Preliminary Assessment of Loran for Required Navigation Performance 1.0

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As part of the ongoing Federal Aviation Administration (FAA) Loran evaluation, the system is being assessed for its ability to back up GPS through all phases of flight. While the focus has mainly been on supporting non precision approach (NPA), such as RNP 0.3, efforts have also been made to examine Loran for enroute RNP 1.0 operations. RNP 1.0 is important as it is the minimum requirement for automatic dependent surveillance – broadcast (ADS-B). The FAA is committed to deploying and utilizing ADS-B as an important part of the aircraft traffic surveillance infrastructure. RNP 1.0 capability enables Loran to provide back up to GPS for aircraft enroute guidance and surveillance.

However, being able to support RNP 0.3 does not imply that Loran can support RNP 1.0. The reason for this is that RNP 1.0 capability needs to be provided throughout the entire airspace whereas RNP 0.3 support needs only be provided near airports of interest. While accurate, calibrated propagation delay (ASF, ECD) values and bounds can be provided for many airports, it is prohibitive to do that for all of CONUS. Because of this difference, the enroute user may have to rely on these values that are less accurate than those available to a user on approach. This requires in larger error bounds on propagation delays. These changes influence availability by affecting the position error bounds and cycle confidence.

This paper presents preliminary analysis of the feasibility of meeting RNP 1.0 requirements.

1.0 Introduction

The Global Positioning System (GPS) has become a key component in the national infrastructure for many critical applications. One such area is aviation where GPS is being adopted into the national airspace infrastructure. In recent years, GPS has become the primary navigation aid for aviation. Various systems have been developed and certified to provide GPS with the integrity, availability, accuracy and continuity necessary for aviation navigation applications such as enroute guidance or approach. For example, both Receiver Autonomous Integrity Monitoring (RAIM) and the Wide Area Augmentation System (WAAS) provide users the capability to use GPS for enroute navigation throughout the conterminous United States (CONUS). WAAS also allows GPS to provide precision approach guidance throughout CONUS. GPS, when augmented by the Local Area Augmentation System (LAAS), is envisioned to give guidance for the most rigorous landings, category III (“zero-zero”). WAAS has been operationally for several years and it is hoped that LAAS will soon become operational.

In addition, GPS may become one of the primary instruments for aircraft surveillance for air traffic control. It is seen as the primary means for providing navigation information such as location and velocity to the Automatic Dependent Surveillance-Broadcast (ADS-B) system. ADS-B is a system by which navigation and other information on ones aircraft throgh is shared with other aircraft and ground surveillance via a one hertz transponder broadcast. The FAA is considering the deployment of ADS-B nationwide as part of the Next Generation Air Transportation System (NGATS)[1]. There are plans to replace some of the current ground surveillance systems with a system based on ADS-B. As a result, GPS will not only be our primary navigation and landing instrument but also an essential part of the air traffic and monitoring infrastructure.

1.1 Loran as Aviation back up to GPS

While GPS is to serve as the primary means of navigation and perhaps surveillance in the future National Airspace (NAS), it has been recognized that back up and redundancy is necessary for such safety critical systems [1][2]. Long Rang Navigation, or Loran, is one of the few position, navigation and timing (PNT) systems capable of providing back up to the GPS in multiple modes of operation. In the context of aviation, Loran is one of the few systems that can serve as both navigation and surveillance back up. However, it is still necessary to demonstrate that it is feasible for Loran to meet the strict requirements of aircraft navigation. The major enroute and non precision approach requirements for systems such as GPS are listed in Table 1. If Loran is to support these operations, it should also meet these requirements

As such, the 2004 Loran Technical Evaluation indicated that it is the feasibility for Loran to meet non precision approach (NPA) requirements in the form of Required Navigation Performance 0.3 (RNP 0.3) [3]. RNP 0.3 was the primary aviation application of interest as there are very few back ups to GPS for approach that is available throughout most of CONUS. The report enumerated the conditions that have to be met for RNP 0.3 [3]. These conditions have to be met by the Loran receiver within the ten nautical mile of the desired airport. Additionally, Loran had previously been approved as supplemental aid for enroute navigation [4][5]. These results support the claim that Loran can provide backup aircraft navigation to GPS for enroute and approach.

Typical Operations	Accuracy Horizontal	Accuracy Vertical	Integrity	HAL	VAL	Time to alert	Continuity	Availability	Assoc RNP Types	Min in track separation
En route	3.7 km (2 NM)	N/A	10^{-7}/h	7.4 km (4 NM)	N/A	5 min	10^{-4} to 10^{-8}/h	.99 to .99999	20 to 10	5 NM
En route terminal	.74 km (.4 NM)	N/A	10^{-7}/h	3.7 km (2 NM)	N/A	15s	10^{-4} to 10^{-8}/h	.99 to .99999	5 to 1	3 NM
NPA	220 m (720 ft)	N/A	10^{-7}/h	1.85 km (1 NM)	N/A	10 s	10^{-4} to 10^{-8}/h	.99 to .99999	0.5 to 0.3	3 NM

Table 1. ICAO Draft Requirements for Global Navigation Satellite Systems (GNSS) [6]

[1] ADS-B is currently being tested in Alaska under the Capstone program. GPS is the source of navigation information for the demonstration

In order to provide navigation information for ADS-B, a system must, at a minimum, meet RNP 1.0 requirement. RNP 1.0 supports enroute navigation and, on the surface, should be easily met if Loran can meet the stricter RNP 0.3 requirements. However, RNP 1.0 must be provided throughout most, if not all, of CONUS. The architecture and hence Loran performance for RNP 0.3 only applies in the vicinity of the airport. It does not extend for CONUS coverage in an economically reasonable manner. Hence it was necessary to explore the feasibility of Loran for meeting RNP 1.0 requirements using a less costly infrastructure. Fortunately, enroute requirements are less stringent and so the accuracy of the Loran errors corrections do not need to be as great as in the case of RNP 0.3. Reducing the correction requirements significantly reduces implementation costs and may allow Loran to provide enroute RNP 1.0 navigation economically throughout CONUS.

1.2 Outline

The paper will discuss the preliminary analysis of the capability of Loran to meet RNP 1.0. The background section will quickly cover Loran aviation integrity. The following section will discuss availability, continuity, and accuracy requirements. The assessment of RNP 1.0 leverages the work already done for RNP 0.3. It will show how the RNP 0.3 analysis can be leveraged to demonstrate RNP 1.0. It will also go over the differences between the RNP 0.3 and 1.0 environment. The body of the paper concentrates RNP 1.0 availability. It will show results from the Loran aviation availability coverage tool modified to analyze RNP 1.0. The coverage tool is discussed in [7].

2.0 Background

The goal of this paper is to assess the feasibility of meeting RNP 1.0 requirements with a reasonably designed Loran system. In order to do that, we need to understand what those RNP 1.0 requirements. It is also instructive to understand how meeting those RNP 0.3 requirements can be leveraged to meet RNP 1.0 requirements.

2.1 Requirements

For safety critical applications such as aviation, four major requirements, integrity, availability, continuity, accuracy, are specified. These RNP 0.3 and 1.0 requirements for each of these areas are given in Table 2. The acronyms used in the table are defined in the footnote and the following sections. In the 2004 FAA Loran Technical Evaluation demonstrated that Loran could feasibility meet RNP 0.3 integrity, continuity, and accuracy requirements throughout CONUS. Additionally, it was shown that the availability target could be met throughout much of CONUS. The work of this technical evaluation is the starting point for the feasibility assessment of Loran for RNP 1.0.

Requirement	RNP 0.3 (Target)	RNP 1.0 (Target)
Integrity	Probability HMI ≤ 10^{-7}/hour	Probability HMI ≤ 10^{-7}/hour
Availability	99.9% with HAL of 556 m	99.9% with HAL of 1853 m
Continuity	99.9% per approach (150 seconds)	99.9% per hour
Accuracy	307 m horizontal error, 95%	? m horizontal error, 95%

Table 2. RNP 0.3 and 1.0 Requirements[2]

2.2 Aviation Integrity for Loran

Aviation integrity for Loran essentially means being able to provide the user with timely (10 seconds) warnings of situations where the navigation information cannot be trusted. Incidences of hazardously misleading information (HMI) occur when such a warning is not provided. It is important to discuss integrity first as it is meaningless to meet the other requirements if integrity cannot be demonstrated.

