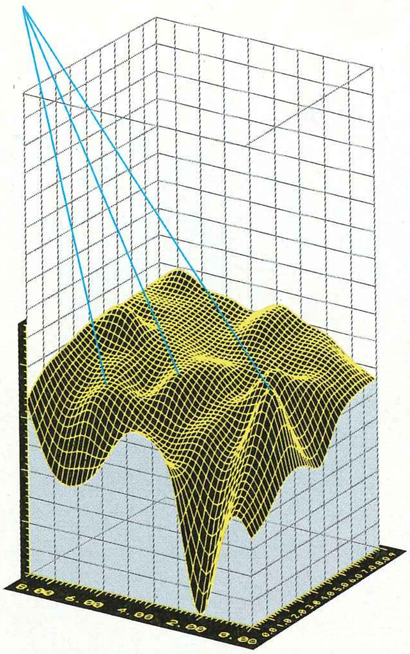

GLONASS: Review and Update

Richard B. Langley
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The Navstar Global Positioning System is not the only game in town. Russia's GLONASS is also essentially operational and, despite currently having an incomplete constellation, provides civilian stand-alone positioning accuracies typically much better than those of GPS with the current practice of selective availability. In this month's column, we will briefly review the technical characteristics of GLONASS, comparing and contrasting them with GPS. We will also assess the current development and performance of GLONASS and briefly describe GLONASS and combined GPS/GLONASS receivers.

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as about the fundamentals of GPS positioning. The column is coordinated by Richard B. Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as suggestions of topics for future columns. To contact him, see the "Columnists" section on page 4 of this issue.

In the early 1970s, perhaps as a response to the announced development of GPS, the former Soviet Ministry of Defence conceived the Global'naya Navigatsionnaya Sputnikova Sistema or the Global Navigation Satellite System — GLONASS for short. GLONASS is similar to GPS in many respects — although as we shall shortly see, there are important differences too.

In 1993, the Russian government officially placed the GLONASS program under the auspices of the Russian Military Space Forces (*Voenno-Kosmicheski Sily* or VKS). VKS is responsible for GLONASS spacecraft deployment, on-orbit maintenance, and user equipment certification. VKS operates the Coordinational Scientific Information Center (a slightly awkward translation of *Koordinatsionniy Nauchno-Informatsionniy Tsentr*), which disseminates GLONASS information to the public.

During the 1980s, information about GLONASS was scarce. Apart from the general characteristics of the satellite orbits and the frequencies used for transmitting the navigation signals, the Ministry of Defence of the former Soviet Union revealed little else. However, sleuthing by Professor Peter Daly and his students at the University of Leeds provided some details about the signals' structure. With the advent of *glasnost* and *perestroika*, and the eventual demise of the Soviet Union, information about GLONASS became more readily available.

Eventually, the Russians released the Interface Control Document (ICD). This document, similar in structure to the Navstar GPS Space Segment/Navigation User Interfaces ICD-GPS-200, describes the system, its components, and the structure of the signal and the navigation message intended for civil use. Its latest version appeared as a 43-page appendix to working paper GNSSP/2-WP/66, which was submitted to the International Civil Aviation Organization's Global Navigation Satellite System Panel (GNSSP) on November 14, 1995, during its second meeting in Montreal, Canada. The working paper stated that this version of the ICD "was produced with the purpose of contributing to the development of global navigation satellite system (GNSS) Standards and Recommended Practices (SARPs)."

This article will summarize some of the important characteristics of GLONASS and its signals. Table 1 lists the system's primary distinguishing attributes together with those of GPS. For further details about GLONASS, the interested reader should consult the ICD, which is available from the Coordinational Scientific Information Center.

GLONASS SEGMENTS

As with GPS, GLONASS comprises three segments: control, space, and users.

Control Segment. Referred to as the Ground-based Control Complex, the control segment consists of the system control center and a network of command tracking stations spread out across Russia. The GLONASS control segment, similarly to GPS, must monitor the status of its satellites; determine the ephemerides and satellite clock offsets with respect to GLONASS time and the Russian National Etalon time scale, UTC(SU); and upload the navigation data to the satellites. Uploads occur twice per day.

