GLONASS Precise Orbit Determination

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ABSTRACT

Although operating with a limited number of satellites, the GLONASS GNSS constellation is of some interest to scientists needing a high number of precise measurements, and to high-end users working in high elevation mask areas. With the advent of several dual-frequency commercial GPS + GLONASS receivers and their worldwide installation, the International GPS Service (IGS) started a Pilot Project in 2000 to produce high quality GLONASS orbit ephemerides. This paper describes the implementation at ESOC, the orbit determination processing strategy, the specific GLONASS modelling issues implemented and a discussion of the processing results.

INTRODUCTION

ESOC has been processing GNSS data for precise orbit determination since 1991 with the analysis of the data from the GPS CIGNET-91 campaign. When GLONASS data started becoming available in 1998, ESOC started developing the capabilities to process, to determine precise satellite orbits for the entire GLONASS constellation. This effort began as part of the International GLONASS Experiment (IGEX) which started within the IGS in 1998 (Willis et al. 1999). ESOC's submissions started in March 1999 with the analysis of GLONASS data from October 1998. IGEX finished during the year 2000 but about 30 stations continue to provide regular observation files and two of the IGS Analysis Centres continue processing this data to produce precise ephemerides for the constellation (ESA/ESOC and BKG) (Weber and Fragner, 2000).

The structure of this paper is as follows: After this introduction the processing method for obtaining precise orbits of the GLONASS satellites is explained. The detailed processing strategy is then presented, followed by some results and finally conclusions.

PROCESSING METHOD

The aim of the GLONASS data processing is to produce the highest possible quality satellite orbits for use by the scientific community. These orbit ephemerides are comprised of satellite positions every 15 minutes in an Earth reference coordinate system. To produce these orbits the observables from high quality, dual-frequency GLONASS+GPS receivers are processed using the GPS-TDAF (Global Positioning System – Tracking and Data Analysis Facility). The GPS-TDAF is a set of software tools developed entirely at ESOC consisting of a data retrieval and storage system, a data pre-processor, a batch least-squares estimator for dynamic orbit determination and station parameter estimation, and a post-processor for formatting and presentation of satellite and station parameters. This section presents a general description of the GPS-TDAF and some specific details and enhancements introduced for GLONASS POD activities.

Observation Data Transfer and Pre-processing

The GPS-TDAF is used to obtain the observation data from the worldwide stations equipped with dual frequency GLONASS+GPS receivers. A world map showing the distribution of stations used is shown in Figure 1. The receiver network will be further developed in the near future to improve its worldwide coverage.

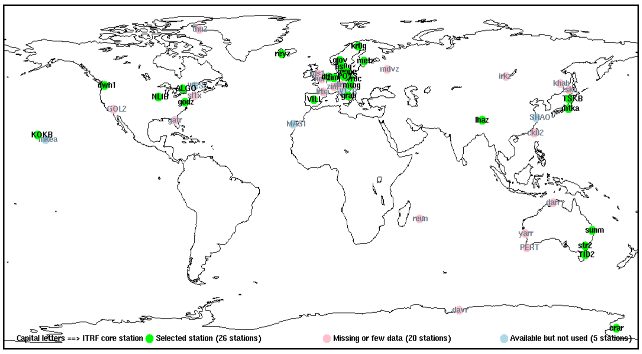

Fig. 1: World-wide stations processed in GLONASS POD

When the precise orbits for a specific day are calculated, the raw observation data are first pre-processed to remove outliers, short passes and to perform ionospheric and antenna displacement corrections. An observation file containing undifferenced pseudorange and carrier phase measurements at five minute intervals is then written for use by the least square estimator.

The outliers in the observation files are discarded by comparing the actual measurements for each day with estimates calculated from the propagated orbits of the previous day. If the observations are too far off the estimated values then the observations are discarded for that station-satellite combination. Currently about 75 to 80

% of observations are kept for each day of GLONASS data processing.

Least-Squares Dynamic Estimator

The least squares batch estimator used at ESOC is in continuous development for precise orbit determination. It can currently process most kinds of observations used for satellite orbit determination such as SLR (Satellite Laser Ranging), DORIS, altimetry, range, range-rate, plus the GNSS observables; pseudo-range and carrier phase in double-differenced and undifferenced mode. The latter capability was specifically developed for GLONASS processing due to the fact that a small number of stations are available (around 30), and they are not well distributed around the globe (as shown in Fig. 1).

