize in operation. They may result from intrinsic antenna design as well as manufacturing variation.

While the particular orientation of each antenna and bias may be random, it is also static. Therefore, there may exist some points in the service volume where the biases tend to add together coherently and consistently. Thus, these locations will experience this effect day after day. To protect these regions, the biases should be treated pessimistically as though they are all nearly worst-case and coherent. Calibration may be applied, although individual variation, the difficulty of maintaining proper orientation, and the possibility of temporal changes, hamper its practicality.

Survey Errors

Errors in the surveyed coordinates of the antenna code phase center can affect users in the same manner as antenna biases. However, survey errors tend to be much smaller in magnitude and affect all frequencies identically.

These errors can typically be lumped in with antenna bias protection terms and mitigated in the same manner.

Receiver Errors

The receivers themselves can introduce errors through false lock or other mechanisms including hardware failure (GPS receiver, antenna, atomic frequency standard) or software design error (tracking loop implementation).

These may be mitigated through the use of redundant and independent receivers, antennas, and clocks, at the same reference station [29]. However, the UDRE and GIVE must still protect against small errors may exist, but are not large enough to be guaranteed detection.

Interfrequency Bias Estimation Errors

For the current L1-only WAAS service, the correction algorithms need to know the hardware differential delay between the L1 and L2 frequencies. These are referred to as Tau group delay (Tgd) for the bias on the satellite and IFB for the Inter-Frequency Bias in the reference station receivers. These values are typically estimated in tandem with the ionospheric delay estimation [30]. Although these values are nominally constant, there are some conditions under which they may change their value. One method is component switching, if a new receiver or antenna is used to replace an old one, or if different components or paths are made active on a satellite. Another means is through thermal variation either at the reference station or on the satellite as it goes through its eclipse season. Finally, component aging may also induce a slow variation

The estimation process may have difficulty in distinguishing changes in these values from changes in the ionosphere. The steady state bias value and step changes may be readily observable, but slow changes comparable to the ionosphere may be particularly difficult to distinguish. Ionospheric disturbances that do not follow the assumed model of the ionosphere may also corrupt the bias estimates. The UDREs and GIVEs must bound the uncertainty that may result from such estimation errors.

Receiver Clock Estimate Errors

Similarly, the satellite correction algorithm must estimate and remove the time offsets between the reference station receivers. These differences are nominally linear over long times for atomic frequency standards. However, component replacement or failure may invalidate that model. Nominally, these differences are easily separated, however, reference station clock failures and/or satellite ephemeris errors may make this task more difficult. The UDRE must protect against errors that may propagate into the satellite clock and ephemeris correction due to these errors. Particular attention must be paid to correlations that may result from this type of misestimation

THE IONOSPHERE-FREE COMBINATION

GPS satellites originally only offered one civil signal at the GPS L1 frequency (1575.42 MHz). As this frequency falls in an Aeronautical Radio Navigation Service (ARNS) band it may be used for civil aviation. It has already been incorporated into several systems to provide guidance to aircraft [1] [31] [32]. Two additional civil frequencies are starting to be added to the GPS satellites. L2 (1227 MHz) is further along, but is not in an ARNS band and may not be used for aviation. L5 has only just started to be implemented but is in an ARNS band and may be used for aircraft guidance. Thus, L5 is the chosen second civil frequency for the aviation community.

An advantage of having two signals at two distinct frequencies is that the pseudorange error caused by the ionosphere may now be directly estimated and removed, by using the following ionosphere -free combination

$$\begin{aligned} PR_{iono-free} &= \frac{f_1^2}{f_1^2 - f_5^2} PR_{L1} - \frac{f_5^2}{f_1^2 - f_5^2} PR_{L5} \\ &\approx 2.26 \times PR_{L1} - 1.26 \times PR_{L5} \end{aligned} \quad (1)$$

The ionosphere is the largest source of uncertainty for single-frequency, augmented, GPS-based, aircraft navigation. Often, the ionospheric delay is small and smoothly varying. However, there can be disturbances that create significant variations over time and/or space. L1-only systems must account for this risk as they assess the potential bounds on position errors.