Space Segment. The GLONASS satellites make up the space segment. The full constellation will consist of 24 satellites, with 21 currently operational (although one or more of the 21 may be unusable for extended periods because of maintenance; one spare satellite, yet to be operationally activated, is also in orbit). GLONASS satellite orbits are arrayed in three planes, separated from one another in right ascension of ascending node by 120 degrees, with eight satellites in each plane. The satellites within a plane are equally spaced, separated in argument of latitude by 45 degrees. Satellites in adjoining planes are shifted in argument of latitude by 15 degrees. The satellites are placed into nominally circular orbits with target inclinations of 64.8 degrees and semimajor axis of approximately 25,510 kilometers, giving them an orbital period of about 675.8 minutes. These satellites have ground tracks that repeat every 17 orbits or eight sidereal days.

The GLONASS orbit planes are numbered 1–3 and contain orbital slots 1–8, 9–16, and 17–24, respectively (see Table 2). The satellites are sent up three at a time by the Proton DM (SL-12) booster from the Baikonur Cosmodrome near Leninsk in Kazakhstan.

The first launch of a GLONASS satellite (also known as *Uragan*, Russian for "hurricane") occurred on October 12, 1982. There have been a total of 27 GLONASS launches, including two failures, through the end of 1996. The first seven deployments included "dummy" satellites acting as ballast. Altogether, the Russians have sent up 71 GLONASS satellites (plus eight dummy and two Etalon laser ranging satellites). Every GLONASS satellite is fitted with a small retroreflector so that it can be tracked using satellite

Table 1. Comparison of GLONASS and GPS nominal characteristics

Parameter/technique		GLONASS	GPS
Satellites			
Number of satellites		21 + 3 spares	21 + 3 spares
Number of orbital planes		3	6
Orbital plane inclination (degrees)		64.8	55
Orbital radius (kilometers)		25,510	26,560
Signals			
Fundamental clock frequency		5.0 MHz	10.23 MHz
Signal separation technique		FDMA	CDMA
Carrier frequencies (MHz)	L1	1602.0–1615.5	1575.42
(original assignment)	L2	1246.0–1256.5	1227.60
Code clock rate (MHz)	C/A	0.511	1.023
	P	5.11	10.23
Code length (chips)	C/A	511	1,023
	P	5.11×10^6	6.187104×10^{12}
C/A-code navigation message			
Superframe duration (minutes)		2.5	12.5
Superframe capacity (bits)		7,500	37,500
Superframe reserve capacity (bits)		~620	~2,750
Word duration (seconds)		2.0	0.6
Word capacity (bits)		100	30
Number of words within a frame		15	50
Technique for specifying satellite ephemeris		geocentric Cartesian coordinates and their derivatives	Keplerian orbital elements and perturbation factors
Time reference		UTC (SU)	UTC (USNO)
Position reference (geodetic datum)		PZ-90	WGS 84

laser ranging by the Quantum Optical Tracking Stations scattered across the former Soviet Union.

The Russians consider all satellites deployed thus far to be prototypes, of which there have been four models. Russia (actually the former Soviet Union) launched the first 10 satellites, called Block I, between October 1982 and May 1985. It sent up six Block IIa satellites between May 1985 and September 1986 and 12 Block IIb satellites between April 1987 and May 1988, of which six were lost because of launch vehicle–related failures. The fourth model was the Block IIv (v is the English transliteration of the Russian alphabet's third letter). By the end of 1996, the Russians had deployed 43 Block IIvs.

Each subsequent satellite generation contained equipment enhancements and also achieved longer lifetimes. The GLONASS-M Block II operational satellites are said to feature improved frequency and timing accuracies and to have expected lifetimes of five to seven years. They will also reportedly have the C/A-code on both L1 and L2. Russia expected to launch the first GLONASS-M satellite in 1995, but as of press time, this still has not occurred. The Almanac on page 55 shows the current GLONASS constellation status.

