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LAAS Availability Assessment: The Effects of Augmentations and Critical Satellites on Service Availability

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ABSTRACT

LAAS availability is affected by a number of factors including the number and accuracy of the ground reference receivers, the accuracy of the airborne receiver, the airfield location, the desired level of service, and the number and location of operational GPS satellites. Long-term service availability is determined by using a weighted average of the availability computed under different states of the satellite constellation.

This paper builds upon previous work performed during development of the availability appendix of the RTCA SC-159 LAAS Minimum Aviation System Specification (MASPS), which evaluated the projected performance of LAAS at select locations across the United States. In this paper availability is examined over a larger geographic region, and several augmented GPS constellations of 30 to 48 satellites are evaluated applying the failure and restoration model used in previous work to weight the number of operational satellites.

Other satellite augmentations to the LAAS such as geostationary, GLONASS, and Medium Earth Orbit (MEO) are evaluated to determine their improvement in availability and whether the requirements can be met for CAT I through CAT IIIb precision approach operations. The use of airport pseudolites (APLs) as an augmentation also is evaluated, including optimal placement of the APL to maximize availability. One goal of this paper is to illustrate the relative improvement in availability of each of these augmentations.

This paper also addresses the issue of Continuity of Service for Performance Type 2 & 3 Service. The signal in space allocation of continuity for LAAS uses the concept of the number of critical satellites. This paper examines the implications of this concept on the availability of LAAS service.

INTRODUCTION

Any landing system design requires a compromise between integrity and availability (or continuity). This is especially true for a DGPS-based system, since its guidance information is corrupted by random errors resulting from multipath and receiver noise effects. The performance of a DGPS landing system is continuously monitored by comparing pseudorange measurements (corrected for clock biases) among two or more receivers. A test statistic is defined as the difference between the average of pseudorange corrections for a particular satellite over all receivers and the average with one receiver excluded. There is a "B" (for bias) test statistic for each satellite and receiver combination. The Bs are transmitted to the airborne system which computes vertical and lateral protection limits (VPL and LPL) based on them. If a protection limit exceeds an alert limit which is a function of aircraft position along the approach path integrity cannot be guaranteed and the system is unavailable. VPL and LPL are functions of satellite geometry. Therefore, availability will vary as a function of time, the number of satellites in the GPS constellation, and the presence of augmentations such as airport pseudolites (APLs) or geostationary satellites.

Since the integrity requirements are very stringent for precision approach, this paper examines the availability provided by the proposed LAAS architecture with augmentations to the nominal 24-satellite GPS constellation, with a 30-satellite GPS constellation, airport pseudolites (APLs), space-based augmentation system (SBAS) satellites, i.e., with geosynchronous satellite ranging sources, and GLONASS satellites.

This paper first describes the analysis parameters used in this study and the local-area availability model, and then discusses the results and their implications for implementation of the LAAS system. Since LAAS vertical requirements are significantly more stringent than lateral ones, the analysis is based on VPL, not LPL.

The availability of LAAS service is compared for a number of different potential GPS augmentations. In all cases, uniform assumptions on satellite reliability were used so that the relative change in availability could be compared. These assumptions are somewhat conservative when compared to actual GPS operating experience. Hence the predicted availabilities are probably lower than the availability that would actually be achieved. However, the relative change in availability between the various augmentation options should be valid.

ANALYSIS PARAMETERS

The following analysis parameters selected to conduct this precision approach availability study are largely based on the criteria established by the RTCA SC-159 LAAS Working Group (WG-4):

The nominal GPS constellation used in this analysis is the 24-satellite constellation from RTCA SC-159 DO-229A Appendix B Table B-1 [1]. In addition to all 24 satellites operational, all combinations of 1, 2, 3, and 4 satellite failures, weighted according to the constellation state values in Table 1 from the LAAS MASPS [2], were examined in determining the availability of LAAS. A constellation of 30 satellites in three and six planes was examined in this analysis, as well as the Russian GLONASS constellation as defined in draft Appendix P to DO-229A.

A satellite mask angle of 5 degrees was applied in this analysis. Satellites above 5 degrees are weighted according to elevation angle, as discussed below. Some of the simulations were performed with an APL. When an APL was included in the simulation, it was placed near the runway coordinates in an optimum location. The noise for APLs was modeled as a linear function of range.

Table 1 Assumed Constellation Probabilities

Number of Operational Satellites (N)	Probability of N Operational Satellites
24	72.0 %
23	17.0 %
22	6.4 %
21	2.6 %
20	2.0 %

Models of the total GPS/LAAS signal-in-space (SIS) error and airborne error, as a function of GPS satellite elevation angle, are included in this analysis, as defined in the LAAS MASPS. Currently there are three ground accuracy designators (GAD): A, B, and C. GAD-C provides the highest level of accuracy and assumes use of a multipath limiting antenna. There are two airborne accuracy designators (AAD): A and B. AAD-B is the more accurate of the two and uses narrow correlator spacing.

For LAAS, continuity of function is a more stringent requirement than availability, i.e., if the system is likely to become unavailable during an approach it is better not to initiate the approach at all. In order to minimize missed approaches, the airborne system computes predicted protection levels prior to starting an approach, and declares the system unavailable if a predicted protection level exceeds an alert limit.

PVPL and PLPL are computed for both the H_0 and H_1 hypotheses:

$$PVPL_{H0} = K_{ffmd}\sqrt{\sum_{i=1}^{N} s_{i,vert}^2\sigma_i^2}$$

$$PVPL_{H1} = K_{ffd}\sigma_{B,vert} + K_{md}\sigma_{vert,H1}$$

where

S = $(H^TW^{-1}H)^{-1}H^TW^{-1}$, where $\mathbf{H}$ is the linear connection matrix and $\mathbf{W}$ is the weighting matrix

K_{ffmd} = multiplier which determines the probability of fault-free missed detection

$s_{i,vert} = s_{i,3} + s_{i,1} * \tan\theta_{GS}$ = projection of the vertical component for i^{th} ranging source

