THE GLOBAL NAVIGATION SATELLITE SYSTEM GLONASS: DEVELOPMENT AND USAGE IN THE 21ST CENTURY

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Abstract

At the present, in Russia, great importance is given to the maintenance and further development of space and ground infrastructure to provide all kinds of user and navigation service. The country possessing a satellite navigation system has vast advantages in international policy and economics. So, according to the Russian President's decree, the Global Navigation System (GNSS) GLONASS was granted the status of national patrimony of Russia, and the Russian Federation government was charged to take appropriate measures to unconditionally maintain and develop the GNSS GLONASS and increase the number of system users.

GLONASS's current status is presented, along with a graphical representation of the detailed system development plans, according to the Federal Development Program "Global Navigation System" for the period 2001-2011, during which the main lines of GLONASS's development are established.

INTRODUCTION

The satellite system GLONASS is intended to provide an unlimited number of nautical, air, space, and ground users with navigation data and precise time signals at any moment and at any point on the Earth and the near-Earth space environment.

Since the beginning of system development, the Academician M. F. Reshetnev's State Unitary Enterprise of Applied Mechanics (NPO PM) has been the main system contractor. NPO PM is responsible for the GLONASS system's general development and implementation; development and manufacturing of the navigation satellite and facilities for launch preparation; and development of its automated control system.

The main subcontractors are the Russian Scientific-Research Institute of Space Industry (RNII KP) and the Russian Institute of Radionavigation and Time (RIRV). RNII KP is responsible for development of satellite radio equipment; monitoring and control subsystems; and receivers for nautical and space users. RIRV deals with development of precise satellite and ground frequency standards, as well as means for their synchronization, and receivers for air and ground users.

The GLONASS system is composed of four main elements (see Figure 1):

● orbital constellation of GLONASS satellites
● Ground Control Segment
● rocket-space complex
● users.

The orbital constellation of the fully deployed system is composed of 24 GLONASS satellites orbiting in three orbital planes. The operational orbit parameters are:

● altitude - 19100 km
● inclination - 64.8 degrees
● period - 11 hours 15 minutes.

Orbital planes are spaced at 120 degrees in longitude. There are eight satellites in each plane, which are evenly spaced at 45 degrees in phase. Moreover, the planes themselves are phase-shifted 15 degrees with respect to each other. Such an orbital configuration enables continuous and global coverage of the Earth's surface and near-Earth airspace, as well as an optimal spatial location of the satellites that increases position determination accuracy.

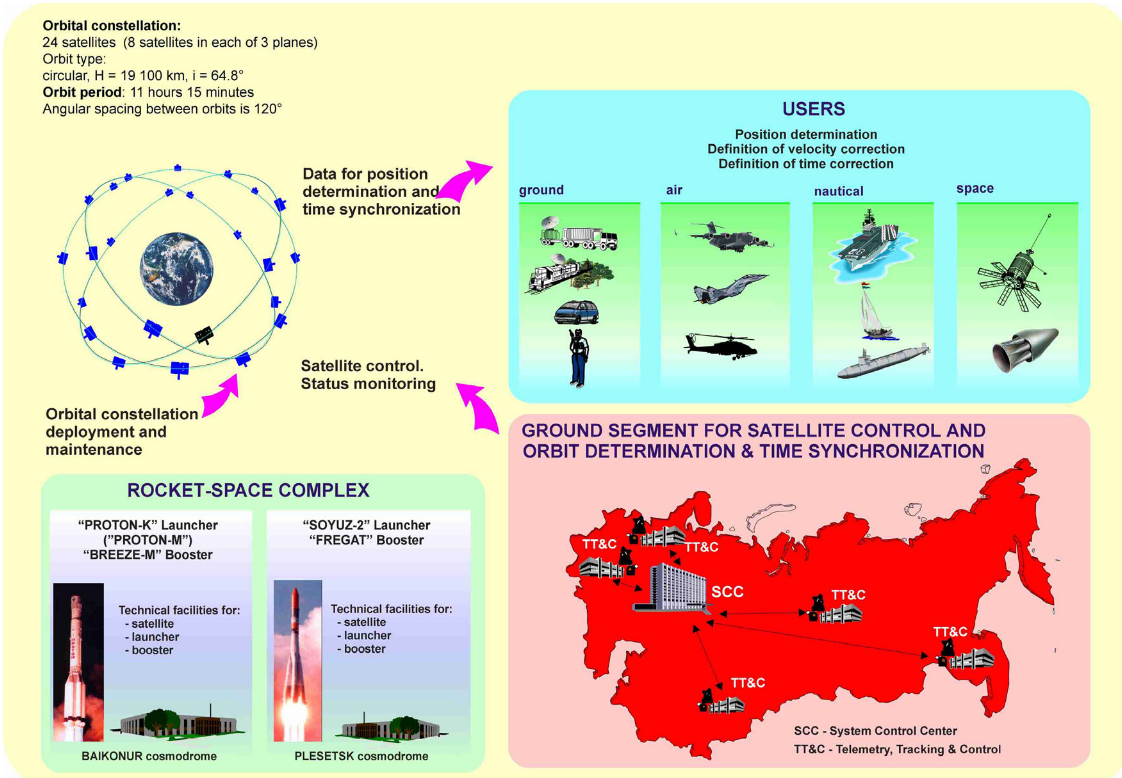

Figure 1. GLONASS system architecture.

