Preliminary Assessment of Alternative Navigation Means for Civil Aviation

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ABSTRACT

The Federal Aviation Administration (FAA) is looking to develop alternative navigation means to global navigation satellite systems (GNSS) and GPS. While the national airspace (NAS) includes many navigation systems such as distance measuring equipment (DME), VHF omni directional ranging (VOR), or non directional beacon (NDB), they are not capable to supporting the increased capabilities, capacity and efficient operations that GPS will provide. Thus it is important to examine, design and develop new alternatives capable of providing similar level of service and operational efficiencies as GPS. One idea is to develop alternatives based on existing or soon to be existing FAA systems and infrastructure. The paper details a preliminary study on using FAA infrastructure such as DME and ground based transceiver (GBT) as building blocks for a future system. The system is to be capable for providing navigation to support future needs of the NAS even in the event of GPS interference or outage.

INTRODUCTION

The increasing integration of GPS and GNSS into critical infrastructure has created tremendous benefits. In aviation, for example, the introduction of GPS avionics will lead to improved capacity and efficiency in the National Airspace (NAS). Its use allows for closer spacing and more flexible procedures in the form of Area Navigation (RNAV) and Required Navigation Performance (RNP). GPS also allows more accurate and frequent surveillance information as it is the predominant source of navigation information in Automatic Dependent Surveillance Broadcast (ADS-B).

Unfortunately, these benefits goes away when GPS and GNSS becomes unavailable. Vulnerabilities of GPS and satellite navigation are well known and documented, particularly by reports such as Volpe [1]. The concern is that once we rely on the operational benefits brought by the use of GPS, it may be difficult or impossible to revert to a without significant economic loss and societal costs. The vulnerability of critical infrastructure and GPS is addressed in Homeland Security Presidential Directive 7 (HSPD-7) and National Security Presidential Directive 39 (NSPD-39), respectively [2][3]. NSPD-39 addresses the need to examine and mitigate GPS vulnerability, particularly where it is relied upon in critical infrastructure. The Federal Aviation Administration (FAA) Navigation Services Directorate has been examining how to mitigate GPS vulnerability. It has recently formed an Alternative Position Navigation and Time (APNT) group to provide a thorough investigation of navigation in the event GPS is unavailable. The goal is to develop a means to maintain aviation operations indefinitely during a GPS interference or outage event. This entails minimizing the economic impact of and maintaining safety during an outage event. To accomplish this, an APNT system should provide en route capabilities over the conterminous United States (CONUS) as well as terminal and approach capabilities at economically important airports.

One area that has been a focus for APNT is examining navigation alternatives based on infrastructure in the NAS. The NAS infrastructure may be useful as building blocks for a future system capable for providing viable alternative navigation. The infrastructure includes distance measuring equipment (DME) and ground based transceiver (GBT) for ADS-B. While the group is examining other alternatives, this paper only covers the use of DME and GBT for APNT.

OUTLINE

This paper starts with some background on the APNT technical study. It discusses the performance desired from an alternative navigation system that supports continued operations in the loss of GPS. This is a critical first step to system design and constrains the infrastructure and designs that have utility.

Additionally, the NAS infrastructure and design possible systems using these components are discussed. Some background on DME and GBT is given. Several possible architectures for using the infrastructure are detailed.

The paper concludes with accuracy coverage studies. It examines the ability of the different architectures to meet RNP 1.0 for en route in CONUS and RNP 0.3 for terminal/approach at high traffic airports and areas.

BACKGROUND

ALTERNATIVE POSITION NAVIGATION & TIME (APNT)

As previous mentioned, the APNT group is assessing alternate navigation means for aviation to mitigate the effects of GPS outage or interference. The overall goal is to develop a comprehensive assessment that will lead to the development of an operational system. As such, it will examine not just technical and performance aspects of alternative navigation means but also institutional, operational and development planning issues. This paper is only focused on one part of the technical efforts.

TECHNICAL EVALUATION

Technical evaluation seeks to develop and examine systems that can achieve the mission of the APNT group. This includes aspects of system design, as well as performance, and integrity analyses. Specifically, the primary requirements of the system are to support en route (RNP 1.0) over CONUS and RNP 0.3 at required airports. The short term goal is to narrow down to a few promising candidates for next phase of study. Many systems such as enhanced Loran, iGPS and others have already been studied for this purpose and will be considered in the evaluation. The focus of this paper is on developing systems based on current or some to be existing FAA infrastructure such as DME and GBT. Specifically, this paper examines the ability of different designs using these systems to meet the primary requirements.

ALTERNATIVES & OPTIONS

Several design alternatives and options are available. Infrastructure includes using DME and/or GBT ground assets. With these assets, several architectures have been proposed and developed. This section will discuss the infrastructure, possible architectures, and the method for analysis.

