INTEGRATED GPS/GLONASS

for

RELIABLE RECEIVER AUTONOMOUS INTEGRITY MONITORING (RAIM)

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BIOGRAPHY

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Alison K. Brown is the President of NAVSYS Corporation. She has over 12 years experience in satellite and inertial navigation systems, estimation and control theory and systems engineering and analysis. Her expertise includes GPS systems design, simulation, integration and test, GPS receiver design, strapdown system algorithms and Kalman filter design. She has a PhD from UCLA, an MS from MIT and a BA in engineering from Cambridge University, England.

ABSTRACT

GPS integrity monitoring is key to obtaining FAA approval for civil aviation use in the National Air Space (NAS). Receiver autonomous integrity monitoring (RAIM) is the simplest and most cost effective technique currently available. The performance requirements for integrity monitoring have been established by the Radio Technical Commission for Aeronautics (RTCA) Special Committee 159. RAIM availability is defined as the fraction of space and time that adequate geometry is provided by the satellite constellation to provide reliable integrity monitoring consistent with the requirements for the phase of flight.

RAIM availability for the GPS 21 Satellite Primary constellation, the operational GLONASS constellation, and the Integrated GPS/GLONASS constellation is evaluated in this paper. It is shown that after 3 satellite failures the individual GPS and GLONASS constellations RAIM availability degrades to 92% for enroute and terminal phases of flight and 87% for nonprecision approach. The Integrated GPS/GLONASS constellation is shown to provide 100% RAIM availability for all phases of flight even after six satellite failures (3 GPS and 3 GLONASS).

INTRODUCTION

The Global Positioning System (GPS) is a space-based radionavigation system operated by the United States. The full constellation will consist of 21 satellites and three active spares. GPS is scheduled to be fully operational in 1992 and will provide 3-D navigation capability, 24 hours a day worldwide. Two classes of navigation service are provided by GPS. The Precise Positioning Service (PPS) is restricted to users authorized by the U.S. government and provides an accuracy of 16 m SEP. The Standard Positioning Service (SPS) is available for commercial navigation. Present policy is for the accuracy of the SPS to be degraded to 100 m 2 dRMS in the interests of national security.

The Global Orbiting Navigation Satellite System (GLONASS) is a similar space-based navigation system operated by the Soviet Union. The GLONASS constellation will consist of 24 satellites providing 3-D worldwide coverage. The full constellation is scheduled to be operational in the early 1990s. The GLONASS navigation service is freely available to users world-wide and will provide an accuracy equivalent to the GPS SPS.

The current Soviet GLASNOST policy has resulted in an initiative by the United States Department of Transportation's Federal Aviation Administration (FAA) and its Soviet counterpart to explore the combined use of GPS and GLONASS for civil aviation. A program has been initiated at Lincoln Laboratory in Massachusetts to develop and test an integrated GPS/GLONASS receiver. Of particular interest, is the potential of such a receiver to provide the capability for reliable integrity monitoring.

The Federal Radionavigation Plan [1] defines navigation system integrity monitoring as "the ability of a system to provide timely warnings to users when the system should not be used for navigation". The GPS control segment continuously monitors for satellite failures but does not have the capability to promptly notify users when a failure occurs. To meet FAA integrity requirements for supplemental or sole-means navigation, the GPS service must be augmented to provide timely warnings of system failures to users of the service. The integrity monitoring techniques presently under consideration can be divided into two categories, internal methods and external methods. With internal methods, GPS integrity is achieved using only information available to the receiver, such as redundant satellite measurements or receiver clock data. Using external methods, the GPS signals are monitored in real-time through a network of ground monitoring stations and their status is broadcast to a user through a GPS integrity channel (GIC).

This paper concentrates on the application of receiver autonomous integrity monitoring (RAIM) techniques to an integrated GPS/GLONASS receiver. The RAIM algorithm allows the receiver to make use of the redundant information from the GPS and GLONASS satellites to detect and identify failures in either system.

