Orbits and Clocks for GLONASS Precise-Point-Positioning

R. Píriz, D. Calle, A. Mozo, P. Navarro, D. Rodríguez, G. Tobías, *GMV, Spain*

BIOGRAPHY

Ricardo Píriz has a Master of Science in Aerospace Engineering, from the Universidad Politécnica de Madrid, Spain. He is the *magicGNSS* Product Manager within the GNSS Business Unit of GMV.

David Calle has a Master of Science in Computer Engineering, from the Universidad de Salamanca, Spain. He works as Web 2.0 and Human-Computer Interaction specialist at GMV.

Álvaro Mozo has a Master of Science in Aeronautical Engineering, from the Universidad Politécnica de Madrid, Spain. He is Head of the GNSS Algorithms and Products Division within the GNSS Business Unit of GMV.

Pedro Navarro has a Bachelor of Science in Mathematics from the University of Murcia (Spain) and Postgraduate studies in Theoretical Physics at the University of Valencia (Spain). He is a Senior Engineer at GMV.

Daniel Rodríguez has a Masters of Science in Telecommunication Engineering from Polytechnic University of Catalonia, Spain. He is a Senior Engineer at GMV.

Guillermo Tobías has a Masters of Science in Telecommunication Engineering, from the University of Zaragoza. He works as an Orbit Determination & Time Synchronization specialist at GMV.

ABSTRACT

In 2008 GMV introduced *magicGNSS* [Ref. 1], a web application providing a suite of tools for GNSS data processing featuring high-precision and integrity. The main application of *magicGNSS* is the calculation of GPS satellite orbits and clocks, and also of station/receiver coordinates, tropospheric delay and clock. *magicGNSS* current version (1.3) is available online for registered users at http://magicgnss.gmv.com. The Orbit Determination & Time Synchronization (ODTS) module was the first algorithm available in *magicGNSS*. ODTS generates orbits and clocks by processing dual-frequency code and phase measurements from a network of GPS stations distributed worldwide. Past and current data from a set of so-called *core stations* from the *International GNSS Service* (IGS, [Ref. 2]) is available on the *magicGNSS* server, and the possibility also exists to upload and process RINEX observation files from any user station.

Since the beginning of 2009 the Russian constellation GLONASS has 19 operational satellites. The implementation of GLONASS data processing in addition to GPS in *magicGNSS* is then a natural step in order to take advantage of the extended satellite availability. The precise determination and prediction of GLONASS orbits and clocks poses a number of difficulties. One of them is the a priori unknown solar radiation model for the GLONASS satellites, actually the major limitation for sub-decimeter orbital dynamics accuracy. Also, when processing data from a network of GLONASS stations, a so-called inter-channel bias has to be estimated at station level in order to compensate for the different internal delays of the GLONASS signals and codes through the station hardware and software. Finally, the short-term stability of the Russian satellite clocks might pose a problem for clock estimation and interpolation.

Precise-Point-Positioning (PPP) is a relatively new technique for centimeter-level error in positioning, and sub-nanosecond error in timing, using a stand-alone GNSS receiver and precise satellite orbit and clock products calculated beforehand (for example products from IGS). The user receiver can be fixed to the ground (static PPP) or be a roving receiver (dynamic or kinematic PPP). PPP is different from other precise-positioning approaches like Real Time Kinematics (RTK) in that no base stations or reference stations are needed. The only observation data that must be processed is the user receiver data itself, thus reducing the bandwidth and calculation power needed for the service.

Another advantage of PPP is that since the input satellite orbit and clock products are by nature global, the PPP solutions are also global, i.e., the PPP approach works for a receiver located anywhere on or above the Earth surface, and the resulting PPP solution (coordinates) are

referred to a well-known terrestrial reference frame (normally ITRF). A PPP software module is now available in *magicGNSS*. The PPP module processes GPS and GLONASS data.

This paper describes the implementation of GLONASS data processing in the ODTS and PPP modules of the *magicGNSS* web application, from the point of view of both algorithms and usability, and presents the major results in terms of GLONASS orbit and clock estimation accuracy (ODTS), and in terms of the resulting positioning and timing accuracy at user receiver level (PPP). For PPP three scenarios are considered and reported: GPS-only, GLONASS-only, and GPS+GLONASS. Data intervals from 1 hour to 1 day are analyzed.

INTRODUCTION

Three new Russian GLONASS satellites were launched on 25 December 2008. With these three new satellites, the GLONASS constellation consists now of 19 operational satellites. The 'GNSS constellation', including GPS and GLONASS, provides currently up to 50 usable satellites (31 GPS and 19 GLONASS). For the GNSS user this means that up to 19 GPS+GLONASS satellites are simultaneously visible in open-sky areas, as compared to up to 12 GPS-only satellites, i.e., an increase of around 60% in satellite availability with respect to GPS. The benefit of this extended GNSS constellation is even larger in urban areas where buildings blocking the GNSS signals might reduce the visible satellite availability below the minimum number that allows an accurate user solution.

At the same time, the IGS has been steadily incorporating to its tracking network new GPS+GLONASS dual stations, the current situation being that a fairly good global coverage is available, this allowing increasingly accurate orbit and clock determination and prediction possibilities for the GLONASS satellites. Many of these IGS stations provide also data in near-real time, typically in the form of hourly files with a latency of just a couple of hours. This potentially allows the calculation and dissemination of orbits and clocks (especially predictions) in a timely manner for precise user applications. Today, an increasing number of users need high-quality GNSS products, such as precise satellite orbit and clock estimations and predictions, accurate receiver coordinates or tropospheric delays, for their applications (e.g., Precise-Point-Positioning, GNSS augmentation services, weather services, etc).

magicGNSS [Ref. 1] is a web application developed by GMV providing a suite of tools for GNSS data processing featuring high-precision and integrity. Figure 1 shows the application main page.

