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1. Introduction

In this document we will report on the Reference Frame product generation: some technical aspects (i.e. processing scheme) and selected aspects from the quality control results

The reference frame products are the prerequisite for the GPS-derived precise GRACE orbits as needed for gravity field determination. They provide the link between the geometrical (station coordinates) and physical (gravity field) description of the Earth. To get a consistent series of GNSS satellite clock corrections, GNSS orbits, Earth rotation parameters (ERPs), and station coordinates, more than 250 globally distributed tracking stations (see Figure 1 and Figure 3 (right)) of the International GNSS Service (IGS, Dow et al., 2009) are homogeneously processed for the interval between 2003 to the end of 2014. A rigorous combined processing scheme of the GPS and GLONASS measurements according to the processing standards as applied for the IGS activities at the CODE (Center for Orbit Determination in Europe) at AIUB (Astronomical Institute, University of Bern, Bern) was applied (Dach et al., 2015). The latest development version of the Bernese GNSS Software (Dach et al., 2007) has been used.

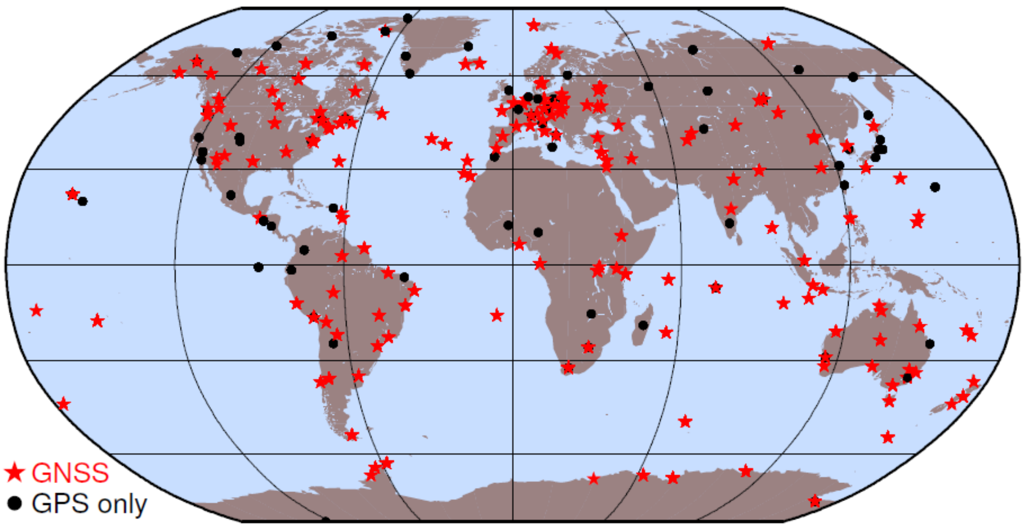


Figure 1: Geographical distribution of the IGS station network used in the current reprocessing activities (as of 2014).

Since the establishment of the IGS in 1994, global GNSS data from the IGS tracking network has been analyzed on an operational basis by its global analysis centers, providing GNSS-based products (i.e. satellite orbits, ERPs, and station coordinates) on a daily basis. During the years, models and methods to analyze GNSS data have been continuously improving. This results in discontinuities in the times series solution. Because also the reference frame was regularly updated, this series is not the optimum to be used as the reference frame products for EGSIEM.

Steigenberger et al. (2011) , Fritsche et al. (2014) as well as other authors have shown that homogeneously reprocessing GNSS observations leads to much better time series of products. The most recent reprocessing campaign of the IGS (repro 02[1]) has been carried out in 2013/2014 to support the generation of the ITRF2014. Dach et al. (2015) document the CODE contribution to this IGS product series.

Spurious spectral lines in geodynamical parameters, in particular in the ERPs and in the estimated geocenter coordinates series are a topic of investigations within the GNSS community since several years (e.g., Rodriguez-Solano et al., 2014). Arnold et al. (2015) proposed an extension of the Empirical CODE orbit model (ECOM, Beutler et al., 1994) that significantly improves the accuracy of the GNSS orbits (in particular for the GLONASS satellites) and reduces the deficiencies in the geodynamical parameters. It is applied to the IGS-related activities of CODE since January 04, 2015 (announced in IGSMAIL 7035[2]).

