Use of Standalone GPS for Approach With Vertical Guidance

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BIOGRAPHY

Karen Van Dyke is a member of the technical staff of the Center for Navigation at the DOT/Volpe Center. Karen has conducted availability and integrity studies of GPS for all phases of flight including precision approach in support of RTCA SC-159. She served as the project lead for a Volpe Center team that designed, developed, and implemented a GPS outage reporting system for the U.S. Air Force and the FAA. This capability has been extended to Australia, Germany, and Chile to provide pilots with the status of GPS during pre-flight planning, as well as to Air Traffic Control. She received her BS and MS degrees in Electrical Engineering from the University of Massachusetts at Lowell. Ms. Van Dyke currently serves as the President of the Institute of Navigation.

ABSTRACT

The accuracy of GPS has improved dramatically over the past year with the removal of Selective Availability. The largest error source now is the ionosphere which can be removed in the future when the additional civil frequencies become available. Presentations at ION GPS 2000 have suggested that clock and ephemeris errors will be able to predicted to within 25-30 cm each in the future, resulting in a User Equivalent Range Error (UERE) as low as 50 cm for both the GPS and Galileo constellations. This UERE would depend on very low receiver noise and multipath mitigation. However, if achieved, this accuracy will result in horizontal position errors on the order of 1.5m 95% and vertical 2.5m 95%.

Although these position errors are small enough to satisfy Category I precision approach operations, could GPS satisfy the more stringent integrity requirements as well? Integrity for standalone GPS generally is provided by algorithms within the receiver known as Receiver Autonomous Integrity Monitoring (RAIM) and Fault Detection and Exclusion (FDE), although these algorithms usually are focused on meeting horizontal navigation requirements. For operations involving the approach phase of flight, it is likely that only the detection capability provided by RAIM is required, assuming that the exclusion function is available in the terminal phase of flight if an anomaly is detected. However, one of the limitations of the RAIM and FDE algorithms typically is not having enough ranging sources to form a solution. Therefore, in this paper the availability of standalone GPS, as well as a combined GPS/Galileo constellation, will be evaluated.

Tradeoffs between accuracy and availability are examined in this analysis. For example, in practice a UERE of 50 cm may not be achievable. This paper will examine the resulting availability if higher UEREs are used. The paper evaluates vertical alert limits for both categories of approach with vertical guidance (APV) which range from 50m for APV-I to 20m for APV-II.

INTRODUCTION

The concept of approach with vertical guidance (APV) is not new, although the acronym APV has been adopted by the International Civil Aviation Organization (ICAO) Global Navigation Satellite System Panel (GNSSP) only recently. The basic concept is to provide vertical guidance to the aircraft at a decision height higher than the 200 ft. decision height traditionally used for Category I precision approaches. For this reason, the concept of APV has been referred to as “near” Category I in the past. Other terms which have been to describe these operations include instrument approach with vertical guidance (IPV), nonprecision approach with vertical guidance (NPV), and lateral navigation with vertical guidance (LNAV/VNAV).

The analysis in this paper is an extension of work that was presented in paper at ION GPS 2000 [1] which examined the ability of standalone GPS to satisfy the performance requirements in the ICAO GNSSP Standards and

Recommended Practices (SARPS) for oceanic through nonprecision approach operations now that Selective Availability (SA) has been turned off. The results demonstrated that very high RAIM and FDE availability can be achieved and meeting the minimum availability requirement of 99% in the SARPS will not be a problem. Even the most stringent SARPS availability requirement of 99.999% can be met in most cases if one considers the use of augmentations such as barometric altimeter aiding, geostationary satellites, or perhaps additional GPS satellites or the Galileo constellation.

With SA turned off, the largest error source now is the ionosphere which will be able be removed within the receiver in the future when the additional civil frequencies with C/A code become available through the GPS modernization program. Therefore, the next logical step to the analysis presented at ION GPS-2000 is examine applications that use vertical guidance in order to determine what level of performance can be achieved.

Although it is recognized that it will most likely be at least 2010 before enough satellites have dual C/A code frequencies to take advantage of the ionospheric correction within the receiver, there are many reasons for considering the ability of standalone GPS to satisfy APV criteria. First of all, there are many countries who may not have satellite-based augmentation systems (SBAS) such as the U.S. Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay System (EGNOS), but who would like to gain as much performance from GPS as possible. Also, countries who have airfields at high latitudes will not have coverage from the geostationary satellites to provide the GPS SBAS corrections and integrity data so they are interested in what alternatives may be available to them as well.

