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Availability Assessment of Alternative Precision Approach and Landing System Architectures

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ABSTRACT

This paper presents results of a comparative assessment of the availability of alternative differential Global Positioning System (DGPS) precision approach and landing system architectures. The baseline availability for comparison is developed based on the performance of the current Instrument Landing System (ILS). The analysis addresses the number and positioning of geostationary satellites that are needed to achieve the availability requirements and identifies a possible role for pseudolites. Analysis of temporal availability characteristics of DGPS provides additional operational insight.

INTRODUCTION

The Federal Aviation Administration (FAA) is defining the long-term future National Airspace System (NAS) Precision Approach and Landing System (NASPALS) architecture. The technical performance factors that must be considered for determining feasibility of a precision approach and landing system include accuracy, integrity, continuity of service, and availability. This paper focuses on availability, particularly of the satellite elements of DGPS. Estimates of DGPS availability are compared with baseline availability, which is developed based on IILS performance and on operational considerations. The DGPS variations assessed include a wide area augmentation system (WAAS) and local area DGPS (LDGPS). The analysis also examines the effects of geostationary ranging satellites and pseudolites. The sensitivities of the results to the accuracy requirement and the satellite mask angle are presented.

A coarse assessment compares the average availability and identifies complementary roles for LDGPS and WAAS. An analysis of the temporal characteristics examines the peak periods of poor availability and identifies a fail-soft characteristic of DGPS that may offer a benefit.

AVAILABILITY REQUIREMENTS

This analysis is concerned with the availability of an airport to accept landings. Depending on the weather (i.e., ceiling and visibility), ability to land at an airport is based on visual approaches or instrument approaches. The focus of this paper is on operations down to Category I (CAT I) precision approach minimums (down to 200 ft decision height and 1800 ft runway visual range (RVR) visibility). The requirements for small, single-ILS airports; medium, dual-ILS airports; and large, multiple-ILS airports are considered separately. The requirements for small and medium airports are given as ranges covering an order of magnitude. The requirement for large airports is given as a minimum requirement.

Small, Single-ILS Airports

There are approximately 500 airports with a single ILS in the U.S.

The average availability of an FAA-operated ILS considering only unscheduled causes of outage was approximately 0.995 in 1992-93 [1]. Unscheduled availability is considered the most relevant measure of availability because an effort is made to plan scheduled outages, e.g., preventive maintenance, for when the weather is such that landing operations would not be affected. The unscheduled outage availability is higher at many larger airports because most of the time technicians are on duty to initiate repairs promptly.

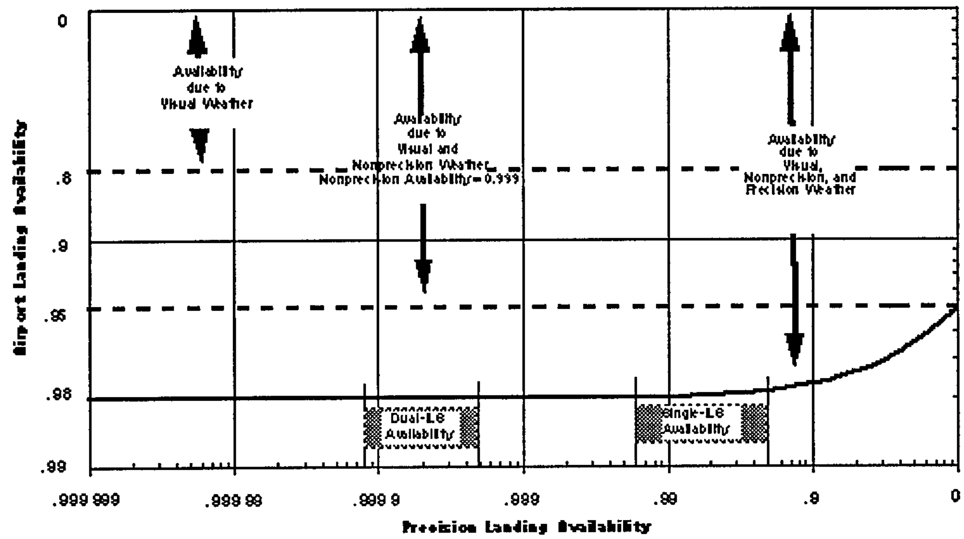

Figure 1. Sensitivity of Airport Landing Availability to Precision Landing Availability