A variety of RAIM algorithms have been discussed in the literature. A bibliography of relevant papers is included in reference [2]. It has been shown [3], that the performance of all RAIM algorithms is dependent on the same factors. The probability of detecting a failure is a function of the acceptable probability of a false alarm, the navigation error threshold being protected against, the geometry provided by the visible satellites, and the pseudorange residual noise variance.

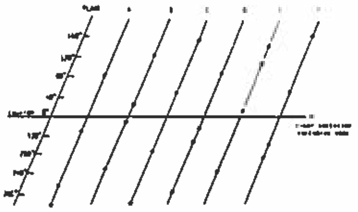
In the following sections, models are derived for the GPS and GLONASS errors and the satellite geometry provided by a combined constellation is simulated. The results of this simulation are used to evaluate the navigation and RAIM availability provided by GPS receivers, GLONASS receivers, and integrated GPS/GLONASS receivers. The simulation was performed assuming that all the GPS and GLONASS satellites are operational, and also allowing for up to three satellite failures in each system leaving 21 operational GPS satellites and 21 operational GLONASS satellites.

SIMULATION MODELS

Satellite Constellations

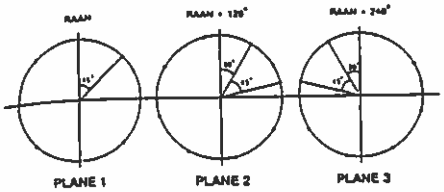
The satellite distribution for the GPS 21 Primary Satellite Constellation is shown in Figure 1 [4]. This constellation consists of 24 satellites in six 55° inclined equally spaced orbital planes. It is optimized to provide the best possible coverage in the event of any single satellite failure. USAF Space Command will have responsibility to ensure that at least 21 satellites are operational at all times. Most of the time, all 24 satellites should be active and it should be very rare for there to only be 21 satellites available.

Figure 1 Satellite Distribution for the GPS 21 Primary Satellite Constellation



The planned satellite distribution for the operational GLONASS constellation is shown in Figure 2 [5]. This constellation will consist of 24 satellites in three equally spaced orbital planes. All satellites have the same nominal orbital period of 675.73° with longitude change of 169.41°. This orbit produces a ground-track repeat every 17 orbits requiring 8 whole days less 32.56 minutes. This diurnal offset of δT = 4.07 minutes is very close to the daily advance in time of the GPS satellite ground tracks. Over a one day less δT period each GLONASS satellite completes 17/8 orbits (2 complete revolutions plus 45°). Since the eight satellites in each orbital plane are separated by 45°, the constellation geometry repeats every one day less δT.

Figure 2. Satellite Distribution for the GLONASS Constellation



Since both the GPS and GLONASS constellation geometries have an approximately 24 hour period, only 24 hours of data is required to simulate the complete integrated constellation geometry.

Solo Measurement Models

The GPS only or GLONASS only measurement model is given by:

$$\underline{z} = H \cdot \underline{x} + \underline{n}$$

where $\underline{z}$ is the M x 1 vector of GPS or GLONASS pseudorange measurement residuals

H is the M x 4 GPS or GLONASS pseudorange observation matrix consisting of the line-of-sight vectors to the satellites with 1s in the fourth column corresponding to the clock bias state

$\underline{x}$ is the 4 x 1 navigation error state vector, $\underline{x}^T = [\delta x, \delta y, \delta z, \delta B]$

$\underline{n}$ is the M x 1 vector of Gaussian pseudorange residual measurement noise, $E[\underline{n}] = 0$ and $COV[\underline{n}] = \sigma_n^2 \cdot I_M$.

The GPS pseudorange noise budget is shown in Table 1 [6]:

Table 1. GPS Pseudorange Residual Noise Budget

Noise Source	Standard Deviation	Noise Type
Satellite Clock and Ephemeris	5 m	Colored
Propagation Uncertainties	10 m	Colored
Receiver Noise and Multipath	15 m	White
Selective Availability	30 m	Colored

The correlation times of the colored noise source are modeled as significantly greater than 30 seconds. The GPS pseudorange measurement noise standard deviation is the RSS of the individual sources, 35.4 meters. For a T second pseudorange measurement formed by averaging the 1 second pseudorange measurements over a T second interval the contribution of the white noise sources is reduced by $1/\sqrt{T}$. Thus for 10 second averages the standard deviation is 32.4 meters and for 30 second averages, 32.1 meters.

