Integrated Use of GPS and GLONASS in Civil Aviation

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■ The combination of signals planned to be available for civil use from the U.S.'s Global Positioning System (GPS) and the former U.S.S.R.'s GLONASS system offers the promise of an accurate and economical sole-means navigation system for civil aviation. An FAA-sponsored program at Lincoln Laboratory has examined the technical issues associated with the integrated use of the two autonomous systems, and has established the level of performance so achievable.

THE DEVELOPMENT OF TWO satellite-based global navigation systems, the U.S.'s Global Positioning System (GPS) and the former U.S.S.R.'s GLONASS system (now Russian owned), represents a revolutionary change in the technology of navigation and positioning. Both systems promise highly accurate continuous measurements of position, velocity, and time to users worldwide. And best of all, these measurements are free—at least for a while.

The planning for GPS began in the early seventies, and the first satellite was launched in 1978 [1]. The first GLONASS launch occurred in 1982. The two systems are based on the same fundamental idea (namely, passive one-way ranging), and indeed, as we know now, have much in common [2]. Both systems are owned and operated by their respective departments of defense, but each government has pledged to maintain partial capabilities of their system for open civil use [3].

The civil sector was quick to recognize the potential value of these positioning systems in the areas of civil aviation, marine and surface navigation, surveying and geodesy, and recreation, and in recent years the development of products and services has proceeded in high gear. The civil aviation industry, in particular, has recognized the potential for enhanced safety and greater economy, and is committed to a quick transition to this technology at the airports and in the cockpits [4].

At this writing, GPS is close to its projected full satellite constellation, and is expected to be declared operational in 1995. The GLONASS constellation, however, remains sparse, and the political and economic difficulties in the former Soviet Union continue to be a source of uncertainty about its future.

Lincoln Laboratory's involvement in studying the potential application of satellite navigation in civil aviation began in 1981 with the development and test of a GPS receiver for general aviation aircraft under the sponsorship of the Federal Aviation Administration (FAA) [5]. A subsequent program began following a bilateral agreement between the U.S. and the Soviet Union in 1988 to examine jointly how the signals available for civil use from the two systems could be combined for the benefit of civil aviation.

The objectives of this program were (1) to understand the GLONASS signal structure and the system, and to offer an independent appraisal of its capabilities to the FAA, (2) to analyze and resolve technical issues related to combining signals from the two autonomous systems, and (3) to determine the level of performance achievable from such integrated use of the two systems vis-à-vis the requirements of civil aviation. This program is now substantially completed, and the findings are summarized in this article.

After a brief review of the principles of satellite navigation, and a discussion of the origins and status of GPS and GLONASS, we consider the requirements of civil aviation, and present results on how well the integrated use of the two systems meets these requirements.

Satellite Navigation

The idea behind satellite navigation is both simple and ancient, but implemented now with the technology of the 1970s and 1980s. The satellites, under control of precise and stable frequency references, transmit timing signals and data on their positions to the earth. A receiver measures the transit time of the signal, and deciphers the data. If the receiver clock were synchronized with the satellite clocks, measurements of range to three different satellites at known locations would allow a user to compute a 3-D position. The process is called *multilateration.* If the receiver clock were not synchronized with the satellite clocks, the transit time measurements would have a common bias reflecting this difference. This bias is an additional unknown quantity. The measurement of transit time from a fourth satellite would then solve the problem. Given four measurements, we can solve for the four unknowns, which are the x, y, and z coordinates of the user location and the receiver clock bias. The biased range measurements are called *pseudoranges.* Figure 1 illustrates the concept of using navigation satellites for position estimation. The sidebar entitled "GPS and GLONASS Signals" provides additional details on the structure of the signals transmitted by the satellites.

Having four satellites in view is only a necessary condition to compute a three-dimensional position estimate; it does not assure a good position estimate. The quality of a position estimate depends upon two factors: (1) the number of satellites in view and their spatial distribution relative to the user, and (2) the quality of the pseudorange measurements. The first

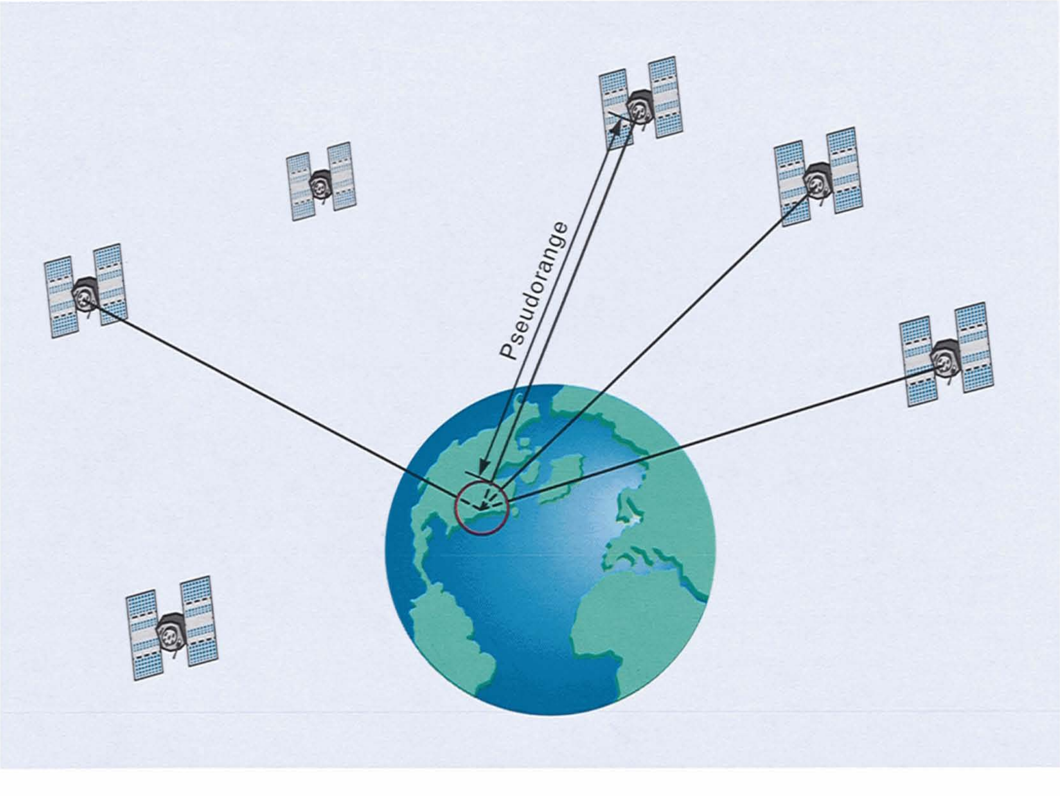

FIGURE 1. The principles of satellite navigation. If the receiver clock were synchronized with the satellite clocks, then measurement of ranges to three satellites would allow a user to compute a precise 3-D position. Otherwise, the range measurements contain a common bias, which is an additional unknown, and are referred to as *pseudoranges*. Estimation of the 3-D position and the common bias requires measurement of ranges to four satellites at a minimum. The quality of a position estimate depends on the number of satellites in view and their distribution relative to the user, as well as on the quality of the pseudorange measurements.