$s_{i,1}$ = i^{th} element of first column of S

$s_{i,3}$ = i^{th} element of third column of S
θ_{GS} = glidepath angle for the final approach path
N = number of ranging sources used in the position solution
i = ranging source index

$$\sigma^2_{i,H1} = \frac{M[i]\sigma^2_{pr\_gnd}[i]}{M[i]-1} + \sigma^2_{pr\_air}[i] + \sigma^2_{tropo}[i]$$

$$\sigma^2_{vert,H1} = \sum_{i=1}^{N} s^2_{i,vert}\sigma^2_{i,H1}$$

K_{ffd} = multiplier which determines the probability of fault-free detection given M reference receivers

$$\sigma_{B,vert} = \sqrt{\sum_{i=1}^{N} s^2_{i,vert}\frac{\sigma^2_{pr\_gnd}[i]}{(M[i]-1)}}$$

The integrity and continuity of function requirements for a landing system are ultimately derived from a required overall level of safety. For LAAS, RTCA SC-159 WG4 is currently taking the approach of adapting ILS requirements established by the International Civil Aviation Organization (ICAO). Such an adaptation is not an entirely straightforward process since DGPS and ILS function very differently, have different error characteristics, and have different failure modes. Table 2 shows the requirements, which represent current WG4 thinking, used in this study.

Table 2 LAAS Signal-in-Space Integrity and Continuity Requirements

Performance Type	LAAS SIS Integrity	LAAS SIS Continuity
1	2×10^{-7}/ approach	8×10^{-6}/15 seconds
2	10^{-9}/approach	4×10^{-6}/15 seconds
3	10^{-9}/approach	2×10^{-6}/15 seconds (vert) 2×10^{-6}/30 seconds (lat)

The multipliers K_{md} and K_{ffmd} are determined from the LAAS SIS integrity and continuity requirements, respectively. The missed detection multiplier (K_{md}) must be made large enough to ensure that the probability of failing to detect an error of hazardous magnitude in a broadcast pseudorange correction is less than the integrity requirement given in Table 2. The fault free missed detection multiplier (K_{ffmd}) must be sufficiently small to guarantee that there are not too many false alarms to meet the continuity requirement in Table 2.

The LAAS vertical and lateral alert limits (VAL and LAL) recommended by RTCA are shown in Table 3. These were the values used in this analysis. VAL and LAL increase as distance from the decision point increases. Values shown are minimum limits at the decision point.

Table 3 Lateral and Vertical Alert Limits

Performance Type	LAL	VAL
1	40.0 m	10.0 m
2	17.3 m	5.3 m
3	15.5 m	5.3 m

Table 4 presents results for long-term availability at Seattle for all combinations of ground station facility classes and airborne accuracy designators. This simulation assumed a 24-satellite GPS constellation, no APLs and no geostationary satellites. Note that the system was never considered to be available for Performance Types 2 and 3 (equivalent to Category II and III) with only two operating reference receivers in the ground station.

The simulation was then run for seven locations with all ground accuracy designators, but only airborne accuracy designator A. The results are shown in Table 5. The LAAS MASPS does not establish precise availability requirements since these will depend on operational considerations for any particular installation. The MASPS specifies availability to be in the range of 0.99 to 0.99999.

LAAS AVAILABILITY AT ADDITIONAL LOCATIONS

As shown in Table 5, LAAS availability does vary by location. Although this is not surprising, given the variation in satellite geometry, it is interesting to note that locations at lower latitudes appear to have slightly lower availability. Further examination of VDOP distribution for these locations, as given in Table 6 and described in Annex B of the GPS SPS Signal Specification [3], confirms this geographic variation. LAAS availability for PT1 at seven additional locations within North America are provided in Table 7.

Table 4 Long Term Availability of Service at Seattle

	Airborne Accuracy Designator – A			Airborne Accuracy Designator - B		
Ground Accuracy Designator	Performance Type 1 AAD=A	Performance Type 2 AAD=A	Performance Type 3 AAD=A	Performance Type 1 AAD=B	Performance Type 2 AAD=B	Performance Type 3 AAD=B
A2	92.168%	N/A	N/A	92.821%	N/A	N/A
A3	99.531%	5.963%	3.634%	99.558%	8.242%	6.352%
A4	99.761%	65.233%	61.799%	99.779%	71.536%	68.818%
B2	99.815%	N/A	N/A	99.838%	N/A	N/A
B3	99.912%	99.107%	99.049%	99.930%	99.420%	99.378%
B4	99.922%	99.490%	99.487%	99.950%	99.689%	99.678%
C2	99.914%	N/A	N/A	99.931%	N/A	N/A
C3	99.939%	99.615%	99.614%	99.957%	99.748%	99.739%
C4	99.943%	99.640%	99.640%	99.958%	99.834%	99.831%

Table 5 Long Term Availability of Performance Type 1 Service for 7 Locations (Airborne Equipment Class A)

Ground Accuracy Designator	Seattle	Chicago	New York	Dallas	Los Angeles	Anchorage	Miami
A2	92.168	87.133	89.187	83.323	86.894	88.299	83.544
A3	99.531	99.320	99.531	99.306	99.354	98.948	99.340
A4	99.761	99.750	99.830	99.730	99.774	99.637	99.798
B2	99.815	99.827	99.869	99.792	99.843	99.731	99.863
B3	99.912	99.932	99.935	99.894	99.927	99.921	99.947
B4	99.922	99.940	99.942	99.901	99.935	99.931	99.952
C2	99.914	99.933	99.937	99.888	99.923	99.927	99.946
C3	99.939	99.950	99.950	99.907	99.941	99.946	99.960
C4	99.943	99.952	99.952	99.908	99.942	99.948	99.962

Table 6 Distribution of VDOP

Location	Latitude	Max.	Avg.	Std.
Anchorage	61.17°N	2.742	1.558	0.3062
Seattle	47.45°N	2.573	1.539	0.3343
Chicago	41.98°N	2.577	1.551	0.3577
New York	40.63°N	2.449	1.526	0.2865
Los Angeles	33.93°N	2.853	1.564	0.3298
Dallas	32.95°N	2.589	1.561	0.3433
Miami	25.80°N	2.804	1.555	0.3235

IMPROVED LAAS AVAILABILITY WITH ADDITIONAL SATELLITES

The availability of LAAS service has been evaluated for a number of hypothetical expanded GPS constellations ranging from 24 to 48 satellites. There has been serious discussion of increasing the number GPS satellites [4,5,6,7]. Also, there are other initiatives such as the European studies for GNSS2 [8,9,10,11] and the Boeing MEO system [12] that may result in additional navigation satellites being available in the future. Therefore, there is interest is determining how much the availability of LAAS precision approach services is increased as satellites are added to the constellation.

