A Coverage Analysis Methodology for APNT Pseudolite Ground Network

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BIOGRAPHY

Dr. Euiho Kim has worked for SELEX Systems Integration Inc as a satellite navigation engineer since 2008. He was the technical lead for SELEX Inc's Ground-Based Augmentation System (GBAS) and Alternative Position, Navigation, and Timing (APNT) programs. Before joining SELEX Inc, Dr. Kim completed his Ph.D. and Masters degree in the department of Aeronautics and Astronautics at Stanford University. His current research areas are secondary surveillance radar, satellite navigation integrity monitoring, and alternative methods of positioning and timing for aviation.

ABSTRACT

The Federal Aviation Administration (FAA) is looking into a robust Alternative Positioning, Navigation, and Timing (APNT) solution that can provide seamless operation from en route to non-precision approach during expected and unexpected outages of the Global Navigation Satellites System (GNSS). A promising alternative of FAA's APNT architecture is a pseudolite-based ground network that utilizes the existing infrastructure of widespread Distance Measuring Equipment (DME) and Automatic Dependent Surveillance –Broadcast (ADS-B) Ground Based Transceivers (GBT) over the Contiguous United States (CONUS). However, the technical and economic feasibility of the proposed APNT architecture against the intended operation has not been assessed. To evaluate the feasibility of the pseudolite-based APNT architecture, one method is to conduct a coverage analysis that shows the accuracy and integrity performance trade-off between ranging accuracy and user-to-ranging source geometry. From this analysis, a system developer would be able to see the level of ranging signal accuracy, the required number of ground stations, and the network lay-out. This paper discusses the formulation necessary to evaluate the coverage analysis against the APNT accuracy and integrity requirements and the typical coverage limitations resulting from the requirements. Additionally, given an existing DME/GBT infrastructure in select CONUS regions, the coverage differences with respect to varying levels of ranging accuracy are investigated to determine the level of ranging accuracy that yields the desired coverage. Further, a systematic strategy is presented to determine the placement of additional ground stations in optimal locations of an existing DME/GBT infrastructure to fill in APNT coverage gaps. The result from this systematic ground station placement strategy will provide the required number of additional stations and network geometry in the selected areas.

INTRODUCTION

The capacity and efficiency demands placed on the National Airspace (NAS) of the U.S. are expected to increase by a factor of 2 or 3 by the year 2025. To meet these demands, the U.S. is pursuing Next Generation Air Transportation System (NextGen) as its air traffic modernization program [1]. In the NextGen program, future aviation operation depends heavily on the use of GNSS, because GNSS-enabled operations allow closer spacing between aircraft and more flexible procedures than conventional ground navaids. In turn, the great benefits and heavy reliance on GNSS have also revealed GNSS system operation vulnerability to atmospheric effects, and intentional or unintentional interference and jamming. When a GNSS outage occurs, it is possible to encounter widespread disruption of position, navigation, and timing service (PNT). Therefore, FAA has recently formed an APNT study group and has been investigating alternative and robust means of position, navigation, and timing service (APNT) as a back-up to GNSS [2, 3].

One of the envisioned APNT operational objectives from the FAA APNT study group is to support Area Navigation (RNAV) and Required Navigation Performance (RNP), both enabled through GNSS. By 2025, FAA plans for performance based operations, maybe summarized as "RNAV everywhere and RNP where beneficial" [1]. For en route procedures, RNAV or RNP 2.0 is required. RNP 0.3 is required for non-precision approach and RNP 1.0 for missed approach. Along with the operational objective, the backward compatibility to DME/DME users and minimal impact on user avionic equipment are also important requirements. So far, there have been three proposed APNT architectures; DME/DME optimized network, DME/GBT pseudolite network, and passive Wide-Area Multilateration (WAM). The DME/DME optimized network adds additional DME ground stations to the existing DME network and takes credit for actual performance of today's DME equipment and potential signal enhancements in order to improve the position accuracy and the service coverage. The WAM architecture utilizes the existing 1100 DME ground facilities along with the planned 800 ADS-B GBT facilities by installing Mode A/C/S and ADS-B receivers. The distributed receivers measure the time of arrival of aircraft ADS-B broadcasts (1090ES and UAT) and forward them to the WAM master station. The WAM master station computes the aircraft position and integrity bounds and broadcasts them back to each respective aircraft via Traffic Information Service-Broadcast (TIS-B). The DME/GBT pseudolite architecture is the opposite of the WAM. Here, DME/GBT stations broadcast time-stamped GPS-like pseudo random noise signals, which the aircraft receives in order to compute its own position and integrity level.

Although the three possible APNT architectures have been identified, their feasibility in the aspects of the required range accuracy, the number of the additional ground units, and the ground network layout has not been rigorously discussed. This paper presents a coverage analysis methodology for the pseudolite architecture. This methodology shows the interrelationships of the above three parameters, thus it leads to an answer of the feasibility analysis for the particular architecture based on accuracy and integrity requirements. As far as coverage analysis against accuracy requirement is concerned, the methodology can be applied to the all three proposed architectures because it uses Horizontal Dilution of Precision (HDOP) for the accuracy coverage analysis. However, the coverage analysis methodology against integrity requirements can only be applied to the APNT pseudolite architecture because a typical GPS Receiver Autonomous Integrity Monitoring (RAIM) technique is assumed to be used.

OUTLINE

This paper first overviews APNT accuracy and integrity requirements with the formulation of key parameters. For each requirement, some coverage examples with simple station network geometries are presented to see which requirements are the most demanding. Using the formulation representing the accuracy and integrity requirements, the RNP 0.3 and 1.0 coverage will be evaluated for the existing DME/GBT ground stations in southern Florida. Then, the APNT station placement problem is defined, and a novel HDOP/Horizontal Protection Level (HPL) based station placement algorithms are described. The algorithms will be applied to the same southern Florida region, and the recommended ground station network with respect to different levels of ranging source accuracy will be presented. Conclusions will be followed.

APNT NAVIGATION REQUIREMENTS

The target navigation operation for APNT is RNP 1.0/2.0 for en route air space and RNP 0.3 for non-precision approach. Therefore, APNT accuracy and integrity requirements are determined by the target RNP values. RNP-based navigation system performance is characterized by accuracy (95 %) and containment integrity (10^{-7} per flight hour) [3]. The accuracy and containment with integrity requirements for RNP 1.0 are 1.0 nm and 2.0 nm, respectively. And, the accuracy and containment with integrity requirements for RNP 0.3 are 0.3 nm and 0.6 nm, respectively.

Coverage Analysis by Accuracy

The navigation accuracy is characterized by the total system error (TSE) that is the sum of navigation system error (NSE) and flight technical error (FTE). NSE and FTE are taken at 95% (2σ) of their zero-mean Gaussian distribution. The NSE (position accuracy using range measurements) is parameterized by Dilution of Precision (DOP) as shown below

$$\sigma_{pos} = DOP \cdot \sigma_{range} \tag{1}$$

where σ_{pos} and σ_{range} are the Gaussian standard deviation of position and range, respectively. In this paper, we will treat DOP as HDOP (Horizontal DOP) assuming that only horizontal position is computed by the aircraft.

Then, TSE can be expanded as follows

$$\begin{aligned} TSE &= \sqrt{FTE^2 + NSE^2} \\ &= 2\sqrt{(FTE/2)^2 + \sigma_{pos}^2} \\ &= 2\sqrt{(FTE/2)^2 + HDOP^2 \cdot \sigma_{range}^2}. \end{aligned} \tag{2}$$

From equation (1), the minimum or required HDOP is

$$HDOP_{\min} = \sqrt{\frac{TSE^2 - FTE^2}{4\sigma_{range}^2}}. \tag{3}$$

From reference [2], FTE (95%) is assumed to be 0.5 nm for RNP 1.0 and 0.125 nm for RNP 0.3 in this paper. With these values, $HDOP_{min}$ with respect to σ_{range} for RNP 1.0 and 0.3 is shown in Figure 1.