Integrity is provided by two sources: the system and the receiver. The system will provide timely warning should the signal demonstrate anomalous behavior. This is broadcast on the ninth pulse message [8]. The receiver should provide a horizontal position and a high confidence bound, known as the horizontal protection level (HPL), for the horizontal position error (HPE) on the solution. For integrity, the receiver calculated HPL must bound on the HPE with very high probability (99.99999%). The system is available for use for a particular operation provided the HPL is below the horizontal alert limit (HAL) for that operation. The process of providing a navigation solution that has integrity has two steps: cycle confidence and HPL calculation.

2.2.1 Determining Cycle and Calculating Cycle Confidence

The receiver must first track the correct cycle, typically the standard zero crossing (6th zero crossing), for each of the signal used. Figure 1 shows the Loran pulse and this standard tracking point. Determination of the standard tracking point is necessary to establish a consistent point of measure between all signals. The determination is complicated by the presence of noise on the signal and group delay between the envelope and the carrier of the signal due to propagation. The group delay is typically referred to as the envelope to cycle difference (ECD). If a different cycle is unwitting tracked, the result is an undetected range error of three kilometers or more. For RNP 0.3 and generally for RNP 1.0, an undetected cycle error will cause an incidence of HMI. Hence, it was determined that the receiver should guarantee that correct cycles are being tracked with a probability of having a wrong cycle of approximately 7×10^{-8} [9]. A simple description of the cycle confidence process is given in the next section.

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[2] HMI = Hazardously Misleading Information. A navigation HMI is an incident where the true navigation system errors exceeds the stated bounds on the navigation error. This bound is known as the protection level (PL). HAL = Horizontal Alert Limit. The HAL is the maximum value of the bound of horizontal position error (HPE), known as the Horizontal Protection Level (HPL), for which the system can be considered available for the desired operation.

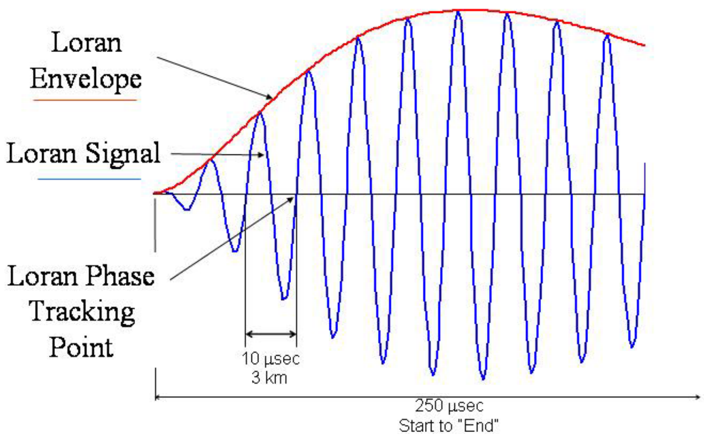

Figure 1. Loran Pulse, Envelope, and Tracking Point

2.2.2 Cycle Confidence

Determining a confidence level for cycle selection provides integrity for the process. The determination requires estimating the probability that the cycles that are being tracked are all correct. For any individual signal, we can calculate the probability of being on an incorrect cycle (P_{IC}) seen in Equation (1). The calculation depends on the variance of the ECD due to noise. The general formula for the variance is seen in Equation (2) and can be derived either theoretically [10] or empirically [11]. The results from the cited papers are consistent with only the value of C varying (depending on receiver performance)[3]. Given the ECD bias, the probability is solely dependent on SNR. For the cycle selection to be considered usable for the position solution, a probability of 7×10^{-8} or lower of tracking a wrong cycle on any signal is required. This probability is denoted as P_{WC}. The basic way of making this determination is given by Equation (3). An additional probability that is required is P_{MD}, the probability of missed detection of cycle error given that there is a cycle error. One of two methods of determining P_{WC} is used depending on the quality and number of measurements available.

$$p_{IC} = normcdf\left(-5\mu\sec, ECD_{bias}, \sigma^{ECD}_{noise}\right) + normcdf\left(-5\mu\sec, -ECD_{bias}, \sigma^{ECD}_{noise}\right) \quad (1)$$

$$\sigma^{ECD}_{noise} = \frac{C}{\sqrt{N * SNR}}\mu s \quad (2)$$

$$P_{WC} \sim \Sigma P_{MD} P_{IC} \text{ over all cases} \quad (3)$$

The first method of determining the overall probability of having an undetected wrong cycle (P_{WC}) is to calculate the probability based on each individual signal. The probability is roughly the sum of the probability of being on the incorrect cycle for each signal (P_{IC}). The method is simple, yet there is no true attempt at detecting incorrect

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[3] Boyce derived a value of roughly C = 21 μsec for the theoretical best performance while Peterson estimates that C = 29 μsec is currently achievable. C = 42 μsec is the value derived by Peterson using the Austron 5000 receiver

cycle selection. Hence P_{MD} is equaled to one. The method is used when there are only three stations and hence there is no redundancy of measurements. The method is also used when there are three strong signals (signals with a very low P_{IC}) such that they form a "trusted triad."

Redundant measurements can be leveraged for detection of the presence of incorrect cycle when there are more than three signals. This allows for greater availability than the first method, which strictly uses estimation. The details of this algorithm are given in [11]. The algorithm first derives a position solution and calculates the residual errors. A weighted sum square error (WSSE) statistic is formed from the residual errors. This statistic is used for deciding if an incorrect cycle selection exists. If the statistic is above a specified threshold, then the receiver assumes that there is a fault, i.e., there is at least one incorrect cycle. Otherwise it is assumed that there are no faults - all cycles correct. Estimates of the distribution of the statistic for the no fault and faulted cases are used to determine the confidence of the calculation.

The weighting used for the position solution and the WSSE determines the distribution of the statistic. In this paper, we examine two different weightings. One is based on random errors only (denote by σ weighting) and one is based on random plus bias errors (denote by σ+b weighting). The σ weighting results in distributions that are more mathematically tractable and hence easier to demonstrate integrity. However it comes at the cost of receiver complexity. The σ+b weighting is simpler to implement but is more difficult to demonstrate integrity. This was the weighting initially used for the 2004 evaluation [3]. Details of the advantages and disadvantages of these weightings are given by [12].

For additional information on the cycle confidence algorithm, see [11][12].

2.2.3 Determining HPL

If the cycles are known to the desired level of confidence, then the horizontal position and HPL can be calculated. The calculation of the HPL assumes that all cycles are correctly tracked. The HPL is calculated using the Loran integrity equation and is based on models for the significant measurement errors on Loran such as noise, transmitter jitter, errors in estimates of additional secondary factor (ASF), etc. The HPL or integrity equation is detailed in [7]. Bounds for errors such ASF estimate errors are incorporated into the calculation of the HPL. As a result, the HPL is only as valid as the bounds and models used to generate it values.

For RNP 0.3, these models and values have been determined with adequate confidence to believe they are reasonable. An HPL will also need to be calculated for the RNP 1.0 case. However, the models and values for bounds may differ. If the calculated HPL is less than the HAL for the desired application, then the navigation solution can be considered available for the desired application. The whole process of determining when a position is available for the desired operation is shown in Figure 2.