Table 7 Long Term Availability of Performance Type 1 Service for 7 Locations (Airborne Equipment Class A)

Ground Accuracy Designator	San Antonio	New Orleans	Nashville	Fairbanks	Denver	Bangor	Great Falls
A2	83.399	83.962	83.118	80.710	83.997	92.049	93.771
A3	99.392	99.377	99.203	98.175	99.351	99.560	99.642
A4	99.783	99.805	99.651	99.541	99.795	99.796	99.828
B2	99.777	99.792	99.643	99.393	99.777	99.791	99.835
B3	99.928	99.927	99.790	99.851	99.905	99.917	99.922
B4	99.943	99.937	99.810	99.882	99.921	99.926	99.932
C2	99.943	99.934	99.804	99.918	99.924	99.928	99.923
C3	99.958	99.951	99.828	99.943	99.939	99.945	99.948
C4	99.960	99.953	99.830	99.945	99.941	99.947	99.949

Table 8 summarizes the availability of various levels of service given various levels of ground station and airborne equipment accuracy and 4 different satellite constellations. The ground Accuracy Designator (GAD), Airborne Accuracy Designators (AAD) and Performance Types (PT) are as described in the LAAS MASPS [2]. The GPS 24 constellation is the Martinez constellation defined in the WAAS MOPS Appendix B [13]. The other three constellations are hypothetical GPS constellations, which increase the number of satellites to 30 or 33. Two of these constellations have the satellites organized into 3 planes rather than 6. These hypothetical constellations have been used in a number of studies done by Boeing and the Aerospace Corp. [6,7]. The placement of the satellites within these constellation have been carefully optimized to provide high availability of good vertical geometry.

The availability analysis is based on computing service availability for randomly chosen times with 0 to 6 satellites removed from the constellation. The overall long term availability is then computed by weighting the results by an assumed probability of being in the particular constellation state. These constellation state probabilities were determined using a Markov Model as described in [14]. The Markov model determines the probability of a constellation being in a particular state (i.e. having a certain number of satellites unavailable) given an assumed Mean Time Before Failure (MTBF) and Mean Time To Repair (MTTR) for the satellites. The MTBF and MTTR values assumed in this study are the same as those assumed in [14]. These values are summarized in Table 9.

Additional studies have also been conducted with look at the availability of LAAS service when the GPS constellation is augmented with an additional complementary constellation of Medium Earth Orbit satellites. Walker has developed a simple method for describing constellations of satellites [15,16,17]. Using Walker's method, a constellation is described by the triplet (T/P/F) where:

- T - is the number of satellites in the constellation.
- P - is the number of equally-spaced orbital planes.
- F - defines the relative phasing of satellites in adjacent planes in units of 360 divided by T.

This triplet, along with the semimajor axis and inclination completely describes a satellite constellation configuration. In all the cases studied, the semimajor axis was assumed to be equal to the nominal GPS quantity of 26,559.145 km and the orbital plane inclination was set to 51 degrees (with the exception of 16/16/3 which used a 53 degrees inclination). The first orbital plane is assumed to cross the equator at 0° longitude.

Table 8 Long Term Availability of LAAS Service for 4 Different Constellations as Observed From Seattle.

AD and Performance Type			GPS 24	GPS 30x3	GPS 30x6	GPS 33x3
GAD	AAD	PT				
A2	A	1	94.0938	98.1232	99.3079	99.905
A3	A	1	99.7398	99.9646	99.9562	99.992
A3	A	3	6.0093	13.2712	31.2375	37.094
A4	A	1	99.8849	99.9876	99.989	>99.999
A4	A	3	65.0438	91.877	88.07	98.227
B2	B	1	99.8893	99.9888	99.9891	>99.999
B3	B	1	99.9538	99.9952	99.9981	>99.999
B3	B	3	99.2385	99.8931	99.8786	99.968
B4	B	1	99.9635	99.9956	99.9993	>99.999
B4	B	3	99.7039	99.9642	99.9427	99.989
C2	B	1	99.9663	99.9951	99.9984	>99.999
C3	B	1	99.9776	99.9957	99.9995	>99.999
C3	B	3	99.8542	99.9845	99.9811	99.999
C4	B	1	99.978	99.9957	99.9995	>99.999
C4	B	3	99.9018	99.9896	99.9963	>99.999

Table 9 Assumed Satellite Reliability used in Evaluating Expanded Constellations

Long Term MTBF	124 months
Long Term MTTR	1 month
Short Term MTBF	7300 hours
Short Term MTTR	36 hours
Maneuver MTBF	6 months
Maneuver MTTR	4 hours

Table 10 summarizes the availability of LAAS service when GPS is augmented with 5 different GPS-like MEO constellations consisting of 12 to 24 satellites. The availability provided by the 3 hypothetical GPS constellations discussed earlier is included also for comparison purposes. The results are ordered according to increasing availability. The results show that very high availability is obtained when 9 or more satellites are added to the basic GPS constellation. Also, the results show that optimal placement of the satellites is important. For example the GPS 33x3 constellation provides better availability than the combination of GPS with independent 12 or 16 satellite constellations which are not added in an integrated or optimized manner.

Table 10 Performance Type 3 Service Availability at Seattle for GAD C3 and AAD B

Constellation	Availability %
16 MEO Stand Alone (16/16/3)	71.497
12/3/2	85.552
24/6/1	99.708
24/3/1	99.816
24 GPS (Martinez)	99.850
24/3/2	99.925
GPS 30x6	99.981
GPS 30x3	99.985
24 GPS (Martinez) + 16 AIS (16/16/3)	99.996
24 GPS (Martinez) + 12/3/2	99.998
GPS 33x3	99.999
24 GPS (Martinez) + 24/6/1	>99.999
24 GPS (Martinez) + 24/3/1	>99.999
24 GPS (Martinez) + 24/3/2	>99.999

GEOSTATIONARY SATELLITES

Another possible augmentation to improve availability is to use additional ranging sources provided by geostationary satellites, i.e., a space-based augmentation system (SBAS). Long-term availability was computed assuming 3 geostationary satellites covering the U.S. at 15.5° W, 55.5° W and 179.5° W. Availability of ranging signals from the geostationary satellites was provided by A.J. Van Dierendonck. These values are shown in Table 11. Table K2 shows the long term service availability at 3 locations for Performance Type 3 service when SBAS ranging sources are added to the mix of ranging sources used in the position solution and VPL computations.