INFRASTRUCTURE

DME is a two way or request-reply ranging system. Traditional DME, known as DME/N, utilize pulse pairs between 962 to 1213 MHz to conduct this transaction. Each DME is assigned a frequency for uplink and another for downlink. The difference between these two frequencies is 63 MHz. The frequency is typically selected to minimize interference with other DMEs. DME equipment is limited to about 3000 pulse pair per second resulting in a capacity of about 300 aircraft. Additional background on DME is given in [4]. Figure 1 shows the current location of DME stations in CONUS. These are the locations used in the analysis. Note that future plans will add a few additional stations to improve en route coverage.

DME/N performance has been specified in a couple of standards. ICAO annex 10 specifies DME/N accuracy as being 0.17 nautical miles (nm), 95% [5]. FAA Advisory Circular (AC90-100A) specifies a more complicated formulation where accuracy depends on signal in space (sis) and airborne receiver (air) [6]. This is seen in Equation 1 where σ_{sis} is given as 0.05 nm. The specified accuracy of the airborne receiver is dependent on distance from the transmitter and is given in Equation 2.

$$\sigma_{range} = \sqrt{\sigma_{air}^2 + \sigma_{sis}^2} \qquad (1)$$

$$\sigma_{air} = \max\left(0.085nm, .00125d\right) \qquad (2)$$

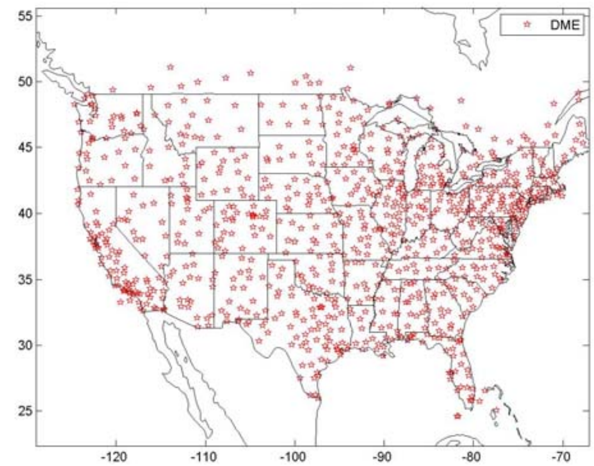

Figure 1. DME station locations in CONUS

Improved version of DME can have better performance. For example, precision DME (DME/P) provides greater accuracy in part by using a different pulse shape [7]. However, the improvement is only at close range (within a few nautical miles) and is not available to DME/N users. ICAO Annex 10 also specifies DME/P accuracies. Note that the study and coverage map does not show DME/P and approach DMEs. Another example is that DME manufacturers have indicated newer DMEs can support higher limits on number of pulses.

Modification to existing DME may be necessary to support some of the architectures. One change may be the need to provide some data capability. Another is increasing the limit on number of pulses. Such potential modifications have been examined and are believed feasible. The exact method and feasibility is still being worked on and is beyond the scope of this paper.

Additionally, we will also consider reasonable improvements for these systems such as better ranging or data capacity. The installation of a few additional stations and use of DME/P will also be considered.

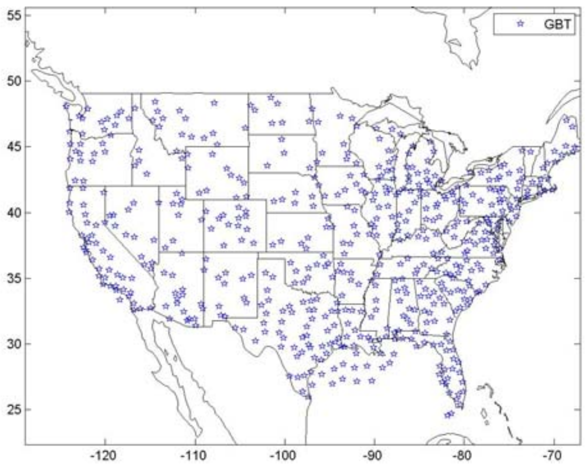

Figure 2. Proposed GBT station locations in CONUS

Ground based transceivers (GBT) are the basic ground element supporting automatic dependent broadcast-surveillance (ADS-B). GBTs receive aircraft broadcasted ADS-B reports and sends the information to air traffic. Additionally, GBTs can transmit traffic information services broadcast (TIS-B) and other flight information services broadcast (FIS-B) to nearby aircraft. There are two basic ADS-B communication protocols: 1090 Extended Squitter at 1090 MHz and Universal Access Transceiver (UAT) at 978 MHz [8][9][10]. Figure 2 shows the proposed locations for GBT in CONUS. There are about 800 planned sites. The locations of the actual installed sites may differ from the plan.

