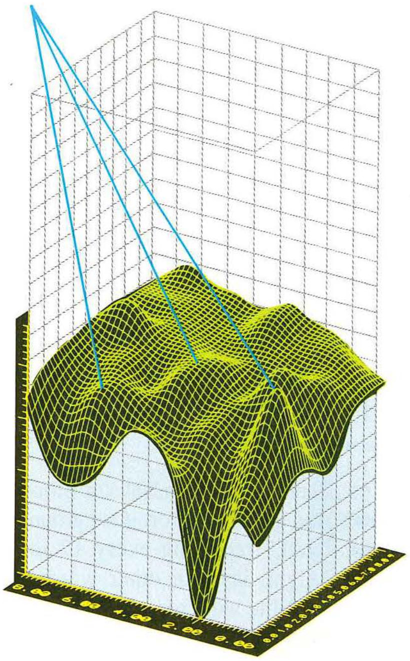

GLONASS Spacecraft

Nicholas L. Johnson

Kaman Sciences Corporation

Despite the significant economic hardships associated with the breakup of the Soviet Union and the transition to a modern market economy, Russia continues to develop its space programs, albeit at a reduced level compared with that of the Cold War era. In particular, the Russian Global Navigation Satellite System (GLONASS), cousin to the U.S. Navstar Global Positioning System, continues to evolve toward full operational capability with the promise of enhancing the reliability and integrity of positioning using GPS alone. Although Russia is making GLONASS available to the world community, information on certain aspects of its operation is still hard to find. In this month's "Innovation" article, Nicholas Johnson, a senior scientist with Kaman Sciences Corporation in Colorado Springs, Colorado, helps to fill the data gap with a detailed description of GLONASS spacecraft, how they are launched, and how the constellation of spacecraft has evolved since the first one was put into orbit in October 1982. Johnson is a leading expert on the former Soviet Union's (and now the Commonwealth of Independent States's) space programs and is a consultant on space systems to private industry and the U.S. federal government. His latest book, Europe and Asia in Space 1991–1992, *was published in July.*

"Innovation" is a regular column in GPS World *featuring discussions on recent advances in GPS technology and its applications as well as on the fundamentals of GPS positioning. The column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick. We appreciate receiving your comments and suggestions of topics for future columns.*

Fourteen years after the launch of the first test spacecraft, the Russian Global Navigation Satellite System (Global'naya Navigatsionnaya Sputnikovaya Sistema or GLONASS) program remains viable and essentially on schedule despite the economic and political turmoil surrounding the final years of the Soviet Union and the emergence of the Commonwealth of Independent States (CIS). By the summer of 1994, a total of 53 GLONASS spacecraft had been successfully deployed in nearly semisynchronous orbits; of the 53, nearly 12 had been normally operational since the establishment of the Phase I constellation in 1990. With the commissioning of a third orbital plane in August 1994, the 1988 goal of a complete 21-spacecraft constellation by the year 1995 is within reach, and support for the high-precision, real-time navigation network has expanded from its national military origins to the international civil sector.

PROGRAM BACKGROUND

Development of GLONASS in the former Soviet Union closely paralleled the evolution of space-based navigation systems in the United States, with the first serious Soviet designs emerging during 1958–59. The first Soviet navigation satellite, *Tsyklon* (launched as Kosmos 192 into a low earth orbit [LEO] in 1967) was based upon Doppler techniques demonstrated by the U.S. Navy's Transit program, which began in the late 1950s. Today, Russia still maintains two LEO navigation systems: the six-satellite military Parus (also known as Tsikada-M) and the four-satellite civil Tsikada systems.

Doppler satellite navigation systems, however, have inherent limitations. They provide only two-dimensional positions (with roughly 500-meter predictable accuracy in each coordinate at the 95 percent probability level using single-frequency observations from a single satellite pass), output no velocity information, and have poor system timeliness. These three factors spurred the former Soviet Union to once again follow the American lead, this time mimicking the U.S. Global Positioning System (GPS).

The task of designing and developing the GLONASS spacecraft fell to the Scientific Production Association of Applied Mechanics (Nauchno Proizvodstvennoe Ob"edinenie Prikladnoi Mekaniki or NPO PM), located near Krasnoyarsk in Siberia. This major aerospace industrial complex was established in 1959 as a division of Sergei Korolev's Experimental Design Bureau (Opytno Konstruktorskoe Byuro or OKB). (Korolev, among other notable achievements, led the effort to develop the Soviet Union's first launch vehicle — the A launcher — which placed Sputnik 1 into orbit.) The founding and current general director and chief designer is Mikhail Fyodorovich Reshetnev, one of only two still-active chief designers from Russia's fledgling 1950s-era space program.