Table 2. Planes, slots, and channels

Plane 1								
Slot:	01	02	03	04	05	06	07	08
Channel:	—	05	21	12	—	13	21	02
Plane 2								
Slot:	09	10	11	12	13	14	15	16
Channel:	06	09	04	22	06	09	04	22
Plane 3								
Slot:	17	18	19	20	21	22	23	24
Channel:	24	10	03	01	24	10	03	—

User Segment. GLONASS, the same as GPS, is a dual military/civil system. All military and civil GLONASS users constitute the user segment. The system's potential civil applications are vast and mirror those of GPS.

SYSTEM CHARACTERISTICS

Like the GPS satellites, GLONASS satellites transmit two pseudorandom noise signals with binary phase-shift keying. However, the clock rate of the GLONASS signals is about one-half that of GPS: 5.11 and 0.511 MHz for the equivalent of the P-code and C/A-code, respectively. Fifty–bits-per-second messages are also superimposed on the signals. Originally, the system transmitted the signals within two bands: L1, 1602–1615.5

MHz, and L2, 1246–1256.5 MHz, at frequencies spaced by 0.5625 MHz at L1 and by 0.4375 MHz at L2. This arrangement provided 25 channels, so that each satellite in the full 24-satellite constellation could be assigned a unique frequency (with the remaining channel reserved for testing). Such a system of simultaneous multiple transmissions is known as frequency division multiple access (FDMA) and distinguishes GLONASS from GPS, which is a code division multiple access (CDMA) system.

Some of the GLONASS transmissions initially caused interference to radio astronomers, who study very weak natural radio emissions in the vicinity of the GLONASS frequencies. Radio astronomers use the frequency bands of 1610.6–1613.8 and 1660–1670 MHz to observe the spectral emissions from hydroxyl radical clouds in interstellar space, and the International Telecommunications Union (ITU) has afforded them primary user status for this spectrum space. Also, ITU has allocated the 1610–1626.5-MHz band to operators of low-earth-orbiting mobile communications satellites. As a result, the GLONASS authorities decided to reduce the number of frequencies used by the satellites and shift the bands to slightly lower frequencies.

Eventually, the system will use only 12 primary frequency channels (plus two additional channels for testing purposes). The bands will be shifted to 1598.0625–1604.25 and 1242.9375–1247.75 MHz. How can 24 satellites get by with only 12 channels? The solution is for antipodal satellites — satellites in the same orbit plane separated by 180 degrees in argument of latitude — to share the same channel. This approach is quite feasible because a user at any location on earth will never simultaneously receive the signals from such a pair of satellites.

The move to the new frequency assignments started in September 1993 with the initial pairing of satellite channels. Now eight pairs of satellites share channels (see Table 2 and the Almanac). Table 3 details the current and future GLONASS frequency channels.

As with GPS, GLONASS transmits the P-code on both L1 and L2, with the C/A-code, at present, only on the L1 signal. The C/A-code is 511 chips long with a rate of 511 kilochips per second, giving a repetition interval of 1 millisecond. The P-code is 33,554,432 chips long with a rate of 5.11 megachips per second. The code sequence is truncated to give a repetition interval of 1 second. Unlike GPS satellites, all GLONASS satellites transmit the same codes. They derive signal timing and frequencies from one of three onboard cesium atomic clocks operating at 5 MHz. The signals are right-hand circularly polarized, like GPS signals, and have comparable signal strengths.

Table 3. GLONASS frequencies

Originally
f_{k1} = 1602 MHz + k × 0.5625 MHz f_{k2} = 1246 MHz + k × 0.4375 MHz where k = 0, 1, 2, ..., 24 (0 — for testing only)
Present to 1998
k = 0, ..., 12, 22, 23, 24 New satellites might use k = –7 to –1
1998–2005:
k = –7, ..., 12
After 2005:
k = –7, ..., 4 (5, 6 — for testing only)

Navigation Message. Separate 50–bits-per-second navigation messages are modulo-2 added to the C/A- and P-codes. The C/A-code message includes satellite clock epoch and rate offsets from GLONASS time; the satellite ephemeris given in terms of the satellite position, velocity, and acceleration vectors at a reference epoch; and additional information such as synchronization bits, data age, satellite health, offset of GLONASS time from Coordinated Universal Time (UTC) as maintained by the National Time and Frequency Service (NTFS) of the Russian Federation — UTC(SU), and almanacs (approximate ephemerides) of all other GLONASS satellites. The full message lasts 2.5 minutes, but the ephemeris and clock information is repeated every 30 seconds.