APNT has examined basic ways of modifying these GBT to support the ranging and positioning methods discussed next. Preliminary study indicates that there are feasible methods to achieve ranging. The difficulty of achieving the implementation depends on both the method and data channel. As GBT transmissions were not developed for ranging, range accuracy is not known. For the preliminary analysis, GBT ranging performance is assumed to be similar to that of DME. Additionally, it is assumed that they have the same coverage profile as a DME transmitter. While these two assumptions are likely not precisely true, they are adequate for initial analysis.

With these infrastructures, multiple configurations are possible. Four options are to use the current DME sites only, the GBT sites only, both DME and GBT sites, or all sites with a few reasonable additions to the infrastructure. The final option is conceivable as it is possible to field both DME and GBT at locations such as cellular towers. The addition of a few such sites could be useful for improving coverage in vital areas (such as a busy airport).

ARCHITECTURES

With the infrastructure, there are several architectures that can be developed for navigation. Three possible architectures are: 1) Broadcast, 2) Request-Reply and 3) Hybrid. Additionally, positioning in these architectures can be aircraft based or ground based. In aircraft based, the aircraft determines positions from measurements that it makes. In ground based, the FAA calculates the aircraft position from measurements made on the ground and transmits it to the aircraft. The position transmission is an additional step over aircraft based design and may need security such as encryption to prevent spoofing. However, the payoff for ground based designs is that it could minimize the changes required on board the aircraft to have APNT. This enhances adoption of the technology.

The first architecture is broadcast. In this architecture, the aircraft position can be derived with only one party sending a broadcast. In an aircraft based design, the ground infrastructure will broadcast in a time coordinated manner. Given DME and GBT will be used, the broadcast will likely be time multiplexed. The aircraft will then be able to calculate pseudo ranges to each station that it receives a broadcast. Hence, it operates like GPS or GPS pseudolites. In a ground based design, the aircraft broadcasts. The broadcast is then received by multiple, time synchronized ground stations. The reception by each ground station results in a pseudo range to the aircraft which is then used to determine position. With the position transmitted back to aircraft. This technique, known as multilateration, has been utilized and has been tested in several locations using ADS-B. The broadcast architecture is passive and so has very high capacity. However, it requires the ground to be time synchronized and needs a minimum of three stations for horizontal positioning since pseudo ranges are used.

Another potential architecture is request-reply or traditional two way ranging. Utilizing this architecture begins by having one party sends a request or interrogation. Once the second party receives the request, it transmits a response after a known delay. The first party then calculates range from reception of the reply. DME operates in this fashion and an aircraft based design using request-reply should operate similar to DME. A ground base design is similar to the ranging function performed by secondary surveillance radars (SSR). A SSR queries an aircraft and calculates distance to the aircraft from the reply. Because of the interactive nature of request-reply, there is limited capacity. However, the minimum number of measurements need for horizontal positioning is only two as we have true range measurements.

Ideally, we would like a system with high capacity while requiring only two stations for positioning. High capacity is needed to support for crowded airspaces such as New York or Los Angeles. Reducing the number of stations needed for positioning is vital for approach. DME and GBT are line of sight (LOS) systems and the number of stations visible decreases with altitude. As a result, we developed hybrid architectures.

Hybrid architectures contain some aspects of both the previous architecture. Transforming pseudo ranges to true ranges requires knowing the time offset between the ground and the aircraft. This can be accomplished using two way communications between the aircraft and the ground. Afterwards, the broadcast approach can be used for as long as the ground and aircraft clocks are synchronized. This minimizes the number of two communications required while only needing a minimum of two required station for horizontal positioning. However, it also requires the ground to be time synchronized and increases system complexity.

ORGANIZING THE ACCURACY ANALYSIS

With so many options possible, it is necessary to develop a methodology to analyze the potential systems architectures in an organized and manageable manner. As such, we take three steps. First, the architectures are grouped into two basic categories. The second step is to generalize the analysis by parameterizing by ranging accuracy. The third step is to examine the base level of requirements. This means starting with the basic infrastructure (DME only, DME and GBT) and one flight level for each of two basic operations (en route, approach).

ARCHITECTURE

The architectures can be organized into two basic categories: true range and pseudo range based. The request-reply and hybrid architectures utilize true range and require a minimum of two stations for horizontal position. The broadcast architectures are pseudo range based and require a minimum of three stations for positioning.