A closed facility until the early 1990s, NPO PM has been responsible for all major Russian operational communications, navigation, and geodetic satellite systems to date. Serial (or assembly-line) production of some spacecraft, including Tsikada and GLONASS, has been transferred to the Flight Production Association (Polet Proizvodstvennoe Ob"edinenie or Polet PO) in Omsk, Russia, while the design of payloads and significant subsystems has been accomplished by the Institute for Space Device Engineering (also known as the Russian Scientific Research Institute of Space Instrument Manufacture or Rossiyskiy Nauchno Issledovatelskiy Institut Kosmicheskikh Priborov [RNII KP]) in Moscow. In the development of the GLONASS system, another principal partner has been the Russian Institute of Radionavigation and Time (Rossiyskiy Institut Radionavigatsii i Vremeni or RIRV), which has been responsible for time synchronization and related equipment.

Conceived and promoted in the early 1970s by the former Soviet Ministry of Defense, and in particular by the Soviet Navy, GLONASS is now the centerpiece of the CIS's Intergovernmental Radionavigation Program, which has close ties with the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO). By presidential decree on September 24, 1993, just before the 13th anniversary of the maiden GLONASS flight, the GLONASS program was officially placed under the auspices of the Russian Military Space Forces (Voenno Kosmicheski Sily or VKS). VKS is responsible not only for the deployment and on-orbit maintenance of GLONASS spacecraft (the latter through the Golitsino-2 System Control Center southwest of Moscow) but also, through its Scientific Information Coordination Center (Koordinatsiya Nauchno Informatsiya Tsentr or KNITs), for certification of GLONASS user equipment (for example, the Shkiper for maritime use, the A-724 for aviation use, and the ITI29 and ITI30M for land use).

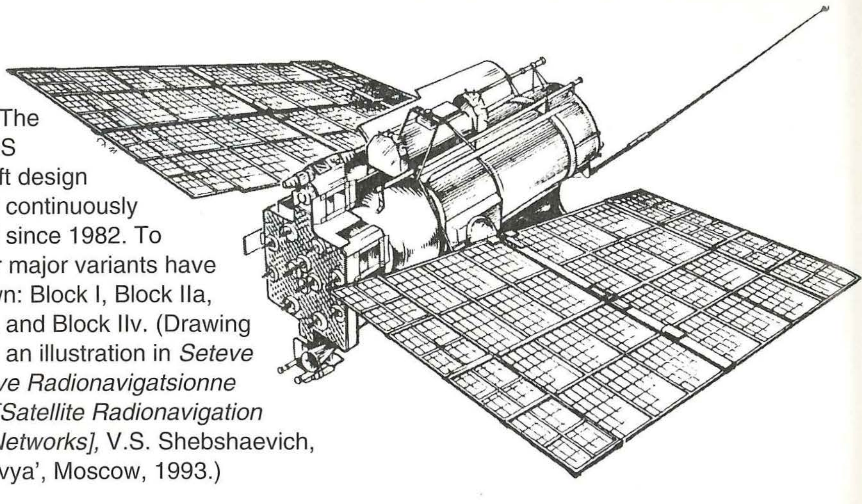

Figure 1. The GLONASS spacecraft design has been continuously improved since 1982. To date, four major variants have been flown: Block I, Block IIa, Block IIb, and Block IIv. (Drawing based on an illustration in *Seteve Sputnikove Radionavigatsionne Sistemy [Satellite Radionavigation System Networks]*, V.S. Shebshaevich, Radio i Svya', Moscow, 1993.)

THE SPACECRAFT

Each GLONASS spacecraft (also known as Uragan, Russian for *hurricane*) has a mass of as much as 1,400 kilograms, compared with 840 kilograms and 930 kilograms for Navstar Block II and IIA spacecraft, respectively. Like many Russian spacecraft, the GLONASS vehicle consists primarily of a roughly cylindrical pressure vessel equipped with a small aft payload platform and two large solar arrays. The total spacecraft bus height exceeds three meters, and the solar arrays have a total span of more than seven meters, with an electrical power generation capacity of 1.6 kilowatts at beginning of life (see Figure 1).

The aft structure houses the 12 primary payload antennas for L-band transmissions, which originally used operational frequencies from 1246 to 1257 MHz and from 1603 to 1616 MHz. (Recently, antipodal GLONASS spacecraft have started to share frequencies. The reduction of spectrum occupation should reduce interference with radio astronomy observations, which has been a problem.) The pressure vessel contains the bulk of the electrical; thermal-control; and tracking, telemetry, and control (TT&C) subsystems as well as the payload electronics. The interior is maintained with a typical terrestrial environment (temperature and pressure), partly to relax space-certification requirements on many components. Forced-air circulation in conjunction with heat exchangers and special external fins regulates the internal temperature.