Given that most aviation authorities will not begin to phase out existing ground-based navaids before 2008, this analysis will assist in long range architecture planning. Finally, it is beneficial to assess the benefits that the GPS modernization program will provide to the civilian community.

It should be pointed out that although the analysis presented in this paper is focused on the standalone use of GPS, it is purely from a technical standpoint to determine what performance levels can be achieved. Additional navigation systems may be required to be carried onboard as a backup due to the susceptibility of GPS to interference.

REQUIREMENTS FOR APV

Approach with vertical guidance is the term that has been adopted by ICAO to describe operations involving lateral navigation with vertical guidance based on GPS altitude or barometric altimeter aiding. The performance requirements for APV, which were developed in the ICAO GNSS Panel, are provided in Table 1 [2]. Note that there are two categories of APV service: APV-I and APV-II.

APV-I is the less stringent of the two APV categories and the horizontal performance requirements for APV-I are the same as those required for nonprecision approach. However, the integrity requirement is now on a per approach basis instead of on a per hour basis. The duration of an approach generally is assumed to be 150 sec. The continuity requirement is further broken down into 15 sec. intervals along the approach.

Note that the horizontal and vertical performance requirements for APV-II are far more stringent than those for APV-I. Although Category I precision approach is not analyzed in this paper, the horizontal performance requirements are the same as for APV-II, but the CAT I vertical accuracy ranges from 4m to 6m and the vertical alert limit ranges from 10m to 15m. The integrity and continuity requirements are the same as for both APV-I and APV-II.

Similar to the availability requirements for the other phases of flight in the SARPS, the range is from 99% to 99.999%.

Table 1 Performance Requirements for APV

Performance Requirement	APV-I	APV-II
Horizontal Accuracy (95%)	220 m	16 m
Vertical Accuracy (95%)	20 m	8 m
Integrity	$1\text{-}2\times10^{-7}$/ Approach	$1\text{-}2\times10^{-7}$/ Approach
Continuity	$1\text{-}8\times10^{-6}$/ 15 sec	$1\text{-}8\times10^{-6}$/ 15 sec
Horizontal Alert Limit (HAL)	0.3 nmi	40 m
Vertical Alert Limit (VAL)	50 m	20 m
Availability	99% - 99.999%	99% - 99.999%
Time To Alert (TTA)	10 sec	6 sec

RAIM ALGORITHM

An overview of the Receiver Autonomous Integrity Monitoring (RAIM) algorithm used to conduct the analyses in this study is provided in this section. The algorithm is based on the parity space concept and uses the magnitude of the parity vector as the test statistic for detection of a satellite failure. As previously mentioned, for the approach phase of flight we are only concerned with the detection of a satellite failure and not the exclusion of it. If a failure is detected then it is assumed that the pilot conducts a missed approach. Based on the analysis in [1], it is appears that the availability of the fault detection and exclusion (FDE) function will have a high availability in the terminal airspace for the aircraft to revert to before either attempting another APV approach or perhaps a nonprecision approach depending on the duration of the outage and what other options are available.

The inputs to the parity space algorithm are the standard deviation of the measurement noise, the measurement geometry, as well as the maximum allowable probabilities for a false alert and a missed detection. The output of the algorithm is the horizontal and vertical protection levels, which are the radii of two circles, each centered at the true aircraft position that are assured to contain the indicated horizontal and vertical positions with the given probability of false alert and missed detection that are discussed below.

As indicated in Table 1, both APV-I and APV-II have maximum horizontal and vertical alert limits, HAL and VAL respectively. If the horizontal protection level (HPL) exceeds HAL or the vertical protection level (VPL) exceeds the VAL, integrity is said to be unavailable for that phase of flight.

According to the RTCA SC-159 WAAS Minimum Operational Performance Standards (MOPS), the probability of a false alert is $2\text{x}10^{-5}$ per approach with two independent samples per approach [3]. The false alert rate therefore is assumed to be 10^{-5} per independent sample.

The detection threshold, T_D, is determined by integrating the chi-square density function as shown in Equation (1)

$$P_{FA} = \int_{T_D^2}^{\infty} (x^{(k/2)-1} e^{-x/2}) / 2^{k/2} \Gamma(k/2) dx \quad (1)$$

where k is the number of degrees of freedom equal to n-4, where n is the number of visible satellites.

The probability of a GPS major service failure, defined as a pseudorange error greater than 150m, is on the order of 10^{-4}/hr, assuming that there are three events per year [4] and an average of eight visible satellites. For an approach of 150 sec., the probability of a GPS major service failure during the approach is $4.167\text{x}10^{-6}$.

