Multi-Layer Modeling and Simulation of the Effects of Ionospheric Scintillation on Service Availability of the GPS Augmentation Systems

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***Abstract*— This paper describes a multi-layer technique using modeling and simulation to assess the impact of ionospheric scintillation on satellite navigation systems. It is well known that GPS receivers in low- and high-latitude regions may suffer from rapid amplitude and phase fluctuations and signal scatter due to scintillation, causing loss of lock and cycle slips to dual as well as single frequency users. Scintillation poses a challenge to the GPS augmentation service providers including Space Based Augmentation Systems (SBAS) and Ground Based Augmentation Systems (GBAS) to provide a high probability of navigational service availability in affected regions. Over the recent decades, many studies and data analyses have been conducted to understand effect of scintillation which affects users of satellite based navigation systems. Some significant data has been translated into modeling and simulation tools to help characterize scintillation effects and the world-wide scintillation environment.**

Keywords-Scintillation, Ionosphere, GPS Augmentation

I. OBJECTIVES AND OVERVIEW

The objective of our modeling and simulation process is to combine hardware-in-the-loop assessments of scintillation effects on GPS sensors with probabilistic models to predict the overall system impact with respect to time and location. The technique involves the use of three steps. The first provides a high fidelity assessment of the performance of the GPS sensors to determine the levels of tolerable scintillation. The second step uses the output of the first step as thresholds to determine the probability of disruption for the given scintillation environment (based on an ionospheric model). Lastly, the overall system impact is assessed using the probabilities of disruption determined in the second step with a system availability model which reflects the target system's architecture and algorithms.

To perform the three steps, a combination of three simulation tools was used for characterization, data generation and analysis. For the first step, the Cornell Scintillation Simulator was used by permission of Cornell University to inject simulated scintillation effects, in a hardware-in-the-loop fashion, into the GPS receiver [1]. Figure 1 illustrates the block diagram to set up the Cornell Scintillation Simulator (Cornell tool). The GPS receiver and steps of hardware-in-loop are accomplished by the Spirent test equipment. The scintillation simulated by the Cornell tool is based on extensive libraries of past scintillation data including equatorial data [2]. Measures of scintillation in amplitude and phase are quantified by S4 index and σ_ϕ phase variations respectively. The actual output files are in User Action Files (UAF) with respect to desired S4 index and time correlation parameters. The Spirent 7700 GPS Simulator which is connected to the GPS receiver to be tested is loaded with UAF. The data collected from the receiver is then analyzed to determine the quantity and duration of loss of lock as well as cycle slip counts and other anomalies. Assessment of these statistics seeks to define tolerable levels of scintillation for the receiver under test. These corresponding tolerable levels of scintillation can be parameterized as functions of S4 and σ_ϕ.