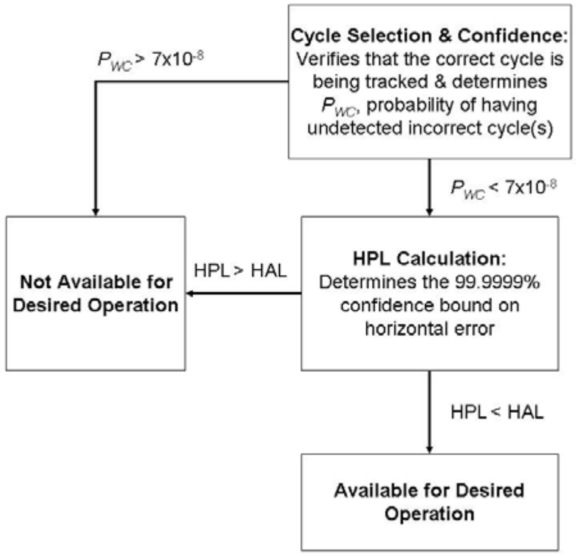

Figure 2. Loran receiver flow diagram for deciding availability

2.3 Differences between RNP 0.3 & RNP 1.0 Integrity Calculations

The difference between the two operations lies in the quality of information available to the receiver. It is envisioned that the Loran receiver will have to operate with different qualities of information in the approach (RNP 0.3) and enroute (RNP 1.0) environment. The architecture for RNP 0.3 assumes calibration values for Loran parameters such as additional secondary factor (ASF) near the airport. RNP 0.3 approach conditions are necessary only within 10 miles of the airport and within 4000 feet above ground level (AGL). Hence, the receiver, when being used for RNP 0.3, will have local values of ASF and ECD. For RNP 1.0, it is not economically reasonable to provide these parameters at a density and quality such that users will have similarly accurate values for ASF/ECD anywhere enroute.

Two methods for economically providing a CONUS wide grid of the necessary propagation parameters to the receiver have been proposed. One method is to generate the grid using surveys similar to the airport surveys conducted for RNP 0.3. For this method to be economically reasonable, the grid will be fairly sparse. The grid points may be one degree of arc or 60 nm apart. Additionally, the ASF and ECD measured on the ground and the air can significantly differ with greater differences at higher altitudes. For enroute flight, an aircraft may be 40,000 feet or more AGL. As a result, the user may be significantly far from calibrated values of ASF and ECD. Another method is to provide user ASF and ECD values derived from theoretical models rather than empirical measurements. A much denser grid is achievable. Altitude effects may potentially be incorporated in the grid. However, there is modeling error that limits the accuracy of the model generated grid. Thus, for either implementation, the end result is that the variation of the error in the values of ASF, ECD and other propagation delays used by the RNP 1.0 user will be significantly larger than that for RNP 0.3.

The increase in residual propagation errors is of tremendous significance to the feasibility analysis. The Loran aviation architecture and receiver algorithms described in the technical evaluation were meant to provide integrity for RNP 0.3. The same architecture and algorithms will be used for RNP 1.0 and as such, the integrity argument for RNP 1.0 should follow that for RNP 0.3. The primary difference is the bound for propagation errors such as ASF and ECD.

2.4 Baseline Values for RNP 1.0 Assessment

The previous section showed that residual values of propagation errors such as ASF, phase, and ECD will be different for RNP 0.3 and RNP 1.0. So, while the procedure for calculating cycle confidence and HPL is essentially the same for the RNP 0.3 and 1.0, the analysis must account for these differences. These differences are not well known and bounds for the value will depend on the accuracy of the propagation estimates implemented for RNP 1.0. For the feasibility analysis, we will take the error bound on our estimates of ECD and ASF as variables. The baseline values used is provided in Table 3 and compared with those values used for RNP 0.3.

Residual Error	RNP 0.3	RNP 1.0	Effected Calculation
Spatial ASF Range Domain	100 m	1000 m	Cycle
Spatial ASF Position Domain	120 m	240 m	HPL
ECD	1.0 μsec	2.0 μsec	Cycle
Temporal Variation of Phase	Based on Map	Same as RNP 0.3	Cycle, HPL

Table 3. Baseline values for Residual ASF and ECD for RNP 1.0 analysis (compared to RNP 0.3)[4]

The residual error in the temporal variation of phase was left unchanged from RNP 0.3. Under RNP 0.3, the bound on the temporal variation residual at any given location was derived from a model. It was assumed that the user receiver stored the values of the model in memory. The same calculation can be done for the RNP 1.0 scenario. Thus, for RNP 1.0, the bound on the temporal variation residual can also be pre-calculated and stored. One factor that complicates the error bound is that a median value of ASF is assumed to be used. The error in estimating this median value will be greater under RNP 1.0. As a result, while the residual error in the temporal variation should notionally be the same as in RNP 0.3, it will actually increase due the greater uncertainty in ASF. In the analysis, we have chosen to incorporate the increase into the spatial range and position domain error for cycle and HPL calculations respectively. Another uncertainty is the appropriate value of the residual error in spatial ASF in the position domain. However, it is easy to see its effects should it change as any change results in a commensurate change in the HPL calculated.

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[4] Note on terminology. Spatial ASF refers to the …. It is static and the ASF as defined by Last [Last ASF]. Temporal variation of phase, in other papers denoted as temporal ASF, refers to the seasonal variation of phase relative to the (spatial) ASF.

3.0 Overview of RNP 1.0 Feasibility

The previous section discussed integrity and the algorithms that the RNP 1.0 receiver will employ to ensure it. Feasibility also means being able to meet other requirements such as availability, continuity, and accuracy. These requirements are shown in Table 4. This section touches how each of these requirements has been examined. The next section goes into detail of the availability analysis.

Requirement	Definition (Metric)	Target Requirement
Integrity	Hazardously Misleading Information (HMI) is when HPL > HPE Alarm in 10 seconds	Probability HMI ≤ 10^{-7}/hour
Availability	HPL ≤ HAL (1852? m) No HPL means not available	99.9%
Continuity	Given HPL ≤ HAL initially HPL must exist & HPL ≤ HAL per hour	99.9%
Accuracy	95% horizontal error performance	1000 m?

Table 4. Primary Requirements for Aviation (RNP 1.0)

3.1 RNP 1.0 Availability

As is the case for RNP 0.3, the most difficult requirement to meet after integrity is availability. The increased uncertainty in ASF and ECD has direct consequences on availability particularly because they affect our ability to obtain adequate cycle confidence. The cycle selection and confidence algorithm will be discussed in more detail later. However, for more details, the reader is directed to [11]. Like in the RNP 0.3 case, RNP 1.0 availability is primarily driven by the availability of having adequate confidence in our cycle selection. As a result, our availability analysis focused primarily on the effect of increased error in ASF and ECD estimates on cycle confidence.

3.2 RNP 1.0 Continuity

Continuity is the probability of maintaining availability over a given period provided that the system was initially available for the desired operations. The RNP 0.3 continuity assessment is given in [7] and a similar assessment will be followed for RNP 1.0. The requirements for RNP 1.0 differs in that the requirement is on a per hour versus a per approach (150 seconds) basis for RNP 0.3. It was shown in [7] that station continuity over 150 seconds was well over 99.99%. Under RNP 1.0, provided that cycle confidence can be maintained, it is expected that the loss of one or two stations will still yield HPLs that will allow the use of the position solution for the operations. This is because the

HAL is the less stringent than for RNP 0.3. The probability of two or three stations being out simultaneously is well below 99.9%. So the only issue is maintaining cycle confidence. With cycle slip detection for checking cycles, it is expected that cycle confidence can be maintained with over 99.9% continuity. So while a complete, formal analysis has not been conducted, it seems that RNP 1.0 continuity should be quite feasible. A later paper will explore the continuity issue for RNP 1.0.

3.3 RNP 1.0 Accuracy

Meeting accuracy is also best assessed primarily through modeling with supporting flight data. It will be seen later in this paper that the estimated HPL, a 99.99999% bound on the horizontal position error, is less than 1000 m throughout CONUS which suggests that the 95% level should be significantly less. Flight data collected also suggests that such a level can be achieved with ASF values derived from modeling [14]. Hence, our initial assessment did not examine accuracy closely as it is not a prime driver of feasibility.

4.0 Availability Analysis

The availability analysis for RNP 1.0 evaluates the two necessary conditions for declaring the system available for RNP 1.0: 1) passing cycle selection with adequate confidence and 2) determining an HPL that is below the 1853 m HAL for RNP 1.0. The assessment depends on two factors discussed in Section 2.0: 1) weighting matrix and 2) bounds for measurement error. These two factors must be chosen to provide integrity while maintaining reasonable availability. In this section, the effect of weighting and different values of measurement error bounds on overall availability is examined. The weighting assessment is necessary for determining a weighting that will yield reasonable availability with integrity. The error bound assessment is important as these values are not well known. The determination the maximum acceptable bound values will indicate whether those values can be feasibility met.