In order to meet the loss of integrity requirement of $2\text{x}10^{-7}$ per approach from Table 1,

Prob(GPS Major Service Failure) x $P_{MD} = 2\text{x}10^{-7}$

where P_{MD} is the probability of a missed detection. Therefore, the required probability for a missed detection is 0.048. Note that this P_{MD} value is much higher than the 10^{-3} traditionally required for the en route through nonprecision approach phases of flight where the requirements are on a per hour basis.

P_{MD} is determined by integrating the noncentral chi-square density function, as shown in Equation (2), where λ is the noncentrality parameter and T_D is the normalized chi-square threshold.

$$P_{MD} = \int_0^{T_D^2} 1/2 e^{-(x+\lambda)/2} \sum_{j=0}^{\infty} \left[\lambda^j x^j / (2^{2j} j! j!) \right] dx \quad (2)$$

Figure 1 shows the relationship between the chi-square and noncentral chi-square density functions for two degrees of freedom in determination of the detection threshold and noncentrality parameter.

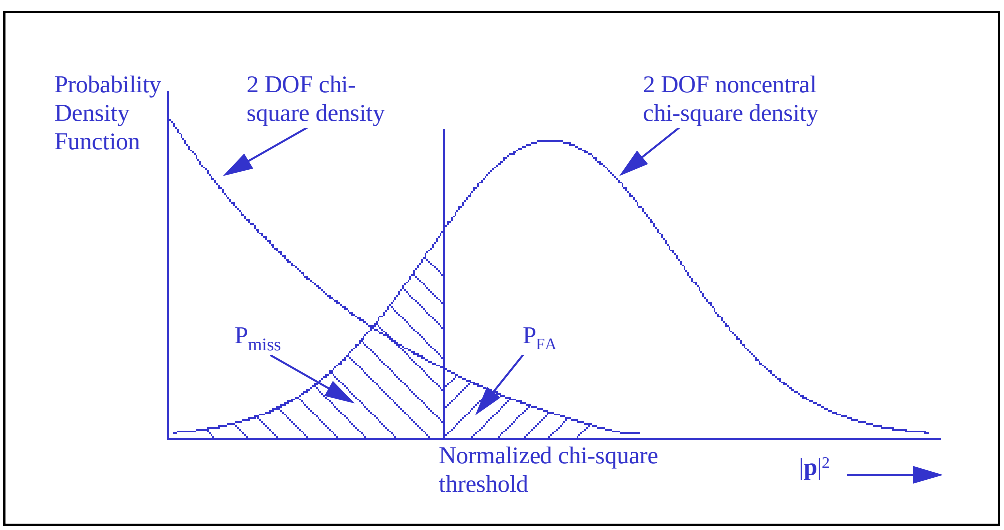

Figure 1 Chi-Square Density Functions for Two Degrees of Freedom

The minimum detectable bias based on the selected probabilities of false alert and missed detection is denoted as pbias, where pbias= $\sigma_{UERE}\sqrt{\lambda}$. The values for the User Equivalent Range Error (UERE) will be discussed in the next section. The horizontal and vertical protection levels are determined as shown in Equations 3 and 4 by multiplying the pbias value by the maximum horizontal and vertical slopes.

$HPL = pbias * Hslope_{max}$ (3)

$VPL = pbias * Vslope_{max}$ (4)

The horizontal and vertical $slope_{max}$ terms are formed by creating a slope for each visible satellite as a function of the estimated horizontal and vertical position errors respectively vs. the test statistic and then selecting the maximum slope value. For a given position error, the satellite with the largest slope has the smallest test statistic and will be the most difficult to detect.

The equations for determining the horizontal and vertical slope values for i=1:*n* visible satellites are given below:

$$\mathrm{Hslope}(i) = \sqrt{A_{1i}^2 + A_{2i}^2} \,/\, \sqrt{S_{ii}} \quad (5)$$

$$\mathrm{Vslope}(i) = \sqrt{A_{3i}^2} \,/\, \sqrt{S_{ii}} \quad (6)$$

where $\mathbf{A=(H^TH)^{-1}H^T}$ and H is the nx4 linear connection or geometry matrix. $\mathbf{S=I_n - H(H^TH)^{-1}H^T}$.

ANALYSIS PARAMETERS

This section describes the analysis parameters evaluated in determining the availability of the use of standalone GPS to meet APV criteria.