PARAMETERIZING BY ACCURACY

One major difference between the architectures is ranging accuracy. The categorization above allows us to perform analysis with range accuracy being a sensitivity parameter. This is accomplished by developing dilution of precision (DOP) coverage maps based on the basic categories. A MITRE DME coverage tool was used to generate such DOP maps. This tool utilizes high resolution digital terrain elevation data (DTED Level 1) as well as standard models for DME propagation model, performance and coverage. With the DOP map, we can determine the positioning accuracy as a function of ranging accuracy as seen in Equation 3.

$$\sigma_{pos} = DOP \bullet \sigma_{range} = DOP \bullet \sqrt{\sigma_{air}^2 + \sigma_{sis}^2} \quad (3)$$

However, having positioning error is only one step the determining if RNP accuracy is met. RNP level is the total system error (TSE) accuracy (95%). For example, RNP 0.3 means the 95% TSE level is at or below 0.3 nautical miles. TSE is the sum of flight technical error (FTE) and navigation system error (NSE). The position error gives the NSE. FTE depends on the airframe and the flight system. For the initial analysis, FTE from RTCA document DO-208 is used. A basic summary is seen in Table 1 [11]. More extensive models are provided for each airframe and flight instrument as seen in Boeing documents [12].

Source/Air frame	737	747-400	757/767	777	DO-208
Manual with MAP	0.15/0.208	0.402	0.5	0.5	0.5
LNAV with FD	0.05/0.073	0.206	0.206	0.206	0.25
LNAV w. autopilot	0.025/0.068	0.088	0.088	0.088	0.125

Table 1. FTE assumptions (in nm) form various air frame documents and DO-208

INFRASTRUCTURE & FLIGHT ALTITUDES

Two infrastructure options are used in the initial analysis. DME sites only represent the base case of using one system. Additionally, using DME also represents the baseline case. This case will also provide some indication of the performance of using GBT sites only as there is a similar density of GBT stations. The second case is to examine using both DME and GBT sites. This will indicate what is achievable if both systems can be used together. Additionally, seeing where the coverage of this case fails will help us determine if the addition of a few extra stations will be beneficial.

Several flight levels (FL) need to be supported to provide en route or approach capabilities. For the initial analysis, we used 5000 feet above ground level (AGL) for en route. This altitude is envisioned as the lowest needed to support en route. It also represents a worst case scenario as the number of visible DME and GBT decreases with altitude. For approach, 500 feet AGL was used as it is near the minimum altitude for RNP 0.3.

COVERAGE ANALYSIS

The methodology allows to us organize the analysis in a meaningful manner. This section presents the coverage analysis results for en route over CONUS and approach at two major airspaces: San Francisco Bay Area and Washington DC.

CONUS AT 5000 FT AGL

The first case to consider is the en route over CONUS. We begin by examining the DOP coverage for each architecture and infrastructure. Figure 3 shows the DOP coverage for true range architectures when using DME and GBT ground infrastructure.

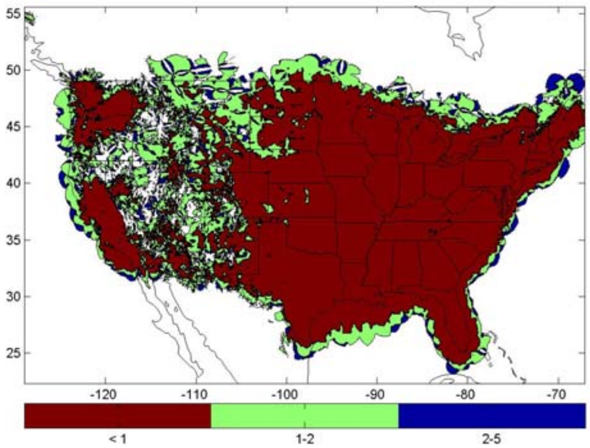

Figure 3. CONUS DOPs for True Range at 5000 ft AGL with DME & GBT

The target operation for the en route airspace over CONUS is RNP 1.0. For RNP 1.0, a total system accuracy (95%) of 1 nm must be achieved. Some of the error is due to FTE and a value of 0.25 nm (1 σ), equivalent to roughly 0.5 nm (95%), is used. This value is consistent with standards such as DO-208 and AC90-100A. For ranging, σ_{range} = 0.17 nm is used. This value is the worst expect performance of DME given the standards. Figure 4 shows the RNP coverage for true range architectures provided both DME and GBT stations are used. The results show that coverage for RNP 1.0 essentially follows that of the DOP (down to the resolution of the plots). In examining each case, it was found that given the assumptions on FTE and range accuracy, the DOP coverage (DOP <= 5) and RNP 1.0 is essentially the same. Figure 5, Figure 6 and Figure 7 show the DOP coverage for the scenarios true range with DME only, pseudo range with DME and GBT, and pseudo range with DME only, respectively. From these figures, it can be seen that all have coverage holes. However, the coverage holes of the pseudo range, DME only scenario is very significant and likely not acceptable.

