INTEGRATED USE OF GPS AND GLONASS IN CIVIL AVIATION NAVIGATION I: COVERAGE & DATA MODELS

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Abstract

Pursuant to a bilateral agreement signed in 1988, both US and USSR are currently in the process of examining integrated use of GPS and GLONASS for sole-means civil aviation navigation. This paper presents results from the initial phase of a program underway at MIT Lincoln Laboratory to support this effort. Specifically, we present results on satellite coverage and quality of the range measurements from GPS and GLONASS. The coverage results highlight the extent to which each system alone falls short of providing a self-contained system integrity check. In integrated use, however, there are enough redundant measurements to make receiver autonomous integrity monitoring (RAIM) practical. The data quality results are based on statistical analysis of the range measurements from GPS, at various levels of selective availability(SA), collected over extended periods. We present empirical cumulative distribution function of the range error, and RMS value of its component, defined as the 'effective' range error, relevant to position estimation. These results are used to project the position estimation accuracy achievable globally with GPS, when operational. Comparable results for GLONASS are being developed.

The coverage and data quality results together provide a basis for development of the navigation and RAIM algorithms for the integrated use. This will be addressed in the next phase of the program. The important considerations in the design of these algorithms, including the differences in the reference systems for space and time employed by the two systems, are briefly reviewed.

This work was sponsored by the Federal Aviation Administration.

I. INTRODUCTION

The agreement between the US and USSR on Cooperation in Transportation Science and Technology [1] provides for, among other things, cooperation in studying how the civil aviation community may take full advantage of the civil capabilities of their navigation satellite systems, GPS and GLONASS, respectively. Impetus for this comes from the recognition that satellite-based civil air navigation offers a great promise of economy and safety, and that each system alone falls short of meeting the requirements as a sole-means navigation device. The nature of the proposed cooperation under the Agreement has been further delineated in discussions between the US Federal Aviation Administration (FAA) and the USSR Ministry of Civil Aviation [2], and focuses on: characterization of signals in space, resolution of the compatibility issues, independent development of integrated GPS-GLONASS receivers, and assessment of their performance vis-à-vis the requirements of sole-means navigation [3]. The final objective is to provide a basis for development of user equipment standards for the integrated receiver. An FAA-sponsored program is underway at MIT Lincoln Laboratory to support this effort. This paper outlines the status, and plans of this program, and presents modeling and data analysis results from its initial phase.

From a users' viewpoint there are two important questions regarding the performance of a satellite navigation system: **How accurately can one estimate a position in general, and, given a set of measurements, how much confidence can one have in the estimate obtained from them?** The first is related to the concept of system availability, defined as the percentage of the times the system provides a position fix to an accuracy required by the user. Given the operational constellation (i.e., satellites and their orbits) and the quality of ranging signals (say, distribution of the range measurement error), the user can determine *a priori* when the system may be usable for a specific purpose and when it may not be, depending upon the number of satellites visible and their geometry [4]. We focus on these issues and consider global characterizations of the accuracy achievable with GPS and GLONASS, when operational. The second question above deals with the users' ability to affirm that a position fix computed from the measurements indeed meets the accuracy requirements. Basically the idea is to guard against anomalous measurements, a vital necessity for civil aviation navigation. Two distinct approaches have been proposed for monitoring the integrity of a satellite navigation system. The first relies on monitoring of the satellite signals at ground facilities, which broadcast a warning to the users when an anomalous situation is detected. The second approach, called receiver autonomous integrity monitoring (RAIM), is based on the premise that enough redundant satellite measurements are available for a consistency check among them to verify the quality of the measurements, and of the resulting position estimate. With the doubling of the number of satellites available for measurements in the combined constellation, we expect that the premise of RAIM would to be satisfied. Here we consider RAIM and its requirements only in general terms, and show it to be practical.

In broad terms, navigation performance achievable in integrated use of GPS and GLONASS, G+G in our notation, would depend upon the two satellite constellations and their coverage, quality of their ranging signals, and the operational control policies. Given the GPS and GLONASS constellations, coverage analysis with computer models is straightforward. The quality of ranging signals is best assessed empirically, but that is not a problem either. The structure of the GLONASS and GPS signals is now well documented [5,6], and there is no basic difficulty in designing GLONASS and integrated GPS-GLONASS receivers [7]. Also, there are enough satellites on orbit (eight of GLONASS, and 14 of GPS, at this writing) to permit methodical data collection and analysis. The third item on our list, operational control policies for the two systems, however, has a number of unknowns at this time. Policies on system health monitoring and user notification, and on replenishment of failed satellites clearly have vital implications for system availability and for integrity monitoring. Apparently these policies are currently under formulation for both systems. We should also note here that the requirements to be met by a sole-means global civil navigation system have also not been fully defined yet [8]. It is recognized that these criteria require a basic reexamination, and cannot simply be extrapolated from the experience with DME/VOR and other 'local' sensors. For our immediate purposes, we shall only draw upon simple criteria: a supplemental navigation device must reliably detect its failure to provide position estimates with the required accuracy; a sole-means device must, in addition, be able to recover.

Results on coverage provided by GPS, and by GPS and GLONASS together, are presented in Section II. Uncertainties about the requirements and operational control policies notwithstanding, we can draw some useful conclusions based on the known necessary conditions for adequacy of a constellation to provide a sole-means navigation service. Data analysis results on signal quality based on measurements from GPS are given in Section III. The coverage and signal quality results are combined in Section IV to give a global characterization of the position error obtained with GPS, when operational. These modeling and analysis results mark the first phase of our program, and constitute the main contribution of this paper. Comparable results on data quality and position estimation accuracy for GLONASS are currently in the works. These results would prepare the necessary groundwork for the next phase: Development and test of navigation and RAIM algorithms for the integrated use of GPS and GLONASS. The issues relevant to such integration, and the proposed approaches currently under study, are discussed briefly in Section V. Specifically, we consider how best to combine measurements from the two autonomous systems for navigation and integrity monitoring, given the differences in their reference systems for space and time, and the unequal quality of their measurements.