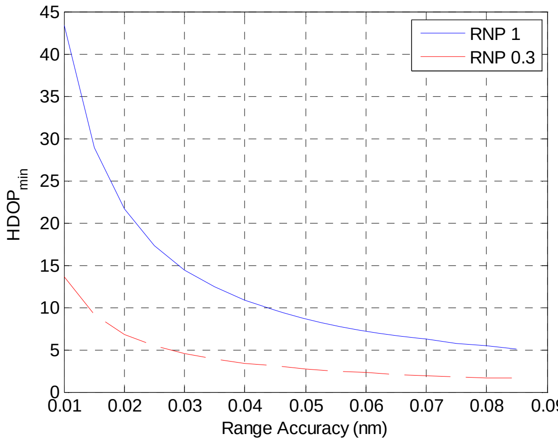
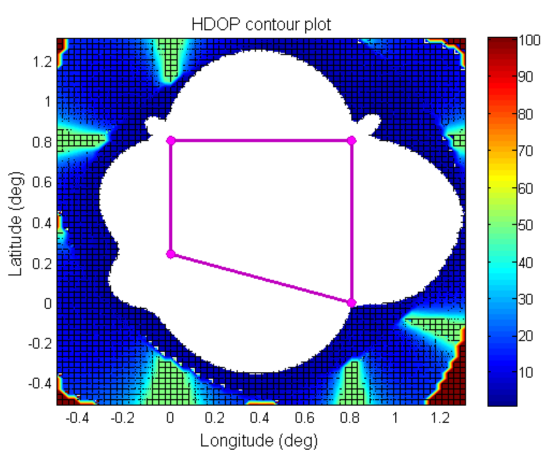
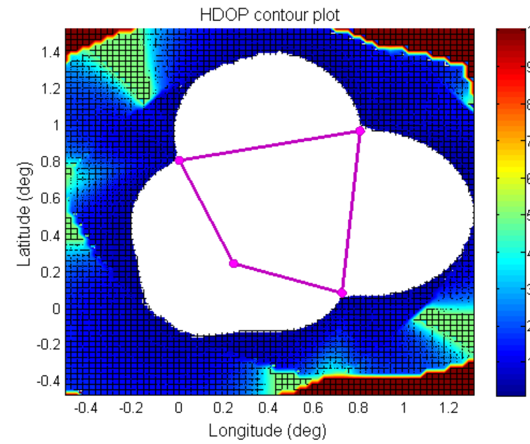


Figure 1: HDOP$_{min}$ vs. σ_{range} for RNP 1.0 and 0.3

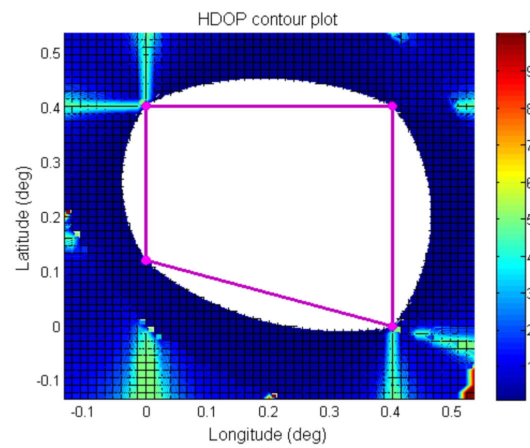
When σ_{range} is 0.085 nm, which is the smallest level of random noise values of the current DME standards [2], the required HDOP$_{min}$ for RNP 1.0 and 0.3 is 5.1 and 1.67, respectively. Taking σ_{range} of 0.085 nm, four coverage analysis examples are shown in Figure 2 for RNP 1.0 and 0.3 with two simple ground station geometries. An aircraft is assumed be at 5000 ft above ground level (AGL) for RNP 1.0 and 500 ft AGL for RNP 0.3. The terrain is assumed to be flat for the entire region and the antenna height for a station is 30 ft. In the plots, the white region is where accuracy coverage is available since HDOP is less than HDOP$_{min}$. The dark brown region has HDOP of 100 and represents the 'No Service' area where an aircraft does not have a line-of-sight (LOS) to at least 3 stations. The maximum number of HDOP is bounded by 50 to differentiate large HDOP and 'No Service' areas. The purple line connects the ground stations and characterizes them as a polygon. Note that the RNP 1.0 region having sufficient HDOP can be far outside from the polygon, whereas the RNP 0.3 region with sufficient HDOP is very close to the area of the polygon.



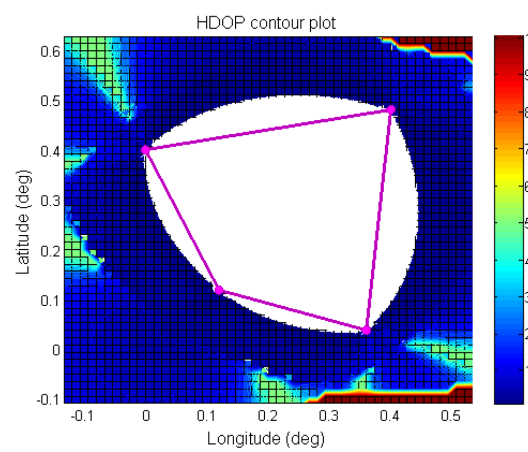
(a) RNP 1.0



(b) RNP 1.0



(c) RNP 0.3



(d) RNP 0.3

Figure 2: (a) and (b) Show HDOP Coverage Examples for RNP 1.0. (c) and (d) Show HDOP Coverage Examples for RNP 0.3. Two Station Geometries with σ_{range} = 0.085 nm Are Used.

Coverage Analysis by Integrity

Receiver Autonomous Integrity Monitoring (RAIM) is a well-known integrity monitoring method for GPS. Due to the same positioning principle as GPS, an aircraft using APNT signal can use the exact same RAIM approach for integrity monitoring. In this section, a fundamental theory of RAIM is briefly introduced. Then, some examples of APNT coverage analysis using RAIM will be considered. For further information on RAIM, see references [3] and [4].

RAIM detects an anomaly in a computed position from the goodness of the least squares fit using redundant measurements. There are four key parameters in RAIM: test statistic, threshold, horizontal protection level (HPL), and horizontal alert limit (HAL). The test statistic in this analysis is the residual sum of squares of error. Threshold is the value of the Chi-square distribution at a specified false alert probability. HPL is the horizontal position error bound with a specified confidence level. HAL is the horizontal position error limit not to be exceeded without issuing an alert. A fault is issued when the test statistic exceeds the threshold. If the horizontal position error also exceeds HPL, the fault detection is successful, but if the actual position error is less than HPL, a false alarm occurs. On the other hand, if the test statistic is less than the threshold and the actual position error is larger than HPL, a missed detection occurs. The reason for the missed detection is likely due to random noise and ranging source-to-user geometry that is parameterized by *Hslope* in RAIM. *Hslope* relates test statistics to horizontal position error. Each ranging source has its own *Hslope*, and the maximum *Hslope* corresponds to the most-difficult-to-detect ranging source. To be conservative, it is assumed that an anomalous condition always happens to the most-difficult-to-detect ranging source. Then, HPL is formulated as the following equation [5]

