GLONASS

Developing Strategies for the Future

Yuri Urlichich, Valeriy Subbotin, Grigory Stupak, Vyacheslav Dvorkin, Alexander Povalyaev, and Sergey Karutin

IT'S NO LONGER JUST A GPS WORLD. Russia's GLONASS, or Global'naya Navigatsionaya Sputnikova Sistema, will soon have a full complement of satellites in orbit providing positioning, navigation, and timing worldwide.

The Soviet Union began development of GLONASS in 1976 just a few years after work started on GPS. The first satellite was launched in 1982 and a fully populated constellation of 24 functioning satellites was achieved in early 1996. However, due to economic difficulties following the dismantling of the Soviet Union, by 2002 the constellation had dropped to as few as seven satellites. But the Russian economy improved, and restoration of GLONASS was given high priority by the Russian government. The satellite constellation was gradually rejuvenated using primarily a new modernized spacecraft, GLONASS-M. The new design offered many improvements, including better onboard electronics, a longer lifetime, an L2 civil signal, and an improved navigation message. The GLONASS-M spacecraft still used a pressurized, hermetically sealed cylinder for the electronics, as had the earlier versions. Today, 26 functional GLONASS-M satellites are on orbit, 22 of them in service and providing usable signals, with four more having reserve status. A full constellation of 24 satellites should be available later this year with launches of several GLONASS-M satellites and the latest variant, the GLONASS-K satellite.

INNOVATION INSIGHTS with Richard Langley

GLONASS-K satellites will transmit a CDMA signal on L3.

GLONASS-K satellites are markedly different from their predecessors. They are lighter, use an unpressurized housing (similar to that of GPS satellites), have improved clock stability, and a longer, 10-year design life. They also include, for the first time, code-division-multiple-access (CDMA) signals accompanying the legacy frequency-division-multiple-access signals. There will be two versions: GLONASS-K1 will transmit a CDMA signal on a new L3 frequency, and GLONASS-K2, in addition, will feature CDMA signals on L1 and L2 frequencies. The first GLONASS-K1 satellite was launched on February 26 and is now undergoing tests.

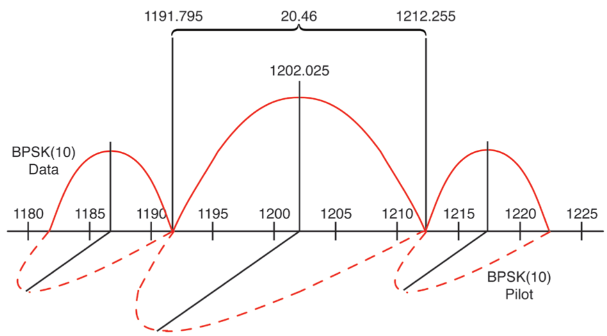
GLONASS is being further improved with a satellite-based augmentation system. Called the System for Differential Correction and Monitoring or SDCM, it will use a ground network of monitoring stations and Luch geostationary communication satellites to transmit correction and integrity data using the GPS L1 frequency. The first of these satellites, Luch-5A, will be launched this year. In this month's column, a team of authors from Russian Space Systems, a key developer of navigation and geospatial technologies in the Russian aerospace industry, describes the new L3 CDMA signal to be broadcast by GLONASS-K satellites and the progress to date in developing the SDCM augmentation system.

The Russian Global Navigation Satellite System (GLONASS) is once again approaching full operation. As of March, 22 satellites are in service, providing nearly continuous global coverage. These satellites are modernized GLONASS or GLONASS-M satellites, transmitting the legacy frequency-domain-multiple-access (FDMA) navigation signals in the L1 and L2 frequency bands.

