

Matlab Simulation Toolset for SBAS Availability Analysis

Shau-Shiun Jan, Wyant Chan, Todd Walter, Per Enge
*Department of Aeronautics and Astronautics
Stanford University, California 94305*

ABSTRACT

This paper describes a set of MATLAB functions currently being developed for SBAS availability analysis. This toolset includes simulation algorithms that are constantly being developed and updated by various working groups. This set of functions is intended for use as a fast, accurate, and highly customizable experimental test bed for algorithm development. A user-friendly interface has also been developed for the tool. It is open source and can be downloaded from Stanford WAAS web site (<http://waas.stanford.edu>). Therefore, it provides a common ground for different working groups to compare their results.

There are four major components of this service volume analysis toolset: confidence computation, simulation configurations, outputs, and the graphic user interface. Algorithms currently implemented for confidence computation of UDRE, GIVE, troposphere, and airborne corrections are used in the tool. Users can also readily modify parameters of the algorithms or include custom algorithms they wish to test. Simulations can be configured to modify the WAAS reference station (WRS) network, user locations, satellite constellation, and ionospheric grid point (IGP) mask as well. The outputs of the toolset include plots of availability, protection levels, UDRE and GIVE maps and histograms. The toolset includes a graphic user interface, which allows the user to specify different options for the simulation very quickly and easily.

In this paper, we demonstrate the utility of this toolset by analyzing the SBAS service volume models for CONUS for a change to the GIVE algorithm. We also simulate a case where vertical troposphere error is reduced. The results show this toolset is valuable for investigating how the algorithms impact availability.

I. INTRODUCTION

The availability of Wide Area Augmentation System (WAAS) [2] is determined by the computation of confidence estimates for the corrections to various error sources. Several groups are revising the algorithms for these confidence computations. Additionally the next generation algorithms are being designed. Service volume model (SVM) analysis [6] has been used by algorithm developers as a tool to assess relative performance benefits of algorithm or parameter changes. A general SVM tool would include the model algorithms, a facility for setting simulation configurations, and a means for assessing performance through simulation outputs. The model algorithms compute confidence estimates of, user differential range error (UDRE) [1] [7], grid ionosphere vertical error (GIVE) [3] [7], code noise and multipath error (CNMP) [5] [8], and troposphere delay (TROP) [7]. Simulation configurations include GPS satellite almanac, WAAS reference station (WRS) [2] information, user information, GEO satellites, ionosphere grid point (IGP) mask [3] [7], and other parameters. The outputs of a SVM tool typically include an availability contour, and vertical/horizontal protection level (V/HPL) [7] contours.

This paper describes a set of MATLAB [4] functions currently being developed for availability analysis. The toolset is called MATLAB Algorithm Availability Simulation Tool or **MAAST**. It was developed and tested in MATLAB version 5. The goal is to develop an experimental testbed for SVM analysis algorithm evaluation that is open-source, can be easily updated, has a friendly interface for the user to set simulation options and parameters, and can ultimately provide fast but reasonably accurate results.

MAAST. One is standard almanac format given in the WAAS MOPS [7]. Another is any almanac file in YUMA format corresponding to the specified week, YUMA formatted ephemeris files can be downloaded from the U.S. Coast Guard website. (<http://www.navcen.uscg.gov/ftp/GPS/almanacs/yuma/>) Files must be stored in the same directory as MAAST and named *almyuma[week number].dat*, where week number can be specified in the GUI.

4. **GEOs:** there are four GEO satellites (INMARSAT) that are currently specified: AOR-E, AOR-W, IOR, and POR. The INMARSAT coverage map is shown in Figure 4. The associated file in MAAST is *geo.dat*, which is in the format of [GEO PRN number, GEO latitude in degree, flag if the button should default to on, and name for the button]. If program users want to customize their own GEO list, then they need to build their own GEO list in the same format as *geo.dat* and replace *geo.dat* with their version. Note the PRNs need to be between 120 and 138 as per the WAAS MOPS [7]. The GUI has space for up to six options.

