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The international GLONASS experiment: products, progress and prospects

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Abstract. In October 1998 the IGEX field campaign, the first coordinated international effort to monitor GLONASS satellites on global basis, was started. Currently about 40 institutions worldwide support this effort either by providing GLONASS tracking data or in operating related data and analysis centers. The increasing quality and consistency of the calculated GLONASS orbits (about 25 cm early in 2000), even after the end of the official IGEX field campaign, are shown. Particular attention is drawn to the combination of precise ephemerides in order to generate a robust, reliable and complete IGEX orbits product. Some problems in modeling the effect of solar radiation pressure on GLONASS satellites are demonstrated. Finally, the expected benefits and prospects of the upcoming International GLOnass Service-Pilot Project (IGLOS-PP) of the International GPS Service (IGS) are discussed in more detail.

Key words: Orbit Modeling – GLONASS – IGLOS

1 Introduction

In October 1998 the IGEX field campaign, the first coordinated international effort to monitor GLONASS satellites on a global basis for geodetic and geodynamic applications, was launched. This ‘International GLONASS Experiment’, basically scheduled as a three-month campaign, was proposed as a joint project of the following:

(1) the CSTG (International Coordination of Space Techniques for Geodesy and Geodynamics);
(2) the IGS (International GPS Service);
(3) the ION (Institute of Navigation);
(4) the IERS (International Earth Rotation Service).

In December 1998, due to the launch of three more GLONASS satellites (increasing the number of active satellites for a short period from 12 to 15), it was decided to extend IGEX until at least April 1999. About 75 organizations agreed to contribute to IGEX in various areas of responsibility. More than 65 proposals dealt with the installation and operation of permanent tracking sites, comprising slightly more combined dual-frequency than single-frequency receivers. In the end, most of these stations (80%) became operational. Over the period of the main campaign the station network consisted of about 30 dual-frequency and 15 single-frequency receivers (Slater et al. 1999; Willis et al. 2000).

Two global and five regional data centers were established to guarantee a smooth data flow. The station representatives were asked to forward IGEX data to the next data center (according to the data flow diagram) within 48 hours of the end of the UT day. These activities were supervised by the IGEX data flow coordinator, C. Noll.

Frequently expressed fears that the status of the operational network would become an element of uncertainty after April 1999 finally turned out to be baseless. Most institutions (operating tracking stations as well as data and analysis centers) agreed to continue their contribution on a best-effort basis. Tracking data, for example, of about 20 dual-frequency and 10 single-frequency receivers is still available today. Figure 1 shows the status of the IGEX network on 1 December 1999. Unfortunately the irregular distribution of the sites, centered in the European region, was and still is not satisfactory and is by no means comparable to the current IGS/GPS network. For a complete list of station names and locations see, for example Noll (2000) and Habrich (2000a).

In September 1999 an IGEX workshop took place in Nashville, Tennessee in order to verify whether if substantial objectives of this project had been achieved. The results may be summarized as follows.

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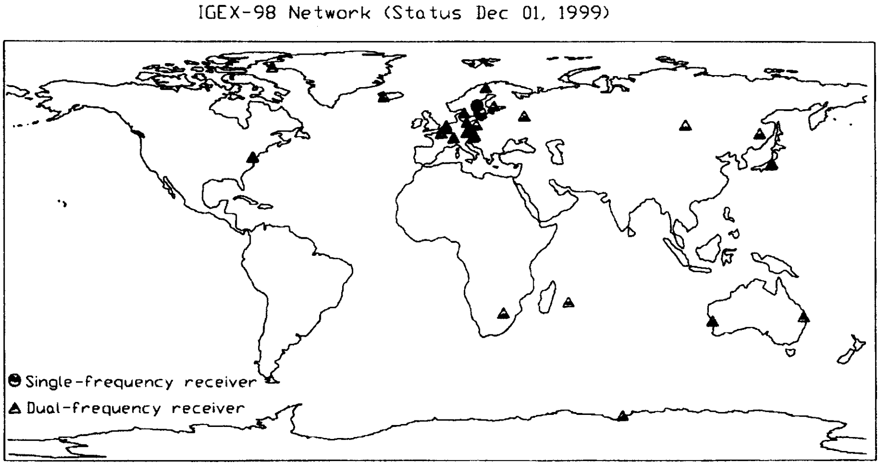

Fig. 1. GLONASS tracking station network

Calls for the determination of GLONASS satellite orbits with 1-m accuracy or better and for the investigation of the (receiver) clock difference between GPS and GLONASS have been fulfilled by far. Processing software which enables the combination of GLONASS and GPS phase data has been developed by several groups at various levels. Compared to the GPS SV35 and SV36, GLONASS satellites are, due to their large corner cubes, simple targets for satellite laser ranging (SLR) tracking stations. This fact allows for the validation of the results obtained from microwave data by means of an independent technique, demonstrated with minor restrictions by Glotov et al. (2000). In terms of setting up a really dense and global GLONASS observation network, the community failed. This situation should improve with the upcoming International GLONASS Service-Pilot Project (IGLOS-PP) (see Sect. 4). On the part of hardware there is still a need for the determination of more accurate phase-center variations of GPS/GLONASS antennas. In terms of orbit accuracy, special emphasis has to be laid on the evaluation of more sophisticated radiation pressure models in the near future. Also, an independent integrity monitoring of the satellites might be an upcoming need.

2 Data analysis and orbit combination

An important role for the success of the experiment falls to the Analysis Center (AC) working groups. Six analysis groups comprising the BKG (Federal Bureau for Cartography and Geodesy), CODE (Center of Orbit Determination, University of Berne), ESA/ESOC (European Space Operations Center), GFZ (Geoforschungszentrum Potsdam, Wks 980-1002), JPL (Jet Propulsion Laboratory, Wks 991-1006) and MCC (Mission Control Moscow) were willing to calculate regularly precise satellite orbits (at least over a limited number of weeks).