Table 1. Characteristics of GPS and GLONASS Systems

	GPS	GLONASS
Constellation		
Number of satellites	24	24
Number of orbital planes	6	3
Orbital inclination	55°	64.8°
Orbital radius (km)	26,560	25,510
Period (hr:min)	11:58	11:16
Ground track repeat	sidereal day	8 sidereal days
Signal Characteristics		
Carrier signal (MHz)	L1: 1575.42	L1: (1602+0.5625*n*),
	L2: 1227.60	L2: (1246+0.4375*n*),
		n =1, 2, … , 24
Code	CDMA	FDMA
	C/A code on L1	C/A code on L1
	P code on L1 and L2	P code on L1 and L2
Code frequency (MHz)	C/A code: 1.023	C/A code: 0.511
	P code: 10.23	P code: 5.11
Reference Standards		
Coordinate System	WGS 84	SGS 85
Time	UTC(USNO)	UTC(SU)
Accuracy Specifications (95%)		
Horizontal (m)	100	100
Vertical (m)	140	150

factor is referred to as *satellite geometry* and is characterized by a parameter called *dilution of precision* (DOP). We can think of DOP as being inversely proportional to the volume of the polyhedron with the user position at the apex and the satellite positions defining the base. Basically, the more spread out the satellites, the lower the DOP, and the better the position estimate.

The quality of the pseudorange measurements is characterized by their rms error. Several sources of error affect the range measurement: errors in the predicted ephemeris of the satellites, instabilities in the satellite and system clocks, unmodeled ionospheric and tropospheric propagation delays, interference from local reflections (multipath), and receiver noise. The collective effect of these errors is referred to as the *user range error* (URE); its rms value is denoted by σ_{URE}. The rms position error is expressed simply in terms of these two factors as

$$\text{rms position error} = \text{DOP} \cdot \sigma_{\text{URE}} \,. \tag{1}$$

For a satellite navigation system to be usable globally, all users must have in view at least four satellites with a good geometry, and the URE must be such that the resulting position estimate meets each user's requirement.

GPS AND GLONASS SIGNALS

Both the GPS and GLONASS navigation satellite systems are realizations of an idea to allow a user to "see" simultaneously a local clock and a make-believe display aboard a satellite that shows the satellite clock and the satellite position [1]. Obviously, the time difference between the two clocks is the transit time of the signal, which determines the range to the satellite. Knowledge of ranges to three or more satellites at known positions would allow a user to compute local position. We see below how this scheme is realized with an RF signal.

There are additional requirements to be taken into account in designing a satellite navigation system: any number of global users must be able to use the system simultaneously; the process of signal acquisition must be rapid enough to allow an initial position fix within minutes of a receiver being switched on; the system must meet the navigation accuracy requirements of users in high dynamics (aircraft and spacecraft); and the system should be able to resist unintentional or halfhearted attempts at interference.

The signal from each satellite consists of three components: (1) an RF carrier, (2) a binary code, and (3) navigation message data. These three components are explained below.

The frequencies chosen for the RF carrier signal are in the L band. The specific selection of frequencies is based on considerations of space losses, the magnitude of the effects of ionospheric propagation, and the availability of frequency allocation of the required bandwidth.

For signals available for civil use, a binary code is a sequence of 1023 bits (511 bits in GLONASS) repeated every 1 msec. GPS assigns a distinct code sequence to each satellite, with the sequences chosen on the basis of their ease of both the signal acquisition and the ability to distinguish among the satellites. The codes chosen are pseudorandom noise codes, generated from linear-feedback shift-register sequences. All GLONASS satellites transmit the same code sequence but at carrier frequencies separated by approximately 0.5 MHz.

The code sequence provides markings on the signal that are lacking in a CW carrier, and are essential to the measurement of time delay. A GPS/GLONASS receiver independently generates the known code sequence assigned to a satellite, and offsets it in time until it matches the code modulation on the received signal. The time shift required to align the receiver-generated code sequence with the sequence received from the satellite is the transit time of the signal, except for the user clock bias. The corresponding distance is referred to as *pseudorange*.

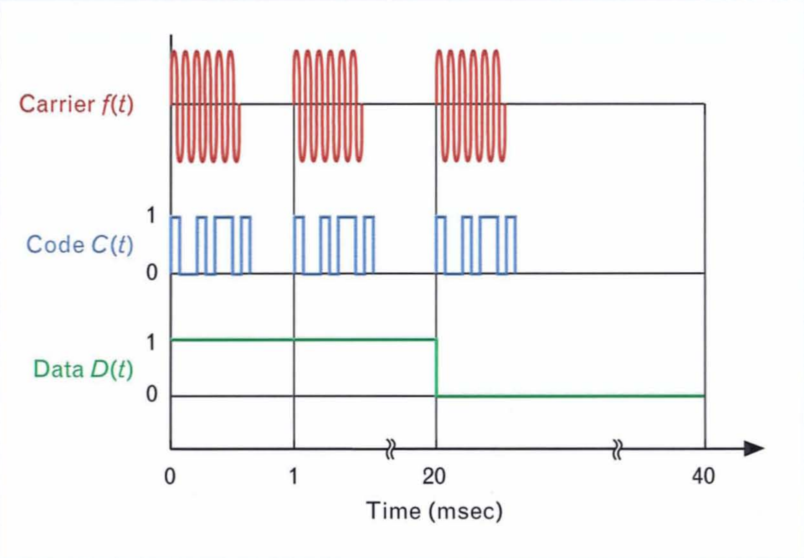

FIGURE A. The three components of the navigation satellite signal: an RF carrier, a binary code sequence, and navigation message data.

The navigation message includes data on satellite ephemeris, parameter values to correct the satellite clock for drift, and data on the other satellites in the constellation and their health status. This message is transmitted at 50 bits/sec.

These three signals—the RF carrier signal, the binary code sequence, and the navigation message—are derived coherently from an atomic frequency standard on board the satellite (see Figure A). The RF carrier signal is biphase modulated by a binary signal that is the mod 2 sum of the binary code sequence and the navigation data stream. The transmitted signal can be represented as

$$s(t) = \left[D(t) \oplus C(t)\right] \otimes f(t),$$

where $D(t)$ represents the navigation data, $C(t)$, the binary code sequence, and $f(t)$ the RF carrier signal; the mod 2 sum is represented by $\oplus$, and biphase modulation is represented by $\otimes$.

The satellite signals reaching a receiver on earth are extremely weak—indeed, well below the receiver noise level. The strength of the received signal at a user employing a 0-dBi antenna is approximately –160 dBW. The SNR in a 2-MHz front-end receiver is approximately –30 dB! The process of aligning and correlating the received and the receiver-generated binary codes gives a boost to the signal power. This processing gain is realized by despreading the 2-MHz spread-spectrum signal, which is the C/A code, to extract the 50-Hz bandwidth navigation message. This step also spreads the energy in a CW interferer over 2 MHz, providing the system with a certain resistance to jamming.

Reference

1. J. J. Spilker, Jr., "GPS Signal Structure and Performance Characteristics," *Global Positioning System,* I (The Institute of Navigation, Washington, DC, 1980), pp. 29–54.

GPS and GLONASS

Table 1 summarizes the salient features of the GPS and GLONASS constellations, signal structure, and specifications on positioning accuracy. As noted earlier, the two systems are quite similar. The differences relate to six orbital planes for GPS versus three for GLONASS, code division versus frequency division of the timing signals, and the chipping rate. GLONASS, with a higher orbital inclination, offers better coverage in the polar regions.

As shown in the table, each system transmits at two frequencies in the L band. Only the coarse acquisition (C/A) code transmitted on L1 frequency is available for civil use from either system. In accordance with the current policy of the U.S. Department of Defense, the signal available from GPS is actually a purposefully degraded version of the C/A code. The signal degradation is achieved by dithering the satellite clock frequency and by providing only a coarse description of the satellite ephemeris. This policy, known as *selective availability* (SA), effectively raises the value of the URE by a factor of four or more (the value of σ_{URE} has been in the range 25 to 40 m when measured with SA versus approximately 7 m without), and remains a source of considerable controversy among the civil users. The specifications on positioning quality for GPS shown in Table 1 are for the Standard Positioning Service available for civil use consistent with SA. While GLONASS has disavowed an SA-like feature (σ_{URE} for GLONASS is approximately 10 m), its positioning specifications are almost identical to those for GPS. The actual positioning capability of each system as measured by us is significantly better than specified, as discussed in a later section.

