# Computation of Precise GLONASS Orbits for IGEX-98

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**Abstract.** On October 19, 1998, at the beginning of the International GLONASS Experiment (IGEX-98), the Center for Orbit Determination in Europe (CODE) has started to compute precise orbits for all active GLONASS satellites. The campaign was initially scheduled for three months, but the activities still continue in September, 1999. One of the main reasons for this extension was the launch of three new GLONASS satellites at the end of the year 1998.

The processing of the IGEX network is done on a routine basis at CODE and precise ephemerides are made available through the global IGEX Data Centers. The improved GLONASS orbits are referred to the International Terrestrial Reference System (ITRF 96) and to GPS system time. They are therefore fully compatible with GPS orbits and allow a combined processing of both satellite systems.

All GLONASS satellites are equipped with a laser reflector array and the SLR ground network is tracking most of the GLONASS satellites. Comparisons of the GLONASS orbits computed by CODE with the SLR measurements show that the orbit accuracy is better than 20 *cm*.

**Keywords.** GLONASS, IGEX-98, Orbit Determination, System Time Difference

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## 1 The IGEX-98 Campaign

The main purpose of the IGEX-98 campaign was to conduct the first global GLONASS observation campaign for geodetic and geodynamic applications. The experiment took place under the auspices of the International Association of Geodesy (IAG), the International GPS Service (IGS), the Institute of Navigation (ION), and the International Earth Rotation Service (IERS). The campaign started on October 19, 1998 (GPS week 980), with a planned duration of 3 months. The IGEX-98 steering committee decided in a first step to extend the campaign for an additional three months, and in a second step to continue on a best effort basis the campaign activities till the IGEX-98 workshop in Nashville, USA (September 13–14, 1999).

The main objectives of the campaign (Willis et al. (1998)) are

- to test and develop GLONASS post-processing software,
- to determine GLONASS orbits with an accuracy of 1 meter or below, realized in a well defined Earth-fixed reference frame,
- to determine transformation parameters between the GLONASS reference frame (PZ-90) and the GPS reference frame (ITRF 96),
- to investigate the system time difference between GLONASS and GPS, and
- to collaborate with the SLR community to evaluate the accuracy of the computed GLONASS orbits.

A map of the IGEX-98 network as used by CODE for orbit determination processing may be found in Figure 1. Only the sites providing dual-frequency GLONASS data are shown on the map (and only those sites were used for the processing). Most of the sites are located in Europe. The connection to the receivers located in other parts of the World is quite weak (using observations on the double difference level). The map shows all used sites during the campaign (about 35 sites). For some weeks, however, the number of available sites decreased to 20.

The measurement data of these sites are collected and made available at five Regional and two Global Data Centers (Noll (1998)). Until now, six Analysis Centers were or are making use of the data for computing improved GLONASS orbits.