At small airports, landing system availability may not need to be as high as 0.995 to achieve a reasonable airport landing availability. Consider Figure 1 (Sensitivity of Airport Landing Availability to Precision Landing Availability), which shows the sensitivity of airport landing availability to precision landing system availability. The airport landing availability is determined by noting that weather allowing visual approaches prevails 80 percent of the time, hence landing availability is 0.80, even with no nonprecision or precision approach capability. Weather requiring nonprecision approaches, that is, approaches that depend upon horizontal guidance only, prevails another 15 percent of the time. The result is that an airport is available for landing nearly 95 percent of the time if there is a high availability of nonprecision approaches. Airports with an ILS almost always have at least one nonprecision approach based on a VOR and another based on the localizer element of the ILS that can be used when the glide slope is out of service. Weather requiring precision approaches to CAT I minimums prevails another three percent of the time, resulting in a maximum airport landing availabiltiy of 98 percent, depending on precision landing system availability. Landing operations cannot be conducted two percent of the time due to weather or operational reasons.

Figure 1 shows that as CAT I landing system availability is improved (along the horizontal axis), the improvement in airport landing availability becomes negligible beyond a certain point. The ILS unscheduled availability is 0.995, providing an upper bound on availability. By inspection a reasonable lower bound on precision landing system availability can be set at about 0.95 without significantly degrading the airport landing availability. The range of single-ILS availabilities is shown in the figure.

Medium, Dual-ILS Airports

There are approximately 120 airports with two ILSs in the U.S. Some of these airports can be considered airports with a higher level of traffic, which may need a higher availability than the single-ILS airports.

One estimate of landing availability at dual-ILS airports can be obtained by assuming that either of the two ILS runways can be used at any time, so that, if one ILS fails, the other ILS runway can be used. This is an upper bound because weather prevents the two ILS runways from being completely interchangeable, particularly where dual-ILS installations are on the opposite ends of the same runway. If we again assume that scheduled outages occur only when neither ILS is needed, then their combined availability is approximately $1 - (1 - 0.995)^2 = 0.99998$.

From Figure 1 (discussed in the previous section), it can be seen that the effect of this level of availability on airport landing availability is very small. A reasonable lower bound on the precision landing system availability of 0.9995 is chosen. This range of dual-ILS availability is shown in the figure.

Large, Multiple-ILS Airports

There are approximately 55 airports with three or more ILSs in the U.S. These airports have the highest level of traffic, and uninterrupted operation is of great importance to them. The largest of these airports have many landing configurations and are practically immune to a single ILS outage. They would simply change to another landing configuration that did not use the failed system. As a preliminary requirement, availability of the precision landing systems at these airports should exceed 0.99999.

AVAILABILITY ANALYSIS

Model Description

MITRE/CAASD developed a computer model [2] to estimate the availability performance of satellite navigation systems. This model is a comprehensive model of satellite-user geometry in conjunction with a Markov-process failure model for individual satellites. The total model estimates the average, temporal, and spatial characteristics of satellite system availability. Availability to perform a particular operation is based on the satellite system's ability to satisfy the geometric dilution of precision (DOP) criterion (DOP< n) that is needed for the accuracy required for that operation. In the case of precision approach operations, vertical dilution of precision (VDOP) criteria are used because vertical accuracy requirements are more stringent than horizontal accuracy requirements, and generally when the required vertical accuracy is achieved the required horizontal accuracy is also achieved.

The analysis presented in this paper considers only GPS satellite, geostationary satellite, and pseudolite outages. The outage frequency and restoration data shown in Table 1 are applicable to GPS satellites and are based on information obtained from the USAF Consolidated Space Operations Command. Both geostationary satellites (GEOS) and pseudolites were assumed to have failure characteristics similar to GPS; this is probably a conservative assumption.