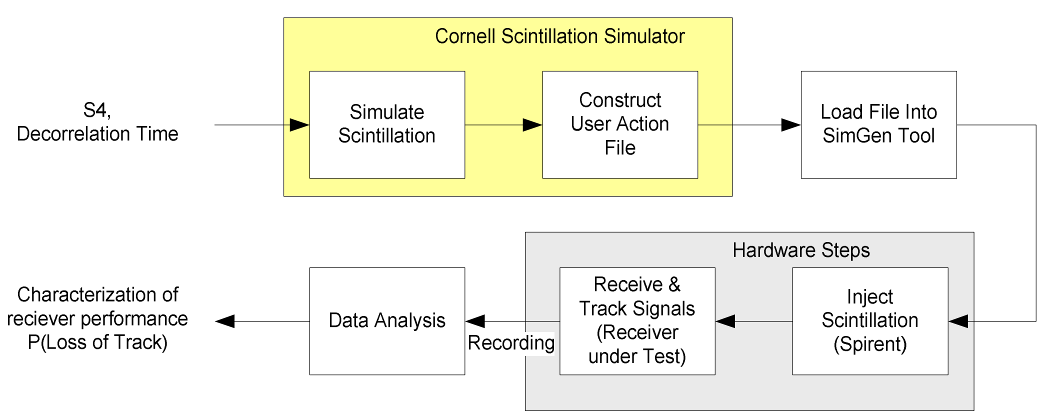

Figure 1. Usage of the Cornell Scintillation Simulator

The next tool is the Wideband Model (WBMOD) which was used by permission from the Air Force Research Laboratory (AFRL) to predict the probability of scintillation effects in terms of S4 and σ_ϕ. The WBMOD tool has commonly been used to obtain scintillation parameters as a function of ionospheric conditions for given time of day and day of year [1, 3]. The estimates are based on climatological models for global distribution and behavior of ionospheric plasma-density irregularities causing scintillation and are parameterized based on solar activity (sunspot number), level of ionospheric disturbance (Kp), day of year and other parameters to define the world-wide scintillation environment [4]. The scintillation characterized by the WBMOD tool is also based on extensive libraries of past scintillation data including equatorial and polar-cap data [5]. The outputs are given in terms of probability of the threshold levels of S4 or σ_ϕ along the lines of site for the desired scenario.

The availability model reads the probabilities of disruption per line of sight and assesses the system performance for the architecture and algorithms of the system of interest. The Local Area Augmentation System (LAAS) architecture is used here as the system of interest to illustrate the results of the technique in this paper. However, given sufficient fidelity of the tool, any desired system design could be studied.

II. HARDWARE-IN-THE-LOOP RESULTS

The initial step to gather receiver impacts due to scintillation requires lab testing using the simulators. The lab setup was completed as shown in Figure 2. The setup essentially consists of a Spirent 7700 simulator and a GPS receiver to be tested. The simulator includes a SimGen PC interface. The receiver is connected physically via coax cable interface to input the RF signal, issue commands as well as to record the data. The results presented here were obtained by controlling the GPS receiver over the Serial Host Control Interface (SHCI).

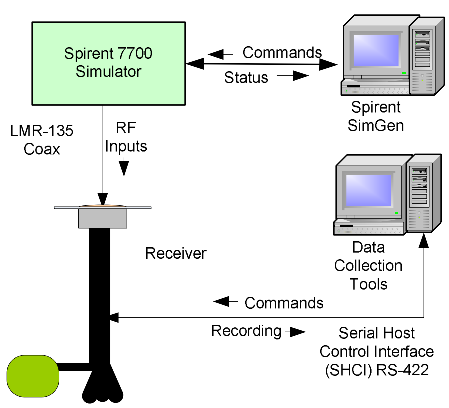

Figure 2. Hardware-in-the-loop Lab Setup

In testing of the receiver, the approach used was to parametrically apply the scintillation inputs over numerous runs. The results obtained allow assessing where tracking performance begins to break down and continue to degrade to a point that the signal becomes unusable for its intended operation. The breakdown of the signals is generalized as follows:

1) Loss of lock
2) Cycle slips
3) Bit errors in the navigation message

The Spirent UAF input files are pre-generated prior to the lab testing (see Figure 1). Parameterization of the UAF files is based on two inputs: S4 level and the decorrelation time (τ_0) in seconds. The phase variation (σ_ϕ) required for the climatological modeling is determined from the resultant phase history generated in the Cornell Simulator.

After completion of data generation, the simulation files are taken to the lab and run through the receiver with data recording option enabled. The recorded data are then processed to determine the metrics of interest. These metrics include counts and durations of loss-of-track, counts of cycle slips and bit errors. Each of these data metrics is carefully correlated to the proper input times of the simulated data. As an example Table I shows the hardware-in-the-loop results illustrating the parameterization. It can be seen for decorrelation time of 0.2 seconds, the resultant values of loss of lock and cycle slips for S4 values varying from 0.1 to 1.0 over fairly tight increments. The cycle slips and loss of lock counts radically increase for the S4 values above 0.7. This indicates that the value of S4 above 0.7 is likely to render an unusable signal and thus can help establish a threshold for operations. Other parameters (τ_0 and σ_ϕ) are similarly varied and considered to choose the ultimate performance thresholds for the later steps in the analysis.