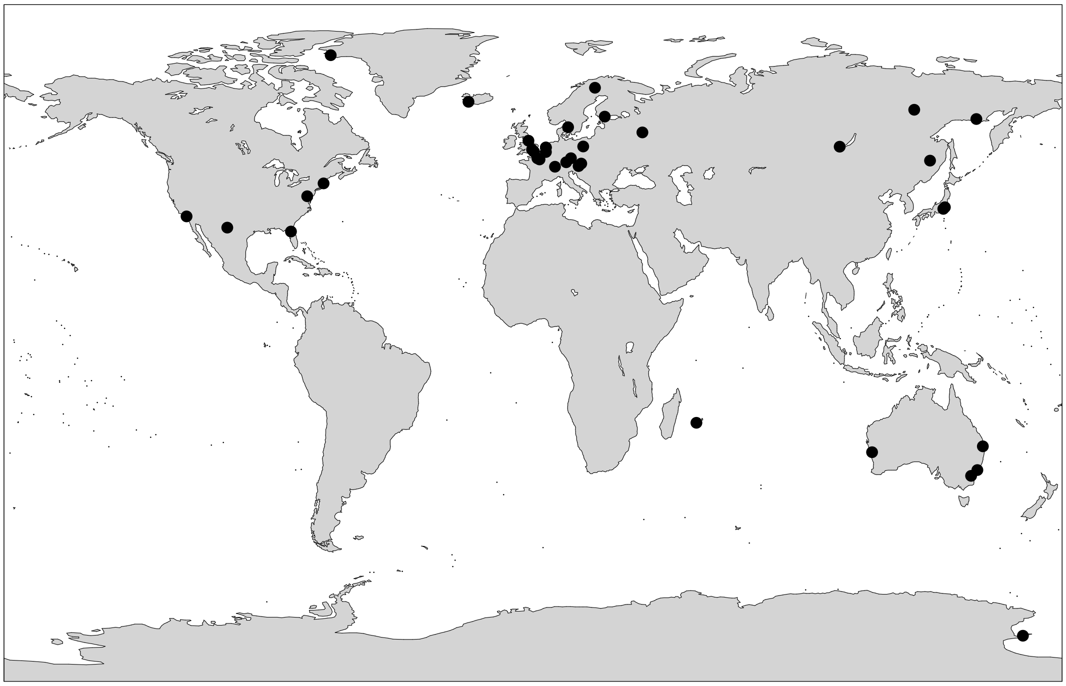

**Figure 1.** IGEX Observation Network as used by the CODE Analysis Center.

## 2 Determination of Precise GLONASS Orbits

### 2.1 Processing Strategies

For the combined processing of GLONASS and GPS data the enhanced Version 4.1 of the Bernese GPS Software is used, see Rothacher and Mervart (1996), Habrich (1999). The analysis is done by fixing both, the GPS orbits and Earth rotation parameters to CODE's final IGS solutions. The orbital parameters for the GLONASS satellites are estimated using double difference phase observations (including double differences between GLONASS and GPS satellites). The processing of the IGEX network is done without fixing the ambiguities to their integer values.

Six initial conditions and nine radiation pressure parameters are determined for each satellite and arc. Pseudo-stochastic pulses have been set up every 12 hours for test purposes, but have been constrained to zero for the official CODE solution. Only receivers providing dual-frequency GPS and GLONASS data or dual frequency GLONASS data are included in the processing procedure. The final precise orbits stem from the middle day of a 5-day arc. The satellite clock values included in the precise orbit files are broadcast clock values for the GLONASS satellites, because no satellite clock estimation is performed so far. In order to align the GLONASS orbits to the terrestial reference frame the coordinates of five sites (Greenbelt, Kiruna, Metsahovi, Onsala, Yaragadee, and Zimmerwald), are constrained to their ITRF 96 coordinates.

### 2.2 Quality Assessment

**Long arc fits**

In order to check the internal consistency of our precise GLONASS orbits, we perform a long-arc fit for each processed week. For each satellite, one orbital arc is fitted through the seven consecutive daily solutions of the week. As an example, the result of such a long arc fit is given in Table 1 for GPS week 1002. The Table shows the rms of this fit for each satellite and day. In the last

