GLONASS

8. GLONASS

Sergey Revnivykh, Alexey Bolkunov, Alexander Serdyukov (deceased), Oliver Montenbruck

The Global'naya Navigatsionnaya Sputnikova Sistema (GLONASS) is a global navigation satellite system developed by the Russian Federation. Similar to its US counterpart, the NAVSTAR global positioning system (GPS), GLONASS provides dual-frequency L-band navigation signals for civil and military navigation. Initiated in the 1980s, the system first achieved its full operational capability in 1995. Following a temporary degradation, the nominal constellation of 24 satellites was ultimately reestablished in 2011 and the system has been in continued service since then. This chapter describes the architecture and operations of GLONASS and discusses its current performance. In addition, the planned evolution of the space and ground segment are outlined.

8.1 Overview

Next to GPS, GLONASS is the second fully operational and global navigation satellite system. This section outlines the history of GLONASS and describes its basic characteristics.

8.1.1 History and Evolution

GLONASS is the second-generation dual-use governmental global satellite navigation system of the Russian Federation. The predecessor of GLONASS – the low-altitude satellite navigation/communication system Tsyclon/Tsikada – became operational in 1976 [8.1, 2]. It was available for civil users as well. The system provided a positioning accuracy of 80–100 m with a delay of 1.5–2 h. The idea of using the Doppler radio-frequency shift of signals transmitted from the satellites for navigation implemented in Tsyclon/Tsikada was introduced by Prof. Shebshayevich from the Mozhaysky Military Space Academy in 1957.

GLONASS research and development started in the beginning of the 1970s and was based on the method of instant position determination using measurements of time differences between a navigation receiver and a group of satellites emitting navigation signals with synchronized time tags. The first test satellite of the GLONASS system (named Uragan, or Hurricane, at that time) was successfully launched on 12 October 1982. On 24 September 1993, the GLONASS system with initial operational capability of 12 satellites was commissioned for military service. GLONASS with full operational capability (24 satellites) was deployed in 1995.

Civil use of GLONASS for air safety was first offered in 1988, when details of the GLONASS system and signal were released to the International Organization for Air Safety (ICAO) [8.3]. In parallel to these activities, various Western researchers had already made efforts to identify key properties of the

GLONASS signals through high-gain antenna measurements and a systematic code search [8.4–6]. These enabled early developments of standalone-GLONASS and GPS/GLONASS receivers. In 1995, through the decree of the President of the Russian Federation, GLONASS received the status of a dual-use system available for civil users worldwide. A comprehensive interface control document (ICD) describing the open service signals and navigation message was first made available in the English language in 1998 and has been continuously maintained since then [8.7].

Due to a limited operational lifetime of the early generation of GLONASS satellites and an insufficient replenishment, the number of active satellites gradually decreased down to a minimum of seven active satellites in 2001 (Fig. 8.1) [8.2, 8]. Since 2002, GLONASS sustainment and evolution have been conducted in the framework of the long-term GLONASS Federal Program with a secured budget enabling significant step-by-step performance improvements. Within the following decade, regular launches and the extended lifetime of the new GLONASS-M satellites helped to gradually increase the number of operational satellites. The 24-satellite constellation (Fig. 8.2) required for a fully global service was ultimately re-established in 2011 with the launch of GLONASS-M No. 44.

On 17 May 2007, the decree of the President of the Russian Federation declared the GLONASS open service available to all national and international users without any limitations [8.9]. At the same time, it was demanded that GLONASS-based navigation equipment shall be used by federal authorities for the sake of national security [8.10]. The GLONASS system is thus considered a core element in the implementation of the National Navigation Policy. Its maintenance and modernization in the 2012–2020 time frame are pursued within the GLONASS Federal Program, which aims for a continued performance increase through improvements of both the ground and space system.

The value of GLONASS as a standalone or complementary system for geodesy and precise navigation was recognized early on by the scientific community [8.11] and promoted the buildup of global tracking networks with GLONASS-capable global navigation satellite system (GNSS) receivers. Within the International GLONASS Experiment (IGEX-98 [8.12]) precise orbit solutions were generated for the first time and transformation parameters between the various realizations of the terrestrial reference frame (PZ-90, WGS-84, etc.) could be established. This work was later continued in the International GLONASS Service (IGLOS) pilot project [8.13], which provided the starting point for high-precision GLONASS point positioning applications.

8.1.2 Constellation

The GLONASS space segment nominally consists of 24 operational satellites, evenly distributed over three orbital planes (Fig. 8.2). The nominal constellation parameters are summarized in Table 8.1.

For best coverage, GLONASS adopts a so-called Walker 24/3/1 constellation geometry, where the parameters $t/p/f$ specify the total number of satellites, the number of orbital planes and the phasing parameter [8.14]. The longitude of ascending node of each

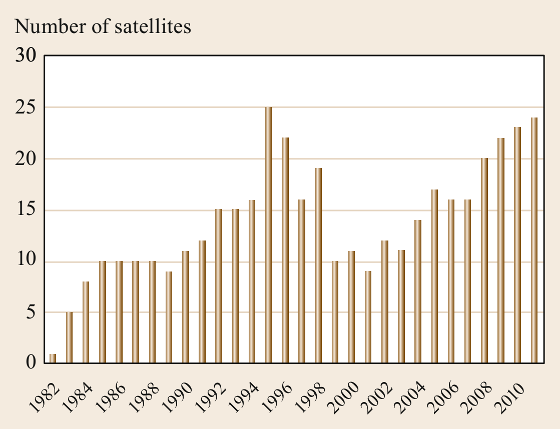

Fig. 8.1 GLONASS constellation development (after [8.8], courtesy of Springer)

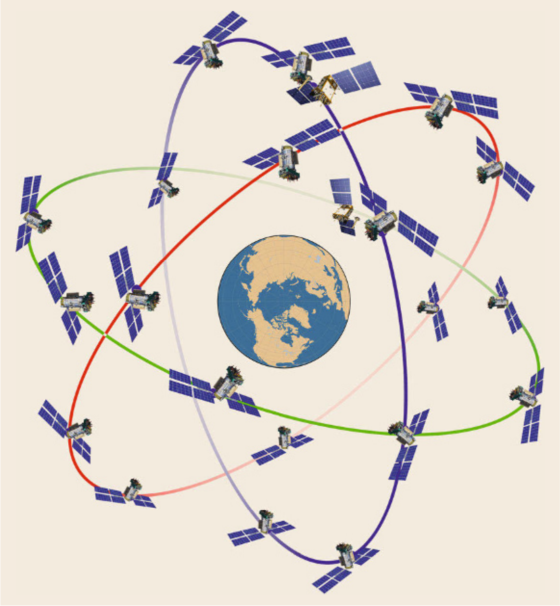

Fig. 8.2 GLONASS constellation in spring 2016 (courtesy of ISS Reshetnev)

Table 8.1 Nominal GLONASS constellation parameters

Parameter	Value
Number of operational satellites	$t = 24$
Number of orbital planes, p	$p = 3$
Number of satellites in a plane	$t/p = 8$
Phasing parameter	$f = 1$
Orbit type	Near circular
Eccentricity	$e < 0.01$
Inclination	$i = 64.8° \pm 0.3°$
Nominal altitude	$h = 19\,100\,\mathrm{km}$
Period of revolution	$T = 11\,\mathrm{h}\,15\,\mathrm{min}\,44\,\mathrm{s} \pm 5\,\mathrm{s}$
Longitude of ascending node between planes	$\Delta\Omega = 120°$
Argument of latitude difference	$\Delta u = 45°$
Latitude shift between planes	$\Delta u f/n = 15°$
Ground track repeat cycle	17 orbits/8 d

plane differs by $\Delta\Omega = 360°/p = 120°$ from plane to plane. There are $t/p = 8$ satellites per plane, separated by $360° p/t = 45°$ in argument of latitude. The difference in the argument of latitude of satellites in equivalent slots in two different orbital planes is $\Delta u = 360° f/t = 15°$.

Each GLONASS satellite is identified by its *slot* number, which defines the orbital plane and its location within the plane (Fig. 8.3). Slot numbers 1–8 belong to orbital plane 1, while planes 2 and 3 comprise slot numbers 9–16 and 17–24 respectively.

The GLONASS satellites have no resonance with rotation of the Earth (based on gravitational field harmonics). The satellite's period is selected so that satellites make 17 full orbits for eight equinoctial days (approximately eight constituent days). Furthermore, the beginning of each orbit shifts with respect to the Earth's surface. Each eight days a satellite passes over the same point on the Earth's surface. Due to shifting in orbital planes, all the satellites are moving relative to Earth's surface practically along the same ground tracks (Fig. 8.4).

The orbital inclination of the GLONASS satellites ($\approx 65°$) is roughly ten degrees higher than that of other medium altitude Earth orbit (MEO) navigation systems (GPS, BeiDou, Galileo), which provides improved visibility conditions over the area of the Russian Federation. Worldwide GLONASS users likewise benefit from a good sky coverage with a reduced visibility gap around the celestial pole (Fig. 3.8 of Chap. 3).

8.1.3 GLONASS Geodesy Reference PZ-90

The parameters and data of the Earth Model PZ-90 [8.15] are applied for GLONASS satellite orbit determination and ephemeris calculation. The PZ-90 system was established in 1990 and superseded the Soviet Geodetic System (SGS-85) that was used by GLONASS until 1993 [8.16].

The PZ-90 definition comprises fundamental geodetic constants, parameters of the Earth ellipsoid, and the Earth gravity field parameters (Table 8.2) as well as the geocentric reference system (GRS), which is defined in accord with common conventions of the International Earth Rotation and Reference Systems Service (IERS) and Bureau International De l'Heure (BIH). The PZ-90 system originates in the Earth's center of mass including the oceans and atmosphere. Its z-axis is directed to the conventional reference pole and its x-axis points to the intersection of the equatorial plane and the zero meridian as defined by the BIH [8.17, 18].

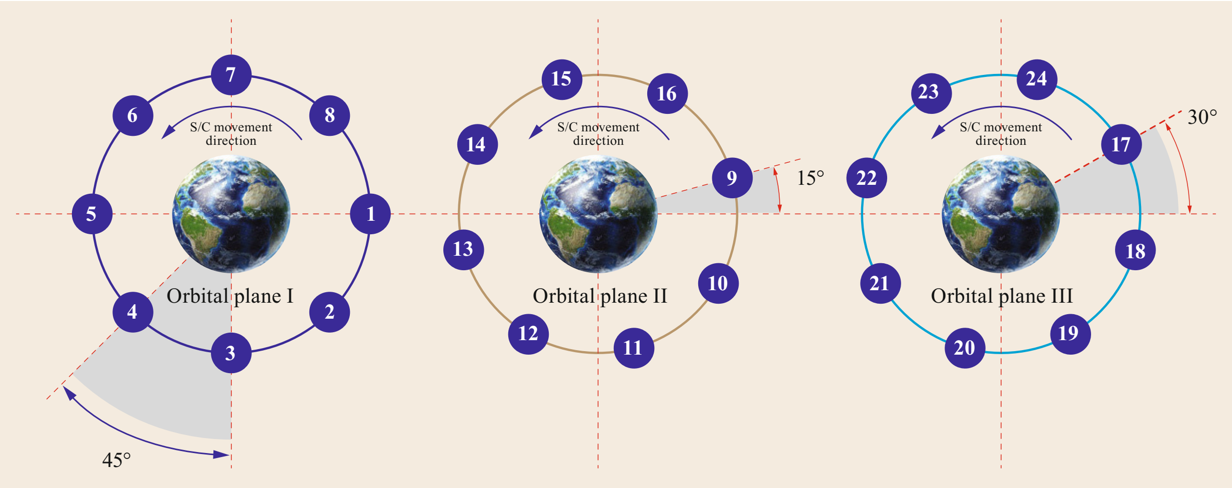

Fig. 8.3 GLONASS satellite positions within orbital planes (courtesy of ISS Reshetnev)

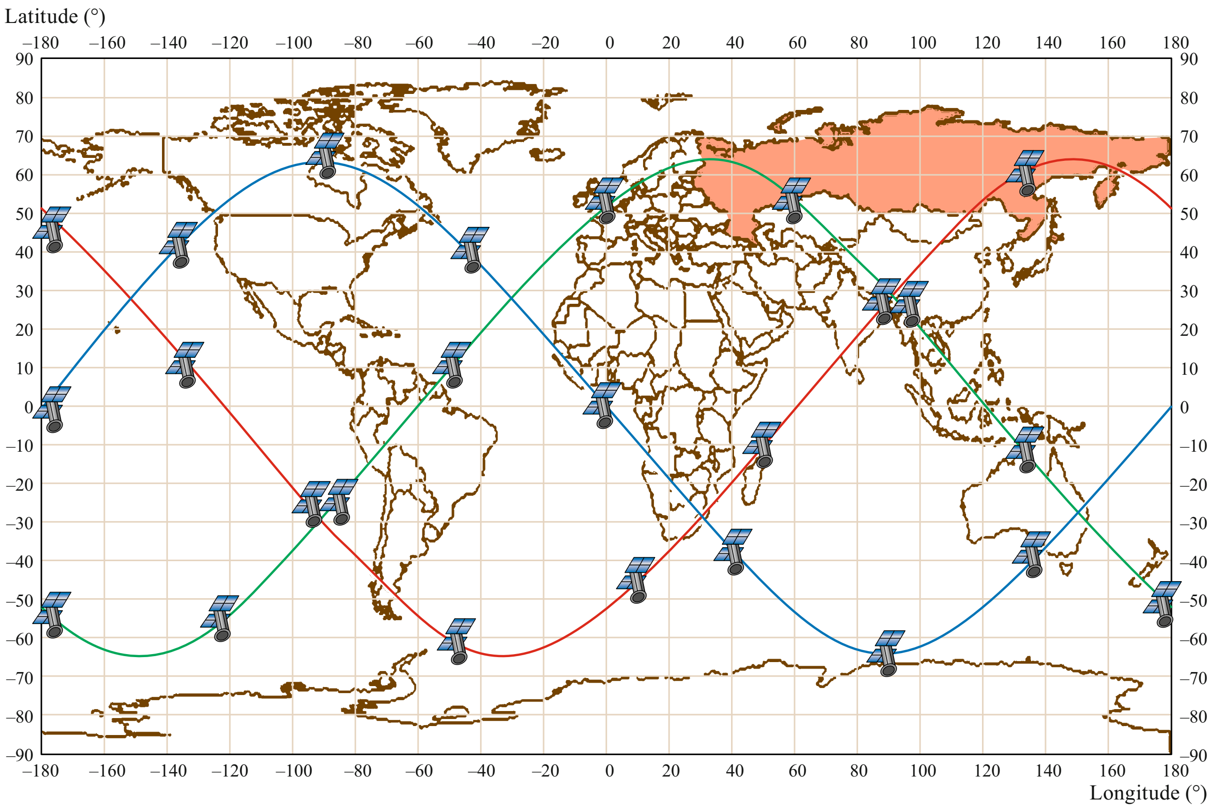

Fig. 8.4 GLONASS satellite ground tracks

Table 8.2 Fundamental parameters of the Earth model PZ-90 (after [8.15])

Parameter	Value
Speed of light in vacuum	$c = 299\,792\,458\,\mathrm{m/s}$
Gravitational constant	$G = 6.67259 \cdot 10^{-11}\,\mathrm{m^3/(kg\,s^2)}$
Geocentric gravitational coefficient (including atmosphere)	$GM_\oplus = 398\,600.4418 \cdot 10^9\,\mathrm{m^3/s^2}$
Angular velocity	$\omega_\oplus = 7.292115 \cdot 10^{-5}\,\mathrm{rad/s}$
Semimajor axis	$a = 6\,378\,136.0\,\mathrm{m}$
Flattening	$f = 1/298.257\,84$

The initial realization of the PZ-90 system had an accuracy of about 1–2 m. In the late 1990s, various efforts were made to establish the transformation between PZ-90 and the WGS-84 frame of GPS based on the joint processing of GPS/GLONASS observations in global networks and the comparison of postprocessed and broadcast GLONASS orbits [8.19–21].