Developing an undifferenced processing capability was deemed necessary for GLONASS POD activities since there are times when data could not be combined in a double difference link and would therefore be lost. Processing undifferenced measurements has the advantage of using all of the available data from the stations, also the clocks and orbits calculated are consistent with each other, this can sometimes be a problem if they are solved in two different steps as is generally the case using double-differenced observations. Processing undifferenced measurements does have the added complexity of having to estimate the satellite and station clock biases which can be rapidly changing time-varying parameters.

The least squares estimator uses the dynamical and measurement models and the reference frames and time scales as specified in Dow and Martin-Mur (1999).

There was no previous knowledge of a GLONASS satellite solar radiation pressure model, therefore an empirical model has been developed and tested at ESOC. The final implementation of the empirical model assumes the following form for the force component on each of the three axes:

$$F_x = K(a_{x0}) \qquad (1)$$

$$F_y = K(a_{y0}) \qquad (2)$$

$$F_z = K(a_{z0} + a_{zc}\cos(A) + a_{zs}\sin(A)) \qquad (3)$$

where K is a global scaling factor, the a variables are the five estimated coefficients, and A is the solar anomaly, the angle in the orbital plane of the projected Earth-Sun vector and the Spacecraft-Earth vector as shown in Figure 2. The x direction in the equations above corresponds to the anti-sun, the y direction approximately along the solar panels and the z direction completes the right-handed coordinate system (Figure 2). The selection of this model was based on the residuals of the orbit determination and the observability of the selected parameters.

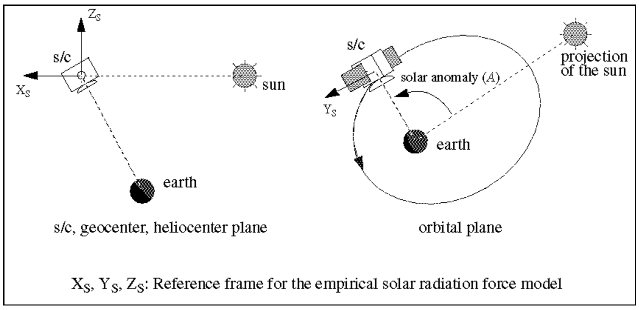

Fig. 2. The empirical solar radiation pressure model.

Finally the estimated parameters in the least-squares estimator are: The station coordinates, the satellite state vectors, and the solar radiation pressure model parameters, the undifferenced carrier phase ambiguities, the GPS-GLONASS receiver biases, the Earth rotation parameters: x and y pole position and rates and Length of Day, the tropospheric zenith delay for every station every 2 hours, and station and satellite clock biases, estimated as time-dependent parameters (one value for every observation epoch).

Post-Processing

After the parameter estimation process is complete the results are formatted into standard ASCII file formats for distribution. This applies to the Earth Rotation Parameters, to the daily satellite ephemerides and clock biases and to the station coordinates, which are combined into a weekly SINEX file.

PROCESSING STRATEGY

Using the GPS-TDAF as described in the previous section the GLONASS precise orbit determination is conducted as follows:

1. RINEX observation and navigation files are retrieved from IGEX and IGS stations and stored locally in our computer system. The role of the IGS stations is to fix the solution to the ITRF-97 so that GLONASS orbits and station coordinates solutions are represented in ITRF-97. Seven IGS stations are selected for this purpose. The IGEX and IGS stations normally used are (since GPS week 1065):

   IGEX stations: DLFT (Holland), CRAR and DAVR (Antarctica), GOPE (Czech Rep.), GODZ (USA), GRAB and MTBG (Austria), KR0G and OS0G (Sweden), MTKA (Japan), REUN (La Reunion), REYZ (Iceland), SUNM, STR2, DARR and YARR (Australia), WTZZ (Germany), ZIMJ and ZIMZ (Switzerland), LHAZ (China).

   IGS stations: ALGO (Canada), GOL2 (USA), KOKB (Hawaii), TID2 (Australia), ONSA (Sweden), VILL (Spain), TSKB (Japan).