The ionosphere-free combination is not vulnerable to this uncertainty and can form smaller bounds on the possible positioning error. Table 1 highlights this advantage. The table and the equation above also identify a disadvantage with this approach. The ionosphere-free combination of signals increases the effect of errors that affect the L1 and L5 signals differently. Although the combination eliminates dependence on ionospheric delay error and keeps the same dependence on tropospheric and satellite clock and ephemeris errors, other L1 only errors such as multipath are multiplied by 2.26 and L5 only errors are multiplied by 1.26. Thus, if the same level of multipath exists on L1 and L5, the overall contribution is increased to 2.6 times that of L1-only.

The use of the ionosphere-free combination is a poor choice most of the time, in that the nominal accuracy of the WAAS ionospheric correction is smaller than the increase in the contribution from the airborne multipath. However, under extreme conditions, the ionosphere delay error can grow much larger than the multipath error. Therefore, the largest possible errors are reduced by this combination. It is these extreme errors that we are most interested in for integrity. By reducing them, we can reduce the possible position error bound and improve availability.

The following sections briefly describe how each threat changes due to the use of the ionosphere-free combination.

SV Clock/Ephemeris Estimation Errors

Satellite clock and ephemeris threats are largely independent of frequency and therefore these threats are essentially unchanged. There will be a small difference between the satellite L1-only clock and the ionosphere-free clock. For the current L1-only system the clock and ephemeris errors are estimated and bounded using the L1/L2 ionosphere-free combination and the interfrequency bias error estimate and uncertainty are applied to adjust the correction and confidence bound to the L1-only user. For the dual frequency case, WAAS and the avionics are using the exact same frequency combination and so there is no need to apply an interfrequency bias correction or uncertainty. Therefore the dual frequency clock corrections are slightly different from the L1-only correction and the confidence bound may be slightly smaller.

Signal Deformations

Signal deformation threats are unlikely be identical on L1 and on L5. Thus, the effects may be greatly magnified compared to L1-only. The signal deformation errors on L1 will be multiplied by 2.26 and any such errors on L5 will be increased by 1.26. This threat may easily become the largest source of uncertainty on the ionosphere-free combination.

Code-Carrier Incoherency

This threat also is likely to be different on L1 and L5 and the errors will also be magnified. Both the ground monitors and the avionics will be using the same ionosphere-free combination, but the effect of possible drift between the code and carrier or between the two frequencies will be greater than the L1-only case. This threat will also be a significant source of uncertainty on the ionosphere-free combination.

Ionosphere and Ionospheric Estimation Errors

The first order ionospheric delay term is completely eliminated by the use of the ionsphere-free combination. So this delay effect and any estimation errors have no impact on the dual frequency user. However, there are higher order terms in the ionspheric delay. While these higher order terms are not completely eliminated, they are

	Iono error	Clock / ephemeris	Tropo error	L1 error	L5 error	RSS
L1 Only	1	1	1	1	0	1
Iono-free	0	1	1	$\frac{f_1^2}{f_1^2 - f_5^2}$ $= 2.26$	$\frac{f_5^2}{f_1^2 - f_5^2}$ $= 1.26$	2.6
Nominal Error	0.2 - 1 m	0.3 - 0.5 m	0.05 - 0.5 m	0.15 - 0.5 m	0.15 - 0.5 m	0.4 - 1.3 m
Max Error	50 m	Unlimited	5 m	0.5 m	0.5 m	1.3 m

Table 1. *This table shows the dependencies of the L1-only and L1/L5 approaches on different error sources. Also shown are nominal and extreme expected values of the errors.*

quite small, particularly in the mid-latitudes where WAAS operates. At worst these are expected to be a few tens of centimeters and likely much smaller. They still require further study to determine if further protection is required against these higher order delay terms.

Another concern is ionospheric scintillation. Although this is not expected to affect integrity, scintillation can cause the receiver to temporarily lose lock on one or more satellites. This may lead to a loss of continuity. It is still an open question how significant these effects may be. One concern is that scintillation strength increases with lower frequency, so the new L5 signal may be more vulnerable.

Tropospheric Errors

Tropospheric errors are unaffected by the switch to the ionosphere-free combination. The existing protection applies equally well to the dual frequency user.