The U.S has pledged to maintain the GPS Standard Positioning Service, when operational, for a period of ten years without any direct user fees. The U.S.S.R. had offered the GLONASS signals for civil use on the same terms for a period of fifteen years [3]. The important practical issues of constellation management and availability remain to be fully specified for either system. On the basis of the information currently available, at least twenty-one of the twenty-four satellites in each constellation would be available most of the time. Figure 2 illustrates the planned full constellation of twenty-four satellites for each system.

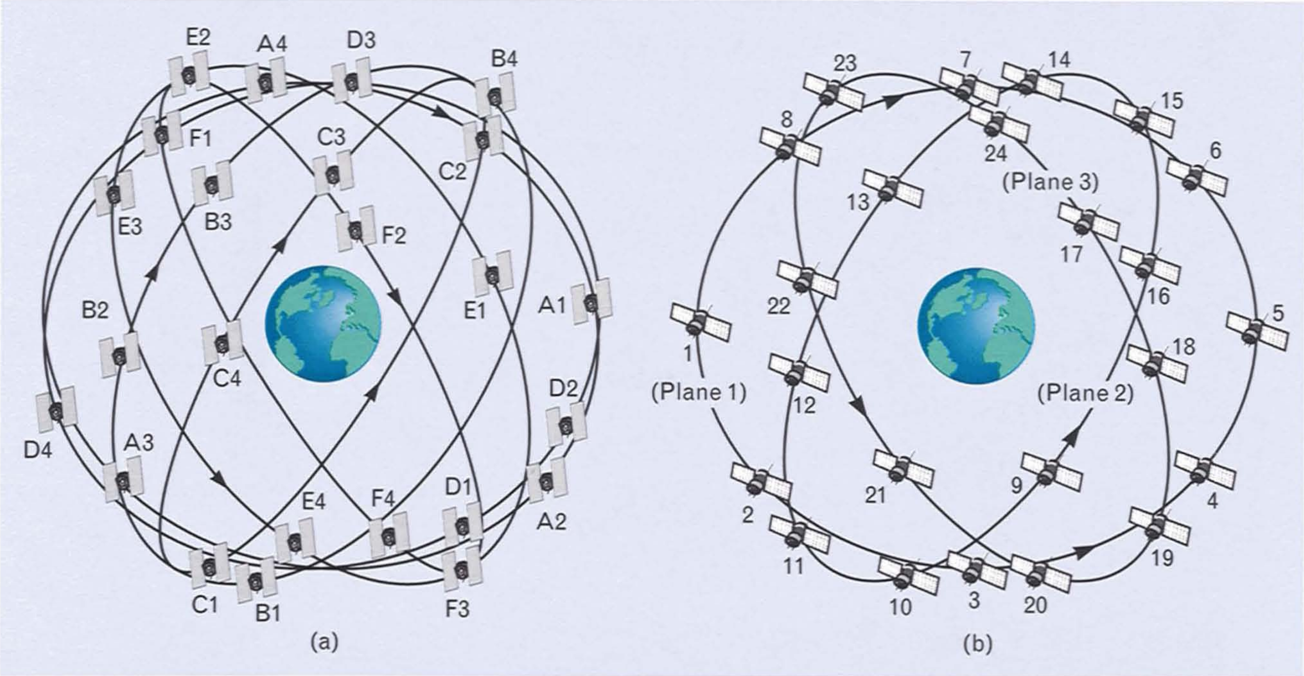

FIGURE 2. The constellation of navigation satellites in (a) GPS and (b) GLONASS. Each system is planned as a twenty-four-satellite constellation. GPS has satellites in six orbital planes and GLONASS has satellites in three orbital planes.

On 1 September 1993, GPS had twenty-four working satellites on orbit, including twenty production units, and four prototype units. These satellites have generally been trouble free and have exceeded their design life of seven years. GLONASS has had significant problems with premature loss of service from their satellites, however, and the constellation strength has remained at about twelve in the last two years. The problem is illustrated by noting that GLONASS began 1993 with thirteen working satellites; three new satellites were added in a launch in February, but the number of working satellites has remained at about twelve.

Requirements of Civil Aviation

For a navigation system to be adopted for use in civil aviation, it must meet certain stringent criteria. The criteria are stated as standards and certification procedures for each piece of equipment installed in the cockpit of an aircraft, or deployed at the airports or elsewhere for use in navigation. International civil aviation rules require agreement on the standards and procedures among the national and regional regulatory agencies.

These requirements relate to three areas: coverage, accuracy, and integrity monitoring. The coverage of a navigation system deals with where and when the system can be used. As noted earlier, a satellite-based navigation system is usable for 3-D positioning only when four or more satellites are in view of the user. A global system must, therefore, deploy a large enough constellation of satellites such that all users at different locations and times see at least four satellites.

The requirement on accuracy refers to the positioning accuracy provided by the navigation system. The accuracy requirements in civil aviation depend upon the specific phase of the flight, and currently range from several kilometers during the en-route phase to several hundreds of meters during a non-precision approach. The precision approaches, which are executed under poor visibility conditions on specially equipped runways, are another story. These approaches require that the navigation system guide an aircraft down to an altitude of 60 m or less with precision. Satellite-based navigation appears promising for precision approaches also, and is an active area of research and development. The FAA is sponsoring demonstrations in 1994 and 1995 of Category II and

Category III precision approaches, requiring submeter navigation accuracy. Our focus in this paper, however, is on en-route and terminal phases of flight and nonprecision approaches.

The requirement on integrity monitoring deals with an issue vital to civil aviation—namely, the ability of a navigation system and its users to detect a system malfunction in a timely manner. The main point is that a user must be able to rely on the position estimate provided by the system. A system may be certified as either *supplemental* or *sole means*. A supplemental system must provide a position estimate of the required accuracy, when it can, and recognize a situation when it cannot. In the latter case, the system must warn the user, who can then switch to an alternate system available for navigation. A sole-means system, as the name suggests, should require no other navigation system as a backup. The sole-means system or its users, therefore, must be able to recover from possible system malfunctions.

Obviously, the idea of a sole-means system is economically attractive, and the integrated use of GPS and GLONASS was originally seen as a potential sole-means system. Indeed, if this promise can be met, there would be no need for any of the current ground-based navigation aids, such as VOR, DME, Loran and Omega. This fact is particularly important because at present there are no ground-based navigation aids over large areas in economically underdeveloped parts of the world, or in sparsely populated areas such as Alaska and parts of Russia and Canada.

The integrity-monitoring requirements are typically stated as follows. If the error in a position estimate exceeds a certain threshold, the user must be notified within a certain time interval. Both the error threshold and the required response time depend upon the specific phase of the flight and can range widely. The system-failure scenario for a satellite navigation system is defined as an erroneous or out-of-tolerance signal transmitted by one of the satellites in the constellation. The constellations are to be managed so that at any instant the probability of two or more satellites simultaneously transmitting anomalous signals while marked as healthy is considered negligible.

Table 2 gives a current view of the accuracy and integrity-monitoring requirements for the various phases of flight. These requirements reflect the abilities of the navigation systems in use today, and are intended only for the purpose of illustration. Note that in en-route and terminal phases of flight, and during a nonprecision approach, a navigation system is required to provide only a 2-D location of the aircraft; altitude is provided by a baro-altimeter.

The navigational uncertainty determines the aircraft separation standards provided for traffic in the different phases of flight. In view of the much greater navigational accuracy that can be achieved with the satellite navigation systems, both the accuracy requirements and the separation standards are expected to be revised.