Table 11 Geostationary Satellite Signal Availability

Number of Geos	Availability
3	0.971734
2	0.027863
1	0.000400
0	0.000003

GLONASS

Availability improvement by augmenting GPS with GLONASS was examined using the nominal GLONASS constellation as provided in the draft Appendix P to RTCA SC-159 DO-229A. Although the GLONASS constellation currently has its problems due to lack of satellites and operational maintainability, it may be available in the future. Even if the Russians do not maintain 24 satellites, there will be benefit just in having additional satellites available. Therefore, in addition to examining a full 24 satellite constellation, one and two planes of eight satellites also were examined. The same constellation state probabilities were applied to GLONASS since these are assumed to be fairly conservative

Table 12 Long Term Availability of Performance Type 3 Service for 3 Locations With SBAS Satellites (Airborne Equipment Class A)

Ground Accuracy Designator	Seattle No SBAS Ranges	Seattle With SBAS Ranges	Miami No SBAS Ranges	Miami With SBAS Ranges	New York No SBAS Ranges	New York With SBAS Ranges
A3	3.634	10.515	0.000	0.232	3.350	4.962
A4	61.799	79.640	40.552	57.187	47.362	63.473
B3	99.049	99.745	96.970	99.533	98.691	99.603
B4	99.487	99.903	99.234	99.885	99.420	99.867
C3	99.614	99.974	99.519	99.939	99.639	99.910
C4	99.640	99.976	99.587	99.959	99.669	99.927

Table 13 Long Term Service Availability for Seattle Using GPS and GLONASS

AD and Performance Type			GPS 24	GPS 24 GLONASS 24	GPS 24 GLONASS 16	GPS 24 GLONASS 8
GAD	AAD	PT				
A2	A	1	94.093	>99.999	99.979	99.678
A3	A	1	99.739	>99.999	99.999	99.943
A3	A	3	6.009	98.916	82.529	33.864
A4	A	1	99.884	>99.999	>99.999	99.980
A4	B	3	65.043	99.983	99.696	92.217
B2	B	1	99.889	>99.999	>99.999	99.978
B3	B	1	99.953	>99.999	>99.999	99.990
B3	B	3	99.238	>99.999	99.996	99.890
B4	B	1	99.963	>99.999	>99.999	99.991
B4	B	3	99.703	>99.999	99.999	99.932
C2	B	1	99.966	>99.999	>99.999	99.991
C3	B	1	99.977	>99.999	>99.999	99.994
C3	B	3	99.854	>99.999	>99.999	99.984
C4	B	1	99.978	>99.999	>99.999	99.994
C4	B	3	99.901	>99.999	>99.999	99.987

AIRPORT PSEUDOLITES

A leading candidate to augment the GPS LAAS is the use of Airport Pseudolites (APLs). This section addresses the availability improvement for seven locations using one or two optimally placed APLs.

To optimize APL siting, an iterative search was performed using a degraded state of the Martinez 24 constellation, P(22 operational) = 1.0. The APL was assumed to be available 100% of the time. The optimal location is directly below the aircraft, but that is impractical in actual implementation. Therefore, the APL was placed at a distance of 1 nmi from the aircraft, and the aircraft height was chosen as a function of performance type. The tightest requirements for vertical navigation system error (NSE) limits occur at 100-200 ft for PT1, 50-100 ft for PT2 and 0-100 ft for PT3 [2]. The elevation angle to the APL was derived from the aircraft heights listed in Table 14 which represent the mid range values.

Table 14 Pseudolite Location Relative to Aircraft

Performance Type	Aircraft Height	APL Elevation
PT 1	150 ft	-1.414°
PT 2	75 ft	-0.707°
PT 3	50 ft	-0.471°

The search was performed for Airborne Accuracy Designator A, Ground Accuracy Designator C4. Pseudolites are most likely to be implemented to improve LAAS PT3 service availability, which is why GAD C4 was chosen for the optimization. For the one APL case, the pseudolite was placed at 36 azimuths in 10° increments. A time step of 1200 seconds was used and availability was assessed for performance types 1, 2 and 3 over one day. The APL placement was subsequently fine tuned using a 2° search increment over a smaller region determined by the results of the initial search.

For two APLs the search was performed for Airborne Accuracy Designator A, Ground Accuracy Designator C4 as well. However, other states such as GAD B3 were used if needed to differentiate among the azimuths that had equal availability for GAD C4. For simplicity, one APL was kept at the optimal single-pseudolite azimuth, and a search using a 10° increment was conducted for the second APL. A fine tuning step was then performed using a 2° increment. The results of the search are given in Table 14, which shows the chosen azimuth angles. There could be a more optimal way of siting two APLs, but this method yields a probability that the remaining APL would be at the optimal location if one failed.

Table 15 Optimal Azimuths for APL Siting

Location	One APL	Two APLs
Seattle	182°	[182°, 357°]
Miami	0°	[0°, 200°]
NY JFK	336°	[336°, 147°]
Chicago	74°	[74°, 240°]
Dallas	14°	[14°, 192°]
Los Angeles	242°	[242°, 76°]
Anchorage	174°	[174°, 254°]

It is interesting to note the optimal placement as a function of airport location. The greatest availability enhancement for Miami and Dallas is predicted using a northerly APL placement, while Seattle and Anchorage benefit more from southerly APL placements. Placing APLs to the north and south often provides the optimal placement for two pseudolites.

LAAS availability was determined for each location using zero, one and two APLs. The results are shown in Tables Table 16-Table 18 for Performance Type 1, 2 and 3.