The GLONASS authorities have not published, at least publicly, details of the P-code navigation message. It is known, however, that the full message takes 12 minutes and that the ephemeris and clock information are repeated every 10 seconds.

GLONASS and GPS use different time and position reference systems. GLONASS time is referenced to UTC(SU), whereas GPS time is referenced to UTC as maintained by the U.S. Naval Observatory — UTC(USNO). This time is within about 20 nanoseconds or so of the international UTC standard maintained by the Bureau International des Poids et Mesures — UTC(BIPM) or just UTC.

UTC(SU) has been a number of microseconds different from UTC(BIPM). In an effort to reduce this offset to 1 microsecond or less, NTFS corrected UTC(SU) by 9 microseconds on November 27, 1996. GLONASS time, as this magazine went to press, is about 35 microseconds ahead of UTC. To bring the system's time within several hundred nanoseconds of UTC, the GLONASS control segment will reportedly apply a time step of about 35 microseconds at midnight beginning July 1, 1997, along with the previously announced UTC leap second. Note that GLONASS time also includes UTC leap seconds, whereas GPS time does not.

Geodetic Datum. GLONASS ephemerides are referenced to the Parametry Zemli 1990 (PZ-90 or, in English translation, Parameters of the Earth 1990, PE-90) geodetic datum. PZ-90 replaced the Soviet Geodetic System 1985, SGS 85, used by GLONASS until 1993. PZ-90 is a terrestrial reference system with its coordinate frame defined in the same way as that of the International Terrestrial Reference Frame (ITRF). Table 4 lists the defining constants and parameters of PZ-90.

The realization of the PZ-90 frame through adopted reference station coordinates has resulted in offsets in origin and orientation as well as a difference in scale with respect to ITRF and also the World Geodetic System 1984 (WGS 84). The current paucity of GLONASS receivers creates some difficulty in accurately determining the relationships between the frames. However, at least two research groups have attempted to establish preliminary relationships.

Using six sites in Europe (including Maspalomos in the Canary Islands and Zwenigorod in Russia) and dual-frequency GPS/GLONASS receivers capable of tracking the GLONASS P-code, Udo Rossbach and others from geodetic institutes in Germany determined a preliminary transformation between PZ-90 and ITRF. Using the GLONASS broadcast ephemerides, they concluded that the only statistically significant transformation parameter between PZ-90 and ITRF-94 was a rotation about the z-axis. They assumed ITRF to be identical to WGS 84's frame and reported the transformation, based on baseline solutions, as

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{WGS\,84} = \begin{bmatrix} 1 & -1.6\times10^{-6} & 0 \\ 1.6\times10^{-6} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}_{PZ-90}$$

The rotation of 1.6×10^{-6} radians, or 0.33 arcseconds, gives a displacement, along the equator, of about 10 meters. The Rossbach team also estimated seven- and four-parameter transformations using single-point and baseline solutions, respectively, but concluded that the additional estimated transformation parameters were not statistically significant.

Pratap Misra and coworkers at the Massachusetts Institute of Technology's Lincoln Laboratory, in Lexington, have also determined a set of transformation parameters relating PZ-90 and WGS 84. Earlier, they had determined the parameters relating SGS 85 and WGS 84. The scarcity of a widely distributed GLONASS receiver reference network led the team to use a different approach from that of Rossbach's group. Rather than relating the coordinates of receivers on the earth's surface in the two systems, they related the orbital positions of two GLONASS satellites expressed in the two systems.