4.1 Baseline Availability & Cycle Availability

The baseline case described in Section 2.4 is first examined. The overall availability under the worst case noise condition for the σ+b and σ weighting cases is shown in Figure 3 and Figure 4, respectively. The worst case noise condition is for each location is used. The value is extrapolated from the model derived by the International Telecommunications Union – Radio (ITU-R) [15]. The use of this noise model for Loran was validated in [13]. Since the high levels of noise is generally impulsive and non linear, the analysis assumed a conservative non linear processing credit of 12 dB. This is the same assumption used for the technical evaluation. As seen from the resulting plots, the σ+b weighting results in unacceptable availability while the σ weighting results in reasonable availability. Analysis of the result indicate that the σ+b weighting causes the cycle confidence estimate to be extremely conservative. In the next sections, sensitivities to increase error bound values will be examined. As these cases will only decrease the availability, we will only look at σ weighting case.

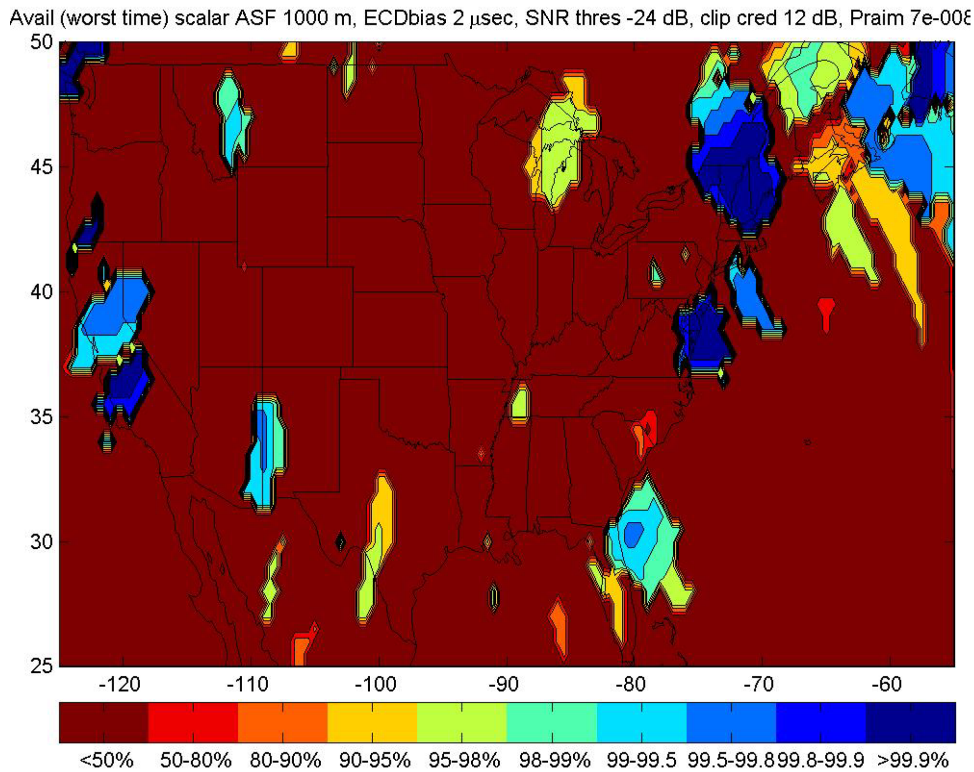

Figure 3. RNP 1.0 Availability for σ+b weighting using the baseline values in Table 2

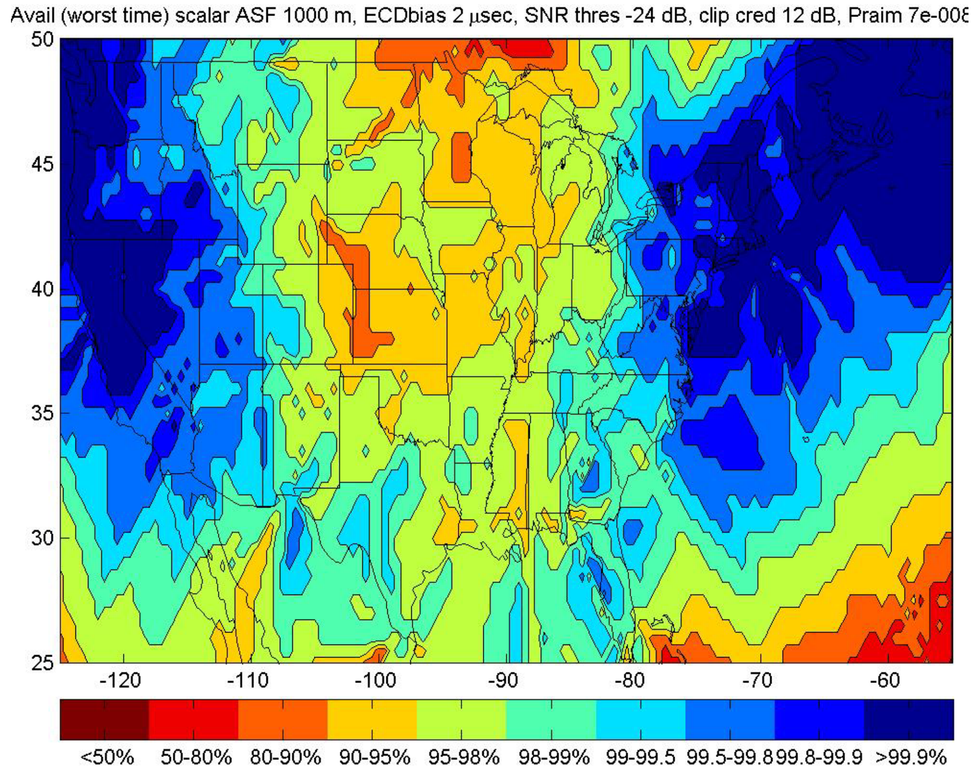

Figure 4. RNP 1.0 Availability for σ weighting using the baseline values in Table 2

Analysis of RNP 0.3 demonstrated that availability was primarily driven by the availability of tracking the desired cycles at adequate confidence levels. This result is true also for the RNP 1.0 case. This can be seen by examining Figure 5 which shows just the cycle availability. The availability map is essentially the same as that seen in Figure 4. The result is not surprising. The RNP 0.3 result suggested that if we could get adequate confidence in the cycle selection, achieving an HPL of 556 m should not be difficult. In essence, the result for RNP 1.0 is stating that if same confidence on cycle selection could be achieved as in RNP 0.3, then achieving an HPL of 1853 m should not be difficult. These results are confirmed in the next section where the HPL is examined.