The first major revision of the PZ-90 frame realization refers to the year 2002 and is known as PZ-90.02. It was introduced in GLONASS operations on 20 September 2007 [8.22] and notably improved the consistency of broadcast orbits with WGS-84 and the ITRF.

A further update, PZ-90.11 [8.15, 18] was implemented in the GLONASS operations on 31 December 2013 at 3:00 p.m. The PZ-90.11 GRS is a practical realization of the International Terrestrial Reference System (ITRS) at epoch 2010.0, which is based on the results of GPS/GLONASS data processing from space geodetic network (SGN) sites and a number of International GNSS Service (IGS) sites (Fig. 8.5). The accuracy (root mean square, RMS) of the PZ-90.11 GRS with respect to the Earth center is 0.05 m with relative accuracy of the reference point position on the level of 0.001–0.005 m.

The transition between different frames is commonly described by a seven-parameter similarity transformation (*Helmert* transformation)

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\mathrm{B}} = \begin{pmatrix} 1+m & +\omega_z & -\omega_y \\ -\omega_z & 1+m & +\omega_x \\ +\omega_y & -\omega_x & 1+m \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\mathrm{A}} + \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix} \tag{8.1}$$

for the coordinates $\boldsymbol{r}_{\mathrm{A}} = (x, y, z)_{\mathrm{A}}^{\top}$ and $\boldsymbol{r}_{\mathrm{B}} = (x, y, z)_{\mathrm{B}}^{\top}$ in the original (A) and transformed (B) system, where

Fig. 8.5 PZ-90.11 reference points on the Russian territory (as of 2011)

Table 8.3 PZ-90 transformation parameters

From	To	ΔX (m)	ΔY (m)	ΔZ (m)	ω_x ($10^{-3}{''}$)	ω_y ($10^{-3}{''}$)	ω_z ($10^{-3}{''}$)	m (10^{-6})	Epoch	Reference
PZ-90	WGS-84	−1.10	−0.30	−0.90	0	0	−200	−0.12	1990.0	[8.17, 23]
PZ-90	ITRF-97	+0.07	+0.00	−0.77	−19	−4	+353	−0.003		[8.21]
PZ-90	PZ-90.02	−1.07	−0.03	+0.02	0	0	−130	−0.22	2002.0	[8.17, 23]
PZ-90.02	WGS-84(1150)/ ITRF-2000	−0.36	+0.08	+0.18	0	0	0	0	2002.0	[8.17, 23]
PZ-90.11	ITRF-2008	−0.003	−0.001	+0.000	+0.019	−0.042	+0.002	−0.000	2010.0	[8.18]

$\Delta \boldsymbol{r}_B = (\Delta x, \Delta y, \Delta z)^\top$ is the translational offset, $\boldsymbol{\omega} = (\omega_x, \omega_y, \omega_z)^\top$ describes the rotational transformation and m denotes the scale difference. Transformation parameters for past and current realizations of the PZ-90, WGS84, and the International Terrestrial Reference Frame (ITRFs) are summarized in Table 8.3.

8.1.4 GLONASS Time

GLONASS System Time (GLST) provides the common reference to which all GLONASS satellite clocks are synchronized. It is based on observations of an ensemble of continuously operating hydrogen masers in the GLONASS ground segment and synchronized to Universal Time Coordinated of Russia, UTC(SU) as a reference timescale. UTC(SU) is itself maintained by the National Metrology Institute of the Russian Federation (VNIIFTRI) [8.24] in Mendeleevo near Moscow as part of the State Time and Frequency Service (STFS). It is realized through an ensemble of hydrogen masers and continuously steered to Coordinated Universal Time (UTC) through satellite time and frequency transfer techniques [8.25]. Differences of UTC and UTC(SU) are routinely monitored by the Bureau International des Poids et Mesures (BIPM) and have decreased from a few tens of ns in 2011 [8.26] to less than 2 ns in 2016.

The comparison of the national timescale, GLST, and UTC is accomplished through common-view GNSS time transfer (using either GPS or GLONASS satellites; Chap. 41) and two-way time and frequency transfer via geostationary satellites (Fig. 8.6).

Unlike GPS time, the GLONASS System Time exhibits no integer offset from UTC, but is offset by 3 h to match the local time zone of Moscow as adopted by the GLONASS ground control segment

$$\text{GLST} = \text{UTC(SU)} + 3\,\text{h} - C\,. \tag{8.2}$$

The fractional difference C is controlled to be less than 1 µs [8.7]. A predicted value thereof, the GLONASS

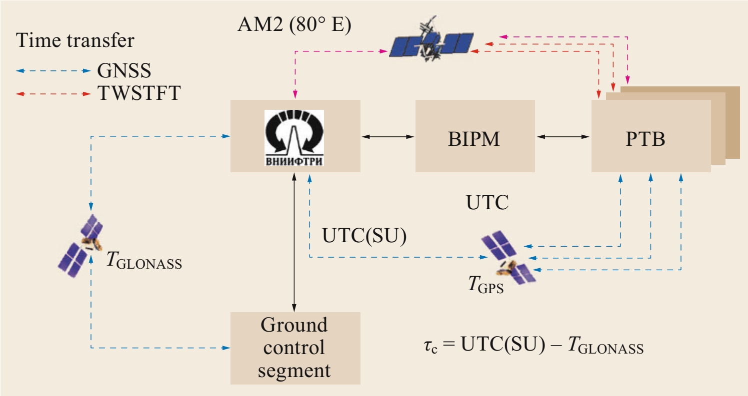

Fig. 8.6 Generation and monitoring of UTC(SU) and GLONASS system time (GLST) (after [8.27])

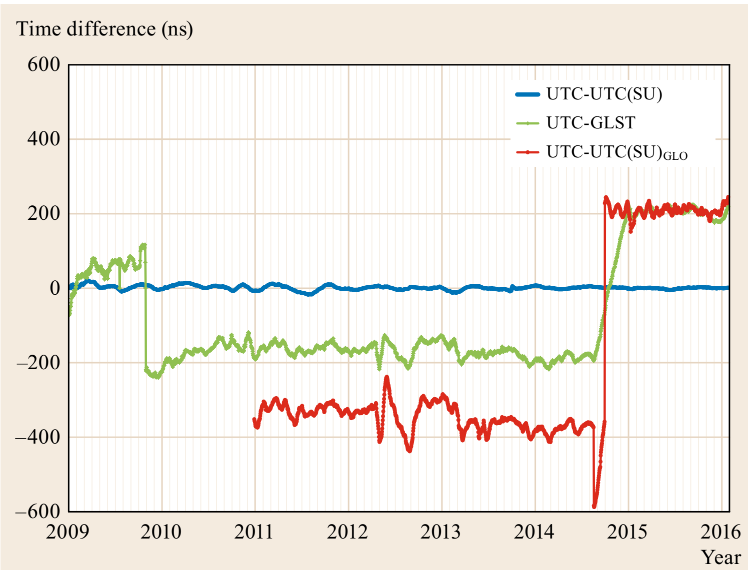

Fig. 8.7 Difference of UTC with respect to UTC(SU) (*blue*), GLONASS System Time (*green*) and the prediction of UTC(SU) as broadcast by the GLONASS satellites. Illustration based on data provided by the BIPM [8.26]

time correction parameter τ_c, is broadcast as part of the navigation message to provide users with direct access to UTC(SU).

Integer second corrections of the GLST by ± 1 s are performed simultaneously with those of UTC. These UTC corrections are conducted by the Bureau International de l'Heure following the recommendation of the International Earth Rotation and Reference Systems Service (IERS). They are required whenever the UT1-UTC difference grows beyond 0.9 s and normally carried out at the turn of one of the quarters (i. e., at 00:00:00 on 1 January, 1 April, 1 July, or 1 October) of a calendar year.

The GLONASS time synchronization system of the ground control segment generates the system timescale, calculates frequency and time corrections, determines the difference between the system timescale and UTC(SU), and calculates corrections between onboard timescales and the system timescale. The frequency and time corrections are calculated for each orbit and uploaded on board the satellites for transmission to the users. The frequency and time corrections are two parameters of the linear approximation of the onboard timescale offset relative to the system timescale.

Within the frequency and timekeeping facility of the GLONASS *central synchronizer* (CS), the frequencies and phases of four hydrogen frequency standards are continuously compared and the best clock is used as primary standard. The resulting 5 MHz signal exhibits a frequency error of less than $3 \cdot 10^{-14}$ and a stability of better than $2 \cdot 10^{-15}$ over one day. For redundancy purposes, an independent master and backup CS system are operated at Schelkovo (near Moscow) and Komsomolsk, respectively. Monitoring of the CS time with respect to UTC(SU) is performed through common-view time transfer between the CS and STFS. Depending on the employed equipment and signals (GPS or GLONASS), a monitoring precision of 3–13 ns is achieved.

The fractional differences between UTC and GLST as well as that of UTC and the prediction $UTC(SU)_{GLO}$ broadcast by the GLONASS satellites are routinely monitored by the BIPM and published as part of the monthly *Circular T*. The values presently demonstrate a stability of better than 10 ns, but are potentially affected by systematic offsets at the level of few hundreds of ns due to overall calibration uncertainties (Fig. 8.7). To improve the alignment of GLONASS System Time and the predicted UTC(SU), various adjustments have been performed starting on 18 August 2014. These included corrected offsets for the broadcast time parameters and a gradual tuning of the ground clocks [8.28]. As a result of the alignment, GLST and $UTC(SU)_{GLO}$ have exhibited a consistency of about 10 ns since early 2015.

8.2 Navigation Signals and Services

8.2.1 GLONASS Services

In accord with its dual-use status, GLONASS provides two types of services:

- An open service with unencrypted signals in up to three frequency bands (L1, L2, and recently L3) that is globally available for all users without any limitations
- A service for authorized users, using encrypted signals in presently two frequency bands (L1, L2).

The terminology of these services is not well defined, however, and alternative expressions such as *standard positioning service* and *high-precision service* are commonly used in the open literature.

Performance specifications for the two service types have not been released so far, but a GLONASS Open Service Performance Parameters Standard is under discussion within the International Committee on GNSS (ICG). Initial drafts suggest a performance specification of about 5 and 10 m, respectively for the 95% (2σ) global average position error in horizontal and vertical directions [8.29]. The option of an intentional accuracy degradation of the open service (similar to the *Selective Availability* employed by GPS up to the year 2000) has never been considered in the GLONASS system design.

The authorized service is primarily intended for military users [8.7]:

> *The PP [pinpoint accuracy] signal is modulated by a special code and intended for usage in interests of the Ministry of Defense. Usage of a PP signal should be agreed with the Russian Federation Defense Ministry.*

Unlike GPS, the signals of the authorized service are presently not encrypted. Even though their structure and data contents have not been publicly released by the system providers, the employed ranging code has, nevertheless, been revealed already in the early days of GLONASS through a systematic code search [8.5]. This has enabled the design of geodetic dual-frequency GLONASS receivers and allowed for an early use of GLONASS in precise point positioning applications. In accord with the above disclaimer, access to these signals may, however, be inhibited and its *unofficial* use should be considered with due care.

Each GLONASS satellite transmits signals for both the open and the authorized service. The L1/L2 signals for these two services are designated as standard-accuracy (ST) and high-precision (or pinpoint, PP) signals in the GLONASS ICD [8.7], to reflect the different performance of the employed ranging codes.

Traditionally, GLONASS makes use of frequency division multiply access (FDMA) modulation. Here, signals transmitted by individual satellites employ the same ranging code, but slightly different frequencies to allow concurrent processing in the receiver. With the first *GLONASS-K1* satellite launched in 2011, GLONASS started to transmit additional code division multiple access modulation (CDMA) signals on the new L3 signal. As part of the ongoing GLONASS modernization, CDMA signals will also be transmitted in the L1 and L2 bands to improve interoperability with other GNSSs, specifically GPS. An overview of current and planned signals is given in Table 8.4.