They obtained the satellites' positions in the PZ-90 frame from the broadcast ephemerides and those in the WGS 84 frame from a global network of laser tracking stations and radar systems. Estimates of one-, two-, four-, and seven-parameter transformations revealed that only a rotation about the z-axis and possibly an offset of the origin along the y-axis were statistically significant. Accordingly, Misra and coworkers report the transformation as

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{WGS\,84} = \begin{bmatrix} 0 \\ 2.5\,\mathrm{m} \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & -1.9\times10^{-6} & 0 \\ 1.9\times10^{-6} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}_{PZ-90}$$

The major source of error in the transformation parameters is likely the broadcast ephemerides.

To facilitate combined use of GLONASS and GPS, Russian authorities plan to include the differences between the two systems' time and position references in the navigation message.

GLONASS RECEIVERS

Until recently, the lack of readily available GLONASS receivers at costs comparable with GPS units posed a stumbling block to widespread use of the Russian system. However, with several manufacturers introducing production receivers, including two U.S.-based companies, this situation is starting to change. Nevertheless, the number of GLONASS-capable receivers currently used is still probably well less than 10,000 worldwide.

The production of GLONASS receivers in the former Soviet Union is a combined effort of design bureaus and manufacturing plants. Russia, the Ukraine, and Belarus have major plants.

Essentially two generations of Russian GLONASS receivers have evolved. The first were large, heavy units with one, two, and four channels. The second — dating from the early 1990s and based on large-scale integrated circuits and digital signal processing — were much more compact and lighter. The second generation receivers include five-, six-, and 12-channel designs and, for civil applications, have dual GPS/GLONASS capability.

At least one survey-quality Russian GLONASS receiver exists — the "Reper" (meaning reference or datum point), developed by the Scientific Production Association of Space Device Engineering (NPO KP). This six-channel, L1 receiver weighs about five kilograms and is reportedly capable of centimeter-level positioning.

Outside the former Soviet Union, a number of manufacturers, research organizations, and universities have designed and built GLONASS receivers. Some were prototypes, developed to gain experience with GLONASS. Others were receivers developed for a specific application, such as use on low-earth-orbiting satellites. At least two companies currently market GLONASS or GPS/GLONASS receivers, including a dual-frequency, C/A- plus P-code unit.

GLONASS PERFORMANCE

The Russian Federation government has declared that GLONASS will provide civil users worldwide with a real-time point-position (stand-alone) accuracy, based on the C/A-code (the so-called Channel of Standard Accuracy), of at least 60 meters in the horizontal (99.7 percent probability level) and at least 75 meters in the vertical (99.7 percent probability level). The Russians have also announced that they do not plan to introduce any measures to intentionally degrade system accuracy.

The Russian Space Forces monitors GLONASS performance, and it issues Notice Advisories to GLONASS Users (NAGUSs) to announce satellite outages caused by anomalies or planned maintenance.

Several other organizations also monitor GLONASS performance, including the GLONASS Group of the Lincoln Laboratory. Figure 1a shows typical GLONASS C/A-code point-positioning accuracy during a 24-hour period as determined at the laboratory. The monitored accuracy normally exceeds the levels guaranteed by the Russian government. GLONASS accuracy is typically much better than that of GPS with

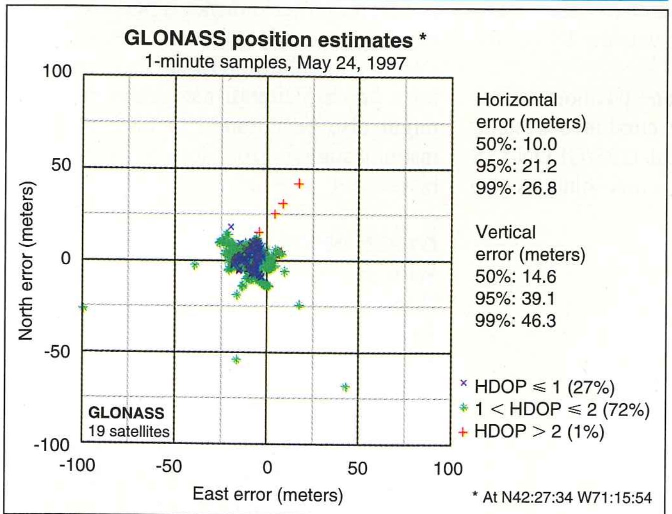

Figure 1a. The Lincoln Laboratory GLONASS position estimates for May 24, 1997, show 95 percent horizontal and vertical position errors of 21.2 and 39.1 meters respectively. Even with only 19 usable satellites, horizontal dilution of precision was less than or equal to 2, 99 percent of the time.