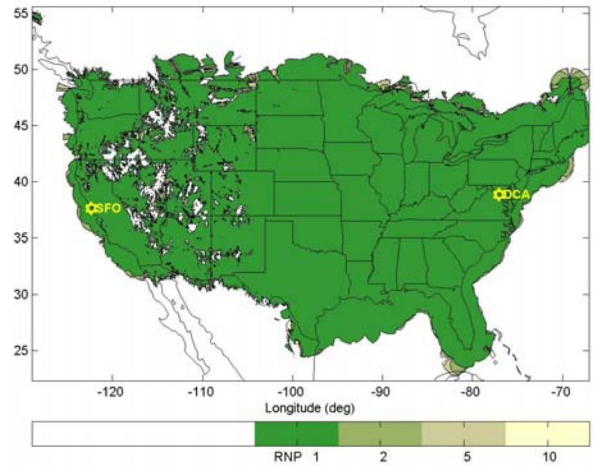

Figure 4. RNP coverage in CONUS for True Range at 5000 ft AGL with DME & GBT

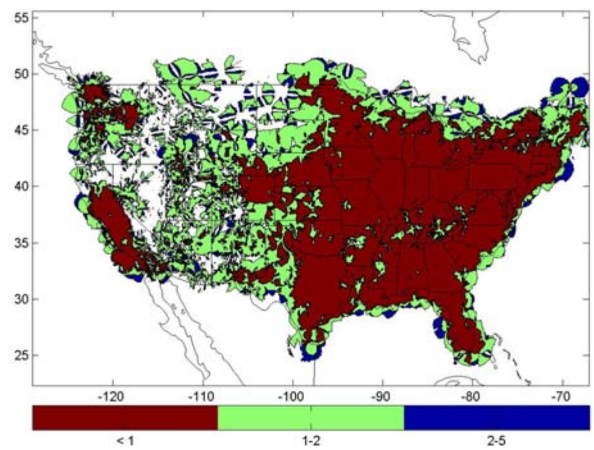

Figure 5. CONUS DOPs for True Range at 5000 ft AGL with DME

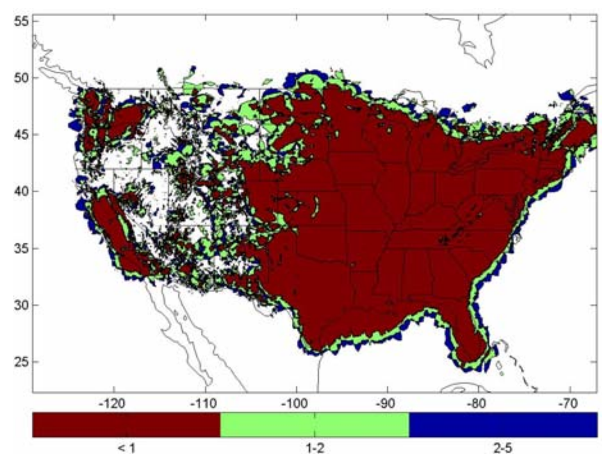

Figure 6. CONUS DOPs for Pseudo Range at 5000 ft AGL with DME & GBT

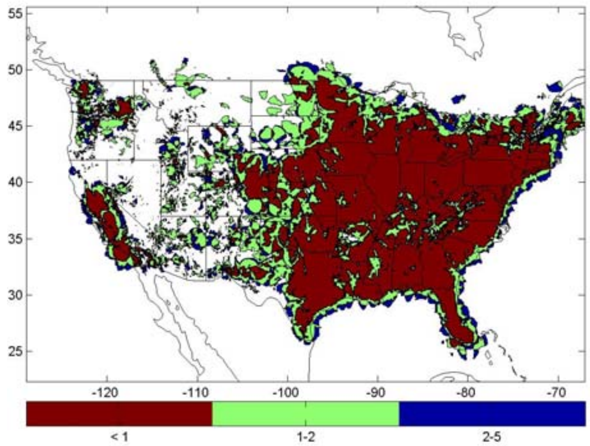

Figure 7. CONUS DOPs for Pseudo Range at 5000 ft AGL with DME only

The results are summarized in Table 2. The summary indicates the method and a judgment on the amount of coverage gaps based on the evaluation. The architecture/infrastructure combinations are ranked from 1 to 4 in descending order of coverage.