TABLE I. SAMPLE HARDWARE-IN-THE-LOOP RESULTS

S4	*τ_0 (s)*	*σ_ϕ (rad.)*	Loss of Lock *Count*	*Max(s)*	*Avg(s)*	**Cycle Slip Count**
0.1	0.2	0.05	0	0	0	0
0.2	0.2	0.07	0	0	0	0
0.3	0.2	0.09	0	0	0	1
0.4	0.2	0.12	0	0	0	1
0.5	0.2	0.27	0	0	0	1
0.55	0.2	0.30	0	0	0	0
0.6	0.2	0.42	0	0	0	0
0.65	0.2	0.49	2	2	2	2
0.7	0.2	0.57	2	1	1	6
0.75	0.2	0.74	5	13	3.8	48
0.8	0.2	0.93	10	3	2	50
0.85	0.2	1.05	7	2	1.7	55
0.9	0.2	1.13	10	2	1.6	49
0.95	0.2	1.46	10	4	1.7	59
1.0	0.2	1.80	14	12	2.9	61

Note that in addition to determining performance thresholds, the testing here is also instrumental in uncovering anomalies in receiver performance. Since the testing was conducted in a controlled lab environment, there is a significant opportunity for repeatable conditions which can be invaluable to test improvements to performance in scintillation.

III. ENVIRONMENTAL PARAMETERIZATION

For the next phase of the analysis, consideration is switched to the scintillation environment. The intent here is to relate the desired environmental conditions in terms of Sunspot Number (SSN), planetary geomagnetic index (Kp), time of year, time of day, and location. WBMOD implements a single-scatter phase-screen propagation model and a number of empirical models of the global morphology of ionospheric density irregularities [6]. To implement its modeling, WBMOD defines the power law Power Spectral Density (PSD) which relates the two calculated scintillation indices: (a) S4-the square root of the normalized intensity variance; and (b) σ_ϕ-the square root of the phase variance across the phase screen. The propagation then applies a three-dimensional representation of plasma density irregularities through which the modeled signal may be traced and the indices determined.

To implement the desired threshold behavior by the modeling approach, the parameterization option of WBMOD is set to provide "Percent of time threshold exceeded". This selection turns out to be useful for the desired purposes as the thresholds to implement were determined in the previous step. By outputting the probability of the threshold scintillation effects from WBMOD and using them as inputs, the availability model can simulate the disruptive features of scintillation to the probabilities determined in the model. It should be noted that the version of WBMOD used at Raytheon was modified to allow for easier access to the GPS constellation and to provide specialized outputs to the availability model to communicate the probabilities along the lines of sight.

Prior to the WBMOD run, it remains necessary to determine the environmental conditions to be assumed. For this determination, it is possible to either use records of the conditions that were present historically or use projections of the levels of sunspot numbers and other parameters. Selection of these parameters depends on the timeline for the system being evaluated. In general, for purposes of parameter determination, parameters are selected to be conservative estimates of the true impacts until experience develops with the technique. Likewise, it is advisable to assess multiple combinations of parameter settings to assess sensitivity. Hence, as a system developer in preparation for deployment, a strategy of looking at a solar peak is advisable. Sensitivity analysis will consider the average, higher than average, extreme condition of solar peak, and so on. WBMOD has the capability to accomplish this analysis through its method of parameterization.

Figure 3 shows a sample of WBMOD output. The figure shows a single time step from the model predicted for day 45 (February 14th) for S4 effects on zenith measurements at L2 with SSN 200 and Kp 3.0, which would equate to an above average condition with no storm. As can be seen in the figure, the model provides the time and location of severe scintillation effects. According to this outputted plot, the users in equatorial regions are expected to potentially experience high scintillation while the users in polar-cap regions would experience relatively weaker scintillation at this time step. Having these conditions as given, the availability of the navigation service can be calculated. In the section to follow the determination of the availability of service under a given condition is presented.