Table 2. The Projected Navigation Accuracy and Integrity Requirements in Civil Aviation

Phase of Flight		*Position Accuracy (95%)* (m)	*Integrity* Alarm Limit (m)	Time to Alarm (sec)
En Route	(horizontal)	1000	3700	30
Terminal	(horizontal)	500	1850	10
Nonprecision Approach	(horizontal)	100	550	10
Precision Approach (Category I)	(horizontal)	15	50	6
	(vertical)	7	15	6

The SatNav Laboratory

In 1989, when our program began, most of the available information on GLONASS signal structure was the result of independent monitoring and analysis of the radio signals by Professor P. Daly and his students at the University of Leeds [6]. The Soviets had provided a partial account in 1988, which generally confirmed Daly's conclusions, but many issues related to the GLONASS signal and system remained unclear. These issues were addressed by us in direct communications with the Soviet authorities, as provided for in the bilateral agreement of 1988. It was not until 1991, however, that a draft of the Interface Control Document describing the GLONASS signals in space became available.

Our first task was to set up a satellite navigation data-collection-and-analysis facility equipped with GPS and GLONASS receivers and computer systems to record and analyze the measurements. This facility was called the SatNav Laboratory. The initial focus was on the GLONASS signal structure and data quality, and on monitoring the system maintenance and upkeep. GPS receivers were available commercially in 1989, but GLONASS receivers were not. (Actually, laboratory-quality GLONASS receivers are still rare.) The SatNav Laboratory began operation in 1990 with the acquisition of two GLONASS receivers, designed and built by Magnavox to our specifications. These receivers have been a unique resource and the mainstay of our data collection and analysis program. Subsequently, we also acquired a GLONASS receiver built for aviation by the erstwhile Leningrad Radiotechnical Research Institute; this receiver was obtained by the FAA in exchange for a U.S.-built GPS receiver.

The SatNav Laboratory has grown further with the recent acquisition of additional laboratory-quality GPS receivers and an integrated GPS+GLONASS receiver currently under development by 3S Navigation of Laguna Hills, California. We estimated recently that two-thirds of all working GLONASS receivers in North America were in our SatNav Laboratory! With these receivers we have monitored the GLONASS satellites nearly continuously since 1990; the results of our data analysis are published elsewhere [7, 8], and summarized here.

Integrated Use of GPS and GLONASS

GPS and GLONASS are autonomous systems, each with its own time scale and coordinate frame in which to express a 3-D position. The time scale adopted by GPS is that of the Coordinated Universal Time as kept by the U.S. Naval Observatory, or UTC(USNO), the U.S. national standard. The time scale adopted by GLONASS is UTC(SU), the Soviet Union national standard. The offset between the two time scales in recent years has been stable, having changed slowly from -2 μsec a year ago to $+2$ μsec now, but the stability of this bias cannot be taken for granted.

Since the definition and precise measurement of time is vital to satellite navigation, a user interested in the integrated use of the two systems must be able to determine the instantaneous difference between the two time scales. The problem can be thought of as one of position estimation from two sets of pseudoranges, each with an unknown time bias, which makes five unknowns in all. Obviously, one or both systems could carry information on this bias as a part of their navigation messages. At worst, without this information, we could solve for the additional unknown by sacrificing a range measurement. As we'll see, the integrated use of GPS and GLONASS offers amply redundant measurements, and the additional unknown does not create a problem.

The two systems express the positions of their satellites and, therefore, of their users, in different geocentric coordinate frames. GPS has adopted the WGS84 system [9]; GLONASS has adopted the SGS85 system, about which less is known. Combining measurements from the two systems requires that we estimate a transformation between the two coordinate frames. Estimation of the transformation is straightforward in principle; it requires the positions of a set of points expressed in both coordinate frames. While a point on earth can now be surveyed to centimeter-level accuracy in WGS84 by using GPS measurements, the corresponding SGS85 coordinates are difficult to determine. The main reason for this difficulty is the current lack of precise and sturdy GLONASS receivers.

The GLONASS receivers in our SatNav Laboratory, and the facilities of the Deep-Space Tracking

Network (DSTN) operated by the Aerospace Division of Lincoln Laboratory, gave us the resources to take a different approach to this problem. We took advantage of the fact that the positions of GLONASS satellites as defined in SGS85 are available to us as a part of the navigation messages broadcast by the satellites. The remaining task, then, was to obtain the corresponding coordinates in WGS84, and that's where the resources of the DSTN came in. We tracked several GLONASS satellites independently to characterize their ephemerides in WGS84, and compared these to the satellite positions in SGS85 as broadcast by the satellites themselves and recorded by the GLONASS receivers in our SatNav Laboratory. The results show that the coordinates of points on earth as expressed in the two coordinate frames differ by no more than 20 m [10], and that the two geocentric coordinate frames are brought substantially into coincidence by a small rotation (0.6″) of the *z*-axis, and a small displacement of the origin. Figure 3 illustrates the process of gathering the position data in the two coordinate frames, and the resulting estimated transformation.

With the time and space reference standards reconciled, the design of a receiver to obtain measurements from both GPS and GLONASS poses no basic challenge. That such receivers remain rare is attributable primarily to current uncertainty about the future of GLONASS.

Performance of GPS and GLONASS

We discuss next the level of performance achievable from GPS and GLONASS, first from each individual system and then from their integrated use. In particular, we review coverage, accuracy, and integrity-monitoring capability, and compare the performance in each of these areas with the requirements of civil aviation.

