Analysis of a Three-Frequency GPS/WAAS Receiver to Land an Airplane

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BIOGRAPHY

Shau-Shiun Jan is a Ph.D. candidate in the Department of Aeronautics and Astronautics at Stanford University. His research is focused on wide area differential GPS design, analysis, and application. He received his M.S. degree in Aeronautics and Astronautics from Stanford University in 1998. He received his B.S. degree in Aerospace Engineering from TamKang University in Taiwan in 1994.

ABSTRACT

This paper investigates the vertical guidance performance of a multiple frequency Global Positioning System (GPS) (L1, L2, and L5)/Wide Area Augmentation System (WAAS) receiver in the presence of inclement weather and radio frequency interference (RFI). There are several ways to take advantage of the multiple frequencies. For example, one can calculate ionosphere delay in the airplane. This would be used in place of the grid of ionosphere delay corrections broadcast by WAAS. This direct use of multiple frequencies would be more accurate and offer higher availability. Another way to take advantage of the multiple frequencies is to use the additional GPS frequencies as a backup navigation method when RFI is present. This would require the user to continue using the grid. This paper presents the results of a trade-off study evaluating the performance of various architectures for a multiple-frequency GPS landing system. The architectures evaluated depend on the number of available GPS frequencies and include the following:

- Case 1: All three GPS frequencies are available,
- Case 2: Two of three GPS Frequencies are available,
- Case 3: One of three GPS frequencies is available.

The design evaluation criterion compares the coverage of availabilities versus the vertical alert limit (VAL) under these three cases.

This paper also investigates the effects on the WAAS master station (WMS) using coded L1 and coded L5 signals instead of using coded L1 and codeless L2 signals.

This paper discusses the parameter changes in the protection level calculation of the WAAS MOPS (RTCA DO-229C) for the above three cases. These changes affect the fast and long term correction degradation confidence (σ_{flt}), user ionosphere range error confidence ($\sigma_{i,UIRE}$), airborne receiver confidence ($\sigma_{i,air}$), and troposphere delay confidence ($\sigma_{i,tropo}$). The MATLAB® Algorithm Availability Simulation Tool (MAAST) [5] was used to simulate these parameter changes in the WAAS confidence estimation algorithm and evaluate the effect of service availability with these parameter changes.

I. INTRODUCTION

Beginning around 2008, civilians will have access to three GPS signals: L1 (1575.42 MHz), L2 (1227.60 MHz), and L5 (1176.45 MHz) [12]. Both L1 and L5 are for civil aviation safety-of-life services. L2 is for non-safety critical applications. The use of these additional frequencies is expected to enhance the performance (accuracy, integrity, continuity, availability) of GPS. There are several ways to take advantage of the new frequencies:

- Calculate ionosphere delay in the airplane. This might eliminate the grid which is used for ionosphere delay corrections in WAAS [3]. As a result, one would have fewer wide area reference stations (WRS). This system would be less expensive.
- When radio frequency interference (RFI) is present, one can use the additional GPS frequencies as a backup navigation method. This system requires WAAS to continue broadcasting the ionosphere grid.
- Combine the above two methods to form a more robust navigation system. This combined system is more preferable than the two above methods.

The current WAAS [3] corrections are specified for L1 only, and, thus, use of other frequencies will require some additional modification to the WAAS master station (WMS) [3], airborne avionics, and WAAS MOPS (RTCA DO-229C) [11] before they can apply WAAS corrections to their position fix. Previously [6] the performance of single frequency GPS with WAAS and a barometric altimeter aiding to enhance vertical guidance has been studied. More specifically, [6] discussed the changes in calculation of user ionosphere range error confidence ($\sigma_{i,UIRE}$) for the different single frequency users.

This paper discusses the changes in other terms of protection level calculation in WAAS MOPS, that are the result of using the additional GPS frequencies. These terms are the fast and long term correction degradation confidence (σ_{flt}), airborne receiver confidence ($\sigma_{i,air}$), and troposphere delay confidence ($\sigma_{i,tropo}$). The changes in calculation of user ionosphere range error confidence ($\sigma_{i,UIRE}$) for the dual-frequency GPS user and the three-frequency GPS user are also investigated.

Accordingly, this paper is organized as follows: Section II discusses system configuration and analysis assumptions. The changes in protection level calculation are discussed in Section III. Section IV discusses the change in the WAAS Master Station (WMS) required to support new GPS frequencies. In Section V, the dual-frequency GPS user and three-frequency GPS user are investigated. The changes in WAAS corrections are discussed in Section VI. A short description of the simulation tool to be used as well as analysis of results of some simulated cases is given in Section VII. Section VIII presents a summary and concluding remarks.

II. CONFIGURATION AND ASSUMPTIONS

The analysis in this paper assumes that the user in question is an aircraft equipped with a three-frequency GPS receiver and two other assets: the WAAS real time correction, and a barometric altimeter to enhance vertical performance. Because of the presence of RFI, a three-frequency WAAS receiver might lose tracking on one or two of three GPS frequencies. Depending on the number of available GPS frequencies, seven potential system configurations are possible as shown in Figure 1. The single frequency cases were discussed previously in [6]. The remaining cases are the subject of this paper.

Adding two new civil GPS frequencies are the main objective of GPS modernization [12]. In addition to the current GPS which has C/A code on L1, and P(Y) on L1 and L2, there will be a second civil code on L2, and a third civil signal (L5) with new civil code (I, Q) on it. A short description of these three GPS frequencies is as follows:

- The center frequency of L1 is 1575.42 MHz, and the bandwidth is 20MHz. It has a C/A and P(Y) codes. The C/A pseudo random noise (PRN) code has a chipping-rate of 1.023MHz [4], and is for civil use.
- The center frequency of L2 is 1227.6MHz, and the bandwidth is 20MHz. It has civil code and P(Y) codes. The civil PRN code on L2 has the same chipping-rate as L1. This modernized L2 is expected to have the same performance as the current L1 frequency [7].
- The center frequency of L5 is 1176.45MHz, and the bandwidth is 24MHz. It has I and Q codes. The civil PRN code on L5 has a chipping rate of 10.23MHz. This new L5 frequency is expected to have better performance than the current L1 frequency [12].