User Equivalent Range Error Budget

A range of UERE values ranging from 5m (1σ) to 0.5m (1σ) was used in the analysis. An example error budget for several of the UERE values used is provided in Table 2. In a recent paper by Karl Kovach [5], he points out that one of the largest error sources in dual frequency C/A code (L1/L2) receivers will be the differential group delay stability in part because the GPS operational control segment does not monitor the C/A code. The error budget for a UERE of 3.8m is taken from [5].

The 0.5m error budget is representative of an error budget that has been presented for Galileo [6]. Although fairly optimistic, it is thought to be possible with new clock technology that is being developed.

Table 2 UERE Budgets

Segment	Error Source	σ (m)	σ (m)	σ (m)	σ (m)
Space	Clock Stability	1.0	0.5	0.4	0.25
	Group Delay Stability	1.5	1.1	0.7	0.2
	Diff. Group Delay Stability	3.5	3.3	1.7	0.15
	Other (Thermal)	0.5	0.3	0.1	0.05
Control	Ephemeris Prediction Error	2.5	1.0	0.5	0.25
	Other	0.5	0.3	0.1	0.05
User	Iono Delay	1.0	0.4	0.2	0.1
	Tropo Delay	1.0	0.5	0.3	0.15
	Receiver Noise	0.5	0.2	0.2	0.1
	Multipath	0.5	0.1	0.1	0.1
	Other	0.5	0.4	0.2	0.05
System UERE	Total (rss)	5.0 m	3.8 m	2.0 m	0.5 m

Satellite Constellations

Several satellite constellations were evaluated in determining the availability of APV. First, the Optimal 24 GPS constellation which traditionally has been used in availability analyses within RTCA [3]. It is a six plane constellation. A 30-satellite six plane GPS constellation as proposed by Boeing [7] also was examined.

The European Commission has stated that the proposed Galileo constellation will become operational in 2008. The primary differences between the GPS and Galileo constellations is that Galileo is a 30 SVconstellation in three planes at an altitude of 23,222 km and the satellites are at a 56^{o} inclination angle [8]. At this altitude, the satellites only repeat their orbits every ten days.

Baro Aiding

Availability of the use of GPS for APV was examined with and without the use of barometric (baro) altimeter aiding. It is assumed that the baro altimeter is calibrated with GPS, as described in Appendix G of the WAAS MOPS [3]. Although the baro altimeter will not be as accurate as GPS, it does assist in improving geometry by providing an additional vertical measurement.

Analysis Grid

The analysis to determine APV availability first examined a worldwide grid of data points sampled every 2^o in both latitude and longitude. The grid was sampled every 2.5 min. (duration of an approach) over a 24 hour period. A mask angle of 5^o was applied. In addition, availability was examined at site-specific airfields.

AVAILABILITY RESULTS

The ability of GPS to satisfy accuracy and integrity requirements was evaluated over the analysis grid described in the previous section. Although both horizontal and vertical accuracy and integrity requirements analyzed, the ability of GPS to meet the vertical requirements drove the availability. Within the vertical requirements, the integrity requirement was more difficult to satisfy than the accuracy requirement. Therefore the availability results presented are the percentage of time that VPL<VAL.

The worldwide availability of standalone GPS for APV-I and APV-II are displayed in Figures 2 and 3, respectively. Availability data for each of the constellations analyzed also is provided in Tables 3 and 4.

The results for APV-I demonstrate that the minimum ICAO GNSS SARPS availability requirement of 99% can be met with a combined GPS/Galileo constellation if the σ_{UERE} is 5m or lower. 5 9's availability can be met for the GPS/Galileo constellation with a σ_{UERE} of 3m or lower and the 30 satellite Galileo constellation meets 5 9's of availability with a σ_{UERE} of 2m or lower. All constellations considered meet a minimum availability of 99% if the σ_{UERE} is less than 1m.

Note that the 30 satellite GPS constellation provides a higher availability than Galileo when the UERE is greater than 3m, however Galileo provides a higher availability when the UERE is 3m and lower. This phenomenon has been pointed out in a paper presented by Boeing [9], demonstrating that a three plane 30-satellite constellation provides better availability than a six plane constellation for Category I precision approach (which would assume very low noise sigmas). A six plane 30-satellite constellation, on other hand, was shown to provide better RAIM availability than a three plane constellation. RAIM in this context refers to nonprecision approach (horizontal guidance only) and generally would assume higher UERE values due to the inability to correct for the ionospheric error. Boeing currently is examining a hybrid of the two constellations to maximize performance[10].

The results for APV-II reveal that standalone GPS has very low availability until the σ_{UERE} can be reduced to the 1m level or below. At the 1m level, Galileo with baro aiding and the combined GPS/Galileo constellation achieve 5 9's availbility. If a σ_{UERE} of 0.5m can be achieved, 5 9's availability is possible for all of the constellations considered except for the Optimal 24 Constellation without baro aiding.