Table 8.4 GLONASS signals overview. Signals are identified by the frequency band (first two characters), the service type (O: open, S: authorized special), and the modulation type (F: FDMA, C: CDMA)

Satellites	FDMA		CDMA		
	L1	L2	L1	L2	L3
GLONASS	L1OF L1SF	L2SF			
GLONASS-M	L1OF L1SF	L2OF L2SF			(L3OC)
GLONASS-K1	L1OF L1SF	L2OF L2SF			L3OC
GLONASS-K2	L1OF L1SF	L2OF L2SF	L1OC L1SC	L2OC L2SC	L3OC

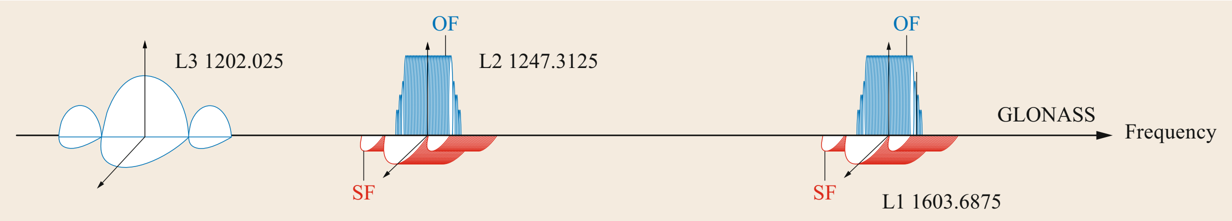

Fig. 8.8 GLONASS frequency division multiple access (FDMA) and code division multiple access (CDMA) signals in the L1, L2 and L3 band (status 2015)

The spectral distribution of currently transmitted signals in the L1, L2, and L3 bands is illustrated in Fig. 8.8. The L1 and L2 FDMA signals employ slightly higher ($\approx 20\,$MHz) frequencies than the corresponding GPS signals. The GLONASS L3 signal, in contrast, is transmitted at a widely different frequency ($f_{L3} = 1202.025\,$MHz) than the L3 frequency allocated to the GPS nuclear detection (NUDET) payload ($f_{L3} = 1381.05\,$MHz). In fact, the GLONASS L3 frequency closely matches the Galileo E5b frequency with only a small negative offset.

For the provision of positioning, navigation and timing services, the GLONASS signals include navigation messages with ephemeris data in the PZ90 reference system and timing parameters related to GLONASS System Time.

The open service signals as well as the contents of the navigation message are detailed in the public signal ICD [8.7], which presently covers the L1/L2 FDMA signals and will be updated with L3 and CDMA signals as soon as these become fully operational.

8.2.2 FDMA Signals

GLONASS has been transmitting FDMA signals since the first satellite was launched. Despite the ongoing system evolution and the introduction of new CDMA signals, GLONASS will continue to provide the legacy FDMA signals in the future to provide backward compatibility with the user equipment already in use.

FDMA signals are transmitted in the L1 and L2 bands and comprise the open service (standard-accuracy) and authorized service (high-precision) ranging codes (Table 8.5). In analogy with GPS, the two codes are commonly described as GLONASS C/A-code (coarse and acquisition code) and P-code (precise code) respectively, even though these terms are not mentioned in the ICD and do not represent an official designation.

The open service signal was only transmitted on the L1 frequency in the first generation of GLONASS satellites, but has been made available on both frequencies starting with the GLONASS-M series of spacecraft. Also, the L2 signal power, which was initially about 6 dB lower, has been adjusted to the same level as L1.

Signal Frequencies

GLONASS FDMA signals use a distinct set of *channels* for different signals. Each channel is identified by its channel number k, which uniquely defines the corresponding signal frequency

$$f_{L1}(k) = (1602.0 + k\,0.5625)\text{ MHz}\,,$$
$$f_{L2}(k) = (1246.0 + k\,0.4375)\text{ MHz}\,. \quad (8.3)$$

Table 8.5 Main characteristics of the legacy GLONASS FDMA signals. Parameters of the authorized service signals (L1SF, L2SF) that have not been publicly released are marked as N/A (not available)

Signal	Received power (dBW)	Center frequency (MHz)	Code and Data	Modulation	Bandwidth (MHz)	Data rate (bps)
L1OF	−161	1598.0625 ... 1605.375	C/A-code (511 chips, 1 ms) Open service navigation message	BPSK(0.5)	$\approx \pm 0.5$	50
L1SF	−161	same	P-code (5.11 MHz) Authorized service navigation message	N/A	$\approx \pm 5$	N/A
L2OF	−161	1242.9375 ... 1248.625	C/A-code (511 chips, 1 ms) Open service navigation message	BPSK(0.5)	$\approx \pm 0.5$	50
L2SF	−161	Same	P-code (5.11 MHz) Authorized service navigation message	N/A	$\approx \pm 5$	N/A

Neighboring channels are separated by $\Delta f \approx 0.5$ MHz, which roughly corresponds to the half-width of the open service signal spectral and is sufficient to distinguish transmissions from different satellites in the receiver. For a given channel number k, the ratio of the L1 and L2 frequencies attains a fixed value of

$$\frac{f_{L1}(k)}{f_{L2}(k)} = \frac{9}{7} . \tag{8.4}$$

In the original GLONASS design, use of a unique frequency channel number in the range of $k = 0, \ldots, 24$ (corresponding to an L1 frequency in the range of 1602.0–1615.5 MHz) was considered for each individual spacecraft in the 24-satellite constellation along with a spare channel for testing purposes [8.30].

The initial frequency allocation was later modified in compliance with recommendation RA 769 of the International Telecommunication Union (ITU) on protection criteria used for radio astronomical observations [8.31], when it became obvious that GLONASS L1 transmissions interfered with observations of the hydroxyl radical (OH) near 1612 MHz [8.32]. Starting in 1998, the frequency indices were restricted to $k = 0, \ldots, 12$ (yielding a maximum center frequency of 1608.75 MHz). In a second update, conducted in 2005, negative channel numbers were introduced and the covered range was changed to $k = -7, \ldots, +6$ [8.7] (including two channels commonly used for testing new satellites). In addition, the GLONASS satellites were equipped with bandpass filters to reduce transmissions in the frequency band relevant for radio astronomy. This can readily be seen from the L1 signal spectrum of the GLONASS satellites, which exhibits a sharp gap around 1612 MHz (Fig. 8.9).

The limitation of only 12–14 channels for 24 satellites is handled by assigning identical frequency channel numbers to antipodal satellites, that is satellites in opposite slots of the same orbital plane. Such satellites should never be jointly visible for a terrestrial observer and can therefore make use of the same signal frequency.

The use of different signal frequencies in the GLONASS FDMA signals enables use of a common ranging code for all satellites and offers protection against narrow-band interference compared to CDMA signals, since such interferences would only affect one or a few satellites at a time [8.33]. However, it also results in an increased complexity of the front-end design and is commonly a source of undesired group and phase delay variations in GLONASS receivers (Chap. 13). Nevertheless, the existing data processing methodology allows the detection of these delays at the user level providing precise point positioning computations.

Open Service Signal

The FDMA open service signal transmitted on the L1 and L2 frequencies employs a binary phase-shift keying (BPSK) modulation. The carrier is modulated with a binary sequence, which results from the modulo-2 addition (i. e., exclusive or combination) of three individual components:

- The pseudorandom noise (PRN) ranging code
- The navigation data
- An auxiliary meander sequence.

The ranging code has a length of 511 chips and is clocked at 511 MHz, thus yielding a total duration of 1 ms. Data bits are transmitted at a 50 Hz rate and have a length of 20 ms per data bit. The third component is a 100 Hz sequence of alternating 1 s and 0 s with a duration of 10 ms per symbol. It is termed a *meander* sequence or *Manchester code* and ensures that there is at least one transition in the modulo-2 sum of the meander and data sequence within each data bit interval. The

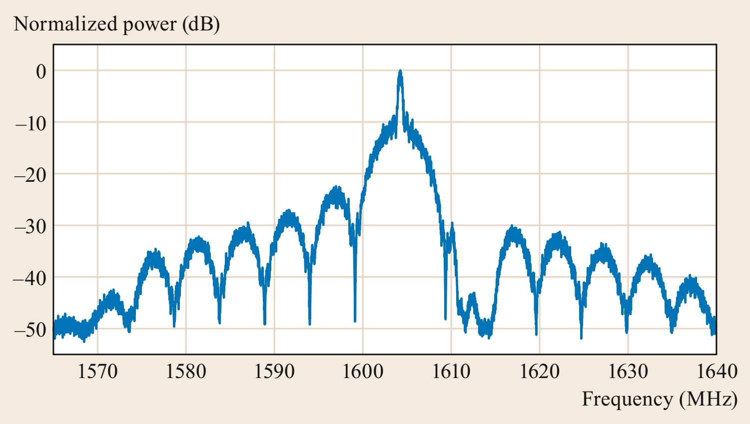

Fig. 8.9 Example of GLONASS L1 signal spectrum. The center frequency of 1604.25 MHz corresponds to a frequency channel number $k = +4$. The central peak results from the 511 kHz open service coarse and acquisition (C/A) code, while the wider lobes reflect the 5.11 MHz P-code modulation. Transmissions near 1612 MHz are masked by a bandpass filter to protect radio astronomical observations of hydroxyl (OH) emissions (courtesy of S. Thölert, Deutsches Zentrum für Luft- und Raumfahrt (DLR))

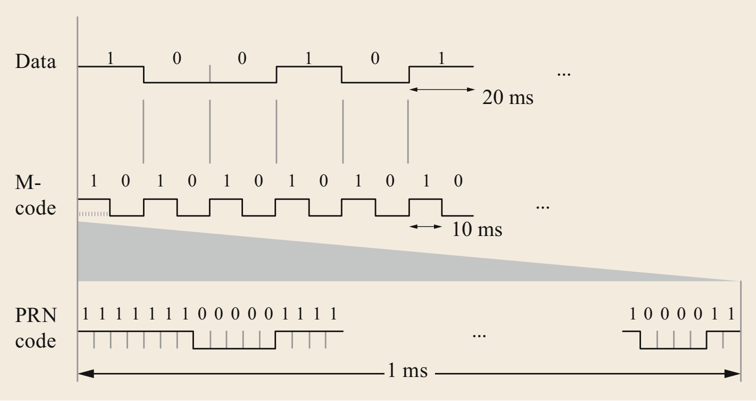

Fig. 8.10 Structure of the GLONASS open service signal

three signal components are synchronized to each other, that is there are 10 full ranging codes within a Manchester code symbol and 20 codes within a data bit. The overall signal structure is illustrated in Fig. 8.10.

The FDMA concept allows for use of a common PRN code by all GLONASS satellites and the same code is in fact also used on the two frequencies. Unlike the Gold codes of GPS, the GLONASS ranging code is obtained from just a single maximum-length linear feedback shift register (LFSR). Gold codes, in contrast, require a combination of two shift registers, from which a large family of PRN sequences with good cross-correlation properties can be constructed. This is important for use of CDMA signals in a GNSS constellation such as GPS, since distinct, high-quality PRN sequences are needed for the various spacecraft [8.34]. GLONASS, in contrast requires only a single ranging code and achieves a low cross-correlation between different satellites through the frequency separation of different transmission channels [8.33].

A more simple PRN code generator based on a 9 bit register can therefore be employed, which provides a maximum length pseudorandom sequence of 511 (= $2^9 - 1$) chips (Fig. 8.11). The register is initialized with all 1s and the PRN ranging code is extracted at the output of the seventh stage of the shift register (Fig. 8.11).

The chipping rate and duration of the GLONASS ranging code are directly reflected in the corresponding

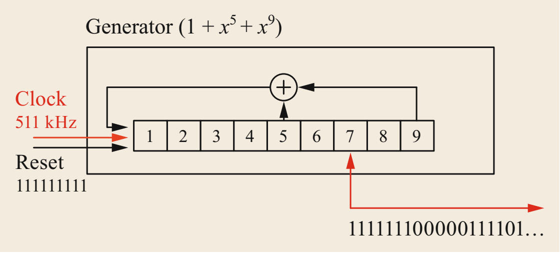

Fig. 8.11 GLONASS C/A-code generator

open service signal spectrum [8.4]. It exhibits an overall bandwidth of about 1 MHz with spectral nulls at multiples of 511 kHz relative to the center frequency and individual lines spaced at 1 kHz (i. e., the inverse of the code length). It may be noted that the bandwidth is larger than the spacing of individual frequency channels on both the L1 and L2 frequencies. This does not, however, inhibit a safe acquisition and tracking of the GLONASS signals, since the correlation bandwidth is substantially smaller (about 1 kHz for a 1 ms integration interval).

Authorized Service Signal

Both the L1 and L2 frequencies carry an additional authorized service signal, which is transmitted in phase quadrature to the open service signal. The authorized signal is intended for military use only, and its signal structure has never been publicly disclosed by official sources.

Nevertheless, it has been possible to reveal important properties already in the early days of GLONASS from inspection with a high-gain antenna and a systematic testing of different hypotheses on the code design. This work has mainly been conducted by the University of Leeds [8.4, 5, 35, 36] and forms the basis of today's understanding of the military signal and its implementation in geodetic receivers. Knowledge of the GLONASS P-code was of particular interest prior to the GLONASS-M satellite generation, since it provided access to the signal second frequency and thus enabled ionospheric correction of GLONASS observations in precise positioning applications. Also, the higher chipping rate offered a somewhat better noise and multipath performance [8.36] than the C/A-code. It must be kept in mind, though, that the P-code signal is not intended for public use and may change without prior notice.

Navigation Message Structure

GLONASS navigation messages for the FDMA open service use a fixed structure made up of individual *frames* and *strings*. The entire set of frames is designated a *superframe* and repeated at regular intervals (Table 8.6).

The structure of the FDMA open service navigation message is illustrated in Fig. 8.12 based on information in [8.7]. Each string is made up of 85 bit and a time mark. This time mark consists of 30 symbols (corresponding to a hexadecimal value of 0x3E375096 [8.36]) and serves as a postamble. At a bit length of 20 ms and a symbol length of 10 ms, the entire string is transmitted in $1.7\,\mathrm{s}+0.3\,\mathrm{s}=2\,\mathrm{s}$. The 85 bit comprise of a zero bit, the 4 bit string number, 72 bit of navigation data and 8 Hamming code parity bits offering single-error correction [8.36].

Strings 1–4 of each frame provide *immediate* (ephemeris) data of the transmitting satellite, which are required for the positioning and repeated once every 30 s. The remaining strings 4–15 contain subcommutated *nonimmediate* (almanac) data for up to five satellites. The remaining bytes in the fifth frame hold additional parameters for conversion from GLONASS System Time to UT1 as well as the announcement of leap-second adjustments.