Multipath and Thermal Noise

Multipath is a threat both on the ground and in the air. On the ground the switch to L5 has minimal impact as the ground segment already uses L2 semi-codeless to separate ionospheric effects from other errors. The L5 signal has more power and a better design against multipath, so the net impact on the ground should be reduced, but not substantially so. In the air, the effect is more dramatic. The use of the ionosphere-free combination significantly increases the contribution of the airborne multipath to the user's positioning errors. If similar levels of multipath exist on L1 and L5 the net effect is an increase of approximately 2.6 times the current L1 only multipath error. Thus, this term could become the most significant contributor to the overall user ranging error budget. It may be possible to reduce this somewhat as L5 mutlipath should be smaller and the aircraft can increase its smoothing time as ionospheric delay will not cause any divergence. However, how much reduction will be possible will have to wait until we can collect relevant L1/L5 data.

Antenna Bias

Antenna biases affect both the ground and the air. Like multipath, the effect on the ground will change little going to L1/L5. However, in the aircraft, the effects are multiplied by the same factors on L1 and L5. Thus, the overall effect in the air is significantly increased. This effect on L1-only is sufficiently small as to be virtually neglected; however, that is less likely to be valid for the ionosphere-free combination. Determining the impact of this threat will also require collecting dual frequency data from aviation antennas.

Survey Errors

Survey errors are also unaffected by the switch to the ionosphere-free combination. The existing protection applies equally well to the dual frequency user.

Receiver Errors

Receiver errors can be worse for the ionosphere-free combination as faults often affect the L1 and L5 measurements differently. However, the current ground monitoring already makes use of the L1/L2 ionosphere-free combination and has measurement screening that compares receiver measurements across the three receivers at each reference station and across different reference stations. Thus, it is not expected that the WAAS corrections will be more vulnerable to this error for the dual frequency user. However, receiver errors in the aircraft would have a greater impact and it is imperative that the aviation receivers ensure that their receiver monitoring adequately protects against this increased effect.

Interfrequency Bias Estimation Errors

As in the case for the first order ionosphere delay errors, interfrequency bias errors are completely eliminated with the use of the ionospheric-free combination. Because the identical frequency combination is used by both the ground and the avionics, there is no need for interfrequency bias terms and any such error cancels differentially. Changes in this bias would manifest themselves as an ionosphere-free code-carrier divergence. The dual frequency CCC monitor must detect this change, if it is large enough to create a hazard.

Receiver Clock Estimate Errors

As is the case for satellite clock and ephemeris errors, receiver clock errors are minimally affected by the switch to the ionosphere-free combination. The IFB is now lumped in with the overall clock term and the existing protection applies equally well to the dual frequency user.

CURRENT WAAS ARCHITECTURE

WAAS has been operational since 2003 and has been designed to mitigate all of the threats identified for an L1 only user. Figure 1 shows a high level overview of the major integrity monitors. Code Noise and MultiPath (CNMP) algorithms process the receiver measurements from each of three receivers at 38 reference stations. Inconsistent measurements are identified and removed or deweighted, and then used for carrier smoothing. The residual mutipath and noise effects are bounded in CNMP. These cross-checked and smoothed

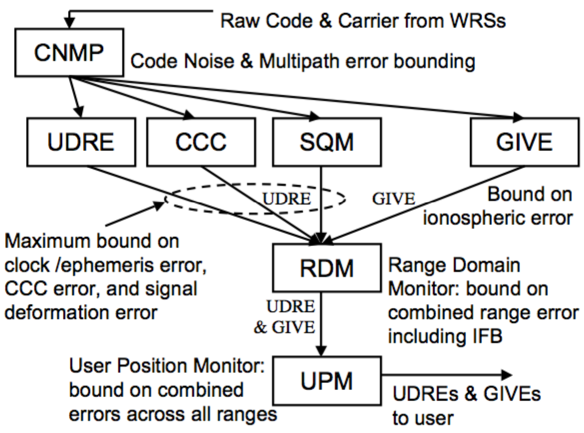

Figure 1. *A high-level schematic of the major integrity monitors of the current WAAS system.*

measurements are passed on to the other monitors. Threats are grouped into one of two categories: those that are likely to affect only a single satellite's ranging accuracy, or those that affect the ionospheric estimation at each grid point. The first set of threats is protected by the broadcast UDRE for each satellite and the second group is protected by the broadcast GIVE for each grid point.