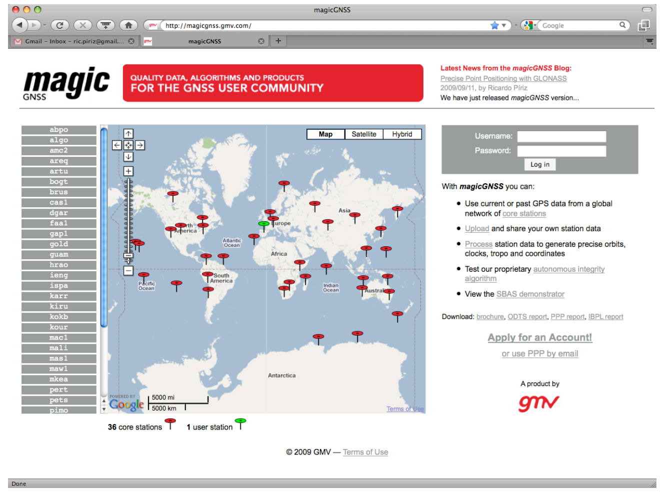

Figure 1: The *magicGNSS* web site

Until version 1.2 *magicGNSS* processed GPS data exclusively. In the following sections we will describe how GLONASS data processing has been implemented in *magicGNSS* version 1.3 in order to generate satellite orbits and clocks, and then using these products in Precise Point Positioning, with or without GPS in addition.

THE ODTS AND PPP ALGORITHMS

The algorithms that process station data to generate products in *magicGNSS* are called ODTS (Orbit Determination & Time Synchronization) and PPP (Precise Point Positioning). ODTS is a network solution requiring a set of stations distributed worldwide. PPP is a single-station solution (although several stations can be processed together for convenience). In ODTS and PPP, the stations must be static.

The basic ODTS and PPP input measurements are pseudorange (code) and phase L1-L2 dual-frequency iono-free combinations. On L1, the P1 code is used in order to be consistent with IGS. The raw input code and phase measurements are decimated and used internally by ODTS and PPP at a typical rate of 5 minutes (down to 30 sec can be used in PPP). The code measurements are smoothed using the phase with a Hatch filter, thus reducing the code error from the meter lever to typically 25-30 cm.

ODTS and PPP are based on a batch least-squares algorithm that minimizes measurement residuals solving for orbits, satellite and station clock offsets, phase ambiguities and station tropospheric zenith delays. In the case of PPP, satellite orbits and clocks are not solved for, but read from external IGS products (*ultra-rapid*, *rapid* or *final*) and interpolated if necessary.

Satellite and station clocks are calculated as 'snapshot' values, i.e., as instantaneous values at the measurement time epoch, without correlation to previous estimates. Clocks are estimated at the same rate as and coinciding with the decimated measurements (typically every 5 minutes).

In ODTS, satellite and station clock offsets are estimated with respect to a reference clock, provided by one of the ground stations, as chosen by the user. In PPP, the station clock is referred to the IGS Time scale (IGST), as derived from the satellite clocks in the IGS products.

In ODTS, the satellite and Earth dynamics are based on high-fidelity models that follow IERS recommendations. Modeled effects include a full Earth gravity model, Sun, Moon and planetary attractions, solid and ocean Earth tides, ocean loading, and solar radiation pressure (SRP), including eclipses. Radiation force discontinuities during eclipse entry/exit are smoothed in order to improve orbit accuracy. The satellite attitude is modeled as a generic nadir-pointing yaw-steering law applicable to all GNSS satellites. The orbit is adjusted estimating the initial state vector (position and velocity) and 8 *empirical* SRP parameters. No additional *empirical accelerations* are used.

Earth Rotation Parameters (ERPs) are automatically downloaded from the IERS server, but they can also be estimated by ODTS itself. The tropospheric correction is based on the estimation of a zenith delay per station (a constant value every 1 or 2 hours), using a mapping function to account for the satellite-station signal elevation. Small effects such as relativity and carrier-phase wind-up are also implemented.

For the ODTS ground stations, a priori station coordinate values come from ITRF or IGS solutions, and they can be refined within the ODTS process. For user stations, the precise coordinates from PPP can be used as input values for ODTS. Satellite and station antenna offsets and phase centre variations are taken into account, the latest ANTEX file from IGS is always used.

Products generated with ODTS and PPP have an accuracy similar to that of IGS products. Table 1 shows an overview of the *magicGNSS* products for GPS and their typical accuracy.

Product	ODTS	PPP	Format	Accuracy (RMS)
Report	✓	✓	pdf	N/A
Satellite orbits	✓	✗	sp3	~2/6/4 cm(*)
Satellite clocks	✓	✗	clk	~0.15 ns
Station clocks	✓	✓	clk	~0.15 ns
Station tropo	✓	✓	txt	<1 cm (zenith)
Station coords	✓	✓	snx	<1 cm

(*) In the Radial/Along/Normal directions

Table 1: Summary of ODTS and PPP products (GPS)

GLONASS PROCESSING SETUP IN ODTS

One of the motivations to generate GLONASS orbits and clocks using the ODTS algorithm is the lack of GLONASS satellite clocks from IGS. Precise GPS orbits and clocks are published by IGS, and also precise GLONASS orbits, but not GLONASS clocks at the time of writing this paper. Since one of our objectives is to study the performance of Precise Point Positioning using GLONASS, it is necessary to have a source of GLONASS orbits and clocks to be used as input in PPP.