Since the MCC solution is solely based on laser distance measurements, the delivered ephemerides are restricted to the number of satellites tracked by the ILRS (nine satellites from October 1998 through April 1999). After the end of the official IGEX-98 campaign ILRS returned to tracking only three satellites (generally one satellite per GLONASS orbital plane but in particular dependent on the varying health status of the satellites and on the analysis needs). This independent orbit computation should allow for the detection of systematic differences between both techniques on condition that the biases are larger than the obtained orbit quality. The coordinate RMS of overlapping arcs might be seen as an indicator of the orbit quality of the individual center submissions. Currently these numbers, given in the weekly summary files, range from 10 to 30 cm per satellite.

Orbital information is delivered by the ACs in the well-known SP3 format (version b allows for GLONASS and mixed GPS/GLONASS orbit files). The given satellite clocks are usually broadcast values. The ESA submission, based on undifferenced measurements as basic variable, makes an exception and provides precise clock information at the nanosecond level (Garcia et al. 2000).

Concerning the reference frame, a strategy common to all ACs is to introduce and to hold fixed GPS orbits and ERPs (Earth Rotation Parameters) from the final IGS solution (or from the AC–IGS submission). In addition, the coordinates of one (or a few) station(s) are fixed to their ITRF96 (since August 1999: ITRF97) values. Three ACs, namely ESA (uninterrupted since October 1998), GFZ (11 weeks) and JPL (15 weeks) provided minimally constrained coordinate solutions in SINEX format. All center-specific precise orbit solutions as well as corresponding SINEX files are available on the Crustal Dynamics Data Information System (CDDIS).

Initially, because of the considerable workload within the ACs, precise GLONASS orbit information was distributed with a delay of 10 weeks or more. The situation became worse in summer 1999 (around weeks 1010–1025). Figure 2 shows this delay of the weekly center submissions. On the other hand, most of the user groups (e.g. the timekeeping community, time transfer applications) requested ephemerides within four weeks or less.

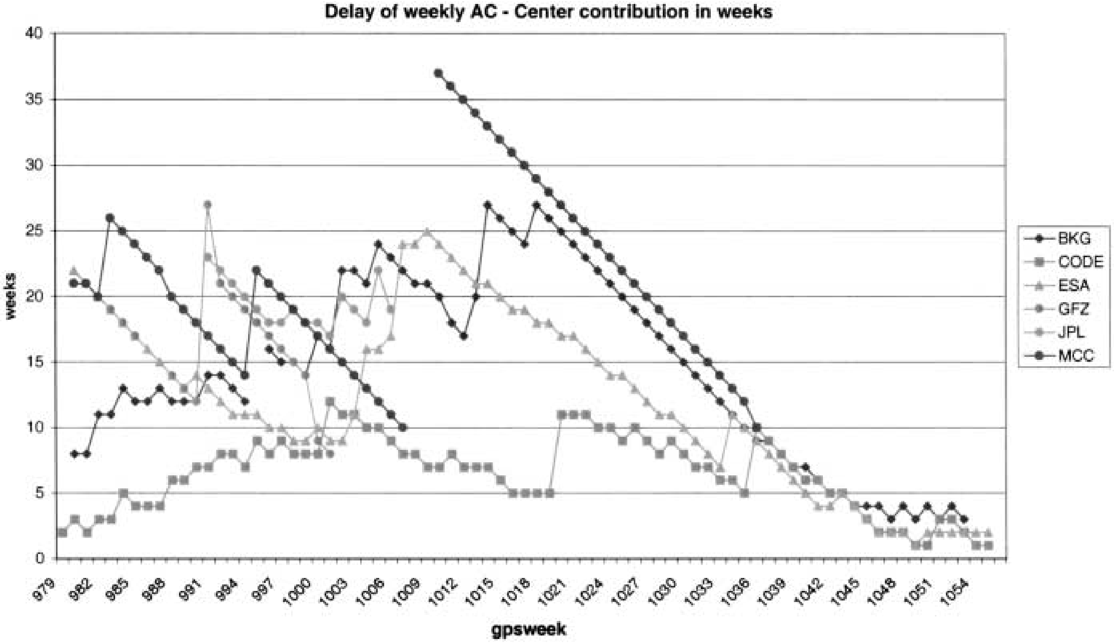

Fig. 2. Delay of center submission in weeks

The situation improved considerably at the end of 1999 when the AC representatives agreed at the Nashville workshop to speed up computations and to deliver their orbit solutions within 3–5 weeks of observation. Since January 2000 (week 1042), the remaining delay of the center submissions has never exceeded four weeks.

Since GPS week 980, a combined GLONASS Orbit (IGX), based on the individual precise center solutions, has also been made available to the user community. The advantages of such a combination are that it fosters reliability of the orbit product and considers all satellites, which show up in at least one center solution. The basic principles of the combination are outlined roughly as follows.

At the start (weeks 980–1005) the combination process was based on long-arc fits of the individual center submissions. Satellite positions were used as pseudo observations to establish seven-day arcs and afterwards the center weights were calculated from the post-fit residuals. Unfortunately this weighting scheme favoured extremely center solutions based on increased arc lengths (five days or more).

Later on, a combination strategy more similar to the IGS–GPS combination (Beutler et al. 1995) was applied. Common to both combination schemes is that the Earth Orientation Parameters (EOPs) are fixed to the values of the final IGS combination of the week and (contrary to the IGS–GPS combination) the satellite clocks given in the IGX SP3 files are broadcast values.