The GLONASS pseudorange noise budget is shown in Table 2 [7]:

Table 2. GLONASS Pseudorange Residual Noise Budget

Noise Source	Standard Deviation	Noise Type
Satellite Ephemeris and Clock	9 m	Colored
Propagation Uncertainties	30 m	Colored
Receiver Noise and Multipath	15 m	White

The correlation times of the colored noise sources are modeled as significantly greater than 30 seconds. The GLONASS pseudorange measurement noise standard deviation is the RSS of the individual sources, 34.7 meters. This is so close to the GPS value of 35.4, that the same value was used in the simulations for both GPS and GLONASS.

Integrated Measurement Model

The GPS and GLONASS master stations operate with different time and datum references. For an integrated GPS/GLONASS navigation solution the measurement model must be modified to add a state for the error between GPS time and GLONASS time. Although the time offset between GPS and GLONASS could theoretically be calibrated, it would be difficult to continually update receivers with the current offset between the two time references. Instead, it is simpler to solve for the offset inside the receiver using the redundant information available from the GPS and GLONASS satellites. Additional states to account for the different datum are not required. Both datums, WGS-84 for GPS and SGS-85 for GLONASS, are known and fixed. Thus it is possible to use a mathematical transformation to convert the GLONASS satellite position into WGS-84 coordinates (or vice versa) when forming pseudorange estimates for GLONASS satellite measurements.

The integrated GPS/GLONASS measurement model is:

$$\underline{z} = H\cdot\underline{x} + \underline{n}$$

where $\underline{z}$ is the M x 1 vector of GPS and GLONASS pseudorange measurement residuals

H is the M x 5 GPS/GLONASS pseudorange observation matrix consisting of the line-of-sight vectors to the satellites with 1s in the fourth column corresponding to the clock bias state and 1s in the fifth column for GLONASS measurements corresponding to the GPS to GLONASS master station clock offset.

$\underline{x}$ is the 5 x 1 navigation error state vector,

$\underline{x}^T = [\delta x, \delta y, \delta z, \delta B, \delta B_{GPS\text{-}GLONASS}]$

$\underline{n}$ is the M x 1 vector of Gaussian pseudorange residual measurement noise, $E[\underline{n}] = 0$ and $COV[\underline{n}] = \sigma_n^2\cdot I_M$.

The accuracy of the integrated solution can be determined from a 5 x 5 GDOP matrix G, in a similar fashion to the normal GDOP computation for solo GPS or GLONASS.

$$G = (H^TH)^{-1}$$

$$HDOP^2 = G_{11} + G_{22}$$

CONSTELLATION PERFORMANCE

The GPS and GLONASS constellations were simulated to evaluate navigation and RAIM availability of the solo and integrated constellations for an all-in-view receiver. All simulation results were averaged over the CONUS (N25° to N50°, W125° to W70°) and over a 24 hour period. Because of the large number of possible failure combinations (4 million for the integrated constellation with 3 GPS and 3 GLONASS failures), a limited number of cases were simulated with random selection of the failed satellites. An antenna mask angle of 7.5° was used.

Navigation Performance

Two measures of constellation navigation performance are considered: constellation value (CV) and 95th percentile horizontal dilution of precision (HDOP). CV is the fraction of space and time that PDOP is less that 10. HDOP is the amplification factor, due to satellite geometry, of pseudorange measurement noise to 2-D horizontal position noise. The 2dRMS horizontal position accuracy of the constellation is given by:

$$2\cdot(95\text{th percentile HDOP})\cdot\sigma_{PR}.$$

Figures 3 and 4 show the HDOP probability distributions for the solo GPS and GLONASS constellations for all satellites operational and for 3 satellite failures. A significant change is observed between the fully operational and the 3 satellite failure curves for both GPS and GLONASS. Figure 5 shows the HDOP probability distribution for the integrated GPS/GLONASS constellation for all satellites operational and for 3 GPS satellite failures and 3 GLONASS satellite failures (total of 6 failed satellites). The difference between the curves is much less pronounced indicating that the navigation performance of the integrated constellation is less sensitive to satellite failures then that of the solo constellations.

