Augmentation of GPS/LAAS with GLONASS: Performance Assessment

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Abstract

GLONASS has been proposed as an augmentation to GPS/LAAS. We examine the incremental benefits of the additional signals from GLONASS to the availability of service for precision approaches. The methodology used for the modeling of availability is the same as that adopted previously for the analysis of GPS/LAAS. The inclusion of GLONASS signals requires provision for adapting the models of measurement errors to account for the differences between GPS and GLONASS. The main difference of significance to LAAS is due to the frequency division multiple access scheme used by GLONASS, and the resultant inter-frequency biases in the measurements. The errors introduced by such biases at the reference and user receivers are uncorrelated, and have to be accounted for in the error models.

As expected, the availability of service improves considerably with the additional ranging sources. The combined GPS and GLONASS signals provide consistent and robust performance with high levels of availability of service for the most demanding precision approaches.

I. INTRODUCTION

The Local Area Augmentation System (LAAS) is a realization of local-area differential GPS (DGPS) being developed by the Federal Aviation Administration (FAA) mainly to support instrument approach and landing of aircraft under poor visibility conditions [1]. The system is to provide vertical and lateral guidance for IFR precision approach and landing from about 20 nm from the runway threshold through touchdown and rollout. Civil aviation is an extremely demanding application with stringent requirements on the accuracy, integrity, and continuity of the navigational guidance. As expected, the requirements become more stringent as such guidance is required at lower altitudes.

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A comprehensive discussion of the LAAS architecture and the requirements of the precision approaches is given in [1-3]. We offer a summary below. In LAAS, corrections to be applied to the measurements at the airborne receiver are computed on the basis of measurements by multiple receivers at the airport ground station, and are communicated to the users via VHF data broadcasts. The signal processing at the ground station consists of data checks to prevent transmission of misleading information to the aircraft. The integrity of the differential corrections is assured by steps to detect and exclude any receivers which may be malfunctioning or have large error, and by characterizing the error in the pseudorange correction for each satellite on the basis of consistency of the differential corrections produced by the multiple receivers. The LAAS data broadcast includes the differential corrections for the satellites in view, and the error parameters associated with each.

The airborne receiver uses its own measurements and the differential corrections and error parameters from the broadcast to compute a position estimate and a high-confidence bound on the error in it. Such error bound, called *protection level*, delineates an area or volume around the estimated position in which the true position lies with near certainty. The size of this area or volume depends upon the number of ranging sources and their geometry, and the quality of the differential corrections and the airborne measurements. The computed protection level is compared with an *alert limit*, defined as the maximum error that can be tolerated for the intended operation. The alert limit depends upon the position of the aircraft along the approach path and, as expected, becomes tighter as the distance from, and height above, the runway threshold decrease. The operation can be conducted only if the navigation system error can be assured to be less than the corresponding alert limit. A failure to detect that the navigation system error has exceeded the alert limit would represent an integrity failure. The probability of such an event is required to be extremely remote (say, one in ten million to one billion approaches, depending upon the approach category).

In order for GPS/LAAS to be economically viable, it must be useable when needed. This requirement is formalized as *availability of service*, defined as the probability that the accuracy, integrity, and continuity requirements of the intended operation would be met at a specific place and time. The availability of service for precision approaches from GPS/LAAS can be increased by providing additional ranging signals from ground-based or space-based sources. In this paper, we examine the improvement resulting from the combined use of signals from GPS and GLONASS within the LAAS architecture. The LAAS uses GPS signals available under Standard Positioning Service (SPS); GLONASS has a similar feature called Channel of Standard Accuracy. We denote the combined use of these signals in LAAS as GPS+GLONASS/LAAS.

The development of LAAS is progressing well. The feasibility of DGPS Category III precision approaches has been demonstrated in extensive trials. The RTCA SC-159 WG-4 has nearly completed work on the Minimum Aviation System Performance Standards (MASPS) [2]. The system specifications and Minimum Operational Performance Standards (MOPS) are planned to be ready late in 1998. The LAAS architecture has been accepted by the International Civil Aviation Organization (ICAO) Global Navigation Satellite Systems Panel (GNSSP) for international use, and the Standards and Recommended Practices (SARPs) are under preparation. U.S. Government-industry partnerships are being formed to develop and test LAAS further.