Springer and Beutler (1993) presented a similar scheme, which obtains the combined orbits as daily weighted averages of the ephemerides computed by different ACs. Daily center- and satellite-specific weights are calculated from the RMS errors of a Helmert transformation between an unweighted mean for every satellite position and the individual center solutions. Again, the orbits are combined in the ITRF system. For details, see Weber and Fragner (2000).

The IGX precise ephemerides and weekly reports can be retrieved from the global IGEX data centers (e.g. CDDIS). The report files contain comprehensive information on the quality and consistency of the individual center solutions. For example, the seven parameters of a daily-performed spatial Helmert transformation with respect to the combined orbit and the center-specific RMS of this transformation are listed (see Fig. 3).

The graphics clearly show a continous improvement in the consistency of the submitted orbit solutions. For a detailed description of the individual data analysis techniques of the ACs we refer to Slater et al. (2000). In summary, the ACs base their computation on different data types (microwave phase and code data, laser ranges), different observables (zero and double differences), a varying parametrization of the force field (two, five or nine parameters to characterize solar radiation pressure; in addition, stochastic pulses/revolution and different arc lengths (3 days up to 8 days). Nevertheless, all of them were able to estimate GLONASS orbits well below the 1-m accuracy level and were consistent at about 40 cm from the start. In this context we may ask how the reduction in the number of tracking sites (since May 1999, just after the basic field experiment) degrades the quality of the GLONASS ephemerides and satellite clock estimates. Contrary to expectations, Fig. 3 indicates a slight but continous improvement of the microwave orbit solutions. Currently, precise GLONASS ephemerides with an internal consistency of about 25 cm are available from the various ACs. This might be explained first by the growing experience of all centers in handling the GLONASS data and, second, by the fact that the reduction of sites concerns primarily single-frequency receiver sites and most of the stations equipped with dual-frequency receivers have resumed operation. The quality of the MCC solution again is solely dependent on the laser tracking data whose availability is governed by weather conditions and ILRS tracking priority. As mentioned previously, precise satellite clock information is available from the ESA submission which is based on undifferenced observables.

It is worthwhile to have a closer look at the scale and rotation parameters estimated to align the individual center solutions to a common frame. They reflect, of course, to a significant extent the weights given to the center submission in the combination process. However, some strange features which originate from differences in the orbit parametrization may be detected. Figure 4 shows in particular the scale parameter with respect to the combined orbit. Numbers are usually at the ±4 ppb level, but some deviations up to 12 ppb in the BKG solution can be related to periods of exceptional orbit geometry and most likely result from differences in the solar radiation pressure modeling (see Sect. 3).

Figure 5a–d shows the rotations with respect to the combined orbit. Rotations ωx, ωy are very small for all center submissions, never exceeding the ±1 mas level. ωz rotations are at the 2–3 mas level. Again the amplitudes not necessarily indicate an orbit mismodeling; they also reflect the weight of the submission determined from 'majority voting'. ωz rotations of the ESA submission seemed to be affected by a small yearly signal (Fig. 5c). The most prominent jumps (up to 6 mas) show up in the ωz rotation of the MCC ephemerides (Fig. 5d).

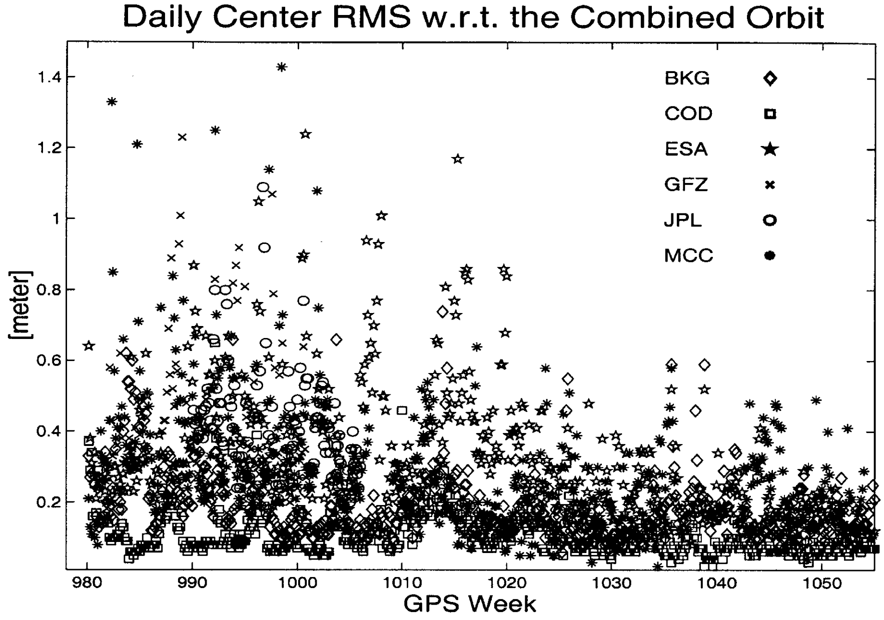

Fig. 3. Period GPS week 980–week 1054 (Oct 1998–Mar 2000)