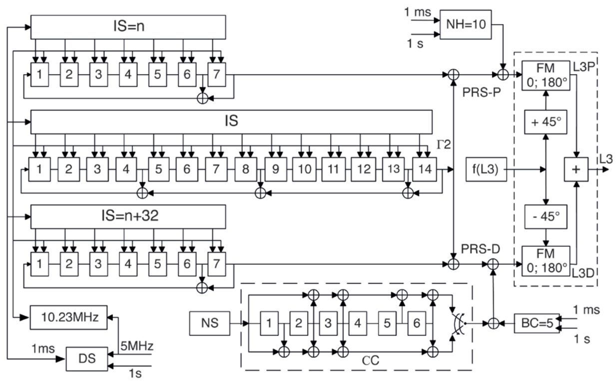
The structure of the navigation signals transmitted by the satellites determines the accuracy of the pseudorange measurements, which, in turn, affects a user's position accuracy. Evolution of the GLONASS navigation signals is a top priority for the overall system development. A new version of the satellites, GLONASS-K, will broadcast a code-division-multiple-access (CDMA) signal in the L3 band for the first time in the system's history. In addition to the change in signal parameters, new navigation information will be transmitted to users through this signal. Further GLONASS navigation signal development assumes that a new CDMA civil signal will also become available in the L1 and L2 bands.

The evolution of GNSS augmentation is also an important task in the development of satellite navigation in Russia. The Russian satellite-based augmentation system (SBAS), the System for Differential Correction and Monitoring (SDCM), is entering into the deployment phase and that is why some aspects of interoperability and compatibility with other SBASs become important. Taking into account the fact that satellite channels are the most efficient and universal tool to supply GNSS users with precise ephemeris and clock parameters and the positive experience of regional systems (such as the Quasi-Zenith Satellite System), we can see the potential for the development of a precise positioning service.

In this article, we will discuss plans for modernizing GLONASS, covering both the new signals and the augmentation service.



▲ **FIGURE 1** L3 CDMA signal spectrum (frequencies in MHz).



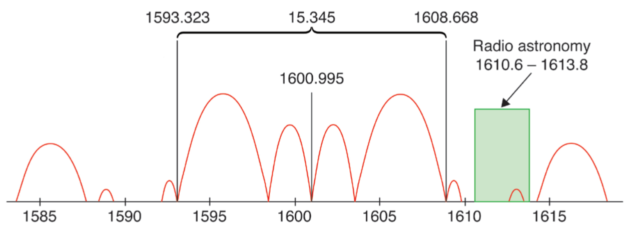
▲ **FIGURE 2** Formulation of L3 CDMA signal.

Navigation Signals

The main task for GLONASS development is an extension of the ensemble of navigation signals. This extension means that new CDMA signals in the L1, L2, and L3 bands will be added to the existing FDMA signals. The GLONASS satellites will keep broadcasting the legacy signals until the last receiver stops working.

The first phase in the implementation of CDMA technology on GLONASS-K satellites includes a new signal in the L3 band on a carrier frequency of 1202.025 MHz. The first GLONASS-K satellite was launched on February 26, 2011, and is undergoing tests. The ranging code chipping rate for the CDMA signal is 10.23 megachips per second with a period of 1 milliseconds. It is modulated onto the carrier using quadrature phase-shift keying (QPSK), with an in-phase data channel and a quadrature pilot channel. The signal spectrum is shown in **FIGURE 1**.

A block diagram of how the GLONASS L3 signal is formed is presented in **FIGURE 2**. The set of possible ranging codes consists of 31 truncated Kasami sequences. (Kasami



▲ **FIGURE 3** BOC(5, 2.5) signal spectrum (frequencies in MHz).