Figure 3. HDOP Probability Distribution for Solo GPS

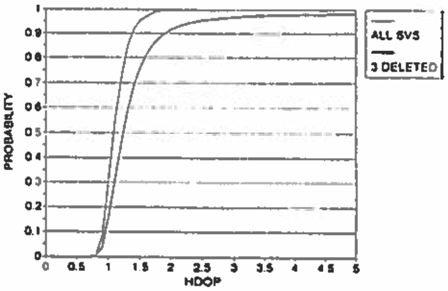


Figure 4. HDOP Probability Distribution for Solo GLONASS

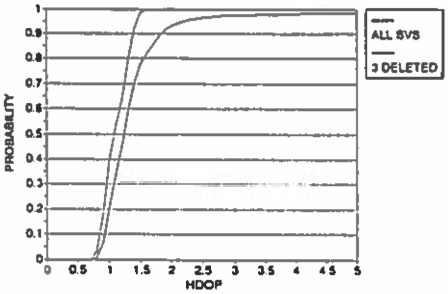


Figure 5. HDOP Probability Distribution for Integrated GPS/GLONASS

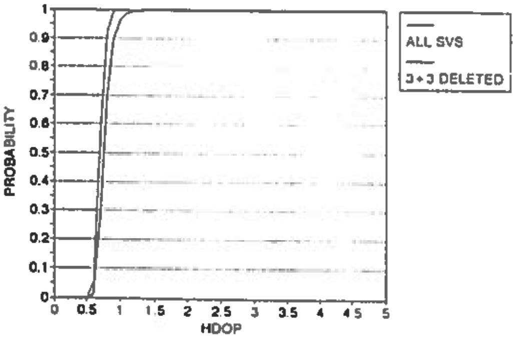


Table 3 shows the CVs and 95th percentile HDOPs for the GPS only, GLONASS only, and integrated GPS/GLONASS constellations with all satellites; and with 1 each, 2 each, and 3 each GPS and GLONASS satellites deleted. Also shown in the table is the 2dRMS position accuracy assuming a pseudorange measurement noise standard deviation of 35.4 meters.

Table 3 Navigation Accuracy

Constellation Configuration	CV	95% HDOP	2dRMS
GPS Only			
All SVs	1.0000	1.49	106 meters
1 SV Deleted	0.9968	1.67	118 meters
2 SVs Deleted	0.9958	1.96	139 meters
3 SVs Deleted	0.9824	2.42	171 meters
GLONASS Only			
All SVs	1.0000	1.44	102 meters
1 SV Deleted	0.9997	1.71	121 meters
2 SVs Deleted	0.9956	1.92	136 meters
3 SVs Deleted	0.9867	2.20	156 meters
Integrated GPS/GLONASS			
All SVs	1.0000	0.83	59 meters
1 Each Deleted	1.0000	0.87	62 meters
2 Each Deleted	1.0000	0.91	64 meters
3 Each Deleted	1.0000	0.98	69 meters

The solo constellations provide CVs of 1 and 2dRMS horizontal position accuracy of approximately 100 meters when all satellites are operational. After 3 satellite failures the CVs are approximately 0.985 and the 2dRMS horizontal position accuracy is worse then 150 meters. This means that, averaged over 24 hours, outage areas occur over CONUS 1.5% of the time and that the average navigation accuracy is degraded by over 50% from the nominal level for the SPS of 100m.

The integrated constellation provides a CV of 1 and better then 70 meter 2dRMS horizontal position accuracy even after 3 GPS and 3 GLONASS satellite failures. Thus, even after six satellite failures, an integrated GPS/GLONASS receiver would provide better navigation performance than a GPS only or a GLONASS only receiver with all satellites operational in each constellation.

