COMBINED MULTI–SYSTEM GNSS ANALYSIS FOR TIME AND FREQUENCY TRANSFER

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Abstract

The Center for Orbit Determination in Europe (CODE) is one of the Analysis Centers (AC) of the International GNSS Service (IGS). It is located at the Astronomical Institute of the University of Bern (AIUB). Since May 2003, CODE provides consistent GPS and GLONASS satellite orbits from a combined analysis using the Bernese GPS Software package. The data of about 30 stations in the IGS network that are equipped with GNSS receivers tracking GPS as well as GLONASS satellites are analyzed for that purpose together with numerous stations that only track the GPS satellites.

With the background of the experience in orbit determination for more than one satellite system, we discuss the use of both GPS and GLONASS observations in a combined analysis for geodetic time and frequency transfer using code and phase measurements. The number of satellites that can be used for time transfer is increased when adding the GLONASS observations to the analysis. This may help to improve the redundancy for the receiver clock parameters that are estimated for each station from all satellites in view.

GLONASS satellites emit the signals on individual frequencies. This may lead to frequency–dependent biases in the receivers that have been investigated, e.g., in [1]. Of course, these biases must be considered in a combined analysis of GPS and GLONASS code data. Corresponding parameters can be estimated for all GNSS receivers even if they are not connected to an external reference clock. This offers the possibility to investigate the frequency–dependent biases for all receiver types that are represented in the IGS network. The estimated biases can be interpreted as a relative "calibration" of each individual frequency used by a GLONASS satellite with respect to the GPS frequency.

The rigorous common analysis of GPS and GLONASS measurements is considered as a good preparation for including the upcoming European GALILEO system into the processing for geodetic time and frequency transfer with a maximum benefit for the solution.

1 Introduction

The Center for Orbit Determination in Europe (CODE) is one of the global Analysis Centers (AC) of the International GNSS Service (IGS). It is a collaboration between the Astronomical Institute at the University of Bern (AIUB, Switzerland), the Federal Office of Topography (swisstopo, Switzerland), the Federal Agency for Cartography and Geodesy (BKG, Germany), and the Institut Géographique National (IGN, France). It is located at AIUB. The development version of the Bernese GPS Software package [2] is used for all analyses.

Since May 2003, CODE includes not only GPS but also GLONASS satellites in all its orbit determination procedures for the submission to the different IGS product lines: the final, rapid, and even ultra–rapid products[1]. It is — at least up today — the only AC of the IGS that performs a rigorous GNSS analysis by processing the observations from different Global Navigation Satellite Systems (GNSS) together in one common parameter estimation procedure. On one hand, this strategy requires a higher computer performance because of the higher number of observations that have to be processed together and because of the higher number of parameters that have to be solved for. On the other hand, the resulting orbits for all satellites of both GNSS have the best possible consistency. Further details on the processing strategy at CODE may be found in [3].

Up to now, CODE does not include GLONASS in its final and rapid clock products. The most important reason for this is, that interfrequency biases as described and calibrated, e.g., in [4] are unknown for the GNSS receivers that are used in the IGS network. For a combined GNSS analysis they have to be considered by estimating them as unknown parameters in the processing. A summary of the results will be given in Section 3.

In addition, the number of additional observations (including the corresponding increased number of phase am-

[1]The IGS product lines are defined by their latencies between the observation and the availability of the products. The ultra–rapid products are generated four times per day and are available three hours after the last observation. The rapid products are made available at 17:00 UT for the previous day whereas the final products have a latency of about two weeks.