2. For every day of processing five days of data are used. This constitutes our data arc: the day we need plus two days before and after.

3. The orbit determination using a least squares dynamic estimator is then started. The IGS GPS orbits from

the ESA final solution and the station positions for the seven IGS stations are fixed, all other parameters for the stations and the parameters for the GLONASS satellites are estimated. The list of GLONASS satellites in the constellation and its recent status and changes are in Table 1.

Table 1. GLONASS Constellation Status (March 2000)

	Slot no.	Desig-nation	Intro. Date	Status
Plane 1	1	gv-82	18.02.1999	Processing OK
	3	gv-68	15.12.1994	Removed 05.10.1999
	4	gv-70	11.12.1994	Removed 03.12.1998
	6	gv-69	16.12.1994	Removed 30.11.1999
	7	gv-80	29.01.1999	Processing OK
	8	gv-81	29.01.1999	Processing OK
Plane 2	9	gv-77	07.01.1996	Removed 28.09.2000
	10	gv-75	22.08.1995	Only L1
	11	gv-76	22.08.1995	Processing OK
	13	gv-79	18.01.1996	Processing OK
	15	gv-78	26.04.1999	Processing OK
	16	gv-66	07.09.1994	Removed 28.09.2000
Plane 3	17	gv-84	04.11.2000	Processing OK
	18	gv-83	04.01.2001	Processing OK
	24	gv-85	21.11.2000	Processing OK

4. Finally orbits and clocks are combined to produce an sp3 file for every day of processing, and station positions are combined into a SINEX file after a complete week is processed. The results are distributed weekly trying keeping the delay with real time around three weeks.

RESULTS

Orbit Comparisons

To ensure that the orbit and clocks solutions for every day processed is of high quality an orbit and clock comparison is done for every day of processing between that day's solution and the solution for the same period during the previous day's processing. Since for every day of processing we process a five-day arc of data we always have an overlap period to compare. Figures 3 and 4 present RMS orbit differences for each day's orbit solution with the overlapping period of the previous day's solution for satellites gv-80 and gv-82, launched in Dec. 1998. Both figures show the RMS of the differences in the calculated orbits to be around or below the 20 cm value from day to day.

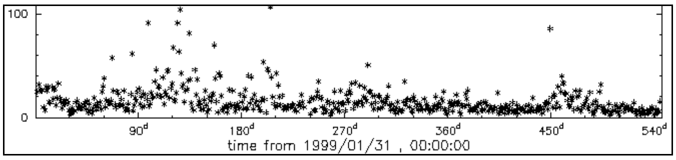

Fig. 3: gv-80 RMS orbit differences for overlapping processed data arcs.

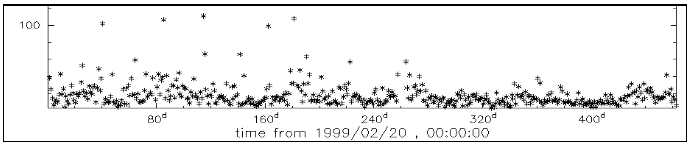

Fig. 4: gv-82 RMS orbit differences for overlapping processed data arcs.

For older satellites in the constellation the RMS of the differences for overlapping data arcs show considerable more scatter and larger differences from day to day. Figures 5 and 6 show results for satellites gv-77 and gv-66, launched in 1995 and 1994, respectively and now no longer transmitting.

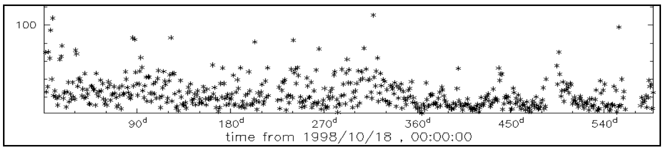

Fig. 5: gv-77 RMS orbit differences for overlapping processed data arcs.

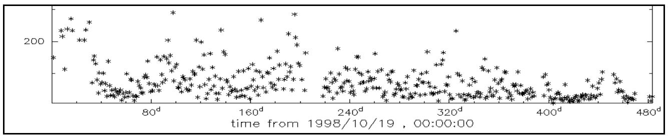

Fig. 6: gv-66 RMS orbit differences for overlapping processed data arcs.