RAIM Performance

RAIM performance is related to satellite geometry by the following equation [3, 8]:

$$P_{MD} = P(Q^{-1}(PFA|M\text{-}N) \mid M\text{-}N, RPE^2/[\Delta H_{MAX}^2 \cdot \sigma_n^2])$$

where P_{MD} is the required probability of missed detection

$P(X^2|r,e)$ is the noncentral chi-square probability function

$Q^{-1}(p|r)$ is the inverse of $Q(X^2|r) = 1 - P(X^2|r)$ and

$P(X^2|r)$ is the chi-square probability function

P_{FA} is the acceptable probability of false alarm

M is the number of visible satellites

N is the number of navigation states (4 for solo GPS or GLONASS and 5 for integrated GPS/GLONASS)

ΔH_{MAX} is a function of the satellite geometry

RPE is the acceptable radial position error

σ_n is the pseudorange measurement noise standard deviation.

It is shown in [3] that :

$$\Delta H_i^2 = HDOP_i^2 - HDOP^2$$

where $HDOP_i$ is HDOP calculated with the i-th satellite deleted. The least detectable satellite failure corresponds to the largest ΔH_i. Thus worst case results are obtained by using:

$$\Delta H_{MAX} = \underset{i}{MAX}\{\Delta H_i\}.$$

For given RAIM requirements (P_{MD}, P_{FA}, M, N, RPE, and σ_n) the performance equation can be solved numerically for the required integrity geometry parameter, ΔH_{MAX}. Then the fraction of space and time that the constellation provides geometry with parameter less than or equal to this value can be calculated by simulation. This fraction of time is the RAIM availability (or RAIM Reliability).

The requirements for integrity monitoring performance have been established by the Radio Technical Commission for Aeronautics (RTCA) Special Committee 159 and are summarized in Table 4 [9]. Different requirements have been established for each phase of flight. The requirements are stated in terms of alarm limit, maximum allowable false alarm rate, time to alarm and minimum detection probability. These requirements are easily converted to the form required for evaluation of the RAIM performance equation. A maximum allowable alarm rate of 0.0002/hour with a decision every 30 seconds is equivalent to an acceptable probability of false alarm of 1.7×10^{-6}. Similarly 0.005/hour with a decision every 10 seconds is equivalent 1.4×10^{-5}. A minimum detection probability of 0.9999 is equivalent to a required probability of missed detection of 10^{-4}, 0.999999 is equivalent to 10^{-6}, and 0.9995 is equivalent to 5×10^{-4}. The converted RAIM requirements are shown in Table 5. The acceptable radial position error is stated directly in Table 4 and appears in Table 5 scaled by the pseudorange residual noise standard deviation, σ_{PR}, corresponding to the time to alarm.

Table 4. RAIM Requirements

Phase of Flight	Alarm Limit	Maximum Allowable Alarm Rate	Time to Alarm	Minimum Detection Probability
Enroute	2200 m (1.2 nm)	.0002/hr	30 s	0.9999
Terminal	1100 m (0.6 nm)	.0002/hr	30 s	0.9999
Nonprecision Approach	550 m (0.3 nm)	.005/hr	10 s	0.9999
Alternate Enroute/Terminal	1100 m (0.6 nm)	.0002/hr	30 s	0.999999
Alternate Nonprecision Approach	550 m (0.3 nm)	.005/hr	10 s	0.9995

Table 5. Converted RAIM Requirements

Phase of Flight	Probability of False Alarm	Probability of Missed Detection	RPE/σ_{PR}
Enroute	1.7×10^{-6}	10^{-4}	68.5
Terminal	1.7×10^{-6}	10^{-4}	34.3
Nonprecision Approach	1.4×10^{-5}	10^{-4}	17.0
Alternate Enroute/Terminal	1.7×10^{-6}	10^{-6}	34.3
Alternate Nonprecision Approach	1.4×10^{-5}	5×10^{-4}	17.0

The values in Table 5 are used to numerically solve for the maximum allowable satellite geometry parameter for each phase of flight. Figure 6 shows the maximum allowable satellite geometry parameter as a function of the number of visible satellites for the terminal and non-precision approach phases. If the constellation geometry provides a maximum ΔH less than the value shown for the visible number of satellites then the integrity requirements for the phase of flight are met.