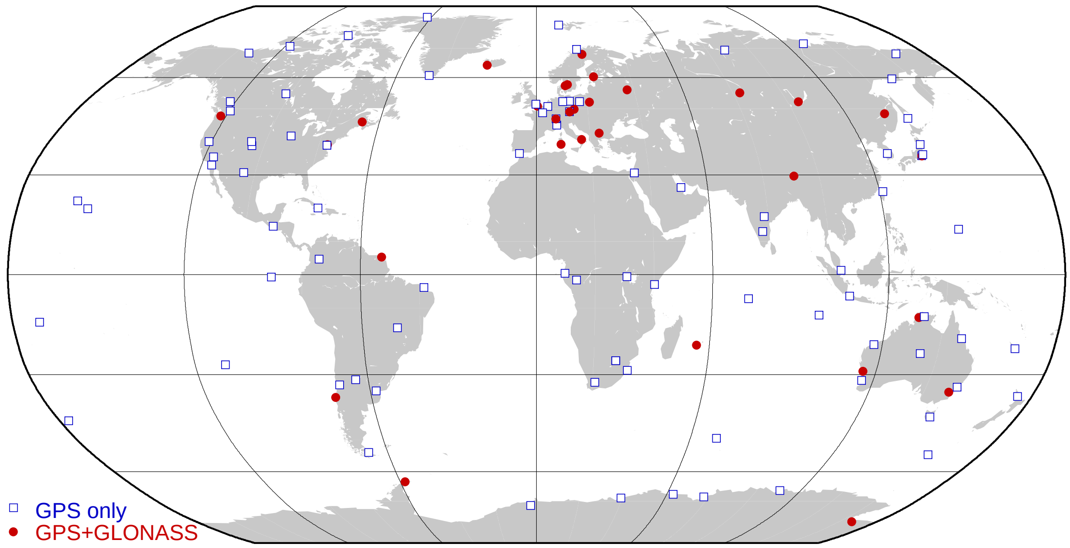


Figure 1: Location of the IGS stations included in the CODE GNSS clock processing.

biguity parameters) and the number of interfrequency bias parameters that have to be estimated as well, increases the required computing effort that is necessary to provide also satellite clocks for GLONASS satellites.

On the other hand, the stations currently providing GNSS data for GPS and GLONASS do not allow for a complete coverage of the GLONASS orbits. A few gaps remain over the Pacific Ocean and the southern part of the Atlantic Ocean and Africa. For the orbit determination these gaps can easily be bridged by dynamic orbit modeling, but for the clock products epochs with missing satellite clocks result. This sparse station distribution may effect the results when only the GLONASS satellite clocks are introduced for a precise point positioning (PPP) resp. a PPP solution needs not to be improved by adding the GLONASS to the GPS observations in a combined GNSS analysis — especially outside from Europe where most of the GNSS receivers are located in the IGS network. More details will be discussed in Section 2.

In this paper we present results of a series of test solutions set up to compute fully consistent satellite clock corrections for different GNSS. Problems and the benefit for time and frequency transfer from a combined analysis using carrier phase data from multiple GNSS are discussed in Section 4.

2 Description of the combined GNSS Analysis

To compute the GPS satellite clock corrections from the tracking network of nearly 350 IGS stations a subset of 90 stations for the rapid and 120 stations for the final products are selected for the processing at CODE. As long as no data problems are encounted the IGS stations located at timing laboratories contributing to TAI and the IGS stations equipped with H-maser clocks to support the generation of the IGS time scale ([5]) are included in the solution every day. Further IGS stations with a low noise in the code data (e.g., because of a low impact from multipath or environmental effects) are added to get a network with global coverage that allows to compute the satellite clock corrections for all satellites and epochs from the observations of at least three stations.

Today the IGS network contains about 30 stations equipped with GNSS receivers that track signals from GPS as well as from GLONASS satellites. As illustrated by Figure 1 most of them are located in Europe while the coverage of other region is very sparse. No redundancy is available (except in Europe) to cope with station outages or late data submissions. When requesting a minimum number of stations to contribute to the estimation of a satellite clock parameter it is for most GLONASS satellites not possible to provide clock corrections for all epochs (usually only for about 90%). Regions where no GLONASS satellite clock parameters can be provided due to lack of data are the Pacific Ocean and the southern part of the Atlantic ocean as well as southern Africa.

As shown in Figure 2 the GPS satellite clock corrections are computed from the data of at least ten stations. However, there are daily intervals where the GLONASS satellites are not observed by any of the GNSS receivers in the IGS network. As a consequence, independent parts in the resulting GLONASS satellite clock time series result that are not connected by continuous carrier phase data. Discontinuities analogous to day boundary discontinuities for station clocks (see, e.g., [6]) have to be expected.

Because of the lower redundancy for the estimation of GLONASS satellite clock corrections stations with a higher noise level in the code data may have a higher impact on the results because they cannot be replaced by other sites in the analysis. Figure 3 shows the Al-