Each three-axis stabilized spacecraft is equipped with a propulsion system for initial orbit acquisition and positioning, for station keeping, and for relocation. Attitude-control sensors, including a geomagnetic sensor on the tall boom at the top of the spacecraft, ensure that the spacecraft remains in a proper orientation for transmission of navigational signals and enable the solar arrays to track the sun through each orbit. Laser corner-cube reflectors are also carried to aid in precise orbit determination and geodetic research.

Satellite Lifetimes. The GLONASS Block I and Block IIa spacecraft were originally designed with an expected lifetime of only one year, but several improvements have already tripled that specification. The 10 original Block I spacecraft were put into service during 1982–85 (Kosmos 1414–1650) and achieved an average operational lifetime of 14 months. Six Block IIa spacecraft launched during 1985–86 (Kosmos 1651–1780) averaged about 17 months, about a 20 percent increase in lifetime. Moreover, Block IIa also introduced new time and frequency standards and increased frequency stability by an order of magnitude.

The next group of spacecraft, the Block IIb, had expected design lives of two years. Twelve Block IIb spacecraft were launched during 1987–88 (Kosmos 1838–1948). Although six were lost in launch-vehicle failures, the remaining six almost met their specifications, operating for an average of nearly 22 months each.

Again, the next generation of satellites was expected to exceed the lifetimes of its predecessors by another year. A total of 31 Block IIv (*v* is the English transliteration of the third letter of the Russian alphabet) spacecraft (Kosmos 1970–2289) had been launched by the summer of 1994, with a minimum expected operational lifetime of three years. In addition, since April 1991, GLONASS spacecraft have incorporated enhanced radiation-hardening designs that may lead to life expectancies of three to five years. One Block IIv spacecraft was operational for 50 months before it was placed in a standby status.

ORBIT AND DELIVERY

Unlike its Western counterpart, GLONASS does not employ a truly semisynchronous circular orbit, which would require a mean altitude of approximately 20,200 kilometers and an orbital period of 718 minutes. Instead, GLONASS spacecraft circle the earth at a mean altitude of 19,100 kilometers and an orbital period of nearly 676 minutes. This altitude was selected along with a particular antenna radiation pattern to provide a complete radionavigation field anywhere on the earth and up to an altitude of 2,000 kilometers. Coupled with an orbital inclination of almost 65 degrees (similar to Navstar Block I spacecraft), the GLONASS orbit is "groundtrack stabilized," repeating every 17 revolutions or eight days. In other words, a GLONASS satellite will cross the equator in a northbound direction, at only 17 locations approximately 21.2 degrees apart, before repeating the cycle. Such groundtrack stabilization techniques are widely used by other Russian spacecraft, including military early-warning and ocean-surveillance satellites. (Readers unfamiliar with satellite orbit terminology may wish to consult the artilce "The Orbits of GPS Satellites," in the May 1991 issue of *GPS World.)*

To provide continuous global navigational coverage when fully deployed, the GLONASS constellation will consist of three orbital planes with eight spacecraft in each plane. The orbital planes will be separated evenly along the equator at 120-degree intervals, with the satellites in each plane spaced 45 degrees from one another. To improve coverage uniformity, satellites in one plane will be phased 15 degrees from satellites in adjacent planes. Hence, GLONASS satellites will cross the equator northbound and southbound at regular intervals of approximately 28 minutes. Initially, one spacecraft in each plane will be placed in a standby status, ready to be activated quickly should a spacecraft in its plane become disabled. However, GLONASS program managers are considering ultimately increasing the constellation to 27 spacecraft, with eight active and one spare spacecraft in each plane.

A GLONASS spacecraft is allowed to vary from its assigned position by as much as 5 degrees of arc in its orbital plane. Kosmos 2111 is the only satellite that has substantially exceeded this limitation, apparently losing orbital maneuvering control soon after arriving on station. By the summer of 1994, Kosmos 2111 had drifted more than 12 degrees from its desired location; but even then, it was still part of the operating GLONASS constellation.