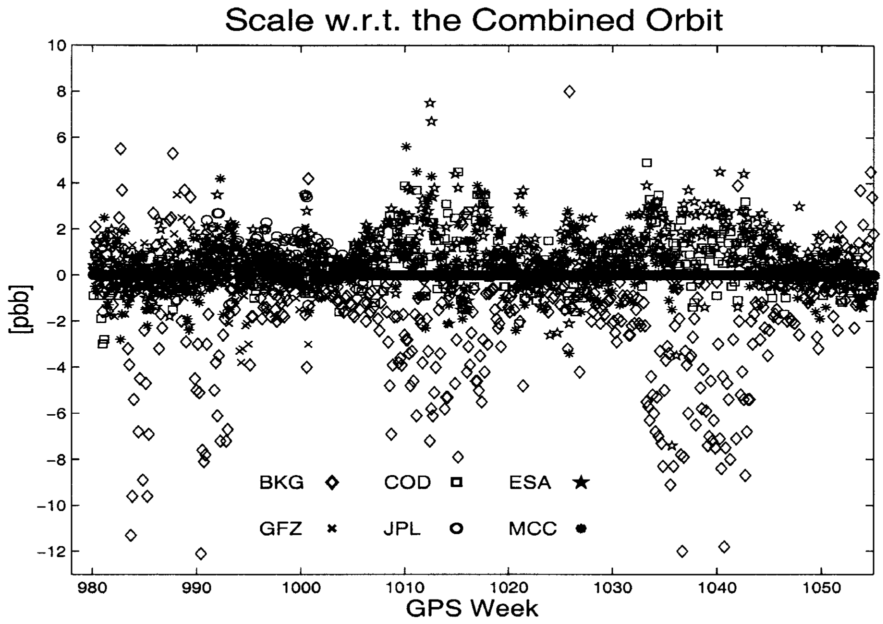

Fig. 4. Scale parameter

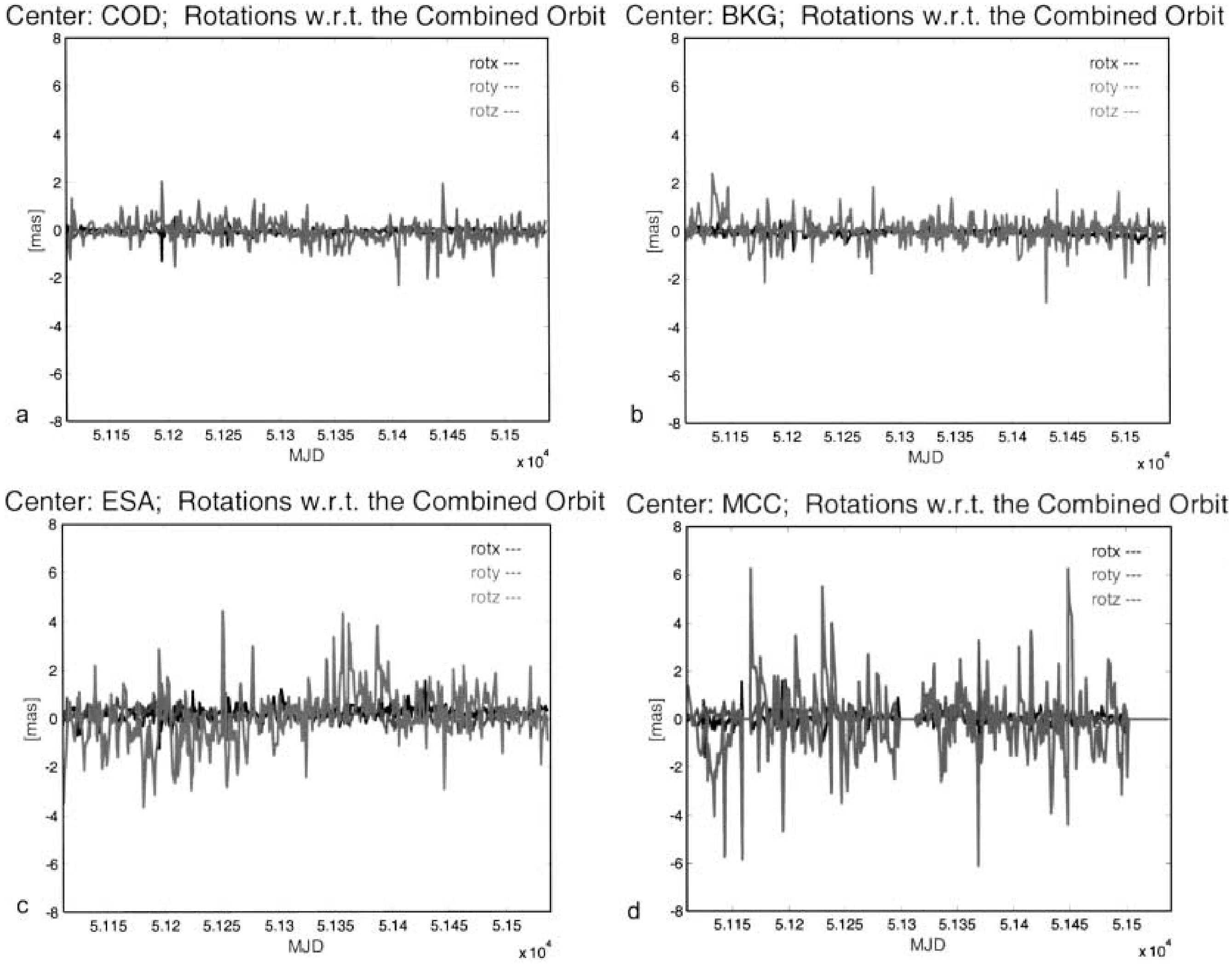

Fig. 5. Rotation with respect to the combined orbit (note the uniform scaling of **a–d**)

The 8-day period coincides with the arc length of these solutions.

3 Radiation pressure model

The solar radiation pressure is a major error source in GLONASS orbit modeling. Fortunately, most of the ACs have a lot of experience in handling this effect because various parametrizations have been tested to describe GPS orbits over recent years. Besides the famous Rock 4/42 models (Fliegel et al. 1992), pure empirical models with two, five or nine or even more parameters are available for the GPS (see e.g. Springer et al. 1998), sometimes in combination with additional stochastic accelerations (in the body-fixed system).