For this study we have chosen a particular time period: June 2009. For this month we have generated GLONASS orbits and clocks using ODTS. Over 40 IGS stations providing dual GPS+GLONASS data have been selected to be used in ODTS. These stations provide a fairly good global coverage, as shown in Figure 2.

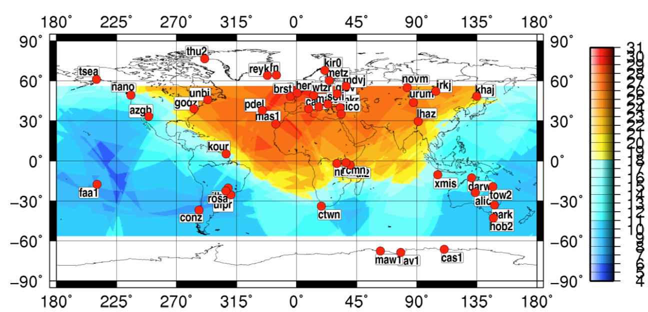

Figure 2: GLONASS tracking network

In Figure 2 the color code indicates the number of stations in view of the GLONASS satellites, at the sub-satellite point. The station network coverage is calculated based on station-satellite geometry exclusively, and not on the actual data availability from the stations. Therefore it is a *theoretical* or *optimistic* coverage. It is also important to highlight that only GLONASS data is used in ODTS, i.e., the GPS data from the dual station receivers in *not* used at all.

One particularity of ODTS is that all clocks (satellites and stations) are estimated with respect to a reference clock, provided by one of the ground stations, as selected by the user. In our case the MATE station in Matera, Italy, has been selected as clock reference. MATE is connected to a very stable external clock, a Hydrogen maser.

During the processing of GLONASS data in ODTS a few satellites (R04, R06, R07, R09 and R24) had to be discarded in the solution due to different problems. Although not all the discarded satellites are permanently *unusable* during June 2009, we have decided to discard them for the whole month in order to have a homogenous dataset. In total 15 GLONASS satellites remain in the ODTS solution. An historical archive of so-called NAGUs (Notice Advisory to GLONASS Users) can be found in the following web page: http://www.galtecproject.de/galtec_web/status_glonass_nagu.jsf

Satellite clocks in ODTS are estimated at the same rate as the input measurements are decimated. A rate of 5 minutes has been chosen for GLONASS clocks in order to be consistent with IGS *rapid* clocks for GPS.

Station data is processed in ODTS in batches of 2-day duration, starting and ending at 12:00 GPS Time. Then the first and last 12 hours of the 2-day solution are discarded in order to keep the central day for greater orbit and clock accuracy. Hence the output products from ODTS are daily orbit and clock files in SP3 and CLK format, respectively. This is consistent with IGS products for GPS.

Finally, it is necessary to estimate an *inter-channel bias* when processing GLONASS data. This must be done in order to compensate for the different internal delays in the pseudorange measurements through the GLONASS receiver. Otherwise the station clock estimation would not be coherent with the pseudoranges. It has been observed that in GPS data this effect is much smaller and therefore negligible, normally it is not necessary to estimate such an inter-channel bias for GPS data. GLONASS inter-channel biases are estimated as float numbers per station-satellite combination, as constant values per each batch of data (2 days in our case).

Manufacturers of modern GNSS receivers such as the Javad Triumph claim that GLONASS biases are automatically calibrated by the receiver, and therefore the resulting inter-channel bias should be zero. Unfortunately at the time of writing we could not find RINEX data from such a receiver type.

ODTS RESULTS

This section presents some excerpts from the 'ODTS Report' that is automatically generated by *magicGNSS* in PDF format. The results come from the 2-day data batch starting June 13 at 12:00 and ending June 15 at 12:00.

Figure 3 and Figure 4 show the measurement residuals per station in code and phase, respectively. Figure 5 and Figure 6 show the measurement residuals per satellite in code and phase, respectively. The *residual* is the part of the measurement that cannot be modeled by ODTS, and is mainly due to the multipath error, which is much larger in code than in phase.