DME & GBT True Range (Request-Reply, Hybrid) A few coverage gaps (1)	DME only True Range (Request-Reply, Hybrid) Some coverage gaps (2)
DME & GBT Pseudo Range (Broadcast) Some coverage gaps (3)	DME only Pseudo Range (Broadcast) Significant coverage gaps (4)

Table 2. CONUS Results

APPROACH AT 500 FT AGL

The other consideration is approach and supporting RNP 0.3 in the terminal area. For the initial study, a few major airports were examined. Two areas with multiple major airports were used. The San Francisco bay area has three major airports in San Francisco (SFO), Oakland (OAK), and San Jose (SJC) International. The Washington D.C. area also has three major airports – Dulles (IAD), National (DCA), and Baltimore-Washington (BWI) International. As the minimum altitude for coverage can vary, a value of 500 ft AGL was selected is as a reasonable approximation to the minimum altitude.

The analysis examines the resulting RNP coverage given different level of ranging errors. Two levels, σ_{range} = 0.085 nm and 0.17 nm, are first examined as they represent the smallest and largest level of random error from the standards. Another value to determine is the maximum allowable level of ranging error that will provide acceptable RNP 0.3 coverage about the airport. For the preliminary analysis, the determination is partly subjective and examines just the area about the airport without consideration to the specific approaches utilized. More detailed analysis will involve overlaying the approaches for each airport. The maximum range error allows us to make some comparisons between the different options with one metric.

SAN FRANCISCO BAY AREA

The San Francisco bay area was selected both due to the density of major airports in the vicinity and the mountainous terrain. The terrain makes coverage challenging for line of sight transmissions such as DME and GBT.

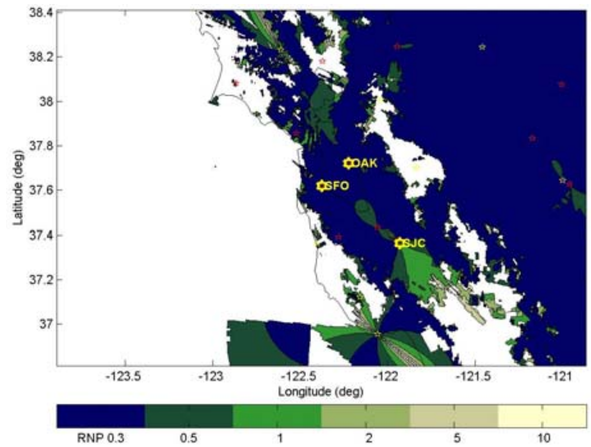

Figure 8. RNP 0.3 coverage using true range architecture and DME & GBT sites (σ_{range} = 0.085 nm)

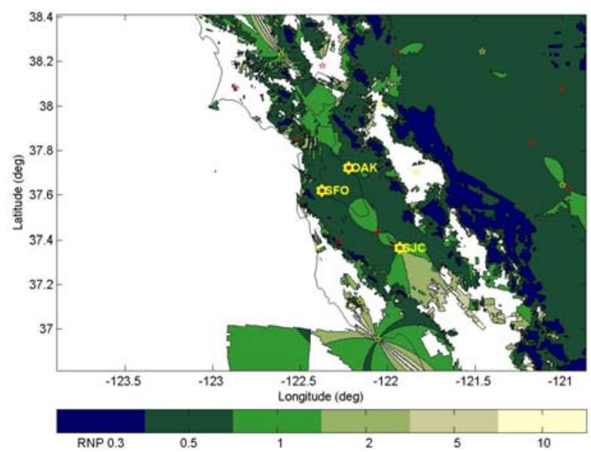

Figure 9. RNP 0.3 coverage using true range architecture and DME & GBT sites (σ_{range} = 0.17 nm)

The most optimistic case is that of a true range system using both DME and GBT sites. Figure 8 and Figure 9 show the RNP 0.3 coverage for σ_{range} = 0.085 nm and 0.17 nm range error. RNP 0.3 coverage seems adequate for the σ_{range} = 0.085 nm case with the exception of perhaps SJC from the southeast. If σ_{range} is increased to 0.17 nm, RNP 0.3 coverage at the airports considered is essentially eliminated. Further study shows that to support RNP 0.3 for all airports (with the exception of SJC from the southwest), the maximum allowable ranging error is roughly 0.10 nm. It turns out that regardless of the method used, additional coverage is needed to support SJC from the southeast. Given this, SJC from the southeast is not considered when determining the maximum range error for RNP 0.3 coverage in all cases.

Next, we examine the true range scenario using only DME. Figure 10 and Figure 11 show the RNP 0.3 coverage for σ_{range} = .085 nm and 0.17 nm range error, respectively. The results are similar to the previous case. Again, analysis indicates that to support the RNP 0.3, the maximum allowable ranging error is roughly 0.10 nm.