The entire superframe is transmitted in 2.5 min and continuously repeated between ephemeris updates (nominally once every 30 min). The overall message structure is adapted to support the current 24-satellite constellations but leaves some spare bytes for adding additional information.

Unlike GPS, the GLONASS system does not make use of an orbital elements representation of the ephemeris data, but provides the state vector (position and velocity) along with corrections in the Earth-fixed PZ90 coordinate system at the given reference epoch. Based on this information, the trajectory in the vicinity of this epoch can be obtained by numerical integration of the equation of motion (Sect. 3.3.3). To simplify the complexity of the orbit model, only the dominating Earth oblateness term is explicitly considered. However, additional acceleration corrections accounting for the effect of lunisolar perturbations are provided as part of the navigation message for improved accuracy. The ephemeris data are typically updated at half-hourly intervals (i. e., at full and half hours) and are valid for ± 15 min around the reference epoch in the center of the interval. Satellite clock offsets of the satellite with respect to GLST are described through a linear clock polynomial, which directly yields the apparent clock with no need for application of a relativistic correction. Furthermore, the immediate data of the GLONASS navigation message comprise health information, GLST to UTC time conversion data and a timing group delay parameter for consideration of differential code biases in single-frequency positioning.

Table 8.6 Navigation data structure of open service GLONASS FDMA signals. HC and TM denote the 8 bytes of the Hamming error correction code and the 30 symbols of the time mark

Structure	Duration	Elements
Superframe	2.5 min	5 frames
Frame	30 s	15 strings
String	2 s	85 bit + timemark
Bit	0.02 s	–
Timemark	0.3 s	30 symbols
Symbol	0.01 s	–

The *nonimmediate* data of the FDMA open service navigation message provide timescale information (for GLST to UTC(SU) and GLST to GPS time conversion), which is repeated in string 5 of each frame as well as two strings of almanac data per satellite. Aside from orbital elements and a coarse clock offset value, the almanac includes health information as well as the slot and frequency channel number of the respective satellite.

Descriptions of the FDMA authorized navigation message as inferred from the analysis of transmitted P-code data in the late 1990s are provided in [8.35, 36].

It may be noted that the GLONASS FDMA navigation messages provide ephemeris, almanac and time system information but no ionospheric correction data for single-frequency users. For best positioning accuracy, an ionospheric compensation using dual-frequency L1/L2 observations is therefore recommended.

8.2.3 CDMA Signals

As part of the GLONASS signal evolution plan, new CDMA signals are made available to the users as a complement to the legacy FDMA signals. Key reasons for introducing CDMA signals include an improved navigation accuracy, an improved resistance to interference, and the improved separation of open and authorized services. The GLONASS signal evolution plan is based on a phased approach. A first CDMA signal in the L3 band has been made available since 2011 and further signals will be added with each new generation of GLONASS satellites. An initial assessment of GLONASS CDMA L3 ambiguity resolution and positioning performance is provided in [8.37].

Similar to FDMA signals, there are two types of GLONASS CDMA signals: open and encrypted, providing public and authorized services. The frequency allocations for L1 and L2 CDMA signals are defined within the original GLONASS frequency bands (Fig. 8.13), while L3 is a newly allocated frequency next to the Galileo E5b and BeiDou B2 band. In addition, the provision of modernized civil navigation signals (L1OCM, L5OCM) on the L1/E1 and L5/E5a

Frame	String	2.0 s			
		1.7 s			0.3 s
I	1	0	Immediate data for transmitting satellite	HC	TM
	2	0		HC	TM
	3	0		HC	TM
	4	0		HC	TM
	5	0	Non-immediate data (almanac) for five satellites	HC	TM
	…	..		…	…
	15	0		HC	TM
II	1	0	Immediate data for transmitting satellite	HC	TM
	2	0		HC	TM
	3	0		HC	TM
	4	0		HC	TM
	5	0	Non-immediate data (almanac) for five satellites	HC	TM
	…	..		…	…
	15	0		HC	TM
III	1	0	Immediate data for transmitting satellite	HC	TM
	2	0		HC	TM
	3	0		HC	TM
	4	0		HC	TM
	5	0	Non-immediate data (almanac) for five satellites	HC	TM
	…	..		…	…
	15	0		HC	TM
IV	1	0	Immediate data for transmitting satellite	HC	TM
	2	0		HC	TM
	3	0		HC	TM
	4	0		HC	TM
	5	0	Non-immediate data (almanac) for five satellites	HC	TM
	…	..		…	…
	15	0		HC	TM
V	1	0	Immediate data for transmitting satellite	HC	TM
	2	0		HC	TM
	3	0		HC	TM
	4	0		HC	TM
	5	0	Non-immediate data (almanac) for four satellites; time system; spare bytes	HC	TM
	…	..		…	…
	15	0		HC	TM
Bits		85	84…………………………….....9	8….…..1	

30 s (one frame); 5 x 30 s = 2.5 min (superframe)

Fig. 8.12 Navigation message superframe structure for FDMA open service signals

frequencies of the GPS and Galileo system are under study to achieve a maximum compatibility with these other constellations.

The main parameters of current and proposed GLONASS CDMA signals are presented in Table 8.7 [8.8, 38, 39]. The open service L1OC and L2OC signals are planned to provide time-multiplexed data and pilot components using BPSK(1) and BOC(1,1) modulations respectively [8.8]. The L1SC and L2SC authorized service signals, in contrast, will use BOC(5,2.5) modulation for both the pilot and data components and are transmitted in phase quadrature relative to the open signals. The BOC(5,2.5) modulation offers a good spectral separation of open and authorized signals, while simultaneously suppressing emissions in the radio astronomical frequency band around 1612 MHz [8.38].

A first CDMA signal, namely the L3OC open service signal, was introduced by the GLONASS-K1 satellite launched in 2011 and is also made available by the latest version of GLONASS-M satellites launched since 2014. While a formal ICD is pending, basic information on the signal structure has been publicly released in [8.38]. The signal comprises a data and

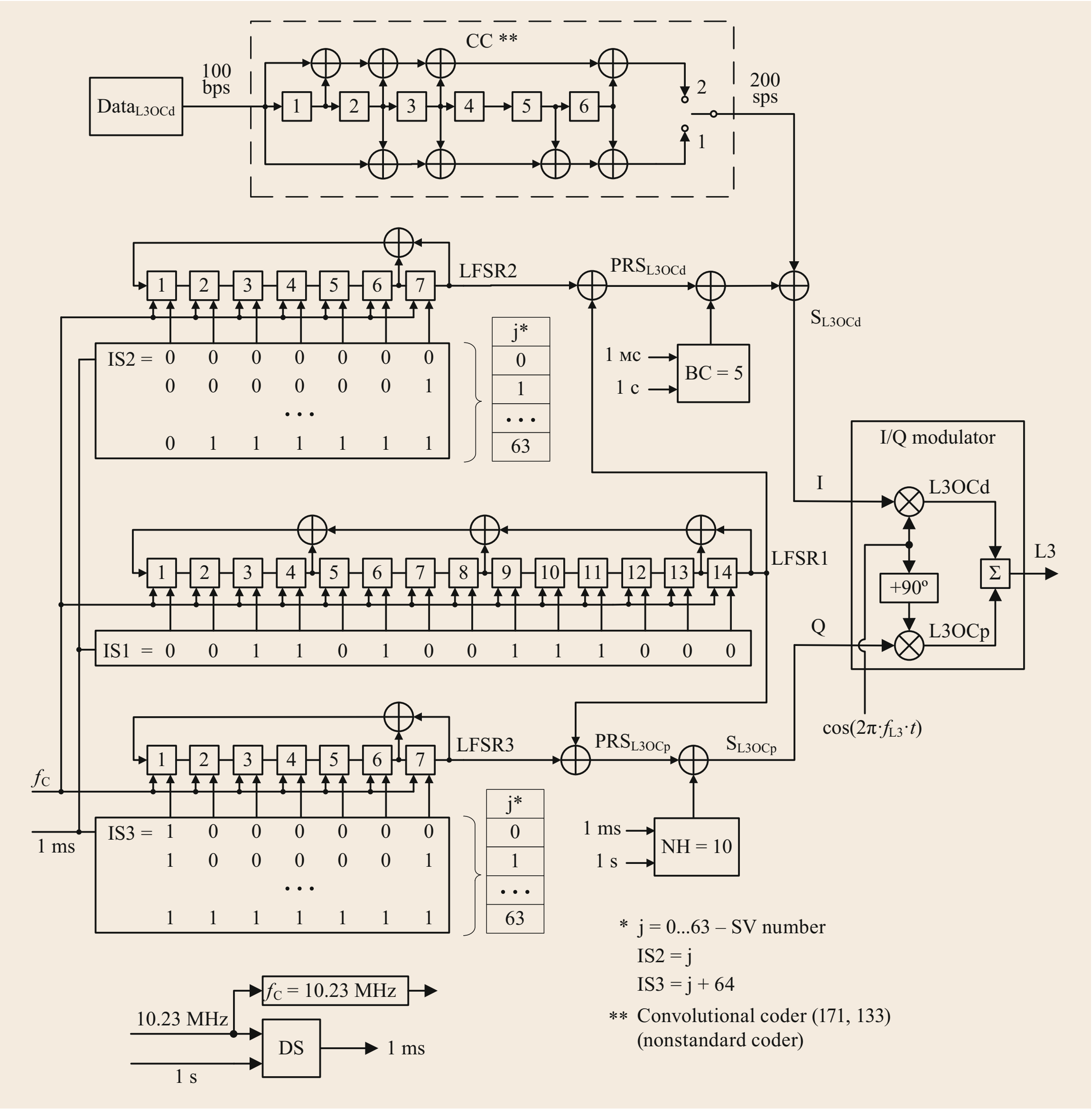

Fig. 8.14 GLONASS L3 open service CDMA signal generation (courtesy of Russian Space Systems Corporation)

a pilot component in phase quadrature using BPSK(10) modulation.

As illustrated in Fig. 8.14, the pseudorandom code for both components is generated from the modulo-2 addition of the outputs of a 14 bit shift register (IS2; with feedback taps 4, 8, 13, and 14) and a seven-stage shift register (IS1/IS3 for the pilot/data code; with feedback taps 6 and 7). While the initial state of the IS2 register is common to all spacecraft, satellite-dependent initial values are used for the IS1 and IS3 registers. The resulting PRN sequences are known as *Kasami* sequences [8.40] and exhibit a very low cross correlation for an entire family of individual codes [8.41]. The L3OC codes have a native length of $2^{14}-1 = 16\,383$ bit, but are truncated at 10 230 chips and achieve a cross correlation of −40 dB. At the employed chipping rate of 10.23 MHz, the primary code duration amounts to 1 ms.

Navigation data are modulated at a rate of 100 bps using a 1/2 convolutional encoding for error correction (yielding a symbol rate of 200 sps). In addition to the ranging code and the encoded navigation data, the data channel is modulated with a 5-bit Barker code at a rate of 1 kHz. The Barker code (BC) is synchronized with

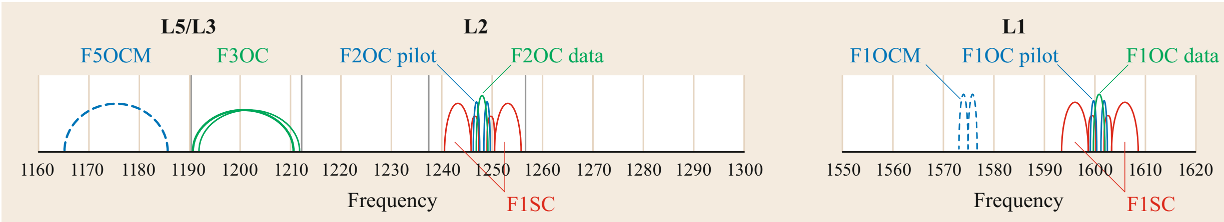

Fig. 8.13 GLONASS CDMA signal frequency allocations

Table 8.7 GLONASS CDMA signal parameters. Parameters of the authorized service signals that are not publicly disclosed are marked as N/A (not available). Parameters of signals currently under study are marked as TBD (to be defined)

Band	L5/L3		L2		L1		
Signal	**L5OCM**	**L3OC**	**L2SC**	**L2OC**	**L1OCM**	**L1SC**	**L1OC**
Access	Open	Open	Authorized	Open	Open	Authorized	Open
Carrier frequency (MHz)	1176.45	1202.025	1248.06		1575.42	1600.995	
Data signal modulation	BPSK(10)	BPSK(10)	BOC(5,2.5)	BPSK(1)	TBD	BOC(5,2.5)	BPSK(1)
Pilot signal modulation	BPSK(10)	BPSK(10)	BOC(5,2.5)	BOC(1,1)	TBD	BOC(5,2.5)	BOC(1,1)
Data rate (bps)	TBD	100	N/A	250	TBD	N/A	125
Navigation data (ms)	TBD	10	N/A	4	TBD	N/A	8
Chip rate rate (MHz)	10.23	10.23	N/A	0.5115	TBD	N/A	0.5115
Status	study	implementation			study	implementation	

the ranging sequence and covers the duration of a single navigation data symbol (i. e., 5 ms). For the pilot channel, a secondary (or Neuman–Hofman, NH) code with a length of 10 bit is employed. This yields an effective code length of 10 ms and offers increased robustness and weak-signal tracking capabilities. A detailed characterization of the L3OC signal as transmitted by the GLONASS-K1-1 satellite is provided in [8.42] based on analyses with a high-gain antenna and a software receiver.

Along with the advanced modulation scheme, the L3 CDMA signal also introduces a new navigation message concept. Unlike the fixed superframe structure of the FDMA navigation message, the L3OC signal uses a flexible message system [8.38, 39]. Similar to the CNAV (civil navigation) message of the GPS L2C and L5 signals, a set of distinct messages is defined, each of which provides a specific subset of navigation data. Each message is uniquely identified by its message number and carries a cyclic redundancy check (CRC) field for error protection. Information from different messages is combined at user level to obtain the full set of navigation data. Since unknown messages types are specified to be ignored by a receiver, the new scheme greatly facilitates the addition of new messages along with signal upgrades and service improvements. Among others, the new navigation message is not limited to a predetermined size of the constellation but can accommodate a variable number of satellites.