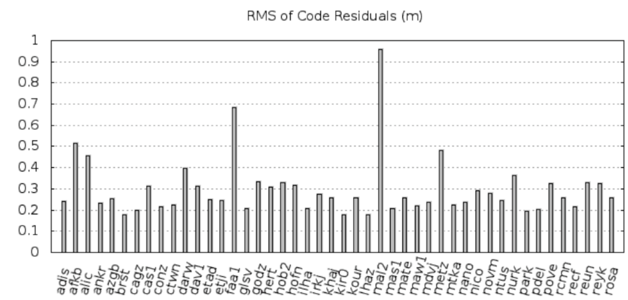

Figure 3: GLONASS code residuals per station

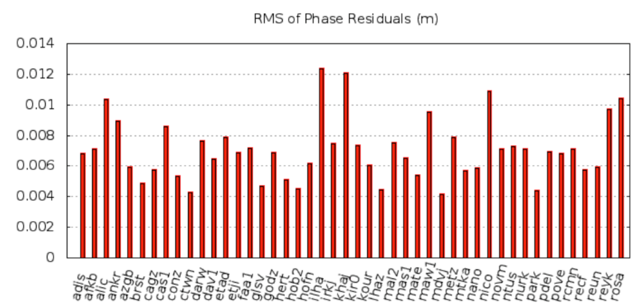

Figure 4: GLONASS phase residuals per station

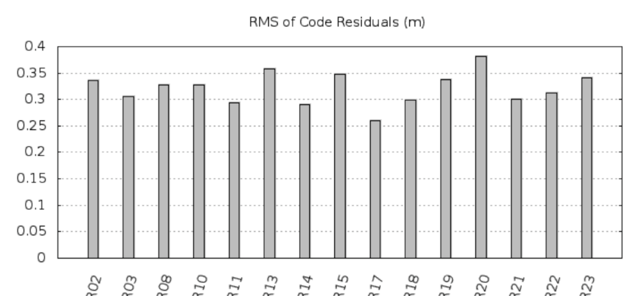

Figure 5: GLONASS code residuals per satellite

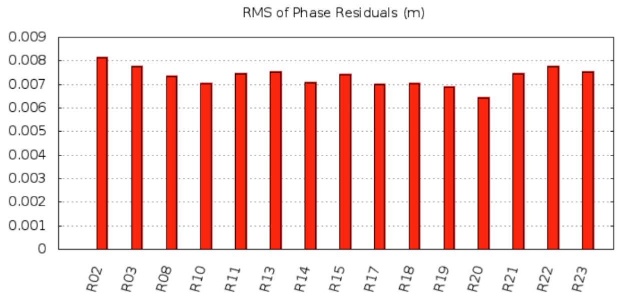

Figure 6: GLONASS phase residuals per satellite

The overall (RMS) residual level is of the order of 30 cm in code and 7 mm in phase (recall that the code is smoothed using phase in a Hatch filter at pre-processing level). These values are very much in line with the ones obtained when processing GPS data, therefore we have confidence in the correct modeling of GLONASS in ODTS and in the adequate convergence of the batch least-squares algorithm.

Figure 7 shows the satellite radiation pressure (SRP) parameters estimated by ODTS to adjust the orbits with sub-decimeter accuracy. 8 empirical SRP parameters are estimated per satellite in 3 orthogonal directions.

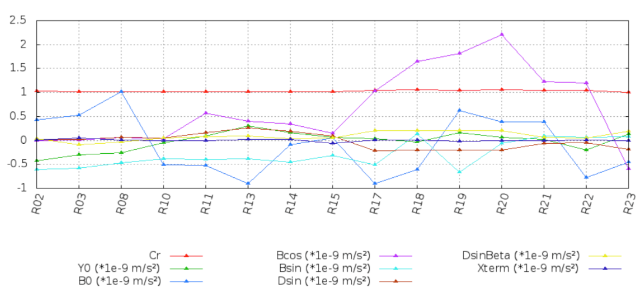

Figure 7: Satellite radiation pressure coefficients

The Cr coefficient is non-dimensional and is in the direction Sun-satellite (*cannonball* term). The Y direction is along the solar panel rotation axis. One term (Y0) is estimated in this direction (also called *Y-bias*).

Figure 8 shows the receiver inter-channel biases for all station and satellites used in the ODTS processing.

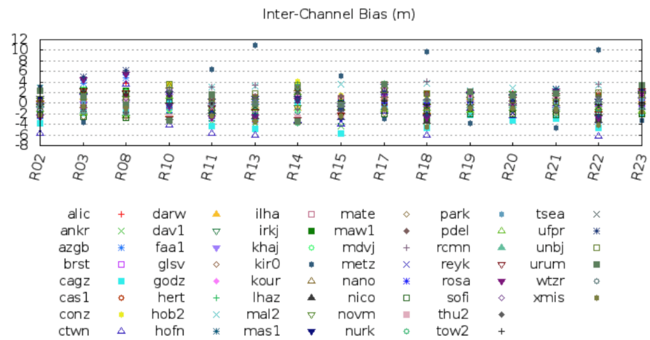

Figure 8: Receiver inter-channel biases

The central day (June 14) of the 2-day ODTS batch reported above has been compared with the GLONASS orbits published by IGS. The orbit differences are shown in the following figures. Figure 9 shows the RMS of the differences (ODTS-IGS) for all the satellites versus time, in the radial, along, and normal directions. Figure 10 shows the RMS of the differences during the 1-day comparison per satellite.

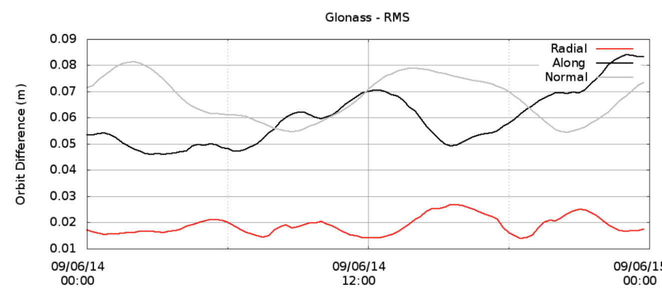

Figure 9: Orbit comparison with IGS (vs time)

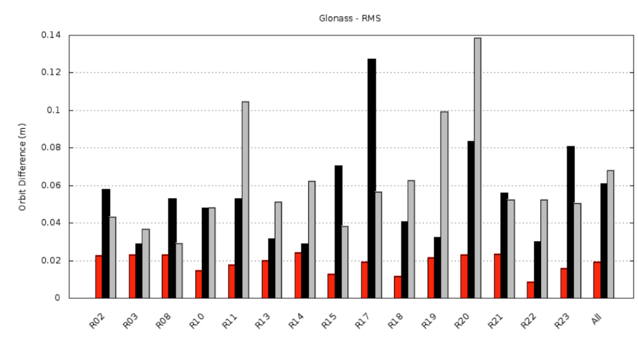

Figure 10: Orbit comparison with IGS (per satellite)

As can be seen in Figure 10 (right) the RMS of the orbit difference for all satellites is around 2 cm, 6 cm, and 6 cm, in the radial, along, and normal directions, respectively. According to the IGS Products web page (http://igscb.jpl.nasa.gov/components/prods.html) the accuracy of the GLONASS orbits is of the order of 5 cm, therefore it can be considered that the orbits from ODTS have a quality similar to the IGS orbits.