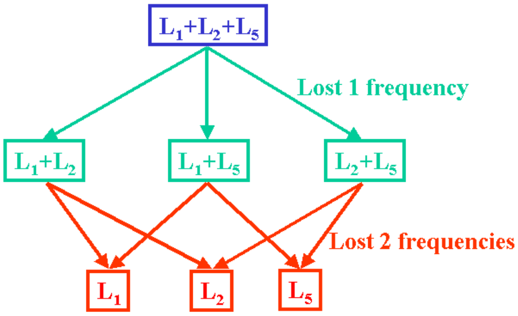

Figure 1. Depending on the number of available GPS frequencies, a three-frequency WAAS receiver can use these frequencies in one of the seven ways shown above.

The Wide Area Augmentation System (WAAS) [3] enhances GPS with the following three services:

- Ranging using "GPS-like" signals from geostationary satellites (GEOs) at L1 frequency.
- Accuracy improvements by sending differential corrections via the same GEO signal.
- Integrity maintenance by sending integrity messages over the same signal.

It should be noted that the current WAAS corrections are specified for L1 only. The other GPS frequency users will require some additional modification of WAAS protection level calculation before they can apply WAAS corrections to their position fix. A more detailed discussion of the referred calculation changes will be presented in next section.

One assumption that has been made in this paper is that the WAAS corrections are always available to the user, even when the GPS L1 signal is blocked by RFI. This is a reasonable assumption, provided one can leverage the fact that the WAAS messages can also be transmitted via the same GEOs but on the other frequencies (L2, L5) or via other channels, such as LORAN (LOng RAnge Navigation) [13].

III. PROTECTION LEVEL CALCULATION

The protection level calculation is summarized in Figure 2. The detailed description of these calculations can be found in WAAS MOPS (RTCA DO-229C) [11]. The previous paper [6] investigated the changes in the calculation of user ionosphere range error (UIRE) confidence [2] [11] for the single frequency users, which is the yellow highlighted portion in Figure 2. The changes in calculations of other terms will be discussed in this section.

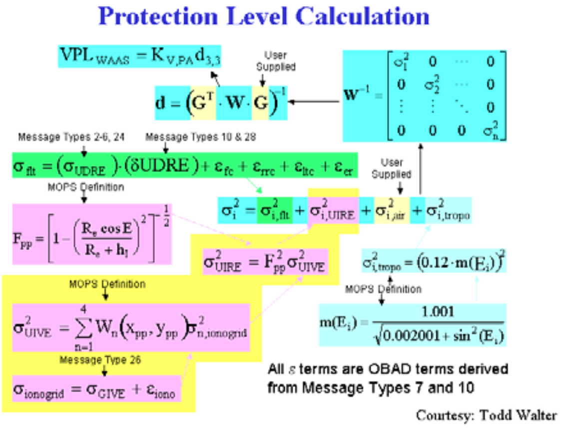

Figure 2. The protection level calculation. (See Appendices A and J of RTCA DO-229C) [11]

The first term to be discussed is the troposphere delay confidence ($\sigma_{i,tropo}$). The residual troposphere error model is defined in WAAS MOPS [11] as follows,

$$\sigma_{i,tropo}^2 = \left(0.12 \cdot m(E_i)\right)^2 \tag{1}$$

where $m(E_i)$ is the troposphere correction mapping function for satellite elevation, and it is calculated as:

$$m(E_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(E_i)}} \tag{2}$$

where E_i is the satellite elevation angle. Equation (2) is valid for satellite elevation angles of not less than 5 degrees. As shown in Equation (1), the residual troposphere error model is a function of the satellite elevation angles, and it is not a frequency dependent function. Therefore, the calculation of troposphere delay confidence ($\sigma_{i,tropo}$) will remain the same for all seven system configurations in Section II. The WAAS MOPS troposphere delay confidence is shown in Figure 3.

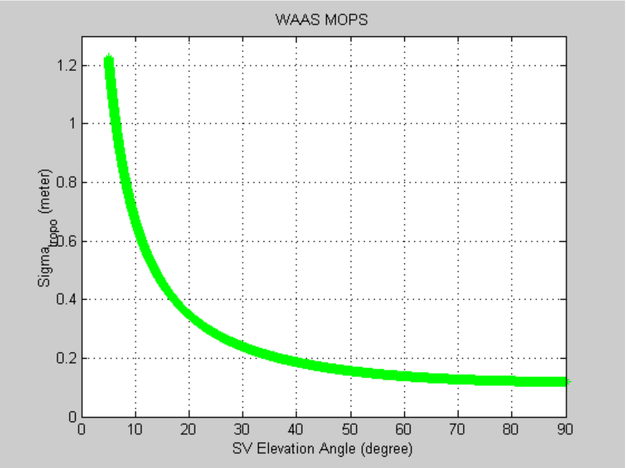

Figure 3. The WAAS MOPS confidence model for the troposphere delay [11].

The next term to investigate is airborne receiver confidence ($\sigma_{i,air}$), which is calculated by the user. This paper used a model of airborne receiver confidence which is defined in the Local Area Augmentation System (LAAS) Airborne Accuracy Designator (LAAS AAD-B) [8]. This confidence model is applicable for the L1 frequency only and is defined as follows:

- Carrier-smoothed code processing.
- Early-minus-late (EML) correlator spacing for the delay-lock detector is 0.1 chip.
- Satellite signal power: -158 dBw at an elevation angle of 40°, -160 dBw at elevation angles of 90° and 5°.
- Airborne antenna gain follows DO-228A.
- Multipath error is noise-like because of the motion of the aircraft.