A consistent trend that can be observed in the four figures above is that for the most part, as time has gone on, the differences with respect to the overlapping arc of the previous day of processing have become smaller, even for older satellites. This is due to two reasons, on the one hand our processing strategy has changed and improved in this time. Also the size of the constellation has reduced from 14 satellites in the fall of 1998, when this activity started at ESOC, to only about eight in the summer of 2000, to the current nine satellites in the spring of 2001. With less satellites to estimate the solution tends to be more repeatable from day to day since there are less chances of unpredictable behaviour in one of the satellites which tends to affect the solution of the entire constellation.

Satellite Clock Bias Comparisons

The solution of the satellite clock biases is always included in the processed result files for each day of processing. This advises the user at every epoch of the differences between the satellite clock and a constant time scale. Results of comparisons between the calculated satellite clock biases from one day to the next in the overlapping data arc are shown in Figures 7 and 8 for satellites gv-82 and gv-77.

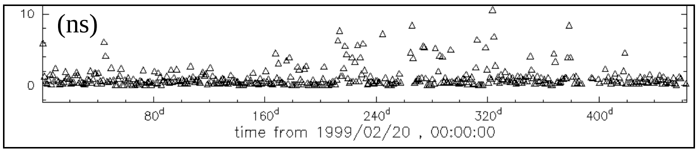

Fig. 7: gv-82 RMS Clock bias differences for overlapping processed data arcs.

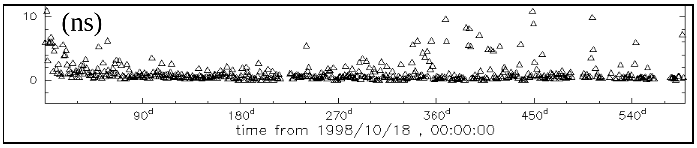

Fig. 8: gv-77 RMS Clock bias differences for overlapping processed data arcs.

The clock bias differences can be seen to be for the most part around or below 1 ns, showing that the repeatability for the satellites' clock biases is good.

GPS-GLONASS Bias

To be able to process GPS and GLONASS data at the same time a bias has to be estimated for each receiver at every station which models the different signal path or processing delay within the antenna, cable, amplifier or receiver for the GLONASS and GPS signals. The GPS-GLONASS biases are in most cases stable and depend mainly on the type of receiver being operated at each station. For example, the ASHTECH Z-18 receivers have values with offsets between -55 to 40 ns and day to day variations in the range of 1 to 5 ns, and the JPS Legacy receivers (now Topcon) have values of between -150 to -220 ns, with similar day to day variations. This bias and the variations between receivers is shown in Figure 10 for several stations plotted together. There is a clear grouping associated with each of the two receiver brands.

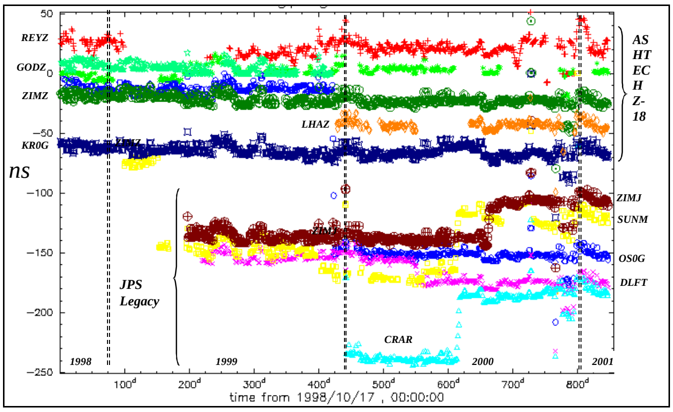

Fig. 9: GPS-GLONASS receiver bias for several stations.

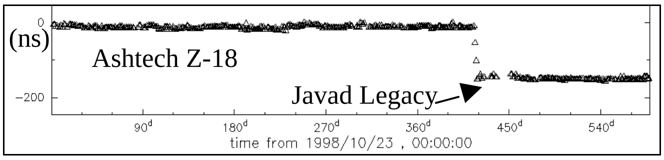

Fig. 10: GPS-GLONASS receiver bias for station OS0G at Onsala, Sweden.