The Ground Control Segment provides GLONASS satellite control. It is composed of the System Control Center (SCC), located in Moscow Territory, and several Telemetry, Tracking, and Control stations (TT&C) distributed throughout the Russian territory. GCS performs the following tasks:

- monitoring of the orbital constellation's normal operation
- continuous adjustment of satellite orbit parameters
- generation and uploading of time-tagged programs, control commands, and special information.

For normal operation of the navigation satellite system, it is very important to synchronize all the processes taking place during system operation. That is to say, these processes shall take place on the single time scale. To satisfy this requirement, the Synchronization System contains a Central Synchronizer – a stationary ultra-stable hydrogen frequency standard, which is used as the basis for GLONASS time scale generation. All onboard time scales are synchronized with the system time scale. The Central Synchronizer is synchronized with the State Time and Frequency Reference, located in C. Mendeleev (Moscow Territory).

Deployment and maintenance of the orbital constellation is provided by two rocket-space systems: one based on the "Proton" launcher and one based on the "Soyuz" launcher. Each rocket-space system includes:

- a launcher system
- a booster system
- a satellite system.

GLONASS HISTORY

Phase 1 (1983 – 1985):
Experimental tests. System concept refinement. Orbital constellation of 4 - 6 satellites.
Phase 2 (1986 – 1993):
Orbital constellation of 12 satellites. Flight test completion. Initial system operation.
Phase 3 (1993 –1995):
Deployment of nominal orbital constellation of 24 satellites. System operation.

In March 1995, the Russian Federation Government Resolution offered NSS GLONASS for civil use by International Organizations (ICAO, IMO) for a long period. Between 1996 and 1998, due to the lack of funding, the GLONASS orbital constellation was not maintained. As a result, the number of operational satellites significantly declined, even with an increased lifetime (from 3 to 4.5 years).

Nowadays there are seven GLONASS operational satellites in orbit; three other satellites have been successfully launched and are being commissioned.

Acknowledging that navigation satellite system GLONASS is the national property of Russia, in 2001 several directive documents were approved by the Russian President and Government aimed at unconditional maintenance and development of the GLONASS system. One of them is the Federal Dedicated (Mission-Oriented) Program "Global Navigation System."

FEDERAL DEDICATED PROGRAM "GLOBAL NAVIGATION SYSTEM"

Approved by the Government of the Russian Federation in 20 August 2001 (Government Decision N 587), the program's duration is from 2002 to 2011. The main goals of the program are:

- successive development and effective use of GLONASS, applying advanced SatNav technology to provide State social and economy development and State security
- saving the leading role for Russia in SatNav by guaranteed service provision for Russian and international users.

The main program tasks are:

- development and implementation of Space Segment and Ground Control infrastructure for GNSS
- GLONASS constellation maintenance at the required level
- GLONASS geodetic system improvement
- fulfillment of International commitments of Russia in the field of satellite navigation, development of international cooperation, and participation in international projects
- development and manufacturing of competitive user equipment to be provided for the Russian and international markets
- creation of new geodesy network structure implementing a highly accurate geocentric reference coordinate system
- creation and development of a scientific, technical, and technological basis for further SatNav development.

Program State customers are:

- Russian Aviation and Space Agency (Rosaviakosmos) – Program Coordinator
- Ministry of Defense of Russian Federation (MoD) – Coordinator of program tasks for Russian Federation defense and security
- Ministry of Industry, Science, and Technology of the Russian Federation (MoIST)
- Ministry of Transport of the Russian Federation (MoT)
- Russian Agency of Control Systems (RACS)

● Russian Federal Mapping Service (Roskartographia).

The content of the Federal program "Global Navigation System" is:

● Subprogram 1. Provision of GLONASS operation and development. State customers: Rosaviacosmos, MoD.
● Subprogram 2. Development, industry preparation, and manufacture of user equipment for civil users. State customer: RACS.
● Subprogram 3. Implementation and use of SatNav for transportion. State customer: MoT.
● Subprogram 4. Use of SatNav for geodetic provision of Russia. State customer: Roskartographia.