Airborne RMS pseudorange error for carrier-smoothed code:

$$\sigma_{air} = \sqrt{\sigma_n^2 + \sigma_{mp}^2} \tag{3}$$

where the individual RMS errors are modeled as a function of Space Vehicle (SV) elevation angle:

$$\sigma(\theta) = a_0 + a_1 e^{-\theta/\theta_c}, \quad 5^\circ \le \theta \le 90^\circ \tag{4}$$

where the airborne thermal noise and interference error model is given by:

$$a_0 = 0.11(m),\ a_1 = 0.13(m),\ \theta_c = 4.0^\circ$$

Airframe multipath model is given by:

$$a_0 = 0.13(m),\ a_1 = 0.53(m),\ \theta_c = 10^\circ$$

The modernized L2 frequency is expected to have the same performance as L1 [7]. The new L5 frequency is expected to have better performance than the L1 frequency [12]. Thus, this paper uses this LAAS AAD-B model for the single frequency system architectures. The LAAS AAD-B model is shown in Figure 4.

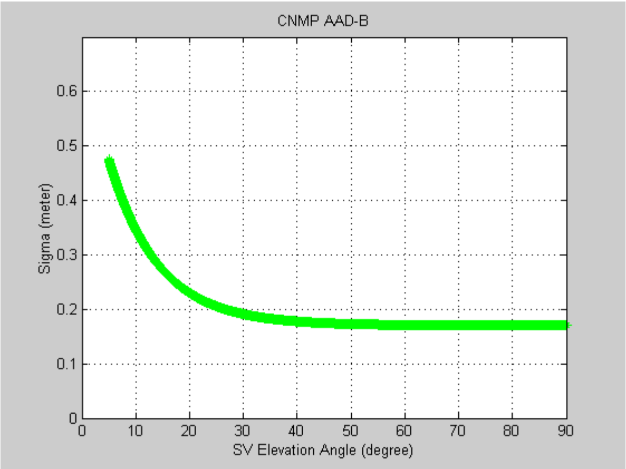

Figure 4. The LAAS AAD-B confidence model for the airborne receiver [8].

The next term to investigate is fast and long term correction degradation confidence (σ_{flt}) [11],

$$\sigma_{flt} = (\sigma_{UDRE}) \cdot (\delta UDRE) + \varepsilon_{fc} + \varepsilon_{rrc} + \varepsilon_{ltc} + \varepsilon_{er} \tag{5}$$

where,

σ_{UDRE} = model parameter from Message Type 2-6, 24

$\delta UDRE$ = $\delta UDRE$ factor for user location, if defined in Message Type 27, otherwise δUDRE equals 1

ε_{fc} = degradation parameter for fast correction data

ε_{rrc} = degradation parameter for range rate correction data

ε_{ltc} = degradation parameter for long term correction or GEO navigation message data

ε_{er} = degradation parameter for en route through NPA applications

The old but active data (OBAD) ε terms, as shown in Equation (5), are not modeled in this paper. The user differential range error (UDRE) [1] [11] is the confidence bound on GPS/GEO clock and ephemeris corrections, and the UDRE is not a frequency dependent model. Thus, this paper uses this UDRE model for all system architectures. In summary, there is no change in the calculation of fast and long term correction degradation confidence (σ_{flt}), airborne receiver confidence ($\sigma_{i,air}$), and troposphere delay confidence ($\sigma_{i,tropo}$) for all single frequency system configurations in Figure 1. The parameter changes in the protection level calculation for the multi-frequency GPS users will be addressed in Section V.

IV. WMS CHANGES

The current WAAS Master Station (WMS) algorithms use the coded L1 signal and codeless L2 signal to generate the real time ionospheric delay correction. For modernized GPS, there are three civil coded GPS signals: L1, L2, and L5. Both L1 and L5 are for civil aviation safety-of-life services. Thus, WMS will use the L1 and L5 signals to generate the real time ionospheric delay correction.

The simulation tool in this paper is MATLAB® Algorithm Availability Simulation Tool (MAAST) [5], MAAST is a publicly available software tool, which can be customized to simulate the WAAS confidence estimation algorithms and evaluate the effect of service availability with algorithms change. MAAST is available for downloading at *http://waas.stanford.edu*.

This paper uses MAAST to show what additional benefit the user can expect when WMS uses coded L1 and coded L5 signals, in comparison to WMS using coded L1 and codeless L2 signals. In MAAST, the UDRE (*af_uderadd.m*) [1], GIVE (*af_giveadd.m*) [2], and CNMP (*af_cnmpagg.m*) [10] algorithm files were modified to use the L5 frequency. The other important parameters used in the simulation are the vertical alert limit (VAL), which equals 50 m, and the horizontal alert limit (HAL), which equals 40 m (L/VNAV APV 1.5). Figure 5 shows the coverage of L/VNAV for an L1-only user when WMS uses coded L1 and coded L5 signals to generate ionospheric delay correction.

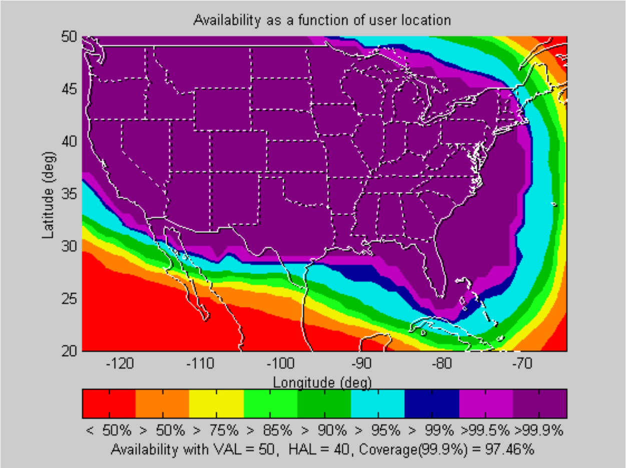

Figure 5. Coverage of an L1 single frequency user in CONUS is 97.46% with VAL=50m, HAL=40m, when WMS uses coded L1 and L5 signals.

The 97.46% shown in the figure, represents the fraction of users within those regions that had a time availability of 99.9% or greater. The coverage of an L1-only user, when WMS uses coded L1 and coded L5 signals to generate ionospheric delay correction, is slightly better than the coverage achieved for an L1-only user where WMS used coded L1 and codeless L2 signals to generate ionospheric delay corrections. The major factor of coverage improvement is the lower GIVE values when WMS uses coded L1 and coded L5 signals to generate the ionospheric delay correction. For all analysis and simulation in the rest of this paper, the WMS uses coded L1 and coded L5 signals to generate ionospheric delay correction.