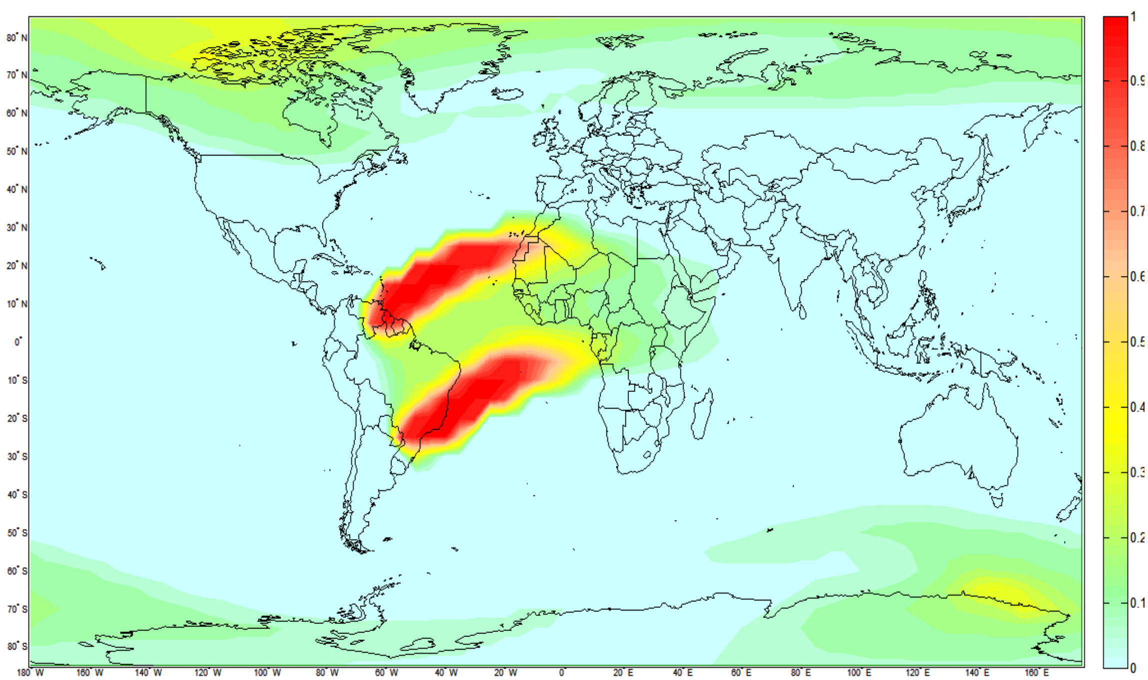

Figure 3. L2 Zenith 95% S4 Values for GMT 0:00, SSN=200, K_P=3.0, February 14th

IV. AVAILABILITY MODELING

Here the Local Area Augmentation System (LAAS) architecture is used to illustrate the technique of determining it's availability of service. LAAS is an example of a GBAS system which is impacted by scintillation if placed in a susceptible environment. Similarly other augmentation systems are also subject to suffer similar effects due to scintillation. To provide the modeling for LAAS, the Raytheon Availability Model is configured to represent the LAAS architecture providing required navigation service to the users. Some of the LAAS parameters are shown in Table II, below. The availability model consists of model representations of the ground and airborne sensors, the GPS constellation, airborne and ground processing algorithms, and environmental effects such as multipath, ionospheric effects, and tropospheric effects. The scintillation probabilistic effects have been added to this base model. A limitation of the availability model is that it only provides for a single set of ground broadcast ionospheric parameters. The equatorial setting was selected for this analysis.