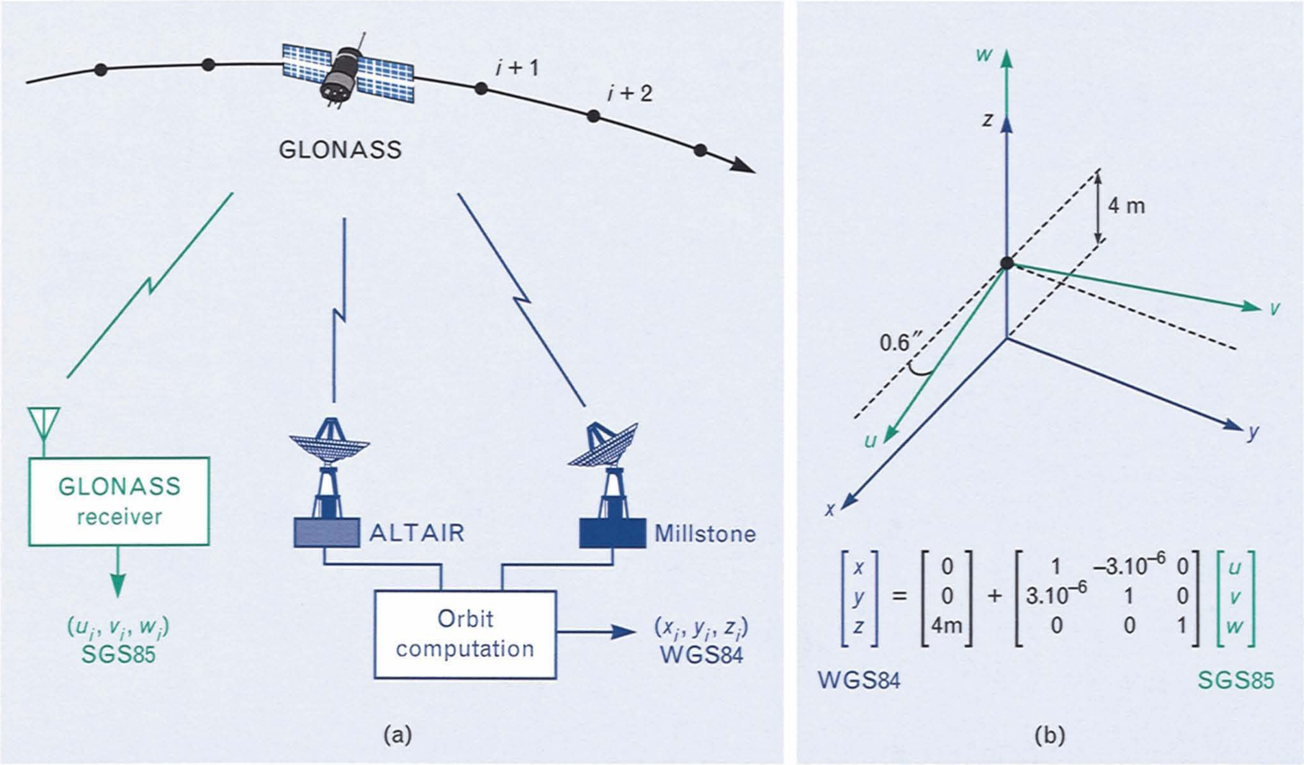

FIGURE 3. Estimation of the transformation between the SGS85 and WGS84 geocentric coordinate frames. (a) The GLONASS satellites broadcast their positions in SGS85, which is recorded by a GLONASS receiver. The corresponding coordinates in WGS84 are obtained by tracking the satellites independently and fitting an orbit to the measurements. (b) The estimated transformation between the two coordinate frames can be expressed as a small displacement of the origin and a small rotation of the *z* axis.

Coverage

Figure 4 shows the distribution of the number of satellites visible to a user at a random location on earth at a random time. We look first at the GPS constellation alone, and then at the constellations of GPS and GLONASS combined (GPS+GLONASS). Because of the current uncertainty about constellation management issues, we have modeled each constellation as consisting of twenty-one operational satellites. The constellation is defined independently in each trial by randomly failing satellites at three of the twenty-four satellite positions defined by each system. Obviously, this approach can open up holes in satellite coverage that would normally not be allowed by any prudent constellation maintenance policy. So ours is a conservative estimate. In addition, we count only the satellites that are well above the horizon (i.e., elevation > 7.5°).

The two histograms in Figure 4(a) correspond to a GPS constellation of twenty-one satellites (GPS-21) and the GPS+GLONASS constellation of 2 × 21 satellites, based on simulations. With GPS alone, a small percentage (0.4%) of the users see fewer than four satellites; the situation with GLONASS alone would be similar. With the combined constellation, though, all users would see eight or more satellites, 99% see ten or more, and nearly half would see fourteen or more. Clearly, some users may not be able to estimate their position by using GPS or GLONASS alone. With the combined constellation, however, *all* users would have abundantly redundant measurement sets on which to base a position estimate.

Figure 4(b), which gives the cumulative distribution functions of the horizontal dilution of precision (HDOP), describes the quality of the position estimates available to users globally. These curves characterize the availability of favorable satellite geometries for position estimation, and are to be interpreted in view of the relationship given earlier in Equation 1. With GPS-21, satellite geometries characterized by HDOP < 2 would be available to 95% of the users; the situation is similar with GLONASS-21. With GPS+GLONASS, however, such favorable geometries would be available to *every* user.

Accuracy

We turn next to the accuracy of the position estimates actually obtained from GPS and GLONASS, based on the measurements recorded in the SatNav Laboratory. The results for two days in August 1993 are shown in Figure 5. Each of the four plots in Figure 5 was generated in the same way. A snapshot of range measurements was taken from the satellites in our

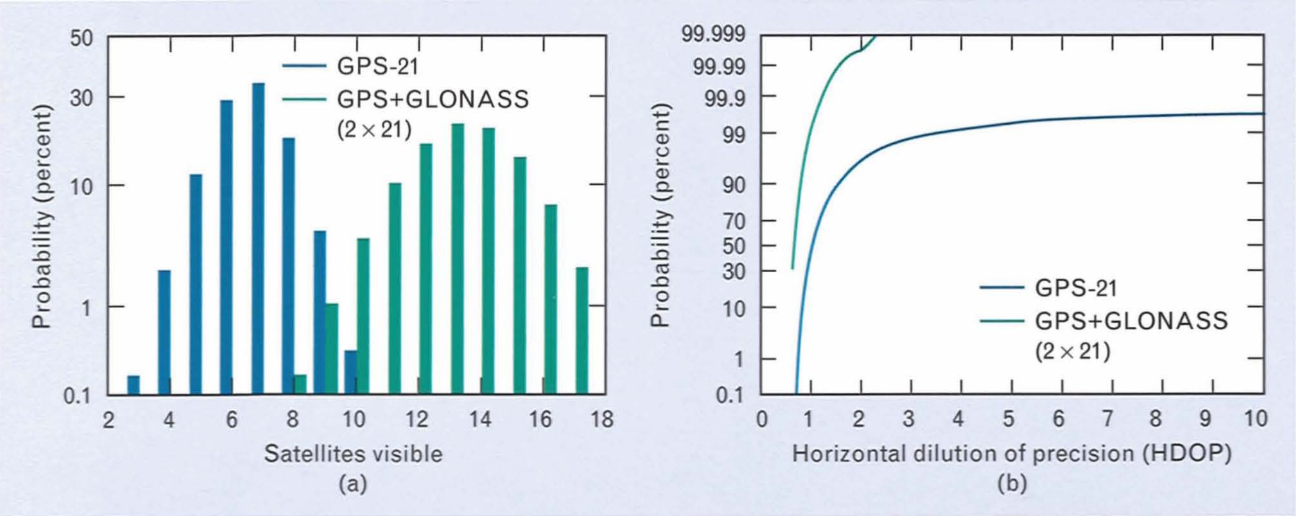

FIGURE 4. (a) The percentage of users who see a given number of satellites from a random location at a random time. A small percentage (0.4%) of users of the GPS-21 system see fewer than four satellites. With the GPS+GLONASS system, all users would see at least eight satellites at a time (a minimum of four satellites is required for position estimation). (b) The distribution of the horizontal dilution of precision (HDOP) for the GPS-21 and GPS+GLONASS (2 × 21) constellations.

view at one-minute intervals over a period of a day, and a position estimate was computed whenever the number of satellites in view exceeded four. The discrepancy in each position estimate was computed relative to the known, surveyed location of the antenna in the WGS84 coordinate frame, and the horizontal components of the discrepancy were plotted. Because the accuracy of a position estimate depends upon the satellite geometry at the time, each point is color coded to reflect the corresponding HDOP. The distribution of HDOP depends upon the strength of the constellation. During August 1993 GPS had twenty-four satellites on orbit, twenty-one of which were capable of SA, while GLONASS had twelve working satellites.

The scatterplots in Figures 5(a) and 5(b) show the quality of the GPS position estimates. The difference between the two plots is SA, and a dramatic difference it is. On 24 August 1993, all but four of the GPS satellites had SA switched off. The position estimates shown in Figure 5(a) were computed by disregarding measurements from these four satellites; the constel-