ALIGNING GLONASS CLOCKS TO IGS TIME

The final objective of this paper is to evaluate the possibility to do Precise Point Positioning using GLONASS data, with or without GPS data in addition. In order to mix GPS and GLONASS data in the same PPP solution it is essential that input products are expressed in the same terrestrial reference frame (orbits) and time scale (clocks).

In the case of orbits, both IGS orbits for GPS and ODTS orbits for GLONASS are given in the International Terrestrial Reference Frame (ITRF), therefore IGS and ODTS are compatible.

Regarding satellite clocks, IGS clocks for GPS are given with respect to the IGS Time Scale (IGST), and ODTS clocks for GLONASS are given with respect to the selected ground station clock (MATE). In order to align GLONASS clocks to IGST the output clocks from ODTS are post-processed adding the MATE clock estimation from IGS clock files:

$$\underbrace{(CLK_{SAT} - CLK_{MATE})}_{ODTS} + \underbrace{(CLK_{MATE} - IGST)}_{IGS} = CLK_{SAT} - IGST$$

where CLK_{SAT} is the GLONASS satellite clock, CLK_{MATE} is the MATE station clock, and IGST is IGS Time. The ODTS output clock files post-processed in this way are then used as input to PPP.

PPP CONFIGURATION

As explained in previous sections, the PPP algorithm in *magicGNSS* is essentially the same one as ODTS. The main difference is that in ODTS satellite orbits and clocks are estimated, and in PPP they are read from external input files (and interpolated if necessary). The underlying physical models are the same in ODTS and PPP, therefore the compatibility between ODTS output products for PPP input is guaranteed.

The station parameters estimated by PPP are position (XYZ coordinates), clock, zenith tropospheric delay (constant value every hour), and float phase ambiguities. Cycle slips are detected but not corrected: if a cycle slip is identified a new phase ambiguity is estimated. Cycle slips are obviously undesired because they increase the number of *nuisance* parameters (ambiguities) to be estimated and, more importantly, they reduce the observability and convergence of each of the ambiguities to be estimated. Together with satellite visibility and geometry, the occurrence of phase cycle slips is the main factor affecting PPP accuracy in position when using short data periods (of the order of one hour or less).

The station clock is estimated by our PPP at the same rate as the (decimated) input measurements. Two rates are currently supported: 5 minutes and 30 seconds. Since the GPS and GLONASS clocks input to PPP are given every 5 minutes, they must be interpolated if a data rate of 30 second is used in PPP.

As explained above, the PPP algorithm in *magicGNSS* currently works in static mode exclusively. In order to test PPP with GLONASS we have processed data from a subset of around 20 *control stations* worldwide distributed, as shown in Figure 11. Recall that each station is processed independently by PPP, i.e. each station solution is autonomously calculated using measurements from that station exclusively (plus the input orbit and clock products).

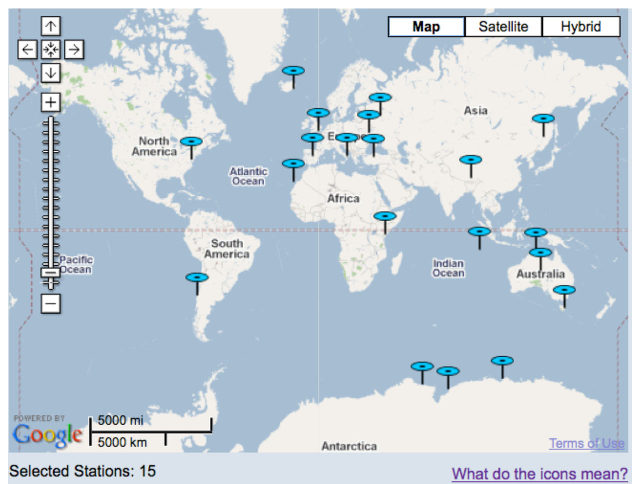

Figure 11: Control stations for PPP

Two kinds of PPP scenarios are considered for this paper:

1. Using **one day** of station data: this scenario is mainly oriented to assess the maximum accuracy obtainable on the station position, and to the possibility to characterize atomic ground clocks with PPP.

2. Using **one hour** of station data: this scenario is intended to evaluate the level of positioning accuracy using 'short' periods of data, and specifically to study whether the incorporation of GLONASS data improves the station position with respect to the GPS-only solution.

For each of the two previous scenarios three configurations are used: GPS-only, GLONASS-only and GPS+GLONASS.

It is important to emphasize that since *magicGNSS*' PPP is based on a batch least squares scheme (not on a filter), the resulting position and clock accuracy is homogeneous throughout the data time interval. There is no *convergence period* at the start of the data interval, although the global accuracy depends of course on the length of the data span.

PPP USING ONE DAY OF STATION DATA

It is a well documented fact that position accuracy in static PPP using GPS data and products from IGS, processing 'long' periods of station data, is below the centimeter on the horizontal component and at the centimeter level in the vertical component. See for example [Ref. 3], Section 7.1.

We have carried out a test to compare the GPS-only and the GLONASS-only position for 19 control stations, processing one day of data in PPP. The results are shown in Figure 12.

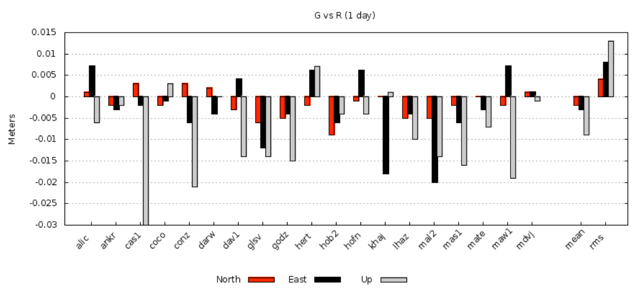

Figure 12: GPS-only versus GLONASS-only position

As can be seen in Figure 12, the agreement between GPS and GLONASS is remarkably good. The RMS of the position differences is around 5 mm in the horizontal components and just above 1 cm in vertical. A systematic bias of around 1 cm (see *mean* in Figure 12) seems to be present in the vertical component. The systematic difference in the horizontal direction is just a few mm.