For comparison, availability results were computed for Seattle using suboptimal pseudolite placement. The search methodology used to determine the optimal pseudolite siting was also be used to identify regions where pseudolites are a less effective augmentation. For

Seattle, a suboptimal siting is 350° for one APL and [0°, 330°] for two APLs. The results are shown in Table 19.

The results show that there is still an availability enhancement from poorly placed APLs, but the impact is diminished. This also shows that availability should not be predicted using optimal APL placement because the azimuth and elevation of the pseudolite changes relatively quickly as the aircraft approaches the runway. Therefore, the true availability lies somewhere between the best and worst case APL siting for a given airport.

Table 16 Long Term Service Availability of Performance Type 1 Service for 7 Locations (Airborne Accuracy Designator A)

Seattle	No APL	1 APL	2 APLs
GAD A3	99.531%	99.924%	>99.999%
GAD A4	99.761%	99.959%	>99.999%
GAD B3	99.897%	99.986%	>99.999%
GAD B4	99.911%	99.989%	>99.999%
GAD C3	99.939%	99.991%	>99.999%
GAD C4	99.943%	99.991%	>99.999%
Miami	No APL	1 APL	2 APLs
GAD A3	99.340%	99.974%	>99.999%
GAD A4	99.798%	99.988%	>99.999%
GAD B3	99.935%	99.995%	>99.999%
GAD B4	99.945%	99.996%	>99.999%
GAD C3	99.960%	99.996%	>99.999%
GAD C4	99.962%	99.997%	>99.999%
NY JFK	No APL	1 APL	2 APLs
GAD A3	99.531%	99.920%	>99.999%
GAD A4	99.830%	99.951%	>99.999%
GAD B3	99.924%	99.979%	>99.999%
GAD B4	99.933%	99.983%	>99.999%
GAD C3	99.950%	99.986%	>99.999%
GAD C4	99.952%	99.987%	>99.999%
Chicago	No APL	1 APL	2 APLs
GAD A3	99.320%	99.949%	99.999%
GAD A4	99.750%	99.972%	>99.999%
GAD B3	99.919%	99.985%	>99.999%
GAD B4	99.931%	99.988%	>99.999%
GAD C3	99.950%	99.992%	>99.999%
GAD C4	99.952%	99.992%	>99.999%
Dallas	No APL	1 APL	2 APLs
GAD A3	99.325%	99.946%	>99.999%
GAD A4	99.756%	99.976%	>99.999%
GAD B3	99.910%	99.987%	>99.999%
GAD B4	99.928%	99.989%	>99.999%
GAD C3	99.946%	99.992%	>99.999%
GAD C4	99.947%	99.992%	>99.999%
LAX	No APL	1 APL	2 APLs
GAD A3	99.354%	99.947%	99.999%
GAD A4	99.774%	99.974%	>99.999%
GAD B3	99.906%	99.986%	>99.999%
GAD B4	99.925%	99.988%	>99.999%
GAD C3	99.941%	99.990%	>99.999%
GAD C4	99.942%	99.990%	>99.999%
Anchorage	No APL	1 APL	2 APLs
GAD A3	98.948%	99.988%	99.997%
GAD A4	99.637%	99.996%	99.998%
GAD B3	99.895%	99.997%	99.999%
GAD B4	99.915%	99.998%	99.999%
GAD C3	99.946%	99.998%	>99.999%
GAD C4	99.948%	99.998%	>99.999%

Table 17 Long Term Service Availability of Performance Type 2 Service for 7 Locations (Airborne Accuracy Designator A)

Seattle	No APL	1 APL	2 APLs
GAD A3	5.963%	62.330%	99.157%
GAD A4	65.233%	94.846%	99.831%
GAD B3	98.432%	99.574%	99.926%
GAD B4	99.241%	99.775%	99.966%
GAD C3	99.615%	99.850%	99.961%
GAD C4	99.640%	99.898%	99.979%
Miami	No APL	1 APL	2 APLs
GAD A3	0.000%	61.405%	92.478%
GAD A4	45.679%	89.655%	99.586%
GAD B3	93.523%	99.367%	99.842%
GAD B4	98.605%	99.755%	99.965%
GAD C3	99.527%	99.882%	99.968%
GAD C4	99.587%	99.941%	99.983%
NY JFK	No APL	1 APL	2 APLs
GAD A3	4.117%	57.919%	99.120%
GAD A4	52.063%	93.282%	99.792%
GAD B3	97.159%	99.443%	99.936%
GAD B4	99.092%	99.782%	99.967%
GAD C3	99.640%	99.886%	99.969%
GAD C4	99.669%	99.907%	99.980%
Chicago	No APL	1 APL	2 APLs
GAD A3	6.707%	62.710%	95.013%
GAD A4	55.341%	95.353%	99.685%
GAD B3	93.551%	99.327%	99.895%
GAD B4	98.875%	99.838%	99.962%
GAD C3	99.466%	99.848%	99.964%
GAD C4	99.526%	99.896%	99.979%
Dallas	No APL	1 APL	2 APLs
GAD A3	0.000%	52.740%	94.171%
GAD A4	43.471%	93.156%	99.711%
GAD B3	92.874%	99.371%	99.912%
GAD B4	97.765%	99.774%	99.971%
GAD C3	99.499%	99.879%	99.973%
GAD C4	99.545%	99.916%	99.985%
LAX	No APL	1 APL	2 APLs
GAD A3	0.000%	49.625%	97.525%
GAD A4	46.328%	91.176%	99.596%
GAD B3	95.869%	99.196%	99.886%
GAD B4	98.542%	99.667%	99.963%
GAD C3	99.515%	99.825%	99.965%
GAD C4	99.551%	99.887%	99.981%
Anchorage	No APL	1 APL	2 APLs
GAD A3	1.075%	80.370%	98.429%
GAD A4	49.676%	98.582%	99.431%
GAD B3	95.562%	99.507%	99.770%
GAD B4	97.901%	99.778%	99.934%
GAD C3	99.366%	99.868%	99.964%
GAD C4	99.409%	99.950%	99.986%

Table 18 Long Term Service Availability of Performance Type 3 Service for 7 Locations (Airborne Accuracy Designator A)