At first glance, similar models are in use to characterize solar radiation pressure acting on the GLONASS satellites, with the exception that until now data analysts have not normally made use of Rock 4/42 as a priori information. For example, the ESA/ESOC analysis group estimates in a solar frame (model and unit vectors as described below) a constant term per coordinate axis and in addition both periodic accelerations in B-direction (Garcia et al. 2000). Contrary to the model below, the ESOC group selects the solar angle as argument, which is the argument of latitude corrected for the latitude of the Sun in the orbital plane (see also Rothacher et al. 1995). At the JPL AC the solar radiation pressure force is modeled by a scale factor, a constant Y bias and stochastic accelerations (Da Kuang et al. 2000).

Although the combined IGX-orbit originates from a weighted mean (not from a dynamical fit), it satisfies the equation of motion under the assumption that the sum of the center weights equals 1. In our approach the IGX satellite positions of seven consecutive days (GPS week) were input to an LS adjustment (pseudo-observations) to establish best-fitting satellite arcs and to validate the combined orbit.

The acceleration a_{rpr} due to the solar radiation pressure has been modeled as (Beutler et al. 1994; Springer et al. 1998)

$$a_{\mathrm{rpr}} = D(u) \cdot \mathbf{e}_D + Y(u) \cdot \mathbf{e}_Y + B(u) \cdot \mathbf{e}_B$$

with

$$D(u) = a_{D0} + a_{DC} \cdot \cos(u) + a_{DS} \cdot \sin(u)$$
$$Y(u) = a_{Y0} + a_{YC} \cdot \cos(u) + a_{YS} \cdot \sin(u)$$
$$B(u) = a_{B0} + a_{BC} \cdot \cos(u) + a_{BS} \cdot \sin(u)$$

and

$\mathbf{e}_D$	the unit vector Sun–satellite
$\mathbf{e}_Y$	the unit vector pointing along the spacecraft's solar panels axis
$\mathbf{e}_B$	the unit vector in direction $\mathbf{e}_B = \mathbf{e}_Y \times \mathbf{e}_D$
u	the argument of latitude
a_{i0}	the constant terms in the three orthogonal axes
a_{iC}, a_{iS}	the periodic coefficients in the three axes.

Note that the *Y* direction of this system corresponds to the *Y* direction of the traditional body-fixed system. The complete set of nine coefficients has been estimated for each satellite and each week. The behavior of the constant direct term and the traditional *Y* bias are shown in Figs. 6 and 7. The diagrams in Figs. 6 and 7 distinguish between satellites in the three orbital planes (plane I: dotted; plane II: dashed; plane III: solid line). Neither diagram includes SVN 758 (Slot 18), which showed a considerably smaller (about 60%) constant direct radiation pressure coefficient (SVN 758 has been out of operation since March 1999). SVNs 778, 779, 784, and 786 (Slots 15, 1, 8, and 7) became operational during the period considered here.

First of all we recognize the similar behavior for all satellites in the same plane. The direct solar radiation pressure acceleration is usually about $110 \cdot 10^{-9}$ m/s^2 (the negative sign in Fig. 6 is due to the orientation of the coordinate axis), the *Y* bias is of the order of $0.2 \cdot 10^{-9}$ m/s^2. The latter is significantly smaller than the corresponding value for GPS satellites. The constant term in B direction (not shown here) is larger by a factor of 2–4 than the *Y* bias, but more poorly determined.

Moreover, noticeable in Fig. 6 are distinct peaks at weeks 988, 1013, and 1039, indicated by all satellites of plane II. Later we will explain these 'jumps' with a special orbital geometry and slightly enlarged sigmas of a_{D0}. The *Y* bias shows a completely different behaviour. Compared to planes I and III this value is very well determined for satellites in plane II around week 988, while 3 months later the RMS of a_{Y0} increases considerably.

In order to interpret these features we need to look at the eclipsing periods of the three orbital planes between October 1998 and December 1999. Plane I satellites enter the central eclipsing phase at weeks 985, 1010, and 1035, plane II satellites at weeks 1000 and 1026, and finally plane III satellites at weeks 990, 1015, and 1040.

For further discussion we have to introduce the angle β, denoting the elevation of the Sun above (or below) the orbital plane. β can vary between $\pm(i + 23.45°)$, where i stands for the inclination of the orbital plane. In the case of $\beta \rightarrow 0$ (central eclipse), a perturbation in the Sun–satellite direction causes radial and along-track acceleration oscillating with the revolution period of the satellite. A perturbation due to the *Y* bias (constant term in *Y*) consists of an along-track and an out-of-plane component. The eclipse phases indicated by a somewhat noisier and worse-determined *Y* bias can be detected in Fig. 7.

Calculating β, e.g. for week 988, we find that the elevation of the Sun above plane II became approximately 88°. According to Rothacher et al. (1995), in the