Subprogram 1. Provision of GLONASS operation and development. State customers: Rosaviacosmos, MoD:

- GLONASS system development. GLONASS S/C modernization (GLONASS-M). New GLONASS S/C development (GLONASS-K) with advanced performance
- GLONASS Ground Segment modernization and development
- System research and development to provide GLONASS advanced performance
- Research and development of GLONASS use for international cooperation
- GLONASS operation provision (serial product orders).

The Space Segment creation and maintenance program consists of three phases:

Phase 1. Maintenance of the orbital constellation at minimum required level by GLONASS satellite launches.
Phase 2. Development of the GLONASS-M satellite with increased lifetime and enhanced performance and deployment of the orbital constellation, consisting of 18 GLONASS-M/GLONASS satellites.
Phase 3. Development of the small-class GLONASS-K satellite with increased and enhanced Performance and deployment of the orbital constellation, consisting of 24 GLONASS-K/GLONASS-M satellites, followed by exploitation of the system by domestic and foreign users.

The GLONASS-M satellite, being created during Phase 1 of GNSS GLONASS modernization, has the following distinctive features compared to the GLONASS satellite that is operated nowadays:

a) Modernized navigation signal

● The frequency band is shifted to the left: L1 = (1598.0625 – 1605.375) ± 5,11 MHz, L2 = (1242.9375 – 1248.625) ± 5,11 MHz
● Output power is doubled on the frequency L2
● Previously reserved bytes are used for additional information, such as:

- Divergence of GPS and GLONASS time scales
- Navigation frame authenticity (validity) flag (transmitted every 4 seconds)
- Indication of expected second correction of UTC (SU) time scale (8 weeks prior to correction);
- Navigation data age.

● Filters are installed that reduce out-of-band emission in (1610.6 – 1613.8) MHz and (1660.0 – 1670.0) MHz frequency ranges down to the level specified in Recommendation 769 of the International Consulting Radio Committee
● On both frequencies L1 and L2, civil and special signals are transmitted that contain digital data and ranging codes for pseudorange measurements

b) the stability of navigation signal was increased to $1 \cdot 10^{-13}$, thanks to precise temperature stabilization of the Cs clocks
c) navigation accuracy was doubled

d) satellite lifetime was increased to 7 years
e) onboard reserves were envisaged (up to 50 kg of mass reserve; up to 350 watts of power reserve; data interface reserve) to enable accommodation of additional payload.

The GLONASS-M satellite can be launched in tandem (three satellites simultaneously from the Baykonour Cosmodrome using a Proton-M launcher with a Breeze-M booster) and in a single launch (from the Plesetsk Cosmodrome using a Soyuz-2 launcher with a Fregat booster).

Figure 2. GLONASS-M satellite overall view.

The GLONASS-K satellite to be developed during Phase 3 of the GNSS GLONASS modernization has the following distinctive features compared to GLONASS-M satellite:

a) a third frequency is introduced in the L-band to improve reliability and accuracy of user navigation solutions;
b) the satellite lifetime is increased to 10 years;
c) satellite mass is reduced to half
d) due to onboard reserves available, additional payload is accommodated, including Search and Rescue payload.

The GLONASS-K satellite can be launched according to one of the following tandem launch schemes:

- six satellites simultaneously from the Baykonour Cosmodrome using a Proton-M launcher with a Breeze-M Booster
- two satellites simultaneously from Plesetsk Cosmodrome using a Soyuz-2 launcher with a Freget booster.

Significant progress in improving the GLONASS system's operational performance is in many respects due to improvement of the time synchronization performance. The GLONASS Synchronization Subsystem includes the following elements:

● satellite onboard clocks, providing generation and maintenance of onboard time scale and reference frequency and time signals
● the Central Synchronizer (CS), providing generation and maintenance of the CS time scale
● Synchronization equipment (SA), providing measurements for definition of divergence of the CS

time scale with respect to the State Time and Frequency Reference
- Ground software and onboard software to resolve time synchronization tasks using computing hardware of the SCC and onboard computer.

Figure 3. GLONASS-K satellite overall view.

The Time Synchronization Subsystem is intended for:

- Mutual synchronization of satellite navigation signal phases using both ground facilities measurements and inter-satellite measurements;
- Generation and maintenance of system time scale (STS)
- Generation and maintenance of onboard time scale (OTS)
- Determination of the divergence of system time scale with respect to the State Time and Frequency Reference and generation of corrections
- Determination of the divergence of the GLONASS system time scale with respect to the GPS system's time scale and generation of corrections
- Generation of corrections for the divergence of the time scale of the State Time and Frequency Reference with respect to Universal Time UT1
- Provision of synchronous operation of all GNSS facilities to control satellite flight and to solve other tasks.

Precision quartz oscillators are used as the basis in the loop of onboard and ground clocks.