A ground-based test bed consisting of GPS, GLONASS, and G+G receivers is being implemented at Lincoln Laboratory for extensive data collection and analysis. This test bed will be used for development and evaluation of navigation and RAIM algorithms. The selected algorithms will then be implemented in a real-time system to be used in airborne demonstrations, with a G+G receiver driving the standard pilot displays, and providing the system integrity check. The performance analysis results will form a basis for development of user equipment standards.

II. GPS and GLONASS COVERAGE

We present an analysis of the coverage provided by the proposed operational constellations of GPS and GLONASS, and assess the implications for system availability and integrity. The coverage information is given in terms of probability that a user will encounter a certain scenario, obtained from analysis of the situations for a random sample of the users. For both GPS and GLONASS, our main interest is in the coverage provided by a nominal 21-satellite constellation, which, according to the current view, each system would attempt to maintain. So in each trial we select randomly: the user location on the globe, time in a 24-hour period, and 21 satellites out of the full 24-satellite operational constellation [9, 10]. We give an overall view of the number of satellites visible, and their geometry, the latter characterized, as is usual, in terms of dilution of precision (DOP) experienced by the user [4]. Only the satellites above 7.5° in elevation are counted as visible to the user, and the DOP's are calculated using all satellites visible. Our main interest is in the tails of these distributions: How often does the number of satellites visible fall below a certain number, or, DOP exceed a certain number?

As is well known, a complete 3-D solution from a snapshot of measurements requires that a minimum of four satellites be in view. A typical implementation of RAIM consists of taking each measurement in turn and checking it for consistency against the position estimate obtained with the remaining measurements. It is easy to see that RAIM would require a minimum of five satellites to detect that one of the measurements is anomalous, and six to identify the anomalous measurement. These, of course, are only the necessary conditions. Satisfactory position estimation and integrity monitoring require that the satellites be well distributed spatially. Detection of an anomalous measurement requires that *each* subset of N-1 of the N visible satellites, $N \geq 5$, have a good enough geometry to permit a reasonable position estimation. Similarly, identification of an anomalous measurement requires that each subset of N-2 satellites, $N \geq 6$, provide a good position estimate. The success of a RAIM scheme is thus seen to depend vitally on the quality of the position estimates obtained with the subsets of the measurements. With N satellites visible, we may think of failure detection as being limited by the largest of the values of position dilution of precision (PDOP) obtained with subsets of N-1, and use it as a rough measure of the viability of the approach. We compute the value of this measure, and refer to it as PDOP for failure detection, or **PDOP(Fail Detect)**. A similar measure of success in failure isolation would be the largest of PDOP's from the subsets of N-2 satellites. We refer to this as PDOP for failure identification, or **PDOP(Fail Ident)**.

The results on GPS coverage are given in Figure 1. Figure 1(a) is a histogram of the number of satellites visible; Figure 1(b) gives cumulative distribution functions (cdf's) of horizontal dilution of precision (HDOP), vertical dilution of precision (VDOP), and PDOP; and Figure 1(c) shows cdf's of PDOP(Fail Detect) and PDOP(Fail Ident), our measures of viability of RAIM. Figure 1(a) shows that fewer than four satellites are visible in 0.2% of the trials, below the minimum necessary for position estimation. Fewer than five (six) satellites are visible in 2.3% (14.0%) of the cases, below the minimum necessary for detection (identification) of a failure. Clearly, GPS alone does not meet the necessary conditions for sole-means navigation device. Additional insight into position estimation may be had from the cdf's of HDOP, VDOP, and PDOP, given in Figure 1(b). These show that in a random sample of GPS users, 1% will experience HDOP (VDOP) in excess of 3.5 (7.0). The statements on satellite geometries, or DOP's, can be translated into the corresponding statements on position estimation error as follows [4]:

$$\text{RMS Position Error} = \text{RMS Range Error} \times \text{DOP}.$$

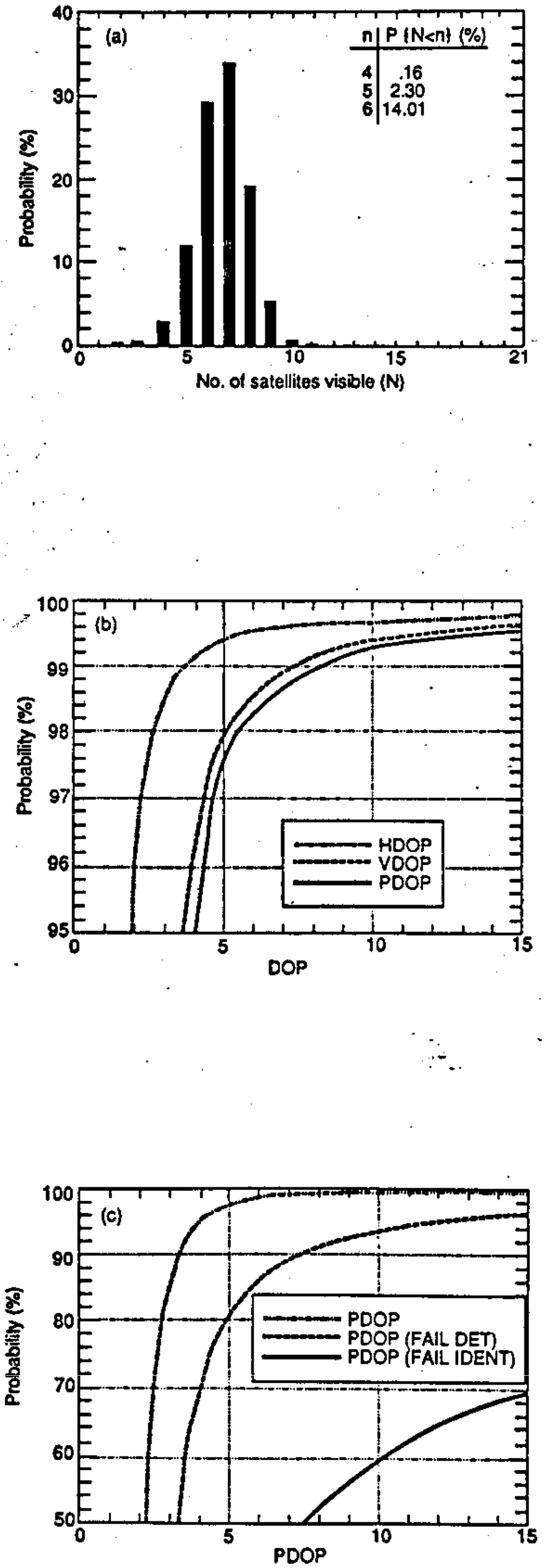

Figure 1. Global coverage due to the 21-satellite GPS constellation (Elevation mask: 7.5°)