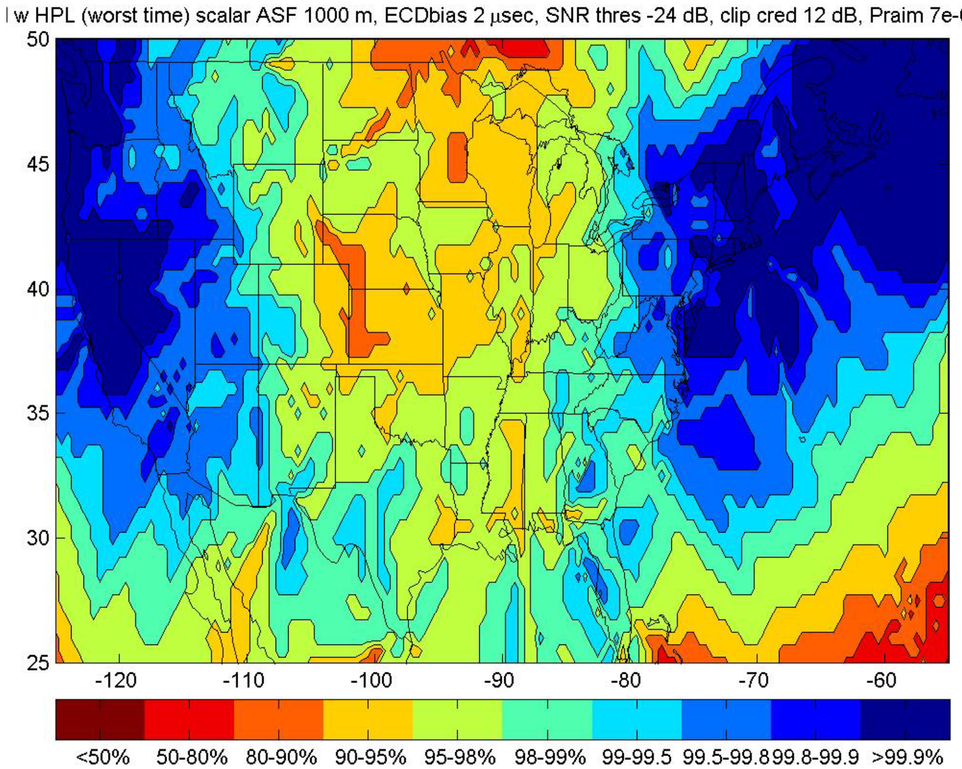

Figure 5. Cycle Availability for σ weighting using the baseline values in Table 2

4.2 Baseline HPL

While cycle confidence drives the overall availability, it is useful to also look at the HPL. Since the values of the residual errors is currently not well known, examining the HPL provides an idea as to whether there is margin with the assumptions made on these errors, Both spatial ASF in the position domain and temporal phase error values affect the HPL though the analyses choose to lump these errors into the position domain term. Having the position domain account for the error increase makes the preliminary analysis simple. A change in position domain error leads to a commensurate change in the HPL. Hence, as Figure 6 shows, the HPL is generally below 1000 m. The result means that the HPL, and, by extension, the position domain error, would have increase by over 800 m before we start to lose significant availability due exceeding the 1853 m HAL. In other words, the same availability can be achieved even if the position domain error is increased by up to 800 m beyond the current 240 m value. Hence the result implies there is significant margin in our assumptions regarding the errors affecting HPL. Thus it provides confidence that the availability is achievable. The results also imply that, provide the error bounds are correct, the accuracy should be easily below 1000 m.

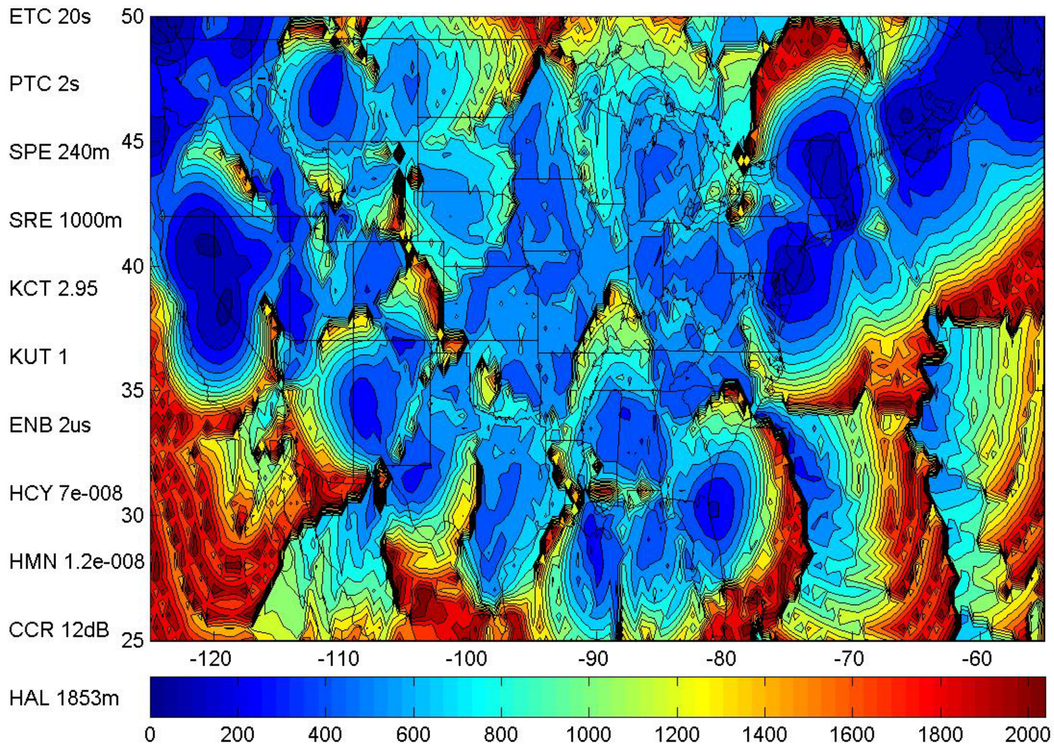

Figure 6. HPL values from σ weighting using the baseline values in Table 2

4.3 ECD Sensitivity

The baseline case provides only a reference. The true bounds may actually be different. The value for spatial ASF range domain error in Table 3 was chosen to be an upper bound. It is likely to be lower. The ECD, however, may be larger than the baseline value. In order to conclude the feasibility of achieving RNP 1.0, reasonable availability should be realizable for any anticipated value of ECD. Hence, sensitivity to larger values of ECD is examined. Figure 7 shows the effect of having ECD of three and four microseconds. An ECD error of four microseconds is roughly the maximum value expected.

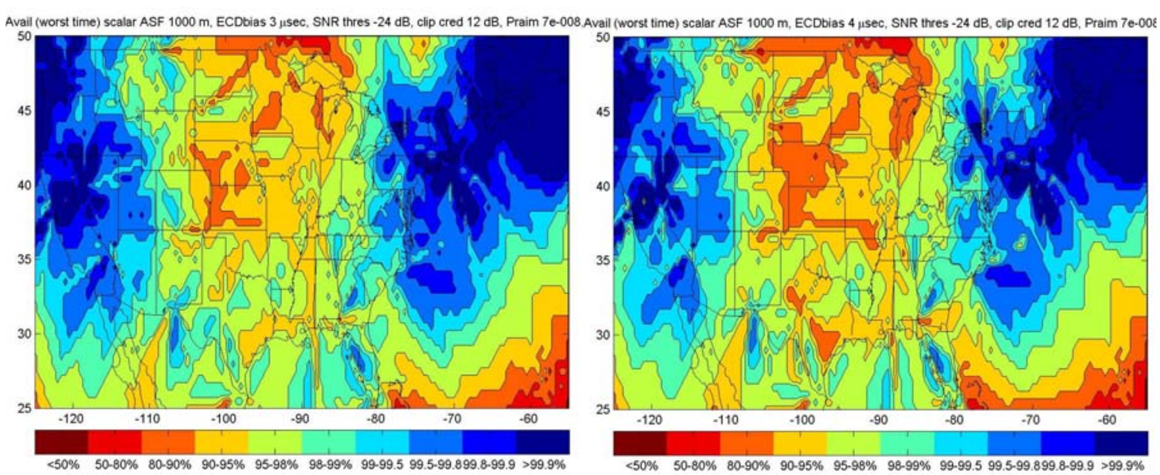

Figure 7. RNP 1.0 Availability for σ weighting with ECD of 3 (LEFT) and 4 μsec (RIGHT) and all other values at baseline

4.4 Other Sensitivities

In assessing RNP 0.3 cycle confidence, it was found that using all stations was not necessarily the solution that produced the highest availability. The addition of a weak station may result in a decreased confidence in having all cycles correct. To assess the best possible availability, availability at each location was calculated with all possible station subsets. Figure 8 shows the performance of this best case. It can be seen that there is some availability increase over the nominal case (all stations) but the increase is very insignificant.