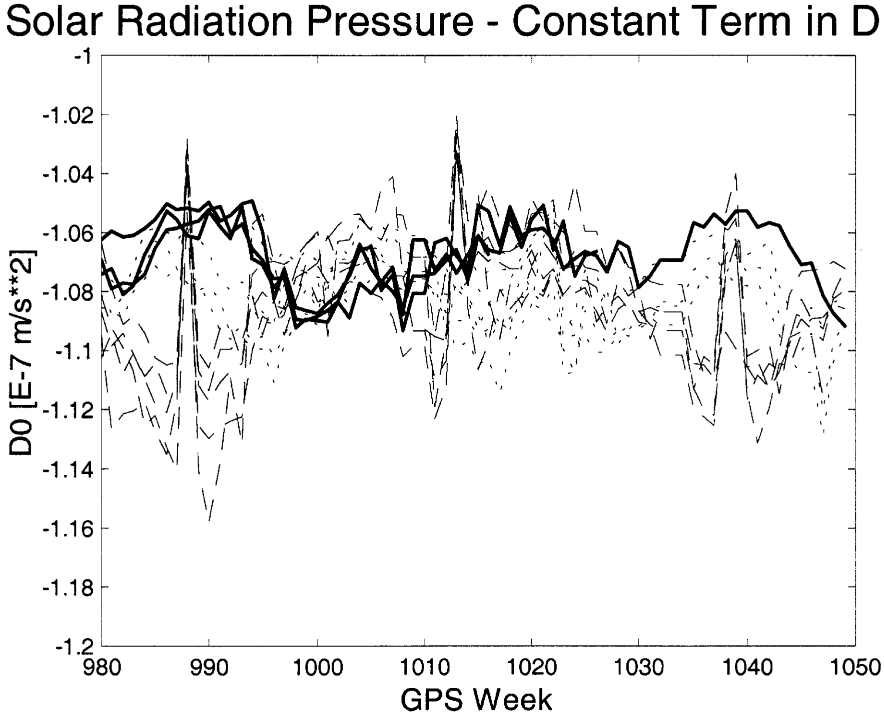

Fig. 6. a_{D0} (scaled for the variable distance Earth–Sun)

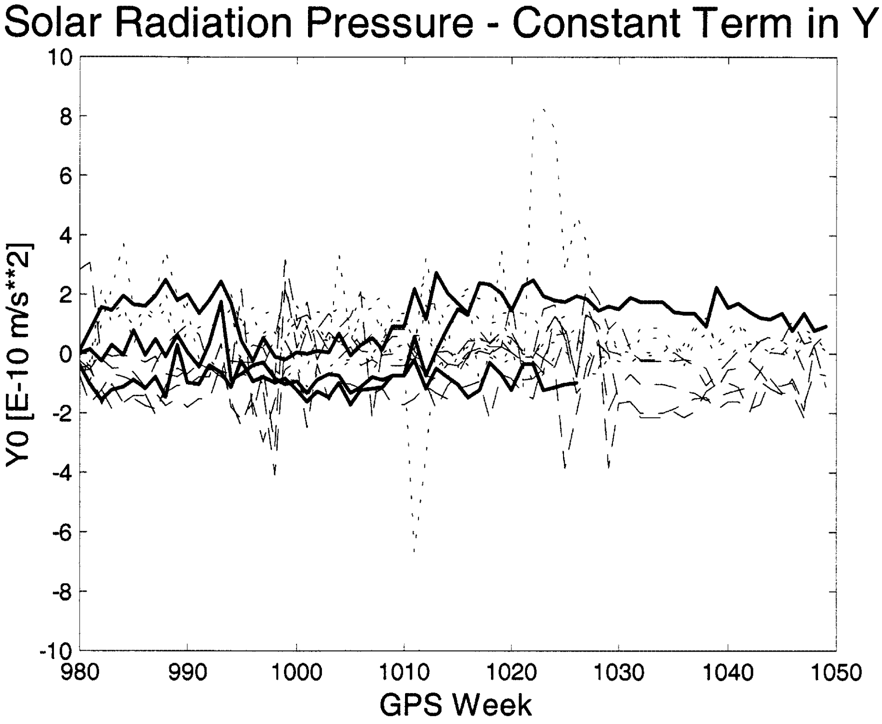

Fig. 7. a_{Y0}

case of $\beta \rightarrow 90^\circ$ a perturbation parallel to the direction Sun–satellite is a constant out-of-plane acceleration which can be verified by the residuals of the long-arc evaluation. Finally, a perturbation due to the Y bias is a constant along-track acceleration.

This special geometry is reflected in our model by significant semi-annual minima in the a_{D0} component (plane II, Fig. 6). The individual ACs' orbit submissions show a 2–3 times larger position RMS in the long-arc (7-day) analysis as usual and, moreover, the orbit combination clearly indicates an increased inconsistency of the submissions over these particular weeks (weeks 988, 1013, and 1039). For example, deviations from the mean of several dm in the radial component are a reasonable explanation of the variations in the BKG solution (Habrich 2000b) scale factor in Fig. 4.

We may conclude that, after all, the solar radiation pressure models currently in use by the ACs differ considerably. Moreover, these models show varying ability to describe the satellite orbits under an exceptional geometry ($\beta \rightarrow 90^\circ$). Orbit determination during eclipse periods, however, is handled largely without problems and very consistently by all the ACs.

4 The international GLONASS service-Pilot project

4.1 Goals of the IGLOS-PP

During the IGEX campaign all ACs have used the orbits and ERP products from the IGS. This means that, in the IGEX analysis, the orbits of the GPS satellites and the EOPs were not estimated. From the IGEX AC point of view this approach is ideal, because first of all it minimizes the number of estimated parameters and second it ensures that the resulting IGEX solutions are compatible with the IGS solutions, i.e. they are given within the IGS reference frame. The IGS satellite clock products were not used for the clock solutions.

The main objective, from our point of view, of the IGLOS-PP is the integration of GPS and GLONASS at the observation level. This means that first all the dual-frequency GPS/GLONASS receivers become an integral part of the IGS network, i.e. these stations become official IGS stations. Second, the GPS and GLONASS observations are processed simultaneously and thus the observations of the GLONASS satellites contribute to all common parameters in the analysis, such as ERPs, tropospheric zenith delays, and geocenter. In this way the results for both systems are given in one unique reference frame. Also, the time systems may be unified in such a combined processing, although here some problems exist because of the different biases within the satellites and receivers. However, the clock estimates will also be based on the same reference frame.

The second objective of the IGLOS-PP is for the IGS to prove its competence in handling multiple satellite navigation systems. This is especially important in view of the probable upcoming GALILEO system. The IGLOS-PP gives the IGS the chance to prove that it can handle any (future) satellite navigation system without too many problems. This should ensure that the expertise available within the IGS is used during the development and the routine operations of all satellite navigation systems.