$$HPL = \max[Hslope] \cdot Thr(N, P_{fa}) \quad (4)$$

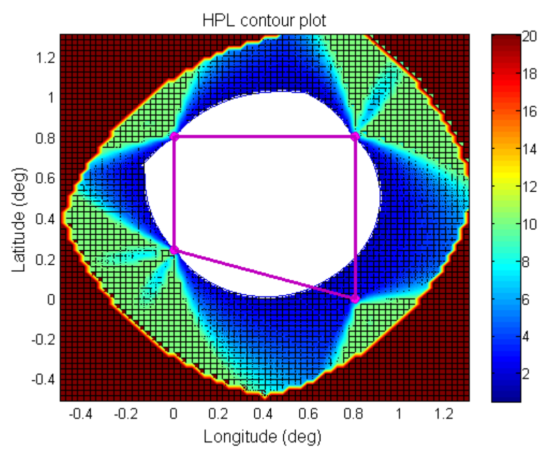
where N is the number of ranging sources. P_{fa} is the probability of false alarm. *Thr* is the threshold and is the product of ranging source accuracy and the value of chi-square distribution corresponding to P_{fa}. As seen from equation (4), HPL is a strong function of ranging source geometry and ranging source accuracy. Thus, when the geometry degrades, RAIM performs poorly and HPL increases. When HPL is larger than HAL, RAIM is declared to be unavailable and no longer guarantees that the actual position error is bounded by HPL within the specified confidence. In this case, an aircraft must fall back on a back-up navigation system.

Therefore, the APNT coverage for integrity will be defined where RAIM is available. The RAIM availability analysis for APNT was evaluated by using the parameter values summarized in Table 1.

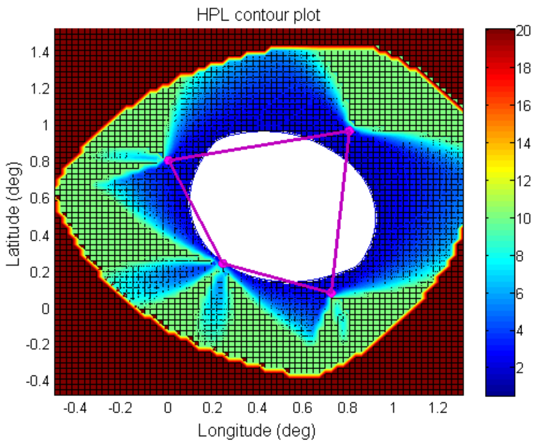
Table 1: RAIM Coverage Evaluation Parameters

Parameter	Probability
P_{fa}	$0.333*10^{-6}$ per test
$HAL_{RNP1.0}$	2 nm
$HAL_{RNP0.3}$	0.6 nm
σ_{range}	0.085 nm

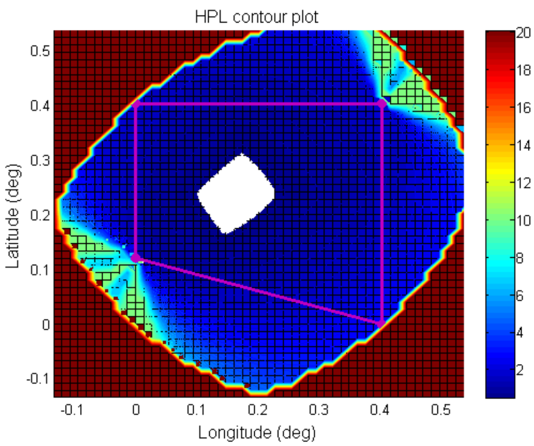
Taking the same simple ground station network geometries and the same aircraft heights used in coverage analysis by accuracy, Figure 3 shows four coverage evaluation examples for RNP 1.0 and 0.3. The white region represents the locations where HPL is smaller than HAL, i.e RAIM is available. The dark brown area has HPL of 20 and represents 'No Service' area where an aircraft does not have a LOS to at least 4 stations. The maximum number of HPL in Figure 3 is bounded by 10 to differentiate large HPL and 'No Service' areas. Figure 3 indicates that the RAIM coverage is significantly smaller than the accuracy coverage. Therefore, it can be said that APNT coverage is likely determined by RAIM coverage rather than accuracy coverage. Another thing to note is that RAIM was available in the very small areas for RNP 0.3. This suggests that a sufficient RNP 0.3 coverage will be very difficult with the specified parameters in Table 1 unless additional stations are added.



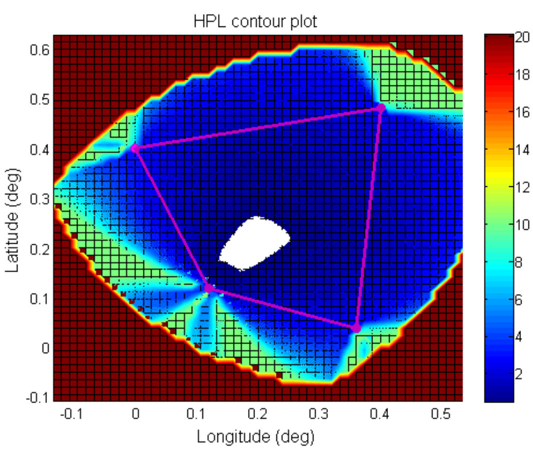
(a) RNP 1.0



(b) RNP 1.0



(c) RNP 0.3



(d) RNP 0.3

Figure 3: (a) and (b) show HPL Coverage Examples for RNP 1.0. (c) and (d) Show HPL Coverage Examples for RNP 0.3. Two Station Geometries with σ_{range} = 0.085 nm Are Used.

RNP 0.3 and 1.0 Coverage with Existing DME/GBT Stations in Southern Florida

By using the formulation in the previous sections, the RNP 0.3 and 1.0 capability in southern Florida was examined with the existing DME/GBT stations. Figure 4 shows the existing 38 DME/GBT stations and 8 international airports in Florida. It should be noted that DME/GBT stations shown in Figure 4 may not represent all of the existing stations.

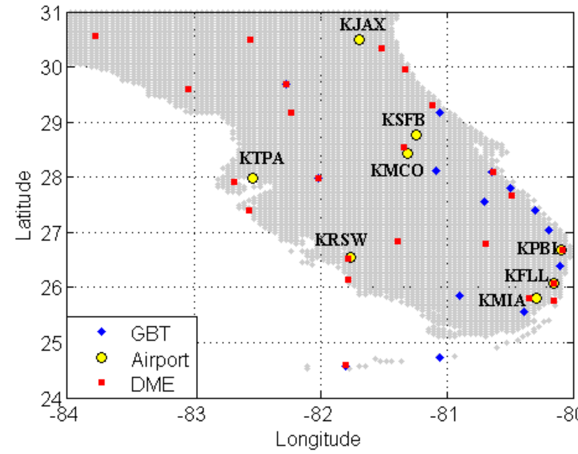
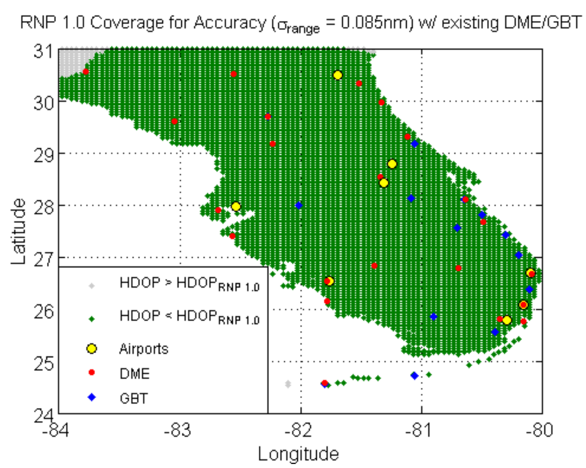


Figure 4: DME/GBT Stations and 8 International Airports in Southern Florida

Figure 5 shows RNP 1.0 accuracy and integrity coverage (green color) in the select region with range accuracy of 0.085 nm. The RNP 1.0 airspace is defined to be at 5000 ft AGL in the region. As shown in Figure 5, the currently existing DME/GBT stations can cover most of RNP 1.0 airspace and would need a very small number of additional stations.