Table 4. Defining parameters of the PZ-90 datum

Parameter	Value
Earth rotation rate	72.921 15 x 10^{-6} radians s^{-1}
Gravitational constant	398 600.44 x 10^9 m^3s^{-2}
Gravitational constant of atmosphere	0.35 x 10^9 m^3s^{-2}
Speed of light	299 792 458 ms^{-1}
Second zonal harmonic of the geopotential	–1082.63 x 10^{-6}
Ellipsoid semimajor axis	6 378 136 m
Ellipsoid flattening	1/298.257
Equatorial acceleration of gravity	978 032.8 mgal
Correction to acceleration of gravity at sea level because of atmosphere	–0.9 mgal

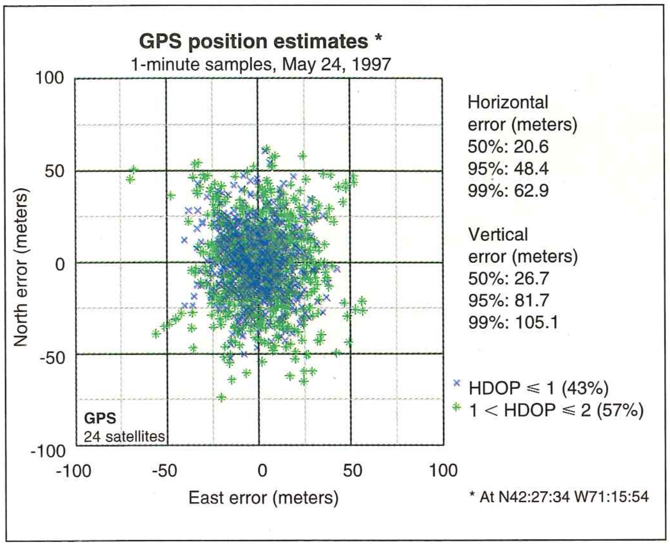

Figure 1b. The Lincoln Laboratory GPS position estimates for May 24, 1997, show 95 percent horizontal and vertical position errors of 48.4 and 81.7 meters respectively — about twice the corresponding GLONASS values.

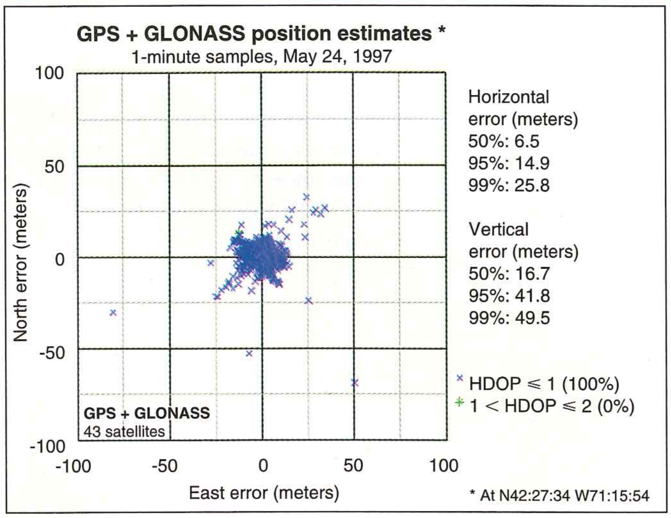

Figure 1c. The Lincoln Laboratory combined GPS/GLONASS position estimates for May 24, 1997, show 95 percent horizontal and vertical position errors of 14.9 and 41.8 meters respectively. The combined constellation yielded horizontal dilution of precision values less than or equal to 1, 100 percent of the time.

selective availability (SA) in effect, as a comparison of Figure 1a with Figure 1b (GPS accuracies over 24 hours) clearly shows. However, with SA off (as it seemed to be most recently on April 20 when, perhaps coincidentally, the Air Force was looking for a crashed A-10 Thunderbolt II ["Warthog"] fighter-bomber attack jet in the mountains of Colorado), GPS accuracy is better than that of GLONASS.