	Outage Frequency	Restoration Time	Restoration Mode
Short-term Outages	1.65/yr = 1/5310 hr	12.2 hours	serial
Long-term Outages	0.1/yr = 1/120 mo	2 months	serial

Table 1. Satellite Outage and Restoration Characteristics
Source: USAF Consolidated Space Operations Command letter to FAA/ARD-70

GPS Configuration Description

The "GPS 21 Primary Satellite Constellation" [3] was used in this analysis. It consists of 24 satellites with 4 satellites equally spaced in each of six 55 degree inclined orbital planes. Comparison with the USAF's latest constellation data showed negligible differences in the results presented in this paper.

The 24 GPS constellation was augmented with up to six GEOS as part of the FAA's planned WAAS. The WAAS uses GEOS to broadcast differential corrections and integrity information provided by a ground monitoring and control segment. The GEOS associated with the WAAS also provide additional ranging signals to improve availability. The positions of the GEOS were those that either provide coverage to all locations in the conterminous U.S. (CONUS) or to benefit specific regions.

LDGPS is another GPS augmentation included in this analysis. LDGPS uses a ground station located on the airport to determine corrections to GPS signals and to broadcast them to the user. LDGPS can also make use of the ranging signals provided by the GEOS associated with the WAAS to improve its availability.

LDGPS may also be augmented with pseudolites to further enhance availability. Pseudolites used in this analysis are located along the approach path to each runway near the CAT I decision height point. Modeling results show that the availability improvement due to pseudolites is not sensitive to their location.

Accuracy Standards

Two accuracy standards were examined to determine the required VDOP criteria to be used in the availability estimations.

One standard is the sensor accuracy requirements of ILS at the CAT I decision height of 200 ft. The 2-sigma vertical sensor accuracy requirement is 4.1 meters at this point [4]. The other accuracy standard is based on the tunnel concept [5]. The specified accuracy is the total system error (TSE). TSE includes flight technical error (FTE) and sensor error which are combined by the root sum square method to obtain TSE. The 95 percent vertical tunnel TSE accuracy standard is 9.8 meters at the CAT I decision height. Assuming an FTE of about 6 meters [6], the vertical accuracy requirement is 7.7 meters.

For WAAS, the differential ranging error is assumed to be 2 meters (95 percent). The resulting VDOP requirement is about 2 using the sensor accuracy standard and about 4 for the tunnel concept. The assumed ranging error performance is based on FAA/Air Force Philips Laboratory data [7]. That data indicates that there is a sharp increase in ionospheric delay errors for satellite elevation angles of less than 15 degrees. The ionospheric data was collected using a codeless, dual-frequency technique with an early technology receiver. Recent improvements in receiver technology [8] suggest the performance achieved at 15 degrees by the older technology could be achieved at lower elevation angles. This analysis assumed a dual frequency user receiver and examined two cases using 10 degree and 7.5 degree mask angles.

For LDGPS, the VDOP criteria is 4.5 for the sensor accuracy standard. This assumes a differential ranging error of approximately 0.9 m, which is consistent with flight test results. For the tunnel accuracy standard, the 0.9 m ranging error results in a VDOP criteria of 8.5. A lower mask angle of 5 degrees is used for the LDGPS estimates; however, a second case using 7.5 degree mask angle was examined to reflect the fact that low angle satellites may not be visible at all airports, especially airports surrounded by mountains.

Average Availability Results

Twenty major airports that span CONUS were evaluated. The twenty airport locations from west to east are as follows: San Francisco, Seattle, Los Angles, Phoenix, Helena (Montana), Salt Lake City, El Paso, Denver, Bismarck (North Dakota), Dallas, Kansas City, Minneapolis, New Orleans, Chicago, Atlanta, Miami, Washington D. C., New York, Boston, and Bangor (Maine).