So, if the RMS range measurement error with GPS were to be 39 m (see Section III), the RMS error in the horizontal (vertical) position estimates for 1% of the users would exceed 137 (273) m. Stated differently, the horizontal error in the position estimates of the users with HDOP≥3.5, and these are 1% of all users, has an RMS value in excess of 137 m. Similarly for the vertical error. Actually, both these statements are meaningless without an understanding of the nature of averaging required. As we shall see in the next section, with GPS the averaging would have to be carried out over a long term, making this characterization even less informative to a user than it might first appear. More informative characterizations of the position error with GPS are discussed in Section III.

Figure 1(c) shows for GPS the distribution of PDOP(Fail Detect) and PDOP(Fail Ident), the measures of viability of RAIM, along with the PDOP for all satellites in view. It is clear that GPS falls far short of meeting the integrity monitoring requirements: PDOP(Fail Detect), the largest PDOP encountered in failure detection process, exceeds five in 20% of the cases, and exceeds 10 in 7% of the cases. The situation for failure identification is worse yet. The coverage results and the conclusions for GLONASS are similar.

Figure 2 gives the coverage results for GPS and GLONASS taken together. The results are for a 2x21 constellation: GPS and GLONASS each contributing 21 satellites, selected at random in each trial out of the full constellation of 24. The results are relatively insensitive to the relative phasing of the two systems, and indeed to the loss of one or two satellites. Again, Figure 2(a) gives a histogram of the number of satellites visible from the combined constellations. Figure 2(b) gives the cdf's of the corresponding DOP's, and Figure 2(c) characterizes the distribution of our measures of viability of RAIM. The doubling of the satellites produces a clear change: the number of satellites visible invariably exceeds seven, with PDOP below 2.5. Detection and identification of anomalous measurements also appear practical: The probability that all PDOP's encountered in the failure detection or isolation step be less than 10 is 99.99%! And that is the principal payoff from integrated use of GPS and GLONASS.

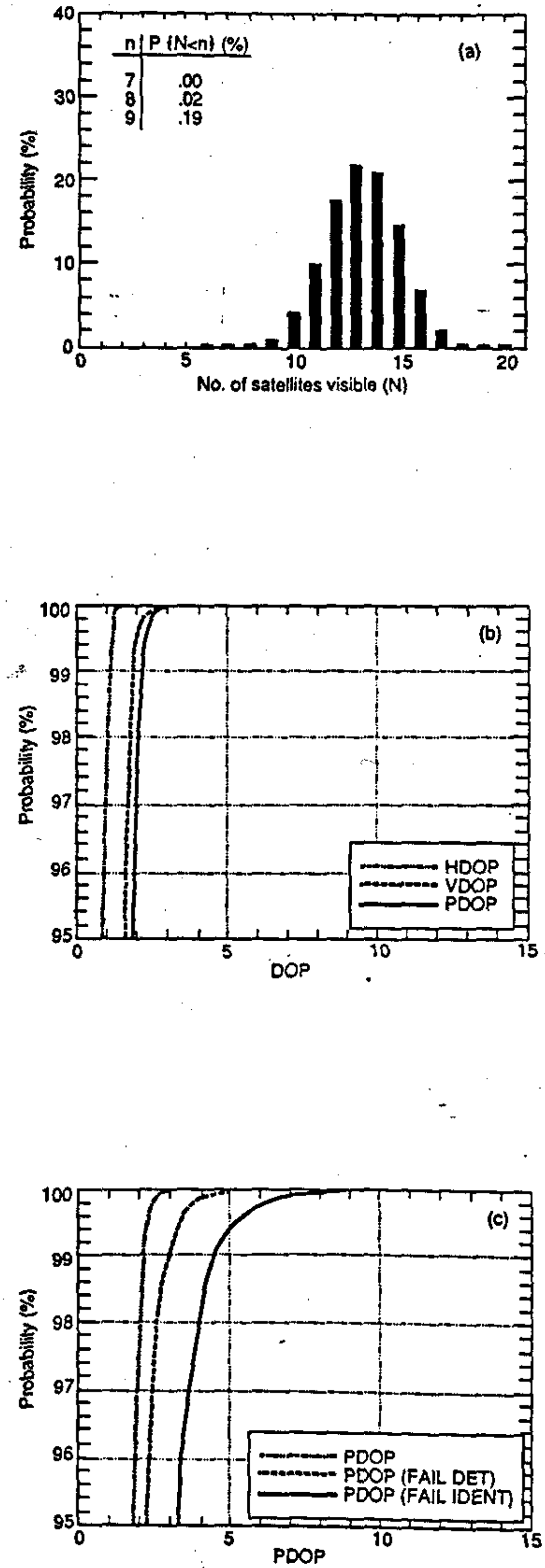

Figure 2. Global coverage due to the combined GPS and GLONASS 2X21 constellation (Elevation mask: 7.5°).

III. DATA ANALYSIS RESULTS

We have been collecting GPS and GLONASS measurements from a site at Lincoln Laboratory whose location is known precisely in the WGS-84 coordinate frame. A commercial receiver is used for the GPS measurements; the GLONASS measurements are taken with a receiver built for this project by Magnavox under a subcontract [7]. The measurements from each system consist of pseudoranges and deltaranges at L1 frequency from all satellites in view. Data analysis results on the quality of the GPS signals presented below are based on nearly-continuous measurements over a two-month period during June-August,1990. The GLONASS measurements are yet to be analyzed fully.