The Lincoln Laboratory also monitors anomalies in the GLONASS signals. Such anomalies include occasional large range measurement errors on a satellite despite the satellite being marked healthy in the navigation message ephemeris and almanacs. The laboratory reported 18 such occurrences during 1996. It also detected an anomaly that lasted a minute or so when the UTC leap second was inserted into GLONASS time at midnight beginning January 1, 1996.

COMBINED GPS/GLONASS USE

With the availability now of dual GPS/GLONASS receivers, users have access to a potential 48-satellite combined system. What will this buy them? With 48 satellites, performance in urban canyons and other locations with restricted visibility, such as forested areas, is improved, as more satellites will be visible in the nonoccluded portions of the sky. A larger satellite constellation will also improve real-time carrier-phase differential positioning performance. According to one U.S. GPS/GLONASS receiver manufacturer, initialization time, to achieve centimeter-level accuracies, improves by a factor of 3–6 with the 48-satellite constellation.

In addition, stand-alone position accuracies improve with the combined system. Figure 1c shows typical GPS/GLONASS positioning accuracy. Position solutions also have a higher integrity. A 99.999-percent GPS position solution confidence level requires continuous reception from six or more satellites in the 24-satellite GPS constellation. The same confidence level with GPS and GLONASS requires continuous reception from seven satellites in the 48-satellite combined GPS/GLONASS constellation. Code differential operation also becomes simpler. In the absence of deliberate accuracy degradation, differential GLONASS requires a much lower correction update rate.

And, nearly 100 percent fault detection and exclusion performance is possible, which meets, for example, the receiver autonomous integrity monitoring (RAIM) requirements for a primary aircraft navigation means. It might also be possible to further reduce instrumentation errors such as interchannel biases.

OTHER DEVELOPMENTS

With the anticipated global use of GLONASS alone or in combination with GPS, the Radiotechnical Commission for Maritime Services (RTCM), in conjunction with the Russian Institute of Radionavigation and Time, has added several differential GLONASS message types to the widely used RTCM SC-104 DGPS standard. The RTCA DO-217 differential GPS message format for aviation can also be used for differential GLONASS. Real-time meter- and, with adequate interchannel bias modeling, submeter positioning accuracy is possible using differential GLONASS pseudorange observations.

The developers of the popular Receiver-Independent Exchange (RINEX) format for raw GPS pseudorange and carrier phase data storage have extended the format to cover raw GLONASS data and the National Marine Electronics Association (NMEA) has extended the NMEA 0183 interface standard to accommodate GLONASS.

GLONASS carrier phases (although a bit more difficult to use and process than those of GPS because of their multiple carrier frequencies) can provide post-processed decimeter- and even centimeter-level positioning results. Receiver manufacturers and independent research groups have reported such accuracies in various tests they have completed.

CONCLUSION

Although there are clearly some delays in the full, sustained deployment of GLONASS, it is currently a reliable positioning system for many applications. This reliability is enhanced through the use of combined GPS/GLONASS observations, which not only provides increased positioning accuracy compared with GPS-only use but also a means to check the integrity of both systems. All GLONASS users and potential users eagerly await the next spacecraft launch and the return to full-constellation operation.

ACKNOWLEDGMENT

I'd like to thank Pratap Misra for the use of the figures displaying GLONASS and GPS position estimates and for helpful comments on a draft of this article. ■

MANUFACTURERS

The Lincoln Laboratory uses the **Ashtech** (Sunnyvale, California) GG24 combined GPS/GLONASS receiver to obtain its daily reports of GLONASS and GPS positioning accuracies. GLONASS and dual GPS/GLONASS receivers are also manufactured by **3S Navigation** (Irvine, California) and **Daimler-Benz Aerospace** (Ulm, Germany) as well as several companies in the former Soviet Union.