GLONASS, the Russian global navigation satellite system, is similar to GPS in its architecture [4]. Some of the differences between the two systems with implications for LAAS performance are discussed below. The principal difference between GPS and GLONASS at this time, however, is related to their status: GPS has been operational for several years; GLONASS is under development, and apparently struggling for want of resources.

There is no basic challenge in design and manufacturing of receivers to take advantage of the combined set of signals from the two systems, and some GPS+GLONASS receivers are now on the market. There are considerable benefits to the civil community from the combined use of the signals from the two autonomous systems, including elimination of a single point of failure, technical and political. The principal technical benefit of the combined use of the two systems is that it makes the positioning performance robust: small degradation of the system would not degrade the system performance appreciably [5].

Our objective in this paper is to analyze the availability of LAAS precision approaches when the space segment consists of the combined constellation of GPS and GLONASS satellites (GPS+GLONASS). The results, however, are more general, and illustrate the incremental benefits of additional satellites offering pseudorange and carrier phase measurements. We include a parametric analysis of the effect of additional measurements of lesser quality than those available from GPS. The basic conclusion is that augmentation of the space segment adds the requisite robustness to the LAAS performance.

We review in the next section the methodology for computing the availability of the LAAS precision approaches. A brief discussion of the differences between GPS and GLONASS measurements and how to account for them in availability modeling is given in Section III. The results on the availability of service for the precision approaches for GPS+GLONASS/LAAS are given in Section IV.

II. AVAILABILITY OF SERVICE FOR LAAS PRECISION APPROACHES

We begin with a summary of the scheme for classification of LAAS performance and the equipment types. This is followed by a brief description of the methodology for the availability analysis for the classes of interest. Both these topics are discussed in detail in the draft MASPS [2]. Our purpose is simply to provide the basic information to make the results presented in Section IV understandable.

A. LAAS Classification Scheme

• *Classification of the Performance Types*: The LAAS performance is classified in terms of well-defined levels of service called *Performance Types* 1, 2, and 3. Each performance type defines a specific level of required accuracy, integrity, and continuity. A navigation system meeting the requirements of performance type 1 would be sufficient to support Category I operations. Similarly, a performance type 3 navigation system would support Category III operations. The availability of a specific performance type at any time at an airport would depend upon the characteristics of the equipment at the ground station and the aircraft (discussed below), and the number and geometry of the ranging sources (satellites and airport pseudolites).

• *Classification of the Ground Subsystems*: The LAAS ground subsystem is classified with a letter and a number in accordance with the quality of the receivers and their number. A receiver is classified on the basis of its accuracy level and multipath mitigation technique as *A, B,* or *C*. Classification *A* represents a basic receiver; classification *C* represents a receiver with advanced features. The number of receivers in the ground segment can range from two to four. According to this convention, a LAAS ground subsystem classified as *A2* would have the minimum required capability; a subsystem classified as *C4* would have the maximum capability.

The error in the pseudorange corrections transmitted by the ground subsystem for a GPS satellite at elevation angle θ can be modeled as a zero-mean normal distribution with a standard deviation

$$\sigma_{gnd}(\theta) \le \sqrt{\frac{(a_0 + a_1 e^{-\theta/\theta_0})^2}{M} + a_2^2 + (\frac{a_3}{\sin\theta})^2}\ , \qquad (1)$$

where M is the number of reference receivers at the ground station tracking the satellite, and a_0, a_1, a_2, a_3 and θ_0 are model parameters whose values depend upon the receiver type (*A, B,* or *C*). The estimated values of these parameters for the different receiver types are listed in [2].

• *Classification of the Airborne Subsystems*: The airborne system is characterized as *A* or *B* depending upon its contribution to the error in the differentially corrected pseudoranges. The error in the corrected pseudoranges attributed to the measurements of the airborne receiver from a GPS satellite at elevation angle θ can be modeled as a zero-mean normal distribution with a standard deviation

$$\sigma_{air}(\theta) \le a_0 + a_1 e^{-\theta/\theta_0}\ , \qquad (2)$$

where a_0, a_1, and θ_0 are model parameters whose values depend upon the receiver type (*A* or *B*) [2].