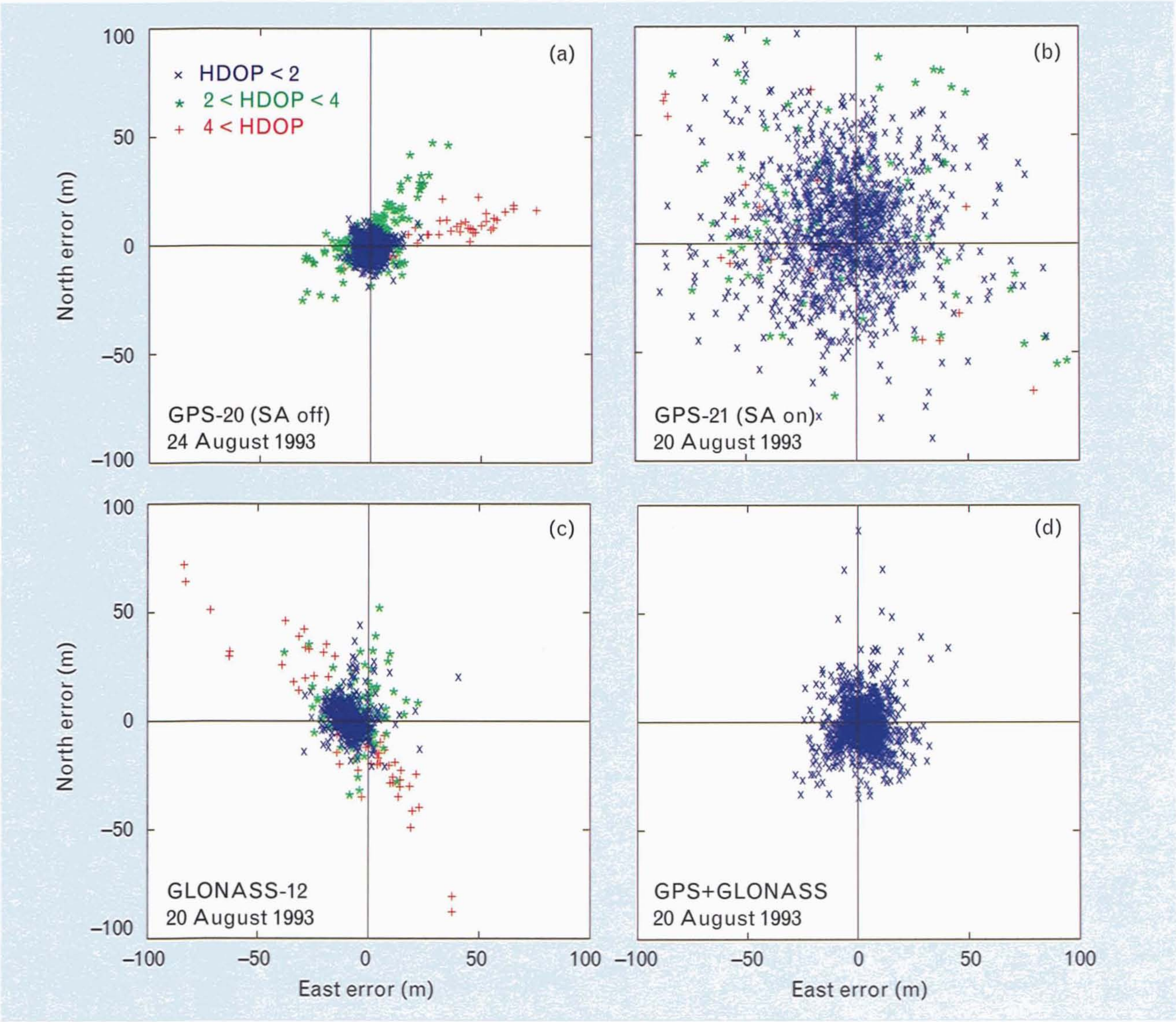

FIGURE 5. Position estimates from GPS and GLONASS obtained from measurement snapshots taken one minute apart over an entire day. Position estimates from (a) GPS with selective availability (SA) off, (b) GPS with SA on, (c) GLONASS, and (d) GPS+GLONASS. The combination of GPS and GLONASS clearly produces estimates of better quality.

lation of the remaining twenty satellites is referred to as GPS-20. On 20 August 1993, as on most days now, SA was switched on. The position estimates shown in Figure 5(b) were computed by disregarding measurements from the three prototype satellites that have no provision for SA.

Figure 5(a) shows a tight blue cluster of position estimates centered at the origin. This cluster of approximately 15-m radius corresponds to favorable satellite geometries (HDOP < 2). As noted earlier, such geometries would be available globally to 95% of the users with a twenty-one-satellite operational GPS constellation. The straggling position estimates shown in red in the figure correspond to poor satellite geometries (HDOP > 4) to be encountered by fewer than 1% of the users. In Figure 5(b), with SA on, the GPS position estimates are widely scattered, as compared to Figure 5(a). These position estimates, however, are consistent with the GPS specifications on horizontal accuracy (see Table 1).

Figure 5(c) shows the position estimates from the GLONASS constellation of twelve satellites for the same day as in Figure 5(b) for GPS. Note that the size of the blue cluster in Figure 5(c) is comparable to that in Figure 5(a). The number of poor position estimates shown in red is significantly larger, though, reflecting the current sparseness of the GLONASS constellation. When an operational constellation of twenty-one satellites is finally achieved, fewer than 2% of the GLONASS users would encounter poor satellite geometries (HDOP > 4). The blue cluster in Figure 5(c) is off center, as expected, because of the differences in the coordinate frames referred to earlier. The observed difference is consistent with our estimated transformation between SGS85 and WGS84.

Finally, we look at the position estimates obtained from the combined set of measurements from GPS and GLONASS. The results, presented in Figure 5(d), illustrate the main reason for our interest in GLONASS. Figure 5(d) combines the best features of Figures 5(b) and 5(c), and is indeed a distinct improvement over both. GPS contributes a larger satellite constellation, and GLONASS contributes measurements of better quality. The ultimate result is consistently good satellite geometries and mitigation of SA. Of course, with a full GLONASS constellation the results would be better yet.

We have also analyzed the range measurements from GPS and GLONASS over an extended period to determine the distribution of the range error for each system. The rms user range error (σ_{URE}) for GPS has been found to be approximately 7 m with SA off. With SA on, the URE is apparently changeable, and was found to have an rms value of 25 to 30 m during 1992 and 1993. For GLONASS, the rms user range error has remained relatively constant at approximately 10 m. The difference in σ_{URE} between GLONASS and GPS (with SA off) is attributed mainly to the fact that GPS transmits in its navigation message the values of certain parameters to compensate partially for the ionospheric delays on the basis of a model; GLONASS does not include this information in its transmissions.

We now have all the elements necessary for a global view of the positioning accuracies achievable from operational GPS and GLONASS systems, both separately and together. To recapitulate, the error in a position estimate is determined by the spatial distribution of the satellites around the user (i.e., the satellite geometry) and by the error in the range measurements; we now have a complete characterization of both.

Table 3 summarizes the global projections for the quality of the position estimates available from GPS and GLONASS, when operational, on the basis of their performance as observed over the past two years. The coverage and position accuracy results presented in Figures 4 and 5, and in Table 3, show that GPS alone may fall short of providing a full coverage of the earth. A navigation system based on the integrated use of GPS and GLONASS, however, is capable of meeting the coverage and accuracy requirements for en-route and terminal phases of flight, and for nonprecision approaches.

Integrity Monitoring

The navigation accuracy results given in Figure 5 and Table 3 assume that each system is operating to specifications. A user, however, cannot take this assumption for granted. Indeed, both GPS and GLONASS have extensive self-diagnosis capabilities on board the satellites, as well as monitoring facilities at the ground

Table 3. The Projected Positioning Accuracy of GPS and GLONASS, Based on the Current Performance

	Horizontal Error (m)		*Vertical Error (m)*
	(50%)	(95%)	(95%)
GPS (SA off)	7	18	34
GPS (SA on)	27	72	135
GLONASS	10	26	45
GPS+GLONASS	9	20	38

control stations. What is not clear, however, is whether an error can be detected by the system and the appropriate flags set in the navigation message transmissions quickly enough to suit a pilot who is using the satellite signals in preparation for a landing. Basically, a critical demand of civil aviation is that the navigation system provide not only a position estimate but also an assurance that the estimate is good (i.e., the position error does not exceed a tolerable level). The idea of guarding against anomalous position estimates is called *system integrity monitoring*.