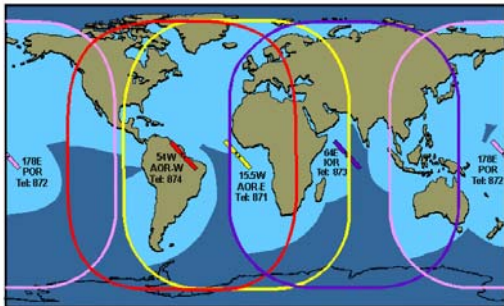


Figure 4. INMARSAT coverage (Courtesy: INMARSAT <http://www.inmarsat.com>)

III. SIMULATION PROCESS

An overview of the main simulation engine of MAAST is shown in the upper right section of Figure 1. It is subdivided into three major components: WAAS master station (WMS) processing, WAAS user processing, and output processing. The corresponding MATLAB functions are *wmsprocess.m*, *usrprocess.m*, and *outputprocess.m*. The WMS processing and user processing blocks constitute the main

computational loop and are stepped through in sequence at every time step. Time step resolution is chosen by the program user through the GUI. WMS processing simulates the computations of UDREs, GIVEs, and Message Type 28 [9] covariance matrices performed by the WAAS master station using data gathered from reference stations. These computations are to be broadcast to WAAS users. User processing, on the other hand, simulates the WAAS user's computation of confidence bounds on clock/ephemeris and ionospheric corrections at the user site, from which VPL/HPL can be derived. The output processing block then takes all these data and creates visual outputs of VPL/HPL and availability contours, as well as UDRE and GIVE plots.

WAAS service availability at user locations are based on vertical and horizontal protection levels, which are determined from confidence estimates on corrections to the different error sources. Algorithms for these confidence estimates are being developed by several working groups. Aside from having predefined algorithm functions, MAAST offers common templates for including custom algorithms. This is achieved by defining standardized input and output arguments for each customizable algorithm function. This provides an efficient way for developers to test their own algorithm implementations against the whole system in a modular fashion. Selectable modules for this tool include algorithms for computing troposphere errors (TROPO), code noise and multipath errors (CNMP), and confidence bounds on GPS/GEO clock and ephemeris corrections (UDRE) and ionospheric corrections (GIVE). Detailed instructions on how to integrate custom algorithm functions will appear in the documentation for MAAST.

The simulation does not include old but active data (OBAD) [12]. Degradation of fast correction, range-rate correction, long-term correction and en route data [7] are not modeled.

To gain some perspective on how these algorithm modules fit in the simulation, refer to Figures 5 and 6 for functional flowcharts of the simulated processing performed by the WAAS master station (WMS) and the WAAS user, respectively to obtain confidence estimations.

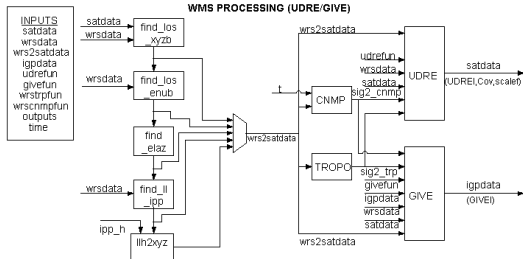


Figure 5. Functional flowchart of WMS processing

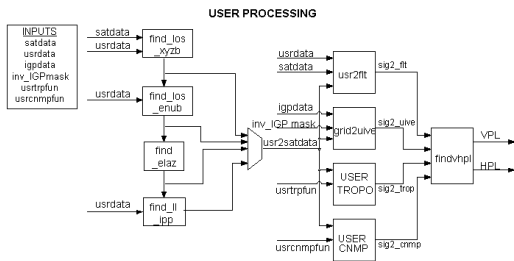


Figure 6. Functional flowchart of user processing

A. WMS Processing

In the simulation of master station processing, location data of reference stations and satellites for the current time step are passed through functional blocks (left half of Figure 5) to compute relevant line-of-sight and ionospheric pierce point information for each reference station-satellite pair. Satellite and WRS information are input into the function *find_los_xyzb.m* to give line-of-sight vectors in ECEF coordinates. These are translated into east-north-up coordinates by the function *find_los_enub.m*. Elevation and azimuth are calculated by *find_elaz.m*. The function *find_ll_ipp.m* then computes ionospheric pierce point (IPP) locations. All these data are packaged into a matrix *wrs2satdata* which is passed into succeeding functions that need line-of-sight information. Each row of this matrix corresponds to a particular line-of-sight, while the rows correspond to information fields. The details of the row definitions corresponding to the fields of the matrix, as well as other relevant

matrices used in the MAAST, can be found in *init_col_labels.m*.