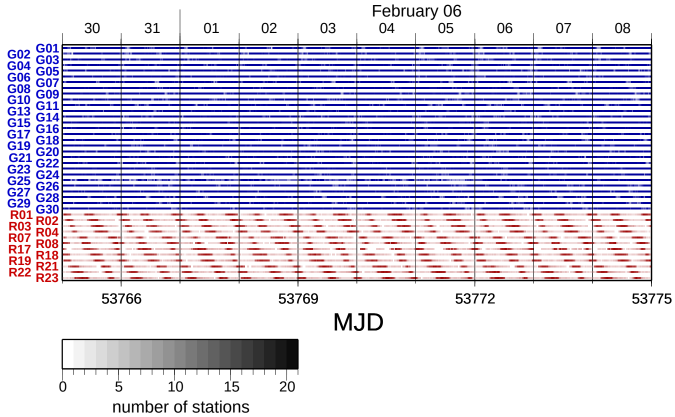


Figure 2: Number of stations that are used to compute the GNSS satellite clocks in the CODE analysis for a period of ten days. According to the RINEX convention the GPS satellites are labeled with Gxx while the GLONASS satellites are named Rxx.

lan variance of the GPS and GLONASS satellite clocks. To achieve a better comparability both the GPS and GLONASS satellite clock corrections are computed from the about thirty GNSS stations in the IGS network only. The performance of the GLONASS satellite clocks is comparable with the GPS Block II resp. IIA Cesium clocks. It is interesting to note that no improvement for clocks onboard of the new generation of GLONASS–M satellites with respect to the older GLONASS satellites can be found in the Allan variance.

For some satellites (GPS as well as GLONASS) a periodic once per revolution signal can be found. These satellites are located on different orbital planes and not all of them are eclipsing during this period. Because the periods of the different satellites are not in phase it can be ruled out that the GNSS station SPT0 (Swedish National Testing and Research Institute, Boras, Sweden) used as reference clock has introduced this disturbation.

As long as the estimated satellite clock corrections are used for a PPP such an effect does not inevitably degrade the results if fully consistent satellite orbits and clocks are used as required for the PPP in general.

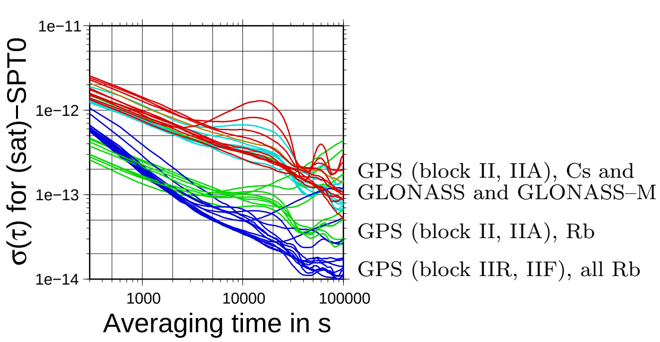


Figure 3: Allan variance of GNSS satellites computed for 10 days in February 2006.

3 Intersystem and Interfrequency Biases in GNSS Receivers

Because the orbits and clock corrections for the satellites of the different GNSS are the result of a combined analysis all these products are fully consistent. They refer to the same geodetic reference frame and to the same reference clock. That's why they can be introduced into a GNSS analysis without considering additional intersystem biases. The only remaining type of intersystem bias relevant for the users are possible receiver time resp. receiver antenna biases. Both are discussed in this section.

3.1 Receiver Antenna Model

Because of the different frequencies and signal structure of the individual GNSS the electronical characteristics of a receiver antenna (described for the processing as models of the antenna phase center variation – PCV) may be different for each satellite navigation system. Calibrations of geodetic GNSS antennas (as described, e.g., in [7, 8]) are done using observations to GPS satellites only. The question is whether these receiver antenna models can also be used for observations to GLONASS satellites or whether there are significant differences.

To generate Figure 4 the GPS derived receiver antenna model was applied for the GPS as well as for the GLONASS observations. Furthermore, from all GLONASS measurements, parameters to characterize an elevation–dependent (i.e. rotation symmetric) receiver antenna model are estimated. It is expected that these corrections are zero if the GPS derived model can also be used for GLONASS observations. The differential phase pattern was computed for five antennas that are used in the IGS network for GNSS receivers from four weeks of data.

The values for very high and low elevations can be ignored:

> 80°: Close to the zenith only a small number of observations is available due to the satellite geometry. This leads to uncertain estimates for the corrections.

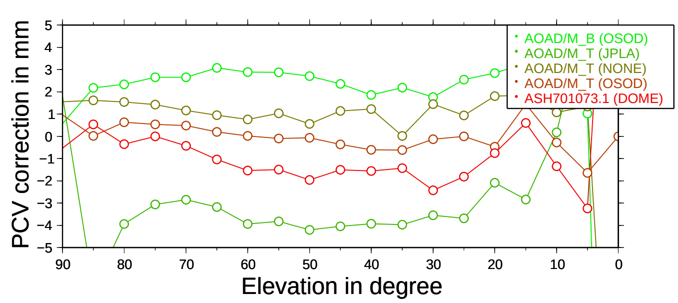


Figure 4: Parameters of an elevation–dependent receiver antenna model for five antennas that are currently used for GNSS receivers in the IGS network. The results are obtained from four weeks of data in January 2006.