TABLE II. AVAILABILITY MODEL PARAMETER SETTINGS FOR THE ILLUSTRATION

Parameter	Setting
Airborne Accuracy Curve	GAD B
Ground Accuracy Curve	GAD C
Lateral Alert Limit	40m
Vertical Alert Limit	25m
Ionospheric Spatial Decorrelation, σ_{LIS} (m/m)	6.0 x 10-6
Ionospheric Temporal Decorrelation, σ_{LIT} (m/s)	0.004
Constellation	As defined in Section 3.1 of [7]

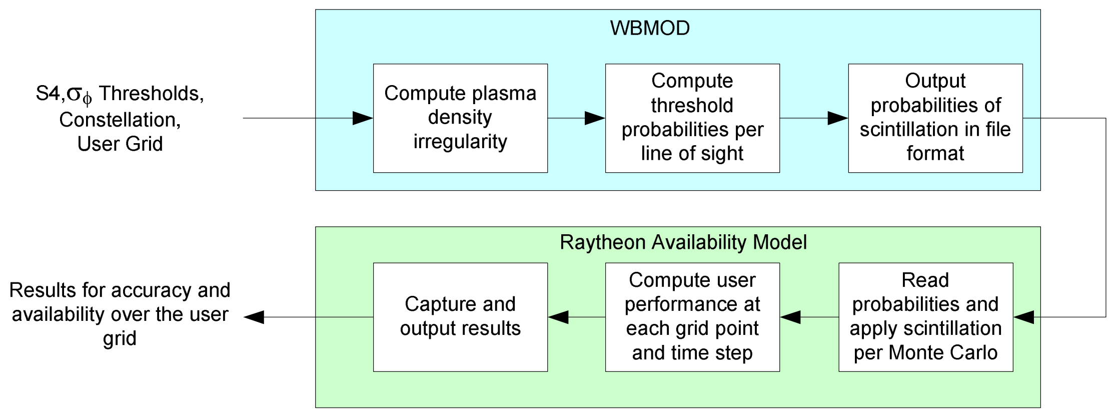

Figure 4. Combined use of WBMOD and the Raytheon Availability Model

Figure 4 shows a block diagram of the availability modeling process following the WBMOD processing. In the top row, WBMOD is shown taking the input desired thresholds, processing the level of irregularity expected, computing the scintillation probabilities per line of sight per location and outputting the results in a file. The availability model then reads the computed probabilities from file and applies a Monte Carlo analysis to assess the impacts. A Monte Carlo is used since the probabilities of scintillation are assumed to be independent across the various lines of sight. Each line of sight affected by scintillation was considered unavailable. Another assumption supported in the availability model is that a measurement affected by scintillation can be interpreted in the tool to be of poor quality but available within the system. The evaluated solution is the average of the Monte Carlo results. Finally, the results are tabulated across users to provide an overview of the user-set. The user-set can be selected to be as a small as a single user point or as large as a world-wide grid covering the whole globe.

To illustrate some results, an availability model run over the global grid was completed and plotted in Figure. 5. This figure was generated for February 14th with high scintillation conditions with SSN of 170 and Kp of 3.0 (no storm). The figure shows the performance globally as percentage of service availability. That is, for each user point (5 x 5 spacing), the percentage of the 24 hour period in which the service was available. This can be compared to Figure 6, which shows the performance prediction with no scintillation effects. As expected, impacts of heavy scintillation can be seen in the areas of the Southern Hemisphere about the magnetic equatorial region, particularly in the South Atlantic / South American region.