After line-of-sight computation is done, the TROPO module takes elevation angles as input and generates troposphere error variances. The CNMP module takes as input the elevation angle and/or track time since last cycle slip of each pair and generates the noise and multipath error variance. Here it was assumed that the carrier phase is continuous while the satellite-to-reference station elevation angle exceeds the visibility limit, currently set as 5 degrees by the WAAS MOPS and cycle slips never occur. Using this assumption, the times a satellite rises into view of a reference station are predetermined up to 1-second accuracy before entering the time step loop. This resulted in marked improvement in execution time of track time calculations. The troposphere and CNMP error variances, together with line-of-sight information are then fed into the UDRE module to generate indexed UDREs and Message Type 28 covariance matrices for each satellite. Likewise, the GIVE module uses these information, together with ionospheric pierce point data to generate indexed GIVES for each ionospheric grid point.

B. User Processing

User processing uses functional blocks similar to those used in WMS processing for computing line-of-sight data between the satellite-user pairs, as shown in Figure 6. Using these line-of-sight data, the *udre2flt* module projects satellite UDREs with MT28 covariance matrices into fast and long-term correction variances σ_{flt}^2 for each user line-of-sight. Similarly the *grid2uive* module derives user ionospheric correction variances σ_{uive}^2 from ionospheric grid point GIVES. Implementation of these two modules is based on the WAAS MOPS. User processing uses its own selectable TROPO and CNMP algorithms independent of the selections made for WMS processing. User VPL and HPL for each time step are the final outputs of the user processing block.

IV. GRAPHIC USER INTERFACE

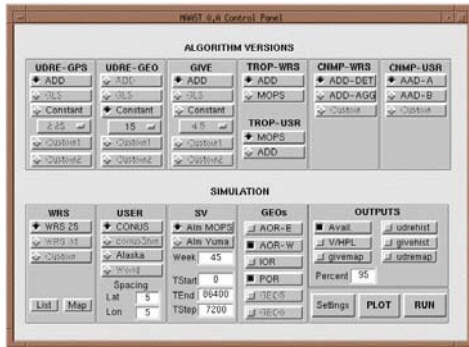


Figure 7. Graphic user interface of MAAST

The top half of the graphic user interface (GUI) contains menus for algorithm selection. The bottom half of the GUI contains menus for simulation configuration, and is described in Section II part B. Grayed out buttons represent options that are not yet available. Due to the proprietary nature of some algorithms, certain options may not be available for general distribution.

A. UDRE-GPS Menu

The UDRE-GPS menu specifies the algorithm for calculating UDREs of GPS satellites. The ADD option activates the GPS UDRE model algorithm from the Algorithm Description Document (ADD) of the WAAS Integrity Performance Panel (WIPP) [1]. The CONSTANT option activates a list of indexed UDRE values to choose from. The list corresponds to the indexed values in the WAAS MOPS and sets all GPS satellite UDREs to the specified constant. Custom algorithms can easily be added by creating modular MATLAB files with appropriate inputs and outputs.

B. UDRE-GEO Menu

This UDRE-GEO menu specifies the algorithm for calculating UDRE for geostationary satellites. Options in this menu are similar to the ones in the UDRE-GPS menu.

C. GIVE Menu

The GIVE menu specifies the algorithm for calculating GIVE for ionosphere grid points (IGPs). The ADD option activates the model algorithm from the GIVE Algorithm Description

Document (ADD) of the WIPP [3]. The CONSTANT sets all IGP GIVES to the specified constant.

D. TROP-WRS / TROP-USR Menus

The TROP menus specify the equations for calculating troposphere error confidence bound for reference stations and for the users to be either the equation specified by the WIPP ADD [1] or the WAAS MOPS.

E. CNMP-WRS / CNMP-USR Menus

The CNMP menus are used to select the method of generating Code Noise and Multipath error confidence bounds (CNMP) at the reference stations and at the user locations. This menu is not needed for constant UDREs and GIVES. Otherwise, the CNMP for WRS is specified by the WIPP CNMP ADD [8], while the CNMP for user is specified by LAAS Airborne Accuracy Designator (AAD) [5].