V. DUAL-FREQUENCY AND THREE-FREQUENCY GPS USERS

The work in [6] discussed the single frequency GPS user in different scenarios. This section studies the dual-frequency and three-frequency users, as shown in Figure 6. For a dual-frequency GPS user or three-frequency GPS user, one can calculate ionosphere delay in the airplane, and this might eliminate the grid, which is used for ionosphere delay corrections in WAAS. When RFI is present, one can use the additional GPS frequencies as a backup navigation method. This system requires WAAS to continue broadcasting the ionosphere grid. The analysis in this section focuses on the changes in the calculation of user ionosphere range error (UIRE) confidence for the multi-frequency GPS user. The additional assumption in this section is that the noises (errors) of the different measurements are uncorrelated. The analysis method compares the noise floor of ionosphere delay estimation and the resulting coverage of L/VNAV in CONUS for the different dual-frequency (L1-L2, L1-L5, and L2-L5) GPS users.

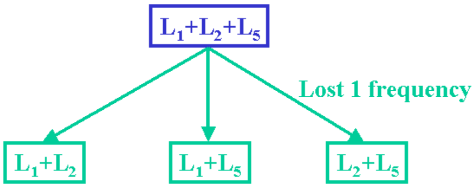

Figure 6. The dual-frequency GPS user and three-frequency GPS user examples.

The first example is an L1-L2 dual-frequency GPS user. An L1-L2 dual-frequency GPS user can directly estimate the ionosphere delay. The user then subtracts this ionosphere delay estimation from the pseudorange measurement. There are three factors which affect the quality of the L1-L2 dual-frequency ionosphere delay measurement:

- The L1-L2 code noise and multipath (CNMP) [10].
- The satellite L1-L2 inter-frequency error (T_{gd}) [4].
- The receiver L1-L2 inter-frequency error (IFB) [4].

The T_{gd} and IFB are caused by the difference between the frequency response of filtering the GPS L1 and L2 signals. The different frequency response results in a time-misalignment of the L1 and L2 pseudorange measurements. This paper assumes that the user receiver receives at least one satellite with two GPS frequencies. The user then estimates the IFB from the difference of two pseudorange measurements. Thus, this paper didn't model the receiver L1-L2 error (IFB).

A confidence model of T_{gd} which is a function of measurements since reset is given in [1]. A confidence model of CNMP which is a function of track time is given in [10]. However, in this paper, simplified but less accurate models of CNMP and T_{gd} were used, which used the constant floor value of CNMP sigma from [10] and the constant floor value of T_{gd} sigma from [1]. That means the acquisition and rising satellites are not modeled in this paper. The CNMP and T_{gd} confidence models for the acquisition and rising satellites will be used in future.

Because L1 and L2 CNMP noises are uncorrelated, the first step is to compute the CNMP noise floor of L1-L2 dual frequency ionosphere delay estimation by using the ionosphere-free pseudorange measurement equation [9]:

$$\sigma^2_{floorL1L2} = \left[\frac{f_1^2}{f_1^2 - f_2^2}\right]^2 \left[\frac{CNMP\_floor^2_{L1}}{3.29^2}\right] + \left[\frac{f_2^2}{f_1^2 - f_2^2}\right]^2 \left[\frac{CNMP\_floor^2_{L2}}{3.29^2}\right] = 0.1311 \text{ m}^2 \quad (6)$$

where,

$\sigma_{floorL1L2}$ = CNMP noise floor of L1-L2

f_i = GPS frequency, $i = 1:\ L1,\ i = 2:\ L2$

$CNMP\_floor_{L1}$ = CNMP noise floor of L1, 0.4 m [10]

$CNMP\_floor_{L2}$ = CNMP noise floor of L2, 0.4 m [10]

3.29 = scale factor to convert mean error bound to 1 sigma level

The other factor (error source) that contributes to the measured differential delay between L1 and L2 is the satellite hardware biases (T_{gd}). The quality of the estimation of T_{gd} would affect the quality of the L1-L2 dual-frequency ionosphere delay estimation. The estimation of the error standard deviation of the satellite L1-L2 bias sigma is given in [1]. Because the L1-L2 CNMP noise floor and the satellite L1-L2 bias (T_{gd}) floor are uncorrelated, the next step is to compute the L1-L2 dual-frequency user ionosphere range error confidence (σ_{Dual_L1L2}):

$$\sigma_{Dual\_L1L2} = \sqrt{\left(\sigma^2_{floorL1L2} + \frac{\sigma^2_{L1L2\_sat\_floor}}{3.29^2}\right)} = 0.3668 \text{ m} \quad (7)$$

where,

σ_{Dual_L1L2} = user ionosphere range error confidence

$\sigma_{L1L2\_sat\_floor}$ = satellite L1-L2 bias (T_{gd}) floor, 0.192m [1]

3.29 = scale factor to convert mean error bound to 1 sigma level

Similarly, the calculation for a L1-L5 dual-frequency user ionosphere range error confidence (σ_{Dual_L1L5}) is as follows:

$$\sigma^2_{floorL1L5} = \left[\frac{f_1^2}{f_1^2 - f_5^2}\right]^2 \left[\frac{CNMP\_floor^2_{L1}}{3.29^2}\right] + \left[\frac{f_5^2}{f_1^2 - f_5^2}\right]^2 \left[\frac{CNMP\_floor^2_{L5}}{3.29^2}\right] = 0.0990 \text{ m}^2 \quad (8)$$

where,

$\sigma_{floorL1L5}$ = CNMP noise floor of L1-L5

f_i = GPS frequency, $i = 1:\ L1,\ i = 5:\ L5$

$CNMP\_floor_{L1}$ = CNMP noise floor of L1, 0.4 m [10]

$CNMP\_floor_{L5}$ = CNMP noise floor of L5, 0.4 m [10]

3.29 = scale factor to convert mean error bound to 1 sigma level

$$\sigma_{Dual\_L1L5} = \sqrt{\left(\sigma^2_{floorL1L5} + \frac{\sigma^2_{L1L5\_sat\_floor}}{3.29^2}\right)} = 0.3201 \text{ m} \quad (9)$$

where,

σ_{Dual_L1L5} = user ionosphere range error confidence

$\sigma_{L1L5\_sat\_floor}$ = satellite L1-L5 bias (T_{gd}) floor, 0.192m [1]