**Table 1.** Orbit Repeatability from a 7-day Fit through Daily Orbit Solutions (Days 80–86, 1999, RMS Values in [cm]).

| Slot No. | 1 | 3 | 4 | 6 | 7 | 8 | 9 | 10 | 11 | 13 | 16 | 17 | 20 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DOY 80 | 5 | 6 | 10 | 11 | 8 | 8 | 7 | 18 | 11 | 8 | 15 | 8 | 10 | 8 |
| DOY 81 | 5 | 4 | 5 | 6 | 7 | 7 | 7 | 9 | 6 | 7 | 9 | 5 | 5 | 6 |
| DOY 82 | 6 | 5 | 3 | 8 | 5 | 6 | 7 | 9 | 9 | 8 | 7 | 7 | 8 | 6 |
| DOY 83 | 5 | 3 | 6 | 7 | 6 | 6 | 4 | 6 | 7 | 11 | 10 | 5 | 5 | 6 |
| DOY 84 | 6 | 6 | 5 | 6 | 5 | 6 | 6 | 6 | 12 | 9 | 7 | 5 | 6 | 4 |
| DOY 85 | 6 | 4 | 6 | 6 | 6 | 4 | 7 | 9 | 7 | 7 | 5 | 4 | 4 | 5 |
| DOY 86 | 6 | 4 | 5 | 9 | 6 | 5 | 10 | 18 | 16 | 11 | 14 | 7 | 5 | 6 |
| Week | 6 | 5 | 6 | 8 | 6 | 6 | 7 | 12 | 10 | 9 | 10 | 6 | 7 | 6 |

line ("Week") the rms of the whole 7-day fit is included for each satellite.

The values of this overall rms are normally between 5 and 20 cm. On the one hand it must be stated that these values might be too optimistic because we fit the middle days of 5-day arcs with a 7-day arc. On the other hand the small values indicate that the adopted orbit model is well suited to describe the motion of the GLONASS satellites over a time period of several days.

### Comparison with the Precise Orbits of Other IGEX Analysis Centers

The IGEX Analysis Center Coordinator R. Weber (Technical University of Vienna) is in charge of comparing the precise GLONASS orbits stemming from the six IGEX-98 Analysis Centers providing precise GLONASS orbits. In addition, he combines the Analysis Centers' precise GLONASS orbits into one official IGEX orbit product. The results of this combination procedure are distributed via IGEX mail and can be found on the following Web page:

`http://lareg.ensg.ign.fr/IGEX/IGEXMAIL/`

At present, combined orbits of ten weeks (0980–0989) are made available at the Global IGEX Data Center at CDDIS. The results of the first ten weeks of orbit comparison confirm that the reached orbit quality is of the order of 20 *cm*.

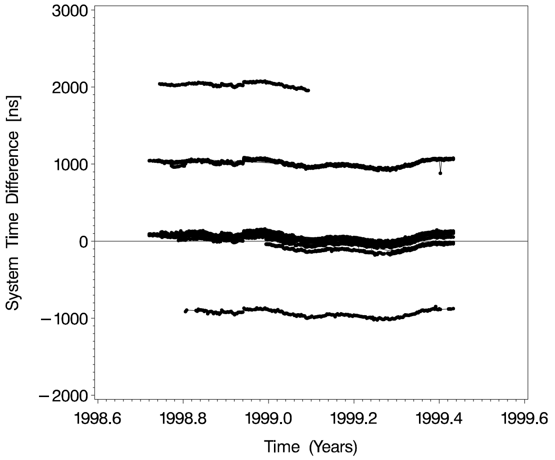

**Figure 2.** System Time Difference Estimated with Different Receiver Types.

### Comparison with SLR Measurements

The comparison of CODE's precise GLONASS orbits with SLR measurements is a fully independent quality check and therefore very valuable for checking the quality of GLONASS orbits determined by means of microwave signals. This method of quality assessment also shows that the precise GLONASS orbits of CODE are on a $10-20$ *cm* accuracy level. More details are given in Section 5 of this report.

## 3 System Time Difference between GLONASS and GPS

When processing GLONASS and GPS data we are setting up one additional parameter for each station and session in our pseudorange pre-processing step: the difference between GLONASS and GPS system time. The estimation is done in the following way: we use broadcast orbits for both systems, estimate the site coordinates and the time offset between GPS and GLONASS once per session and, as usual, one receiver clock correction for each epoch.