V. OUTPUTS

There are seven output plots currently available in MAAST: availability contour, VPL/HPL contours, UDRE/GIVE histograms, and UDRE/GIVE contours, as shown in Figure 8. There is a “percent” option in the outputs menu, and it has different definitions for the different outputs. In this paper, we choose 95% as an example.

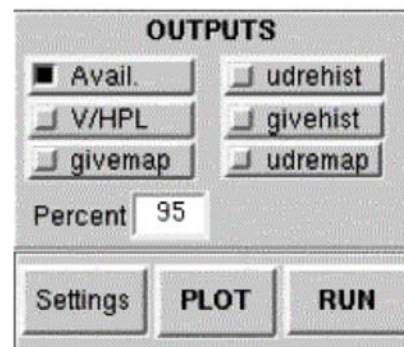


Figure 8. Graphic user interface: outputs menu

The availability contour plots the availability as a function of user location. We compute the percentage of time that user vertical protection limit (VPL) is less than the vertical alarm limit (VAL) and the horizontal protection limit (HPL) is below the horizontal alert limit (HAL) to

determine the availability percentage contour for continental U.S. (CONUS) or Alaska. The option of 95 percent here calculates the fraction of users within those regions that had a time availability of 95% or greater. This measure is referred to as coverage.

The VPL/HPL contours plot the VPL and HPL as a function of user location. The option of 95 percent here indicates that a user at each specific location had a VPL or an HPL equal to or below the value indicated by the color bar. A selection of 50%, for example, would display the median value.

The UDRE histogram plots the probability distributions of UDRE values and the confidences associated with the fast and long-term corrections ($3.29 \cdot \sigma_{fit}$). The GIVE histogram plots the probability distributions of GIVE values and user ionosphere vertical error (UIVE) values. The percent option box is not applicable to either of these plots.

The UDRE map generates a UDRE contour by gathering UDRE data at positions in the satellite orbits and interpolating values to the points in between. The GIVE map generates a GIVE contour by gathering GIVE values at the ionosphere grid points (IGPs). As in the VPL/HPL plots, the percent chosen indicates that the GIVE value at a location is the less than or equal to the displayed contour level 95% of the time.

After making algorithm, simulation, and outputs selections, users then click on the RUN button to begin simulation. The selected output plots are displayed after the simulation, and all relevant data are stored in a temporary binary file *outputs.mat*. Clicking the PLOT button will bypass the simulation process and instead plot the selected output options from data stored in the *outputs.mat*. This allows users to quickly plot other output options if algorithm and simulation configurations have not changed.

Figures 9-15 shows the plots generated by a sample run. For this particular example, we chose WIPP ADDs for UDRE, GIVE, WRS TROP, and WRS CNMP. We used WAAS MOPS for user TROP and LAAS AAD-A for user CNMP. The simulation was configured for a CONUS user grid, using the 25 current U.S. WRSs, satellite almanac from the WAAS MOPS, two GEOs (AOR-W and POR), 1-

degree user grid and 300-second time steps over a 24-hour simulation period.

Figure 9 shows availability contours of CONUS users. It indicates that the coverage for users with availability of at least 95% of time is 100% of the CONUS. Figures 10 and 11 show VPL and HPL contours. As described in Section V, these plots are contours that V/HPLs are less than corresponding values listed in the bottom color bars of the plots for 95% of time. For example, users in the cyan color area of Figure 10 have a VPL less than or equal to 25 meters 95% of time.

Figure 12 shows histograms for the UDRE and the residual errors associated with the fast and long-term corrections ($3.29 \cdot \sigma_{fit}$) plotted in blue. While Figure 13 shows GIVE/UIVE histograms.

Figure 14 is GIVE contour for CONUS and Alaska. The black circles shown in the plot correspond to the ionosphere grid points (IGPs). Figure 15 is UDRE contour as a function of GPS satellite position.