Figure 6. Required Satellite Geometry Parameter

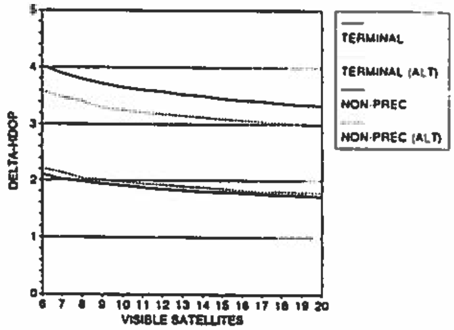


Table 6 shows the RAIM availability for the GPS only, GLONASS only, and integrated GPS/GLONASS constellations with all satellites; and with 1 each, 2 each, and 3 each GPS and GLONASS satellites deleted. The results for the alternate enroute/terminal requirements are very similar to the results for the terminal requirements and the results for the alternate nonprecision approach requirements are very similar to the results for the nonprecision approach requirements.

Table 6. Availability (RAIM Reliability)

	Phase of Flight			
Constellation Configuration	Terminal	Nonprecision Approach	Alternate Enroute/ Terminal	Alternate Nonprecision Approach
GPS Only				
All SVs	0.9962	0.9774	0.9950	0.9808
1 SV Deleted	0.9882	0.9521	0.9856	0.9579
2 SVs Deleted	0.9612	0.9040	0.9556	0.9122
3 SVs Deleted	0.9209	0.8522	0.9136	0.8617
GLONASS Only				
All SVs	1.0000	0.9874	0.9999	0.9905
1 SV Deleted	0.9835	0.9530	0.9800	0.9581
2 SVs Deleted	0.9603	0.9131	0.9539	0.9201
3 SVs Deleted	0.9220	0.8623	0.9136	0.8707
GPS/GLONASS				
All SVs	1.0000	1.0000	1.0000	1.0000
1 Each Deleted	1.0000	1.0000	1.0000	1.0000
2 Each Deleted	1.0000	1.0000	1.0000	1.0000
3 Each Deleted	1.0000	1.0000	1.0000	1.0000

The solo constellations provide RAIM availability of better than 0.995 for the terminal phase and better than 0.975 for the nonprecision approach phase when all satellites are operational. After 3 satellite failures the RAIM availability is significantly reduced to 0.92 for the terminal phase and 0.85 for the nonprecision approach phase.

The integrated constellation provides 100% RAIM availability for all phases of flight even after 6 satellite failures (3 GPS and 3 GLONASS).

CONCLUSION

The simulation results show that in the presence of satellite failures, the navigation accuracy provided by the solo GPS and GLONASS constellations is significantly degraded. Additionally, even after one failure, outage areas start appearing over the CONUS. The redundancy provided by the individual constellations is also insufficient for 100% RAIM reliability. When satellite failures occur in either of the solo constellations, the RAIM reliability deteriorates even further.

By integrating both GPS and GLONASS pseudorange measurements in one navigation solution, navigation performance and RAIM reliability are radically improved. The integrated constellation is sufficiently robust that a 5-state navigation solution, which computes position and both the GPS and GLONASS time offsets, can always be computed, even in the presence of six satellite failures (three GPS and three GLONASS). Sufficient satellites are available in this integrated navigation solution, that the effect of the GPS selective availability errors and the GLONASS system errors is averaged. This results in a navigation accuracy of better than 70 m 2dRMS. The redundancy provided by the integrated GPS/GLONASS constellation also provides 100% RAIM availability for all phases of flight, even in the presence of six satellite failures. This means that failures in either the GPS or GLONASS constellations can always be reliably detected using RAIM with an integrated GPS/GLONASS receiver.

In conclusion, the coverage provided by the combined GPS and GLONASS constellations is more than sufficient to meet civil aviation navigation and integrity requirements. An all-in-view integrated GPS/GLONASS receiver, equipped with suitable RAIM algorithms, is capable of providing sole-means navigation for enroute, terminal and nonprecision approach phases of flight.

ACKNOWLEDGEMENT

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