Similar to the results obtained for APV-I, the six plane 30-satellite GPS constellation provides higher availability for UEREs of 3m and higher. In fact even the 24-satellite six plane constellation outperforms the 30 SV Galileo constellation at a UERE of 3.8 m, but this availability is so low it is operationally insignificant. The Galileo constellation provides much better performance for lower UEREs.

Table 3 Availability of APV-I

	σ_{UERE}					
Constellation	**5 m**	**3.8 m**	**3 m**	**2 m**	**1 m**	**0.5 m**
Optimal 24	27.629	58.435	78.124	93.610	99.578	99.886
Optimal 24 with Baro	36.135	72.157	90.763	99.696	99.999	99.999
30 GPS SVs	68.224	91.196	96.535	99.777	99.999	99.999
30 GPS SVs with Baro	74.998	97.871	99.875	99.993	99.999	99.999
Galileo	61.312	82.710	97.288	99.999	99.999	99.999
Galileo with Baro	67.330	91.712	99.999	99.999	99.999	99.999
GPS/Galileo	99.427	99.991	99.999	99.999	99.999	99.999

Table 4 Availability of APV-II

	σ_{UERE}					
Constellation	**5 m**	**3.8 m**	**3 m**	**2 m**	**1 m**	**0.5 m**
Optimal 24	0.000	0.183	3.067	27.629	86.281	99.165
Optimal 24 with Baro	0.000	0.266	5.148	41.917	96.168	99.999
30 GPS SVs	0.000	1.570	10.119	57.334	98.744	99.999
30 GPS SVs With Baro	0.000	1.914	12.203	68.998	99.831	99.999
Galileo	0.000	0.000	6.869	61.312	99.997	99.999
Galileo With Baro	0.000	0.000	15.763	73.875	99.999	99.999
GPS/Galileo	11.435	53.141	86.032	99.462	99.999	99.999

GPS availability for APV-I and APV-II also was considered for eight site-specific locations distributed across North America. The locations ranged in latitude from 26^oN (Miami) to 68^oN (Inuvik, Canada). Availability at each location was sampled at 1 min intervals over a 24 hour period. The constellations considered for this analysis were the Optimal 24 and Galileo constellations, both with and without baro aiding.