3.29 = scale factor to convert mean error bound to 1 sigma level

Similarly, the calculation for a L2-L5 dual-frequency user ionosphere range error confidence (σ_{Dual_L2L5}) is,

$$\sigma^2_{floorL2L5} = \left[\frac{f_2^2}{f_2^2 - f_5^2}\right]^2 \left[\frac{CNMP\_floor^2_{L2}}{3.29^2}\right] + \left[\frac{f_5^2}{f_2^2 - f_5^2}\right]^2 \left[\frac{CNMP\_floor^2_{L5}}{3.29^2}\right] = 4.0927 \text{ m}^2 \quad (10)$$

where,

$\sigma_{floorL2L5}$ = CNMP noise floor of L2-L5

f_i = GPS frequency, $i = 2:\ L2,\ i = 5:\ L5$

$CNMP\_floor_{L2}$ = CNMP noise floor of L2, 0.4 m [10]

$CNMP\_floor_{L5}$ = CNMP noise floor of L5, 0.4 m [10]

3.29 = scale factor to convert mean error bound to 1 sigma level

$$\sigma_{Dual\_L2L5} = \sqrt{\left(\sigma^2_{floorL2L5} + \frac{\sigma^2_{L2L5\_sat\_floor}}{3.29^2}\right)} = 2.0239 \text{ m} \quad (11)$$

where,

σ_{Dual_L2L5} = user ionosphere range error confidence

$\sigma_{L2L5\_sat\_floor}$ = satellite L2-L5 bias (T_{gd}) floor, 0.192m [1]

3.29 = scale factor to convert mean error bound to 1 sigma level

The user ionosphere range error confidence (σ_{Dual_L1L5}) for an L1-L5 dual-frequency user is 0.3201m which is less than the L1-L2 dual-frequency user which is 0.3668m. It is also less than the L2-L5 dual-frequency user which is 2.0239m. This is because the greater frequency separation enhances the ionosphere delay estimation and removal.

The calculation of the fast and long term correction degradation confidence (σ_{flt}) and the troposphere delay confidence ($\sigma_{i,tropo}$) for the dual-frequency user is the same and is defined in the WAAS MOPS [11] (in Section III Equation (1) and Equation (5)). The airborne receiver confidence ($\sigma_{i,air}$) in protection level calculation for the dual-frequency user is already included in the calculation of the dual-frequency user ionosphere range error confidence (σ_{Dual}), for example, the calculation of σ_{Dual_L1L2} includes the $\sigma_{floorL1L2}$, as shown in Equation (7), which is counted for the airborne receiver confidence ($\sigma_{i,air}$). Thus, there is no additional term needed in protection level calculation for the airborne receiver confidence ($\sigma_{i,air}$) for the dual-frequency user.

For a three-frequency GPS user, one could take advantage of both the dual-frequency ionosphere delay estimation and the frequency redundancies in the presence of RFI.

VI. WAAS CORRECTIONS CHANGES

WAAS provides services including: integrity messages, vector corrections, and ranging signals [3]. The vector corrections are for the orbit and clock errors of the navigation satellites and the signal delays due to the ionosphere. The messages also include the confidence intervals associated with these corrections, such as the UDRE [1] [11] for clock and orbit correction errors, and the GIVE [2] [11] for ionospheric correction errors. With the broadcast of these messages, service accuracy and availability can be improved.

The current WAAS corrections are specified for L1 only, and, thus, use of other frequencies will require some modifications to the WAAS corrections before they can apply WAAS corrections. The Sections III and V suggest that there is no change in the WAAS corrections for the orbit and clock error of the navigation satellites, and there is no change for the UDRE messages. However, the WAAS corrections for the signal delays due to the ionosphere and associated confidence intervals need to be modified for different frequencies. The lower GPS frequency has larger ionospheric delay and larger ionospheric delay uncertainty. Therefore, the WAAS L1 ionosphere delay correction needs to increase 1.65 time for an L2-only user, and the associated variance (confidence) need to increase $(1.65)^2$ time for an L2-only user. For an L5-only user, the WAAS L1 ionosphere delay correction needs to increase 1.80 time, and the associated variance (confidence) need to increase $(1.80)^2$ time.

Multi-frequency GPS users will continue use WAAS corrections for the orbit and clock error of the navigation satellite to enhance the service availability, but will directly use their own multi-frequency ionosphere observation to estimate the signal delays due to the ionosphere, which will be more accurate, and offer higher availability.

VII. SIMULATION AND RESULTS

The criterion of this research is to compare the coverage of availabilities in CONUS versus the vertical alert limit (VAL) under the different cases. The simulation tool used is MAAST [5]. MAAST is used to simulate the parameter changes in protection level calculation and evaluate the effects of service availability with the parameter changes.

The protection level calculation for the single frequency GPS (L1, L2, or L5) user is summarized as follows:

- The calculation of the fast and long term correction degradation confidence (σ_{flt}) is the same as defined in WAAS MOPS [11] for the single frequency GPS (L1, L2, or L5) user.
- The calculation of the user ionosphere range error confidence ($\sigma_{i,UIRE}$) is modified for the L2 or L5 single frequency GPS user as follows [6],

  - For L2-only user,

$$\sigma_{UIVE\_L2} = \sigma_{UIVE\_L1}\left(\frac{f_1}{f_2}\right)^2 = (1.65)^2\,\sigma_{UIVE\_L1}$$

  - For L5-only user,

$$\sigma_{UIVE\_L5} = \sigma_{UIVE\_L1}\left(\frac{f_1}{f_5}\right)^2 = (1.80)^2\,\sigma_{UIVE\_L1}$$

- The calculation of the airborne receiver confidence ($\sigma_{i,air}$) is the same as defined in LAAS AAD-B [8] for the single frequency GPS (L1, L2, or L5) user.
- The calculation of the troposphere delay confidence ($\sigma_{i,tropo}$) is the same as defined in WAAS MOPS [11] for the single frequency GPS (L1, L2, or L5) user.