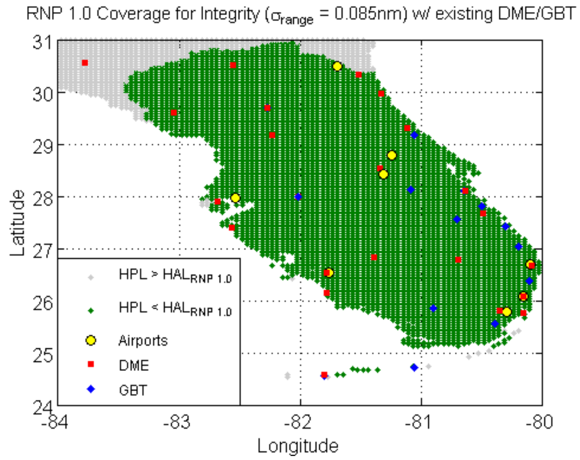


Figure 5: RNP 1.0 Accuracy and Integrity Coverage in Southern Florida with existing DME/GBT Stations (σ_{range} = 0.085 nm)

Figure 6 shows RNP 0.3 accuracy and integrity coverage in the same region with range accuracy of 0.085 nm. In this case, we are only interested in RNP 0.3 coverage near the 8 international airports, which is within about 15 nm from the center of the airports. From Figure 6, it can be observed that the existing DME/GBT stations are able to provide very limited accuracy and integrity coverage for RNP 0.3 with the given range accuracy.

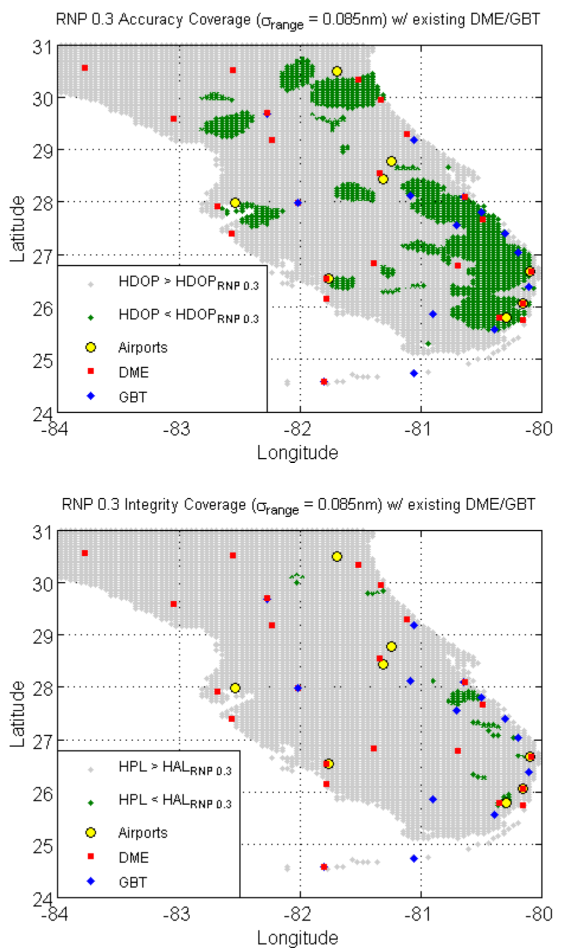


Figure 6: RNP 0.3 Accuracy and Integrity Coverage in Southern Florida with existing DME/GBT Stations (σ_{range} = 0.085 nm)

From equation (4), the higher ranging source accuracy reduces HPL, thus helping to expand the coverage. So, 0.02 nm range accuracy was tested instead of 0.085 nm. 0.02 nm is assumed to be the total range accuracy of the current state-of-art DME ground station and airborne interrogator. Figure 7 shows the accuracy and integrity coverage with 0.02 nm range accuracy.

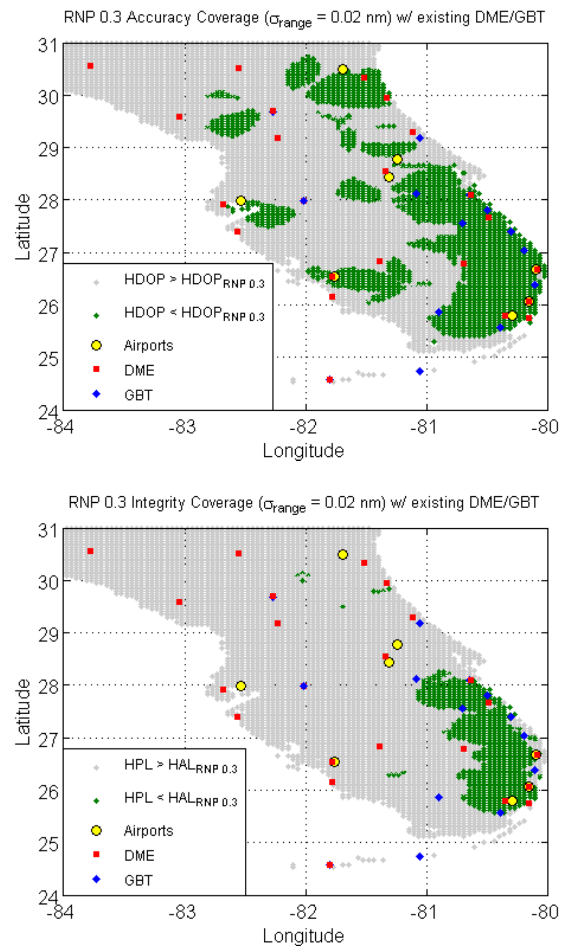


Figure 7: RNP 0.3 Accuracy and Integrity Coverage in Southern Florida with existing DME/GBT Stations (σ_{range} = 0.02 nm)

Figure 6 and Figure 7 show that the increased range accuracy did not significantly improve the RNP 0.3 coverage. The reason is that an aircraft could not see more than 4 stations in the most of RNP 0.3 airspace except the South East region. This result suggests that the existing DME/GBT station network in southern Florida would hardly provide RNP 0.3 capability to all of 8 international airports unless additional stations are placed near the RNP 0.3 airspace. The next section discusses the station placement problem for the APNT pseudolite architecture and introduces the proposed station placement algorithm that will be used in determining the locations of additional stations to enhance the deficient coverage.

STATION PLACEMENT PROBLEM

Additional stations are required when the station geometry does not support the desired APNT navigation operation and results in coverage holes. If only local area coverage gaps exist, a ground station placement would be straightforward but this will not always be the case. When the coverage gaps extend to large area, a station placement becomes quite a complex problem. The additional station placement problem or facility location problem has been a research subject for several decades in the areas of mathematics, computer science, and management science [6]. In computational complex theory, the problem is classified as NP-complete. Loosely speaking, 'NP-complete' means that there are no known general efficient algorithms that output an exact solution(s) other than an (almost) exhaustive search. When faced with the problem of NP-complete, the focus normally shifts from seeking an exact solution to an approximation by using heuristics that can be applied to a particular problem [7]. Along with the same philosophy, the solution to the APNT station placement problem will be sought based on heuristics that are discussed in the next subsection.

