GLONASS: Review and Update

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GLONASS is a major player in the world's constellation of Global Navigation Satellite Systems (GNSS), which also includes the USA's Navstar GPS, the European Union's Galileo (or EGNOS), and China's Beidou. GLONASS is the oldest of the systems, with a constellation numbering 37 satellites. It is managed by the Russian Ministry of Defence and is used by the armed forces, with civilian use also being possible. The system is owned and operated by the Russian military and is used for military communications and navigation.

GLONASS is designed to provide global positioning, navigation, and timing services. It consists of a ground control segment, a space segment, and a user segment. The ground control segment is responsible for commanding and controlling the spacecraft. The space segment consists of a constellation of 37 satellites, and the user segment consists of receivers that use GLONASS signals to determine their position, velocity, and time.

GLONASS receivers are required for GLONASS and combined GPS/GLONASS receivers. Equipment for GLONASS includes receivers, antennas, and software to process the GLONASS signals. GLONASS receiver antennas are typically omnidirectional, allowing the user to receive signals from multiple satellites simultaneously.

The GLONASS system is managed by the Russian Ministry of Defence, and its signals are broadcast to the public. GLONASS is used in a wide range of applications, including military communications, navigation, and surveying. The system is also used for scientific research, including the study of the Earth's gravitational field and the Earth's quasigeoid.

GLONASS is a major system in the world's constellation of GNSS, and its signals are used by a wide range of users. The system is managed by the Russian Ministry of Defence, and its signals are broadcast to the public. GLONASS is used in a wide range of applications, including military communications, navigation, and surveying. The system is also used for scientific research, including the study of the Earth's gravitational field and the Earth's quasigeoid.
Table 1. Comparison of GLONASS and GPS nominal characteristics

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

Table 2. Planes, slots, and channels

<table>
<thead>
<tr>
<th>Plane 1</th>
<th>Slot: 01 02 03 04 05 06 07 08</th>
<th>Channel: 06 21 12 13 21 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane 2</td>
<td>Slot: 09 10 11 12 13 14 15 16</td>
<td>Channel: 06 09 04 22 06 09 04 22</td>
</tr>
<tr>
<td>Plane 3</td>
<td>Slot: 17 18 19 20 21 22 23 24</td>
<td>Channel: 24 10 03 01 24 10 03</td>
</tr>
</tbody>
</table>

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

SYSTEM CHARACTERISTICS

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

The Russians consider all satellites deployed thus far to be prototypes, of which there have been four models. Russia (actually the former Soviet Union) launched the first 10 satellites, called Block I, between October 1982 and May 1985. It sent up six Block IIa satellites between May 1985 and September 1986 and 12 Block IIb satellites between April 1987 and May 1988, of which six were lost because of launch vehicle–related failures. The fourth model was the Block IIv (v is the English transliteration of the Russian alphabet’s third letter). By the end of 1996, the Russians had deployed 43 Block IIvs. Each subsequent satellite generation contained equipment enhancements and also achieved longer lifetimes. The GLONASS-M Block II operational satellites are said to feature improved frequency and timing accuracies and to have expected lifetimes of five to seven years. They will also reportedly have the C/A-code on both L1 and L2. Russia expected to launch the first GLONASS-M satellite in 1995, but as of press time, this still has not occurred. The Almanac on page 55 shows the current GLONASS constellation status.
some of the GLONASS transmissions initially caused interference to radio astronomers, who study very weak natural radio emissions in the vicinity of the GLONASS frequencies. Radio astronomers use the frequency bands of 1610.6–1613.8 and 1660–1670 MHz to observe the spectral emissions from hydroxyl radical clouds in interstellar space, and the International Telecommunications Union (ITU) has afforded them primary user status for this spectrum space. Also, ITU has allocated the 1610–1626.5-MHz band to operators of low-earth-orbiting mobile communications satellites. As a result, the GLONASS authorities decided to reduce the number of frequencies used by the satellites and shift the bands to slightly lower frequencies.

Eventually, the system will use only 12 primary frequency channels (plus two additional channels for testing purposes). The bands will be shifted to 1598.0625–1604.25 and 1242.9375–1247.35 MHz. How can 24 satellites get by with only 12 channels? The solution is for antipodal satellites — satellites in the same orbit plane separated by 180 degrees in argument of latitude — to share a channel reserved for testing. Such a pair of satellites operating at 5 MHz. The signals are right-hand circularly polarized, like GPS signals, and have comparable signal strengths.