By way of example, the layout of the new L3OC almanac message is described in [8.43]. Each message has a length of 300 bit including a 20 bit time mark and a 24 bit CRC. A full description of all L3OC navigation messages will be provided as part of the GLONASS open service signal ICD.

8.3 Satellites

The constellation of GLONASS satellites is a key element of the entire GLONASS system. Throughout the more than 30 years of its history, three generations of GLONASS satellites have been built and operated:

- The initial generation of *GLONASS* satellites first launched in 1982
- The subsequent *GLONASS-M* satellites launched since 2003
- The *GLONASS-K* series introduced in 2011.

Each new generation of GLONASS satellites extended the satellite capabilities and improved the overall system performance. In parallel to technical improvements, the in-orbit lifetime was also continuously increased. Key characteristics of each satellite type are summarized in Table 8.8. All GLONASS satellites were developed by the Academician Reshetnev

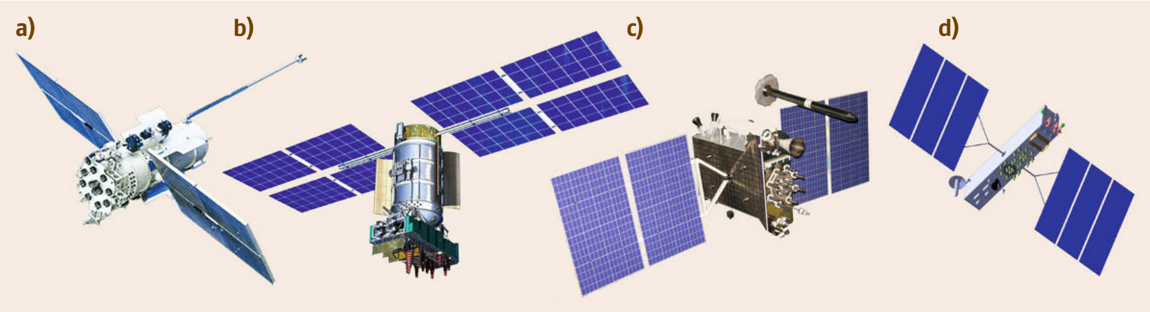

Fig. 8.15a–d The GLONASS satellites family: **(a)** *GLONASS IIv*, **(b)** *GLONASS-M*, **(c)** *GLONASS-K1* **(d)** *GLONASS-K2*. Artist's drawings (courtesy of ISS Reshetnev)

Research and Production Association of Applied Mechanics (NPO PM), which is now part of the joint stock company Information Satellite Systems (ISS)-Reshetnev Company.

While not part of the actual radionavigation system, it is worthwhile to note that the GLONASS constellation is complemented by two geodetic satellites named Etalon (measuring gauge). The ball-shaped satellites of 1.2 m diameter are completely passive and covered with corner cube reflectors for satellite laser ranging (SLR). The Etalon-1 and -2 satellites were launched in 1989 and injected into a typical GLONASS orbit along with two pairs of regular GLONASS navigation satellites. While initially used to study the orbital dynamics of satellites in medium altitude orbit, they still serve the international community today for fundamental studies of geodesy and dynamics of the Earth [8.44].

This section introduces the different spacecraft of the GLONASS family (Fig. 8.15) and describes their characteristic features and performances.

8.3.1 GLONASS I/II

The first generation of GLONASS navigation satellites (originally termed Uragan, the Russian word for hurricane) was developed in the late 1970s. Following [8.1], the GLONASS series comprises four subtypes, which are commonly designated as type (or block) I, IIa, IIb, and IIv (or IIc). A first type I satellite was launched in 1982 and the last IIv satellite was in use from 2005 to 2008.

The GLONASS spacecraft have a mass of roughly 1.4 t (including propellant for orbit maintenance) and are made up of a cylindrical structure with a length of about 3.3 m (Fig. 8.16). Two solar panels with a total surface area of about 24 m^2 delivered a net system power of about 1 kW. The GLONASS I/II satellites employed a pressurized platform design to protect the payload against the space environment. Heat dissipation was achieved through heat exchangers and four thermal control flaps. The opening angle of these shutters could be varied and allowed the adjustment of the internal temperature with an accuracy of about 5 °C.

Attitude control was achieved through reaction wheels, which were periodically unloaded using magnetorquers. Reference measurements of the magnetic fields were provided by a magnetometer, which was mounted on an external boom (Fig. 8.16) to avoid magnetic disturbances by the satellite body. The GLONASS satellites were also equipped with a hydrazine propulsion system. It comprised two 5 N thrusters for orbit correction and 24 0.1 N thrusters for orientation changes and despinning after orbit injection. After reaching their assigned orbital slot, the satellites kept their nominal position within an argument-of-latitude deadband of ±5° throughout their operational lifetime with no need for further correction maneuvers.

The longitudinal $-x$-axis of the cylindrical spacecraft body points towards the Earth and carries the L-band antenna. It is composed of 12 helix elements arranged in an inner ring with four elements and an outer

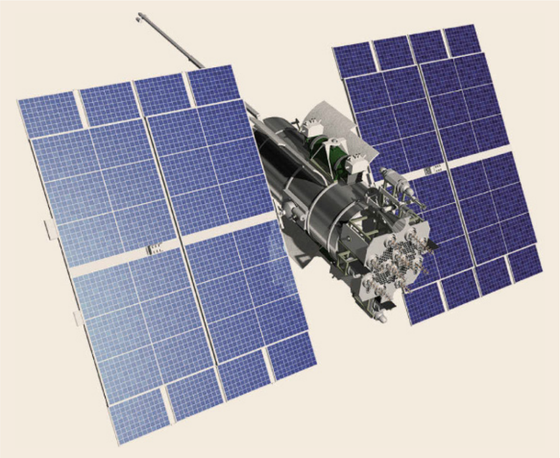

Fig. 8.16 Satellite of the first generation GLONASS system (courtesy of ISS Reshetnev)

Table 8.8 GLONASS satellites overview

Parameter	GLONASS	GLONASS-M	GLONASS-M+	GLONASS-K1	GLONASS-K1+	GLONASS-K2
First launch	1982	2003	2014	2012	2017	2016
Platform design	Pressurized	Pressurized	Pressurized	Unpressurized	Unpressurized	Unpressurized
Design lifetime (years)	3	7	7	10	10	> 10
Mass (kg)	1415	1415	1415+	995	995+	1645
System power (W)	1000	1450	1450	1600	1600	4370
Solar array size (m^2)	25	32	32	17	17	34
Pointing accuracy (Earth) (°)	0.5	0.5	0.5	0.5	0.5	0.25
Pointing accuracy (Sun) (°)	5	2	2	1	1	1
Navigation payload						
Mass (kg)	180	250	250	260	>260	520
Power consumption (W)	600	580	580	750	>750	2600
Clocks	(Rb), Cs	Cs	Cs	Cs, Rb	Cs, Rb	Cs, Rb
Clock stability (daily)	$5 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$(0.5-1) \cdot 10^{-13}$	$5 \cdot 10^{-14}$	$(0.5-5) \cdot 10^{-14}$
FDMA signals	L1, L2	L1, L2	L1, L2	L1, L2	L1, L2	L1, L2
CDMA signals	–	–	L3	L3	L2, L3	L1, L2, L3
Cross link	–	×	×	×	×	×
Laser reflector	×	×	×	×	×	×

ring with eight elements. These elements are phase coherently combined to achieve an M-shaped antenna gain pattern with a slightly higher beam intensity towards the rim of the Earth (Chap. 17). In addition, the GLONASS satellites carry a laser retroreflector array (LRA) for satellite laser ranging measurements [8.45]. The LRA comprises almost 400 individual corner cube reflectors accommodated between the L-band antenna elements to center the effective reflection point on the boresight axis.

In the GLONASS I series, two 5 MHz BERYL rubidium clocks with a stability of $5 \cdot 10^{-12}$ over one day served as the primary atomic frequency standard (AFS). The subsequent type II spacecraft were equipped with three GEM cesium clocks (offering a two-fold cold redundancy) that achieved a ten times better performance [8.46, 47]. The average lifetime of these early clocks amounted to only 1.5 years, which notably restricted the overall mission duration.

In total, 87 GLONASS I and II satellites were launched from 1982 to 2005. This includes six satellites that did not reach their final target orbit. Typical operations periods ranged from about one year for the early satellites to five years for the latest units. The first fully operational GLONASS constellation completed in 1995 was exclusively made up of IIv spacecraft.

8.3.2 GLONASS-M

From 2003 onwards, the first-generation GLONASS satellites were replaced by the modernized GLONASS-M series. These spacecraft share the same core structure and exhibit a similar mass as the GLONASS I/II series but are easily distinguished by the different placement of the solar panel rotation axis and a larger antenna panel on their front side (Fig. 8.17). Also, the satellites no longer carry a magnetometer boom on the zenith-facing side of the spacecraft body.

Like GLONASS I and II, the GLONASS-M satellites make use of a pressurized container and exhibit the characteristic thermal control flaps, but offer better mission and operational performances as well a longer design lifetime (seven years) than their predecessors. The GLONASS-M satellites achieve an 0.5° accuracy for the nadir pointing attitude control and a 2° pointing accuracy for the solar panels. The use of larger solar panels (34 m^2) provides a higher overall system power of 1.5 kW.

The laser retroreflector array uses a more compact design than on GLONASS I/II and is accommodated next to the L-band navigation antenna on the front panel with a small lateral offset from the principal body axis of the spacecraft (Fig. 8.18).

As a novel feature, GLONASS-M satellites include a radio-based intersatellite link [8.48], which is undergoing flight validation and will help to mitigate the limited geographical coverage of the GLONASS ground segment. It provides distance measurements between spacecraft based on dual one-way pseudoranges and can thus contribute to an improved ephemeris and clock accuracy [8.49].

The latest GLONASS-M satellites are also equipped with a prototype Inter-Satellite Laser Navigation and Communication System (ISLNCS, Fig. 8.18). Early in-flight experiments have demonstrated the capability to measure the distance between two satellites with a precision of about 3 cm and to synchronize the onboard clocks to each other with a corresponding error of less than 0.1 cm [8.50, 51].

Fig. 8.17 GLONASS-M spacecraft (courtesy of ISS Reshetnev)

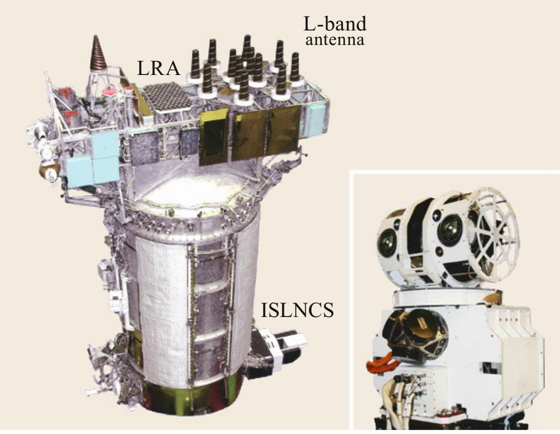

Fig. 8.18 GLONASS-M spacecraft with laser retroreflector array (LRA) and intersatellite laser navigation and communication system (ISLNCS). The *insert* shows the ISLNCS design in use since 2013 (courtesy of Science-Industry Corporation of Precise Device Engineering Systems (NPK SPP))

Besides the modernization of the spacecraft platform, the GLONASS-M satellites introduced various changes to the radio navigation signals [8.52]. The transmitted frequencies were shifted to a lower range ((1598.0625 ... 1605.375) ± 5.11 MHz for L1 and L2 = (1242.9375 ... 11248.625) ± 5.11 MHz for L2) and filters were installed to reduce out-of-band emission in the frequency bands 1610.6–1613.8 MHz and 1660.0–1670.0 MHz down to the level provided in ITU recommendation 769 [8.31]. Furthermore, the transmission power in the L2 band was doubled and the civil navigation signal was added to L2, thus offering the first fully open dual-frequency navigation service. Along with these changes, various improvements to the navigation message were made. Available spare bytes in the original design were populated with new parameters such as the GPS-GLONASS time difference, leap second announcements or the age of orbit and clock data. Starting with spacecraft No. 55 in 2014, transmission of the L3OC was, furthermore, added to the GLONASS-M satellites.

Like their predecessors, the GLONASS-M satellites employ three cesium clocks as the primary frequency standard. According to the technical requirements the frequency stability amounts $1 \cdot 10^{-13}$ over one day, which directly contributes to a better overall navigation performance.

As of early 2015, the operational GLONASS constellation is entirely composed of GLONASS-M satellites.

8.3.3 GLONASS-K

The GLONASS-K series represents the latest generation of spacecraft in the GLONASS constellation. It comprises two subseries, namely the lighter K1 satellites (Fig. 8.19) and the more heavy K2 type with full capabilities. Two GLONASS-K1 satellites were launched in 2011 and 2014. In February 2016, the second GLONASS-K1 satellite was introduced into the constellation for nominal operation, while the first GLONASS-K1 satellite remains reserved for test purposes. Construction and deployment of the GLONASS-K2 satellites is planned for the second half of the decade.

GLONASS-K satellites are the first to use an unpressurized payload and service module. They build upon the Express-1000K spacecraft bus developed by ISS Reshetnev (formerly NPO PM) for various geostationary communication and relay satellites. The box-shaped structure is made up of lightweight hon-

Fig. 8.19 GLONASS-K1 spacecraft (courtesy of ISS Reshetnev)

eycomb panels and heat pipes are used for thermal control [8.48]. With a mass of 935 kg, the K1 satellites have only two thirds of the mass of their predecessors, which offers greater flexibility in the launcher selection. The use of advanced Ga-As solar cells enables a high electrical power (1.6 kW) despite a smaller size of the solar panels (17 m^2) than all previous satellites. The design lifetime of ten years is substantially longer than that of the earlier generations and will assist a smooth and interruption-free GLONASS service.