Regarding station clock, the accuracy than can be obtained in static PPP using GPS data and products from IGS is of the order of 50 ps or better. See for example [Ref. 3], Section 7.3. To illustrate this we have processed one day of data from the CONZ station in Chile (connected to a very stable Hydrogen maser) and estimated its clock with PPP. The result is shown in Figure 13.

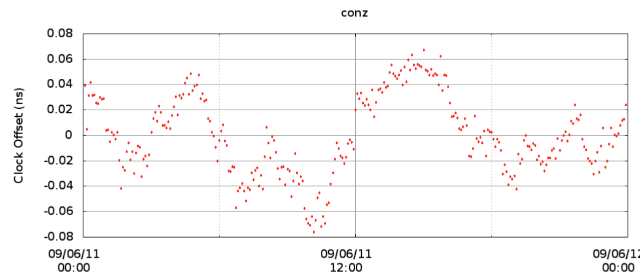

Figure 13: GPS-only CONZ station clock

Recall that the station clock from PPP is given with IGST (a very stable time scale). In Figure 13 a parabola has been removed from the clock time series in order to show only the stochastic clock behavior. As can be seen from Figure 13 the RMS of the clock evolution over 1 day is around 40 ps. This is consistent with the expected accuracy from PPP (actually this value includes also the actual station clock instability and the IGST timescale instability, not only the PPP inaccuracy).

An interesting experiment is to find out whether this level of clock accuracy can be achieved using the GLONASS-only data from the CONZ station in PPP. The results are shown in Figure 14.

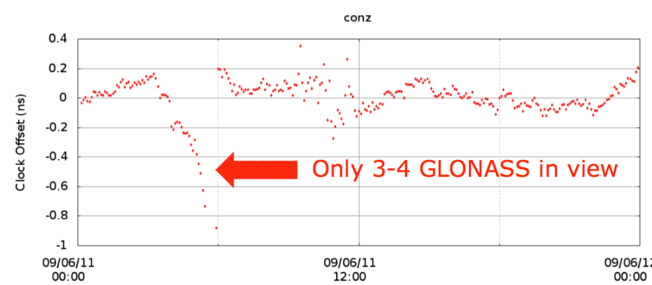

Figure 14: GLONASS-only CONZ station clock

In Figure 14 one can observe 'large' deviations of the clock evolution just during a few hours before 06:00 (compare with Figure 13), with excursions of up to 1 ns. After a detailed analysis of the GLONASS observations during these hours it was found out that only 3 or 4 satellites (depending on the cutoff elevation considered) were being tracked. This shows that the number of GLONASS satellites available on the sky can be a limiting factor for precise ground clock estimation and characterization using GLONASS data exclusively.

For completeness, the CONZ station clock calculated using GPS+GLONASS data is shown in Figure 15.

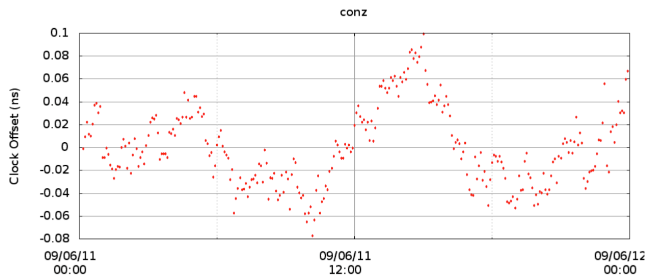

Figure 15: GPS+GLONASS CONZ station clock

The GPS+GLONASS results are nearly identical to the GPS-only case (compare Figure 15 and Figure 13), although a marginally higher instability can be observed in the GPS+GLONASS case. This seems to indicate a slight incompatibility between the GPS and GLONASS systems, whose exact cause we are not able to determine at present.

Concerning the inter-channel biases estimated as part of the GLONASS data processing, the values for CONZ in the GLONASS-only case are shown in Figure 16.

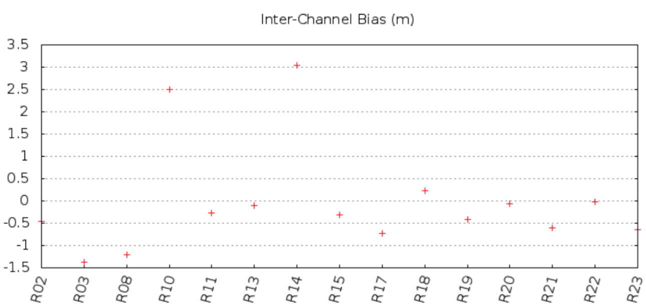

Figure 16: CONZ inter-channel biases

Is the inter-channel bias something inherent to the receiver type or model? In order to answer this question we processed in PPP two stations (CONZ and MATE) with the same receiver, a LEICA GRX1200GGPRO. The results are shown in Figure 17. A very good agreement can be observed for the CONZ and MATE stations.