Table 1. GLONASS spacecraft summary

Launch date	Spacecraft name[1]	GLONASS number[2]	Satellite number	Orbital plane	Initial operational position	Later operational position(s)
Oct. 12, 1982	Kosmos 1414	1	13606	1	1	
Aug. 10, 1983	Kosmos 1490	2	14258	1	3	
	Kosmos 1491	3	14259	1	2	
Dec. 29, 1983	Kosmos 1519	4	14590	3	18[3]	
	Kosmos 1520	5	14591	3	17[3]	19[3] (Nov. '84), 18[3] (June '85)
May 19, 1984	Kosmos 1554	6	14977	3	19[3]	
	Kosmos 1555	7	14978	3	18[3]	
Sept. 4, 1984	Kosmos 1593	8	15259	1	2	
	Kosmos 1595	9	15261	1	3	
May 17, 1985	Kosmos 1650	10	15697	1	1	
	Kosmos 1651	11	15698	1	2	
Dec. 24, 1985	Kosmos 1710	12	16396	3	18	
	Kosmos 1711	13	16397	3	17	
Sept. 16, 1986	Kosmos 1778	14	16961	1	2	
	Kosmos 1779	15	16962	1	3	2 (Mar. '87), 1 (Sept. '87)
	Kosmos 1780	16	16963	1	8	
April 24, 1987	Kosmos 1838	17	17902	3	launch failure	
	Kosmos 1839	18	17903	3	launch failure	
	Kosmos 1840	19	17904	3	launch failure	
Sept. 16, 1987	Kosmos 1883	20	18355	3	18	17 (July '88)
	Kosmos 1884	21	18356	3	17	
	Kosmos 1885	22	18357	3	24	
Feb. 17, 1988	Kosmos 1917	23	18857	1	launch failure	
	Kosmos 1918	24	–	1	launch failure	
	Kosmos 1919	25	–	1	launch failure	
May 21, 1988	Kosmos 1946	26	19163	1	8	
	Kosmos 1947	27	19164	1	7	
	Kosmos 1948	28	19165	1	1	
Sept. 16, 1988	Kosmos 1970	29	19501	3	24	17 (Mar. '89)
	Kosmos 1971	30	19502	3	18	20 (July '89)
	Kosmos 1972	31	19503	3	19	18 (July '89)
Jan. 10, 1989	Kosmos 1987	32	19749	1	2	
	Kosmos 1988	33	19750	1	3	
May 31, 1989	Kosmos 2022	34	20024	3	19	
	Kosmos 2023	35	20025	3	24	
May 19, 1990	Kosmos 2079	36	20619	3	17	
	Kosmos 2080	37	20620	3	19	
	Kosmos 2081	38	20621	3	20	
Dec. 8, 1990	Kosmos 2109	39	21006	1	4	
	Kosmos 2110	40	21007	1	7	
	Kosmos 2111	41	21008	1	5	
April 4, 1991	Kosmos 2139	42	21216	3	21	
	Kosmos 2140	43	21217	3	22	
	Kosmos 2141	44	21218	3	24	
Jan. 29, 1992	Kosmos 2177	45	21853	1	3	
	Kosmos 2178	46	21854	1	8	
	Kosmos 2179	47	21855	1	1	
July 30, 1992	Kosmos 2204	48	22056	3	24	
	Kosmos 2205	49	22057	3	18	21 (Oct. '93)
	Kosmos 2206	50	22058	3	21	20 (Oct. '93)
Feb. 17, 1993	Kosmos 2234	51	22512	1	3	
	Kosmos 2235	52	22513	1	2	
	Kosmos 2236	53	22514	1	6	
April 11, 1994	Kosmos 2275	54	23043	3	17	
	Kosmos 2276	55	23044	3	23	
	Kosmos 2277	56	23045	3	18	
Aug. 11, 1994	Kosmos 2287	57	23203	2	12	
	Kosmos 2288	58	23204	2	16	
	Kosmos 2289	59	23205	2	14	

[1] Spacecraft name is U.S. designator and may differ from USSR/CIS designator.
[2] An alternative GLONASS numbering scheme includes the eight "dummy satellites."
[3] These positions were shifted at the beginning of the operational deployment phase in December 1985.

For GLONASS to meet its 100-meter horizontal and 150-meter vertical position accuracy objectives, the location of each spacecraft must be known to within 20 meters in the along-track, 10 meters in the cross-track, and 5 meters in the radial directions. This challenge is met, in part, with the aid of the Quantum Optical Tracking Stations located across the former Soviet Union.

Placing the Craft in Orbit. The relatively large mass and limited longevity of GLONASS spacecraft led Russian program developers to seek the most efficient means of on-orbit delivery. When GLONASS spacecraft were ready for initial in-space testing, only two options were available. The Molniya (SL-6) booster could insert only a single spacecraft into the desired operational orbit from either the Baikonur Cosmodrome (near Leninsk in Kazakhstan) or the Plesetsk Cosmodrome (south of Arkhangel'sk). A drawback of the Molniya booster was that it needed to perform two major burns of the upper stage to reach the desired GLONASS orbit, rather than just one, which is what is normally needed to place communications and early-warning spacecraft into highly elliptical, semisynchronous orbits with inclinations of approximately 63 degrees. Alternatively, the Proton (SL-12) booster, limited to launches from the Baikonur Cosmodrome only, could carry three spacecraft at a time, reducing the total number of required launches by two-thirds. Moreover, the upper stage of the Proton launch vehicle was already routinely used on missions requiring multiple main-engine starts. This option, which did involve the design of a special multipayload carrier-and-deployment device, was selected.