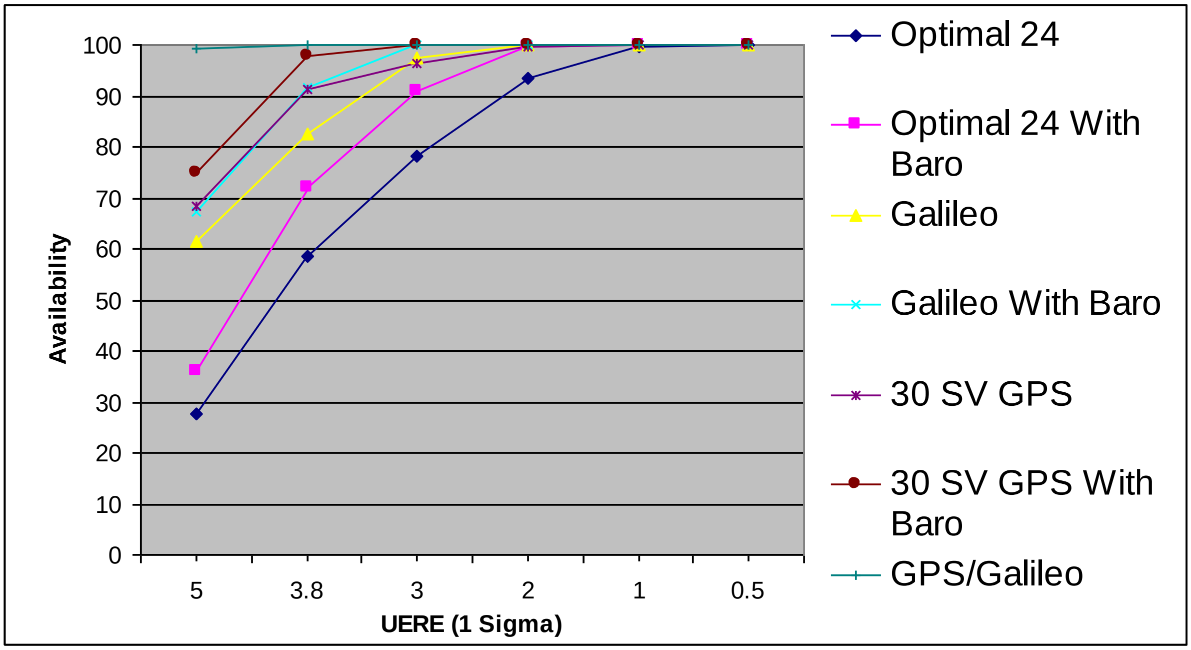

Figure 2 Availability of APV-I

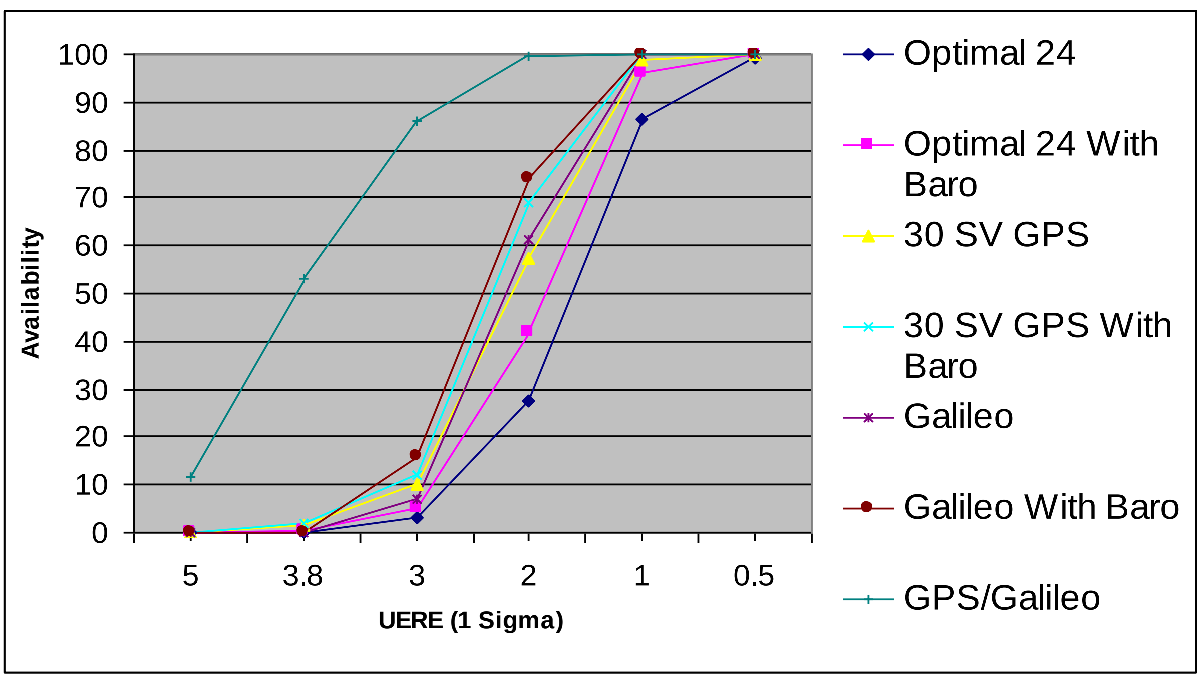

Figure 3 Availability of APV-II

The results for APV-I and APV-II availability are presented in Tables 5 and 6 respectively for the Optimal 24 constellation and Tables 7 and 8 for the Galileo constellation. These results are similar to those for the global average. As shown in these Tables 5 and 6, Optimal 24 availability is significantly lower for the high latitude locations (Fairbanks and Inuvik) than for any of the other locations.

For Galileo, on the other hand, APV availability for Fairbanks is among the highest for any location considered and availability for Inuvik, although one of the lower availability sites, is on par with U.S. locations such as Dallas and Los Angeles.

Perhaps the better availability at these locations was considered in the Galileo constellation design in order to provide coverage to the higher latitude European locations.

A comparison of the availability of the 30-satellite GPS and Galileo constellations for APV-I is presented in Figure 4. Note that the 30 SV GPS constellation provides higher availability for Boston and Miami, while Galileo provides higher availability for Fairbanks and Inuvik. Although not shown in this figure, once the UERE is lower than 3m, Galileo provides higher availability at all locations which is consistent with the previous results.