We adopt the above models for GLONASS measurements as well, and assign appropriate parameter values as discussed in the next section.

B. Methodology for Availability Modeling

Prior to executing a precision approach, the airborne subsystem is required to assess whether approach guidance is available for the selected performance type. The objective of such analysis is to ensure that the accuracy, integrity, and continuity requirements corresponding to the selected performance type are met, given the classification of the equipment in the ground and airborne subsystems, and the number and geometry of the ranging sources.

The methodology of availability modeling for a specific airport at a specific time basically consists of the following steps [2]: (i) given the geometry of the ranging sources, determine the geometry matrix; (ii) given the classification of the ground segment and the airborne segment and the corresponding error models for the signals, determine the measurement weighting matrix for position estimation; (iii) given the values of the appropriate multipliers to assure that the probability of integrity failure is within the specified limit, compute the appropriate DOPs and protection levels (PL). The analysis of continuity requirement entails computation of the *predictive protection level* (PPL), and comparison with the appropriate alert limit (AL). The service of a given performance type is available *only if*:

- the accuracy requirement is met: 2 x weighted DOP < required accuracy, and
- the integrity requirement is met: PL < AL, and
- the continuity requirement is met: PPL < AL.

While requirements exist for both lateral and vertical guidance, the requirements for vertical guidance are much more stringent and determine service availability. Similarly, while requirements exist for accuracy, integrity, and continuity, as listed above, it's the last that's most stringent, and determines availability.

Clearly, the above methodology can be extended to estimate service availability at an airport, defined as average availability over a day. Service availability over a region can be defined similarly by averaging availability over time and place. For a given constellation of ranging sources and models for signal outages, *long-term availability* can be defined by averaging over the various states of the constellation over time. *Operational service availability* and duration of outages are defined given that the satellite constellation is in a particular state, typically two short of the full constellation.

C. Availability of Service for GPS/LAAS Precision Approaches

The availability of different performance types has been analyzed previously in [6] for service at several airports in the U.S. for the basic GPS constellation and several types of augmentation: airport pseudolites, geostationary satellites, and an expanded GPS constellation of 30 satellites. The results are given for both long-term availability and operational availability, defined earlier. These results are discussed briefly in Section IV, along with the results for GPS+GLONASS/LAAS obtained with the methodology outlined above.

III. GPS-GLONASS DIFFERENCES WITH IMPLICATIONS FOR LAAS

There are several differences between GPS and GLONASS which have implications for the quality of the differential corrections to be provided to the users by LAAS. Out of the four differences discussed briefly below, only one is found to have significant impact upon the performance of GPS+GLONASS/LAAS.

• *Different Time References*: The offset between GPS and GLONASS system times at any instant is an unknown. Each system time can be related to the time reference for the system, UTC(USNO) for GPS and UTC(SU) for GLONASS. The two time scales, however, cannot be related to each other without the knowledge of the offset between UTC(USNO) and UTC(SU), which is not available from the navigation messages currently available from the satellites. The net effect is that the number of unknowns for position estimation increases from the usual four to five: three coordinates of user position and the biases of the receiver clock relative to the two time scales. This increase in the number of unknowns, however, is more than compensated for by a much bigger increase in the number of measurements [5]: *all* users of GPS+GLONASS would see 10 or more satellites.

The difference between the two time scales, however, can be handled simply in LAAS in one of two ways. Perhaps the simplest would be to estimate the difference between the two time scales at the ground subsystem and include it in the data broadcast to the users. Alternately, this time difference could be treated as a source of error common to the reference and user receivers. A disadvantage of this approach would be that the differential corrections for GLONASS may become too large. The problem would disappear with the appearance of GLONASS-M, which are planned to broadcast the offset between UTC(SU) and UTC(USNO).