Our focus is on the overall range measurement error; there is no attempt at breakdown of this error into its constituents, or at phenomenological understanding. The data collection covers long enough a period to allow all error sources a fair representation in the measurements. The corrections applied to the pseudoranges are as described in GPS ICD [5] for a one-frequency receiver. The corrections to the GLONASS measurements are similar, and include the benefit of the GPS ionospheric model. Elevation mask angle of 7.5° is used throughout in data collection and analysis. Our aim is to characterize the errors in measurements, and the resultant error in position estimates, at a level consistent with the requirements of civil aviation.

As is well known, GPS Block II satellites have a provision for purposeful degradation of the signal via a feature called selective availability (SA)[5]. Apparently, GLONASS has no such feature, and there is no plan to introduce it [6]. Our knowledge of SA is limited to the description in GPS ICD, according to which the level of such degradation is characterized by value of the parameter User Range Accuracy (URA), carried in the ephemeris message. This parameter is defined to mean that the range accuracy is 'no better than URA meters'. Our GPS data collection period substantially coincided with a test period for SA, and we collected measurements with URA ranging from two to 64. The Block I satellites, without provision for SA, typically have URA ≤ 4. The typical URA setting for the Block II satellites, within or outside the test period, is 32. This appears consistent with the stated performance specification of 100 m (2 drms) position error with GPS [3], and led us to conclude that URA = 32 corresponds to the 'nominal' SA level. There are fewer measurements available at other URA levels (between 4 and 32, and at 64). The measurements with URA 8 appear to be substantially of the same quality as those with URA ≤ 4, and this led us to conclude that URA≤8 corresponds to absence of SA. URA = 64 apparently corresponds to a higher SA level, but not enough measurements were available for a proper characterization. Given the stated DoD policy on SA, we focus mainly on the measurements taken with URA = 32, but present some results for URA ≤ 8 for comparison. The latter results will also be a basis for assessment of the results from GLONASS. As a shorthand, we shall use SA1 (SA On) to denote presence of the nominal-level SA (URA = 32); SA0 (SA Off) would denote the absence of SA (URA≤8).

We follow two approaches to our characterization of the range error. The first entails estimation of the error in each range measurement directly, as described below. These errors are then characterized in terms of their empirical cumulative distribution functions. The second approach is indirect, and consists of estimation of the RMS value of only that component of range error which enters in position estimation. This approach, as we shall see, effectively deweights any common or correlated error components among the measurements, and provides a particularly useful statistic for position estimation error.

In the first approach to characterization of the range measurement error, we estimate it as the difference between the computed range between the satellite and the receiver antenna, and the measured pseudorange corrected for the receiver clock bias. The computed range is based on the satellite position as given in the ephemeris message, and the known antenna position. In the absence of a more stable frequency standard, the clock bias correction is based on a quadratic model: the receiver clock bias relative to the system time is modeled as a quadratic function of time. In GPS measurements, the parameters are estimated for each observation period with a minimum of three Block I satellites in view. In GLONASS measurements, estimates are obtained from a subset of the satellites in view. In each case, we take advantage of the known antenna location, and fit a quadratic function to the measurements typically over hour-long periods to estimate the clock behavior. The fit was found to be good in both cases: The RMS residuals are typically under 5 m. Removing the receiver clock bias from the pseudorange measurements gives us the measured ranges. The range measurement error is then estimated as the difference between the measured and the computed ranges. We have computed the range error for the Block II satellites of GPS with different values of URA.

The results on distribution of the range measurement error for GPS are given in Figures 3 and 4. The sampling interval for these measurements is three minutes. The cdf for GPS(SA0), obtained from the range measurements over several weeks from Block II satellites with URA ≤ 8 is shown in Figure 3; it is substantially Gaussian with mean of -1.1 m and standard deviation of 4.7 m. The negative bias apparently reflects the model error in the atmospheric delay models for our data set. These error measurements are correlated across satellites. Figure 4 shows the distribution of the range error for GPS(SA1) for measurements collected over different periods from Block II satellites with URA = 32. Figure 4(a) shows the cdf's of the measurements collected over a day-long period from three of the satellites (three-minute samples collected over three to eight hours of observations). The three cdf's appear quite dissimilar: the measurements from two of the satellites appear to be uniformly distributed over a 90 m range, entirely positive in one case, and almost entirely negative in the other. The two sample means are 90 m apart. Clearly, the time constants (or, autocorrelation times) of the underlying random processes for SA1 are large. While the results of a comprehensive spectral analysis are awaited, it appears that the range error consists of a random process with a correlation time of about two to three minutes superimposed over another with a much larger variance and correlation time of several hours, or longer. Obviously samples of range error are required over a time period much longer than a day.

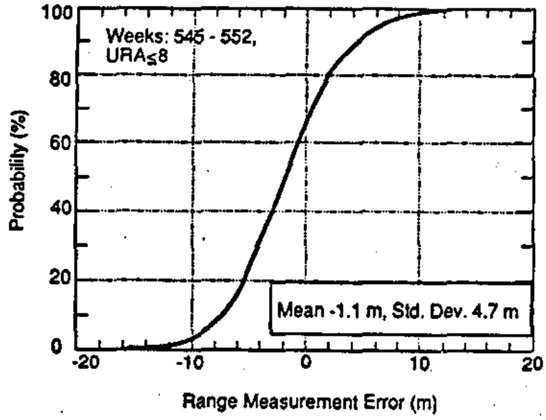

Figure 3. Distribution of the range error for GPS(SA0).

The cdf's of the range error from measurements taken over a week begin to show similarities, as seen in Figure 4(b): the distributions of measurements from the same three satellites as in Figure 4(a) have standard deviations in the range 35 to 42 m. These cdf's were computed using three-minute samples collected over 15 to 40 hours of observations. There is no apparent correlation in the measurement errors from the different satellites. Apparently SA-introduced error is uncorrelated among the satellites, and at SA1 level it also dominates the other error sources. Figure 4(c) gives the cdf of the range error for SA1 from measurements taken from multiple satellites over several weeks. The distribution is essentially Gaussian with zero mean and a standard deviation of 39.4 m. This is our basic data model for range measurement error from GPS(SA1).