APNT Station Placement Problem Statement

The station placement problem in the pseudolite-based APNT architecture can be stated as follows.

Given the defined airspace, terrain geometry, range accuracy and the existing DME/GBT infrastructures, what is the station network, with the minimum costs, that allows the National Air Space (NAS) to meet its specified APNT accuracy and integrity requirements?

In order to avoid an exhaustive search required to find an optimal solution in NP-complete problems, Binary Integer Linear Programming (BILP) will be used as a baseline search engine to efficiently attack the problem.

Baseline BILP Formulation and Useful Heuristics

BILP takes the same standard mathematical form of Linear Programming (LP) where the mathematical expressions of the objective and constraint functions are linear. The difference between BILP and LP is that LP takes real values as variables. On the other hand, BILP only takes 0 and 1 as the value of variables. BILP has widely been used in sensor location problems [8] because the existence of a sensor can be conveniently expressed by 1 (a sensor exists) and 0 (a sensor does not exist). With that, a BILP problem formulation can be expressed as follows

$$\begin{aligned} &\min Z = \sum_{i=1}^{n} x_i \\ &\text{subject to: } Ax \geq b \ . \\ &\qquad x \in \{0,1\} \end{aligned} \tag{5}$$

x is the index vector of a candidate station location whose value is 0 or 1. A is a visibility matrix such that i^{th} row corresponds to an aircraft location and j^{th} column to a candidate station location in a given area. The element of matrix A also takes 0 or 1. For example, if the aircraft at the i^{th} row sees the station at the j^{th} column, $A_{i,j}$ is equal to 1. Otherwise, $A_{i,j}$ is 0. b is the vector having the required minimum number of visible stations at an aircraft location.

In a sensor or facility location problem, the above expression seeks the minimum number of sensors or facilities that meet the specified constraints. One difficulty in applying the above equation to solve the APNT station placement problem is that HDOP/HPL constraints from the accuracy and integrity requirements are highly nonlinear so that they cannot be directly fitted into equation (5). Therefore, alternate linear constraints must be used, which would lead to a ground station network that satisfies HDOP/HPL requirements with a small number of stations if possible. For example, Figure 8 shows an ideal geometry consisting of the airspace, where HDOP/HPL is evaluated, projected on the ground (region 1) and the eligible station placement area outside region 1 (region 2), respectively. The 'x' in red color represents the existing stations that are preferred to be chosen because utilizing the existing stations may have a lower cost than establishing a new station. For the geometry in Figure 8, three basic heuristics and their range are summarized in Table 2, which are useful for efficient station placements in using BILP.

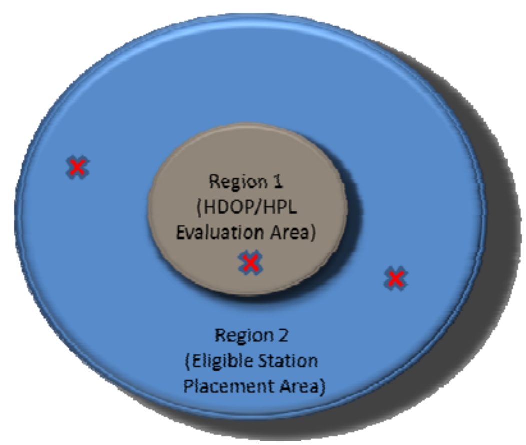


Figure 8: HDOP/HPL Evaluation and Station Placement Area

Table 2: Binary Integer Linear Program (BILP) Constraints and Range

Constraints	Range
Minimum number of stations in view	≥ 3 for HDOP ≥ 4 for HPL
Weights on station location	1 for existing stations 2 for region 2 4 for region 1
Minimum separation between stations	~ 2 x Radio line-of-sight at the flight level for HDOP ~ Radio line-of-sight at the flight level for HPL

Using the heuristics in Table 2 as constraints, an alternate BILP formulation can be expressed as follows.

$$\begin{aligned} \min\ Z &= \sum_{i=1}^{n} w_i \bullet x_i \\ \text{subject to: } & Ax \geq b \\ & Cx \leq d \\ & x \in \{0,1\}. \end{aligned} \tag{6}$$

w is a weighting factor on the value of x depending on the location of the station. C is related to the minimum distance between stations, and it is an $n \times n$ square matrix whose row and column correspond to the candidate station locations. If the distance between i^{th} and j^{th} stations is within the limit, $C_{i,j}$ is equal to 1. Otherwise, $C_{i,j}$ is equal to 0. d is a vector having a value of 1.

Update of BILP Formulation

A solution of the baseline BILP formulation with the heuristics, equation (6), does not guarantee that the resultant station geometry meets the HDOP requirement because it is only trying to minimize Z with the constraints of the number of stations in view and distances between stations. As an example, Figure 9 shows a solution of the baseline BILP formulation, in which the required HDOP is less than 1.67 in the HDOP evaluation area. The aircraft height is set to 500 ft above ground level (AGL) and no existing station is assumed.

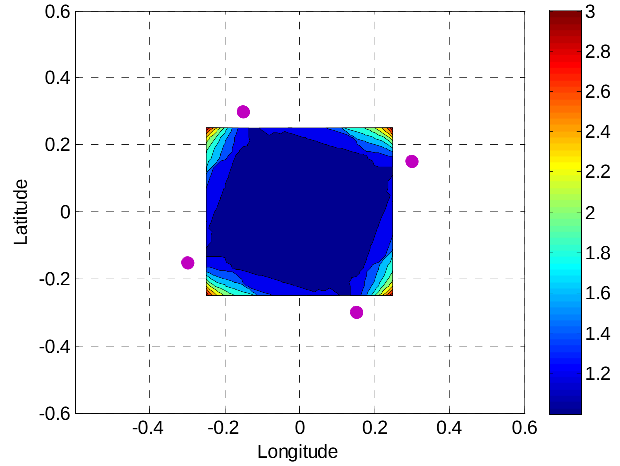


Figure 9: The Resulted Stations (purple circles) of Initial BILP Formulation. The Color Map Represents HDOP Level. The aircraft is at 500 ft AGL and σ_{range} is 0.085 nm.

As seen from Figure 9, the initial solution does not satisfy the HDOP requirement and it seems infeasible to meet the requirement with 4 stations no matter how they are distributed. One approach to find the station geometry that would provide lower HDOP is to add additional stations to the baseline BILP stations. This station augmentation entails a modification of the baseline BILP as follows

$$\begin{aligned} \min\ Z &= \sum_{i=1}^{N} w_i \bullet x_i \\ \text{subject to: } & Ax \geq b_{\text{mod}} \\ & Cx \leq d \\ & Fx = g \\ & x \in \{0,1\} \end{aligned} \tag{7}$$

where the element of b_{mod} is

$$b_{i,\text{mod}} = \begin{Bmatrix} b_i + 1 \ if\ \ HDOP_i > HDOP_{req} \\ b_i \quad\ if\ \ HDOP_i \leq HDOP_{req} \end{Bmatrix}.$$

The effect of b_{mod} is that the locations having insufficient of HDOP/HPL value need to see one more station than the previous formulation. F is $k \times n$ matrix and is constructed to keep the stations from the initial solution, where k is the number of chosen stations in the previous formulation. g is a vector having 1 and its length is k.