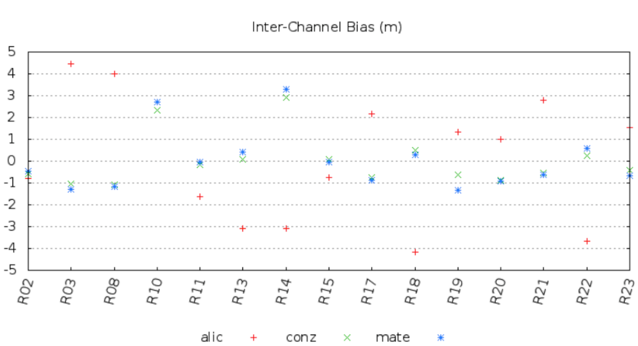

Figure 17: Inter-channel biases and receiver type

PPP USING ONE HOUR OF STATION DATA

When using only one hour of station data, the accuracy of the PPP position solution varies noticeably depending on satellite availability and geometry, and also on the amount of carrier phase cycle slips present on the data. Unlike the case of one-day PPP, in one hour the geometry of satellites in the sky changes little, therefore the Dilution Of Precision (DOP) effect cannot be 'averaged out'. As a result it is not straightforward to give a global figure for one-hour PPP accuracy.

Figure 18, Figure 19, and Figure 20, show examples of the PPP position error obtained using one hour of station data, for the GPS-only, GLONASS-only, and GPS+GLONASS cases, respectively. The reference or 'true' position is always the sub-cm solution using one day of GPS data (see previous section).

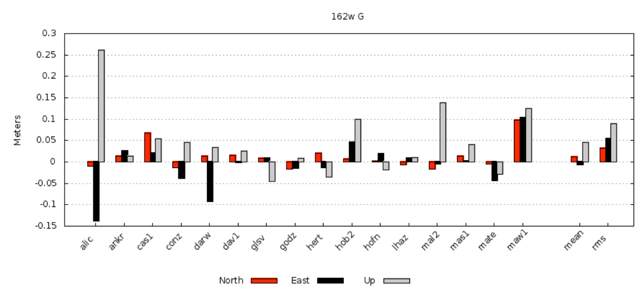

Figure 18: GPS-only position error in 1 hour

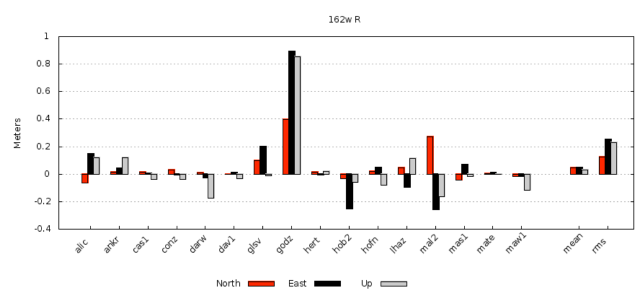

Figure 19: GLONASS-only position error in 1 hour

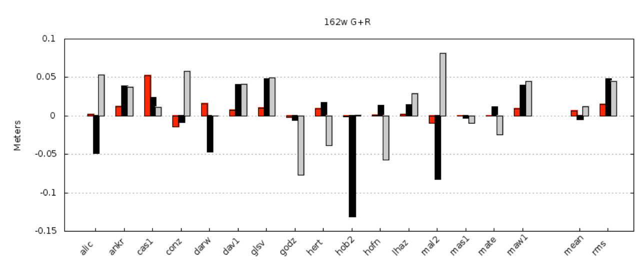

Figure 20: GPS+GLONASS position error in 1 hour

The previous figures do not intend to provide a complete characterization of position accuracy in one hour, they are included as representative examples of 1-hour data processing.

We have carried out additional tests with 1-hour RINEX files and in general it can be said that the GPS+GLONASS solution is noticeably more accurate and considerably more robust than the GPS-only solution. When using GPS-only we get typical horizontal accuracies of the order of 5-10 cm (RMS) with some larger deviations occasionally. When using GPS+GLONASS the error is more consistent for all stations, with a typical horizontal accuracy of around 5 cm RMS and in general no large deviations.

As can be seen in Figure 19, GLONASS-only PPP positioning in one hour is not very reliable, in some cases we get errors similar to GPS-only or GPS+GLONASS, but very often we get quite large deviations. It is expected that this will improve in the future when more healthy satellites become available in the Russian constellation.

THE PROBLEM OF CLOCK INTERPOLATION

The *rapid* clocks published by IGS for GPS, and the GLONASS clocks from ODTS, are given at a 5-min rate. If a higher data date is to be used in PPP, the input GPS and GLONASS satellite clocks must be interpolated.

The problem of satellite interpolation is that, no matter what interpolation algorithm is used, it does not reflect the true satellite clock behavior at the interpolated epochs, therefore if could negatively affect the PPP solution in position and in timing (station clock).

In order to evaluate the effect of satellite clock interpolation on the station clock estimated by PPP, we have re-processed the day of CONZ station data shown in Figure 13 (GPS-only), but using a 30-sec data rate instead of a 5-min one. The results are shown in Figure 21 (the 5-min results are shown on top for easier comparison).

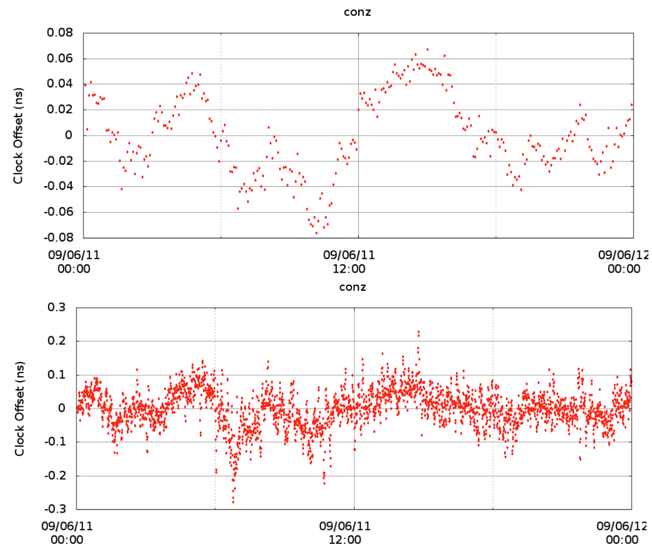

Figure 21: CONZ station clock using a 5-min data rate (above) and a 30-sec data rate (below)