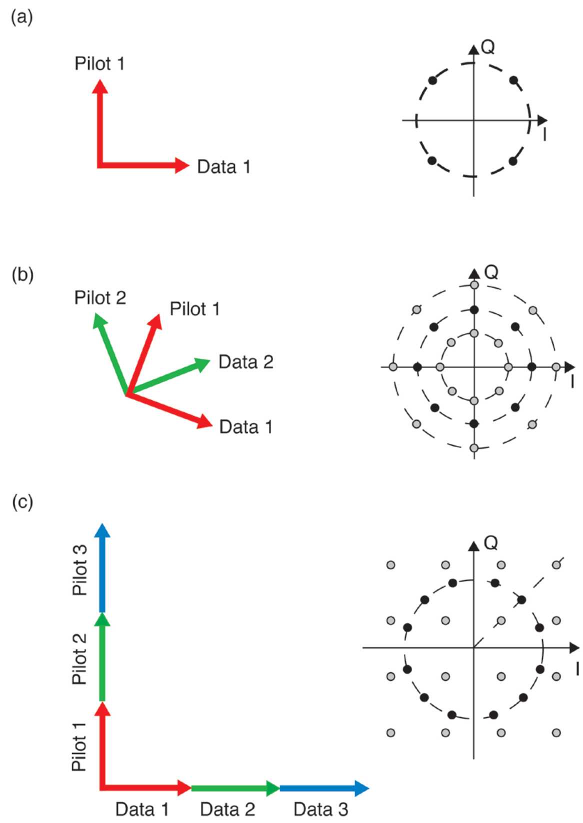
sequences are binary sequences of length $2^m - 1$ where m is an even integer. These sequences have good cross-correlation values approaching a theoretical lower bound. The Gold codes used in GPS are a special case of Kasami codes.) The full length of these sequences is $2^{14} - 1 = 16{,}383$ symbols, but the ranging code is truncated to a length of $N = 10{,}230$ with a period of 1 milliseconds and with the following initial state (IS) in the generator (G) registers: G2 – IS = 00110100111000, G1 IS = n, G3 IS = $n + 32$. It these equations, n is the system number of the satellite in the orbit constellation. For these codes, inter-channel jamming is about –40 dB.

The navigation message symbols (NSs) are transmitted at a rate of 100 bits per second with half-rate convolution coding (CC) with a memory of 6. This means that the duration of an NS is 10 milliseconds and the duration of the CC symbols is 5 milliseconds. The CC switch (see Figure 2) should be in the lower position for the first half of each NS.

The pseudorandom sequence of the L3 data signal, PRS-D, is modulo-2 summed with a periodic 5-bit Barker code (BC = 00010) before phase modulation. Barker code symbols have a duration of 1 millisecond and are synchronized with the pseudorandom code symbols. The pseudorandom sequence of the L3 pilot signal, PRS-P, is modulo-2 summed with a 10-bit Neuman-Hoffman code (NH = 0000110101). The Neuman-Hofman code symbols have a duration of 1 millisecond and are synchronized with the information symbols. The Barker and Neuman-Hoffman codes are used for CC synchronization in the L3 user's receiver (see Further Reading for background details).

The navigation message superframe (2 minutes long) will consist of 8 navigation frames (NFs) for 24 regular satellites in the GLONASS first modernization stage and 10 NFs (lasting 2.5 minutes) for 30 satellites in the future. Each NF (15 seconds long) includes 5 strings (3 seconds each). Every NF has a full set of ephemerides for the current satellite and part of the system almanac for three satellites. The full system almanac is broadcast in one superframe. A time marker is located at the beginning of a string and given as a number of a string within the current day in the satellite time scale.

The GLONASS system and the satellites' time scales are coordinated with the Russian national time scale, UTC(SU), which is periodically adjusted for a leap seconds. A special flag, A, is used in each frame to inform users about an anomalous fifth string of this frame. If $A = 0$, the fifth string will



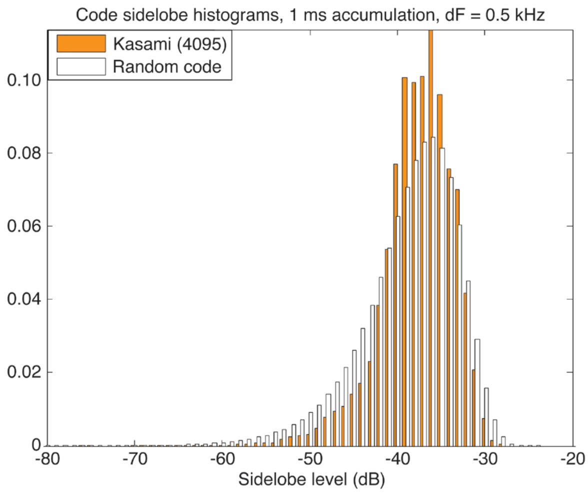
▲ **FIGURE 4** Vector and phase relationships for AltBOC signals with (a) 2-, (b) 4-, and (c) 6-components, with losses of 0, and about 15 and 16 percent respectively.