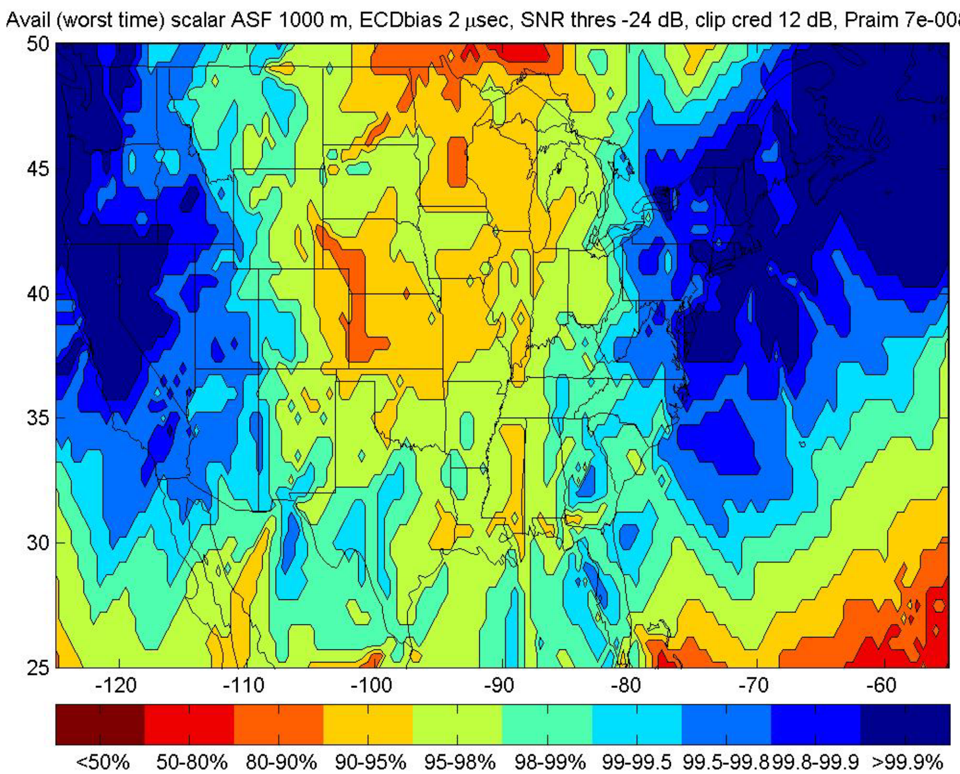

Figure 8. RNP 1.0 Availability for σ weighting with Table 2 baseline values & selecting the station set that yields the best availability

With σ weighting, a weak station will be not be weighted very much in the position solution provided it is not essential to geometry. As a result, it may be possible to have an incorrect cycle on this station and still meet the HPL requirement. We performed an analysis whereby an incorrect cycle selection was permitted on the weakest station and the HPL was calculated assuming a one cycle error on the station. To determine the limits of what is achievable through changes in algorithm, the best station algorithm is also used. Figure 9 shows that the resulting performance is no different than the best station case given in Figure 8. Hence, we conclude there is little to be gained by allowing missed cycles or changing to a best station scenario for RNP 1.0.

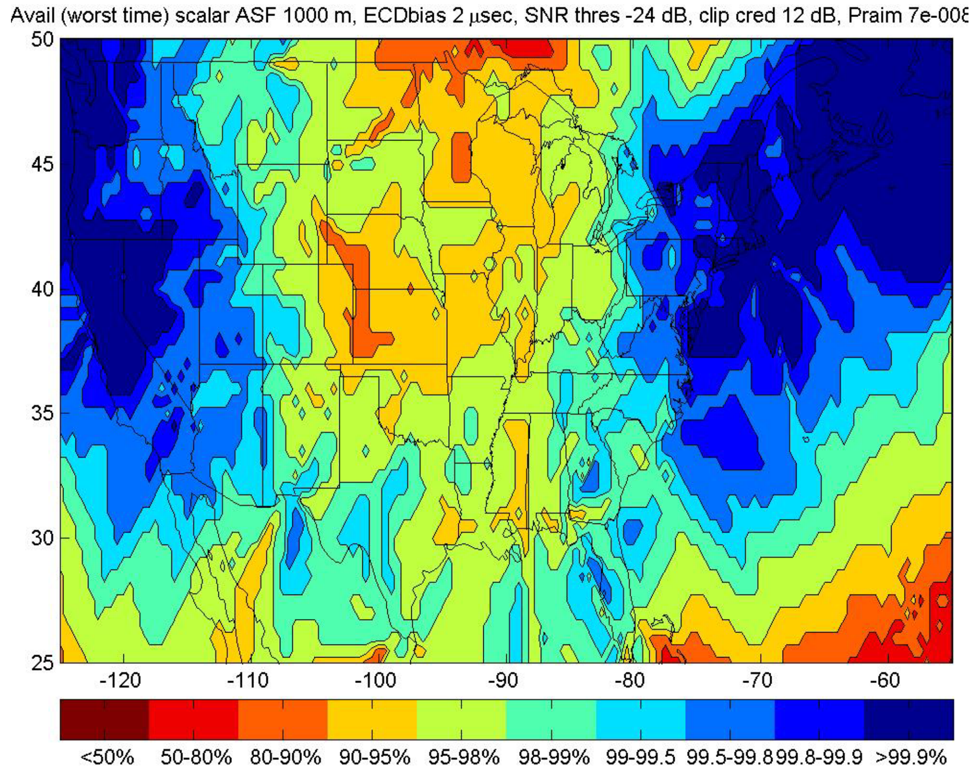

Figure 9. RNP 1.0 Availability for σ weighting with Table 2 baseline values & allowing one cycle selection error on the weakest station (highest P_{wc})

4.5 Conclusions

The preliminary analysis shows that reasonable but not great availability can be achieved with σ weighting. Like in the RNP 0.3 case, RNP 1.0 availability is driven by the availability of adequate cycle selection confidence. While algorithm changes such as using the best station subset and allowing an incorrect cycle on weak stations can improve availability, the improvement is minor. In the next section, it will be shown that better processing of noise can have more significant improvements on availability.

5.0 Noise Model and Availability

As mentioned previously, the 2004 evaluation report, a conservative model for noise processing was used. Since that report, further study of noise have been conducted. We have identified improvements to our noise model that better reflect the nature of atmospheric noise. These are described in [16]. The conclusion of [16] is that higher noise levels are positively correlated to greater degrees of impulsiveness in the noise. With greater impulsiveness, we can get greater non linear processing gain. This results in an overall better availability than under the noise processing model used for the 2004 report. In [16], significant availability improvements was shown for RNP 0.3 when using this refined model vice the model used in the 2004 technical evaluation. In this section, we will examine the affect of the refined noise model on RNP 1.0.

5.1 Nominal Performance with Different Weightings

First examine the nominal RNP 1.0 performance using the two weightings. The results are shown in Figure 10 and Figure 11 for the σ+b and σ weightings, respectively. For the σ+b weighting, the availability is still poor as it was for the original noise model. For the σ weighting, we see that there is 99.9+% availability in almost all of CONUS. The results emphasize the conservatism that exists in the estimated probability of having an undetected wrong cycle due to that σ+b weighting.