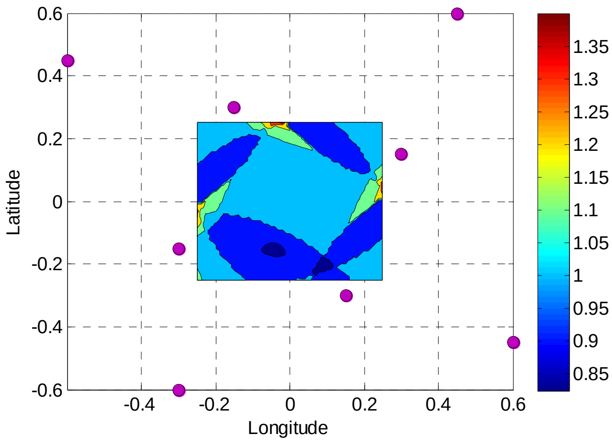


Figure 10: The Resultant Stations (purple circles) of Updated BILP Formulation. The 8 Stations Provide the Required HDOP Level of 1.67. The Color Map Represents HDOP Level. The aircraft is at 500 ft AGL and σ_{range} is 0.085 nm.

The updated BILP results in the station geometry shown in Figure 10, of which HDOP has been greatly improved due to the additional stations. However, the too much lower HDOP values indicate that the redundant stations are placed. It should be noted that a BILP solver usually outputs one solution at a time and there could be hundreds of other valid solutions that may satisfy HDOP/HPL requirements with a fewer number of stations. That is due to the limitation that the BILP formulation is based on the heuristics rather than directly using HDOP/HPL requirements. Therefore, it is necessary to search for a better solution by observing a subset of possible solutions. The search for valid solutions is performed by the following settings. First, equation (7) is added by another constraint that does not allow previously obtained solutions in the new solution sets. In this way, every solution resulting from the BILP is unique. Second, the range of minimum separation between stations and the area of region 2 (eligible station placement area) can be varied. Third, in order to avoid unnecessary search, the BILP does not allow the solutions having a larger number of stations than the current best solution. Figure 11 shows the iterative BILP search procedure. Figure 12 and Figure 13 show the best solutions obtained from the iterative search procedure for HDOP and HPL, respectively.

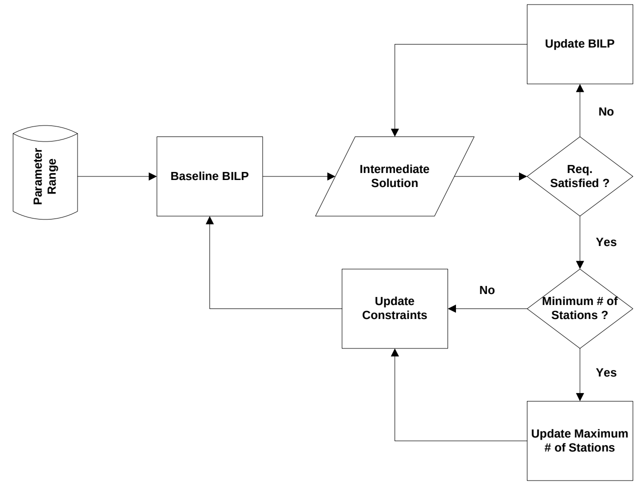


Figure 11: Flowchart of Iterative BILP Procedure

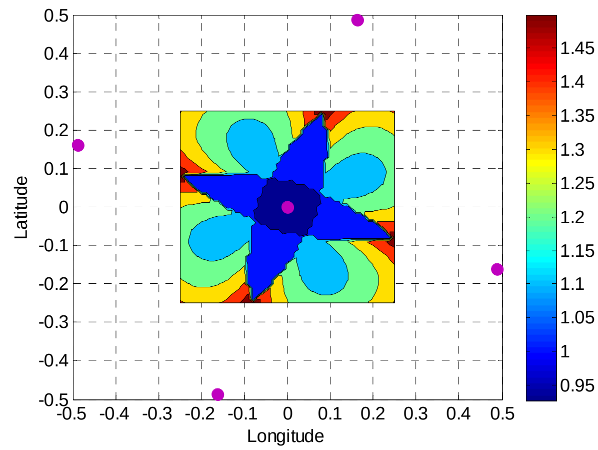


Figure 12: The Best Resultant Stations (purple circles) of the Iterative Procedure. The 5 Stations Provide the Required HDOP Level of 1.67. The Color Map Represents HDOP Level. The aircraft is at 500 ft AGL and σ_{range} is 0.085 nm.

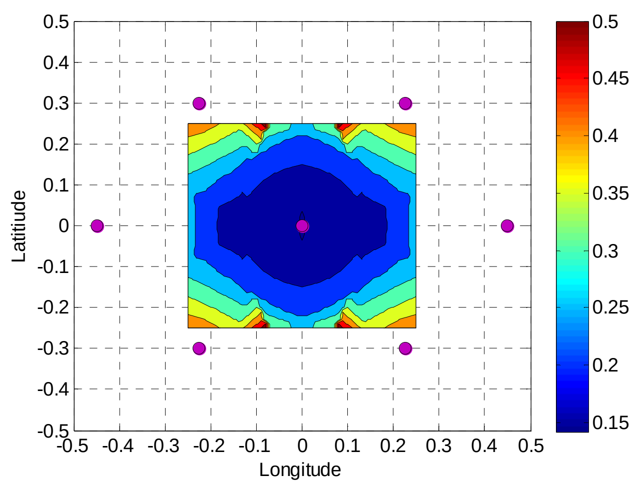


Figure 13: The Best Resulted Stations (purple circles) of the Iterative Procedure. The 7 Stations Provides the Required HPL Level of 0.6. The Color Map Represents HPL Level. The aircraft is at 500 ft AGL and σ_{range} is 0.085 nm.

SOUTHERN FLORIDA CASE STUDY USING ITERATIVE BILP

The proposed iterative BILP procedure is applied to the same southern Florida region shown in Figure 4 to see the possible ground station network that meets the APNT requirements.

Simulation Set-up

The RNP 0.3 airspace was set to 500 ft AGL within 15 nm of the center of each airport. The RNP 1.0 airspace is defined to be the entire region above the ground shown in Figure 4. Two levels of σ_{range}, 0.085 nm and 0.02 nm, are considered again in this analysis to observe the sensitivity of ranging source accuracy on the station network.

It may seem to be arbitrary to search first for RNP 0.3 or RNP 1.0 station network. In this simulation, RNP 0.3 station network is first sought, then RNP 1.0. That is because the RNP 0.3 requirement is harder to meet than RNP 1.0, and the resulting station network from RNP 0.3 could cover most of RNP 1.0 airspace as will be shown later. Also, note that the iterative BILP uses the weighting in Table 2, so it prefers the existing DME/GBT facilities to new locations.

Resultant Station Network for RNP 0.3 by Using the Iterative BILP

As the first step, the station networks for RNP 0.3 were sought. Figure 14 and Figure 15 show the resultant station network and RNP 0.3 accuracy and integrity coverage projected on ground (in green color). Using only the RNP 0.3 accuracy requirement, the total number of the required stations is 27. On the other hand, the RNP 0.3 integrity requirement yielded 59 stations.