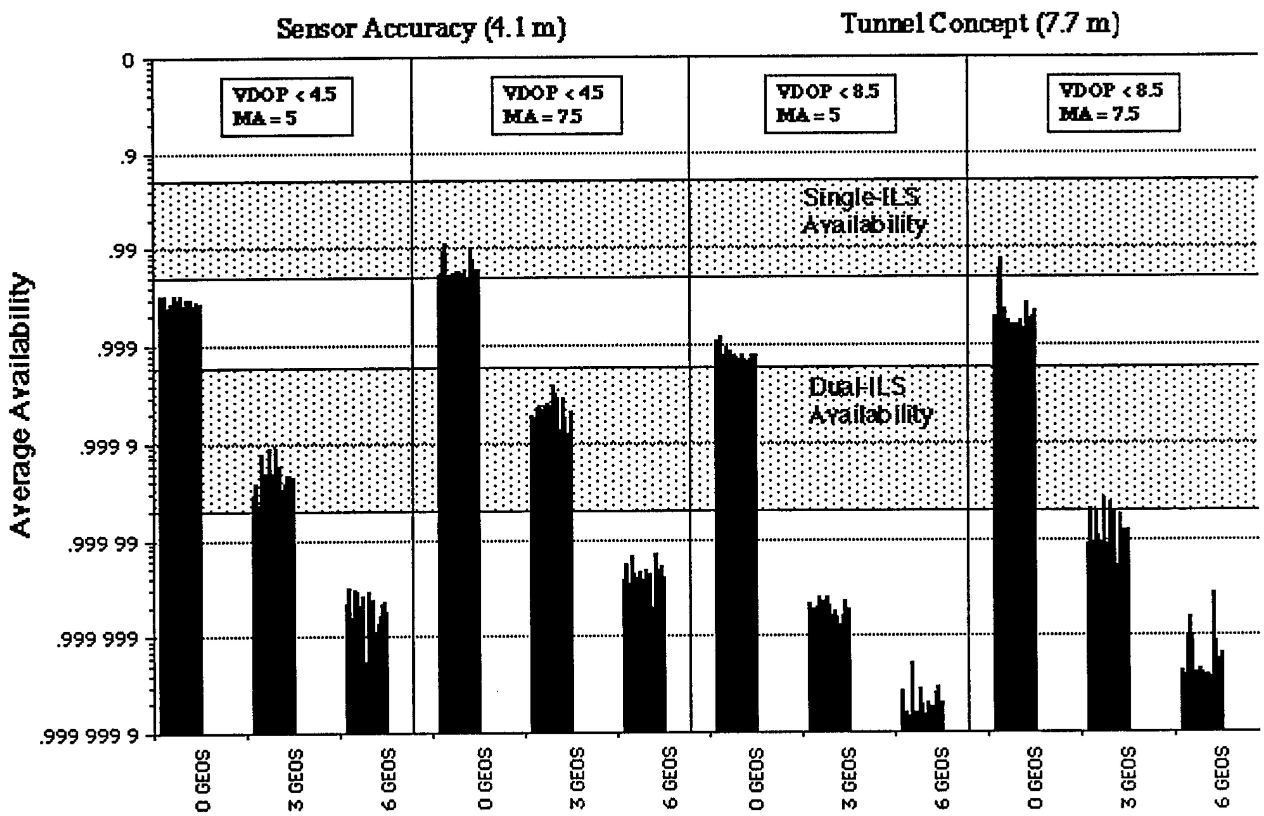

Figure 2. LDGPS Average Availability Results - Effects of GEOS

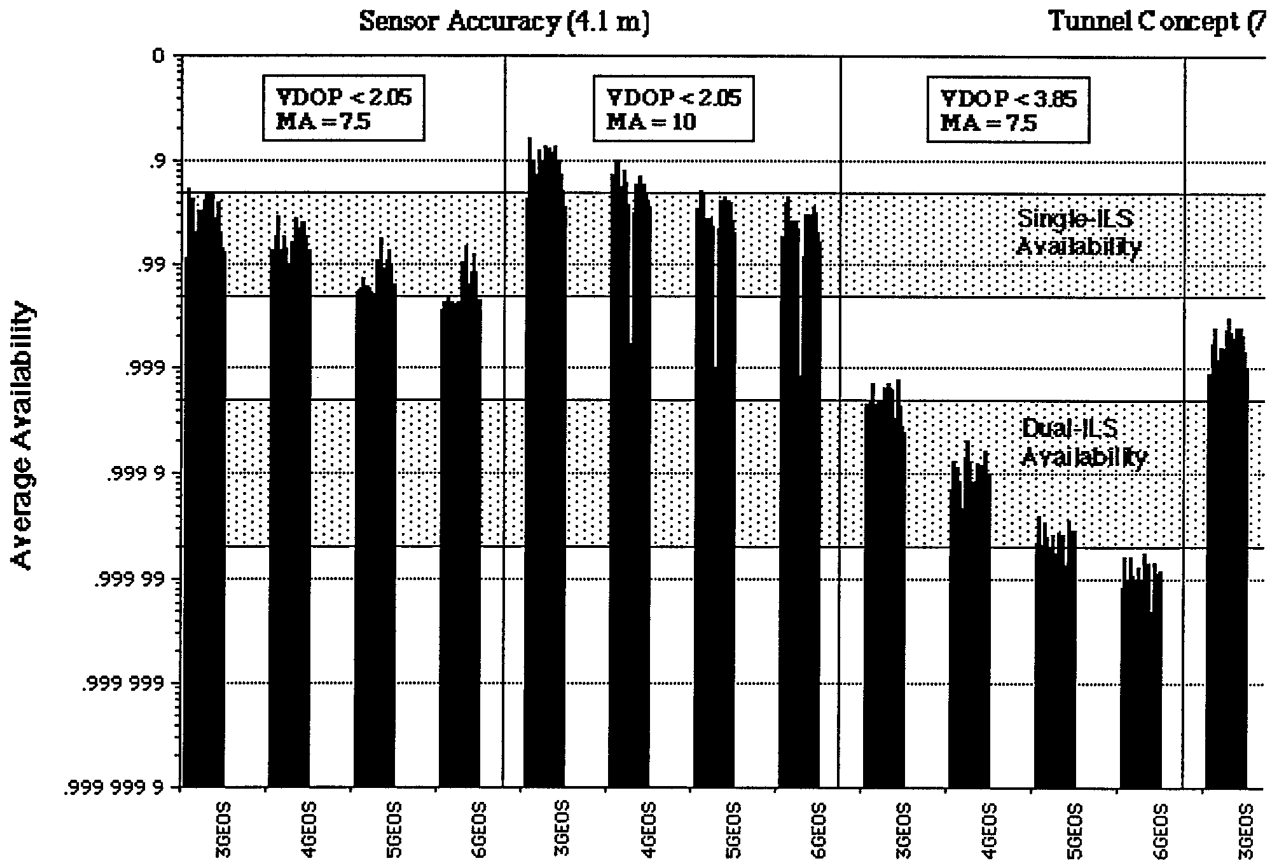

Figure 3. WAAS Average Availability Results

Table 2. Summary of Average Availability Analysis

LDGPS					
		Sensor Accuracy (4.1 m; VDOP<4.5) Mask Angle (deg)		Tunnel Accuracy (7.7 m; VDOP<8.5) Mask Angle (deg)	
		5	7.5	5	7.5
GEOS	0	S	S	S	S
	3	~D	~D	M	D
	6	M	M	M	M

WAAS					
		Sensor Accuracy (4.1 m; VDOP<4.5) Mask Angle (deg)		Tunnel Accuracy (7.7 m; VDOP<8.5) Mask Angle (deg)	
		7.5	10	7.5	10
GEOS	3	~S	-	S	S
	4	~S	-	~D	~D
	5	~S	~S	~D	~D
	6	~S	~S	D	~D

~S In the range of single-ILS airport requirements
S Better than single-ILS airport requirements
~D In the range of dual-ILS airport requirements
D Better than dual-ILS airport requirements
M Better than multiple-ILS airport requirements