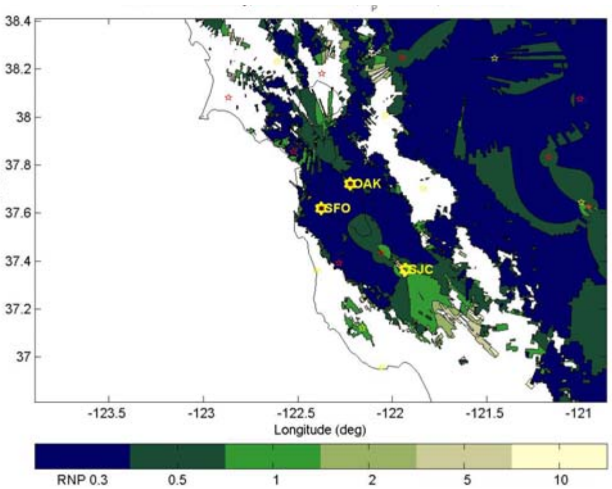

Figure 10. RNP 0.3 coverage using true range architecture and DME sites only (σ_{range} = 0 .085 nm)

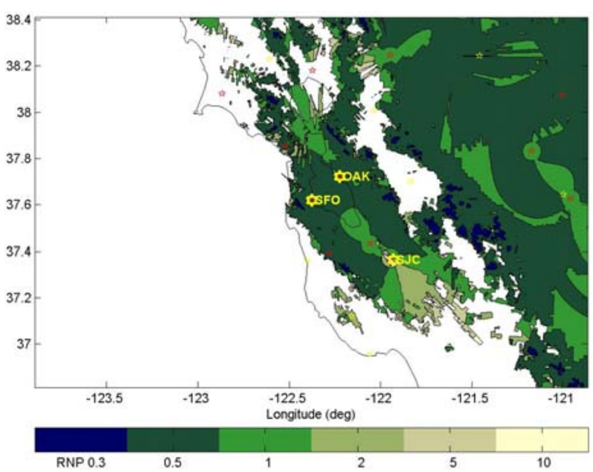

Figure 11. RNP 0.3 coverage using true range architecture and DME only sites (σ_{range} = 0.17 nm)

Pseudo range architectures have worse coverage due to the requirement of having an additional station. Figure 12 and Figure 13 show the RNP 0.3 coverage given σ_{range} = 0.085 nm for the architecture with DME & GBT and DME only, respectively. RNP 0.3 is very limited in these two cases. In fact, to provide reasonable RNP 0.3 coverage, the maximum allowable ranging error is much lower – 0.06 nm or less. Even with this ranging accuracy, there will still be coverage holes around each airport for the DME only infrastructure as seen in the plots.

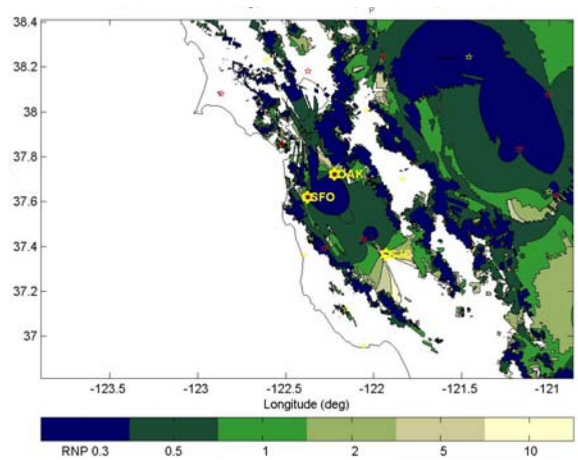

Figure 12. RNP 0.3 coverage using pseudo range architecture and DME & GBT sites (σ_{range} = 0.085 nm)

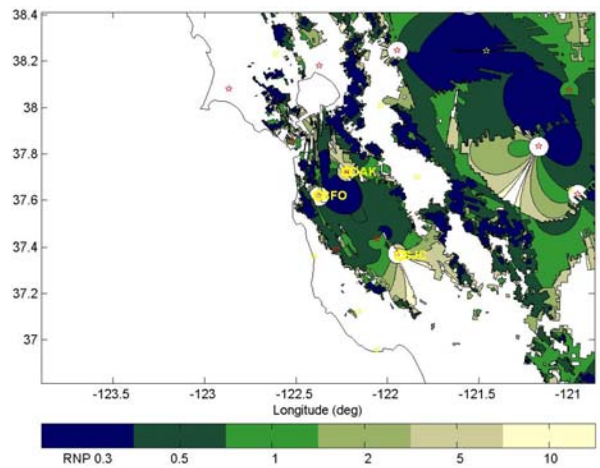

Figure 13. RNP 0.3 coverage using pseudo range architecture and DME sites only (σ_{range} = 0.085 nm)