The UDRE is initially set by the UDRE monitor that evaluates the risk of clock and ephemeris threats for each satellite in view. The Code Carrier Coherency (CCC) monitor then evaluates if it can support that same UDRE or if it needs to be increased. Next, the Signal Quality Monitor (SQM) evaluates if it can support the UDRE resulting from the previous two monitors. Because the clock and ephemeris threat creates errors that may be spatially varying, it generally has greater uncertainty than other satellite threats for the L1-only user. Most often it is the monitor that determines the minimum UDRE that can be safely broadcast.

In parallel, the GIVE monitor determines the ionspheric corrections and the confidence bound that must be applied to each. These ionospheric terms are then combined with the satellite corrections and the UDREs to determine if the total L1 correction on each line of sight between the reference stations and the satellites are properly bounded by the RSS of the UDRE and GIVE terms. This comparison is made by the Range Domain Monitor (RDM) which ensures that the individual corrections can be combined. The primary threat addressed by this monitor is related to interfrequency biases.

Finally, all of the corrections applied to each reference station result in a net WAAS positioning error that is checked against the known survey coordinates of the reference receiver's antenna. This error is compared to a much reduced version of the broadcast bound to ensure that smaller errors, that may not trip the previous monitors, will not combine in a way to create large position errors. If either the RDM or UPM observe faults or lack the observability to validate the input UDREs and GIVEs, they will be increased or flagged unsafe by these monitors.

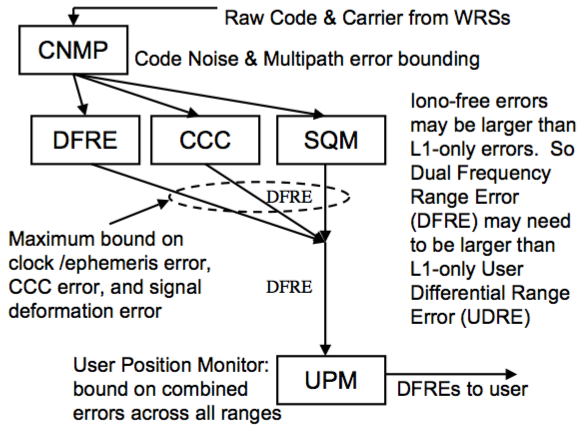

Figure 2. *A high level schematic of the proposed major integrity monitors for the future dual frequency WAAS.*

DUAL FREQUENCY WAAS ARCHITECTURE

The dual frequency WAAS architecture will be based upon the existing single frequency architecture. However, some of the monitors will be replicated and changed as needed to address the dual frequency threats. Thus, the single frequency monitors will be left unchanged (except that they will process L1 C/A and L5 measurements instead of the current L1 C/A and L2 semi-codeless). A new set of monitors, based upon the old, will run in parallel to create corrections and confidences for the dual frequency user.

The dual frequency integrity monitor architecture is shown, at high level, in Figure 2. Most obviously there is no need for ionospheric corrections or a GIVE monitor. The next most obvious change is that we have chosen to name the ionosphere-free satellite confidence bounding parameter the Dual Frequency Range Error (DFRE) as it may need to take on a different numerical value than the UDRE. There is also no need for an RDM as the interfrequency bias has no effect and does not need to be validated.

The DFRE is the maximum bound required among the clock and ephemeris threat, the code carrier divergence threat and the deformed signal threat. Unlike the L1-only case, the clock and ephemeris threat is less likely to be the dominant one and it may not be the primary determiner of the required bound. This is because the clock and ephemeris threat is essentially unchanged between the L1-only and the ionosphere-free pseudoranges, but the CCC and SQM threats are increased by at least a factor of 2.26.

Unlike the L1-only clock and ephemeris corrections and bounding, the ionosphere-free monitor and avionics use the satellite frequencies in the exact same manner. Thus there is no need to add an interfrequency bias term to convert the dual frequency correction for a single frequency user. Thus, the ionosphere-free correction is different from the L1-only clock correction. Further, the DFRE for this term can be slightly reduced, as there is no need to bound the uncertainty in an interfrequency bias term. The DFRE required to bound the dual frequency clock and ephemeris error can be the same or smaller than the UDRE for the same threat.