What kind of components are contributing to the estimated system time difference? On the one hand we have the difference between the national realizations of UTC (Universal Time Co-

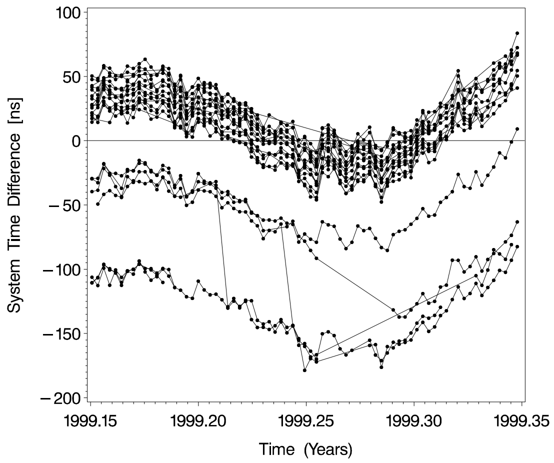

**Figure 3.** Detail of Figure 2: System Time Differences of the Z18 and JPS Receivers.

ordinated) on which the GLONASS and GPS system times are based: UTC (USNO, Washington DC) and UTC (SU, Moscow). Values for the difference between these national time references and UTC are published in the Circular T of the Bureau International des Poids et Mesures (BIPM (1999)). In July 1999, the difference between UTC (USNO) and UTC is below 10 nanoseconds and the difference between UTC (SU) and UTC below 100 nanoseconds. On the other hand we have to take into account the differences between GPS system time and UTC (USNO) and GLONASS system time and UTC (SU).

When comparing the time offsets resulting from the IGEX network processing, it becomes clear that we do not have direct access to the pure difference between GPS and GLONASS system time, but that receiver type specific offsets have to be taken into consideration as well. Figure 2 shows the estimated system time differences for different receiver types covering a time span from September 20, 1998 to June 6, 1999 (260 days). Each line represents a different receiver type. Starting from bottom to top:

- ESA prototype receiver at Leeds, UK (about $-900$ *ns*)
- JPS receivers (about $-50$ *ns*)
- Ashtech Z18 receivers (about 50 *ns*)
- 3S Navigation receivers (about 1000 *ns*)
- Ashtech GG24 receiver (about 2100 *ns*)

The differences between different receivers types are of the order of one microsecond.

Figure 3 shows a detail of Figure 2: the time differences of the Z18 and JPS receivers during a time period of 73 days. The lower two bands represent the JPS receivers, the upper one the Z18 receivers. The time series of the individual stations are highly correlated. It is interesting to note the jumps of three JPS receivers from the medium level to the lower level. These jumps are correlated with software upgrades. The firmware of the JPS receiver at Zimmerwald, Switzerland was, e.g., upgraded from Version 1.4 to Version 1.5 and shows at that time a jump in the estimated system time differences of about $-40$ *ns* (between doy 093 and doy 106, 1999).

## 4 Transformation Parameters Between the two Reference Systems

In principle, there are two possibilities for the determination of transformation parameters between the GLONASS and the GPS reference system: One is based on coordinate sets which are determined in both systems, and the other is based on the comparison of satellite orbits available in both systems. Here, we present results stemming from the orbit comparison method.

Seven Helmert transformation parameters were determined using precise GLONASS orbits in the ITRF 96 reference frame and the broadcast GLONASS orbits in the PZ-90 reference frame. For each day one set of parameters (three translations, three rotations, and one scale factor) was established. Figure 4 shows the time series of the rms values, the translation parameters, and the rotation parameters. Using the described method, the accuracy of the transformation parameters is limited by the quality of the GLONASS broadcast orbits. The rms of the daily Helmert transformations (between 3 *m* and 6 *m*) may be interpreted as indicators of the broadcast orbit quality.