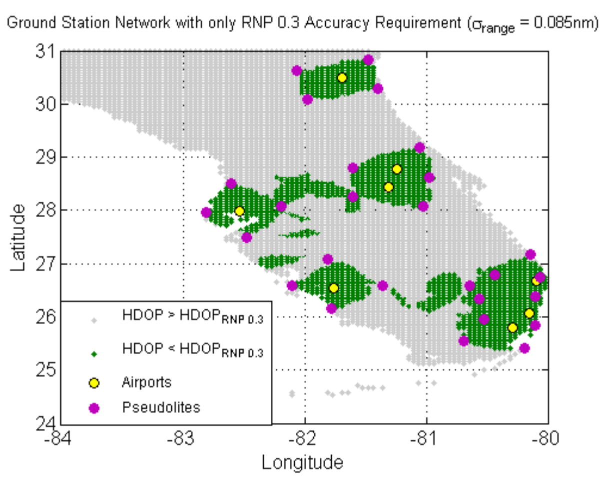


Figure 14: Station Network with RNP 0.3 Accuracy Requirement for the Designated Airports (σ_{range} = 0.085 nm)

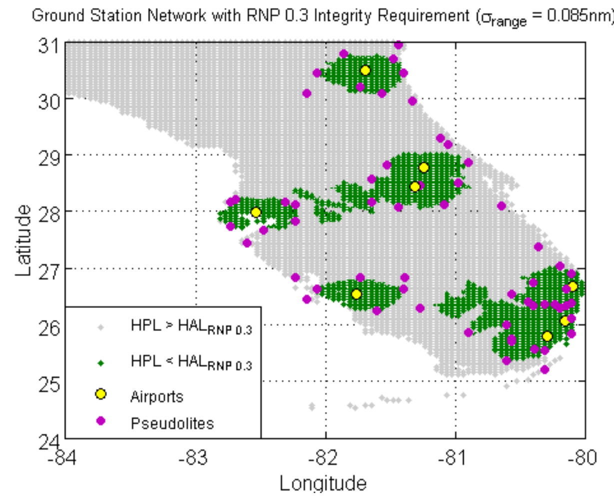


Figure 15: Station Network with RNP 0.3 Integrity Requirement for the Designated Airports (σ_{range} = 0.085 nm)

Figure 16 and Figure 17 show the resulting station network and coverage projected on the ground for RNP 0.3 accuracy and integrity requirements, respectively, with the increased σ_{range} of 0.02 nm. With only RNP 0.3 accuracy requirement, the total number of the required stations is 19. And, the RNP 0.3 integrity requirement yielded 27 stations.

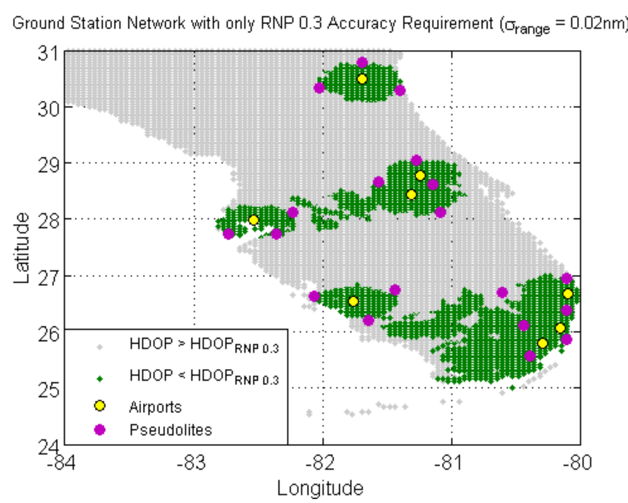


Figure 16: Station Network with RNP 0.3 Accuracy Requirement for the Designated Airports (σ_{range} = 0.02 nm)

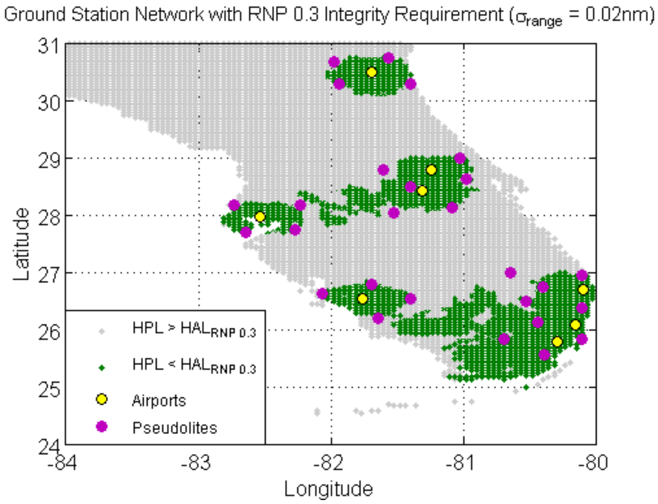


Figure 17: Station Network with RNP 0.3 Integrity Requirement for the Designated Airports (σ_{range} = 0.02 nm)

Resultant Station Network for RNP 1.0 by Using the Iterative BILP

After placing the stations for RNP 0.3, the iterative BILP now undertakes the RNP 1.0 problem. To do that, it is necessary to inspect RNP 1.0 coverage by using the determined station network from the RNP 0.3 integrity requirement since the integrity requirement takes more stations than the accuracy requirement. The station network resulting from the RNP 0.3 integrity requirement with either 0.085 nm or 0.02 nm range accuracy was able to cover the most of the RNP 1.0 airspace except the most southern part of Florida near 24~25 latitude and some northern part near 29~31 latitude. The uncovered northern part is not of interest in this simulation because the coverage of that region also depends on the station geometry above the defined map. Therefore, the iterative BILP ran for the unsatisfied RNP 1.0 airspace only for the southern region and resulted in additional 8 stations for 0.085 nm range accuracy and 4 stations for 0.02nm range accuracy. Therefore, the total numbers of the final station network for σ_{range} of 0.085 nm and σ_{range} of 0.02 nm are 67 and 31, respectively. Figure 18 and Figure 19 show the accuracy and integrity coverage for RNP 1.0 with σ_{range} of 0.085 nm and with the updated station network.

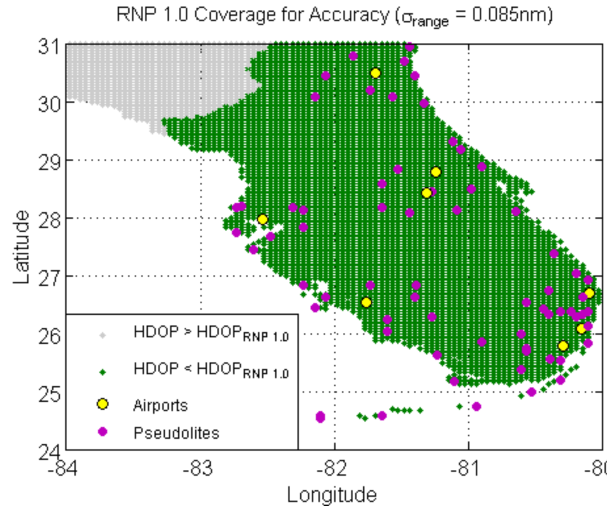


Figure 18: RNP 1.0 Accuracy Coverage with Updated Station Network (σ_{range} = 0.085 nm)

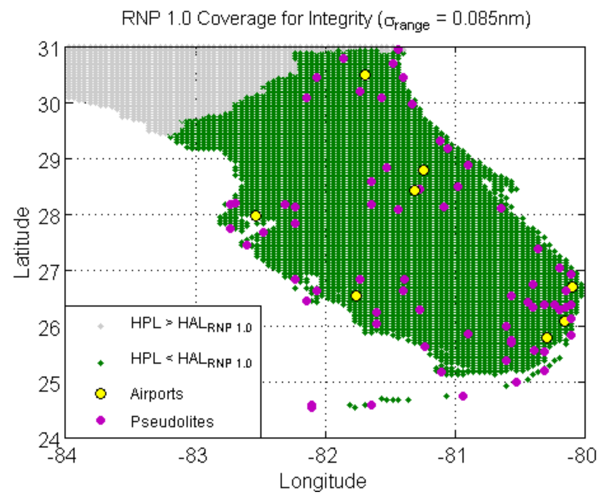


Figure 19: RNP 1.0 Integrity Coverage with Updated Station Network (σ_{range} = 0.085 nm)

Figure 20 and Figure 21 show the accuracy and integrity coverage for RNP 1.0 with σ_{range} of 0.02 nm and with the updated station network.