< **20°:** Close to the horizon troposphere and multipath effects result in a higher noise of the observations. Masking and elevation cutoff in addition reduces the number of observations.

After removing the estimated corrections at the extreme elevations a middle part between 20° and 80° of elevation remains. The curves can now be shifted by a few millimeters so that their mean value becomes zero. This shift corresponds to a time offset between the GPS and GLONASS observations that also can to be considered as intersystem receiver code bias as will be discussed in the following section. For the phase measurement the intersystem time bias is absorbed by the phase ambiguity parameters resp. by the phase shift parameters that have to be estimated if the ambiguities for the GLONASS observations are resolved to their integer values. As conclusion, the estimated corrections for the GLONASS receiver antenna model w.r.t. the GPS derived antenna model are in the order of 1 mm. This means that this experiment did not indicate a significant discrepancy between the antenna models for both GNSS.

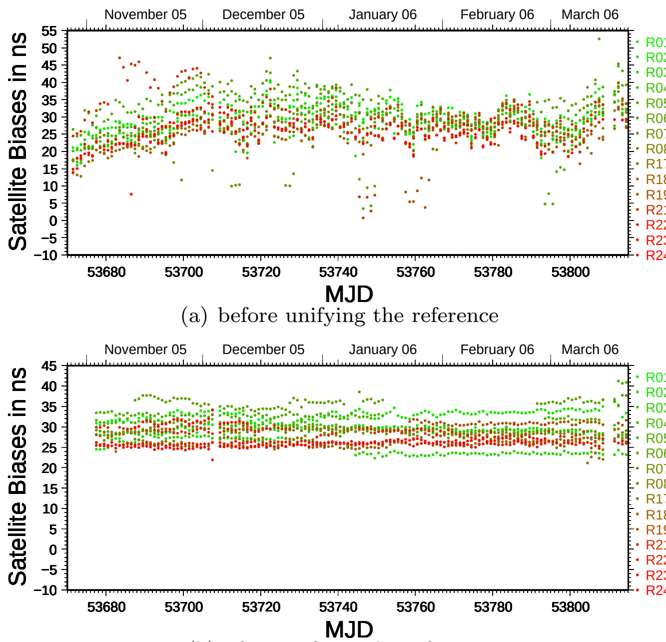
3.2 Receiver Intersystem/Interfrequency Biases

The satellite clock corrections obtained in a combined analysis of the GPS and GLONASS observations refer to one and the same reference clock in the network solution. The difference in the broadcast time scales between GPS and GLONASS are, therefore, not relevant anymore. Nevertheless, an intersystem time bias within each receiver may be expected because of the different frequencies and signal structure of the individual GNSS.
Such a receiver internal time bias is only relevant for processing the code data. When analyzing the phase measurements the corresponding phase ambiguity parameters will absorb the time biases.
Because the GLONASS satellites emit their signal on individual frequencies, in addition to intersystem also interfrequency biases for the receivers are expected (they were detected already by other groups, e.g., [1, 4]). To make this study as general as possible one bias for the code measurements of each satellite (GPS and GLONASS) was setup for each station. Because the receiver and satellite clocks are also computed, two singularities have to be treated. We use to introduce a zero mean condition over all estimated corrections:

- The sum of all estimated biases for the GPS satellites of a station is zero for each day. This means that all computed satellite biases of the GLONASS satellites are relative to the biases for the GPS satellites.

- Furthermore, the sum of the biases of all stations for one and the same satellite is zero.

These zero mean conditions are equivalent to fixing all satellite biases of one receiver resp. to fixing the biases of



(a) before unifying the reference

(b) after unifying the reference

Figure 5: Daily estimated satellite biases for the GLONASS satellites at station ONSA (receiver: JPS E_GGD) before and after unifying the reference realized by the zero mean condition.