• *Different Coordinate Frames*: GPS and GLONASS express the positions of their satellites and, therefore, of their users, in different Earth-centered, Earth-fixed coordinate frames. GPS uses WGS 84; GLONASS uses PZ-90 [4]. In general, combining measurements from the two systems would require knowledge of a transformation between the two coordinate frames. Actually, coordinate frames WGS 84 and PZ-90 are nearly coincident [7, 8]: the error introduced by disregarding the difference in computing a position estimate on the basis of GPS+GLONASS measurements from a single receiver would be less than 10 m. In a local-area differential GPS+GLONASS system, the differences between the coordinate frames may be ignored safely without incurring any significant error: for the reference and user receivers separated by 10 km, such error would be less than 2 cm.

• *Different Signal Bandwidths*: The chipping rate of the GLONASS L1 C/A code signal available for civil use is 0.511 MHz, half that of the corresponding GPS signal. In our tests with GPS+GLONASS receivers, we have found no significant difference between measurement noise associated with the bandwidth (or, sharpness of the correlation peak) for GPS and GLONASS.

• *Different Multiple Access Schemes*: GLONASS uses frequency division multiple access (FDMA), with different satellites transmitting the same pseudorandom noise code but at different carrier frequencies [4]. The RF section of a receiver would typically introduce frequency-dependent biases in the measurements. A receiver system can be calibrated, but the biases can change with temperature [9, 10]. Such biases in the carrier phase measurements, however, would have little effect on LAAS in smoothing of the code measurements. In the case of GPS, the use of a common frequency keeps this bias common to the measurements from the different satellites, allowing it to cancel. Insofar as this frequency-dependent error is receiver-specific, it does not cancel in differential mode, and must be accounted for in the error models.

We have examined the frequency-dependent biases in the pseudorange measurements from several Ashtech GPS-GLONASS receivers (GG24s and Z-18s). Such biases are easily seen in zero-baseline tests where the output of a common antenna is fed to two or more receivers, and the measurements are compared. The provision in the receivers to accept clock signals from an external source simplifies the data analysis. In our experiments, the variability in such biases in the different receivers in laboratory environment has been at decimeter level. The problem may disappear in time with new schemes to keep the receivers calibrated.

In our analysis of availability of service with GPS+GLONASS/LAAS, we use the following model of the GLONASS measurements. The frequency-dependent errors in the GLONASS pseudorange measurements have a zero-mean normal distribution with standard deviation of 0.5 m and 0.25 m for receiver types *A* and *B*, respectively, for both the ground and airborne receivers. Receiver type *C* in the ground segment has been modeled as free of such biases. These errors are accounted for in the measurement error models described by Equations (1) and (2) by increasing the size of the parameter a_0 for the GLONASS measurement. The values of parameter a_0 for both GPS and GLONASS are listed in Table 1.

Table 1. Values of parameter a_0 for the various classes of GLONASS receivers in the ground and airborne subsystems compared with those adopted for GPS [2]

	Ground subsystem			Airborne Subsystem	
	A	*B*	*C*	*A*	*B*
GPS	0.5	0.16	0.15 (>35°) 0.24 (≤35°)	0.16	0.074
GLONASS	0.7	0.3	Same	0.5	0.25

The remaining model parameters for the ground and airborne segments are identical to those for GPS. With this model, the contribution of the GLONASS measurements on positioning is downgraded automatically via the weighting matrix [2] in relation to those from GPS. As a part of sensitivity analysis, we have also analyzed the case where the measurement error models for GPS and GLONASS were identical.

Finally, we should note that the current GLONASS navigation message is missing some parameters essential for its use in LAAS. For example, the navigation message has no Issue of Data Ephemeris (IODE) parameter, essential to ensure that the reference station and the user are operating with the same ephemeris, and the corrections are applied correctly. Problems such as this have been identified, and would be solved with appropriate changes in GLONASS-M.

IV. AVAILABILITY OF SERVICE FOR PRECISION APPROACHES WITH GPS+GLONASS/LAAS

Before discussing the results, we adopt the following notation for convenience: performance type 1, 2 , and 3 are denoted as PT1, PT2, and PT3, respectively. The ground subsystem (GS) is identified with the classification and the number of receivers as discussed in Section II, as, say, *A2* or *C3*. The satellite constellations are represented by the system name followed by the number of satellites, e.g., GPS24, GPS24+GLONASS12 GPS24+GLONASS24.