As can be seen from Figure 21, when using a 30-sec rate, the clock excursions are up to three times larger than when using a 5-min rate, resulting into an apparent worse clock stability. The 30-sec behavior is actually not due to the true station clock but it is an undesired effect introduced by interpolating the PPP input satellite clocks at intermediate epochs. Therefore clock interpolation should be avoided in PPP, and higher resolution satellite clocks should be used as input instead (actually the IGS publishes *final* GPS clocks at a 30-sec rate).

Let us now see the effect of clock interpolation in PPP position accuracy. Using one day of station data the effect of clock interpolation is negligible: over one day the accuracy of PPP positioning is below the centimeter with or without interpolation. However, when we use only one hour of station data the situation is different. Figure 22 shows a 1-hour GPS+GLONASS PPP solution for several stations using a 5-min data rate (above) without clock interpolation, and using a 30-sec data rate (below) with clock interpolation. The reference or ‘true’ position is always the sub-cm solution using one day of GPS data.

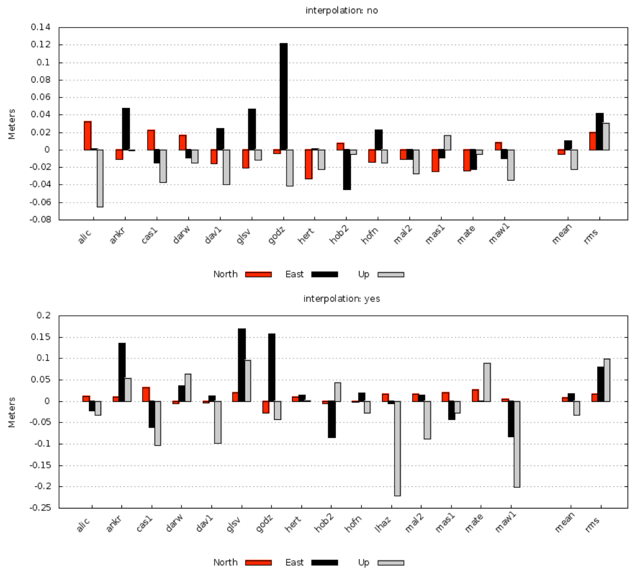

Figure 22: Effect of clock interpolation in 1-hour positioning (above: 5 min; below: 30 sec)

As can be seen from Figure 22, when clock interpolation is done the RMS position error increases from around 5 cm (above) to around 10 cm (below). This leads to the apparent contradiction that using a higher data rate the position accuracy degrades instead if improving. This confirms that clock interpolation is also to be avoided in short-term Precise Point Positioning.

At the time of writing we did not have the opportunity to test PPP using input satellite clocks at a 30-sec rate. 30-sec GPS clocks are available from IGS, but GLONASS clocks have to be re-generated using ODTS for the month of June, with is a time consuming task.

CONCLUSIONS AND FUTURE WORK

The main conclusions of this paper are the following:

1. Version 1.3 of the *magicGNSS* web application (http://magicgnss.gmv.com) allows online processing of GLONASS data in Precise Point Positioning, for station data from June 2009, with or without GPS data in addition.

2. When using PPP with **one day** of static station data, at a 5-min rate, the GPS-only and GLONASS-only position solutions agree at a sub-cm level; GPS+GLONASS positioning does not bring much benefit with respect to GPS-only; GLONASS-only might fail for precise clock station characterization due to lack of sufficient satellites in view at some epochs, causing apparent clock deviations of more than one ns.

3. When using PPP with **one hour** of static station data, at a 5-min rate, the positioning accuracy depends heavily on satellite visibility and geometry (DOP), and on the occurrence of cycle slips as well; it is not straightforward to give a global figure for one-hour PPP accuracy; in general the GPS-only solution has a 5-10 cm RMS error with some larger deviations; the GLONASS-only solution is sometimes at the decimeter level but often is not reliable, and the GPS+GLONASS solution is more robust than GPS-only, with a typical error of 5 cm RMS and in general absence of large deviations.

4. When using PPP with **one hour** of static station data, at a 30-sec rate, the position solution degrades with respect to the 5-min solution, because the input satellite clocks are given at a 5-min rate and must be interpolated; satellite interpolation should be avoided and higher-rate input clocks should be used instead.

This paper shows the very first results using dual constellation data in *magicGNSS*. Intended future areas of experimentation are the generation of higher rate satellite clocks in ODTS (GPS and GLONASS), the evaluation of GPS+GLONASS PPP in shorter data periods (down to 10 minutes or so), and the extension of the PPP technique to kinematic and stop-and-go positioning, and also to real-time applications.

ACKNOWLEDGMENTS

We greatly appreciate the efforts done by IGS, the International GNSS Service [Ref. 2], to generate high quality data and products and make them available to the GNSS community in a timely and reliable way.

REFERENCES

1. R. Píriz, A. Mozo, P. Navarro, D. Rodríguez, *magicGNSS: Precise GNSS Products Out of the Box*, ION GNSS 2008.

2. J.M. Dow, R.E. Neilan, G. Gendt, *The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade*, Adv. Space Res. 36 vol. 36, no. 3, pp. 320-326, 2005.

3. Jan Kouba, *A Guide to Using International GNSS Service (IGS) Products*, May 2009.