PRECISION QUARTZ OSCILLATORS FOR SPACE AND TERRESTRIAL TIME

When creating the basic model of a precision quartz oscillator for the GLONASS system, it is necessary to satisfy a strict, discrepant, and therefore hard-to-realize combination of requirements:

- high frequency stability (before all, short-term) and low phase noise (before all, close to the carrier)
- extremely low power consumption
- compact size and small weight
- fast warm-up after switch-on
- stableness in the severe environmental factors
- high reliability.

This combination of requirements was efficiently realized on the basis of a modified internally heated quartz resonator (IHQR) having an SC-Cut crystal orientation and vacuum insulation of the temperature-controlled part of the crystal holder.

FREQUENCY STANDARDS AND SYNCHRONIZATION EQUIPMENT

Prospects for GNSS GLONASS Synchronization System development are:

- Improvement of onboard frequency standard performance to a frequency stability of $1 \cdot 10^{-13}$/day
- Improvement of Central Synchronizer performances to a frequency stability of $1 \cdot 10^{-15}$/day
- Improvement of synchronization equipment performance
- Determination of the divergence of the Central Synchronizer time scale with respect to UTC (US) with an accuracy better than 5 ns
- Improvement of the Synchronization System reliability and operational performance due to the following:

1. Introduction of a new Central Synchronizer
2. Creation of new measurement facilities: a one-way measurement-processing system and an uploading-measurement station
3. Implementation of inter-satellite measurements.

Implementation of the Federal Dedicated Program will enable:

- subsequent development and effective use of GLONASS, applying advanced SatNav technology to provide State social and economy development and State security
- saving the leading role of Russia in SatNav by guaranteed service provision for Russian and international users.

Table 1. Evolution of GLONASS system performance, reflecting the phases of the Federal Dedicated (Mission-Oriented) Program "Global Navigation System."

	Glonass	Glonass-M	Glonass-K	Glonass-KM
First launch		2003	2005	After 2011
Lifetime	3 years	7 years	10—12 years	improved
Mass	1415 kg	1415 kg	750 kg	(TBD)
Number of satellites per launch: - PROTON - SOYUZ	 3 -	 3 1	 6 2	 6 (TBC) 2 (TBC)
Elec. Power Subsys. output power	1000 W	1600 W	1270 W (TBC)	TBD
Vertical real time navigation accuracy (95%)	60 м	30 м	5-8 м (TBC) (40 – 60 cm, using global differential system)	TBD
Number of civil signals	1	2	3 (TBC)	3 (TBC)
Number of special signals	2	2	3 (TBC)	TBD
On-board clocks stability	$5 \bullet 10^{-13}$	$1 \bullet 10^{-13}$	$1 \bullet 10^{-13}$	TBD
Root-mean-square error of mutual synchronization of navigation signals	15 ns	8 ns	3-4 ns	TBD
Supplementary functions	-	-	Integrity signal (TBC) Different. corrections (TBC) Search&Rescue (TBC)	TBD

TBC - To Be Confirmed TBD - To Be Defined

QUESTIONS AND ANSWERS

JUDAH LEVINE (National Institute of Standards and Technology): There might be some advantage to the timing community if satellites on opposite ends of the orbit had the same PRN number. Is that being considered?

YAKOV VOROKHOVSKY: No, the existing system has no changes in this part.

SIGFRIDO LESCHIUTTA (Istituto Elettrotecnico Nazionale): Just one question. Do you also plan for the next satellite to have some of it along with the retro-reflectors?

VOROKHOVSKY: Three stages of reflectors. GLONASS is the first stage of deployment, GLONASS M is the next stage of deployment, GLONASS K is the third stage. It also belongs to the reflectors. That is three stages of modification.

DEMETRIOS MATSAKIS (U.S. Naval Observatory): Can you tell us how your system handles leap seconds?

[The authors did not understand the question.]

MARTIN BLOCH (Frequency Electronics, Incorporated): I was helpful in trying to get this team together over here, and I think it is the first time that we see the Russian exposure of the system. And I think that all it means at this time is that closer cooperation between all three navigational systems might really improve the accuracy. And I think this is just the beginning of a dialog that I hope we can encourage and pursue.

JAY OAKS (U.S. Naval Research Laboratory): Did I understand on the charts that all the clocks are cesiums?

VOROKHOVSKY: Yes, all of them are cesiums.

OAKS: At one time, I understood, in the past that there was a possibility of a hydrogen maser clock.

VOROKHOVSKY: GLONASS M has only cesiums on board. But on GLONASS K, you have rubidium and cesium.

We want to thank the organization committee for inviting us, and on behalf of the whole Russian team, I thank you very much. My partner and friend, Martin Bloch, pushed us strongly to organize this presentation. Otherwise, it would have never been done.