A. GPS/LAAS

Results on the availability of service for the different performance types with GPS/LAAS for various classifications of the ground subsystem and the airborne subsystem have been presented in [6] for several airports in the U.S. Both the long-term and operational availability were analyzed. The basic conclusions regarding long-term availability appear to be the following:

- When the availability is marginal, variability with the geographical location of the airport can be considerable (10%, or more).
- The classification of the airborne receiver has only a minor influence on the results.
- GS *A4* or *B2* would provide an availability >0.99 for PT1
- GS with receivers of type *A* (say, *A4*) would fall considerably short of meeting the requirements of PT3
- GS *C3* would provide an availability > 0.99 for PT3

B. GPS+GLONASS/LAAS

We have analyzed the availability of service for the precision approaches with GPS+GLONASS/LAAS using the methodology of [6], but present the results slightly differently. The two constellations taken together offer a highly redundant set of signals. We know *a priori* that with a constellation of 24 satellites each of GPS and GLONASS, the loss of a satellite or two in one or both constellation would not have a significant impact. As such, the analysis for long-term availability and operational availability is no longer informative. Our purpose is to perform a parametric analysis to identify a constellation that would be adequate for PT3. Insensitivity to small perturbations in the system is a key requirement.

We present the results of availability analysis over the conterminous U.S. (CONUS). The results are presented for the availability of PT1 in Fig. 1, and for PT3 in Fig. 2. . The constellation GPS24 corresponds to the nominal GPS constellation. The constellation GPS24+GLONASS12 basically adds 12 satellites uniformly distributed in three orbital planes at their current locations relative to the GPS orbital planes. The constellation GPS24+GLONASS24 denotes the combined nominal constellations of the two systems. The GLONASS measurements from receiver types *A* and *B* included the inter-frequency biases, as discussed earlier.

PT1 is not a challenge for GPS/LAAS with GS *B3*, or better. With expanded constellations, it is even less so. Indeed, as seen in Figure 1, full availability is obtained over CONUS with GS *A4* for GPS24 and with GS *A3* for GPS24+GLONASS12. GPS24+GLONASS24 would offer full availability of PT1 with *any* GS, including *A2*. In each case, the classification of the airborne segment has little influence.

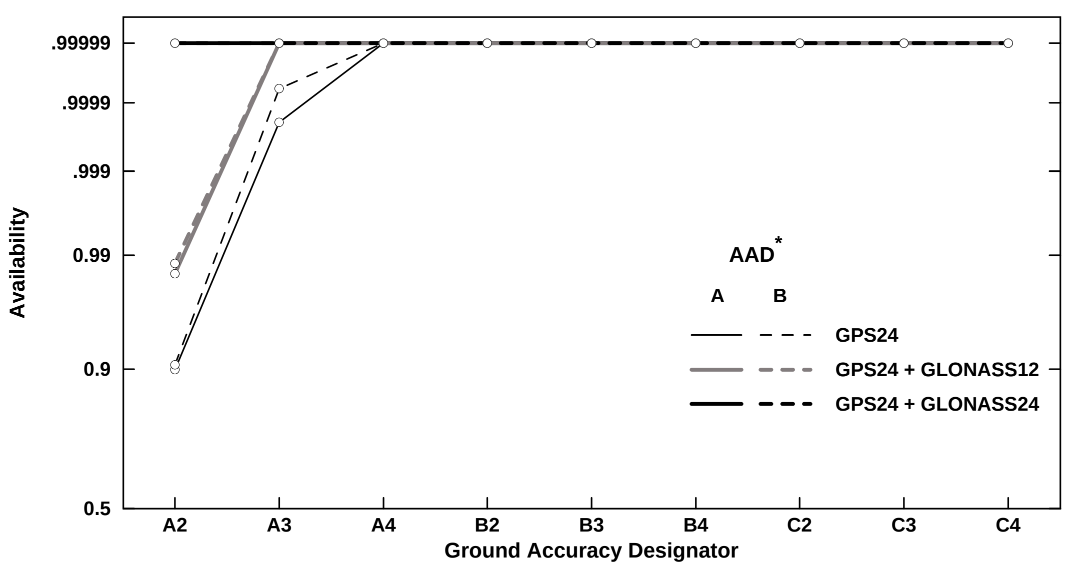

Figure 1: Availablity of Performace Type 1 Service.