In order to provide within the EGSIEM project reference frame products using these latest GNSS orbit modelling effort, a full reprocessing of the GNSS data for the interval of 2003 to 2014 was initiated. Table 1 presents the difference between estimated Solar radiation pressure parameters for the original and the extended ECOM as it was applied for the EGSIEM reprocessing. In both realizations of the ECOM a Sun-oriented orthogonal coordinate system in the satellite is used: D component points from the satellite to the Sun, the Y component goes along the solar panel axis, and the B component completes a right hand orthogonal system (illustrated in Figure 2).

Table 1: Empirical parameters estimated in D Y, B coordinate system for the original ECOM and the extended ECOM (cycle-per-revolution is denoted as cpr).

	Parameters estimated in		
	D	*Y*	*B*
Original ECOM	constant	constant	constant, 1-cpr
Extended ECOM	constant, 2-cpr, 4-cpr	constant	constant, 1-cpr

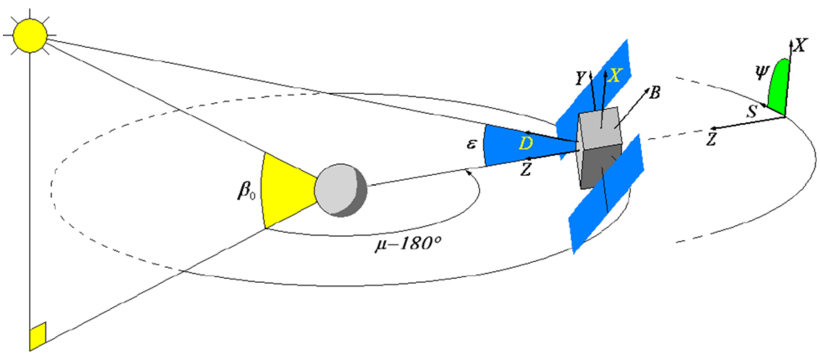
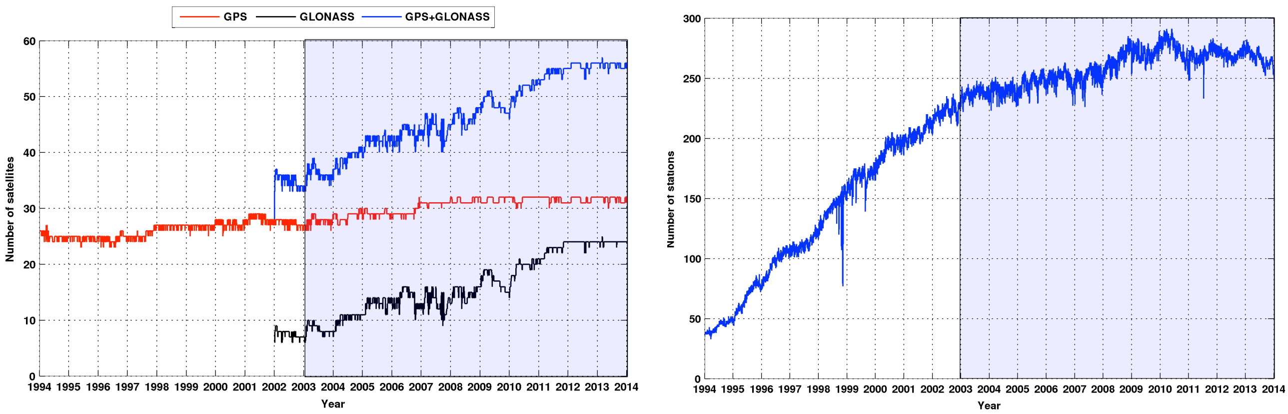


Figure 2: Relative geometry of Sun, Earth and GPS satellites. Nominal yaw-steering attitude as a function of the position of the Sun in the orbital plane. Illustration of DYB (Sun-oriented) and XYZ (body-fixed) orthogonal frames, Rodriguez-Solano et al., (2014).

[1] http://acc.igs.org/reprocess2.html
[2] https://igscb.jpl.nasa.gov/pipermail/igsmail/2015/008225.html

In the repro 02 effort from CODE only GPS stations are processed for the interval from 1994 to 2001, whereas GLONASS measurements are included from 2002 onwards. The complete number of GNSS satellites and IGS tracking stations considered in reprocessing campaign is shown in Figure 3. The light blue shaded area denotes the years processed so far. As can be seen from Figure 3, in 1994 only about 40 stations are available; however the station number increases with time, reaching the maximum of ~270 stations in 2010. The number of satellites increases with time, as well, reaching a maximum value of 56 at the end of 2011, when both GLONASS and GPS reached their full constellation.