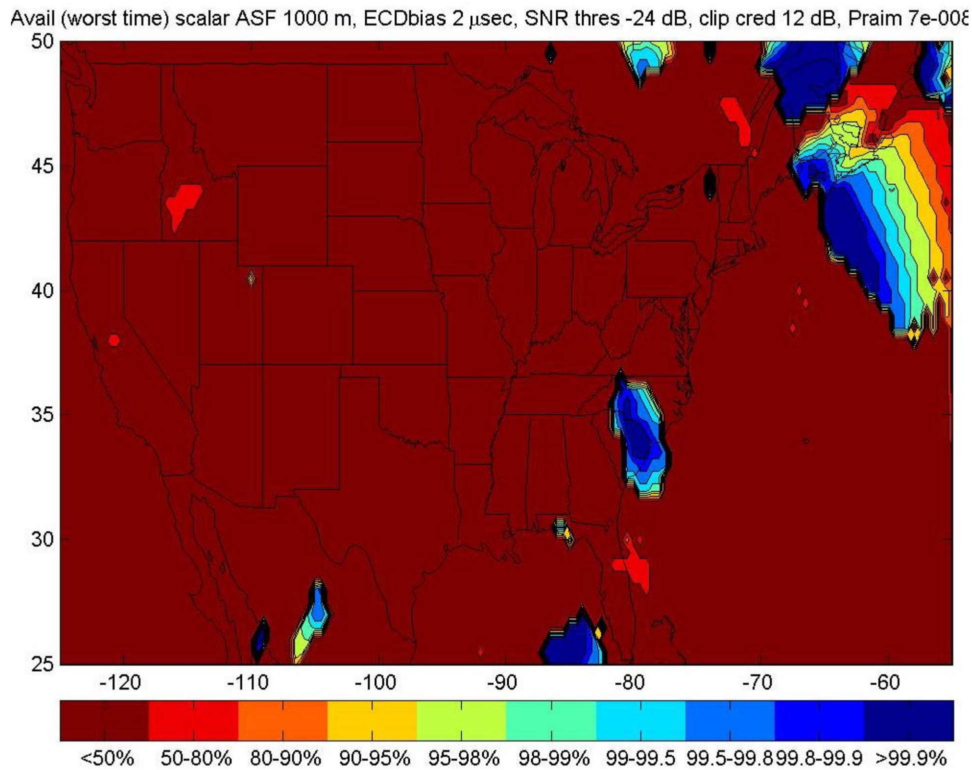

Figure 10. RNP 1.0 Availability for σ+b weighting with Table 2 baseline values in & revised noise model

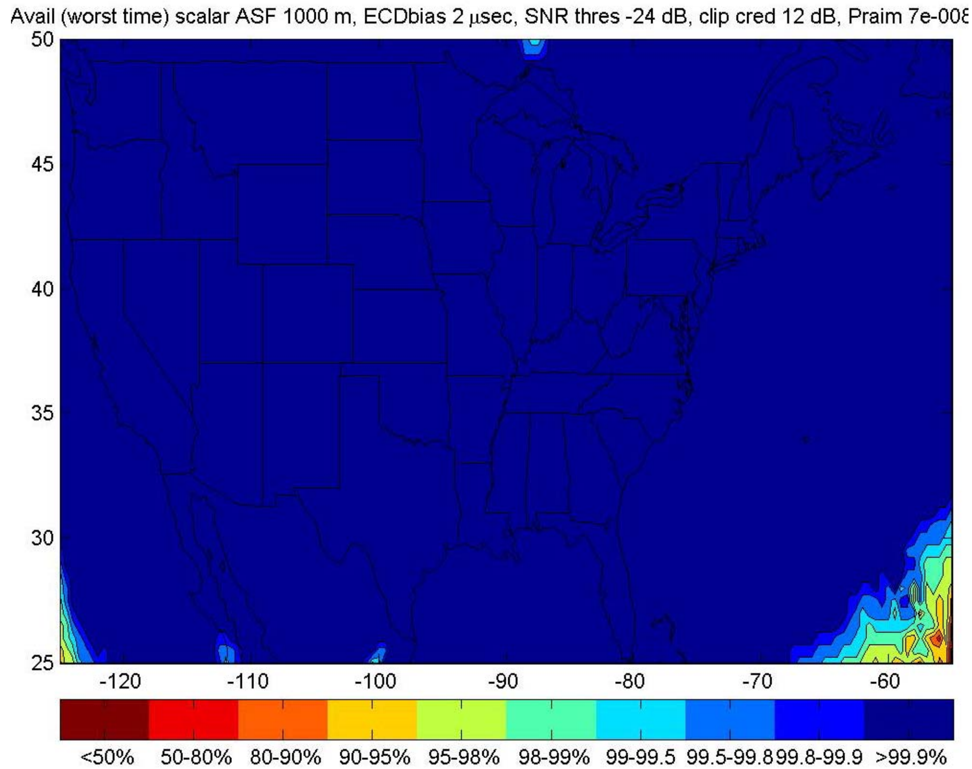

Figure 11. RNP 1.0 Availability for σ weighting with Table 2 baseline values in & revised noise model

The HPL resulting from using the s weighting with the refined noise processing model is shown in Figure 12. The HPL is even lower than seen in Figure 6 with values in CONUS Generally between 400-800 meters. This implies that the spatial ASF position domain error can be as large as 1200 meters before there is an effect on availability due to HPL.

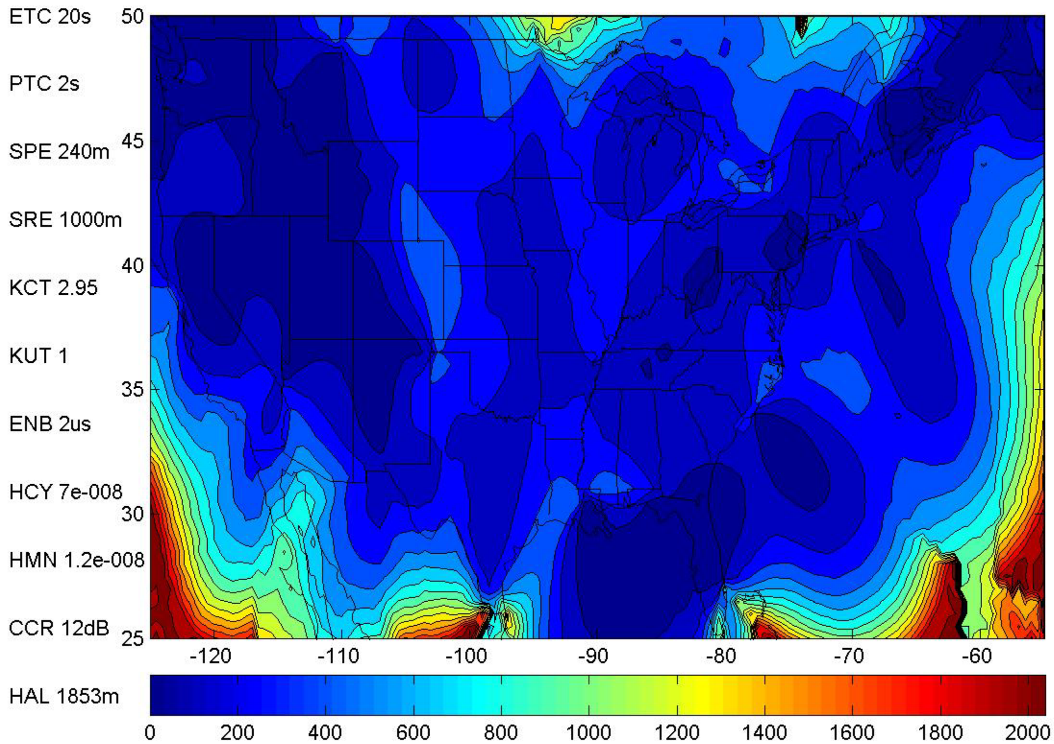

Figure 12. HPL values from σ weighting with Table 2 baseline values in & revised noise model

5.2 Sensitivity of Performance

A study of the sensitivity of the RNP 1.0 availability using σ weighting is also conducted for the new noise processing model. Again, the ECD is increased. This time we look at the case of having an ECD of four microseconds, the worst case examined in Section 4.3. This is shown in Figure 13 and the result is not much different from Figure 10. Hence, if the refined noise processing model is reflective of truth, good RNP 1.0 availability should be possible even with large values of ECD.