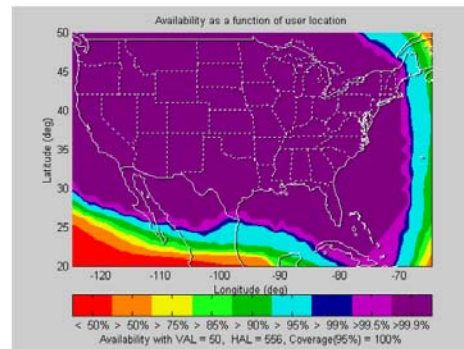


Figure 9. Availability contour of CONUS

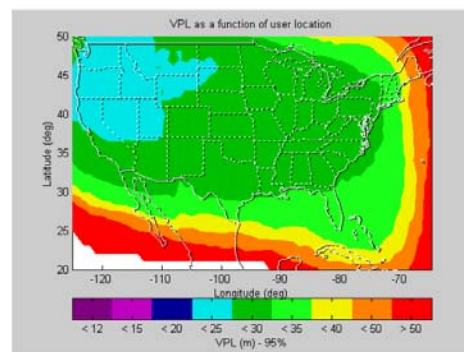


Figure 10. VPL contour of CONUS

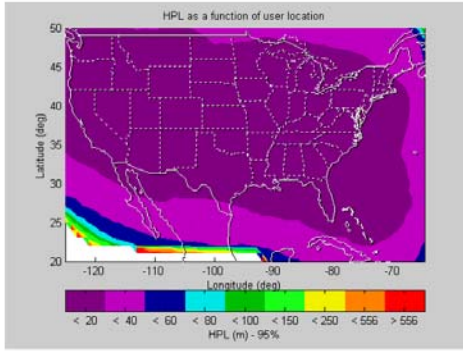


Figure 11. HPL contour of CONUS

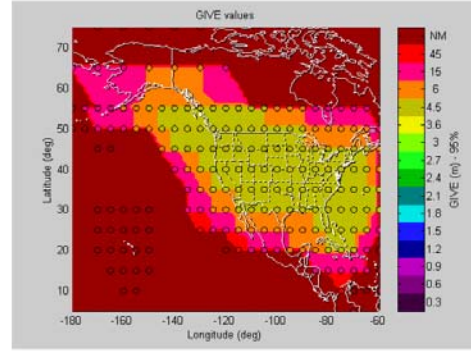


Figure 14. GIVE contour of CONUS and Alaska

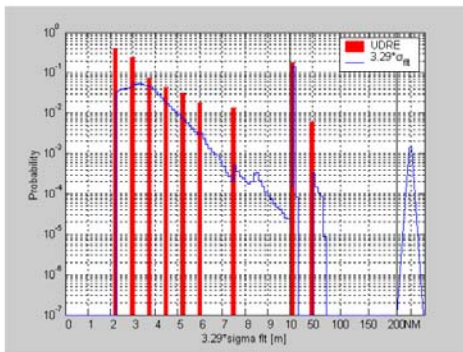


Figure 12. UDRE histogram of CONUS

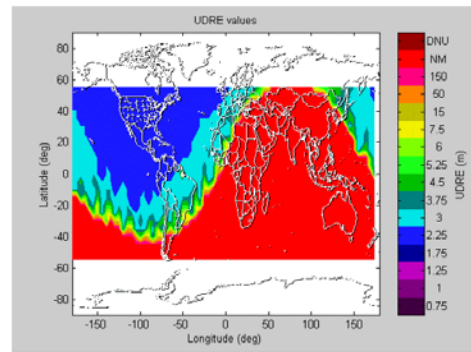


Figure 15. UDRE contour

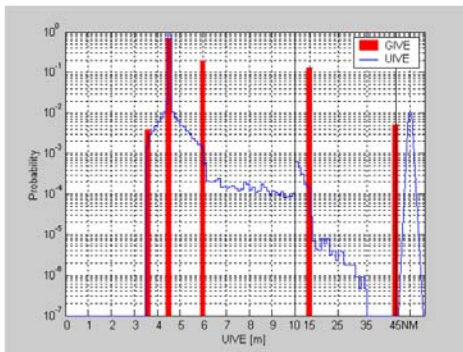


Figure 13. GIVE histogram of CONUS

VI. RESULTS

In this section, we examine performance effects for two cases of parametric changes to the simulation run. The first case investigates the effect of the change of tropospheric confidence estimation algorithm. We modified the tropospheric vertical error (σ_{TVE}) of WAAS MOPS [7] from 0.12 meter to 0.05 meter, and use WAAS MOPS tropospheric model for both user and WRS. The availability contour, VPL contour, and HPL contour outputs are shown in Figures 16-18, respectively. When compared with the nominal outputs in Section V, there seems to be no noticeable change. As a result, we can conclude that the tropospheric vertical error (σ_{TVE}) is not a dominant term in determining availability for the current system. There would be little benefit to devoting resources to dramatically lower the uncertainty of the tropospheric error.