Figure 10 shows the GPS-GLONASS bias for station OS0G from October, 1998 to June, 2000. The plot shows relatively stable biases for long periods of time with one large discontinuity, which corresponds to a receiver change at the station from an ASHTECH Z-18 to a JPS Legacy on the 14th December, 1999.

Empirical Solar Radiation Pressure Force Model

As discussed above at ESA/ESOC we had no previous knowledge of a GLONASS satellite solar radiation pressure model. Therefore an empirical one was created as described by Eqs. 1, 2 and 3 and detailed in Figure 2 above. The results show that the components along each of the axes, as defined in Figure 2, are as follows: the x constant term is around 150 mN for all the satellites, the y constant term ranges between ±0.5 mN with cyclical variations throughout the year, the z constant term and the cosine term are scattered for the entire constellation between ±1 mN and the z sine term is about –3 mN.

GPS/GLONASS COMBINED PROCESSING

Some interest has been shown within IGS to study the possibility of processing GPS and GLONASS data together to produce "Final" quality orbits for both at the same time. At ESOC we have performed some test runs but attach low priority to this task. The main difficulty encountered is the difference in processing arc sizes between each of the processes, the GPS Final solution uses a 48 hour arc and the GLONASS solution a 5 days (preferred) or 3 days arc for optimum results. This increase in arc size increases the amount of data to process. Even if the station selection is kept at the current level used for the ESA Final solution (around 50 stations, by eliminating GPS only stations and including the double constellation receivers) there is at minimum an extra 24 hours of data to process, plus a large number of extra satellites. This considerably increases the requirements for processing power (memory and speed).

Nonetheless, as mentioned above, some tests have been run to evaluate the quality of the orbits obtained for each of the constellations processing them together when compared to the independent processes currently implemented.

The results in Figure 11 for the GPS constellation show the RMS of differences to the IGS Final and Rapid solutions for the entire constellation on an epoch by epoch basis between the normal ESA final processing (bottom two curves) and the combined processing (top curves) over a 24 hour period. The combined solution can be seen to be worse than the independent solution. This is mainly due to the use of the combined GLONASS+GPS stations for which precise coordinates do not exist and which use receivers and antennas not as well characterised as the GPS equipment. The combined process is also not as refined as the independent process so further improvements can be expected as this activity develops.

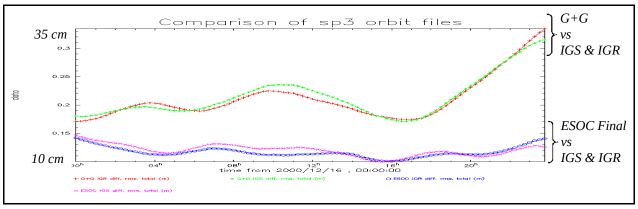

Fig. 11: GPS constellation results versus the IGS final and rapid orbits for a 24-hour period.

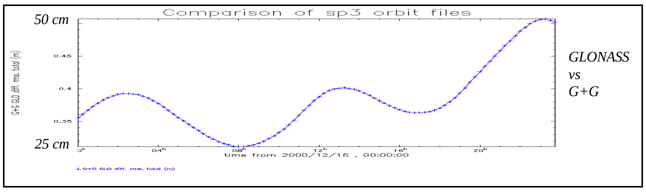

Fig. 12*: GLONASS constellation differences between independent and combined solutions.*

The results for the GLONASS constellation comparison in Figure 12 shows the RMS of differences between the two solutions, one obtained from the combined processing and the other from the independent processing. The solutions can be seen to agree to the 30 cm level. Again the mixing of the satellite constellations, the introduction of many GPS only stations and the fact that there is limited experience in running combined processing contributes to the differences in both solutions.

CONCLUSIONS

The processing of GLONASS data at ESOC for POD has been a positive experience, the modifications necessary to our software and processing strategy have enhanced our capabilities. The processing is similar to that of GPS with the main differences of having to estimate a GPS-GLONASS bias for the receivers in order to simultaneously process GPS and GLONASS data and the implementation of an empirical solar radiation pressure model. ESOC will continue to process GLONASS data for POD independently of the GPS processing, as long as a meaningful number of receivers and satellites are available. This activity will soon be part of the International GLONASS Service Pilot Project (IGLOS PP) organised by the IGS and due to start during 2001.

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