With a launch success record of about 91.3 percent since 1970 (158 out of 173 missions), the four-stage Proton has remained the largest operational launch vehicle in the former Soviet Union and the current CIS since 1965. The first three stages were designed and manufactured by the Salyut Design Bureau and the Khrunichev Machine Building Plant (combined in 1993 into the Khrunichev State Space Scientific Production Center). The Block DM fourth stage, developed by the Korolev OKB (later the Energiya Scientific Production Association, and since early 1994 the S.P. Korolev Energiya Space Rocket Corporation), evolved from an upper stage designed for the Soviet Union's man-on-the-moon program and was first flown in 1974 to support geosynchronous earth orbit (GEO) missions. The Block D designation arose from its use as the fifth (*D* is the fifth letter in the Russian alphabet) stage of the N-1 launch vehicle. The Block DM version differs from its predecessor primarily in the incorporation of an independent navigation and guidance unit. Since the 1960s, the basic Block D stage has been used for unmanned lunar and planetary missions.

Because the Proton launch vehicle carries each trio of GLONASS spacecraft directly into the operational orbital regime (within one minute of the desired orbital period), separate spacecraft apogee kick motors are not required. Of the 23 missions conducted for the GLONASS program from October 1982 to August 1994, 21 (91.3 percent) have been successful. The two failures, one in 1987 and one in 1988, involved a fourth-stage separation failure and a premature shutdown of the fourth-stage propulsion system. In each case, all three GLONASS spacecraft were lost.

Deployment Phases. GLONASS deployment operations can be divided into a preoperational phase (1982–85) and an operational phase (1985 to the present). During the preoperational phase, the Proton launch vehicle was flown on a profile similar to that utilized for GEO missions. Launched from the Baikonur Cosmodrome on a northeast trajectory, the fourth stage and payload were inserted into a low-altitude parking orbit (about 200 kilometers above the earth) at an inclination of 51.6 degrees. Approximately 80 minutes later, the fourth stage was ignited for the first time as the vehicle made its initial northbound equator crossing, maneuvering into a highly elliptical transfer orbit. As it neared an apogee of approximately 19,150 kilometers nearly three hours later, the fourth stage was restarted, circularizing its orbit and increasing the orbital inclination to 64.8 degrees. Subsequently, the payload was deployed. The spacecraft had as many as 25 days to maneuver to their intended position within the orbital plane and to complete their initial on-orbit testing and check-out.

The six-flight preoperational phase was also notable for its use of one or two "dummy" satellites on each mission. The dummy satellites, each of which measured 1.5 × 1.5 × 3.0 meters with a mass of about 1,400 kilograms, acted as ballast while accompanying functional GLONASS spacecraft. However, these dummy objects were assigned official Kosmos designators by the former Soviet Union. On the maiden GLONASS mission, two dummy satellites were used, but the remaining five preoperational flights consisted of two GLONASS spacecraft and only one dummy satellite (see Table 1). All dummy satellites were easily distinguishable by their lack of navigational signals, their inability to maneuver, and even their visual signatures.

During the preoperational phase, a total of 11 GLONASS spacecraft were placed in orbit: seven in Plane 1 and four in Plane 3. However, due to the relatively short lifetimes of the spacecraft, only three positions in each plane (1–3 in Plane 1 and 17–19 in Plane 3) were filled. Unlike their deployment in the operational phase to follow, early GLONASS spacecraft in adjacent orbital planes had zero phase shift. Interestingly, by September 1984, the GLONASS constellation was a replica of the early GPS network established four years earlier with Navstar SVNs 1–6 (see Figure 2).

The seventh mission inaugurated the operational deployment phase of the GLONASS

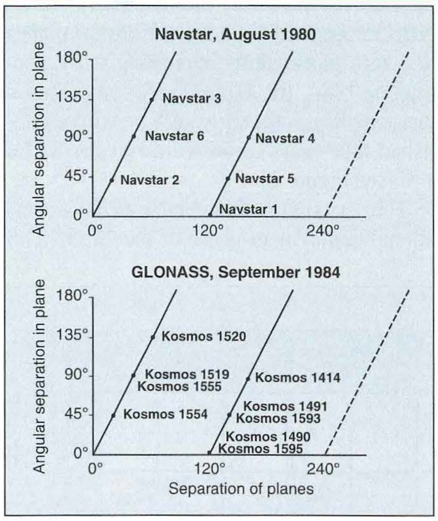

Figure 2. The early GLONASS constellation test configuration was essentially identical to that of GPS. Both systems required more than 10 years to reach full operational capability (FOC). (Diagram from *The Soviet Year in Space 1984,* N.L. Johnson, Teledyne Brown Engineering, Colorado Springs, Colorado, 1985.)