be normal with a 3-second duration; if $A = 1$, the fifth string will be either 2 seconds or 4 seconds. The correction value (+1 second or –1 second) is also transmitted in the special NF flag, KP. If $KP = 11$, the fifth string will be shorter due to a correction of –1 second; if $KP = 01$, it will be longer due to a correction of +1 second. A user should not use the short string. A string is lengthened by adding "0" to the normal string. This algorithm is implemented with the objective of simplifying the time scale correction process in user equipment.

Modulation and Multiplexing. There are intensive studies being carried out for developing new CDMA signals in the L1 and L2 bands in addition to the L3 signal described above. The main difficulties to be overcome in these studies are to ensure a low-power spectral density (PSD) of –238 dBW/m^2/Hz in the 1610.6–1613.8 MHz radio astronomy band and the multiplexing of more than two signal components, providing a constant signal level.

The first task could be solved by using a modulation with a low PSD level in the radio astronomy band, such as a binary offset carrier (BOC) modulation with a subcarrier frequency of 5.115 MHz and a spreading code chipping rate of 2.5575 megachips per second (BOC(5, 2.5)) as shown in **FIGURE 3**.

There are two well-known methods of signal multiplex-



▲ **FIGURE 5** Kasami and random code cross-correlation functions (4,095 symbols).

ing — time multiplexing and amplitude equalizing. The time multiplexing technique is used for the GPS L2C signal, while the amplitude equalizing method is used for the composite BOC (CBOC) signals in the Galileo E1/L1 band and the alternative BOC (AltBOC) signals in E5a-E5b bands. This method has the disadvantage of about 10–16 percent loss of the transmitter power on the equalization. However, it has an advantage: simple user equipment architecture and, more importantly, the possibility of step-wise implementation of the multicomponent signal. The step-wise approach is compatible with older receivers. New user equipment will be able to track both old and new signal components, as well as a combined signal consisting of old and new components. Vector and phase diagrams for two-, four-, and six-component AltBOC signals are shown in **FIGURE 4**. Even with six components, losses are lower than about 16 percent, but it is possible to avoid any loss using time multiplexing. That is why the final decision about future GLONASS signals has not yet been made.

There have been extensive studies on the definition of the ensemble of code sequences with a minimum level of inter-channel jamming. It was found that the jamming level for random shifts does not depend on the code type, but rather depends on the number of symbols, *N*, in a period. Cross-correlation functions for Kasami 4095 and Weil 10230 codes are shown in **FIGURES 5** and **6**. (Kasami codes, as previously mentioned, are being used for the GLONASS L3 CDMA signal. Weil codes are prime length sequences constructed from the well-known Legendre sequences and are used for the GPS L1C signal.) For comparison, we show cross-correlation functions for random codes with equal lengths on the same figures. It is obvious that the histograms of predefined and random codes are close to being equal. Sidelobe dispersion levels are lower than 0.1 dB.

The results obtained from the studies allow us to draw a conclusion about the invariance of the stochastic characteristics of inter-channel interference using a code structure with a fixed length of *N* symbols. That is why it is possible to choose an ensemble of binary code sequences on the basis of generation simplicity.

GLONASS Augmentation Development

SDCM has been under development since 2002. The main elements of the system, including the network of reference stations in Russia and abroad, the central processing facility (CPF), and the SDCM information distribution channel, have been designed.

Ground Stations. The SDCM uses 14 monitor stations in Russia and two in Antarctica at Russia's Bellingshausen and Novolazarevskaya research stations. Eight more monitor stations will be added in Russia and several more outside Russia. The additional overseas stations may include sites in Latin America and the Asia-Pacific region.

Central Processing. Raw measurements (GLONASS and GPS L1 and L2 pseudorange and carrier-phase measurements) from the ground stations come to the SDCM CPF. The CPF calculates the precise satellite ephemerides and clocks, controls integrity, and generates the SBAS messages. The format of these messages is compliant with the international standard also used by the Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), and the Japanese Multi-functional Transport Satellite (MTSAT) Satellite-based Augmentation System (MSAS).