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

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

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

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

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

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

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

\[
\begin{bmatrix}
    x \\
    y \\
    z_{\text{WGS84}}
\end{bmatrix}
= 
\begin{bmatrix}
    1.6 \times 10^{-8} & -1.6 \times 10^{-8} & 0 \\
    1 & 0 & 0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    u \\
    v \\
    w_{\text{ITRF}}
\end{bmatrix}
\]

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

Pratap Misra and coworkers at the Massachusetts Institute of Technology's Lincoln Laboratory, in Lexington, have also determined a set of transformation parameters relating PZ-90 and WGS 84. Earlier, they had determined a preliminary transformation of 1985 and 1993 to 1980, which they planned to extend to 1998. They have developed a software tool, the International Geodetic Archive (IGA), to make this transformation available to researchers. They plan to publish the results in the coming months.

Table 3. GLONASS frequencies

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_1 = 1602 \text{ MHz} + k \times 0.5625 \text{ MHz} )</td>
<td>(k = 0, \ldots, 12, 22, 23, 24)</td>
<td>(k = -7, \ldots, 12)</td>
<td>(k = -7, \ldots, 4)</td>
</tr>
<tr>
<td>(f_2 = 1246 \text{ MHz} + k \times 0.4375 \text{ MHz} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where \(k = 0, 1, 2, \ldots, 24\) (0 — for testing only)

New satellites might use \(k = -7\) to \(-1\)
had determined the parameters relating SGS
85 and WGS 84. The scarcity of a widely dis-
tributed GLONASS receiver reference net-
work led the team to use a different approach
from that of Rossbach's group. Rather than
relating the coordinates of receivers on the
earth's surface in the two systems, they re-
lated the orbital positions of two GLONASS
satellites expressed in the two systems.
They obtained the satellites' positions in
the PZ-90 frame from the broadcast
ephemerides and those in the WGS 84 frame
from a global network of laser tracking
stations and radar systems. Estimates of one-,
two-, four-, and seven-parameter transforma-
tions revealed that only a rotation about the z-
axis and possibly an offset of the origin along
the y-axis were statistically significant.
Accordingly, Misra and coworkers report the
transformation as

$$
\begin{bmatrix}
0 & 2.5 \times 10^{-9} & -1.9 \times 10^{-6} \\
0 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

The major source of error in the transforma-
tion parameters is likely the broadcast
ephemerides.

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

**GLONASS RECEIVERS**

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

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

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

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

Outside the former Soviet Union, a num-
ber of manufacturers, research organiza-
tions, and universities have designed and built
GLONASS receivers. Some were prototypes,
developed to gain experience with GLO-
NASS. Others were receivers developed for a
specific application, such as use on low-
earth-orbiting satellites. At least two compa-
nies currently market GLONASS or GPS/
GLONASS receivers, including a dual-fre-
quency, C/A- plus P-code unit.

**GLONASS PERFORMANCE**

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

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

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

---

**Table 4. Defining parameters of the PZ-90 datum**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth rotation rate</td>
<td>$7.29215 \times 10^{6}$ $\text{rad s}^{-1}$</td>
</tr>
<tr>
<td>Gravitational constant</td>
<td>$398.60044 \times 10^{9} \text{m}^2 \text{s}^{-2}$</td>
</tr>
<tr>
<td>Gravitational constant of</td>
<td>$0.35 \times 10^{9} \text{m}^2 \text{s}^{-2}$</td>
</tr>
<tr>
<td>atmosphere</td>
<td></td>
</tr>
<tr>
<td>Speed of light</td>
<td>$299.792 \text{458 ms}$</td>
</tr>
<tr>
<td>Second zonal harmonic of the</td>
<td>$-1082.63 \times 10^{6}$</td>
</tr>
<tr>
<td>geopotential</td>
<td></td>
</tr>
<tr>
<td>Ellipsoid semimajor axis</td>
<td>$6.378 \text{136 m}$</td>
</tr>
<tr>
<td>Ellipsoid flattening</td>
<td>$1/298.257$</td>
</tr>
<tr>
<td>Equatorial acceleration of</td>
<td>$978.032.8 \text{mgal}$</td>
</tr>
<tr>
<td>gravity</td>
<td></td>
</tr>
<tr>
<td>Correction to acceleration of</td>
<td>$-0.9 \text{mgal}$</td>
</tr>
<tr>
<td>gravity at sea level</td>
<td></td>
</tr>
<tr>
<td>because of atmosphere</td>
<td></td>
</tr>
</tbody>
</table>