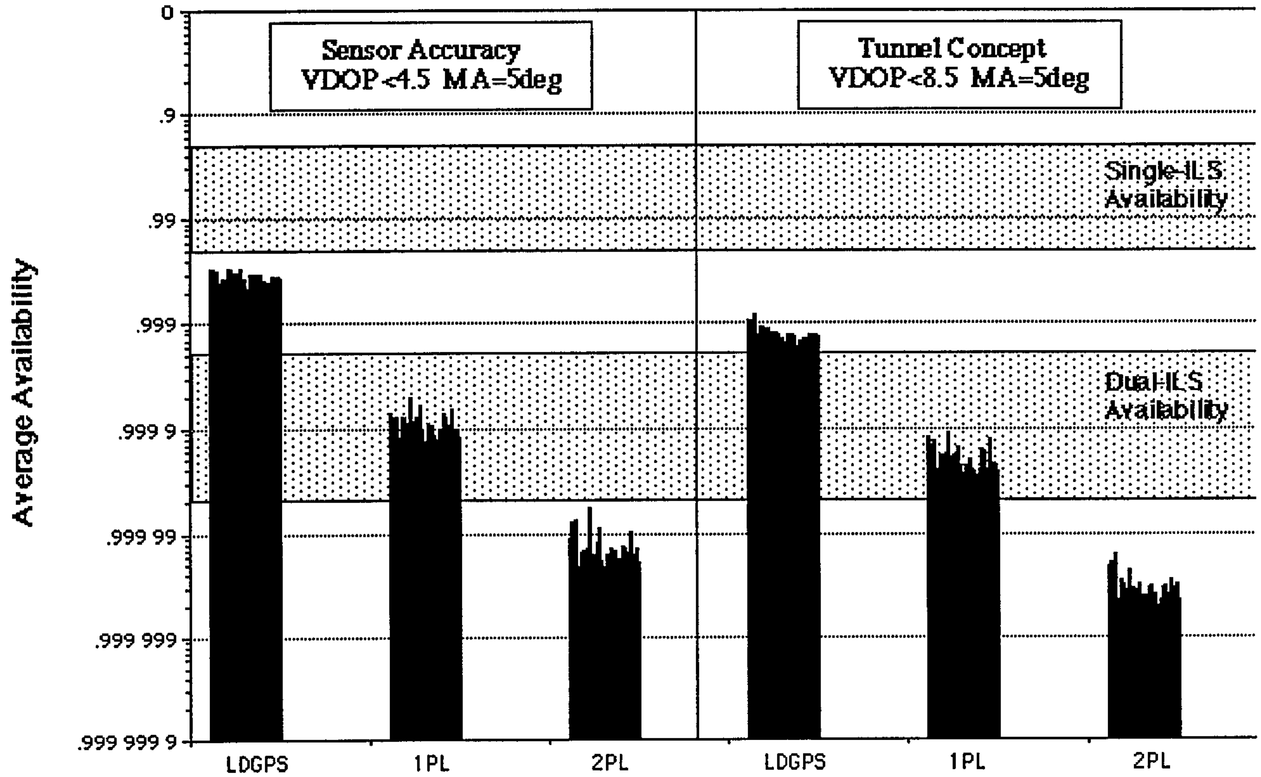

Figure 4. LDGPS Average Availability Results - Effects of Pseudolites

Figures 2 (LDGPS Average Availability Results - Effects of GEOS) and 3 (WAAS Average Availability Results) show the results for LDGPS and WAAS respectively. These results are summarized in Table 2. The information in these figures is as follows. Each bar represents the daily average availability, shown along the vertical axis, at each of the 20 locations, with the locations arranged from west to east. (The reader is not expected to distinguish among the individual locations but to observe that there is about an order of magnitude difference in availability across the U. S.). The twenty bars for each result are grouped into a column. Along the horizontal axis is the number of GEOS associated with that column. Along the top is shown the division of the results by sensor accuracy and tunnel accuracy requirements. Sensor and tunnel accuracy results are each subdivided by the mask angle assumed for the analysis. Figure 4 (LDGPS Average Availability Results - Effects of Pseudolites) shows the results for pseudolites. In this figure the horizontal axis shows the number of pseudolites. The results are divided into sensor accuracy results and tunnel concept results using a 5 degree mask angle. There are no GEOS assumed in these results.

LDGPS (Figure 2 and Table 2) can satisfy single-ILS airport requirements without the use of GEOS, even for the sensor accuracy requirement and the higher 7.5 degree mask angle. To meet the dual-ILS airport requirements, 3 to 6 GEOS are required. Even using the sensor requirements and the 7.5 degree mask angle, six GEOS are sufficient to meet the multiple-ILS airport requirements.