one satellite for all receivers in the network to any value. When using the zero mean condition the reference changes from day to day according to the magnitude of the biases of the receivers contributing to the daily network solution. Nevertheless, there are two strong reasons to prefer the zero mean condition instead of fixing biases: First, there is no preference for a specific receiver or a satellite. Second, when fixing biases and the particular reference receiver resp. satellite is not available during an interval, no solution can be generated or an alternative reference must be defined. The second reason demands that a change of the reference can be considered in a way that the results remain comparable. With the same algorithm the disadvantage of the zero mean condition can be compensated.
The impact of the individual realization of the reference in the case of a zero mean condition is demonstrated in Figure 5. The upper diagram shows the satellite biases as they are computed for each day for the station ONSA (Onsala, Sweden; receiver: JPS E_GGD). There is a clear systematic pattern in the graph that is similar to all satellite biases. In addition, there are several values in the time series that look like outliers. When unifying the reference a long-term solution for the satellite biases of all stations is generated. After that the daily solutions are fitted to the long–term solution with the same zero mean conditions as in the processing. With this algorithm the daily estimated satellite biases are made comparable. The biases obtained for station ONSA after the unification of the reference are shown in the lower graph of Figure 5.
The satellite biases are constant for all stations (apart

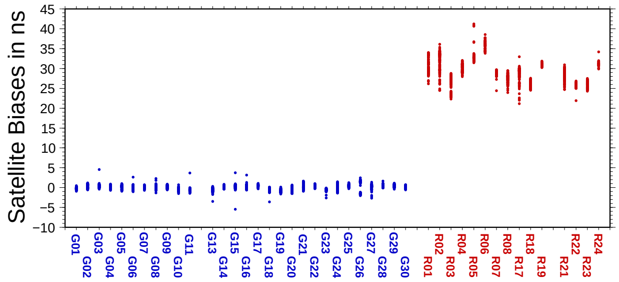


Figure 6: Daily estimated biases for all satellites at the station ONSA (receiver: JPS E_GGD). GPS satellites are named *Gxx* resp. GLONASS satellites *Rxx*.

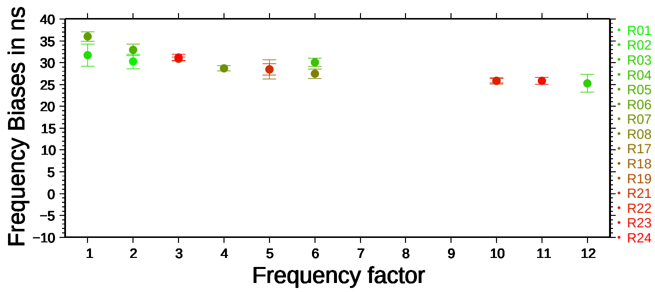


Figure 7: Mean satellite biases for the GLONASS satellites at the station ONSA (receiver: JPS E_GGD) as a function of the frequency factor of the individual satellites.

from receiver changes) over the time interval of more than four months (November 2005 to the mid of March 2006) that was processed here. No significant jumps were found even if a satellite was not available for several days. On the other hand, the repeatability of the satellite biases is very different for individual stations — but it is consistent with the mean noise level of the code data that may be found in the post–fit residuals. The use of one value for each satellite and receiver seems to be reasonable. This is also supported by Figure 6 where the biases obtained for the individual days are plotted in one column for each satellite. The satellite biases for all GPS satellites are zero within the uncertainty level. For the GLONASS satellites a mean bias w.r.t. the GPS satellites of about 30 ns is found. This can be interpreted as an intersystem bias of the receiver at ONSA. Nevertheless, a significant variation between the biases of the individual GLONASS satellites remains.

Figure 7 confirms that these variations depend on the signal frequency. Here the mean satellite biases are ordered in columns labeled with the frequency factors k that are used for the the computation of the carrier phase frequencies of the individual GLONASS satellites ($f_{Rxx} = f_0 + k_{Rxx} \cdot \Delta f$). For the receiver in ONSA as well as for the other stations no significant difference of the mean satellite biases can be found if two satellites are emitting their signal on the same frequency:

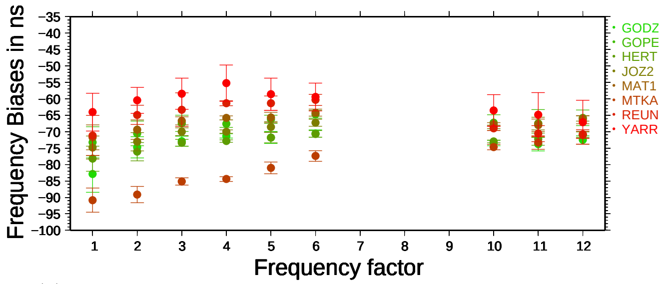
factor 1:	R02 and R06,
factor 2:	R01 and R05,
factor 3:	R19 (since Jan. 2006), R23, and R24 (until Dec. 2005),
factor 5:	R17 and R21,
factor 6:	R04 and R08,
factor 10:	R18 and R22,
factor 11:	R20, as well as
factor 12:	R03.