Table 5 APV-I Availability for GPS Optimal 24 Constellation / With Baro Aiding

Location	σ_{UERE}					
	5 m	**3.8 m**	**3 m**	**2 m**	**1 m**	**0.5m**
Boston	30.247/ 44.306	73.264/ 84.375	89.931/ 93.958	98.403/ 100	100/ 100	100/ 100
Chicago	42.569/ 51.389	76.875/ 85.903	87.847/ 96.389	98.403/ 100	100/ 100	100/ 100
Dallas	45.903/ 54.375	77.083/ 86.458	88.958/ 95.417	96.944/ 99.722	99.722 /100	100/ 100
Fairbanks	20.417/ 25.764	44.444/ 55.139	64.167/ 77.083	88.819/ 98.958	99.097 /100	100/ 100
Inuvik	16.319/ 23.056	40.208/ 54.236	61.181/ 78.889	88.681/ 99.444	99.515 /100	100/ 100
LAX	36.667/ 43.681	63.333/ 73.750	83.194/ 90.208	96.250/ 100	100/ 100	100/ 100
Miami	37.917/ 48.819	68.194/ 80.556	89.583/ 94.375	97.778/ 100	100/ 100	100/ 100
Seattle	37.014/ 51.944	73.264/ 82.569	84.792/ 91.597	94.583/ 99.444	99.444 /100	99.792 /100

Table 6 APV-II Availability for GPS Optimal 24 Constellation / With Baro Aiding

Location	σ_{UERE}					
	5 m	**3.8 m**	**3 m**	**2 m**	**1 m**	**0.5 m**
Boston	0.00/ 0.00	0.764/ 0.903	5.069/ 5.764	30.347/ 44.306	92.986/ 100	100/ 100
Chicago	0.00/ 0.00	0.347/ 0.417	5.347/ 6.042	42.569/ 51.389	93.264/ 99.167	99.792 /100
Dallas	0.00/ 0.00	0.278/ 0.625	7.639/ 9.583	45.903/ 54.375	92.569/ 97.986	99.653 /100
Fairbanks	0.00/ 0.00	0.00/ 0.00	4.028/ 4.653	20.417/ 25.764	75.347/ 92.153	99.097 /100
Inuvik	0.00/ 0.00	0.00/ 0.00	0.972/ 1.319	16.319/ 23.056	73.819/ 91.101	100/ 100
LAX	0.00/ 0.00	0.00/ 0.00	2.222/ 3.750	36.667/ 43.681	88.889/ 98.611	100/ 100
Miami	0.00/ 0.00	0.069/ 0.139	5.347/ 5.903	37.917/ 48.819	93.472/ 98.681	100/ 100
Seattle	0.00/ 0.00	0.972/ 1.042	5.278/ 5.694	37.014/ 51.944	90.903/ 97.222	99.236 /100

Table 7 APV-I Availability for Galileo Constellation / With Baro Aiding

Location	σ_{UERE}					
	5 m	**3.8 m**	**3 m**	**2 m**	**1 m**	**0.5 m**
Boston	62.917/ 71.806	82.500/ 91.042	97.569/ 100	100/ 100	100/ 100	100/ 100
Chicago	62.708/ 71.667	82.669/ 91.597	97.639/ 100	100/ 100	100/ 100	100/ 100
Dallas	55.417/ 69.931	81.736/ 89.722	99.028/ 100	100/ 100	100/ 100	100/ 100
Fairbanks	69.653/ 84.583	93.125/ 96.944	98.611/ 100	100/ 100	100/ 100	100/ 100
Inuvik	54.028/ 74.514	84.722/ 89.236	95.764/ 100	100/ 100	100/ 100	100/ 100
LAX	54.028/ 67.222	82.778/ 88.750	99.931/ 100	100/ 100	100/ 100	100/ 100
Miami	63.819/ 77.500	82.222/ 91.944	98.472/ 100	100/ 100	100/ 100	100/ 100
Seattle	70.694/ 76.181	80.764/ 87.778	97.569/ 100	100/ 100	100/ 100	100/ 100

Table 8 APV-II Availability for Galileo Constellation / With Baro Aiding

Location	σ_{UERE}					
	5 m	**3.8 m**	**3 m**	**2 m**	**1 m**	**0.5 m**
Boston	0.00/ 0.00	0.00/ 0.00	4.306/ 14.722	62.917/ 71.806	100/ 100	100/ 100
Chicago	0.00/ 0.00	0.00/ 0.00	3.958/ 13.750	62.708/ 71.667	100/ 100	100/ 100
Dallas	0.00/ 0.00	0.00/ 0.00	14.653/ 28.056	55.417/ 69.931	100/ 100	100/ 100
Fairbanks	0.00/ 0.00	0.00/ 0.00	3.264/ 7.986	69.653/ 84.583	100/ 100	100/ 100
Inuvik	0.00/ 0.00	0.00/ 0.00	1.667/ 6.458	54.028/ 74.514	100/ 100	100/ 100
LAX	0.00/ 0.00	0.00/ 0.00	15.694/ 27.500	54.028/ 67.222	100/ 100	100/ 100
Miami	0.00/ 0.00	0.00/ 0.00	12.917/ 23.125	63.819/ 77.500	100/ 100	100/ 100
Seattle	0.00/ 0.00	0.00/ 0.00	3.889/ 13.056	70.694/ 76.181	100/ 100	100/ 100