program. Launched in late December 1985, Kosmos 1710 and Kosmos 1711 initiated the shift of Plane 3 positions 15 degrees from their Plane 1 counterparts. This mission also marked the last flight of a dummy satellite, although the two 1989 GLONASS missions carried special geodetic satellites (called Etalon) in the third launch-vehicle position.

Even more distinctive of the operational deployment phase was the introduction of a new, simpler Proton launch profile. Instead of entering a lower-inclination parking orbit and later performing an orbital plane change, all missions since Kosmos 1710–1711 have been launched directly into low altitude, 64.8-degree inclination orbits, from which two standard Hohmann transfers are performed to reach the necessary preliminary orbit. (A *Hohmann transfer orbit* is an elliptical orbit tangent to two circular coplanar orbits and requires the least energy to transfer a spacecraft between the two circular orbits.) Because plane changes are no longer required, the fourth-stage maneuvers into the transfer and preliminary orbits can be performed at virtually any time. However, to date, insertion into the transfer orbit has occurred only near 10 degrees south (with an argument of perigee of 349 degrees) or near 50 degrees south (with an argument of perigee of 297 degrees) on the first northbound pass through the Southern Hemisphere. The former location (see Figure 3) has been the preference for 10 of the first 15 missions of the operational deployment phase. Both profiles permit final orbital insertion and payload deployment to be carried out within radio visibility of Russian territory.

CONSTELLATION DEVELOPMENT

The gradual expansion of the GLONASS constellation began in late 1986, and by the mission of Kosmos 2275–2277 in April 1994, all 16 positions within Planes 1 and 3 had been staffed by operational spacecraft (see Figures 4 and 5). Unfortunately, the GLONASS vehicles continue to have relatively short lifetimes compared with the Navstar spacecraft, so the number of working spacecraft has not grown as rapidly. For example, signal analyses in May 1994 by the University of Leeds in the United Kingdom, one of the foremost institutions in the West conducting research on GLONASS spacecraft, indicated that only 12 of the 16 positions were operational: five in Plane 1 and seven in Plane 3. The mission of Kosmos 2287–2289 in August 1994 opened the long-awaited Plane 2 and moved the system a giant step closer to full operational capability (FOC).

To help compensate for unexpected spacecraft malfunctions, GLONASS maneuvering capability is used to shift healthy satellites to locations where they are most needed. As indicated in Figure 4, repositioning has been rare in Plane 1; however, as shown in Figure 5, several maneuvers have occurred in Plane 3. The last two sequences (Kosmos 1971 and Kosmos 1972 in 1989 and Kosmos 2205 and Kosmos 2206 in 1993) involved the repositioning of two spacecraft of equal age with one taking over for the other, and the moving of the latter to a third location. Relocations normally are accomplished within one to four weeks; in fact, most are completed within just two weeks.

In contrast to the current U.S. policy of retiring old GPS satellites in graveyard orbits above or below the operational altitude, GLONASS satellites are normally abandoned in place. The only exceptions have been Kosmos 1491 and Kosmos 1651. Kosmos 1491 made a substantial maneuver in September 1984, raising its apogee by 350 kilometers while lowering its perigee by about 160 kilometers. The spacecraft remained in this higher orbit for more than a year until December 1985, when it appeared to return to nearly its original orbit. However, the U.S. Space Surveillance Network lost track of Kosmos 1491 during the first quarter of 1986. Later in the year, the spacecraft was found in a lower orbit with a mean altitude of approximately 18,950 kilometers, where it currently resides. (A reexamination of this object in 1994 appeared to confirm that it is indeed Kosmos 1491.) In early 1988, Kosmos 1651 maneuvered into a very slightly lower orbit (orbital period decrease of less than 0.1 minutes); shortly thereafter the spacecraft ceased functioning.