These results allow it to switch from satellite to interfrequency biases. This has the advantage that less unknown parameters have to be estimated. But also another problem may be reduced: Due to the sparse coverage of stations observing the GLONASS satellites it may happen that the network is decomposed into independent clusters that are not connected by simultaneous observations to each of the active GLONASS satellites. In that case, two independent references to compute the satellite biases are required to prevent singularities when resolving for the unknown parameters. If two satellites contribute to one interfrequency bias the decomposition of the network becomes less likely. Furthermore, the number of observations that contribute to the interfrequency biases is two times higher than for satellite biases which improves the uncertainty of the estimated parameters.

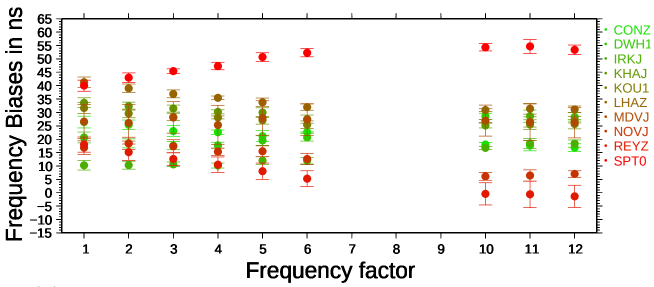
Figure 8 summarizes the mean interfrequency biases that are computed for all GNSS receivers in the IGS network for the period from November 2005 to March 2006. The stations are included in separated diagrams according to their receiver types. The stations equipped with ASHTECH Z18 receivers have a negative bias w.r.t. the GPS satellites whereas the JAVAD receivers show a positive bias. Obviously this is caused by the zero mean condition that was applied for computing these values. No conclusion on the real receiver quality (no significant intersystem as well as interfrequency biases are expected for a perfect receiver) can be derived. It is furthermore noticeable that the biases differ not only between the receiver types but also from station to station that are using the same receiver type (see, e.g., station MTKA for the ASHTECH Z18 receiver, or station SPT0 for the JPS LEGACY receiver).

The estimation of interfrequency biases for each GNSS station introduces a big number of additional parameters when computing GLONASS satellite clock corrections. On the other hand, biases that are computed from a certain time interval for a station can later be applied for the analysis as it is done today with the differential code biases. The interfrequency biases and the obtained satellite clocks are fully correlated. This means that, when using the satellite clocks, e.g., for a PPP of further stations, corresponding biases have also to be estimated or applied for these GNSS receivers.

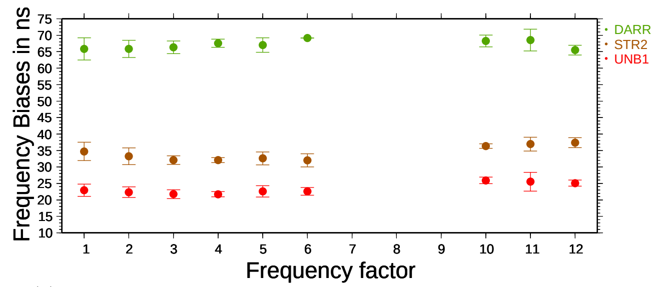
When comparing these results with other calibration results, we have to keep in mind that the estimation of the frequency biases is independent from the broadcast



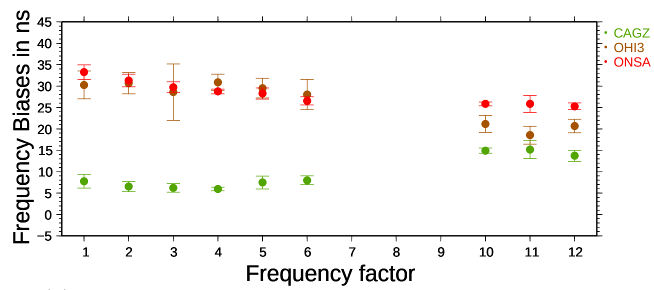
(a) Receiver inter–frequency time biases for ASHTECH Z18



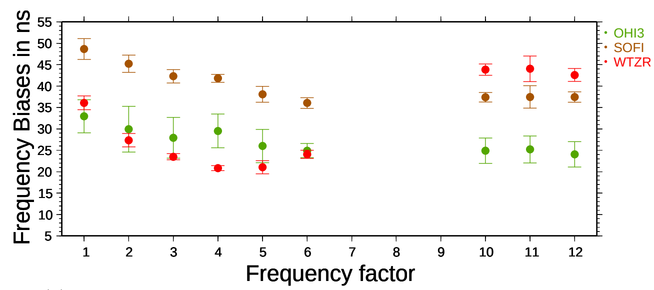
(b) Receiver inter–frequency time biases for JPS LEGACY