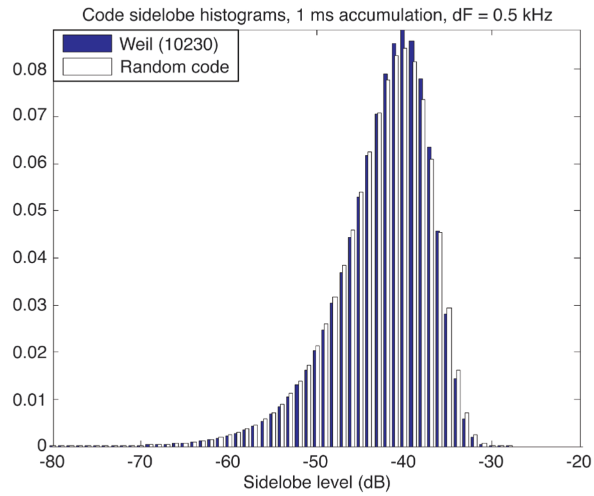
Format Limitations. The current SBAS format has a limited capability for broadcasting corrections for GLONASS and GPS satellites combined. There is space for only 51 satellites, insufficient for the current number of satellites on orbit. As a result, studies are looking into the efficiency of SDCM data broadcasting in an attempt to resolve this contradiction. The three main options are: use a dynamic satellite mask, use two CDMA signals, or provide an additional SBAS message.

Under the first option, SDCM satellites would only broadcast corrections and integrity data for those GLONASS and other GNSS satellites in view of users in the territory of the Russian Federation. For the second option, SDCM satellites would transmit two CDMA signals with independent sets of corrections and integrity data on each signal. The third option assumes that the SDCM data stream would have additional messages with information about satellites not included in the initial list of 51.

The first scenario is possible with the current version of the SBAS format. The other two options require some changes in the format of SBAS messages and international coordination. But the SDCM CPF is ready to operate in all of these modes.

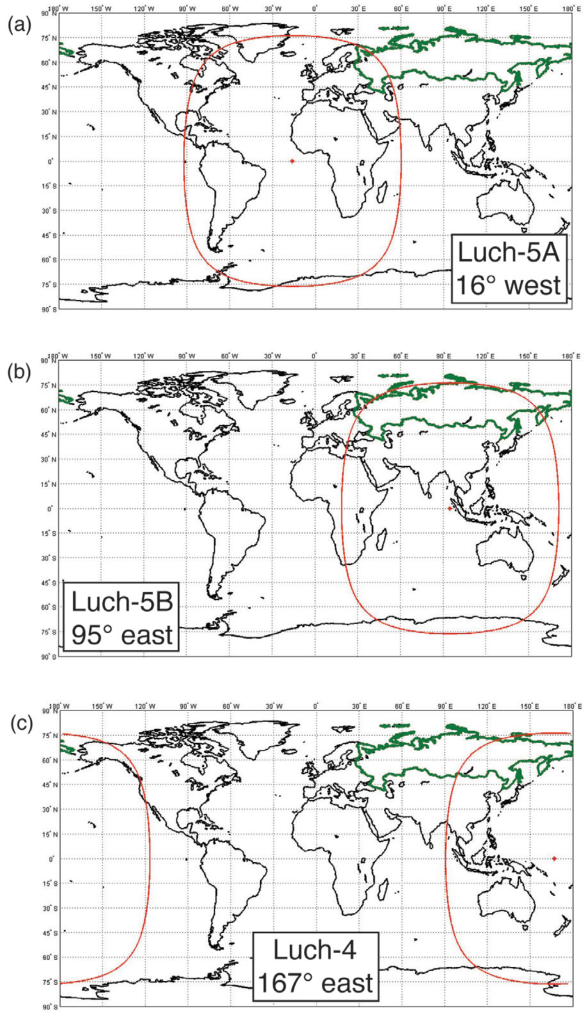
Distribution. The main advantage of SBAS is its universal space channel to users. The SDCM orbit constellation will consist of three geostationary satellites from the multifunctional space relay system Luch (see FIGURE 7). Luch, which means "ray" or "beam" in Russian, will be used to relay communications between low Earth-orbiting spacecraft and ground facilities in Russia in a similar fashion to that of NASA's Tracking and Data Relay Satellite System. The satellites will also include transponders for relaying SDCM signals from the CPF to users. The first satellite, Luch-5A, will be launched this year and will occupy an orbital slot at 16° west longitude. Luch-5B will be launched in 2012 to a slot at 95° east longitude. The full constellation will be deployed by 2014 with the launch of Luch-4 into a slot at 167° east longitude.