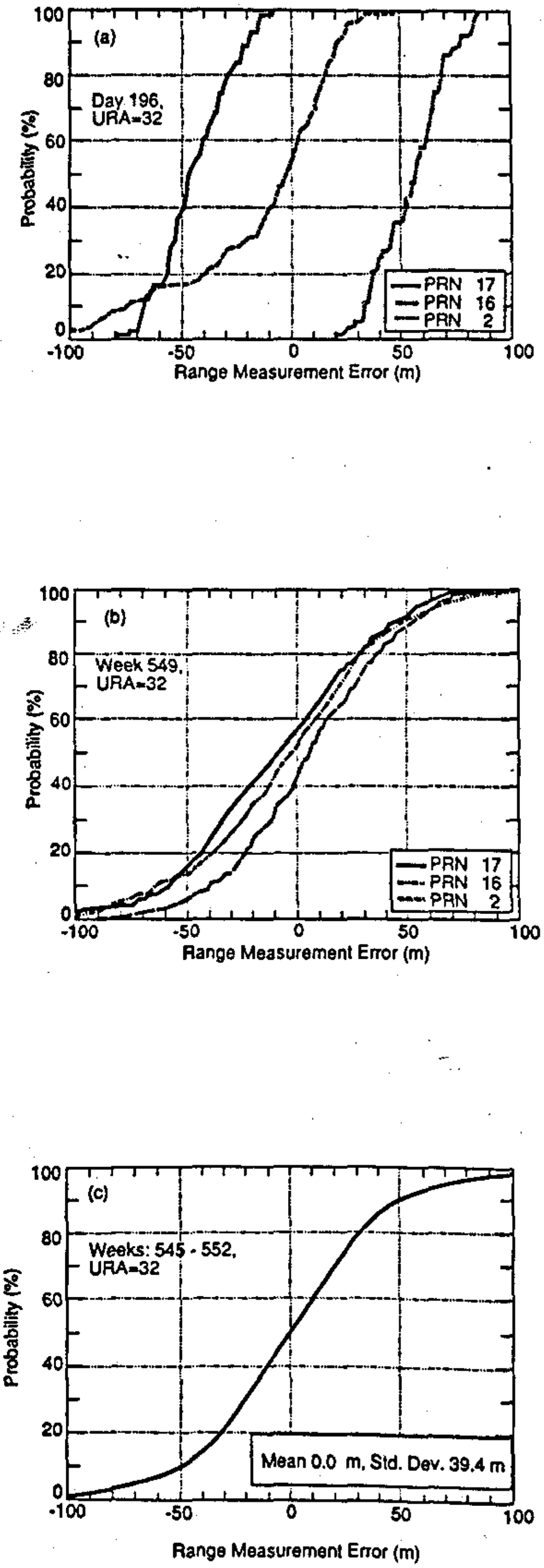

Figure 4. Distribution of the range error for GPS(SA1).

Figures 4(a) and 4(b) together highlight important issues related to the average performance in navigation with GPS(SA1). For example, the present DoD policy provides for the average performance in terms of accuracy of 100 m (2 drms) or better horizontally and 156 m (2 sigma) vertically [3]. However, given such large correlation times, questions arise: (i) over how long a time interval must the averaging be done? and (ii) what does the average performance mean to a civil aviation user? The answers appear to be (i) a week, or more, and (ii) not much. A user cannot expect to average out the error by taking measurements over any realistic time interval. If a measurement (or the corresponding estimate) is poor, it may stay poor for hours.

In the second approach to the characterization of range error, we take an indirect route, and examine the error in position estimates obtained with different subconstellations of GPS (or, GLONASS). Specifically, we look for a relationship between the position estimation errors and the corresponding values of DOP, and estimate the multiplier σ in the well-known and handy equation [4]:

$$\text{RMS Position Error} = \sigma \ \text{DOP}.$$

The equation above is derived for a linear system under idealized circumstances: Errors in the measurements are zero-mean, independent, and identically distributed. If this were true of position estimation with pseudorange measurements, σ would just be the standard deviation of the range measurement error, which we have computed previously. But we know that the above assumptions do not hold true strictly. Consider, for example, the error in the range measurements due to the atmospheric propagation delay. This error depends upon the elevation angle of the satellite, and, therefore, is not identically distributed. Any model-based corrections will still have some error left, and this uncompensated modeling error would be expected to be substantially correlated among the measurements from the satellites in view. Our model for measurements is such that any common or correlated errors among them are less harmful insofar as they are attributed to, or absorbed in, the receiver clock bias. So, the question is: Does the above relationship hold for some value of σ, which we may call the 'effective' range error? The answer, as we shall see, is yes.

We consider position estimation based on GPS(SA0) and GPS(SA1) satellites separately. For each, we extract from our measurements the cases where four or more satellites were visible, making position estimation possible. For each such sample we compute the value of PDOP for the constellation, the position estimate, and the associated radial error. The sampling interval is three minutes. The results are shown in the position error vs. PDOP scatter plots in Figures 5(a) and 6(a). The range of the observed PDOP values reflects a limitation imposed by the current constellation: The lowest PDOP observed in measurements with GPS(SA1) is four because out of the 13 GPS satellites on orbit during most of our data collection period only seven were Block II and capable of SA, and apparently this is the best geometry they can muster. The range of PDOP obtained with GPS(SA0) reaches below two because SA was off during several weeks of data collection and all satellites had URA ≤ 8, creating very favorable geometries. But both scatter plots are seen to have 'holes' reflecting inadequacy of the sample size. With data collection continuing, this deficiency would be corrected in time. The estimates derived, therefore, are only preliminary. Our main purpose in presenting these is to make some qualitative arguments.