Similar to the GLONASS I/II spacecraft, the laser retroreflector of the GLONASS-K1 satellite is integrated into the L-band antenna structure to align both phase centers with the nadir-pointing axis through the center of mass. In this way, the phase center location is invariant under yaw rotations that are continuously performed to keep the solar panels perpendicular to the Sun (Sect. 3.4). The atomic frequency standards of the GLONASS-K1 satellites comprise two cesium and two rubidium clocks with a specified performance of $(0.5-1.0) \cdot 10^{-13}$. All GLONASS-K1 satellites transmit the CDMA L3 open service signal (L3OC) in addition to the legacy FDMA signals of the open and authorized services on L1 and L2. Support of L2 and, subsequently, L1 CDMA signals is foreseen for an enhanced version of K1+ satellites and the larger K2 satellites.

Aside from the core navigation payload, the GLONASS-K satellites are equipped with a radio cross link for data exchange and ranging, an optical cross link, a Cospas-Sarsat [8.53] distress alert detection and routing system, as well as an optical onboard system for simultaneous two-way and one-way laser ranging measurements intended for calibration and remote clock synchronization.

8.4 Launch Vehicles

The buildup and sustainment of the GLONASS constellation is provided through triple launches with the Proton launch vehicle or single launches with the Soyuz rocket (Fig. 8.20). Launches of the Soyuz rocket are performed from the Plesetsk Cosmodrome [8.54] in northern Russia (62.9° N, 40.6° E) and maintained by the Russian Air and Space Defence Forces. Proton launches, in contrast, are conducted from the rocket and space complex in Baikonur [8.55]. The latter site is located in the Republic of Kazakhstan (45.6° N, 63.3° E) and leased by the Russian Federation for its national space program.

The Proton-K rocket and its stronger and modernized M version are heavy-lift launch vehicles with a long flight heritage. The 3(+1)-stage rockets with a height of 53–58 m serve a wide range of missions in different orbits. They can carry up to 22 t into a low Earth orbit (LEO) or about 6 t into geostationary transfer orbit (GTO).

The first stage comprises six RD-275 engines with a common central oxidizer tank and six permanently attached strap-on fuel tanks. The stage provides a total thrust of 10 MN over a burn duration of 2 min and accelerates the rocket to $\approx 1.6\,\mathrm{km/s}$ before burnout at an altitude of about 40 km. The second stage combines four RD-0210/0211 engines with a total thrust of roughly 2 MN. It completes its firing approximately 5 min after liftoff near an altitude of 120 km. The third and final stage combines a single RD-0212 engine and a RD-0214 steering engine for fine control of the injection vector and velocity. All of the aforementioned engines use unsymmetrical dimethyl hydrazine (UDMH, $C_2H_8N_2$) and nitrogen tetroxide (N_2O_4) as fuel and oxidizer, which are known to be highly toxic but do not require cooling for storage.

Fig. 8.20 Launch sites and vehicles for the GLONASS navigation satellites (courtesy of ISS Reshetnev)

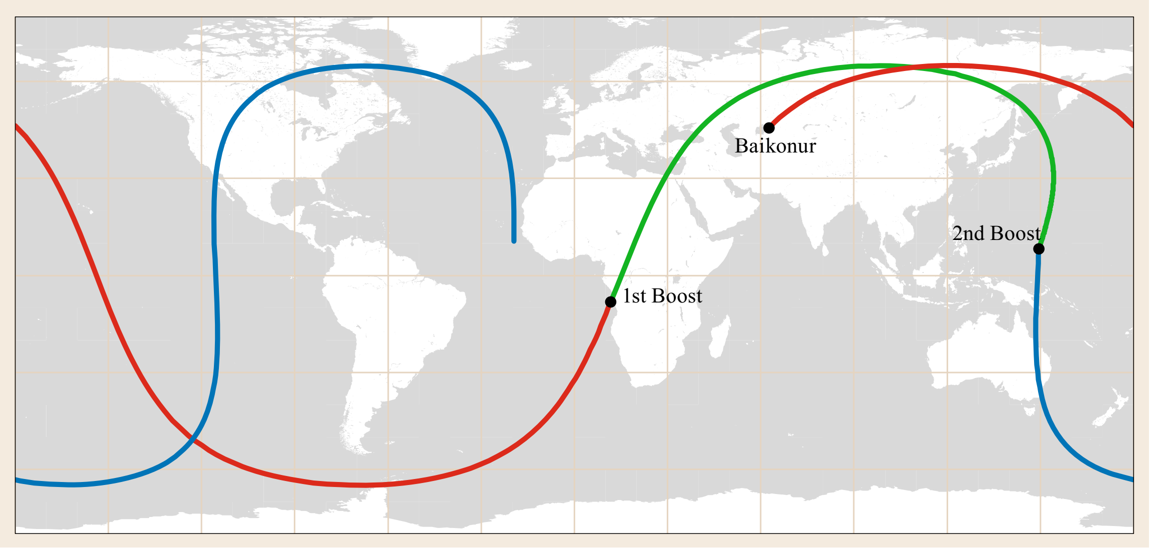

Fig. 8.21 Representative example of the ground track during orbit injection of GLONASS satellites with a Proton rocket. The low Earth parking orbit and the elliptical transfer orbit are marked by *red* and *green lines* respectively, with *gray dots* indicating the approximate location of the upper stage burns. The *blue line* describes the first orbital revolution of the GLONASS spacecraft after separation. The illustration is based on patched Keplerian orbits and does not take into account the actual boost durations

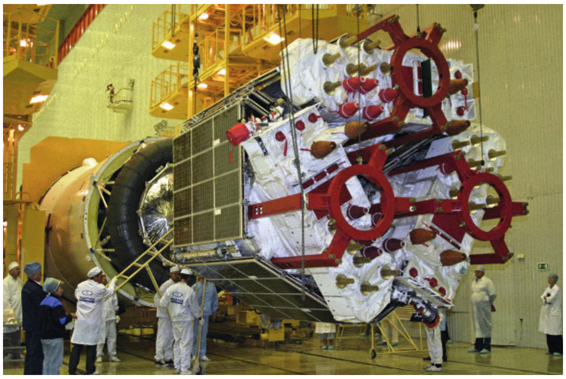

Fig. 8.22 Integration of three GLONASS-M satellites with a Block-DM upper stage (courtesy of ISS Reshetnev)

Aside from the three main stages, the Proton rocket typically employs a reignitable upper stage to realize more complex mission profiles. For GLONASS launches, either the *DM* or *Breeze-M* upper stage are employed, which offer a thrust level of 80 and 20 kN respectively. A typical missions scenario for GLONASS orbit injection is illustrated in Fig. 8.21 based on [8.1, 56]. After ascent of the launcher and burnout of the third stage (roughly 10 min after launch), the upper stage with the attached GLONASS satellites is separated and moves around the Earth at an altitude of about 200 km. This parking orbit has an inclination of $\approx 64.8°$ in accord with the orbit planes of the GLONASS constellation. A first boost of the upper stage raises the apogee to the desired target altitude of 19 130 km. The highly elliptical transfer orbit has an eccentricity of $e \approx 0.6$ and it takes about 3 h to proceed from perigee to apogee. Here, a second burn is performed, which circularizes the orbit. Thereafter, the GLONASS satellites are deployed into their target orbit. Following the separation from the upper stage, the solar panel deployment and the checkout of all onboard systems, the satellites are ultimately moved to their desired position in the orbital plane in a series of small orbit correction maneuvers using their own thruster system.

The large payload capacity of the Proton rocket enables triple launches of GLONASS I/II or GLONASS-M satellites, which was particularly helpful during the buildup and rebuild phase of the constellation. To fit three satellites under the Proton fairing, the solar panels are folded around the satellites in a rhombic shape that enables a tight packing of the triplet on the launch adapter (Fig. 8.22). Out of 51 launches with a total of 132 GLONASS satellites conducted up to 2015, a wide majority were conducted with Proton-K and -M rockets carrying three GLONASS satellites (with occasional replacements by mass dummies or Etalon satellites) at a time.

Starting with the launch of GLONASS-K1 in 2011, the Soyuz-2b [8.54] was introduced as an alternative launch vehicle for GLONASS satellites. The rocket has a height of about 46 m and can carry a payload of 4–8 t into low Earth orbit (depending on the inclination and actual altitude). The Soyuz rocket carries four RD-107A strap-on boosters that serve as the first stage and and develop a thrust of 3.3 MN over a 2 min boost phase. The central second and third stages are based on a single RD-108 and RD-0124 engine respectively, which provide thrust levels of 0.9 and 0.3 MN. Unlike the Proton rocket, the Soyuz launcher employs kerosene and liquid oxygen as propellant. A Fregat upper stage serves as forth stage and performs the transfer orbit injection as well as the final circularization of the orbit at the target altitude of the GLONASS constellation.

The Soyuz vehicle can carry a single GLONASS-M or -K1 satellite and has typically been used for replacing individual aged satellites in the constellation. As a side note, the Soyuz launcher has also been used for in-orbit delivery of various satellites of the Galileo constellation. Aside from the two precursor satellites Galileo in orbit validation element GIOVE-A and -B, most of these launches were, however, conducted from the European spaceport at Kourou, French Guiana.

8.5 Ground Segment

The ground segment is an essential part of the GLONASS architecture providing system operation and ultimate GLONASS performance. There is no formal division between system control and mission control functions. All operational procedures after satellite liftoff are fulfilled by the Air and Space Defense Forces (ASDF). If satellites are launched from the Baikonur launch site, the initial active phase of the launcher trajectory tracking is supported by the Russian Federal Space Agency (RFSA) assets.

The main functions of the GLONASS ground segment comprise:

- Support of operations in the launch and early orbit phase (LEOP)
- Commissioning of satellites and their transfer to dedicated orbit slots (in case of a triple launch or commissioning at an orbital spare position)
- Telemetry monitoring, command and control
- Mission planning and constellation keeping

- Maintenance and decommissioning of satellites at their end of life
- Monitoring of the ground assets status
- Generation of the system timescale and its steering to UTC(SU)
- Generation of orbit and clock data
- Upload of navigation data to the satellites
- Improvement of the satellite dynamics models
- Monitoring of the GLONASS navigation, positioning and timing performance
- Serving of external interfaces with civil institutions.

Core components of the GLONASS ground segment include the GLONASS system control center (SCC) and the central clocks (CCs), the telemetry, tracking and command stations (TT and C) and the uplink stations, as well as one-way monitoring stations and satellite laser ranging (SLR) stations. All major ground segment assets are located within the Russian territory at the ASDF sites shown in Fig. 8.23.

The system control center is located in Krasnoznamensk (formerly known as the closed town of Golitsyno-2) some 40 km southwest of the Moscow city center. It performs the planning and coordinates the work of all ground segment elements. Orbit determination and clock synchronization is implemented through processing of all available sets of data including two-way ranging from TT and C and uplink stations, downloaded radio cross-link ranging data, and one-way ranging data from ASDF monitoring stations. Use of data from the RFSA monitoring stations is planned to improve orbit and clock information as well as the cross-link ranging data.

GLONASS System Time is maintained by the central clock facility. It includes a group of four hydrogen masers, which are continuously steered to the Russian realization of Coordinated Universal time, UTC(SU) [8.27, 28]. The master central clock at Schelkovo near Moscow is complemented by a second facility at Komsomolsk in the far east of Russia.

The telemetry, tracking and control stations are used to receive status information from the GLONASS satellites, to send control commands, and to perform two-way ranging measurements for orbit determination. For maximum coverage, a total of five TT and C stations situated in the western, central and eastern parts of Russia are available. They are complemented by five uplink stations in Schelkovo, Yeniseisk, Komsomolsk, Vorkuta, and Petropavlovsk. Each of these sites is equipped with two antennas, which enables up to three uploads of orbit and clock data to each GLONASS satellite per day.

The monitoring stations collect one-way pseudorange and carrier-phase measurements for orbit and clock determination as well as offline performance and integrity monitoring. Most of them are colo-

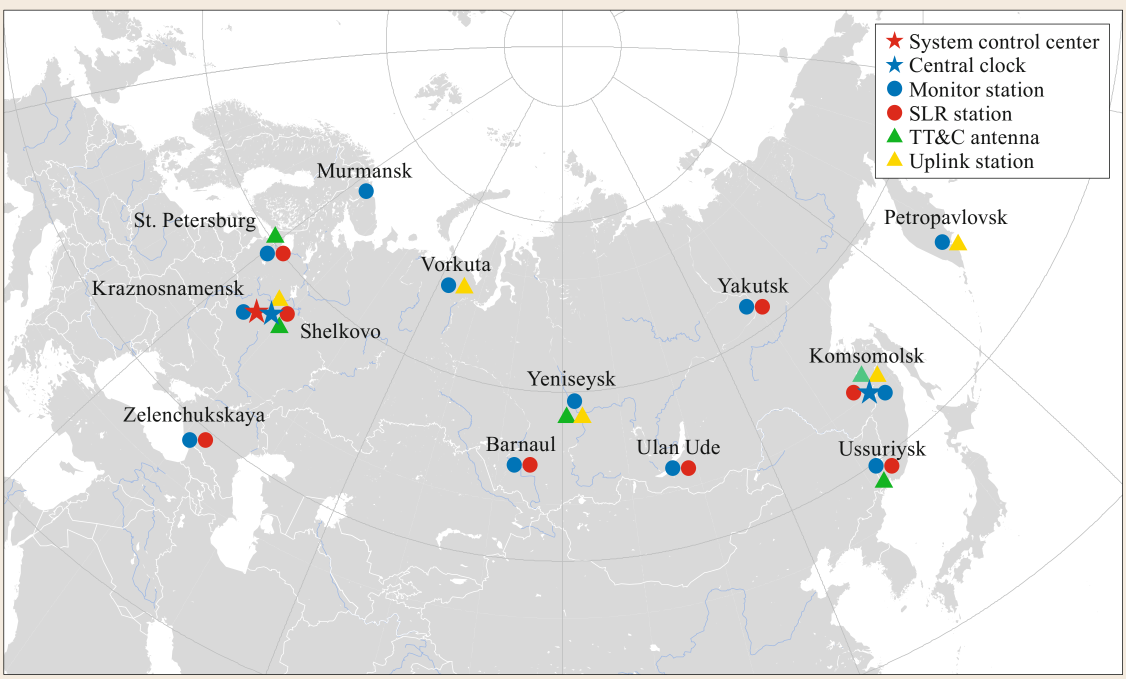

Fig. 8.23 GLONASS ground segment sites

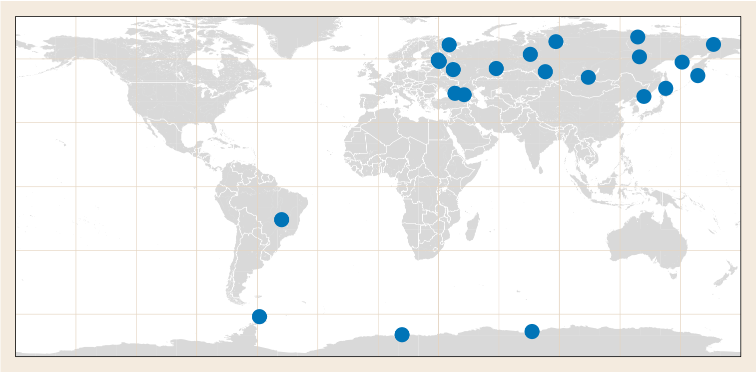

Fig. 8.25 Network of SDCM monitoring stations (status end-2014)

Fig. 8.24 Altay Laser Ranging Center near Barnaul (Altay) (courtesy of Science-Industry Corporation of Precise Device Engineering Systems (NPK SPP))

cated with laser ranging stations (Fig. 8.24), which enables complementary optical two-way distance measurements. The SLR observations are used for calibration of radiometric distance measurements as well as orbit determination and accuracy validation. They also contribute to an improved realization of the GLONASS reference frame. The routine use of SLR for GLONASS operations [8.57] is unique among all navigation satellite systems, but forms an integral part of the system architecture. From the very beginning, all GLONASS satellites were equipped with laser retroreflectors and the high-accuracy SLR measurements have helped in coping with the limited geographical distribution and accuracy of conventional radiometric tracking stations. In total, 13 monitoring and nine laser ranging stations distributed over the Russian territory (and neighboring states of the former Soviet Union) are currently included in the GLONASS ground segment.