(c) Receiver inter–frequency time biases for TPS LEGACY



(d) Receiver inter–frequency time biases for JPS E_GGD



(e) Receiver inter–frequency time biases for TPS E_GGD

Figure 8: Receiver interfrequency biases for the GLONASS frequencies for five GNSS receiver types in the IGS network relative the GPS frequency. The values are computed from four month of data (as long as the observations to the corresponding GLONASS satellites are available). A zero mean condition for each GLONASS frequency was applied.

GPS and GLONASS satellite clocks. This makes sense because of their higher uncertainty. In addition, the computation of GLONASS satellite clock corrections remains independent from the availability of GLONASS broadcast messages. The solution is obtained by analyzing the ionosphere–free linear combination of the phase observations at both frequencies. Calibration results obtained for the individual frequencies of the two signals have to be transformed to make them comparable with the results from this study. Because also the satellite clock corrections are estimated when computing the interfrequency biases for the individual receivers only the differences between the biases of one frequency for different receivers can be directly compared.

It is clear that this approach is not a real calibration. It considers the interfrequency and intersystem time biases of the receivers in such a way that the corresponding code measurement can be used for a geodetic (or also for a code–only) time and frequency transfer. The advantage is that also uncalibrated receivers can be included into the network solution without degrading the quality of the estimated satellite clocks resp. the time transfer results between two calibrated GNSS receivers.

4 Multi-System GNSS Analysis for Time and Frequency Transfer

If two GNSS receivers are used for a time transfer experiment that are both calibrated with GPS (e.g., [9]) the interfrequency biases for both receivers (or at least their difference) have to be considered. Additional observations from the GLONASS satellites may then only help the frequency transfer because the interfrequency biases for the receiver(s) have to be estimated. Since they are constant in time, the additional code observations may help for the time transfer when multiple days are analyzed (even if independent daily solutions are computed accepting the day boundary discontinuities, see [10]). Assuming that multipath effects depend on the frequency of the affected signal, the addition of an alternative GNSS (e.g., GLONASS) may help to reduce the impact of these effects on the results. This is in particular valid for the GLONASS system that has individual frequencies for each satellite and for which the satellite constellation repeats only every eight sidereal days. Assuming that the antipodal satellites emit the signal on the same frequencies, a repeated multipath situation is expected every four sidereal days instead of every single sidereal day in the case of GPS. Nevertheless, the argument for a combined GNSS analysis is mostly the increased number of observations.

Figure 9 displays the number of satellites in view for the station ONSA during 10 days as an example. During this selected period between three and five GLONASS satellites are observed whereas usually measurements to between eight and ten GPS satellites are available. By adding the measurements of the GLONASS satellites to those to the GPS vehicles in a GNSS analysis, the number of available data can be multiplied by a factor of up to 1.5 . With a full GLONASS (and later also GALILEO) constellation, this factor increases to nearly two (resp. three).

As a first rough estimate an improvement of the results of a factor $\sqrt{1.5} = 1.2$ (and in future up to $\sqrt{3} = 1.7$) may be expected from this increased number of observations. Provided that consistent products for the different GNSS (see Section 2) are introduced into the combined analysis only intersystem biases of the user's receivers have to be considered in the processing as it was discussed in Section 3. In the case of GLONASS the interfrequency biases weaken the solution because for each frequency factor (usually one pair of satellites) one additional parameter has to be solved for when the receiver and satellite clocks are computed. For that reason, the factor of 1.2 for the improvement of the combined GPS and GLONASS solution is not realistic.

Figure 10 shows the differences of the GPS resp. GLONASS solution to the combined GNSS solution for the baseline between the two GNSS stations in SPT0 and ONSA, both equipped with H-masers. The GPS and GNSS solution are equal within the 10 ps level. The difference between the GLONASS and GNSS solution reach 50 ps. This higher noise level can be assigned to the solution using only GLONASS satellites which is plausible because of the estimation of the interfrequency biases together with the clock parameters.