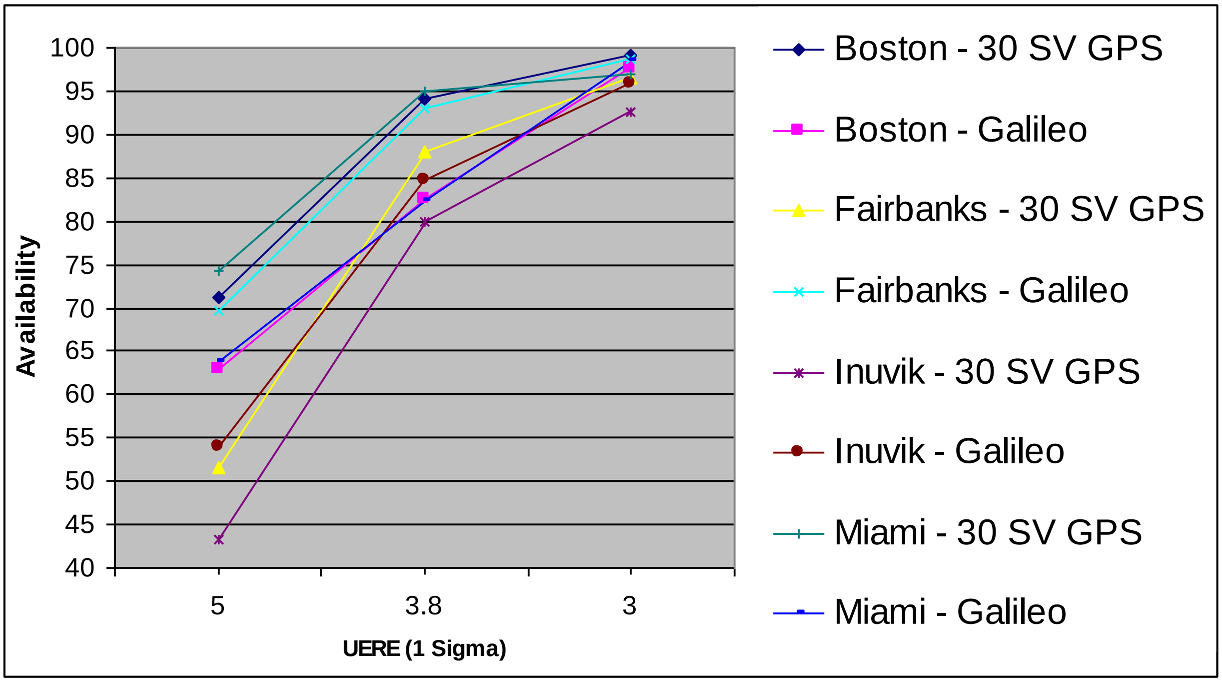

Figure 4 Location-Specific APV-I Availability for the 30 SV GPS and Galileo Constellations

SUMMARY / CONCLUSIONS

The analysis presented in this paper is a first look at the ability of standalone GPS to satisfy APV requirements. As expected, achieving high availability for APV is difficult, given the stringent vertical requirements for the approach phase of flight. It appears that in order to satisfy APV-I criteria with high availability, a UERE of less than 2.5m is required, possibly with a constellation of more than 24 satellites or use of baro aiding. With the far more stringent requirements needed for APV-II, it appears that a UERE of less than 1m will be required, again with a constellation of more than 24 satellites.

Since the purpose of this study was to determine if the ability of standalone satellite navigation without differential corrections is even feasible, extensive analysis of removing satellites from the constellation was not considered. Additional analyses will be performed with satellites removed from both the GPS and Galileo constellations, weighted by the appropriate constellation state probabilities. On the other hand, reducing the mask angle below 5^o will improve availability and this will be examined as well.

Also, further analysis of the frequency and duration of outages will be conducted in addition to evaluating the percentage availability. For example, when the outages occur, are there many short spikes of unavailability or are the outages fairly lengthy in duration? Understanding how they manifest can help determine the operational benefits.

Finally, how the outages are distributed geographically will be looked at, further examining the latitude dependence of APV availability.

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