As part of the ongoing GLONASS modernization and enhancement, the system for differential correction and monitoring (SDCM) [8.58] has been established. SDCM is based on a network of reference stations, which are equipped with combined GPS/GLONASS dual-frequency receivers, hydrogen maser atomic clocks and direct communication links for real-time data transfer. By the end of 2014, a total of 18 station have been deployed in Russian territory as well as four stations in Antarctica and Brazil (Fig. 8.25). Further stations are planned in Cuba and Kazakhstan as well as other countries in South America, Africa and Asia/Oceania to achieve a worldwide coverage. The SDCM network enables a continuous performance and integrity monitoring [8.59] as well as real-time corrections for precise point positioning applications [8.60]. SDCM correction data are provided via the Internet for terrestrial users and through the Luch-5A/B relay and communication satellites. Incorporation of the SDCM reference stations into the GLONASS orbit and clock determination could constitute an important building block for a fully global, high-performance GLONASS navigation service.

For synchronization of the onboard clocks, support of one-way laser ranging is currently under development [8.51]. Using photodetectors on board the GLONASS satellites, the arrival time of laser pulses with precisely known transmission time can be measured relative to the onboard timescale. By comparing these measurements with traditional two-way SLR observations, the difference between the satellite and ground clocks can then be determined [8.61]. Along with the installation of laser time transfer equipment in the future GLONASS satellites, the GLONASS ground segment will be upgraded to support such operations on a routine basis.

8.6 GLONASS Open Service Performance

Continuous monitoring of the GLONASS system performance and integrity is presently provided through various institutions and services in Russia. These include the Information and Analysis Centre of the Russian Federal Space Agency (IAC [8.62]), the System for Differential Correction and Monitoring (SDCM [8.59]), and the System for High-accuracy Determination of Ephemeris and Time Corrections (SVOEVP [8.63, 64]). Complementary to Russian reference stations, these monitoring services make use of stations from the International GNSS Service (IGS [8.65]) network to enable a fully global coverage. Unless otherwise noted, the performance results presented in this section are based on analyses and data of the IAC.

In a statistical sense, the positioning performance of a satellite navigation system can be expressed as the product of the position dilution of precision (PDOP) and the user range error (URE). The PDOP depends only on the number of tracked GNSSs and the geometric distribution of their line-of-sight vectors. The URE in contrast describes the root mean square errors of the difference between modeled and observed pseudoranges. Aside from user equipment errors (UEE) such as noise and multipath or uncompensated atmospheric delays, it comprises the signal-in-space range error (SISRE). The latter describes the impact of errors in the broadcast orbit and clock parameters on the range computation.

Since completion of the nominal 24-satellite constellation in 2012, GLONASS provides global daily availability of a better than 99% at a 5° elevation mask angle and a PDOP of less than 6. An example of the instantaneous PDOP map for the current GLONASS constellation is shown in Fig. 8.26. PDOP values amount to 1.5–2.5 for most of the globe and only exceed a value of 3 in very limited geographic regions.

The signal-in-space range error as monitored by the IAC exhibits typical variations in the range of 1–2 m across individual satellites of the constellation (Fig. 8.27). For comparison, a mean SISRE of 1.9 m has been derived from the analysis of broadcast ephemeris data covering a one year interval in 2013/2014 [8.66] while SISRE values of 1–4 m were obtained by [8.67] for individual GLONASS satellites in the 2009–2011 time frame.

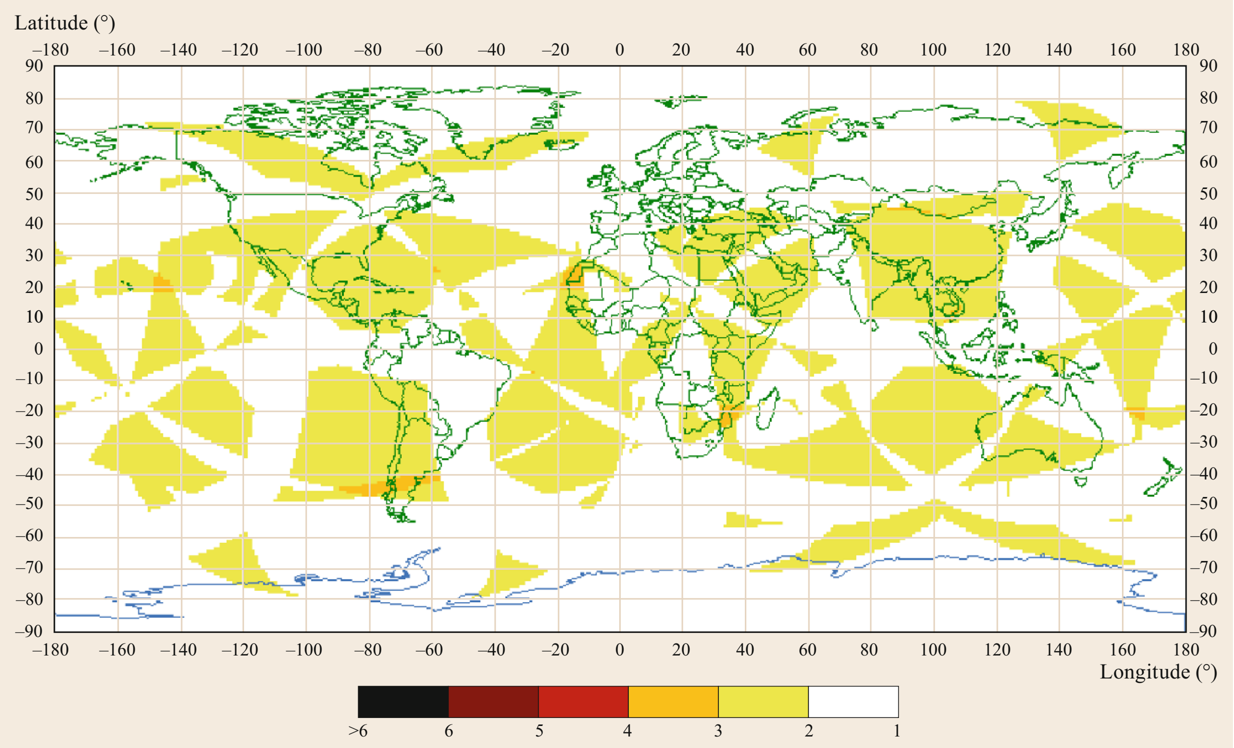

Fig. 8.26 Instantaneous PDOP map for the GLONASS constellation on 8 March 2015, 10:30 UTC (mask elevation angle 5°) (courtesy of Federal Space Agency-Information Analytical Centre)

Fig. 8.27 Average GLONASS constellation SISRE for 6–8 March 2015 (RMS, m) (courtesy of Federal Space Agency-Information Analytical Centre)

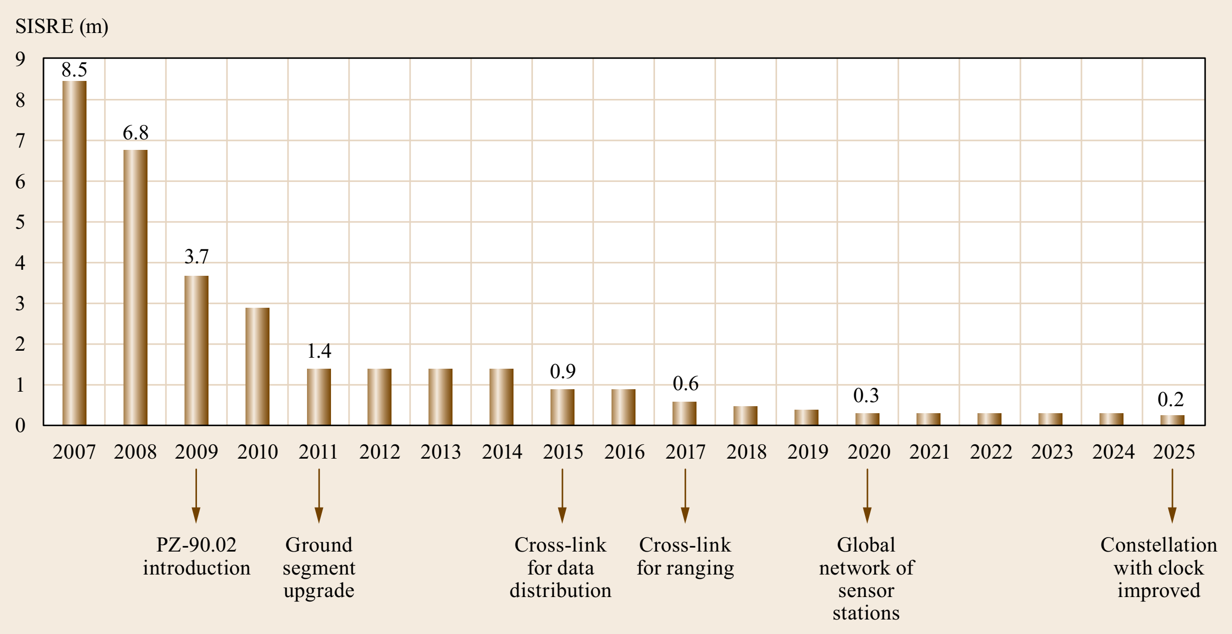

Fig. 8.28 Mean SISRE of the GLONASS constellation through GPI plan implementation

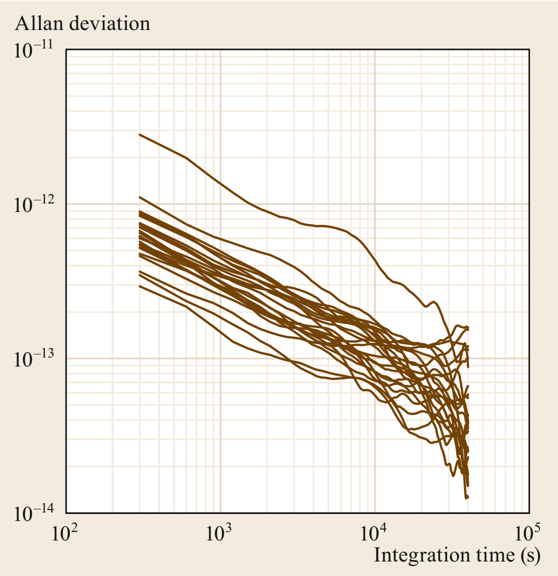

Fig. 8.29 Allan deviation of GLONASS-M satellites on 5 March 2015 as derived from European Space Agency (ESA) clock products (courtesy of P. Steigenberger (DLR))

One of the key factors contributing to the SISRE is the onboard clock stability. It is commonly characterized by the Allan deviation (ADEV), that is the relative frequency error over a specified time interval (Fig. 8.29). For the current constellation of GLONASS-M satellites, the Allan deviation (ADEV) over a one-day correlation time is typically better than $(0.5-1.0)\cdot 10^{-13}$ [8.62, 68]. Over short timescales of 1–100 s, ADEV values of about $1\cdot 10^{-11}$ have been reported in [8.69, 70]. An overall improvement of the onboard clock stability is expected from new types of atomic frequency standards on the next-generation GLONASS-K satellites.

The GLONASS performance improvement (GPI) plan foresees a continuous SISRE reduction to less than 0.5 m by 2020 (Fig. 8.28). Key steps to achieve this improvement include the processing of carrier-phase measurements in the orbit determination and time synchronization process, the use of intersatellite communication cross links for performing up to 24 navigation data uploads per day, use of intersatellite ranging data for orbit and clock determination in the ground segment facilities, and the global expansion of the monitoring network. Further improvements are expected from the introduction of high-performance CDMA signals and new generations of onboard clocks.