Since the reference frame for the most recent reprocessing is still IGb08 (an IGS-specific realization of the ITRF2008 reference frame) the same station selection as in repro 02 from CODE was used for the EGSIEM reprocessing (labelled as repro 03). A special effort have been taken to ensure the completeness of the satellites in this new reprocessing series.

2. Processing Scheme to Derive the Reference Frame Products

As the basis for the GRACE orbit determination based on its onboard GPS receivers, GNSS satellite orbits, Earth rotation parameters (ERPs), and GNSS satellite clock corrections (at 30 and 5 second sampling rate) attached to the IGb08 reference frame are computed. The series does not only cover the years 2006 and 2007 (as stated in the Description of Work), but covers the significantly longer interval from 2003 to end of 2014, which can be extended using the operational final products from CODE for the IGS to the present.

2.1 Processing Scheme

The work flow of the current reprocessing activities is presented in **Figure 4**. The figure also indicates the different levels of validation procedures applied for quality control. Selected aspects will be presented in Section 3.

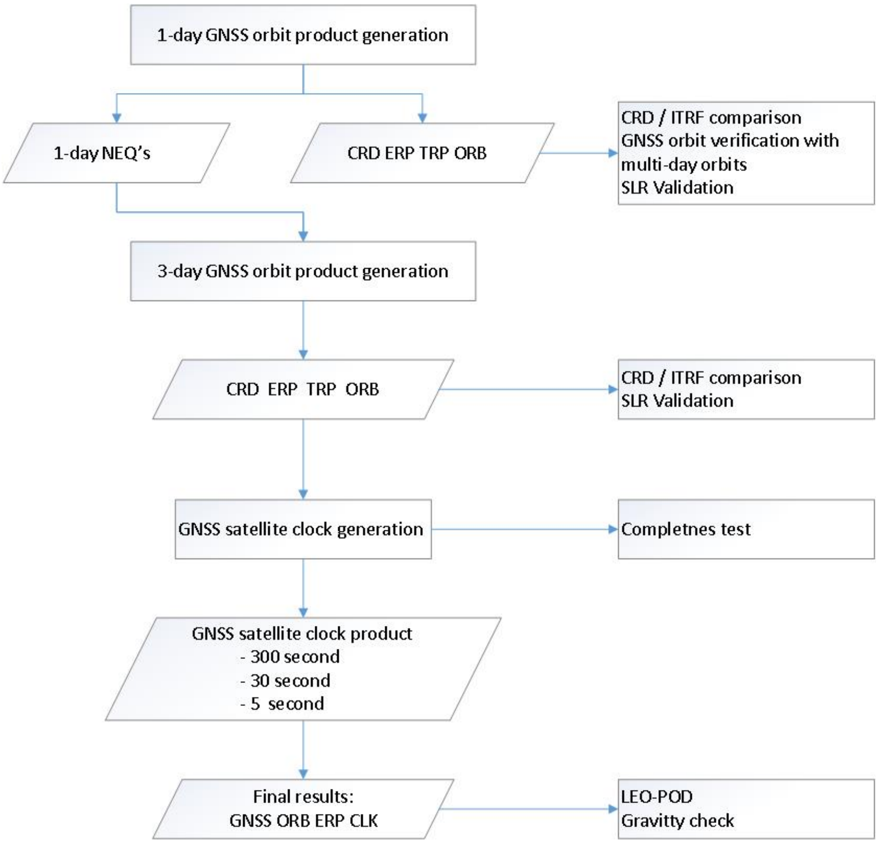


Figure 4: Schematic presentation of the working flow in the current reprocessing campaign. On the right column the related quality control steps are shown.

2.2 GNSS Orbit Product Generation

In a first step 1-day products are generated. The processing starts from the original GNSS observations in the RINEX files, where an extensive check of the meta information is done (e.g., regarding the correctness of receiver and antenna type). After importing the observations, the full pre-processing and ambiguity resolution scheme (for GPS and GLONASS) is applied based on the double-difference approach (receiver and satellite clock parameters are pre-eliminated). As a priori orbit information the results from the previous reprocessing (repro 02) was used and completed by alternative sources (e.g., broadcast orbits) in order to include as many satellites into the processing as possible.

The main product of the one-day processing step are normal equations (NEQs) containing GNSS satellite orbit parameters, ERPs, coordinates, and troposphere zenith path delay parameters together with other parameters included for internal purposes (e.g., satellite antenna calibration parameters). In order to allow a quality control also for the one-day solution step, the NEQs have been solved for coordinates, ERP's, GNSS orbits and troposphere parameters (the additional parameters have been removed from the NEQ to fix the standard values as they are recommended by the IGS standards).