An alternate way for LDGPS to meet dual-ILS and multiple-ILS availability requirements is with pseudolites. This is shown in Figure 4. LDGPS can meet dual-ILS requirements with one or two pseudolites assuming the sensor accuracy requirement and a 5 degree mask angle and multiple-ILS requirements with two pseudolites. Availability is only slightly improved using the tunnel concept.

Turning to the WAAS results (Figure 3 and Table 2), three to six GEOS are needed to meet the single-ILS airport requirements when using the sensor accuracy and a 7.5 degree mask angle. Five or six GEOS are needed when using a 10 degree mask angle. Dual-ILS airport requirements cannot be met using the sensor accuracy requirement. However, using the tunnel accuracy requirement, dual-ILS airport requirements can be met with five to six GEOS. WAAS will not meet multiple-ILS airport requirements using any configuration.

An example of how these figures can be used to define a GPS architecture using WAAS and LDGPS is as follows: A WAAS system meeting the tunnel accuracy requirements could meet the availability requirements at single-ILS airports with three GEOS. Furthermore, the availability requirements at dual-ILS airports can be satisfied with three to six GEOS if the avionics can operate properly at a 7.5 degree mask angle. The most stringent, multiple-ILS airport requirements could be met with LDGPS using the GEOS of the WAAS; at least 3 GEOS would be needed using the tunnel accuracy requirement.

Instantaneous Availability

Although the average value of availability is sufficient for the rough assessment presented above, previous analysis [2;9] has shown that average availability is only a coarse measure of performance, and that analysis of instantaneous availability offers valuable operational insights.