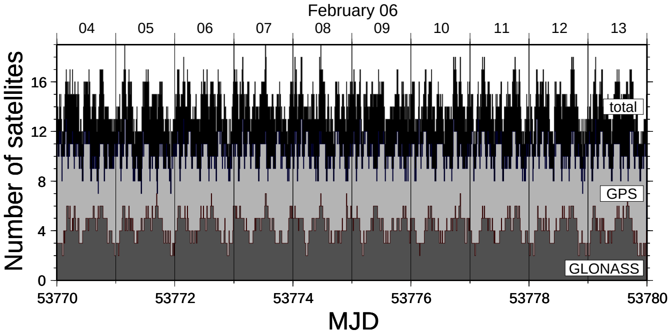


Figure 9: Number of observed satellites from the different GNSS for the station ONSA.

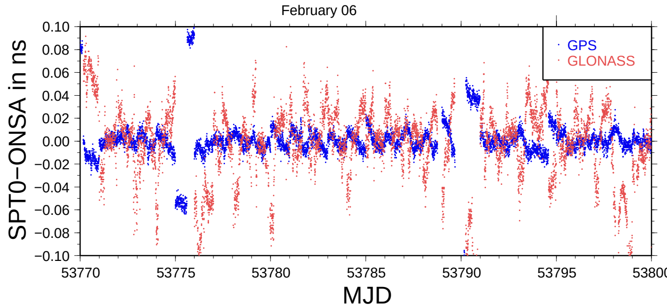
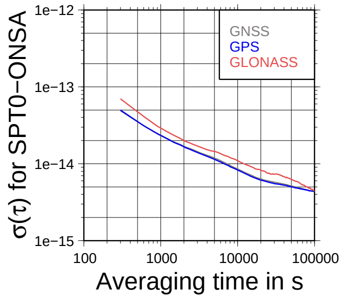


Figure 10: Receiver clock differences for the baseline ONSA→SPT0 between the solutions computed from GLONASS resp. GPS observations only and the receiver clock differences obtained from a combined GPS and GLONASS GNSS solution.

The Allan variances of the three solutions for this baseline in Figure 11 do not allow to favor either the GPS or the GNSS solution. The advantage of the additional observations is compensated by the estimation of the additional parameters, the interfrequency code biases. On the other hand, the addition of the GLONASS to the GPS satellites in the analysis does not degrade the solution. This confirms that all relevant biases are considered in the solutions.

5 Summary and Outlook

To obtain consistent products for different GNSS a rigorous combined analysis of measurements from all systems is preferable. The network may contain single system receiver as long as enough multi–system receivers can be included. At the IGS analysis center CODE, this approach is successfully applied for the combined processing of GPS and GLONASS satellite tracking data to generate consis-



Please not that the curve for the GNSS solution is hidden by the curve for the GPS solution because the Allan variance for both resulting time series are nearly identical.

Figure 11: Allan variance for the receiver clock differences for the baseline ONSA→SPT0 computed only from GLONASS, only from GPS, and from a combined GNSS solution.

tent orbits since May 2003. First experience to extent this combined analysis to the computation of fully consistent precise GNSS satellite clocks are encouraging. The obtained GLONASS satellite clocks have a comparable accuracy to the satellite clock corrections for the GPS satellites. The performance of the GLONASS satellite clocks is comparable with the performance of the GPS block II/IIA satellites with Cs clocks.

A prerequisite for the combined analysis of different GNSS is that also the receiver intersystem biases are taken into account. One item of investigation was the verification of the validity of the GPS derived receiver antenna models also for GLONASS observations. Data from five antennas currently used at GNSS sites in the IGS network are analyzed for an interval of four week. No significant differences were detected, which means that the GPS derived receiver antenna models also can be adopted for GLONASS measurements.

Because the GLONASS satellites emit the signal on individual frequencies, GLONASS (and also GNSS) receivers are affected by interfrequency time biases. For a GNSS receiver, these interfrequency biases also act as intersystem time biases as long as the GLONASS interfrequency biases refer to the GPS frequencies. The corresponding biases have to be considered (estimated or introduced) when analyzing GLONASS code data. These biases are different for individual receivers. As long as interfrequency time biases for the GNSS receivers have to be estimated together with the receiver and satellite clock corrections, the advantage of more satellites due to a GNSS instead of GPS analysis is compensated. For carrier phase measurements these biases are absorbed by the phase ambiguity parameters. They become only relevant if ambiguities are resolved to their integer values.

The launch of further GLONASS satellites and the densification of the GNSS stations in the IGS network will improve the situation for the rigorous GNSS analysis. When adding GALILEO as third GNSS to a combined analysis, only one additional intersystem time bias for each receiver is expected (in the optimistic case, one for each receiver type).

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