Wideband transponders (22 MHz) will be installed on board the Luch-5A and Luch-5B satellites. These transponders will transmit signals on a carrier frequency of 1575.42 MHz. As the SDCM service area is Russian territory, the main beam will be directed to the north with an angle of 7 degrees relative to the direction to the equator. The transmitted power will be 60 watts and will give a signal power level at the Earth's surface roughly equal to that of GLONASS and GPS signals, about –158 dBW.

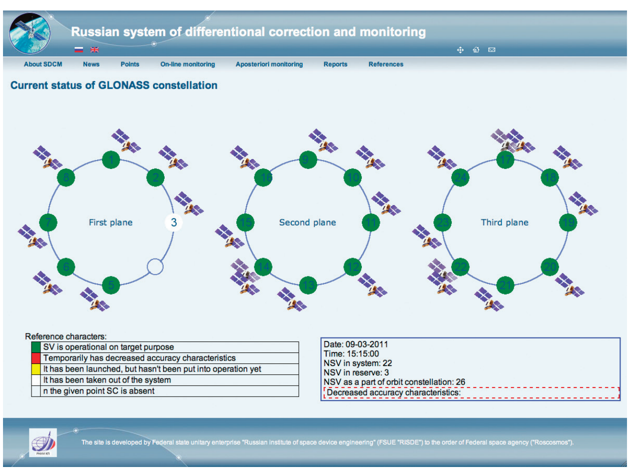


▲ FIGURE 6 Weil and random code cross-correlation functions (10,230 symbols).

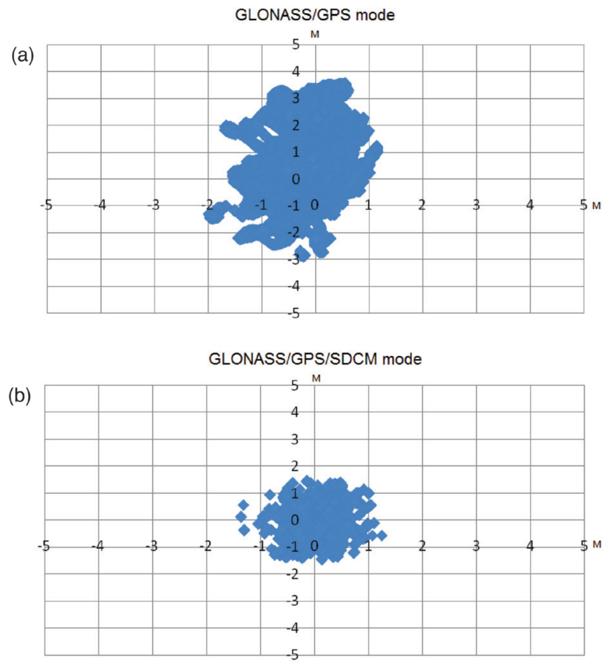
SDCM will also provide service through the Internet. A system website *(www.sdcm.ru)* already gives users information about real-time and *a posteriori* GLONASS and GPS monitoring (see FIGURE 8). An SDCM data-broadcasting



▲ **FIGURE 7** Multifunctional relay system Luch.



▲ **FIGURE 8** SDCM website, www. sdcm.ru.