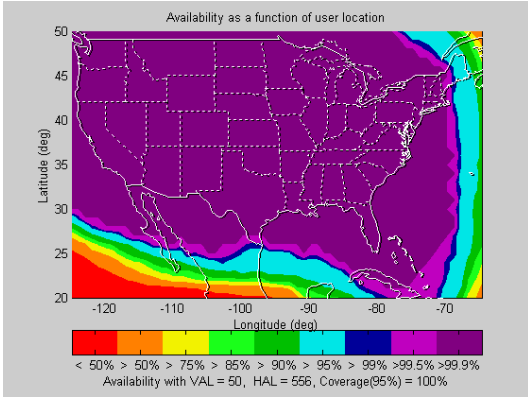


Figure 16. Availability contour of CONUS after the tropospheric vertical error (σ_{TVE}) is lowered.

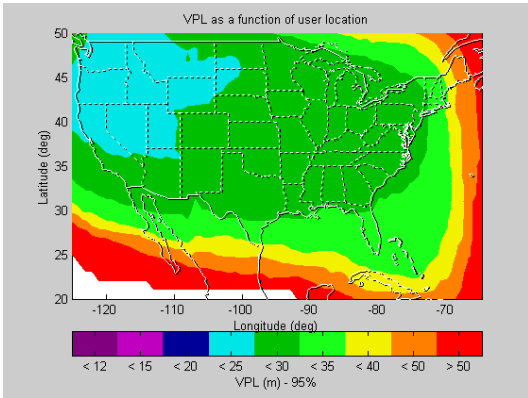


Figure 17. VPL contour of CONUS after the tropospheric vertical error (σ_{TVE}) is lowered.

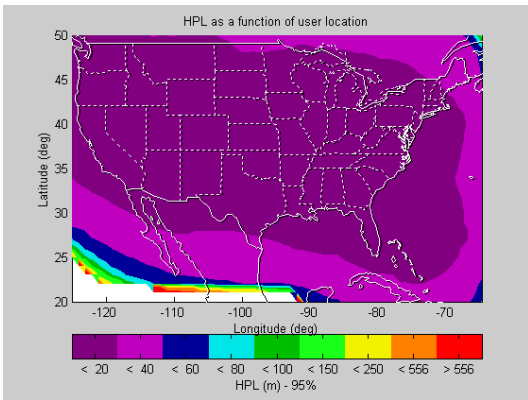


Figure 18. HPL contour of CONUS after the tropospheric vertical error (σ_{TVE}) is lowered.

The second case investigates the effect of modifying the ionospheric decorrelation constant (σ_{decorr}) [3] [7] [10] from 0.35 meter to 0.15 meter based on recent observation results [11]. The decorrelation function is used to describe the nominal variation about the modeled ionosphere [10]. The resulting plots of availability contour, VPL/HPL contour, GIVE histogram, and GIVE map are shown in Figures 19-23, respectively. Comparing these with the nominal results in Section V, we see significant improvements in all outputs. This shows that the ionospheric decorrelation constant (σ_{decorr}) is a significant factor affecting availability. In fact the GIVE values currently dominate availability, so resources should be focused on reducing this term.

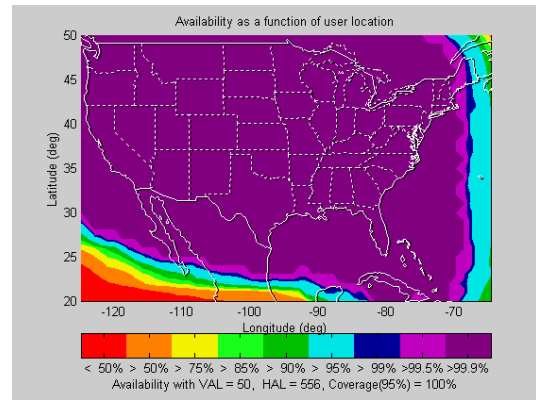


Figure 19. Availability contour of CONUS after the nominal constant ionospheric decorrelation function (σ_{decorr}) is lowered.