References

8.1 N.L. Johnson: GLONASS spacecraft, GPS World **5**(11), 51–58 (1994)
8.2 V.V. Dvorkin, Y.I. Nosenko, Y.M. Urlichich, A.M. Finkel'shtein: The Russian global navigation satellite program, Her. Russ. Acad. Sci. **79**(1), 7–13 (2009)
8.3 T.G. Anodina: *The GLONASS System Technical Characteristics and Performance* (International Civil Aviation Organization, Montreal, Canada 1988), Working Paper FANS/4-WP/75
8.4 S.A. Dale, P. Daly: The Soviet Union's GLONASS navigation satellites, IEEE Aerosp. Electron. Syst. Mag. **2**(5), 13–17 (1987)
8.5 G.R. Lennen: The USSR's GLONASS P-code-determination and initial results, ION GPS 1989, Colorado Springs (ION, Virginia 1989) pp. 77–83
8.6 S.A. Dale, P. Daly, I.D. Kitching: Understanding signals from GLONASS navigation satellites, Int. J. Sat. Commun. **7**(1), 11–22 (1989)
8.7 Global Navigation Satellite System GLONASS – Interface Control Document, v5.1, (Russian Institute of Space Device Engineering, Moscow, 2008)
8.8 Y. Urlichich, V. Subbotin, G. Stupak, V. Dvorkin, A. Povaliaev, S. Karutin: GLONASS modernization, ION GNSS 2011, Portland (ION, Virginia 2010) pp. 3125–3128
8.9 V. Putin: On Use of GLONASS (Global Navigation Satellite System) for the Benefit of Social and Economic Development of the Russian Federation, Presidental Decree No. 638, Kremlin, Moscow (2007)
8.10 T. Mirgorodskaya: GLONASS and critical infrastructure, Proc. 9th Meet. Int. Comm. GNSS (ICG), Work. Group A, Prague (UNOOSA, Vienna 2014)
8.11 N. Zarraoa, W. Mai, E. Sardon, A. Jungstand: Preliminary evaluation of the Russian GLONASS system as a potential geodetic tool, J. Geod. **72**(6), 356–363 (1998)
8.12 P. Willis, J. Slater, G. Beutler, W. Gurtner, C. Noll, R. Weber, R.E. Neilan, G. Hein: The IGEX-98-campaign: Highlights and perspective. In: *Geodesy Beyond 2000, International Association of Geodesy Symposia*, Vol. 121, ed. by K.-P. Schwarz (Springer, Berlin 2000) pp. 22–25
8.13 R. Weber, J.A. Slater, E. Fragner, V. Glotov, H. Habrich, I. Romero, S. Schaer: Precise GLONASS orbit determination within the IGS/IGLOS–pilot project, Adv. Space Res. **36**(3), 369–375 (2005)
8.14 J.G. Walker: Satellite constellations, J. Br. Interplanet. Soc. **37**, 559–572 (1984)
8.15 Parametry Zemli 1990 goda. Version PZ-90.11 (Earth Model PZ-90.11; In Russian). Military Topography Agency of the General Staff of the Armed Forces of the Russian Federation (Moscow 2014) http://structure.mil.ru/files/pz-90.pdf
8.16 S. Feairheller, J. Purvis, R. Clark: The Russian GLONASS system. In: *Understanding GPS – Principles and Applications*, ed. by E.D. Kaplan (Arctech House,

Boston, London 1996) pp. 439–465

8.17 V. Vdovin, A. Dorofeeva: Global geocentric coordinate system of the Russian federation, Proc. 7th Meet. Int. Comm. GNSS (ICG), Work. Group D, Bejing (UNOOSA, Vienna 2012)

8.18 A.N. Zueva, E.V. Novikov, D.I. Pleshakov, I.V. Gusev: System of geodetic parameters parametry zemli 1990 PZ-90.11, Proc. 9th Meet. Int. Comm. GNSS (ICG), Work. Group D, Prague (UNOOSA, Vienna 2014)

8.19 P.N. Misra, R.I. Abbot, E.M. Gaposcbkin: Integrated Use of GPS and GLONASS: Transformation between WGS 84 and PZ-90, ION GPS 1996, Kansas City (ION, Virginia 1996) pp. 307–314

8.20 U. Rossbach, H. Habrich, N. Zarraoa: Transformation Parameters between PZ-90 and WGS 84, ION GPS 1996, Kansas City (ION, Virginia 1996) pp. 279–285

8.21 C. Boucher, Z. Altamimi: ITRS, PZ-90 and WGS 84: Current realizations and the related transformation parameters, J. Geod. **75**(11), 613–619 (2001)

8.22 S.G. Revnivykh: GLONASS status and progress, Proc. 47th CGSIC Meet., Fort Worth (CGSIC, Alexandria 2007)

8.23 Global Navigation Satellite System and Global Positioning System: Coordinate Systems, Methods of Transformations for Determinated Points Coordinate; STB GOST Standard 51794-2008 (Federalnoje agentstwo po technitscheskomu regulirowaniju i metrologii, Moscow, 2008) in Russian

8.24 Yu. Domnin, B. Gaigerov, N. Koshelyaevsky, S. Poushkin, F. Rusin, V. Tatarenkov, G. Yolkin: Fifty years of atomic time-keeping at VNIIFTRI, Metrologia **42**(3), S55–S63 (2005)

8.25 I. Blinov, Y. Domnin, S. Donchenko, N. Koshelyaevsky, V. Kostromin: Progress at the state time and frequency standard of Russia, European Frequency and Time Forum (EFTF) 2012, Gothenburg (2012) pp. 144–147

8.26 W. Lewandowski, E.F. Arias: GNSS times and UTC, Metrologia **48**(4), S219–S224 (2011)

8.27 A. Shchipunov: Generating and transferring the national time scale in GLONASS, ION GNSS 2012, Nashville (ION, Virginia 2012) pp. 3950–3962

8.28 A.V. Druzhin, V. Palchikov: Current state and perspectives of UTC(SU) broadcast by GLONASS, Proc. 9th Meet. Int. Comm. GNSS (ICG), Prague (UNOOSA, Vienna 2014) pp. 1–9

8.29 A. Bolkonov: GLONASS open service performance parameters standard and GNSS open service performance parameters template status, Proc. 9th Meet. Int. Comm. GNSS (ICG), Work. Group A, Prague (UNOOSA, Vienna 2014)

8.30 R.B. Langley: GLONASS: Review and update, GPS World **8**(11), 51–58 (1994)

8.31 Protection criteria used for radio astronomical observations, Recommendation RA 769, rev. 2, May 2003 (ITU, 2003) http://www.itu.int/rec/R-REC-RA.769/en/

8.32 J. Galt: Interference with Astronomical Observations of OH Masers from the Soviet Union's GLONASS satellites. In: *IAU Colloq. 112 Light Pollution, Radio Interference, and Space Debris*, ed. by D.L. Crawford (IAU, Paris 1991) pp. 213–221

8.33 J.A. Ávila Rodríguez: On Generalized Signal Waveforms for Satellite Navigation, Ph.D. Thesis (Univ. der Bundeswehr, Neubiberg 2008)

8.34 B.A. Stein: PRN codes for GPS/GLONASS: A comparison, ION NTM 1990, San Diego (ION, Virginia 1990) pp. 31–35

8.35 J. Beser, J. Danaher: The 3S navigation R-100 family of integrated GPS/GLONASS receivers: Description and performance results, ION NTM 1993, San Francisco (ION, Virginia 1993) pp. 25–45

8.36 P. Daly, S. Riley: GLONASS P-code data message, ION NTM 1994, San Diego (ION, Virginia 1994) pp. 195–202

8.37 S. Zaminpardaz, P.J.G. Teunissen, N. Nadarajah: GLONASS CDMA L3 ambiguity resolution and positioning, GPS Solut. (2016) doi:10.1007/s10291-016-0544-y

8.38 Y. Urlichich, V. Subbotin, G. Stupak, V. Dvorkin, A. Povaliaev, S. Karutin: GLONASS developing strategy, ION GNSS 2010, Portland (ION, Virginia 2010) pp. 1566–1571

8.39 S. Karutin: GLONASS Signals and Augmentations, ION GNSS 2012, Nashville (ION, Virginia 2012) pp. 3878–3911

8.40 T. Kasami: Weight Distribution Formula for Some Class of Cyclic Codes, Tech. Rep. R285 (Univ. Illinois, Illinois 1966) pp. 1–24

8.41 T. Helleseth, P.V. Kumar: Pseudonoise sequences. In: *The Mobile Communications Handbook*, ed. by J.D. Gibson (CRC, Boca Raton 1999) pp. 237–252

8.42 S. Thoelert, S. Erker, J. Furthner, M. Meurer, G.X. Gao, L. Heng, T. Walter, P. Enge: First signal in space analysis of GLONASS K-1, ION GNSS 2011, Portland (ION, Virginia 2011) pp. 3076–3082

8.43 A.A. Povalyaev: GLONASS navigation message format for flexible row structure, ION GNSS 2013, Nashville (ION,, Virginia 2013) pp. 972–974

8.44 G.M. Appleby: Orbit determinations of the lageos and etalon satellites – A comparison of geodetic results and orbital evolution of the etalons, dynamics and astrometry of natural and artificial celestial bodies, Proc. Conf. Astrom. Celest. Mech., Poznan 1993, ed. by K. Kurzynska, F. Barlier, P.K. Seidelmann, I. Wyrtrzyszczak (IAU, Pairs 1994)

8.45 T. Otsubo, G.M. Appleby, P. Gibbs: GLONASS laser ranging accuracy with satellite signature effect, Surv. Geophys. **22**(5/6), 509–516 (2001)

8.46 Y.G. Gouzhva, A.G. Gevorkyan, P.P. Bogdanov: Accuracy estimation of GLONASS satellite oscillators, Proc. 46th Freq. Control Symp., Hershey (1992) pp. 306–309

8.47 A.B. Bassevich, P.P. Bogdanov, A.G. Gevorkyan, A.E. Tyulyakov: GLONASS onboard time/frequency standards: Ten years of operation, Proc. 28th Ann. PTTI Meet., Reston (DTIC, Fort Belvoir 1996) pp. 455–462

8.48 R. Fatkulin, V. Kossenko, S. Storozhev, V. Zvonar, V. Chebotarev: GLONASS space segment: Satellite constellation, GLONASS-M and GLONASS-K spacecraft, main features, ION GNSS 2012, Nashville (ION, Virginia 2012) pp. 3912–3930

8.49 A. Bolkunov, I. Zolkin, E. Ignatovich, A. Schekutiev: Intersatellite links as critical element of advanced satellite navigation technologies, Sci. Tech. J. 'Polyot' (Flight) **4**, 29–33 (2013)

8.50 A. Chubykin, S. Dmitriev, V. Shargorodskiy, V. Sumerin: Intersatellite laser navigating link system, Proc. WPLTN Tech. Workshop One-Way Two-Way SLR GNSS Co-located RF Tech., St.Petersburg

(2012) pp. 1–18
8.51 V.D. Shargorodsky, V.V. Pasynkov, M.A. Sadovnikov, A.A. Chubykin: Laser GLONASS: Era of extended precision, GLONASS Herald **14**, 22–26 (2013)
8.52 G.M. Polischuk, V.I. Kozlov, V.V. Ilitchov, A.G. Kozlov, V.A. Bartenev, V.E. Kossenko, N.A. Anphimov, S.G. Revnivykh, S.B. Pisarev, A.E. Tyulyakov: The global navigation satellite system GLONASS: Development and usage in the 21st century, Proc. 34th PTTI Meet. 2002, Reston (DTIC, Fort Belvoir 2002) pp. 39–50
8.53 D.S. Ilcev: Cospas–Sarsat LEO and GEO: Satellite distress and safety systems (SDSS), Int. J. Satell. Commun. Netw. **25**(6), 559–573 (2007)
8.54 Th. Pirard: Space centres-launch sites: The USSR. In: *The Cambridge Encyclopedia of Space*, ed. by M. Rycroft (Cambridge Univ. Press, Cambridge 1990) pp. 126–127
8.55 Y. Tchourianov: *Baikonur – The Advent of a New Century* (Voennyi parad, Moscow 2005)
8.56 S. Revnivykh: GLONASS status and progress, Proc. CGSIC Meet., Savannah (2008)
8.57 V. Burmistrov, A. Fedotov, N. Parkhomenko, V. Pasinkov, V. Shargorodsky, V. Vasiliev: The Russian laser tracking network, Proc. 15th ILRS Workshop 2006, Canberra (2006) pp. 1–3
8.58 G. Stupak: SDCM status and plans, Proc. 7th Meet. Int. Comm. GNSS (ICG), Bejing (UNOOSA, Vienna 2012) pp. 1–15
8.59 Russian System of Differential Correction and Monitoring (SDCM): http://www.sdcm.ru/index_eng.html
8.60 V.V. Dvorkin, S.N. Karutin: Construction of a system for precise determination of the position of users of global navigation satellite systems, Meas. Tech. **54**(5), 517–523 (2011)
8.61 M.A. Sadovnikov, V.D. Shargorodskiy: Stages of development of stations, networks and SLR usage methods for global space geodetic and navigation systems in Russia, Proc 19th ILRS Workshop 2014, Annapolis (2014) pp. 1–23
8.62 Positioning, Navigation and Timing Information and Analysis Centre, GLONASS system status information: http://www.glonass-center.ru/en/
8.63 A.Y. Suslov, E.V. Titov, A.A. Fedotov, V.D. Shargorodskiy: System for high-accuracy determination of ephemeris and time corrections (SVOEVP) GLONASS, Proc. WPLTN Tech. Workshop One-Way Two-Way SLR GNSS Co-located RF Tech., St.Petersburg (2012) pp. 1–18
8.64 GLONASS navigation performance information: http://www.glonass-svoevp.ru/Func/plotnosti/
8.65 J.M. Dow, R.E. Neilan, C. Rizos: The International GNSS Service in a changing landscape of global navigation satellite systems, J. Geod. **83**(3/4), 191–198 (2009)
8.66 O. Montenbruck, P. Steigenberger, A. Hauschild: Broadcast versus precise ephemerides: A multi-GNSS perspective, GPS Solutions **19**(2), 321–333 (2015)
8.67 L. Heng, G.X. Gao, T. Walter, P. Enge: Statistical characterization of GLONASS broadcast clock errors and signal-in-space errors, ION ITM 2012, Newport Beach (ION, Virginia 2012) pp. 1697–1707
8.68 M. Fritsche, K. Sośnica, C.J. Rodríguez-Solano, P. Steigenberger, K. Wang, R. Dietrich, R. Dach, U. Hugentobler, M. Rothacher: Homogeneous reprocessing of GPS, GLONASS and SLR observations, J. Geod. **88**(7), 625–642 (2014)
8.69 A. Hauschild, O. Montenbruck, P. Steigenberger: Short-term analysis of GNSS clocks, GPS Solutions **17**(3), 295–307 (2013)
8.70 E. Griggs, E.R. Kursinski, D. Akos: Short-term GNSS satellite clock stability, Radio Sci. **50**(8), 813–826 (2015)