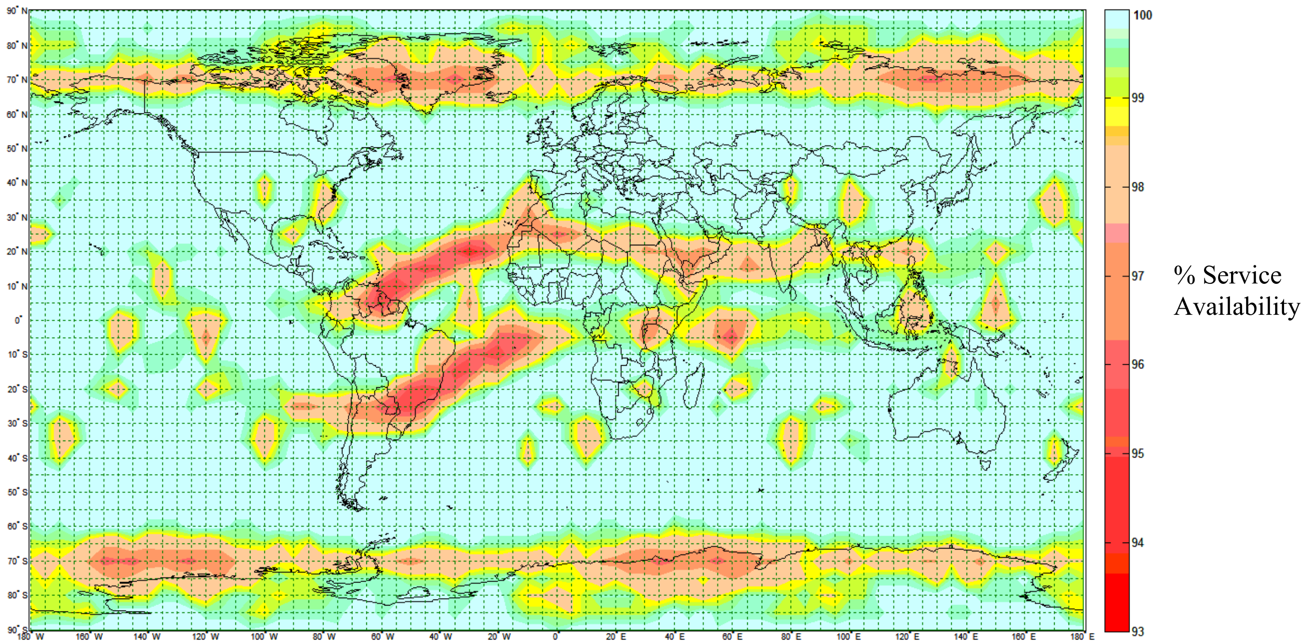

Figure 5. World Wide Grid Results with Combined use of WBMOD and the Raytheon Availability Model