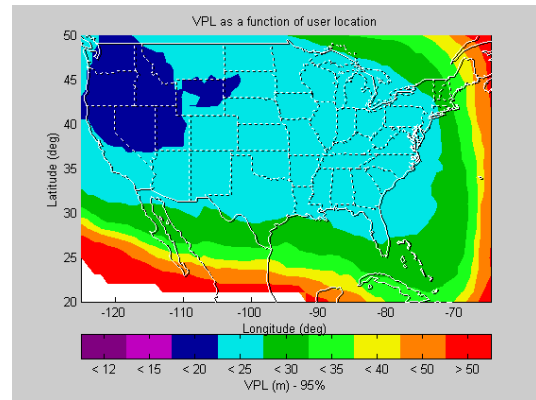


Figure 20. VPL contour of CONUS after the nominal constant ionospheric decorrelation function (σ_{decorr}) is lowered.

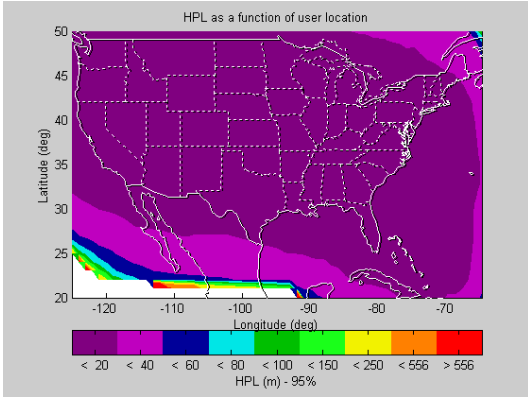


Figure 21. HPL contour of CONUS after the nominal constant ionospheric decorrelation function (σ_{decorr}) is lowered.

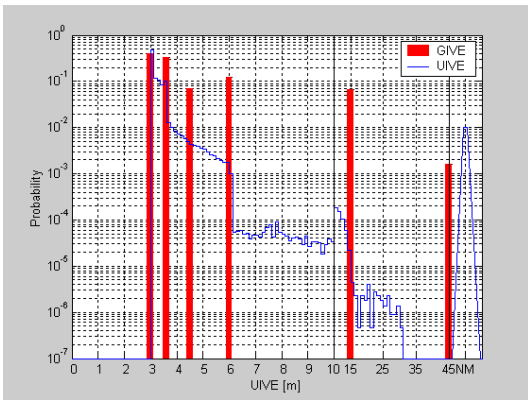


Figure 22. GIVE/UIVE histogram of CONUS after the nominal constant ionospheric decorrelation function (σ_{decorr}) is lowered.

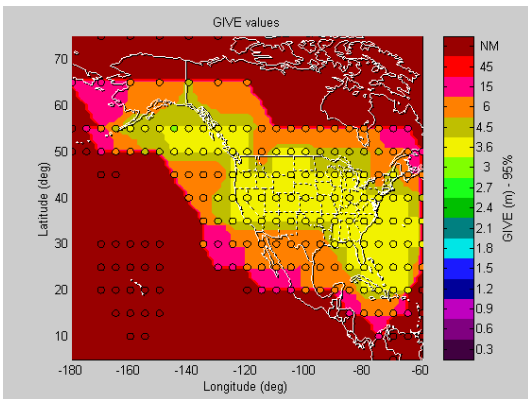


Figure 23. GIVE map after the nominal constant ionospheric decorrelation function (σ_{decorr}) is lowered.

VII. CONCLUSION and FUTURE WORK

We have used MAAST to analyze the SBAS service volume models for CONUS and Alaska and established performance figures for some baseline algorithms. A next step will be to investigate how to modify algorithms and parameters to improve availability and achieve lower VPLs using this tool. We can examine improvements effected by new algorithms. One key area of investigation will be how the incorporation of additional civil frequencies will improve availability.

MAAST was intended as an efficient and effective tool for algorithm development. It was not intended to guarantee that will see exactly that level of availability at each location. In creating MAAST a number of assumptions have been made. MAAST algorithms are for confidence bounding only; it does not model corrections. Furthermore, it is strictly deterministic, and does not model asset failures in a probabilistic manner. Despite these limitations, the results of this paper show that a simple yet powerful framework has been developed that allows us to rapidly model availability and that MAAST can be valuable for SBAS algorithm research.

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