Seattle	No APL	1 APL	2 APLs
GAD A3	3.634%	56.389%	99.004%
GAD A4	61.799%	94.651%	99.788%
GAD B3	97.932%	99.850%	99.916%
GAD B4	99.223%	99.764%	99.963%
GAD C3	99.614%	99.842%	99.955%
GAD C4	99.640%	99.891%	99.977%
Miami	No APL	1 APL	2 APLs
GAD A3	0.000%	53.741%	91.282%
GAD A4	40.552%	88.295%	99.465%
GAD B3	93.013%	99.166%	99.811%
GAD B4	98.396%	99.715%	99.960%
GAD C3	99.519%	99.858%	99.964%
GAD C4	99.587%	99.939%	99.982%
NY JFK	No APL	1 APL	2 APLs
GAD A3	3.350%	50.587%	98.923%
GAD A4	47.362%	92.469%	99.750%
GAD B3	96.876%	99.382%	99.928%
GAD B4	99.051%	99.770%	99.964%
GAD C3	99.639%	99.878%	99.966%
GAD C4	99.669%	99.906%	99.979%
Chicago	No APL	1 APL	2 APLs
GAD A3	4.352%	55.508%	93.587%
GAD A4	52.032%	90.198%	99.616%
GAD B3	93.196%	99.260%	99.874%
GAD B4	98.834%	99.657%	99.957%
GAD C3	99.463%	99.835%	99.960%
GAD C4	99.526%	99.894%	99.977%
Dallas	No APL	1 APL	2 APLs
GAD A3	0.000%	45.394%	92.910%
GAD A4	39.790%	88.372%	99.670%
GAD B3	92.331%	99.303%	99.896%
GAD B4	97.586%	99.755%	99.968%
GAD C3	99.493%	99.872%	99.970%
GAD C4	99.545%	99.913%	99.984%
LAX	No APL	1 APL	2 APLs
GAD A3	0.000%	39.498%	96.256%
GAD A4	42.594%	89.961%	99.509%
GAD B3	95.251%	99.119%	99.855%
GAD B4	98.501%	99.633%	99.959%
GAD C3	99.504%	99.806%	99.960%
GAD C4	99.551%	99.885%	99.979%
Anchorage	No APL	1 APL	2 APLs
GAD A3	0.234%	75.321%	97.960%
GAD A4	46.402%	98.418%	99.350%
GAD B3	95.085%	99.469%	99.736%
GAD B4	97.879%	99.746%	99.925%
GAD C3	99.365%	99.854%	99.953%
GAD C4	99.409%	99.948%	99.985%

Table 19 LAAS Long Term Service Availability for Seattle with Suboptimal APL Siting

Seattle PT1	No APL	1 APL (suboptimal)	2 APLs (suboptimal)
GAD A3	99.531%	99.794%	99.841%
GAD A4	99.761%	99.885%	99.909%
GAD B3	99.897%	99.949%	99.975%
GAD B4	99.911%	99.957%	99.979%
GAD C3	99.939%	99.974%	99.985%
GAD C4	99.943%	99.975%	99.985%
Seattle PT2	No APL	1 APL (suboptimal)	2 APLs (suboptimal)
GAD A3	5.963%	59.434%%	72.761%
GAD A4	65.233%	87.684%	92.479%
GAD B3	98.432%	99.263%	99.443%
GAD B4	99.241%	99.625%	99.681%
GAD C3	99.615%	99.770%	99.792%
GAD C4	99.640%	99.785%	99.807%
Seattle PT3	No APL	1 APL (suboptimal)	2 APLs (suboptimal)
GAD A3	3.634%	54.722%	70.769%
GAD A4	61.799%	86.532%	91.496%
GAD B3	97.932%	99.189%	99.403%
GAD B4	99.223%	99.614%	99.670%
GAD C3	99.614%	99.761%	99.769%
GAD C4	99.640%	99.784%	99.806%

CRITICAL SATELLITES

The concept of critical satellites arises from the allocation of continuity to various parts of the LAAS. This allocation is described in Appendix C of the LAAS MASPS [2]. The overall SIS continuity requirements specified in Section 3.1.2.3 of the LAAS MASPS are sub-allocated among two basic sources of continuity risk: loss of the VHF data broadcast (VDB) and the possibility of a position error protection limit exceeding the required alert limit. Unexpected occurrences of protection limits exceeding alert limits are further subdivided into two categories: those that involve configuration changes and those that do not. Configuration changes are defined to be unexpected events that cause the loss of one or more ranging sources or reference receivers. Protection limits can exceed alert limits without any configuration changes due to data sent by the ground, such as increases in bias values, B_i, and/or sigma values for one or more ranging corrections. PVPL was designed to account for the continuity of protection levels without a configuration change. Far trickier is the allocation of continuity across all the elements that can cause an unexpected configuration change.

Figure 1 shows an example allocation of continuity risk for Performance Type 1. The driving factor in the sub-allocation of the PL > AL continuity risk between 'configuration changes' and 'no configuration changes' is the mean time between unexpected satellite outages. In the PT 1 case, the assumed receiver failure rate is also very important when only two reference receivers are used. The satellite MTBO (over all causes of satellite failures and losses of satellite tracking) is conservatively assumed to be 5550 hours. Given the total continuity risk allocated to PL > AL, the resulting failure rate (~ 7.5×10^{-7} over 15 seconds per satellite) limits N_C, which is the number of *critical satellites* whose failure can not be tolerated without losing continuity for an available geometry. (A critical satellite is one whose loss would cause PL > AL.) Since the continuity allocation is based on N_C then the availability is predicated on there being no more than N_C critical satellites. This might imply that the airborne receiver will check to determine that there are no more than N_C critical satellites when making the determination if a given geometry meets the continuity requirements. This would be done by computing the protection levels for all subset geometries with one satellite removed and counting the number of subset geometries with PL>AL. If the number of subset geometries with PL>AL is > N_C then the service is unavailable because the continuity is not met. To maximize availability, the continuity budget should be defined such that the system will tolerate geometries with as many critical satellites as possible.