***Airborne Accuracy Designator**

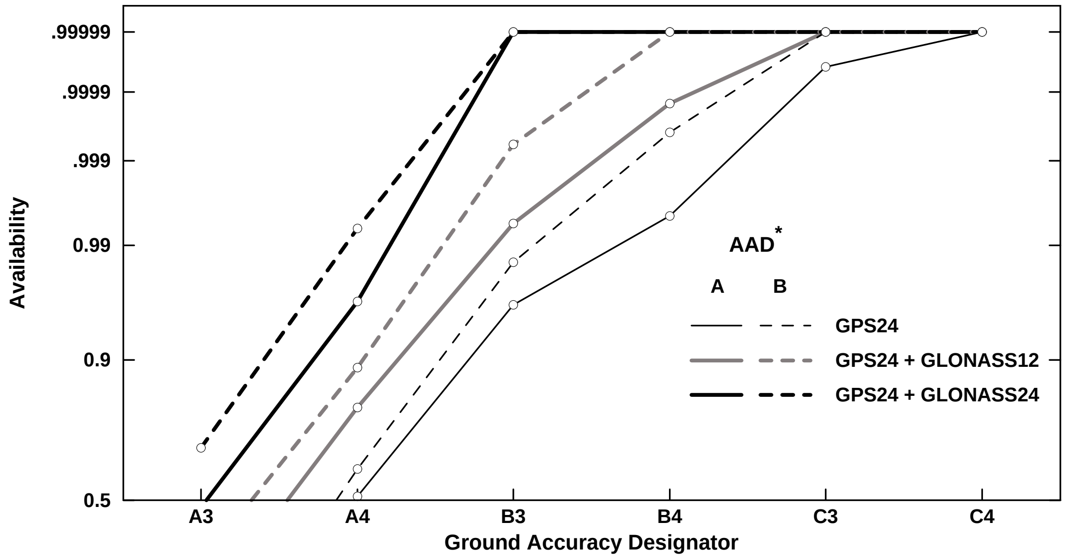

Figure 2: Availablity of Performace Type 3 Service.
***Airborne Accuracy Designator**

The main challenge for LAAS lies in the most stringent of the performance types, PT3. Our conclusions regarding the availability of service for PT3 with the expanded constellations are as follows (Figure 2):

- The availability is determined mainly by the size of the satellite constellation and the classification of the GS. The classification of the airborne segment plays a much smaller role.
- GS with receiver type *A* would be inadequate to support PT3 even with the expanded constellations. Receiver type *B* would be a viable candidate for GS. Receiver type C, designed to exacting standards, would provide nearly full availability even with GPS24.
- With GPS24+GLONASS12, GS *B4* would provide availability > 0.999; *C3* would provide availability > 0.9999
- With GPS24+GLONASS24, GS *B3* would provide availability > 0.9999

Figure 2 shows an interesting order relation in the GS classifications. We know *a priori* that in terms of performance, $A3 \leq A4$, $B3 \leq B4$, and $C3 \leq C4$. It is clear from Figure 2, however, that $A4 \leq B3$, and $B4 \leq C3$.

We have analyzed the availability of service with small variations in the number and placement of the satellites, and in the values of the parameters of the GLONASS error model. The GPS24 and GPS30 constellations exhibited sensitivity to such perturbations. The combined GPS-GLONASS constellations, however, offered a robust performance. As expected, the performance improves further with elimination of the inter-frequency biases in the GLONASS pseudorange measurements.

V. SUMMARY

The performance of GPS/LAAS can be improved substantially by expanding the space segment to include additional signals. The combined constellation of GPS and GLONASS has the potential to provide nearly full availability for the most stringent of the performance types. The resultant performance would also be robust, and relatively insensitive to small perturbations in the system.

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