Mean values and standard deviations for each of the seven Helmert parameters and for the entire time series are summarized in Table 2. In particular, the rotation around the z-axis definitely has to be taken into account when processing combined GLONASS and GPS data. A rotation of $-350$ *mas* around the z-axis cor-

**Table 2.** Mean Values and RMS of the Daily Helmert Transformation Parameters for the Transition from PZ-90 to ITRF 96.

| Parameter | | Mean | RMS |
|---|---|---|---|
| X–Translation | [m] | -0.03 | 0.23 |
| Y–Translation | [m] | -0.02 | 0.27 |
| Z–Translation | [m] | -0.45 | 0.47 |
| X–Rotation | [mas] | 37 | 6 |
| Y–Rotation | [mas] | -10 | 8 |
| Z–Rotation | [mas] | -350 | 21 |
| Scale Value | [ppb] | 13 | 3 |

responds to a maximum satellite position offset of about 45 *m* (if the satellite is close to the equatorial plane). This (and other) transformation parameters are highly significant.

## 5 Comparison of Precise GLONASS Orbits With SLR Measurements

All GLONASS satellites are equipped with a laser retroreflector array. It is an interesting and important aspect of the IGEX-98 campaign that the SLR community was and still is very active in observing the GLONASS satellites: measurements to nine GLONASS satellites were performed during the first six months of the IGEX-98 campaign. At present, during the extended phase of the test campaign, three GLONASS satellites are still tracked by the SLR community. The SLR measurements are completely independent on the orbit determination process based on microwave signals. Comparisons between SLR measurements and improved orbits are therefore an important measure for the achieved quality of the precise GLONASS orbit determination using the microwave observations.

At CODE, we access the SLR data in the quick look format and convert them to the Bernese format. For the comparison of GLONASS orbits with SLR measurements, the residuals between SLR measurements and computed distances (derived from our GLONASS precise orbits and the SLR site coordinates) are analyzed. In addition, one constant offset is estimated for all SLR distances and removed from the residuals.

Figure 5 shows the residuals of the SLR measurements with respect to the GLONASS broadcast orbits and with respect to the CODE final IGEX orbits (middle day of a 5-day arc) over