In order to estimate the effective range error (σ) from the scatter plots of Figures 5(a) and 6(a), we need RMS values of the position error for measurements grouped by their PDOP values. These are shown for SA0 in Figure 5(b), and for SA1 in Figure 6(b). The slope of the straight line through the origin and fitted through these computed values gives our estimate of σ. We have attempted to group the measurements by PDOP so as to have roughly the same number in each group. But the paucity of data, especially at higher PDOP values (say, 10-15) is troublesome, and we may consider fitting a line over a subset of the points only. The preliminary estimates of effective range errors for SA0 and SA1 are 3.3 m and 39.0 m, respectively. It was expected that due to the correlations among the measurements across satellites, the effective range error would be smaller than that shown in Figures 3 and 4(c). This is seen to be true for SA0, where the effective range error is 3.3 m, versus 4.7 m range error standard deviation. This suggests that in SA0 the uncorrelated and the correlated error components are roughly the same size. That, however, is clearly not true of SA1, as was to be expected. As noted earlier, it appears that the uncorrelated error due to SA overwhelms the other error components, and effective range error is roughly equal to range error of 39.4 m.

The equation given above is typically used in the following context: given the DOP value corresponding to a subconstellation visible, how much error might there be in position estimation? The equation gives the RMS value of position error, which, though useful, is an incomplete answer. A user would also like to know: (i) How much variability might there be in the position error for the given DOP, and (ii) how much averaging is required to reach the RMS value? The scatter plots in Figures 5(a) and 6(a) provide a basis for answering the first question. Again, we group the measurements by PDOP as before, and for each group compute the mean and standard deviation of the position error. This characterization of the position error via mean and standard deviation is much more informative than RMS value alone. These are plotted in Figures 5(c) and 6(c) for the measurements available to us now. The reservations about the small sample size apply here also. The second question above was

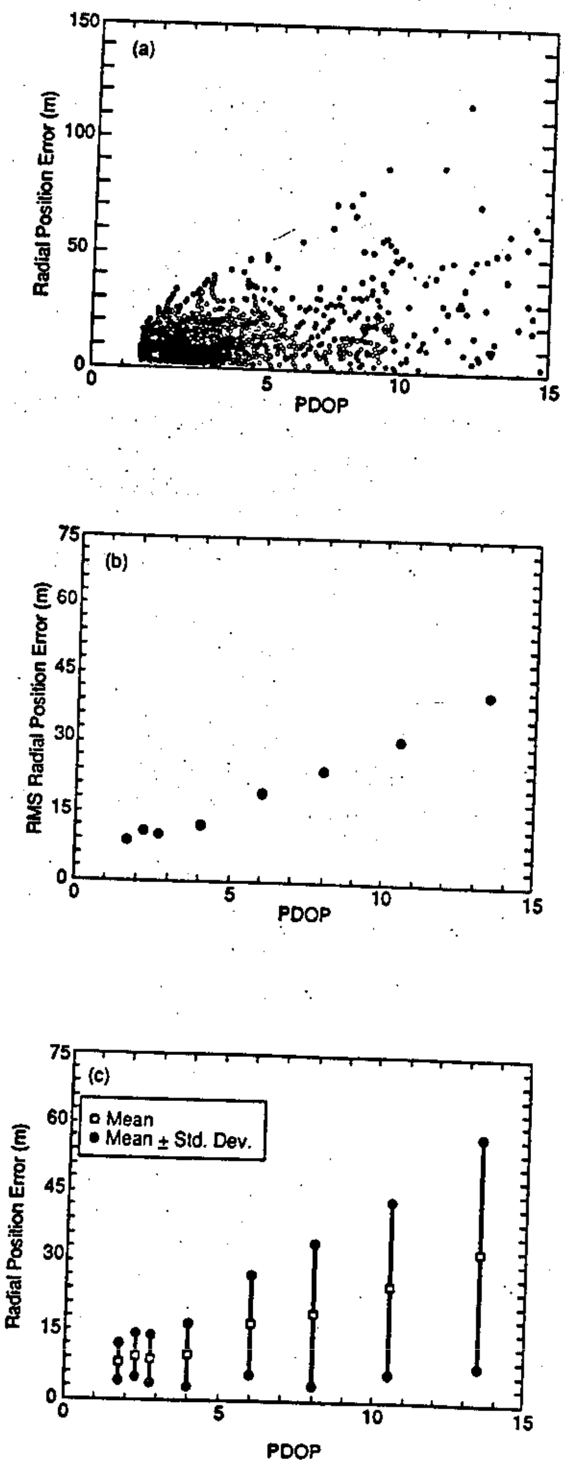

Figure 5. Distribution of the position error, given PDOP, for GPS(SA0).

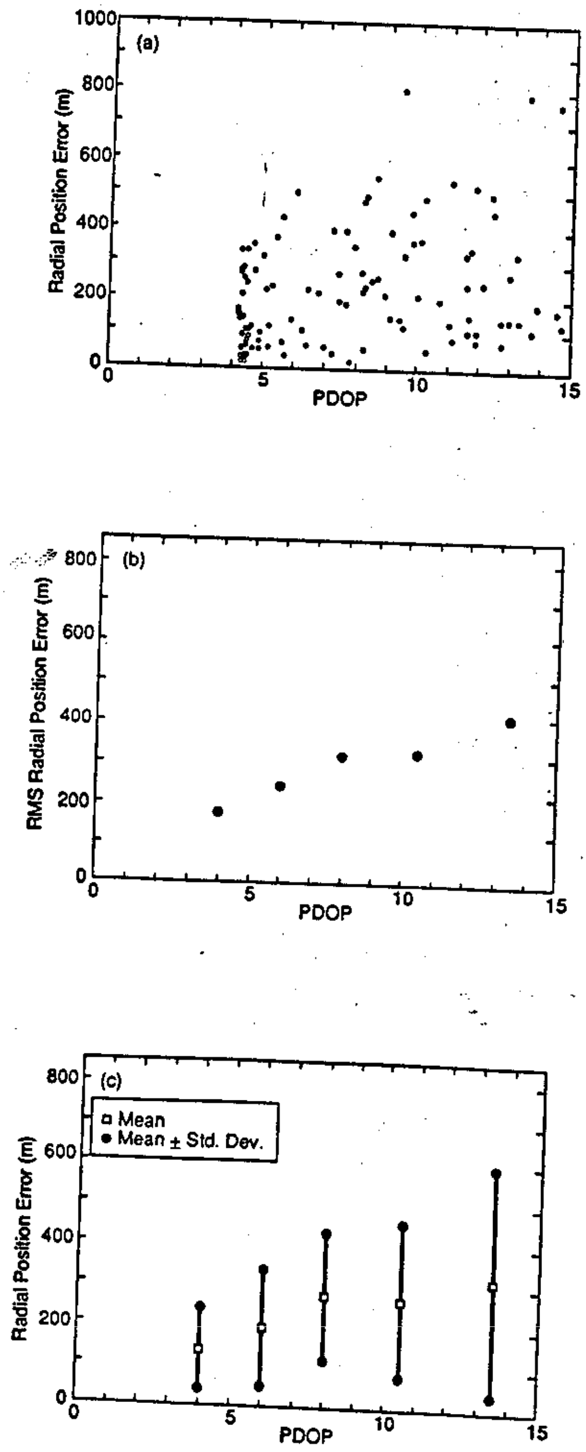

Figure 6. Distribution of the position error, given PDOP, for GPS(SA1).