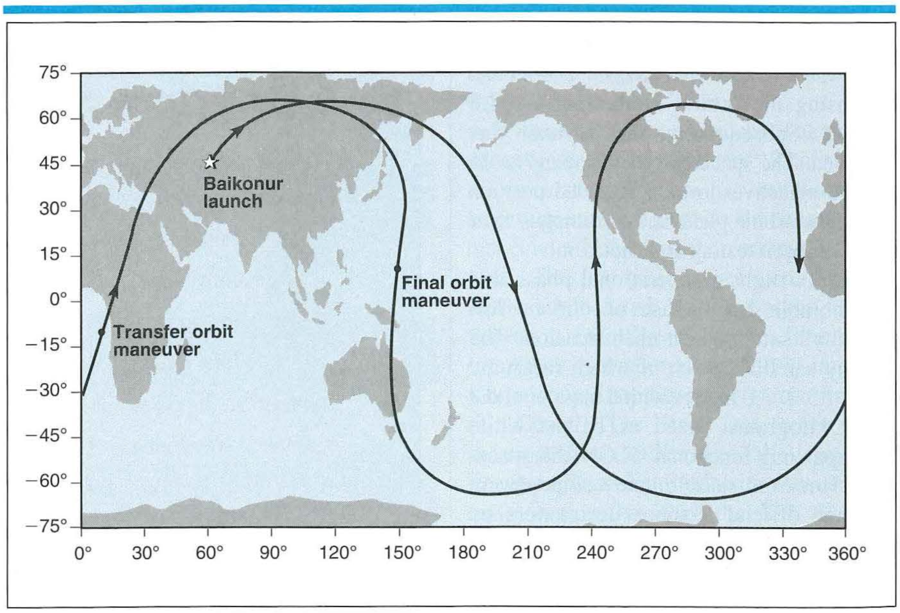

Figure 3. A four-stage Proton launch vehicle, Russia's largest operational booster, can directly deliver as many as three GLONASS spacecraft to a nearly semisynchronous orbit. The current launch profile shown here uses a 64.8-degree inclination parking orbit, compared with the 51.6-degree orbit of the first six missions.

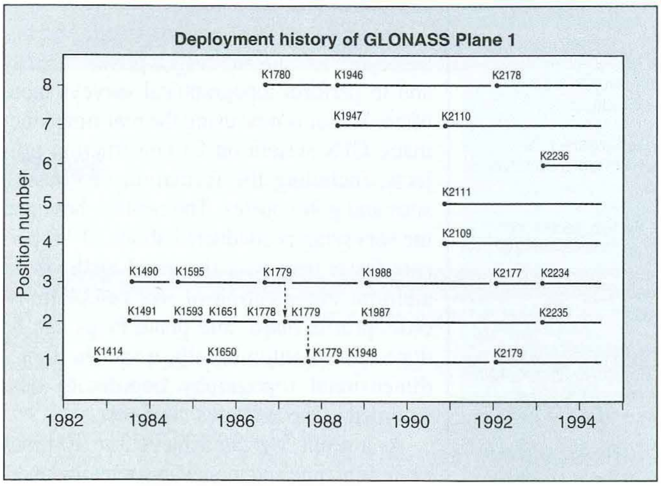

Figure 4. Although started in 1982, GLONASS Plane 1 did not expand into all eight of its nominal positions until 1993. Movements within the plane have been rare. (Diagram current to July 1, 1994.)

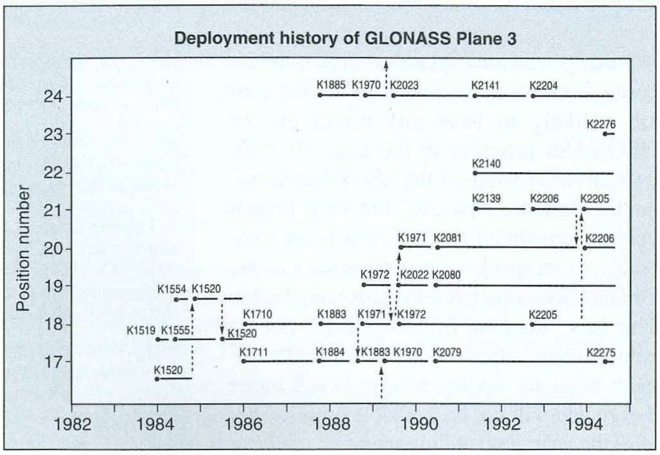

Figure 5. GLONASS Plane 3 has 26 spacecraft, two more than Plane 1, and its history has been much more complex. The last spacecraft deployed, Kosmos 2277, was a spare that did not settle into its operational location (Position 18) until four months after launch. (Diagram current to July 1, 1994.)

FUTURE DIRECTIONS

In 1988, Soviet documents filed with ICAO indicated that Phase I of the GLONASS program would be accomplished during 1989–90 with 10 to 12 spacecraft operational in two planes. This goal was reached in 1990. Figure 6 indicates the anticipated availability of the Phase I network for maritime and aviation use. Phase II of the GLONASS program, consisting of the full 21-member, three-plane network, was scheduled for implementation by 1995. This objective is still obtainable, as evidenced by the August 1994 flight of Kosmos 2287–2289. Despite many concerns about continued program funding, a potentially important international role and projections of significant beneficial domestic economic effects for GLONASS have elevated the priority of the program within Russia and the CIS. In particular, a full GLONASS network would permit the decommissioning of several old and expensive CIS terrestrial navigation systems.