▲ **FIGURE 9** SDCM tests results; (a) without and (b) with SDCM corrections.

ground system has been developed and is being tested now. It will help to verify SDCM data before the Luch satellites are launched. SDCM SBAS messages will be transmitted through the Internet in real time using the SISNeT (Signal in Space through the Internet) approach. The SISNeT protocol was developed for relaying EGNOS messages over the Internet.

A set of experiments was carried out to evaluate SDCM performance. In one experiment, 130 hours of raw pseudorange data was processed to generate the results shown in **FIGURE 9**. The upper plot shows the positioning results of a stand-alone receiver working only with the GLONASS and GPS signals. The lower plot presents results of GLONASS/GPS/SDCM navigation. It is clear that the SDCM ephemeris and clock corrections improve user accuracy by more than a factor of two.

However, precise point positioning (PPP) technology, based on post-processing dual-frequency carrier-phase measurements with precise satellite ephemeris and clock data, expands the areas of practical use of satellite positioning without complex user ground infrastructure of reference stations and wireless communication channels. Studies have already demonstrated that decimeter-level PPP is possible using GLONASS data or GLONASS data in combination with GPS data. Tests are under way to deliver the precise satellite ephemeris and clock data over the Internet to allow real-time PPP. We can envisage that some time in the future, the ephemeris and clock data could be provided to users in real time using satellite signals.

Future SDCM Satellites. The first SDCM satellites will provide service over the main part of Russia, excluding northern regions. To cover those regions, the SDCM orbit constellation could be enlarged using satellites in circular, inclined geosynchronous orbit (GSO); inclined, elliptical geosynchronous orbit (IGSO); or Molniya-type highly elliptical orbit (HEO) with an orbital period of precisely one-half of a sidereal day.

A comparative availability analysis for satellites with different orbits shows that using four GSO/IGSO/HEO satellites in two planes allows a user anywhere in Russia to continuously receive a signal from two satellites with a minimum elevation angle of 5 degrees. If the elevation mask angle is 30 degrees, availability will fall to 0.9 for IGSO satellites and 0.8 for HEO satellites. An orbit constellation of GSO satellites provides an availability of 0.8 and 0.3 for 5- and 30-degree mask angles respectively.

It is important to point out that the development of satellite orbit and clock prediction technology allows us to consider the possibility of using GSO, IGSO, or HEO satellites for ranging signal broadcasting. In that case, the navigation message could include precise ephemerides and clock data for all GNSS satellites to provide the data for a PPP service as mentioned earlier.

Conclusion

GLONASS development is entering a new historical phase. New CDMA navigation signals and deployment of a national SBAS system will provide not only a new quality of navigation service, but the basis for a regional precise navigation system with an accuracy of a few decimeters for users in Russia and neighboring countries.

Acknowledgment

This article is based on the paper "GLONASS Developing Strategy" presented at ION GNSS 2010, the 23rd International Technical Meeting of The Institute of Navigation, Portland, Oregon, September 21–24, 2010.

YURI URLICHICH is the general director and general designer of the Joint Stock Company (JSC) Russian Space Systems, formerly the Russian Institute of Space Device Engineering, headquartered in Moscow. He is a GLONASS general designer, doctor of science, professor, and author of more than 150 papers and 20 patents. **VALERIY SUBBOTIN** is a first deputy general director and general designer of JSC Russian Space Systems and a doctor of science. He has worked in the space industry for more than 40 years and has published more than 45 papers. **GRIGORY STUPAK** is a deputy general director and general designer of JSC Russian Space Systems, a GLONASS deputy general designer, and a professor of Bauman Moscow State Technical University (BMSTU). He has worked in the space industry for 35 years and has published more than 150 papers. **VYACHESLAV DVORKIN** is a deputy general designer of JSC Russian Space Systems and a doctor of science. Dvorkin has been developing GLONASS, GNSS augmentations, and user equipment for more than 35 years. He is an author of 50 papers in the satellite navigation field. **ALEXANDER POVALYAEV** is a deputy head of division in JSC Russian Space Systems and a professor of Moscow Aviation Institute. He has been developing methods and algorithms for processing GNSS carrier-phase measurements for 30 years and has published more than 40 papers. **SERGEY KARUTIN** is a deputy head of division in JSC Russian Space Systems and an assistant professor at BMSTU. Karutin has been on the GLONASS team since 1998, developing GNSS augmentations and user equipment. He received a Ph.D. degree in 2004.