Further Reading

For further details about the GLONASS L1 "standard precision navigation signal," see

■ *Global Orbiting [sic] Navigation Satellite System (GLONASS) Interface Control Document*, available from the Coordinational Scientific Information Center of the Russian Space Forces, Moscow.

For excellent, comprehensive reviews of GLONASS, see

■ "The Russian GLONASS System," by S. Feairheller, J. Purvis, and R. Clark, in *Understanding GPS: Principles and Applications*, edited by E. Kaplan, published by Artech House, Inc., Norwood, Massachusetts, 1996.

■ "GPS and Global Navigation Satellite System (GLONASS)," by P. Daly and P.N. Misra, in *Global Positioning System: Theory and Applications, Vol. II*, edited by B.W. Parkinson and J.J. Spilker, Jr., published as Vol. 164 of *Progress in Astronautics and Aeronautics*, American Institute of Aeronautics and Astronautics, Inc., Washington, D.C., 1996.

For current information on GLONASS, see the following Web sites:

■ The Russian Space Forces's Coordinational Scientific Information Center <http://www.rssi.ru/sfcsic/sfcsic_main.html>.

■ Massachusetts Institute of Technology's Lincoln Laboratory GLONASS Group <http://satnav.atc.ll.mit.edu/>.

■ Czech Technical University's Department of Radioelectronics, Division of Signals and Systems <http://caesar.feld.cvut.cz/systems/glonass.htm>.

■ Deutsche Forshungsanstalt für Luft- und Raumfahrt's GLONASS Updated Information Service <http://www.nz.dlr.de/gps/glonass.html>.

model the process. This suboptimal filter must be evaluated by special covariance analysis algorithms that recognize the differences in the real-world model producing the measurements and the implemented filter model. Finally, once the filter meets all performance requirements, a few simulations of all processes should be run to evaluate the adequacy of the linearization approach and search for numerical computational errors.

In most cases, the extended Kalman filter (with resets after every cycle) will ameliorate any linearization errors. Numeric computational errors caused by finite machine word length manifest themselves in the covariance matrices, which become nonsymmetric or have negative diagonal elements, causing potentially disastrous performance. This problem can be alleviated by increasing the computational precision or by employing a theoretically equivalent but more numerically robust algorithm.

CONCLUSIONS

Because of its deceptively simple and easily programmed optimal algorithm, the Kalman filter continues to be the integration method of choice in GPS-based navigation systems. It requires sufficiently accurate multidimensional statistical models of all variables and noises to properly weight noisy measurement data. These models enable the filter to account for the disparate character of the errors in different systems, providing for an optimal integrated combination of large-scale systems. The recursive nature of the filter allows for efficient real-time processing. Off-line covariance studies enable the integrated system performance to be predicted before development, providing a convenient and easy-to-use system design tool. ■

Correction

Some of the Parametry Zemli 1990 (PZ-90) datum parameter values listed in Table 4 of this column's July 1997 article, "GLONASS: Review and Update," are incorrect. Although these values are identified as pertaining to PZ-90 in the latest version of the GLONASS Interface Control Document (dated October 4, 1995), they actually pertain to its predecessor, the Soviet Geodetic System 1985. The correct PZ-90 parameter values, to be used with GLONASS ephemerides, are listed to the right. The inverse ellipsoid flattening is a rounding of the full precision value of 298.257 839 303. Note also that the sign of the geopotential second zonal harmonic, J_2, is given here as positive in keeping with convention.

Table 4. Defining parameters of the PZ-90 datum

Parameter	Value
Earth rotation rate	72.921 15 x 10^{-6} radians s^{-1}
Gravitational constant	398 600.44 x 10^{9} m^3s^{-2}
Gravitational constant of atmosphere	0.35 x 10^{9} m^3s^{-2}
Speed of light	299 792 458 ms^{-1}
Second zonal harmonic of the geopotential	1082.6257 x 10^{-6}
Ellipsoid semimajor axis	6 378 136 m
Ellipsoid flattening	1/298.257 84
Equatorial acceleration of gravity	978 032.8 mgal
Correction to acceleration of gravity at sea level because of atmosphere	–0.9 mgal