With the integration of GPS and GLONASS it also becomes interesting to study the integration of the SLR measurements of both systems. This integration of SLR with GPS alone was not useful because very few SLR observations of the GPS satellites are available. Since the GLONASS satellites are much easier to track, there are consequently many SLR observations. These observations are of such quantity and quality that they enable the estimation of SLR-only orbits at the few-dm level, as the MCC IGEX AC has shown. Furthermore, with the upcoming LEO (Low Earth Orbiter) satellites equipped with GPS receivers for precise orbit determination, it is clear that several of the GPS software packages, used within the IGS, will be enhanced to enable the processing of LEO satellites. This means that these packages will also be capable of processing all the low-altitude SLR targets, because they are already capable of processing SLR measurements. Although this is clearly not an aim of the IGLOS-PP, it is something where the IGLOS-PP may set an example for future integration steps.

4.2 Advantages of combining GPS and GLONASS

The combination of GPS and GLONASS, or any other future microwave system, has several scientific advantages. First, the number of available satellites increases, which also implies an increased number of observations per epoch. The availability of more satellites will improve the geometry of the observations and therefore will allow for a better decorrelation of the tropospheric zenith delay and the station height estimates. It should also lead to a faster and more reliable ambiguity resolution. For the special case of adding GLONASS to GPS, the coverage over the polar regions will improve because of the higher inclination of the GLONASS satellites compared to GPS satellites (65° versus 55°). Because of the dependence of the LOD (length of day) estimates on the orbital inclination, the combination of GPS and GLONASS should yield better LOD estimates (Rothacher 1998; Rothacher et al. 1999).

$$(\mathrm{UT1} \dot{-} \mathrm{UTC}) = -\mathrm{LOD} = -(\dot{\Omega} + \dot{u}_0 \cos i)/\rho$$

where $\dot{\Omega}$ and $\dot{u}_0$ are time derivatives of the orbital elements (right ascension of the ascending node; argument of latitude at osculating epoch) and, ρ is the ratio of universal time to sideral time.

Because the orbital revolution period of the GPS satellites (11 hours 58 minutes) is approximately half a sidereal day, the GPS satellites are in 2:1 resonance with the Earth's gravity field (Beutler et al. 1996; Hugentobler 1997). The sidereal revolution period also causes other effects, such as annual periods (because of the 4-minute shift of the GPS constellation each day) and problems in observing dynamic tidal effects at sidereal frequencies. The orbital revolution period of the GLONASS satellites (11 hours 15 minutes) avoids resonance with the Earth's gravity field. This indicates that the inclusion of GLONASS data in the GPS data analysis may help to resolve the problems caused by the GPS orbital revolution period.

In order to illustrate the effect of resonance on the GPS satellites, Fig. 8 shows the development of the mean semi-major axis in the time interval from October 1998 until mid 2000 for one GPS and one GLONASS satellite. Besides the semi-major axis, the resonance effects are also clearly visible in the eccentricity of the orbit.

We have chosen GLONASS satellite in Slot 9 as typical for all GLONASS satellites and the behavior of PRN 10 as typical for all GPS satellites (although some differences exist in the behavior of the different GPS satellites). The resulting effect of these resonance

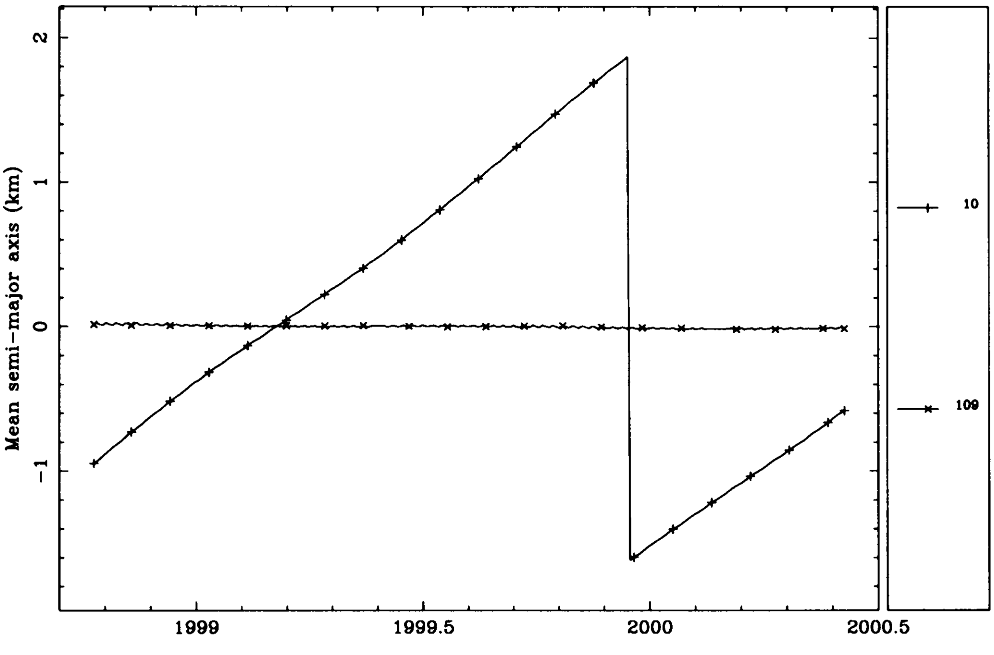

Fig. 8. Variation of mean semi-major axis for GPS PRN 10 and GLONASS Satellite 9 (labeled 109)

phenomena is that most GPS satellites had at least one maneuver during the time interval considered here (only four satellites had no maneuver). These maneuvers are necessary to keep the satellite close to its nominal 'slot' in the orbital plane. None of the GLONASS satellites needed to be repositioned in this time interval.