FURTHER READING

GLONASS Background and Use

"GPS, GLONASS, and More: Multiple Constellation Processing in the International GNSS Service" by T. Springer and R. Dach in *GPS World*, Vol. 21, No. 6, June 2010, pp. 48–58.

"The Future is Now: GPS + GLONASS + SBAS = GNSS" by L. Wanninger in *GPS World*, Vol. 19, No. 7, July 2008, pp. 42–48.

"GLONASS: Review and Update" by R.B. Langley in *GPS World*, Vol. 8, No. 7, July 1997, pp. 46–51.

GLONASS Current and Future Signal Structures

GLONASS Interface Control Document, Edition 5.1, Russian Institute of *Space Device Engineering, Moscow, 2008.*

"The Spreading and Overlay Codes for the L1C Signal" by J.J. Rushanan in *Navigation*, Vol. 54, No. 1, Spring 2007, pp. 43–51.

Spread Spectrum Systems for GNSS and Wireless Communications by J.K. Holmes, Artech House, Inc., Norwood, Massachusetts, 2007.

"The Galileo Code and Others" by G.W. Hein, J.-A. Avila-Rodriguez, and S. Wallner in *Inside GNSS*, Vol. 1, No. 6, September 2006, pp. 62–74.

System for Differential Correction and Monitoring

"Russian System for Differential Correction and Monitoring: A Concept, Present Status, and Prospects for Future" by S.V. Averin, V.V. Dvorkin, and S.N. Karutin in *Proceedings of ION GNSS 2006*, the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation, Fort Worth, Texas, September 26–29, 2006, pp. 3037–3044.

Minimum Operational Performance Standards for Global Positioning/Wide Area Augmentation System Airborne Equipment, RTCA/DO-229D, prepared by SC-159, RTCA Inc., Washington, D.C., December 13, 2006.

"Appendix B. Technical Specifications for the Global Navigation Satellite System (GNSS)" in *Aeronautical Telecommunications: International Standards and Recommended Practices, Annex 10 to the Convention on International Civil Aviation, Vol. I. Radio Navigation Aids,* (6th ed.), International Civil Aviation Organization, Montreal, Quebec, Canada, 2006.

SISNeT

"Proposal of an Internet-Based EGNOS Receiver Architecture and Demonstration of the SISNeT Concept" by E. González, M. Toledo, A. Catalina, C. Barredo, F. Torán, and A. Salonico in *Proceedings of ION GPS/GNSS 2003*, the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation, Portland, Oregon, September 9-12, 2003, pp. 1628–1641.

Precise Point Positioning

"An Evaluation of OmniStar XP and PPP as a Replacement for DGPS in Airborne Applications" by J.S. Booth, and R.N. Snow in *Proceedings of ION GNSS 2009*, the 22nd International Technical Meeting of the Satellite Division of The Institute of Navigation, Savannah, Georgia, September 22–25, 2009, pp. 1188–1194.

"Precise Point Positioning for Real-Time Determination of Co-Seismic Crustal Motion" by P. Collins, J. Henton, Y. Mireault, P. Héroux, M. Schmidt, H. Dragert, and S. Bisnath in *Proceedings of ION GNSS 2009*, Savannah, Georgia, September 22–25, 2009, pp. 2479–2488.

"Orbits and Clocks for GLONASS Precise-Point-Positioning" by R. Píriz, D. Calle, A. Mozo, P. Navarro, D. Rodríguez, and G. Tobías in *Proceedings of ION GNSS* 2009, Savannah, Georgia, September 22–25, 2009, pp. 2415–2424.

"Study on Precise Point Positioning Based on Combined GPS and GLONASS" by X. Li, X. Zhang, and F. Guo in *Proceedings of ION GNSS* 2009, Savannah, Georgia, September 22–25, 2009, pp. 2449–2459.