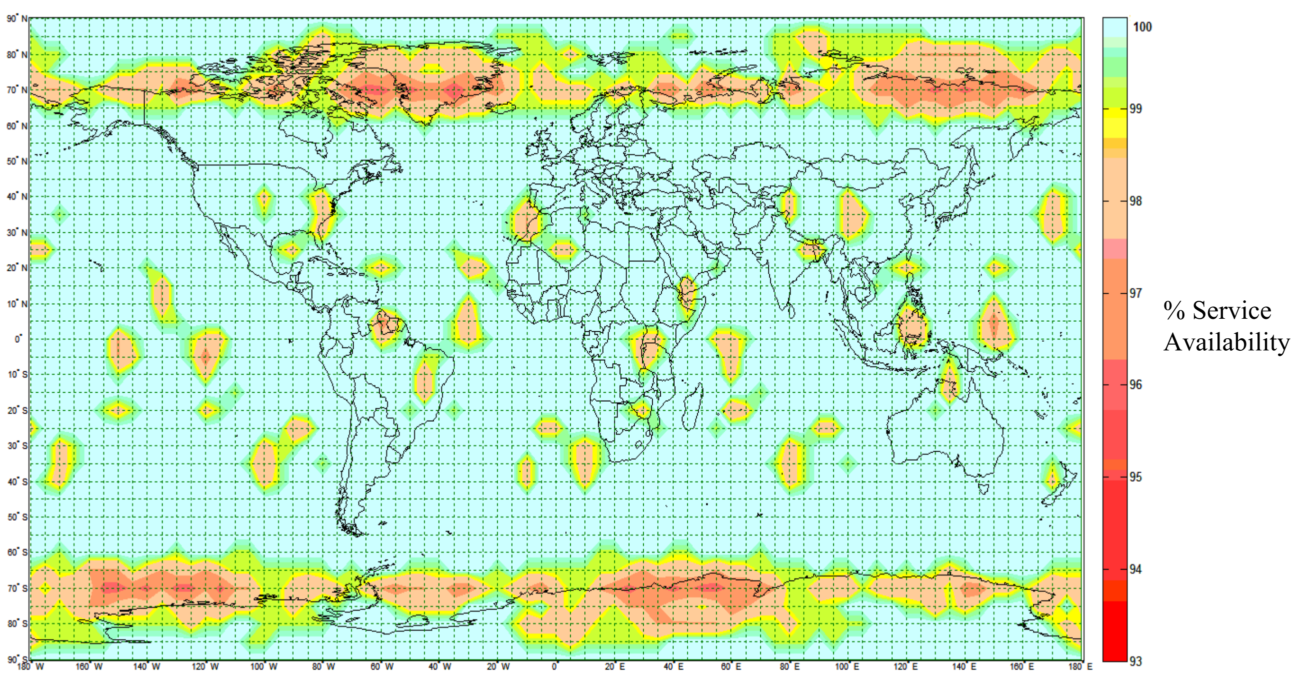

Figure 6. World Wide Grid Results without Scintillation Applied

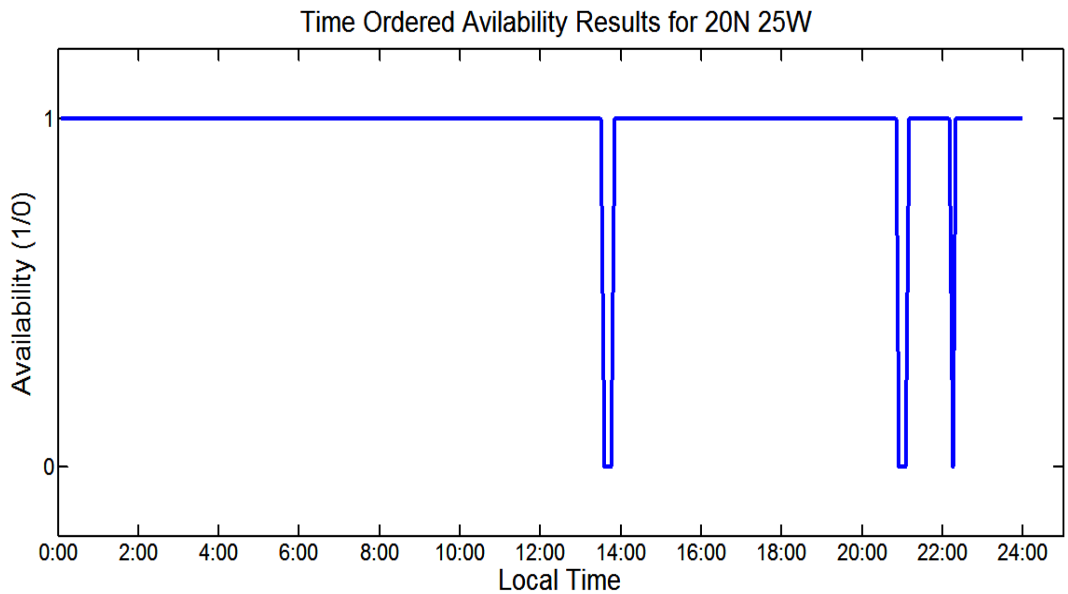

Figure 7. Availability Results with Scintillation Effects on a Single User Point (20°N, 25°W)

The Raytheon Availability Model also allows analyzing results per any user point. Figure 7 illustrates as an example of such analysis results for a single user point over time. In the figure, the value of one indicates service availability and zero indicates unavailability. As can be seen in the figure, the model predicts unavailability in the evening hours which matches well to known scintillation effects.

V. CONCLUSION

A multi-layered technique using modeling and simulation to assess the impact of ionospheric scintillation on GPS augmentation systems has been presented. The combined results are highly controlled and therefore are repeatable. The hardware-in-the-loop test evaluates the GPS receiver performance as well as the overall system under the given climate conditions. This is instrumental in providing characterization and prediction of system performance. The results are obtained on the basis of high fidelity prior data which has a potential to save considerable time and resources. The process can be an alternative to the difficulty of performing live data collection under live scintillation conditions.

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