DME & GBT True Range 0.10 nm	DME only True Range 0.085 nm
DME & GBT[+] Pseudo Range 0.06 nm	DME only[*] Pseudo Range 0.06 nm

Table 3. Summary Results for San Francisco

Table 3 summarizes the results for approach in the major airports of the San Francisco bay area. It shows each combination of architecture and infrastructure along with the estimated maximum allowable ranging error that can still provide reasonable RNP 0.3 coverage. There are additional caveats for the pseudo range cases. For pseudo ranging with DME and GBT, SJC cannot be supported ([+]). For pseudo ranging with DME only, there are coverage holes around each airport (and SJC cannot be supported) (*).

WASHINGTON DC AREA

The Washington DC area was also examined. The results were similar to those found previously for San Francisco though the performance was generally a little better since its terrain is less rugged. Figure 14 shows an example plot from the DC area. It shows the performance of the true range architecture when using DME and GBT with σ_{range} = 0.17 nm. Table 4 summarizes the results in a similar manner as Table 3. Again, there are some caveats. For true ranging with DME only, there are coverage holes around BWI and IAD (+). For pseudo ranging with DME only, there is no coverage at BWI and IAD (*). As seen from the results, the maximum allowable ranging error for RNP 0.3 coverage can be a little higher in the DC area. This is expected as the area has fewer terrain features obstruct the LOS to ground stations at low altitudes.

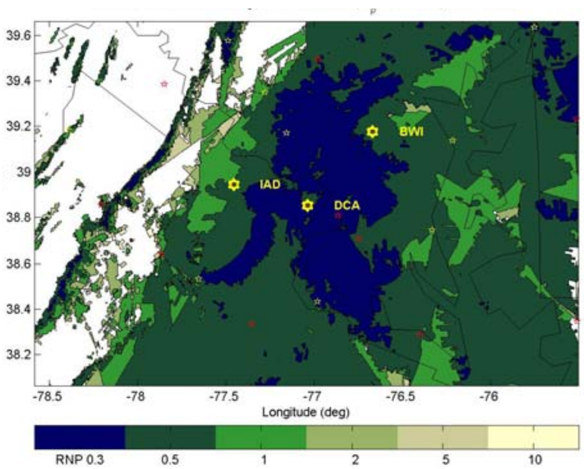

Figure 14. RNP 0.3 coverage using true range architecture and DME & GBT sites (σ_{range} = 0.17 nm)

DME & GBT True Range 0.12 nm	DME only+ True Range 0.085 nm
DME & GBT Pseudo Range 0.085 nm	DME only* Pseudo Range 0.085 nm

Table 4. Summary Results for Washington DC

CONCLUSIONS

This paper examines some of the options being studied by the FAA to provide alternative navigation to GNSS. The paper focuses on systems based on existing or soon to be existing FAA infrastructure such as DME and GBTs. Specifically, the preliminary analysis examines the coverage performance of systems using these elements to support RNP 1.0 through CONUS and RNP 0.3 approach capabilities to vital airports.

Three architectures were studied. Depending on implementation, the position solution can be calculated either in the aircraft or by the ground for any of the architectures studied. One architecture is to use passive ranging which yields pseudo ranges. Three pseudo ranges are needed to derive a horizontal position solution. Another means is request-reply or two way ranging. This reduces the number of required measurements to two since it yields true ranges. However, its capacity is limited. The third means is hybrid technique whereby passive ranging is supplemented by occasional two way communications is used to synchronize the aircraft with the ground transmitters. This provides for capacity benefits. Since true ranges are derived, only two transmitters are needed for horizontal positioning.

Performance and coverage was assessed for both en route in CONUS and for approach at several airports. The result for en route is promising as only one technique (pseudo range with DME infrastructure) has extensive RNP 1.0 coverage gaps for en route at 5000 ft AGL. Both the San Francisco and Washington DC areas were used for the airport study. With the true range based techniques, RNP 0.3 around the airport seems achievable without significant improvement in DME range accuracy. For the pseudo range method, DME range accuracy will need to improve.

The analysis presented here is not meant to be conclusive. Rather, it is an initial analysis meant to provide a general idea of the performance level. For example, the currently existing DME and planned GBT sites were used for the analysis. Future FAA plans include adding a few more DME to fill in some en route gaps. Furthermore, other changes and features such as approach DMEs were not initially included in the analysis.

ACKNOWLEDGMENTS

The authors would like to thank the FAA Navigation Services Directorate for supporting this work. We would also like to acknowledge the rest of the APNT Team for their inputs.

DISCLAIMER

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Federal Aviation Administration or Department of Transportation.

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