In the PT 1 case shown Figure 1, N_C is set to be 6, which eliminates practically no geometries. (This will be shown later). However, a high value for N_C increases the 'SV loss' continuity sub-allocation and therefore reduces the remaining continuity risk that can be allocated elsewhere. In addition to 'SV loss', configuration changes can occur due to reference receiver failures and integrity warnings from ground monitoring under fault-free conditions. 'False alarms' from integrity monitoring are allocated a very small portion of the continuity risk budget because, as noted above, the achievable satellite MTBO is out of the control of LAAS and uses up most of the continuity risk requirement for reasonably high values of N_C.
The remaining continuity risk is then allocated to the 'no configuration change' event, which defines the value of K_{ffd} in the protection limit equations. Because decreasing the 'no configuration change' allocation has only a small effect on K_{ffd}, there is no substantial loss of availability due to the low continuity allocation for this event.

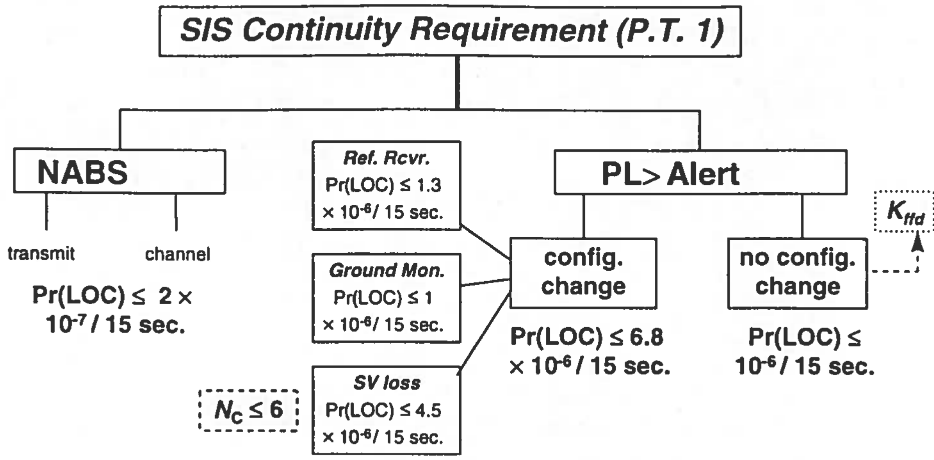

Figure 1 Example Continuity Allocation for PT 1

Some preliminary work has been done to assess the impact of critical satellites on system availability. The analysis was performed by through a Monte Carlo simulation where geometries were generated for randomly sampled times and constellation states at a particular location. At each time and space point, the protection levels were computed as well as the set of protection levels resulting from all of the subset geometries with one satellite removed. The subset protection levels were then ordered and the results were saved in order to develop statistics on the availability of the nth largest subset protection level.

Figure 2 illustrates the effect of Critical satellites on the availability of PT 3 service at Seattle with a GAD C3 and AAD B assuming 24 GPS satellites. In all cases same assumptions on constellation state probabilities were used as those defined in the LAAS MASPS availability appendix. These constellation state values are given in Table 1.

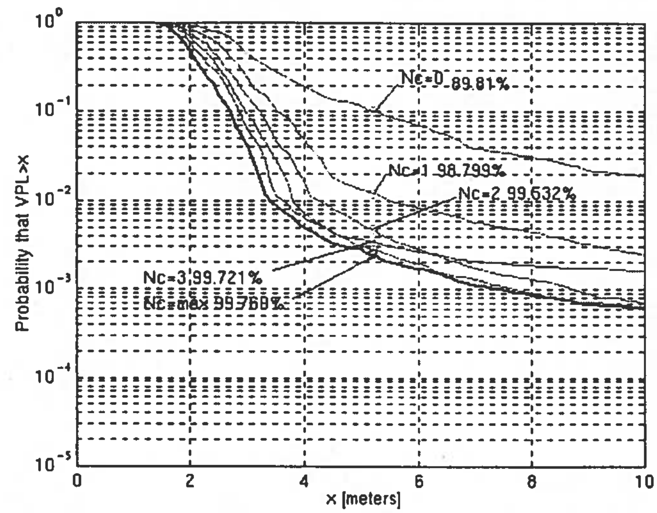

Figure 2 VPL Unavailability for PT 3 with Critical Satellites - GAD C3 AAD B as Observed at Seattle Using the Martinez Constellation

The solid bold line Figure 2 indicates the unavailability of service if all the visible satellites are used. This curve shows the availability of service is 99.76%. The top curve corresponds to the unavailability of service if the tolerable number of critical satellites is 0. In other words, if all of the subset VPL calculations must meet the protection level requirement, the availability is driven by the largest subset VPL. The top curve shows the statistics of the largest subset VPL. The second curve down represents the statistics for the 2nd to the largest subset VPL and so forth. Note the availability of service if N_c=0 (i.e. the largest subset must meet the requirement) is only about 89.81%. The availability with one critical satellite (N_c=1 or the 2nd largest subset must meet the requirement) is much better at about 98.799%. The case of N_c=2 is even better with availability of 99.532%. So, if N_c=0 nearly two orders of magnitude of availability are lost. If N_c=1 approximately one order of magnitude in availability is lost and if N_c=2 the loss is fairly small.

Table 20 gives a summary of the availability for 4 different combinations of ground accuracy, airborne accuracy and PT. This analysis was run for an observer at Seattle and the Phlong and Elrod [14] satellite availability assumptions were used to weight the constellation failure states. The assumed constellation states given in Table 1 could not be used because constellations with more than 24 satellites were considered. The table includes results for four different satellite constellations. Only the VPL was considered. Even with constellations of 30 satellites, a constraint of N_c=0 lowers the availability below 99.9%. In all cases, there is very little difference between availability constrained by N_c=4 and N_c=N (i.e. all satellites could be critical or availability is not predicated on any subset VPL).