4.3 Handling at the CODE AC

Ineichen et al. (2000, 2001) have shown that the amount of GLONASS microwave observations allows precise GLONASS satellite orbits (10 cm) to be derived in the case that the combined GPS–GLONASS receivers are integrated in the IGS network. Currently, the impact of the combined GPS–GLONASS analysis on IGS products would be, compared to the GPS-only analysis, insignificant except for the LOD. The LOD estimates improve when adding GLONASS (and SLR) observations to the GPS observations. The improvement is visible as a reduction of the mean difference with respect to the VLBI based LOD values (by about 20%, depending on the amount of available GLONASS data). For these reasons CODE has planned to integrate the data from all combined GPS–GLONASS receivers in their routine IGS analysis.

In preparation for the full combination of the GPS and GLONASS observations, we have made an effort to enhance the current IGS orbit combination software to handle also the new version of the precise orbit format. This step has almost been completed and for test purposes we plan to combine GLONASS orbits of several weeks of the past year. This GPS–GLONASS combination tool will then be made available for use in the IGLOS-PP to ensure that the same procedures are used for generating the combined products. Ideally, the submissions from those ACs providing a fully combined GPS–GLONASS solution in a timely manner will be included in the normal IGS final orbit combinations.

5 Summary

Since October 1998, IGEX AC solutions have provided precise orbit solutions for all active GLONASS satellites (the number of active satellites varied from nine to 15 within the first 18 months). The accompanying orbit combination shows an accuracy and consistency of all ACs' orbit submissions at the 15–30 cm level. An improvement of that orbit quality is actually hindered to a certain extent by the low number and sparse distribution of tracking sites.

The analysis of 18 months of precise GLONASS orbits showed that in terms of radiation pressure the behavior of the satellites within one orbital plane is very similar. Thus, future studies aiming at revised solar radiation pressure models, advantageously as a function of the Sun's angle above the orbital plane, might be promising and are especially encouraged.

The upcoming IGLOS-PP will offer the scientific community an opportunity to profit from the advantages of the use of combined GPS–GLONASS data and products by providing a more convenient 'test bed' in terms of station distribution as well as data and product availability than today. In addition, it gives IGS the chance to ensure that the available expertise allows the handling of any (future) satellite navigation system in a similar way.

References

Beutler G, Brockmann E, Gurtner E, Hugentobler U, Mervart L, Rothacher M (1994) Extended orbit modeling techniques at the CODE processing center of the International GPS Service for geodynamics: theory and initial results. Manuscr Geod 19: 367–386

Beutler G, Kouba J, Springer T (1995) Combining the orbits of the IGS analysis centers. Bull Geod 69: 200–222

Beutler G, Weber R, Hugentobler U, Rothacher M, Verdun A (1996) GPS satellite orbits. In: Lecture Notes of the International School, GPS for Geodesy. Springer, Berlin Heidelberg New York, pp 43–109

Da Kuang, Bar-Sever Y, Bertiger W, Hurst K, Zumberge J (2000) Determination of GLONASS satellite orbit at JPL – approach and results. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 201–208

Fliegel HF, Gallini TE, Swift ER (1992) Global positioning system radiation force model for geodetic applications. J Geophys Res 97(B1): 559–568

Garcia C, Martin-Mur T, Dow J, Romero I (2000) GLONASS data analysis at ESA/ESOC. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 183–200

Glotov V, Mitrikas V, Zinkovski M (2000) GLONASS precise orbits as a result of the IGEX-98 laser tracking campaign. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 219–226

Habrich H (2000a) BKG's operation of GPS/GLONASS receivers and its regional IGEX data center. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 101–107

Habrich H (2000b) IGEX analysis at BKG. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 169–182

Hugentobler U (1997) Astrometry and satellite orbits: theoretical considerations and typical applications. PhD dissertation, Astronomical Institute, University of Berne

Ineichen D, Rothacher M, Springer T, Beutler G (2000) Results of CODE as an analysis center of the IGEX-98 campaign. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 157–168

Ineichen D, Springer TA, Beutler G (2001) Combined processing of the IGS- and the IGEX-Network. Geod 75: 575–586

Noll CE (2000) IGEX-98 data flow. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 91–99

Rothacher M (1998) Recent contributions of GPS to Earth rotation and reference frames, habilitation. University Press, University of Berne

Rothacher M, Beutler G, Mervart L (1995) The perturbation of the orbital elements of GPS satellites through direct radiation pressure. In: Gendt G, Dick G (eds) IGS Workshop Proceedings on Special Topics and New Directions, Geoforschungszentrum Potsdam, pp 152–166

Rothacher M, Beutler G, Herring TA, Weber R (1999) Estimation of nutation using the global positioning system. J Geophys Res 104(B3): 4835–4859

Slater JA, Willis P, Beutler G, Gurtner W, Lewandowski W, Noll C, Weber R, Neilan RE, Hein G (1999) The International GLONASS Experiment (IGEX-98): organization, preliminary results and future plans. In: Proc ION PS-99, Nashville, TN

Slater JA, Noll CE, Gowey KT (eds) (2000) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau

Springer T, Beutler G (1993) Towards an official IGS orbit by combining the results off all IGS processing centers. In: Proc 1993 IGS workshop, Berne, pp 242–250

Springer T, Beutler G, Rothacher M (1998) A new radiation pressure model for the GPS satellites. In: Dow J, Kouba J, Springer T (eds) Proc IGS 1998 Analyis Center Workshop, ESOC, Darmstadt, pp 89–106

Weber R, Fragner E (2000) Combined GLONASS orbits. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 233–246

Willis P, Slater JA, Gurtner W, Noll C, Beutler G, Weber R, Neilan R, Hein G (2000) The GLONASS IGEX-98 campaign: from its genesis to its realization. In: Slater JA, Noll CE, Gowey KT (eds) International GLONASS Experiment IGEX-98, Workshop Proc, Nashville, TN. IGS Central Bureau, pp 3–9