answered earlier, and the answer is: weeks. This fact, clearly, needs to be taken into account in any navigation or integrity monitoring scheme. There are gaps in Figure 6(c) corresponding to the DOP values not realizable with the current GPS constellation. We attempt to fill in these gaps in the next section for a more complete picture.

IV. POSITION ACCURACY WITH GPS AND GLONASS

The main questions of interest to us are: (i) What are the distributions of position error for GPS (SA1) and GLONASS on a global level? (ii) How should we combine measurements from the two autonomous systems for position estimation and integrity monitoring? and (iii) What is the performance achievable in an integrated use? We are now in a position to answer the first question for GPS(SA1), given the results of our analysis of coverage and data quality. It is important, however, to keep in mind that this analysis is based on the premise that SA is a stationary process, and that our characterization of it as described in Section III continues to hold. The comparable results for GLONASS must wait for characterization of its data quality. Brief discussions of issues relevant to the other two questions are deferred to the next section.

We can extend the global coverage analysis simulation described in Section II by incorporating the empirical results on the quality of the measurements, and computing the distribution of position estimation error. With SA1, the measurements across the satellites are substantially uncorrelated, making such analysis particularly easy. Our model for the range error is: independent (across satellites), identically-distributed Gaussian with zero mean and standard deviation of 39 m. A similar analysis for GPS(SA0), however, would require that the correlations among the measurements be taken into account. A simpler alternative is to use the characterization via the effective range error: independent, Gaussian with zero mean and standard deviation of 3.3 m.

As in coverage analysis, we take a random sample of the user locations and times, and determine for each the number and positions of satellites visible (elevation≥7.5°) from a randomly-drawn subconstellation of 21 out of 24 satellites of GPS. The computed ranges to the satellites are corrupted by the error model to generate the measured ranges, and the position estimates and the corresponding position error calculated. The cdf's of horizontal, vertical, and radial position error are plotted in Figure 7(a) for GPS(SA1). The results are to be compared with the performance specifications for the Standard Positioning Service (SPS) [3]: 100 m (2 drms) horizontally and 156 m (2 sigma) vertically. Note that 2 drms is meant to be interpreted as the 95% point of the error distribution [3, p. C-2]. As seen in Figure 7(a), the horizontal error in our simulation turns out to be below 100 m in about 96% of the cases. The vertical error, however, is found to be larger than that specified for SPS: standard deviation of 98.5 m, and 95% point at 180 m. It is interesting to note that the median horizontal (vertical) position error is 35 (50) m; 99% point for the horizontal (vertical) position error is 160 (320) m.

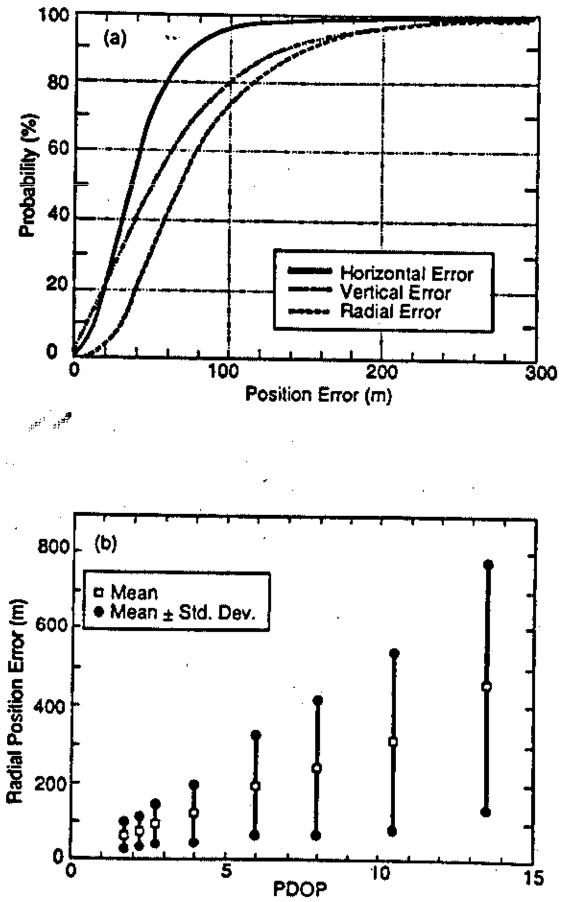

Figure 7. Global position error for GPS(SA1).

Grouping these simulated measurements by PDOP, and computing the mean and standard deviation of each group, provides us with a way to fill in the gaps in Figure 6(c). Figure 7(b) presents the complete picture of position error statistics for values of PDOP realizable with GPS. The validity of these results is established by noting that they agree substantially with the empirical results presented in Figure 6(c) in areas of overlap, small sample in the latter notwithstanding. A simple rescaling of the x-axis in Figs. 7(a) and 7(b) gives us the comparable results for SA0. The scale factor is 3.3/39, or 1/11.8, the ratio of effective range errors for SA0 and SA1. The effect of SA is now clear: The position estimate with SA has 11.8 times as much error on the average as without SA!

V. INTEGRATED USE OF GPS and GLONASS

We examine next the issues related to how we combine measurements from the two self-contained, autonomous systems to obtain their full benefit. Clearly, we need to take into account any differences in their reference systems for space and time, and in data quality. In this section, we outline the essential considerations involved, and the approaches being proposed to address these issues.