The summary of changes in protection level calculation for the single frequency (L1, L2, or L5) GPS user is shown in Figure 7.

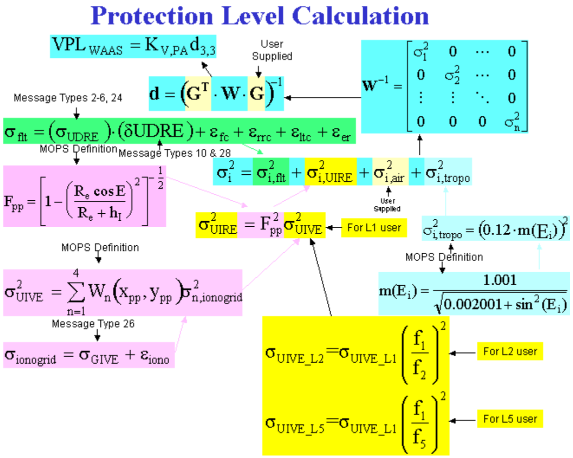

Figure 7. Summary of changes in protection level calculation for the single frequency user, only the yellow highlighted portion is changed, the other terms are unchanged.

The protection level calculation for the dual-frequency GPS (L1-L2, L1-L5, or L2-L5) user is summarized as follows:

- The calculation of the fast and long term correction degradation confidence (σ_{flt}) is the same as defined in WAAS MOPS [11] for the dual-frequency GPS (L1-L2, L1-L5, or L2-L5) user.
- The calculation of the user ionosphere range error confidence ($\sigma_{i,Dual}$) was changed as described in the Section V, and summarized as follows:
  - $\sigma_{Dual\_L1L2} = 0.3668m$
  - $\sigma_{Dual\_L1L5} = 0.3201m$
  - $\sigma_{Dual\_L2L5} = 2.0239m$
- There is no separate airborne receiver confidence ($\sigma_{i,air}$) term in the protection level calculation for the dual-frequency GPS user because it was already included in the calculation of the dual-frequency user ionosphere range error confidence ($\sigma_{i,Dual}$).
- The calculation of the troposphere delay confidence ($\sigma_{i,tropo}$) is the same as defined in WAAS MOPS [11] for the dual-frequency GPS (L1-L2, L1-L5, or L2-L5) user.

The summary of changes in protection level calculation for the dual-frequency (L1-L2, L1-L5, or L2-L5) GPS user is shown in Figure 8.

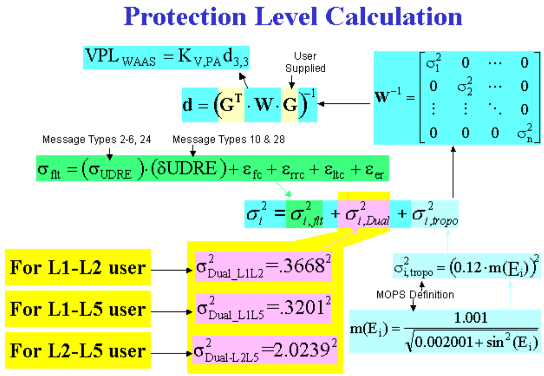

Figure 8. Summary of changes in protection level calculation for the dual-frequency user, only the yellow highlighted portion is changed, the other terms are unchanged.

This paper modified MAAST to adopt all the changes in protection level calculation for both single frequency and multi-frequency GPS users, as summarized in the previous paragraphs. The flowchart of the MAAST simulations for the analysis in this paper is shown in Figure 9. The yellow highlighted portions in Figure 9 are the changes in the protection level calculation for the different architectures. The other important parameters used in the simulation are the vertical alert limit (VAL), which equals 50 m, and the horizontal alert limit (HAL), which equals 40 m (APV 1.5).

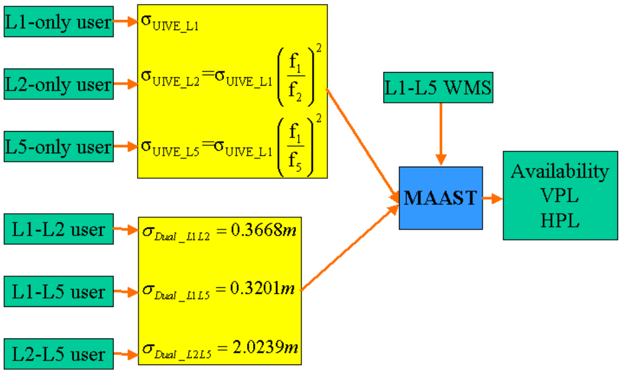

Figure 9. The flowchart of MAAST simulation for the single frequency GPS user and the dual-frequency user.

The simulation results of an L1-L2 dual-frequency user are shown in Figures 10-12. The simulation results of an L1-L5 dual-frequency user are shown in Figures 13-15. The simulation results of an L2-L5 user are shown in Figures 16-18. The WMS uses coded L1 and coded L5 signals for all these simulations. The 95% shown in Figures 10, 13, and 16 represents the fraction of users within those regions that had an availability of 95% or greater.

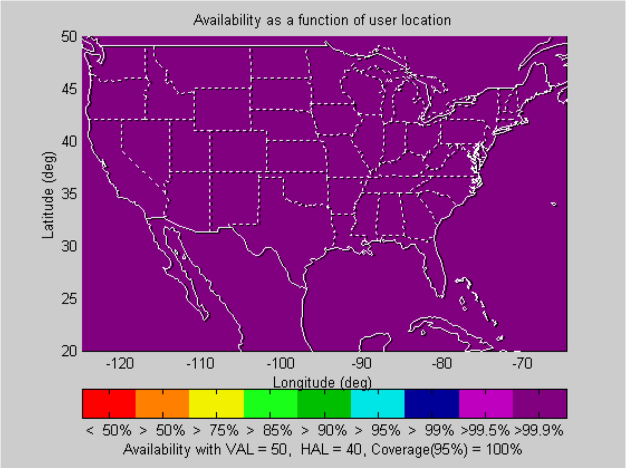

Figure 10. Coverage of an L1-L2 dual-frequency user in CONUS is 100% with VAL=50m, HAL=40m, when WMS uses coded L1 and coded L5 signals.