Table 20 Summary of Effect of Critical Satellites on Service Availaiblity

	Facility Class and PT	All Satellites Used	N_c=4	N_c=3	N_c=2	N_c=1	N_c=0
24 Satellites	PT 1 GAD A3 AAD A	0.99740	0.99679	0.99598	0.99306	0.98244	0.83623
	PT 1 GAD C3 AAD B	0.99978	0.99943	0.99977	0.99973	0.99915	0.98851
	PT 3 GAD C3 AAD B	0.99854	0.99806	0.99810	0.99680	0.99152	0.90413
	PT 3 GAD C4 AAD B	0.99902	0.99870	0.99884	0.99838	0.99470	0.94069
30 Satellites in 3 Planes	PT 1 GAD A3 AAD A	0.99965	0.99951	0.99924	0.99817	0.99705	0.98231
	PT 1 GAD C3 AAD B	0.99996	0.99986	0.99999	1.00000	0.99993	0.99848
	PT 3 GAD C3 AAD B	0.99985	0.99977	0.99976	0.99896	0.99818	0.99258
	PT 3 GAD C4 AAD B	0.99990	0.99981	0.99989	0.99972	0.99872	0.99522
30 Satellites in 6 Planes	PT 1 GAD A3 AAD A	0.99956	0.99946	0.99933	0.99903	0.99808	0.97613
	PT 1 GAD C3 AAD B	0.99999	0.99999	0.99999	0.99999	0.99996	0.99970
	PT 3 GAD C3 AAD B	0.99981	0.99978	0.99977	0.99965	0.99930	0.99080
	PT 3 GAD C4 AAD B	0.99996	0.99995	0.99994	0.99992	0.99963	0.99780
24 GPS + 16 MEO Satellites	PT 1 GAD A3 AAD A	0.99996	0.99987	0.99980	0.99973	0.99926	0.99729
	PT 1 GAD C3 AAD B	1.00000	1.00000	1.00000	1.00000	1.00000	0.99999
	PT 3 GAD C3 AAD B	0.99997	0.99997	0.99997	0.99990	0.99983	0.99879
	PT 3 GAD C4 AAD B	0.99998	0.99998	0.99998	0.99997	0.99996	0.99963

TRADEOFF OF CONTINUITY VS. AVAILABILITY

The FAA Concept of Operations (CONOPS) Team requested RTCA WG4A to examine the tradeoff of an increased risk in continuity vs. improvement in overall availability for Performance Type1. Their goal was to have at least four 9's of availability for PT1. Continuity risk was increased from the stated requirement of 10^{-6} to 10^{-5}, 10^{-4}, and 10^{-3} and the predicted VPL compared to the alert limit of 10m. The results are provided in Table 21. Unfortunately, there was little or no improvement in availability. This is due to the fact that the availability is driven by the null hypothesis ($PVPL_{H0}$).

Table 21 Long Term Service Availability at Seattle (Availability Accuracy Designator A)

Ground Accuracy Designator	Continuity			
	$=1\times10^{-6}$	$=1\times10^{-5}$	$=1\times10^{-4}$	$=1\times10^{-3}$
A2	92.168%	94.335%	97.314%	98.669%
A3	99.531%	99.585%	99.631%	99.668%
A4	99.761%	99.762%	99.762%	99.762%
B2	99.759%	99.780%	99.811%	99.842%
B3	99.897%	99.901%	99.903%	99.903%
B4	99.911%	99.911%	99.911%	99.911%
C2	99.914%	99.920%	99.934%	99.935%
C3	99.939%	99.939%	99.939%	99.939%
C4	99.943%	99.943%	99.943%	99.943%

However, if the goal is to provide improve availability, a closer look should be taken at the constellation state probabilities used for weighting. GPS Full Operational Capability (FOC) was declared on July 17, 1995. Table 22 supplied by Karl Kovach of ARINC provides the number of satellites which have been operational for the first 1000 days since FOC. As shown in this table, 24 or more satellites have been available 94.67% of the time. Applying the operational satellite weighting, long-term service availability at Seattle for PT 1 with AAD-A is shown in Table 23. The substantial improvement in availability is clearly evident and 99.99% availability or greater is easily met for GAD B and C and M>2.

Table 22 Operational GPS Constellation Availability

Number of Operational Satellites (N)	Probability
27	5.74%
26	8.25%
25	43.28%
24	37.40%
23	5.25%
22	0.08%
≤21	0.00%

Table 23 Long-Term Service Availability for Seattle Based on Operational Constellation Weighting

GAD	AAD	PT	24 SVs	23 SVs	22 SVs	21 SVs	20 SVs	Wt. Avg.
A2	A	1	94.861%	89.410%	83.118%	76.099%	68.525%	94.565%
A3	A	1	100%	99.433%	98.124%	95.911%	92.668%	99.969%
A4	A	1	100%	99.751%	99.111%	97.860%	95.787%	99.986%
B2	A	1	100%	99.763%	99.103%	97.808%	95.672%	99.987%
B3	A	1	100%	99.925%	99.665%	99.034%	97.803%	99.996%
B4	A	1	100%	99.936%	99.718%	99.167%	98.062%	99.996%
C2	A	1	100%	99.942%	99.726%	99.188%	98.114%	99.997%
C3	A	1	100%	99.971%	99.823%	99.409%	98.518%	99.998%
C4	A	1	100%	99.977%	99.839%	99.442%	98.575%	99.999%

CONCLUSIONS

This paper has compared the improvements in availability of LAAS service for several different types of candidate augmentations. All the candidate augmentations improve availability but overall adding additional satellites to the constellation provides the greatest improvement in availability. In fact, enhancing the GPS constellation to 30 or more satellites was the only method of augmentation that raised the projected availability of LAAS PT 3 service to greater than 99.999%. The study illustrates that optimally incorporating satellites into the GPS constellation provides the greatest improvement in availability with fewer satellites added to the constellation.

This study has also shown that optimal placement of pseudolites is important if pseudolites are used to augment availability. The study indicates that 2 optimally placed pseudolites may be required to raise the availability of PT 3 service to greater than 99.9%. Furthermore, 2 sub-optimally placed pseudolites would not significantly improve availability at all.

It should be noted that most of the availability results provided in this paper are based on a conservative weighting of GPS constellation state probabilities, which significantly differs from the operational constellation to date. Availability is improved dramatically when the operational constellation probabilities are applied.

Finally, this study included some results concerning the tradeoff between continuity and availability. The results shows that there is no significant gain in availability if the allocation of continuity to VPL without a configuration change is increased. The study also shows that critical satellites can have an impact on availability. The decrease in availability will be minimal if the number of tolerable critical satellites is 4 or more.

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