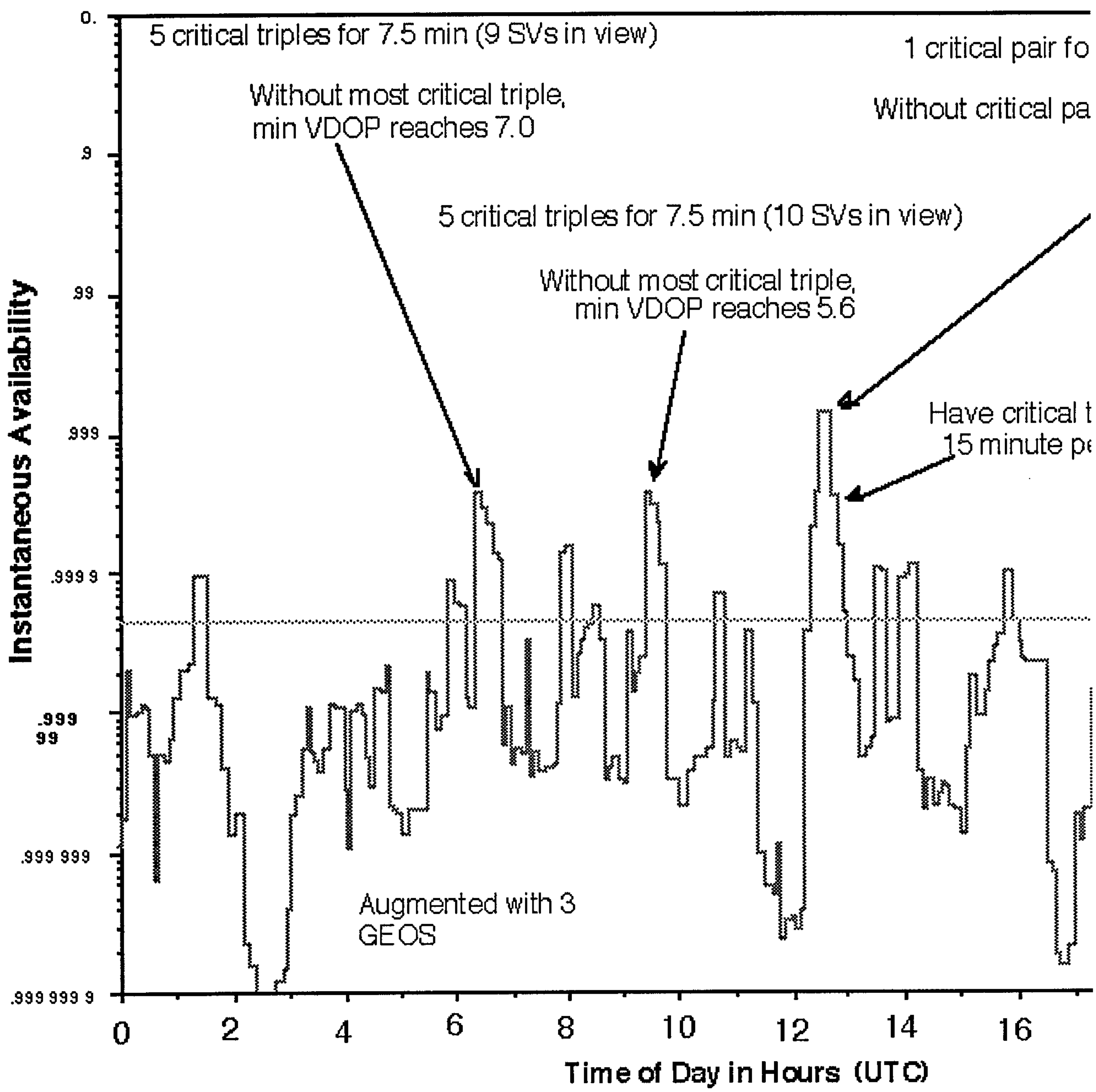

Figure 5. Instantaneous Availability - LDGPS Example

Figure 5 (Instantaneous Availability - LDGPS Example) shows availability vs. time at Pittsburgh for the case of a LDGPS system, using the sensor accuracy requirements; the GPS satellites are augmented by 3 GEOS. The results are typical of those seen at the locations used in the average analysis above.

The average value of availability equals 0.999956 (the dashed line on the graph). For most of the day, however, the graph is below the dashed line, that is, the instantaneous availability is greater than the average most of the day. In fact, there are only 14 periods of time, ranging from 5 to 40 min in length, during which the availability is less than the average value. The total time with availability less than the average is 242.5 min, or 17 percent of the day.

Peaks in the graph are periods of time when the probability is relatively high that service cannot be provided. The worst peak occurs between hours 12 and 13, when the availability drops to 0.9986 for 15 min. The daily average is dominated by this 15 min period, during which ten satellites are in view. The reason availability is so low despite the relatively large number of satellites is that there is a critical pair of satellites [9]. This means that out of the ten satellites in view, there is a unique pair of satellites such that if both of these satellites fail, then there will be a service "outage" with respect to the criterion VDOP < 4.5; this "outage" would last for 15 min.

In some cases, the VDOP that remains during an outage is sufficient to allow precision approaches to continue. For instance, during the 15 min outage considered above, the remaining eight satellites would provide VDOP = 5.0. This would result in roughly an 11 percent increase in the vertical sensor error, given nominal navigation data from the satellites. It should be possible to accommodate an 11 percent increase in sensor error during a 15 min interval, for example, by temporarily raising landing minimums.

CONCLUSIONS

The analyses presented in this paper indicate the sensitivity of the preferred GPS landing system architecture to the following parameters: basis for the accuracy requirement (i.e., sensor accuracy versus tunnel in space accuracy); the mask angle required to obtain acceptable performance; and the operational concept to deal with the temporal characteristics of GPS availability. Nonetheless, it can be concluded that a combination of WAAS and LDGPS will be needed to satisfy the availability requirements for the full range of airport environments. From Figure 2 it can be seen that LDGPS requires augmentation from at least 3 GEOS to satisfy the availability requirement at multiple-ILS airports. From Figure 3, it can be seen that with 3 GEOS the WAAS will support tunnel concept accuracy at single-ILS airports for 10 degree mask angles. The usefulness of additional GEOS will depend on cost/benefit comparisons for providing service via LDGPS or WAAS.

Insights into the temporal and geographic aspects of outages, as well as the slightly degraded accuracy that is available when VDOP criteria are slightly exceeded, will be used for detailed performance characterization of DGPS architecture and to develop an operational concept for using DGPS in the future NAS Precision Approach and Landing System architecture.

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