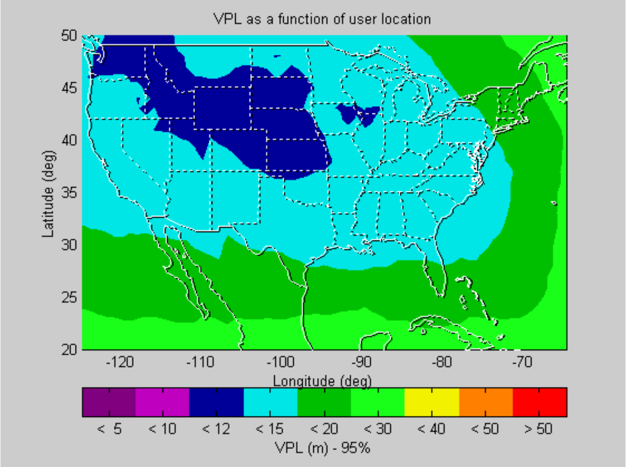

Figure 11. Vertical protection level (VPL) contour of an L1-L2 dual-frequency user in CONUS, when WMS uses coded L1 and coded L5 signals.

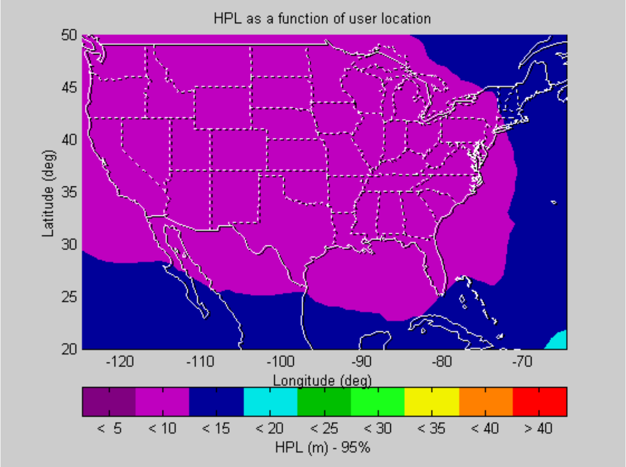

Figure 12. Horizontal protection level (HPL) contour of an L1-L2 dual-frequency user in CONUS, when WMS uses coded L1 and coded L5 signals.

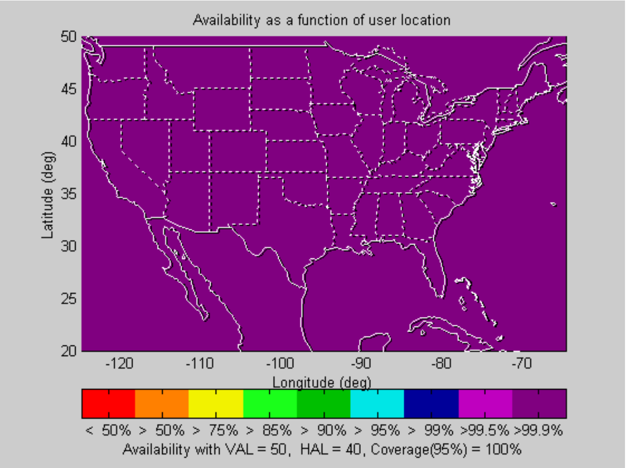

Figure 13. Coverage of an L1-L5 dual-frequency user in CONUS is 100% with VAL=50m, HAL=40m, when WMS uses coded L1 and coded L5 signals.

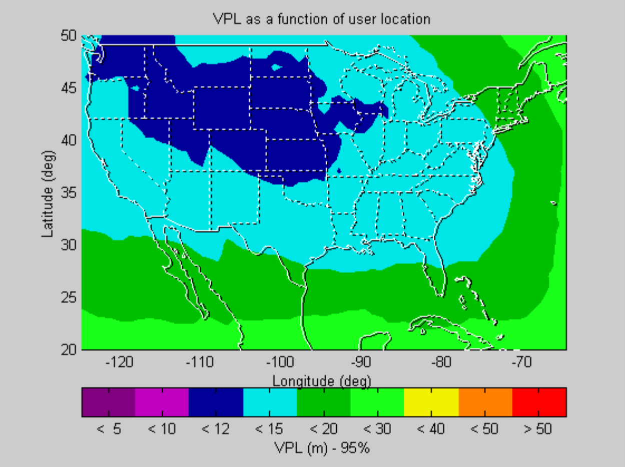

Figure 14. Vertical protection level (VPL) contour of an L1-L5 dual-frequency user in CONUS, when WMS uses coded L1 and coded L5 signals.

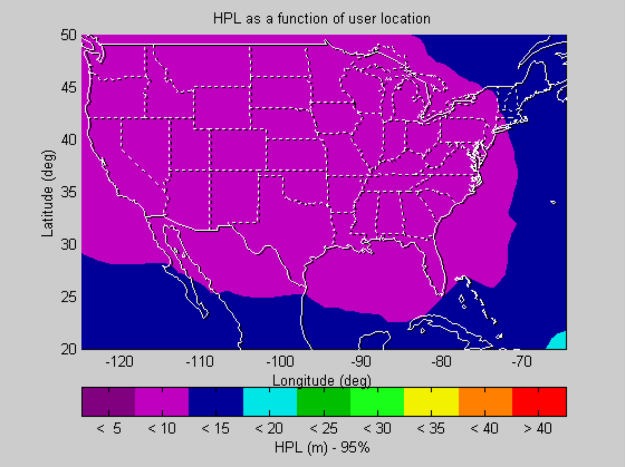

Figure 15. Horizontal protection level (HPL) contour of an L1-L5 dual-frequency user in CONUS, when WMS uses coded L1 and coded L5 signals.