An approach to integrity monitoring of a satellite navigation system is to infer the accuracy of a position estimate on the basis of the measurements themselves. The idea is to verify that the measurements are indeed consistent with the model, and to characterize the quality of a position estimate. This approach can be pursued, as we will see, if the measurement set is redundant (i.e., we have more measurements than the minimum needed for position estimation). An important benefit of this approach, which is known as *receiver autonomous integrity monitoring* (RAIM), is that it eliminates the need for an expensive worldwide system to monitor the satellites to detect system malfunctions, and a communication network to disseminate this information to the users.

The problem of detection and isolation of an anomalous range measurement may be thought of as one of detecting inconsistency in a set of linear equations, and then identifying the anomalous equation. Obviously, at least one redundant equation is required to detect the presence of an anomaly via a consistency check. Similarly, at least two redundant equations are required to identify the anomalous equation. These, however, are only the necessary conditions, and satisfying them does not guarantee an effective consistency check. The effectiveness of the check depends upon the conditioning of the set of equations and their subsets. Our task is complicated further because the equations are only approximate, being based on range measurements that include errors, the sources of which have been cited earlier. As an aside, note that the DOP parameter, introduced earlier as a quantity related inversely to the volume of a polyhedron, basically reflects the notion of linear independence of the direction vectors to the satellites, and it serves as an indicator of the conditioning of the set of measurement equations.

According to the integrity requirements, a supplemental navigation system must provide each user with a position estimate of the required accuracy, or an indication otherwise. Obviously, the more often a system is usable the better. If it were usable 100% of the time, we would have a sole-means system. By definition, the users of a sole-means system must be capable of recovering from system failure.

Since at least four satellites are required to be in view to compute a 3-D position, users with five or more satellites in view may be able to use the system as supplemental. On the other hand, the real economic payoff will follow the adoption of a satellite navigation system as sole means. But this would require that all users have six or more satellites in view. On the basis of the satellite visibility results for GPS

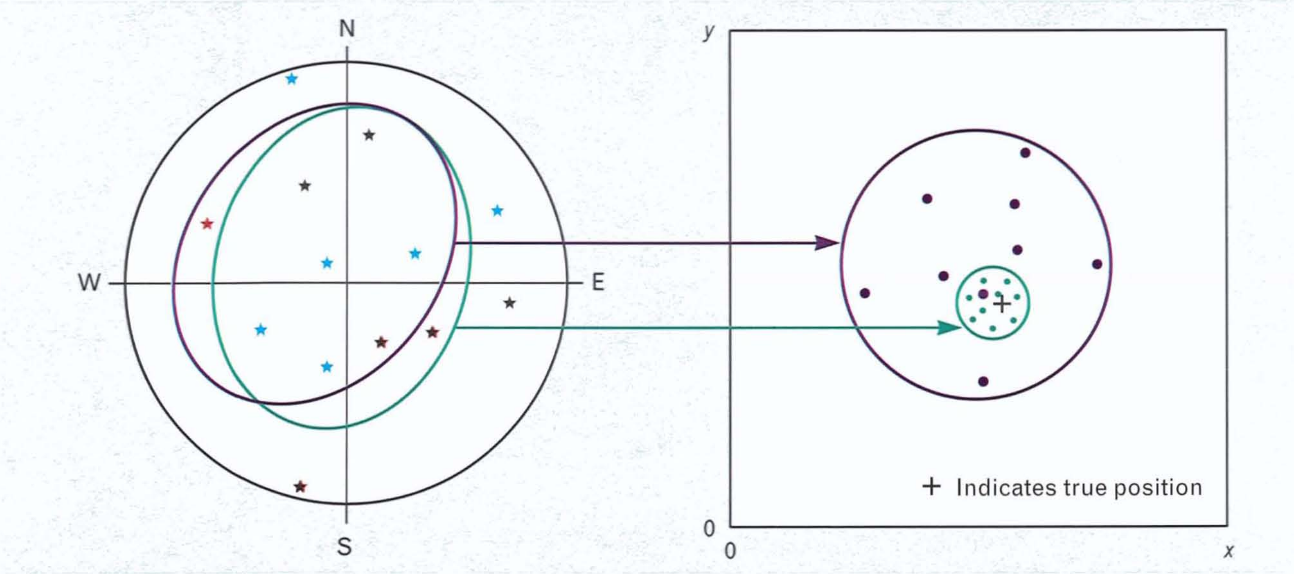

FIGURE 6. Receiver autonomous integrity monitoring (RAIM). The left side of the figure illustrates an azimuth-elevation sky map; the right side of the figure illustrates the position estimates computed from subsets of measurements. The satellite indicated by a red star in the azimuth-elevation sky map is providing anomalous measurements undetected by the system and unknown to the user. A user tracking the eight satellites inside the green ellipse determines position estimates by using all eight measurements, and then seven measurements at a time. The tight cluster of corresponding position estimates assures the user of the consistency of the original measurements and the good quality of the position estimates. A user tracking the eight satellites inside the purple ellipse, which includes the faulty satellite, would see the corresponding larger cluster as an indication of a position estimate of poorer quality.

and GLONASS summarized in Figure 4, each system by itself falls considerably short as a candidate for a sole-means system. Both systems taken together, however, offer amply redundant measurements, and potential for RAIM and a sole-means system.

A simple RAIM scheme could work as follows. Figure 6 is an azimuth-elevation sky map of the satellites from the two constellations in view of a user. The total number of measurements available to the user is considerably larger than the minimum required and is consistent with our results on coverage shown in Figure 4. Suppose that the satellite shown in red is providing anomalous measurements undetected by the system and unknown to the user. A user tracking the eight satellites inside the green ellipse in Figure 6 could compute a position estimate by using all of the measurements and, as a check on its quality, could compare it with the eight additional position estimates obtained when leaving out one measurement at a time. As noted earlier, the quality of a position estimate depends upon two factors: the error in the range measurements and the geometry of the satellites. Because all eight satellites are actually performing to specifications and the satellite geometries involved in all nine position estimates are uniformly good, the position estimates form a tight cluster, which reassures the user of the consistency of the measurements and the quality of the position estimate.

On the other hand, suppose a user tracking the eight satellites inside the purple ellipse in Figure 6, including the faulty satellite, were to try this same check. The resulting cluster in Figure 6 would be larger; the actual size would depend primarily upon the size of the error in the faulty measurement. A user, if assured of good satellite geometries associated with the position estimates computed as a part of this check, could thus treat the size of the cluster as a predictor of the quality of the position estimate.

We have pursued this approach to RAIM, and have developed an algorithm for a position estimate and a measure of its quality, given the probable failure scenario discussed earlier. We define the measure of quality as a high-confidence estimate of an upper bound on the error in the position estimate, and call it the *integrity level*. The integrity level is defined as follows.

$$P(\text{position error} > \text{integrity level}) < \varepsilon,$$

where ε is a suitably low user-defined parameter. To be usable, the integrity level must be a tight error bound consistent with the required alarm limits (see Table 2).

Two other essential points must be mentioned. First, the above relation is to be interpreted as a conditional probability, given that one of the satellite measurements could be in error by an indeterminate amount. Note that the total probability that a position error could exceed its associated integrity level would be even lower; namely, it would be the probability of a system failure (expected to be quite rare) multiplied by ε. Second, the ability to compute the integrity level is predicated on the availability of measurements from n satellites (where $n \geq 5$), which assures good geometries for each subset of $(n - 1)$. To obtain a tight integrity level, we require at least five satellites satisfying the above requirements on geometry and operating to specifications.

Figure 7 illustrates the idea to be implemented. Given a set of measurements, the user computes a position estimate and its associated integrity level. The estimate is acceptable if the integrity level does not exceed the alarm limit for that phase of flight (see Table 2). If a system can assure all its users of the integrity levels they require at all times, then we have a sole-means system.