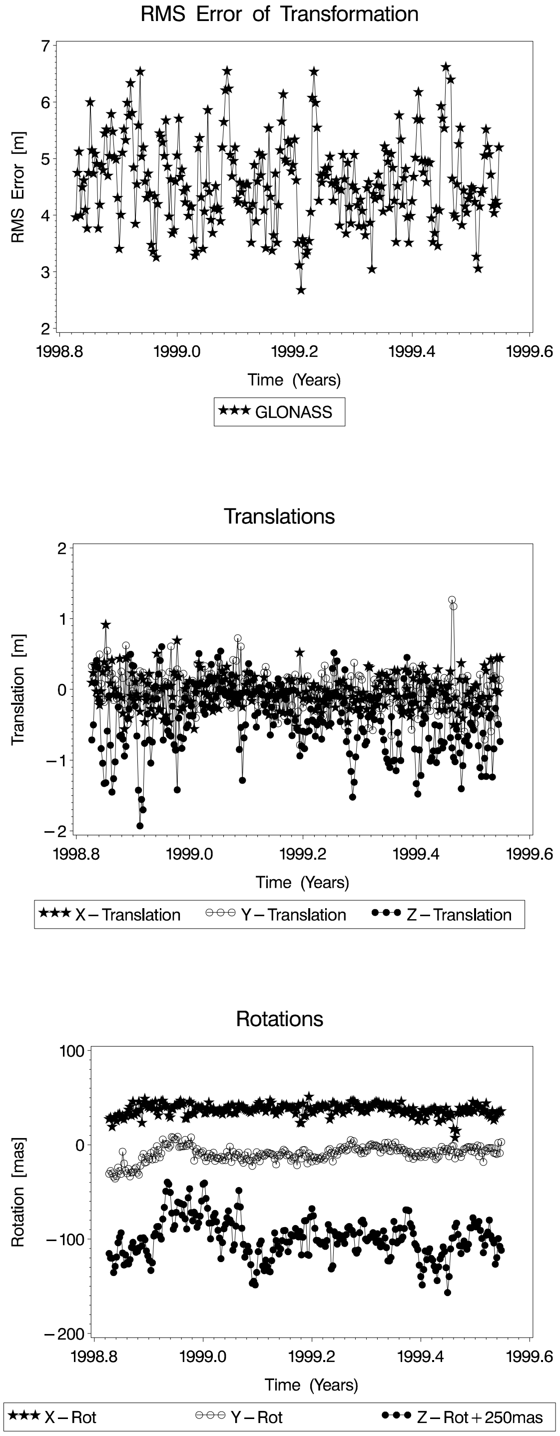

**Figure 4.** RMS, Translation Parameters, and Rotation Parameters of the Helmert Transformation between Broadcast Orbits in the PZ-90 System and CODE's Precise Orbits in the ITRF 96 System.

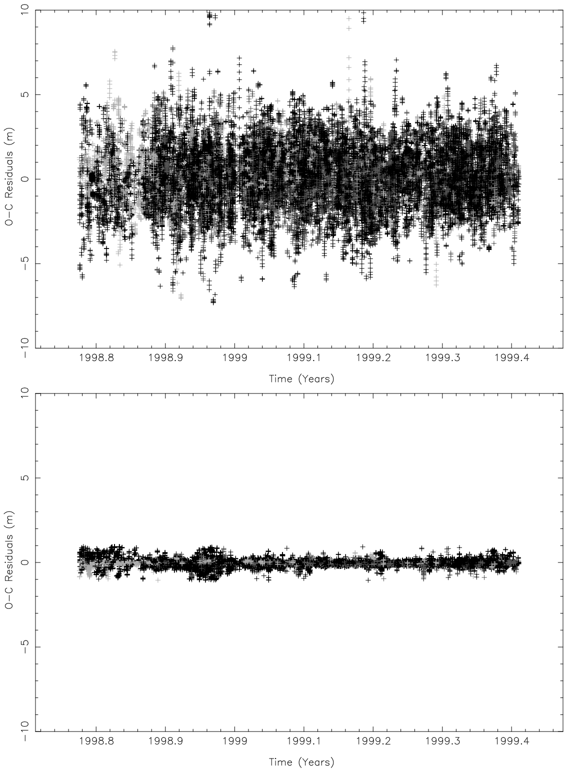

**Figure 5.** Comparison of Broadcast GLONASS Orbits (top) and CODE's Precise Orbits (bottom) with SLR Measurements.

a time span of 230 days (October 10, 1998 to May 29, 1999). The rms decreases from $1,67$ *m* (broadcast orbits) to 0.13 *m* (precise orbits), which proves that we are not only changing the orbits, but actually improve them. An offset of 42 *mm* between improved orbits and SLR measurements was determined (SLR distances are shorter than the distances derived from the CODE orbits). It is interesting to note that this offset agrees well with the offset found for SLR measurements with respect to the GPS orbits (55 *mm*). The reason for this offset is not yet understood.

A comparison of SLR measurements was also done with respect to daily orbits stemming from the mid day of a 3-day arc. The smaller rms of our 5-day solution compared to the 3-day solution is the reason for submitting the mid day of a 5-day arc as CODE's official IGEX orbit product.

## 6 Outlook

In September 1999 an IGEX Workshop will be held at Nashville, USA, where the IGEX Analysis Centers have the opportunity to present their results using IGEX network data. In addition, at this workshop the decision will be made whether or not this global GLONASS experiment will continue and what will be the organizational form for such a project.

On the technical side, there are several issues waiting for investigation, such as:

- Tests concerning the parameterization of GLONASS orbits (reduction of the number of estimated radiation pressure parameters, estimating stochastic pulses).
- Introduction of ambiguity fixing for GLONASS phase measurements within the IGEX network.
- Combination of processing of IGS and IGEX data in one step. Study of the impact of such a combined processing on global parameters, especially on Earth rotation parameters.

A densification of the global dual-frequency receiver network would certainly significantly contribute to the improvement of the accuracy of the estimated GLONASS orbit.

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