The dual frequency CCC threat, however, can be at least 2.26 times larger and depending on what is assumed about simultaneous L1 and L5 divergences, the threat can be even larger still. The current CCC monitor operates on ionosphere divergence free combinations of L1 and L2 separately. The dual frequency system will retain the original monitoring, but will also add a metric that examines the difference between the ionosphere-free code measurement and ionosphere-free carrier measurement for each satellite. The ionosphere-free code measurement has approximately 2.6 times more noise than the L1 only measurement, so an ionosphere-free CCC monitor cannot protect the same magnitude threat with the same probability of detection.

Fortunately, the single frequency design allocates roughly one half of the 10^{-7} integrity budget to the GIVE monitor and only a very small fraction to the CCC monitor. The dual-frequency system need not devote any of the integrity budget to a GIVE monitor and so may dramatically increase the allocation to the ionosphere-free CCC monitor without increasing the overall user risk. In our preliminary studies, there should be sufficient margin in the dual frequency fault tree and CCC monitor design to use the same value of DFRE that mitigates the clock and ephemeris threat to also mitigate the CCC threat.

The ionospheric-free signal deformation threat is even more challenging. The L1 signal deformation is increased by a factor of 2.26. However, there is not yet a coordinated L5 signal deformation threat model, nor is it clear what kind of simultaneous L1 and L5 signal deformations might exist on future dual frequency satellites. We begin by examining the existing L1-only threat space, but increasing the effect on the user by the factor 2.26. Without any other mitigation this results in a significant increase in the DFRE relative to the UDRE.

Not only is the threat increased, but the overall user protection is decreased because there is no longer a GIVE term to inflate the confidence bound on that satellite range measurement. Fortunately, there are some mitigation strategies that can be applied. The next generation reference receiver will have a wider bandwidth that will make these receivers more sensitive to signal deformations. In addition, there are refinements that can be made to the multiple correlator measurement processing algorithms. The SQM currently in WAAS does not drive availability and thus its algorithms are deliberately made simple and conservative. Improvements can be made to the algorithm that may make it a little more complex to analyze, but will allow us to take better credit for what it is able to observe. Like the CCC monitor we can also increase the fault tree allocation to SQM. Finally, if the ground reference receivers and avionics receivers are made more similar to each other, the potential threats become smaller. We can require that all receivers use a narrower range of filters and correlator spacings than the current system allows. It appears to us that this combination of mitigation strategies should also allow us to reduce the ionosphere-free L1 signal deformation threat also to the same magnitude as the clock and ephemeris threat.

As mentioned, there is not yet an agreement on the L5 signal deformation threats. It is our understanding that the L5 signals will be created and distributed on the satellites using nearly identical hardware as is used for the L1 signal. As such it may be logical to use the same L1 threat space for L5. One significant difference may be that we expect there to be less variation in the L5 correlator spacing. Having agreement on a single correlator spacing of one chip and a narrow range of allowed filter bandwidths and group delays can go a long way towards significantly reducing the L5 threat. The L5 threat space and allowed user design space need to be developed carefully to prevent this error from dominating the overall availability.

CONCLUSIONS

Dual Frequency WAAS offers great potential to eliminate the current system's vulnerability to ionospheric storms. The removal of the ionospheric uncertainty, coupled with other improvements to integrity monitoring, may allow guidance under even more demanding environments than currently allowed. Further, elimination of dependency on ionospheric corrections allows for better coverage at the edges of our current system. However, the change to ionosphere-free combination in the aircraft introduces some challenges that must be overcome. Accuracy will be degraded, but still well within specifications for all known operations. However, certain threats, most notably code-carrier divergence and signal deformations, run the risk of now dominating and determining availability.

Our preliminary analyses show that it should be possible to make changes to monitor designs and integrity allocations to adequately lower the contributions from these threats. The dual frequency WAAS integrity monitoring design will have to undergo some changes. The L5 threats and dual frequency avionics design still need further maturing. However, we believe that we will continue to be able to improve the overall monitoring and be able to broadcast future DFRE values that are no larger than the current UDRE values. Further, we are working very hard to produce even lower DFRE values, ultimately enabling even more advanced operations.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the FAA Satellite Product Team for supporting this work under Cooperative Agreement 2008-G-007. However, the opinions expressed in this paper are the author's and this paper does not represent a government position on the future development of L1/L5 WAAS.

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