The RAIM algorithm, described in greater detail elsewhere [11], consists of the following steps. Select n satellites (where $n \geq 5$) among those visible, estimate positions from all n measurements and from $(n - 1)$ measurements at a time, determine the size of the cluster (i.e., our RAIM statistic) formed by these position estimates, and obtain the corresponding integrity level from a precomputed table. If the integrity level is unsatisfactory to the user, then switch satellites for a better estimate, if possible. The computation of the table of scatter of the position estimates versus integrity level is at the heart of the algorithm. It requires estimation of the conditional probability dis-

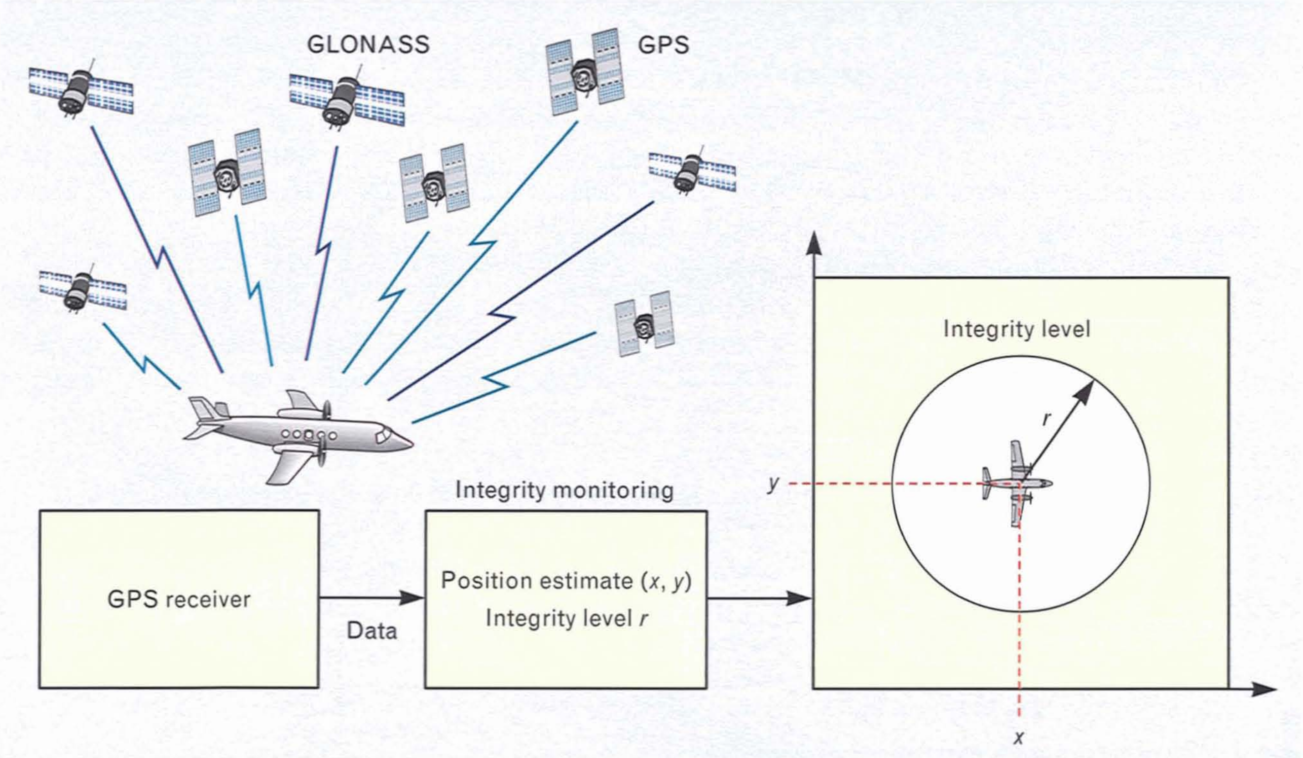

FIGURE 7. An implementation of RAIM. The receiver computes a position estimate and its associated integrity level. The estimate is acceptable if its integrity level does not exceed the alarm limit for the current phase of flight.

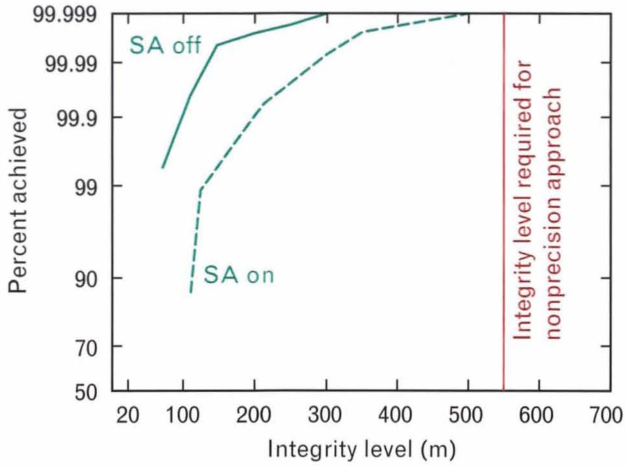

FIGURE 8. The distribution of integrity levels that can be achieved by the users of GPS+GLONASS. Even with SA on, the integrity levels meet the requirements for en-route and terminal phases of flight, and for nonprecision approaches.

tribution function of the position error computed from measurement sets containing a faulty measurement, given the corresponding scatter of the position estimates computed as a part of the consistency check.

Figure 8 gives the distribution of integrity levels available to the users of GPS+GLONASS worldwide, corresponding to the value of 10^{-5} for ε. The conclusion evident in this figure is that the combined measurements from the GPS and GLONASS systems offer a comfortable level of redundancy, so that even if one of the measurements is anomalous, 99.9% of the users would be able to compute position estimates with an assurance that their position error does not exceed 200 m. Nearly all users would be able to obtain position estimates with an error below 500 m, meeting the requirements for a nonprecision approach (see Table 2). If SA were to be switched off in GPS, the estimates would be significantly better, as shown in Figure 8. This performance corresponds to the 2 × 21 constellation of GPS+GLONASS and reflects the other assumptions cited earlier on measurement quality and constellation availability that are believed to be on the safe side. With a RAIM-based approach, therefore, GPS+GLONASS is expected to meet the requirements of a sole-means navigation system for en-route and terminal phases of flight, and for nonprecision approaches.

We should note that while GPS falls short of meeting the requirements of a sole-means system, it can still be used as a supplemental navigation system. GPS-21 can offer nearly 90% of the users the integrity level required for nonprecision approaches; GPS-24 can offer the same integrity level to 99% of the users. GLONASS aside, there are several options for enhancing GPS capabilities, including one of expanded constellations. Another approach being pursued by the FAA is to augment GPS with a geostationary overlay of two satellites visible over the conterminus U.S. (CONUS), and transmitting GPS-like ranging signals. With a GPS-24 constellation, this scheme is also expected to meet the sole-means integrity level requirement over CONUS.

Summary

We have examined the technical issues associated with the integrated use of GPS and GLONASS in civil aviation. The combination of signals planned to be available from the two systems for civil use offers the promise of an accurate and economical sole-means navigation system for en-route and terminal phases of flight, and for nonprecision approaches. While the requirements to be met by a sole-means satellite navigation system are still under discussion, we have concluded that the performance achievable in integrated use in coverage, accuracy, and integrity monitoring appears capable of meeting the requirements as projected now.

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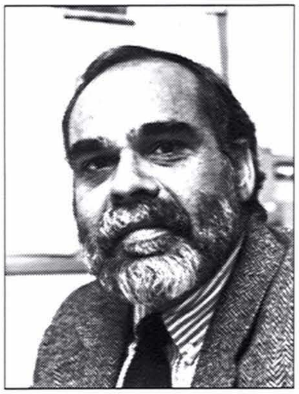

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