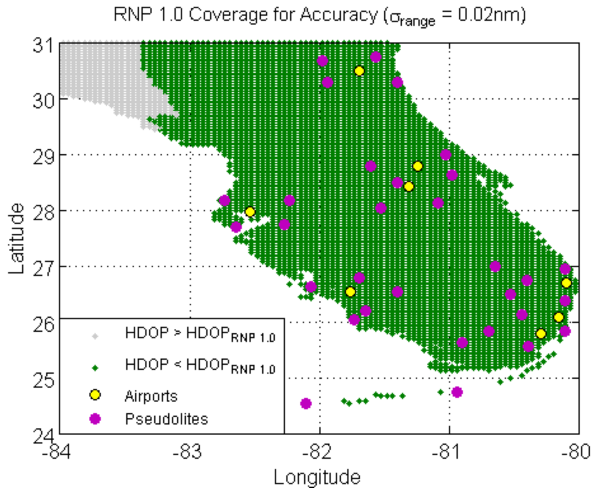


Figure 20: RNP 1.0 Accuracy Coverage with Updated Station Network (σ_{range} = 0.02 nm)

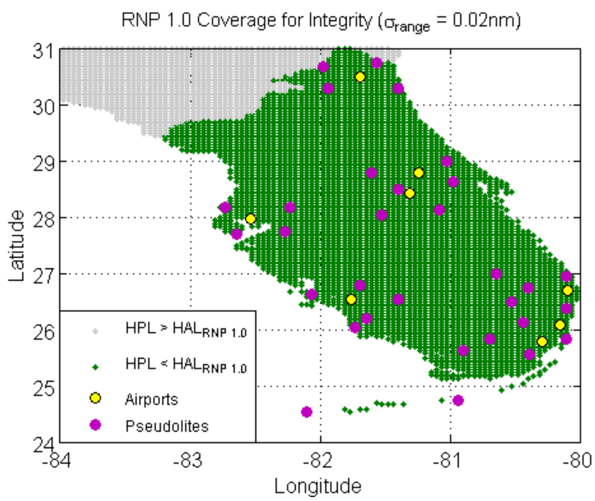


Figure 21: RNP 1.0 Integrity Coverage with Updated Station Network (σ_{range} = 0.02 nm)

The number of the existing DME/GBT stations used for the final station network is 10 for σ_{range} of 0.085 nm and 3 for σ_{range} of 0.02 nm, respectively, out of 38. This number is somewhat disappointing and will be further discussed in conclusion.

CONCLUSION

This paper reviewed the formulations of the key parameters of accuracy and integrity coverage analysis for APNT pseudolite ground network and showed that integrity was more difficult to meet than accuracy. The formulation was used to analyze the accuracy and integrity coverage of the defined RNP 0.3 and 1.0 airspace in southern Florida with the existing DME/GBT stations. The analysis found that a significant lack of RNP 0.3 coverage existed near the 8 international airports in southern Florida for both of 0.085 nm and 0.02 nm range accuracies. Then, a novel algorithm using Binary Integer Linear Programming (BILP) for HDOP/HPL based station placement was introduced. Using the proposed BILP algorithm, possible station networks were investigated in the same area for RNP 0.3 and 1.0 airspace. For the sensitivity analysis of the ranging source on the station placement, 0.085 nm and 0.02 nm range accuracies were used again.

Although the BILP algorithm does not theoretically guarantee the optimality of the solution, it yielded the minimum number of stations, 3 for accuracy and 4 for integrity, when the range accuracy and the airspace were reasonably given as shown in Figure 14, Figure 16, and Figure 17. This result positively suggests the practical usefulness of the iterative BILP as a search engine for HDOP/HPL based station placement.

From the simulation, it has been clearly shown that the BILP algorithm provides solutions having a smaller network with better range accuracy. The 0.02 nm range accuracy results in 36 fewer number of stations than the 0.085 nm range accuracy in the test. However, even if the range accuracy is further increased beyond 0.02 nm, the required number of stations wouldn't change much because the HPL based station network for an isolated airport has 4 stations that are the minimum number of stations to compute HPL. Also, the station network based on RNP 0.3 requirements fulfilled most of RNP 1.0 coverage. Therefore, the resulting station network based on RNP 0.3 requirement would likely determine the pseudolite-based APNT ground network in U.S. CONUS.

One of the desirable factors of the anticipated pseudolite-based APNT ground network is the ability to use the existing DME/GBT stations as best as we can. However, the use of the existing DME/GBT stations was very minimal even though they were set to be preferred to the new station locations in the proposed algorithm. The station network with 0.02 nm range accuracy only selected 3 existing facilities in the test. Although 0.085 nm range accuracy utilized 10 existing facilities, that was just because it had to use many stations. The main reason that only very limited number of existing DME/GBT stations were chosen is as follows. First, many of them are out of radio line-of-sight from the RNP 0.3 airspace. Among the 38 stations, 11 stations can't be seen at all from the defined RNP 0.3 airspace around the 8 airports. Besides, 71 percent of the RNP 0.3 airspace was able to see more than 3 ground stations, and only 20 percent was able to see more than 4 ground stations. Second, the DME/GBT stations that could be seen in RNP 0.3 airspace were often not in HDOP/HPL favorable locations such that the particular station didn't significantly help to lower HDOP/HPL values. Therefore, those DME/GBT stations were ignored to reduce the total number of required stations. In order to utilize more number of existing stations, the further increased range accuracy beyond 0.02 nm may help.

Lastly, the coverage analysis performed in this paper suggests that the feasibility study of the APNT pseudolite architecture consider the effective number, rather than the total number of 1900, of the existing DME/GBT stations that can actually be used for the required APNT performance in CONUS. The effective number of the usable existing stations should be obtained from a systematic station placement procedure that would result in as fewer number of stations as possible.

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REFERENCES

[1] Leo Eldredge et al, *Alternative Positioning, Navigation & Timing (PNT) Study*, ICAO NSP Working Group Meetings, May 2010, Montreal, Canada

[2] Sherman Lo et al, *Preliminary Assessment of Alternative Navigation Means for Civil Aviation,* Proceedings of the 2010 ION ITM, January 2010, San Diego, CA

[3] Mitch Narins et al, *Alternative Position, Navigation, and Timing – The Need for Robust Radio Navigation*, Royal Institute of Navigation – NAV 10, December 2010 London, England, UK

[4] R. G. Brown and G. Chin, GPS RAIM: *Calculation of Threshold and Protection Radius Using Chi-Square Method-A Geometric Approach,* Red Book Series of the Institue of Navigation on Global Positioning System 1998

[5] Young C. Lee and Karen L. Van Dyke, Analysis Performed in Support of the Ad-Hoc Working Group of RTCA SC-159 on RAIM/FDE Issues, ION NTM 2002, San Diego, CA

[6] R. Z. Farahani and M. Hekmatfar, *Facility Location concepts, models, algorithms and case studies*, Physica-Verlag, 2009

[7] S. Dasqupta, C. Papadimitriou, and U. Vazirani, *Algorithms*, 1st Ed, McGraw-Hill Science/Engineering/Math, 2006

[8] O. Tekdas and V. Isler, *Sensor Placement for Triangulation Based Localization*, Department of Computer Science, Rensselaer Polytechnic Institute, 2007