* At N42:27:34 W71:15:54
SELECTIVE AVAILABILITY (SA) in effect, as a comparison of Figure 1a with Figure 1b (GPS accuracies over 24 hours) clearly shows. However, with SA off (as it seemed to be most recently on April 20 when, perhaps coincidentally, the Air Force was looking for a crashed A-10 Thunderbolt II ["Warthog"] fighter-bomber attack jet in the mountains of Colorado), GPS accuracy is better than that of GLONASS.

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

**COMBINED GPS/GLONASS USE**

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

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

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

**OTHER DEVELOPMENTS**

With the anticipated global use of GLONASS alone or in combination with GPS, the Radiotechnical Commission for Maritime Services (RTCM), in conjunction with the Russian Institute of Radioavigation and Time, has added several differential GLONASS message types to the widely used RTCM SC-104 DGPS standard. The RTCA DO-217 differential GPS message format for aviation can also be used for differential GLONASS. Real-time meter-and, with adequate interchannel bias modeling, submeter positioning accuracy is possible using differential GLONASS pseudorange observations.
The developers of the popular Receiver-Independent Exchange (RINEX) format for raw GPS pseudorange and carrier phase data storage have extended the format to cover raw GLONASS data and the National Marine Electronics Association (NMEA) has extended the NMEA 0183 interface standard to accommodate GLONASS.

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

CONCLUSION
Although there are clearly some delays in the full, sustained deployment of GLONASS, it is currently a reliable positioning system for many applications. This reliability is enhanced through the use of combined GPS/GLONASS observations, which not only provides increased positioning accuracy compared with GPS-only use but also a means to check the integrity of both systems.

Further Reading
For further details about the GLONASS L1 "standard precision navigation signal," see
- For excellent, comprehensive reviews of GLONASS, see
- For current information on GLONASS, see the following Web sites:
  - Massachusetts Institute of Technology’s Lincoln Laboratory GLONASS Group <http://satnav.atc.ll.mit.edu/>.
  - Deutsche Forschungsanstalt für Luft- und Raumfahrt’s GLONASS Updated Information Service <http://www.rz.dlr.de/gps/glonass.html>.

All GLONASS users and potential users eagerly await the next spacecraft launch and the return to full-constellation operation.

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

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


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

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

CONCLUSIONS

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

Correction

Some of the Parametry Zenfi 1990 (PZ-90) datum parameter values listed in Table 4 of this column's July 1997 article, "GLONASS: Review and Update," are incorrect. Although these values are identified as pertaining to PZ-90 in the latest version of the GLONASS Interface Control Document (dated October 4, 1995), they actually pertain to its predecessor, the Soviet Geodetic System 1985. The correct PZ-90 parameter values, to be used with GLONASS ephemerides, are listed to the right. The inverse ellipsoid flattening is a rounding of the full precision value of 298.257 303. Note also that the sign of the geopotential second zonal harmonic, J2, is given here as positive in keeping with convention.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth rotation rate</td>
<td>7.2921 15 × 10^-7 radians s^-1</td>
</tr>
<tr>
<td>Gravitational constant</td>
<td>398 600 44 × 10^-10 m^3 s^-2</td>
</tr>
<tr>
<td>Gravitational constant of atmosphere</td>
<td>0.35 × 10^-9 m^3 s^-2</td>
</tr>
<tr>
<td>Speed of light</td>
<td>299 792 458 m s^-1</td>
</tr>
<tr>
<td>Second zonal harmonic of the geopotential</td>
<td>1082.6257 × 10^-6</td>
</tr>
<tr>
<td>Ellipsoid semimajor axis</td>
<td>6 378 136 m</td>
</tr>
<tr>
<td>Ellipsoid flattening</td>
<td>1/298.257 94</td>
</tr>
<tr>
<td>Equatorial acceleration of gravity</td>
<td>978 032.8 mgal</td>
</tr>
<tr>
<td>Correction to acceleration of gravity at sea level because of atmosphere</td>
<td>-0.9 mgal</td>
</tr>
</tbody>
</table>