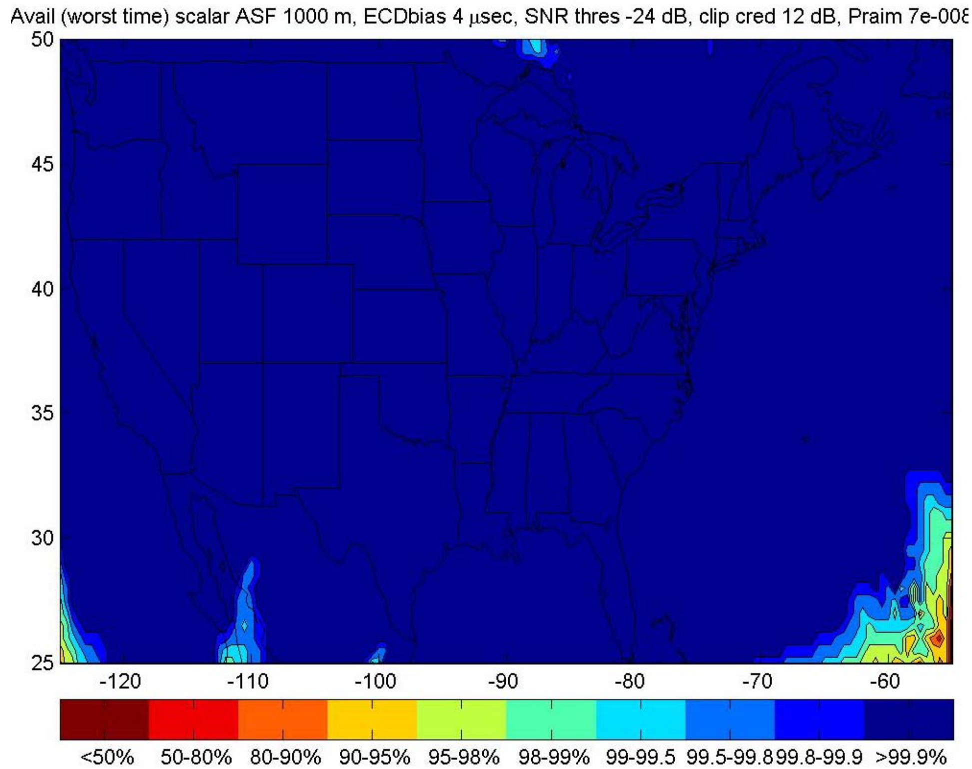

Figure 13. RNP 1.0 Availability for σ weighting with revised noise model, ECD 4 μsec, and all other values at baseline

6.0 ASF and ASF Grid

One important element for both the analysis and the system design is the determination of the residual ASF error experienced by the user receiver. Section 2.3 discussed two implementations, a measurement derived and model derived grid. Both methods will result in increased residual ASF errors. Some of the issues with each of the methods are covered in the following sections.

6.1 Models and Measurements

The FAA Loran evaluation program has several ongoing efforts to measure and assess ASF. These efforts involve data collection, flight test as well as modeling. Flight tests are necessary to determine the veracity of the airport ASF surveys for RNP 0.3. Additionally, these flight tests are used to measure ASF along the baselines between transmitters for comparison with model results. Johnson et al. recently compared the results of the baseline measurements with several models [14]. The baseline apths flown is shown in Figure 14. The models include the Loran User Position Software (LUPS) and several versions of the Bangor Loran (BALOR). The results suggest that using an ASF grid derived from a model of sufficient quality for the RNP 1.0 is feasible. The residual errors seem within the bounds used in the analysis in Section 3.

Figure 14. Path of ASF Data Collection Flights and Loran Stations [Courtesy Greg Johnson, et. al.]

6.2 Grid Density

The prime determinant of the magnitude of residual error is the density of points used for the ASF grid. For a measurement derived grid, increasing the density means increased costs. As it is, over 1000 points are necessary to cover CONUS with a one by one degree grid. It may be difficult to measure ASF at high densities due to the number of locations that will need to be calibrated. Additionally some desirable survey locations may be difficult to survey due to terrain. Some grid points will already be available as we may be able to use airport locations that have surveyed data for RNP 0.3.

Since the grid is sparse, interpolation will be necessary and methods of interpolation will be investigated. Much work on interpolation has been done for the ASF grids to be used for Harbor Entrance Approach (HEA) and it may be possible to leverage this work.

For model derived grid, increasing density does not necessarily drive up costs significantly. Only for a very dense may cost may be a factor due to the fact that the user equipment will need to store the database. That factor aside, a high density can be useful in eliminating the need for user interpolation and altitude variations. Another consideration in generating the model derived grid is ensuring that it is consistent with the surveyed airport location used for RNP 0.3

Regardless of how the grid is derived, one future task is to determine what a reasonable density should be.

7.0 Conclusions

Our initial feasibility study suggests that RNP 1.0 achievable with reasonable availability. The RNP 1.0 receiver will use a grid of propagation delay parameters for positioning and determining the confidence of the solution. The grid, due to implementation factors, will result in errors that will be larger than those encountered by the RNP 0.3 user. An analysis was conducted using expected upper bound values for propagation parameters such as ASF and ECD. As in the RNP 0.3 case, the RNP 1.0 availability is mainly driven by the availability of cycle confidence. While additional gains may be achieved through better algorithms for choosing stations for the cycle confidence solution, the improvements are not significant. If the refined noise processing model is validated, RNP 1.0 can be achieved with very high availability even with extreme values of ASF and ECD. While, additional work needs to be done, particularly determining continuity, system design, and assessing grid density, the preliminary results suggest that RNP 1.0 is feasible using a design that is not too burdensome.

8.0 Disclaimer

The views expressed herein are those of the primary author and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, Department of Transportation or Department of Homeland Security.

9.0 Acknowledgments

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10.0 Bibliography

[1] "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," John A. Volpe National Transportation System Center, August 20, 2001.

[2] Presidential Decision Directive, "U.S. Space-Based Positioning, Navigation, and Timing Policy", December 15, 2004

[3] FAA report to FAA Vice President for Technical Operations Navigation Services Directorate, “Loran’s Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications,” March 2004.

[4] Radio Technical Committee Aviation (RTCA), Minimum Operational Performance Standard for Airbourne Area Navigation Equipment Using Loran-C Inputs, RTCA DO-194 17, November 1986.

[5] AIR-12, AC No: 20-121A Airworthiness Approval of Loran-C navigation systems for use in the U.S. National Airspace System (NAS) and Alaska, August 24, 1988

[6] International Civil Aviation Organization (ICAO) Global Navigation Satellite Systems (GNSS) Standard and Recommended Practices (SARPs), Draft Version, December 1998.

[7] Sherman Lo, et al., "Loran Availability and Continuity Analysis for Required Navigation Performance 0.3” Proceedings of GNSS 2004 – The European Navigation Conference, Rotterdam, The Netherlands, May 2004

[8] Kevin Carroll, et al., "Differential Loran-C,” Proceedings of GNSS 2004 – The European Navigation Conference, Rotterdam, The Netherlands, May 2004

[9] Sherman Lo, et al., "Loran Integrity Analysis for Required Navigation Performance 0.3", Proceedings of the 5th International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo, Munich, Germany, June 2004

[10] Lee Boyce, Sherman Lo, J.D. Powell, Per Enge, “Analysis of Noise and Cycle Selection in a Loran Receiver”, Proceedings of the International Loran Association 35th Annual Meeting, Groton, CT, October 2006

[11] Benjamin Peterson, Lee Boyce, et al., "Hazardously Misleading Information Analysis for Loran LNAV", Proceedings of the 2nd International Symposium on Integration of LORAN-C/Eurofix and EGNOS/Galileo, Munich, Germany, June 2002

[12] Sherman Lo, Per Enge, “Demonstrating Integrity for Loran Cycle Selection Using Weighted Sum Squared Error (WSSE) Statistic”, Proceedings of the International Loran Association 35th Annual Meeting, Groton, CT, October 2006

[13] Lee Boyce, Sherman Lo, J.D. Powell, Per Enge, “Noise Assessment and Mitigation for Loran for Aviation”, Proceedings of the Institute of Navigation Annual Meeting, Cambridge, MA, June 2005

[14] Ruslan Shalaev, Greg Johnson, et al., “The Big Picture on ASFs: the Validity of Predicted ASFs over Long Distances”, Proceedings of the International Loran Association 35th Annual Meeting, Groton, CT, October 2006.

[15] International Radio Consultative Committee, Characteristics and Applications of Atmospheric Radio Noise, CCIR Recommendation 322-3, Geneva 1988.

[16] Lee Boyce, Sherman Lo, J.D. Powell, Per Enge, “Mitigating Atmospheric Noise for Loran”, Proceedings of the Institute of Navigation GNSS Conference, Fort Worth, TX, September 2006

[17] Peter Swaszek, Greg Johnson, Richard Hartnett, “Methods for Developing ASF Grids for Harbor Entrance and Approach”