The year 1995 may also witness the maiden flight of the improved GLONASS-M Block I spacecraft (with a mass of approximately 1,480 kilograms), which has been under development since 1990. In addition to better frequency and timing accuracies, GLONASS-M will have an expected lifetime of five to seven years. The latter is perhaps the most important feature needed to ensure Russia's capability to maintain a 21- to 24-satellite network. More-advanced user equipment (such as the Shkiper-N receiver) with digital signal processing and GPS capability is also under development. Sometime after the turn of the century, a much larger (about 2,000 kilograms) and more capable GLONASS-M Block II spacecraft may be ready. In addition to significant improvements to subsystems, GLONASS-M Block II will be capable of intersatellite communications and monitoring and of autonomous operations for as long as 60 days.

With the 1994 agreement between Russia and Kazakhstan regarding a long-term lease of the Baikonur Cosmodrome, GLONASS missions will likely continue to originate from this southern site for years to come. Although President Yeltsin in 1992 authorized the construction of Proton launch facilities at the Plesetsk Cosmodrome, funds for the necessary pads and infrastructure have not been released. Should these facilities be built, triplet GLONASS missions could be undertaken using either cosmodrome.

Alternatively, the Zenit (SL-16) launch vehicle is scheduled to be operational at Plesetsk by 1996. With the planned three-stage Zenit variant, two GLONASS spacecraft could be inserted into operational orbits by a single launch vehicle from either Baikonur or Plesetsk. This technique may not only be more cost-effective but also more attractive from an environmental standpoint. The first two stages of the Proton launch vehicle burn hazardous nitrogen tetroxide and unsymmetrical dimethyl hydrazine, whereas the Zenit booster employs only liquid oxygen and kerosene-class propellants. Range safety as well as political difficulties could also be re-

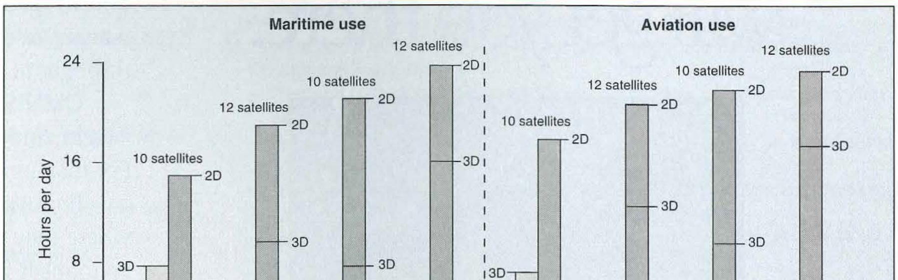

Figure 6. The GLONASS Phase I constellation (10 to 12 satellites) can provide at least 15 hours of two-dimensional positioning each day. At latitudes below 50 degrees, three-dimensional service can be disrupted for as long as eight hours. (Diagram from *The Soviet Year in Space 1988,* N.L. Johnson, Teledyne Brown Engineering, Colorado Springs, Colorado, 1989.)

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duced by shifting missions from Baikonur to Plesetsk.

Finally, tentative plans to create a new cosmodrome near Svobodny in the Far East are unlikely to have any effect on the GLONASS program in the near- or mid-term. Rokot (based on the SS-19 Intercontinental Ballistic Missile), the first launch vehicle scheduled to be flown from Svobodny, is incapable of placing even a single GLONASS spacecraft into the required orbit. The new, medium-lift Angara-24 launch vehicle could support GLONASS replenishment missions, but the booster is still under design and will not be available until shortly after the year 2000 at the earliest.

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possibilities for surveying.

As we had hoped, our system allowed our surveyors to find the target points directly and to perform topographical surveys more often. Mitsui is now using the real-time kinematic GPS system on 25 construction projects, including the formation of housing sites and golf courses. The results show that the surveying is conducted about 70–90 percent faster than with the usual methods. In addition, the creation of soil calculations, cross-profile maps, and plane maps can be done almost automatically using the three-dimensional topography coordinate data recorded in the notebook computer.

As a result, we can achieve 3 to 10 times savings in time and money in surveying operations alone, and several percent reduction of time and cost of whole construction projects. Real-time kinematic GPS is especially good for earthworks such as roads, housings, golf courses, and dams. We plan to promote the technology vigorously and develop software for each surveying method. ■

For product information, turn to page 66 and see Manufacturers.