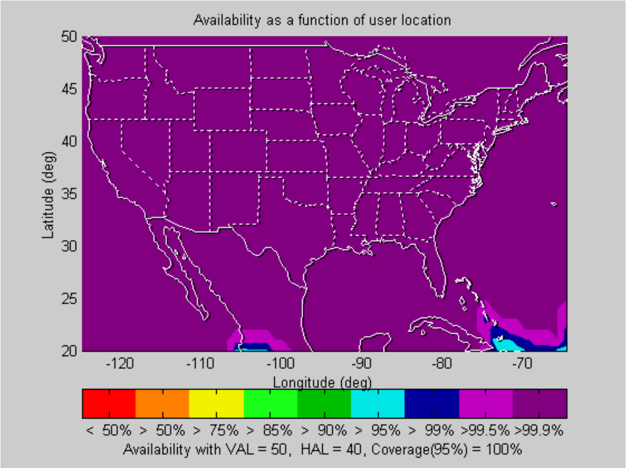

Figure 16. Coverage of an L2-L5 dual-frequency user in CONUS is 100% with VAL=50m, HAL=40m, when WMS uses coded L1 and coded L5 signals.

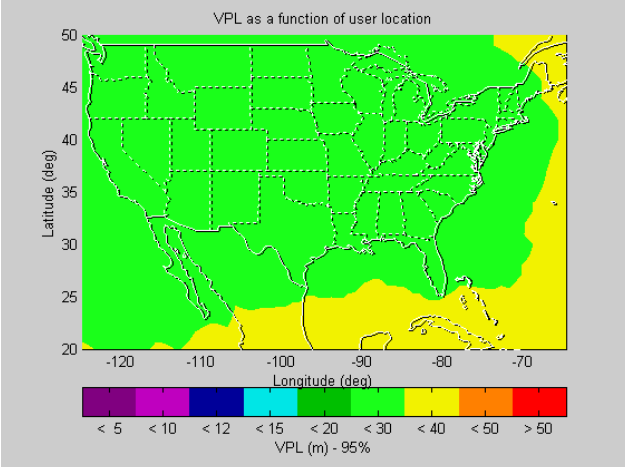

Figure 17. Vertical protection level (VPL) contour of an L2-L5 dual-frequency user in CONUS, when WMS uses coded L1 and coded L5 signals.

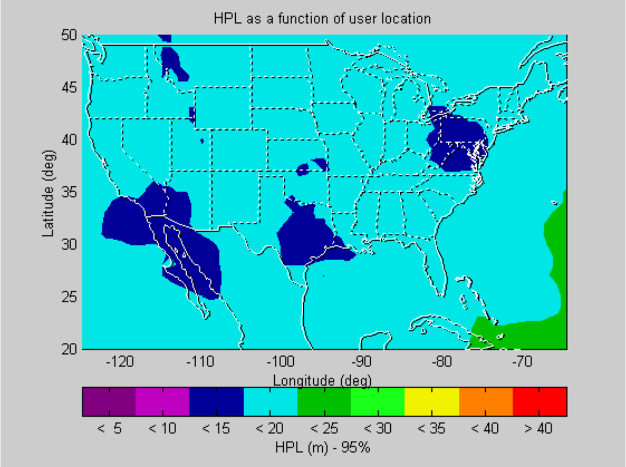

Figure 18. Horizontal protection level (HPL) contour of an L2-L5 dual-frequency user in CONUS, when WMS uses coded L1 and coded L5 signals.

For all dual-frequency user simulation results, the coverage of L/VNAV in CONUS is 100%. When comparing the VPL and HPL contours, the L1-L5 dual-frequency user case has a better time availability than the L1-L2 dual-frequency user case, and it is much better than the L2-L5 dual-frequency user case. Readers interested in more background can refer to the previous paper [6] for more detail.

VIII. CONCLUSION AND FUTURE WORK

This paper used the MAAST to analyze the coverage of APV 1.5 in CONUS for the L1-only user, when WMS used coded L1 and codeless L2 signals, or when WMS used coded L1 and coded L5 signals. The coverage is slightly better with WMS using L1 and L5 because of the lower GIVE values, that is, because of the greater frequency separation which allows better ionosphere delay estimation.

The effects of parameter changes in protection level calculation for different frequency users were discussed. In summary, for a single frequency GPS user, the changes are in the calculation of the user ionosphere range error confidence (σ_{UIRE}), and not in the fast and long term correction degradation confidence (σ_{flt}), the airborne receiver confidence ($\sigma_{i,air}$), or the troposphere delay confidence ($\sigma_{i,tropo}$) in protection level calculation. For a dual-frequency user, the changes are in the calculation of the user ionosphere range error confidence (σ_{Dual}), which included the user ionosphere range error confidence (σ_{UIRE}) and the airborne receiver confidence ($\sigma_{i,air}$). No changes are required for other terms. MAAST simulations show that multi-frequency GPS users have 100% coverage of APV 1.5 for a 95% time availability in CONUS, which is better than the coverage for single frequency WAAS users. The MAAST simulation results are summarized in Table 1.

Table 1. MAAST simulation results: Coverage of L/VNAV in CONUS for 95% availability.*

User	L1	L2	L5	L1-L2	L1-L5	L2-L5
Coverage in CONUS for 95% availability	98.84%	94.36%	90.67%	100%	100%	100%

* Data are based on 300-second intervals on each point in a one-degree by one-degree grid of simulated user location, with WMS using coded L1 and L5 signals.

This paper used the constant CNMP noise floor and the constant satellite dual-frequency error (T_{gd}) floor to calculate the confidence of dual-frequency ionosphere delay estimation. The next step will be to investigate the effects of using a CNMP mean error function, which is computed based on the time of continuous GPS signal tracking. The current satellite dual-frequency error (inter-frequency bias) ($T_{gd1,2}$) is defined for L1-L2 only [4]. For the modernized GPS, there will be three different satellite inter-frequency biases: $T_{gd1,2}$ for L1-L2, $T_{gd1,5}$ for L1-L5, and $T_{gd2,5}$ for L2-L5. As a result, in the future a new model of satellite inter-frequency bias (T_{gd}) will be developed.

In summary, a system that combines three-frequency GPS and WAAS will form a more robust navigation system. This system offers full availability in the presence of moderate RFI (one GPS frequency entirely lost) and high availability in the presence of severe RFI (all but one GPS frequency lost).

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