• Coordinate Frames

The precise definition of the coordinate frame in which the satellite positions are specified is of little interest to a typical user of GPS or GLONASS, only that it be implemented and used in a consistent way. (The fact that the WGS-84 geocentric coordinate frame, as described in the GPS ICD [5] is not exactly the same as defined by the Defense Mapping Agency [11], has probably gone deservedly unnoticed by most GPS users.) However, if the measurements from the two systems are to be combined, a careful accounting of this difference is required.

Our initial approach is to assess the differences empirically: Obtain position coordinates for several, well-dispersed points in both WGS-84 and in SGS-85, and estimate a transformation and a measure of its accuracy. For now we only have GLONASS measurements taken at Lincoln Laboratory (Bedford, MA) and at Magnavox (Torrance, CA) at two sites whose locations in WGS-84 are known accurately. Measurements from additional sites shall be arranged. Given the transformation, the position estimation in either coordinate frame is straightforward.

• System Times

The system time in GPS and GLONASS is maintained by Control Segment of each using very stable cesium and hydrogen maser clocks [12]. The navigation message for each SV in GPS carries the parameters of a quadratic correction model for the SV clock, updated hourly; the GLONASS clock model is linear, and updated half-hourly. The navigation message also carries parameters relating the system time to UTC: UTC(USNO) for GPS, and UTC(SU) for GLONASS.

Given a mix of pseudorange measurements from GPS and GLONASS, as a first cut, we may consider the navigation problem to entail five unknowns: components of the user position vector (3), and receiver clock biases relative to the GPS and GLONASS system times (2). The last two variables may also be thought of in terms of the receiver clock bias relative to, say, the GPS system time, and the time bias between the GPS and GLONASS system times. On any reasonable time scale, the last variable now is really a parameter. It should, then, be possible to estimate this parameter as a part of receiver initialization and calibration process, reducing the position estimation again to a four-variable problem, with the appropriate monitoring of this parameter value.

• Navigation and Integrity Monitoring

There are two basic considerations in designing navigation and integrity monitoring algorithms for G+G. First, in view of the stated U. S. policy on SA, measurements from the two systems may not be of equal quality. Secondly, the number of measurements available can be large: 95% of the time ten or more satellites from the combined constellation are in view, as seen in Figure 2(a). The number of receiver channels to be provided, and their design (dedicated vs. sequential), would depend upon a cost-benefit analysis. Our immediate concern, however, is with benefits only, and we sidestep any economic considerations.

The position accuracy requirements of en route and terminal area navigation, and of nonprecision approach may be substantially met by GPS (Figure 7), or GLONASS, alone. Anticipating a performance from GLONASS comparable to that from GPS(SA0), a navigator may choose to rely on GLONASS alone for position estimation. Actually the position estimation cannot be divorced from integrity monitoring, and from the combined accuracy-integrity consideration, there is a clear-cut case for weighted contributions from GPS and GLONASS. A logical candidate for such weighting is the range error variance. This would downgrade the measurements of poor quality so that their contribution to position estimation may be reduced without undermining their value in RAIM, as discussed below.

The effectiveness of RAIM is tied to the number of redundant satellite measurements available; basically, the more the better. As discussed in Section II, neither GPS nor GLONASS alone offers enough redundancy in measurements for a self-contained integrity check. Together, they make RAIM practical. Indeed, this constitutes the principal payoff from the integrated use. So the question is: How best to use the redundant measurements of unequal quality to address the users' concern about the quality of the position estimate?

The schemes proposed for RAIM so far appear to have focused on the 'lean' satellite environment of GPS alone [13]. A number of snapshot-based algorithms have been proposed. It is assumed that at most one of the satellites may be faulty, and transmitting an out-of-tolerance signal. The algorithm is typically structured as a two-step process: first, detecting in the measurements presence of a malfunctioning satellite, and, if found, identifying and removing it from the solution. Typically, the algorithms are tied to a nominal model for the data, and an explicit model for the anomaly. If the measurements can all be said to be consistent with the nominal model, the position estimate is said to be acceptable. That, however, doesn't reflect the users' needs.

Diagnosing whether a particular satellite is providing anomalous measurements (say, an unexpected bias, or drift) is of no particular importance in itself. This is specially true in a satellite-rich situation of G+G where the number of satellites visible is typically much larger than the minimum needed for position estimation. The point is that a user does not really need all of the satellites in view, and, therefore, does not need a pass-fail declaration on each. Instead, what's needed is a way to select a subset of satellites, **which gives a position estimate consistent with the user's need for accuracy with high confidence.** The focus thus shifts from detection of a cause of a possible problem to verification of the effect of main interest to the user. Development of navigation and RAIM algorithms with this viewpoint is currently underway [14].

SUMMARY

Integrated use of GPS and GLONASS has the potential for meeting the requirements of sole-means civil air navigation. A cooperative program between the U. S. and U. S. S. R. is currently underway to explore and resolve the issues related to such integrated use, and to establish the navigation performance achievable. An FAA-sponsored program has been initiated at MIT Lincoln Laboratory in support of this effort.

A ground-based test bed consisting of GPS, GLONASS and integrated GPS-GLONASS (G+G) receivers is being implemented at Lincoln Laboratory for extensive data collection and analysis. Data analysis results based on GPS measurements show that with nominal selective availability (i) the range error can be modeled as zero mean Gaussian with a standard deviation of 39 m, (ii) the range errors among the satellites are uncorrelated but the autocorrelation time is on the order of hours, or more, (iii) in view of the long correlation times, any statements on the average performance without a measure of variability are of little value to a user. Measurements are currently being made with an eight-channel GLONASS receiver, and data analysis is in progress.

The development of a G+G receiver and of algorithms for navigation and integrity monitoring are underway. The issues associated with integrated use of the two autonomous systems with differences in the system reference times and in the geocentric coordinate frames are being addressed. The selected algorithms will be implemented in a real-time system to be used in airborne demonstrations, with G+G receiver driving standard pilot displays, and providing system integrity check. The performance analysis results will form a basis for development of user equipment standards.

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