As a next step the consistency of three subsequent one-day orbital arcs is verified. If the three subsequent orbits cannot be represented by one orbital arc to a sufficient quality, the day boundaries are indicated. All remaining orbits are then connected to a three-day long arc solution. It is obvious that also a verification of the station related parameters is needed in order to detect stations with discontinuities between the subsequent days (e.g. due to equipment changes) before they can be connected to one set of coordinate parameters over three days. If no event was detected, also the troposphere parameters are connected between the subsequent days by a continuity condition of the piecewise linear parametrization over 2-hours. After these preparatory steps three subsequent NEQs are combined and solved to a three-day long-arc solution.

This improves in the recent years in particular the quality of the GLONASS satellites, unhealthy GPS satellites; whereas in earlier years also the GPS satellites significantly benefits from this measure. The ERPs (in particular the polar motion rates and the Length of Day (LOD) components) do benefit from the longer orbit arcs, as well.

The station coordinate, troposphere parameters, ERPs, and GNSS satellite orbits are obtained based on a minimum constrained solution (with a no-net-rotation condition applied) to keep the inner geometry of the GNSS solution, but align it to the IGb08 reference frame. The stations used for the datum definition are verified before the final solution is generated. The products are subject of a quality control as well (see Section 3 for selected results).

2.3 GNSS clock products

For precise orbit determination (POD) of low Earth orbiting (LEO) satellites the Precise Point Positioning (PPP, Zumberge et al., (1997)) is well established., It requires the knowledge of precise and consistent GNSS orbits and satellite clock corrections. Bock et al. (2009) have shown that the GPS satellite clock corrections cannot be linearly interpolated over a long interval. Assuming 1 Hz sampling of GNSS data of Low Earth Orbiters (LEOs), the GNSS satellite clock corrections are required with a sampling of at least 5 seconds. CODE started to generate 30 second clock corrections already in 1999. In 2008 a procedure to generate GPS satellite clock corrections with a sampling of 5 seconds has been established at CODE. Since then the results are published together with the legacy IGS contribution with a sampling of 30 seconds.

The procedure has extended in the frame of the EGSIEM project to a GPS and GLONASS combined processing scheme. After preprocessing the zero-difference observations a zero-difference network solution estimating all satellite and receiver clock parameters with a sampling of 300 seconds is performed. For this purpose an epoch-wise pre-elimination/back-substitution scheme for the huge number of clock parameters was implemented. The geometry information (station coordinates, troposphere corrections, ERPs, and GNSS satellite orbits) are introduced from the previous three-day long arc solution.

The 300 second clock solution is the basis for the efficient high-rate clock interpolation (EHRI) procedure (described in Bock et al., 2009). The change of the receiver and satellite clock corrections from one to the next epoch are computed based on an epoch-difference solution and fitted into the 300 seconds clock solution. This procedure is limited to a sampling of 30 seconds because the regular IGS stations only provide data with this sampling rate.

For a further densification of the clock corrections, GNSS observation files with a higher sampling are needed. They are available from the IGS real-time project with a sampling of 1 Hz (Caissy et al., 2012). Unfortunately the IGS real-time network is to a large extent independent from the legacy network. This does not matter for the satellite clock computation, but increases the effort for data handling and book-keeping. In the frame of the EGSIEM project this procedure is applied to GLONASS satellites for the first time ever. Another disadvantage of this dataset is that the measurements stem from continuous data streams, where no control about the completeness of the data transfer from the receiver to the datacenter is available. An outage of the network close to the receiving datacenter may, e.g., affect a big number of stations by missing data.

Figure 5 shows the percentage of completeness of the three steps of clock product generation with 300 second, 30 second and 5 second sampling for January 2012. It can be noticed that for the period shown, the overall completeness is 100 % for all four sampling rates, however there are three days (namely 26.01.2012, 27.01.2012, 28.01.2012 and 31.2012) for which the 5 second clock corrections are not complete. Looking into the clock correction files itself, reveals that for this particular days, not only one but all GPS satellites are missing ~1.5 % 5 second data, while 30 second data are complete. A closer look into the available high-rate RINEX data, revealed that for the days when the clock correction are not complete, a reasonable number of stations has missing data. For instance for the January 27 only 6 stations contain all epochs in the high-rate RINEX files where these are typical nearly 50 – out of about 130 – stations on other days. This shows the limitation of the streaming technology to obtain observation files for post-processing purposes.

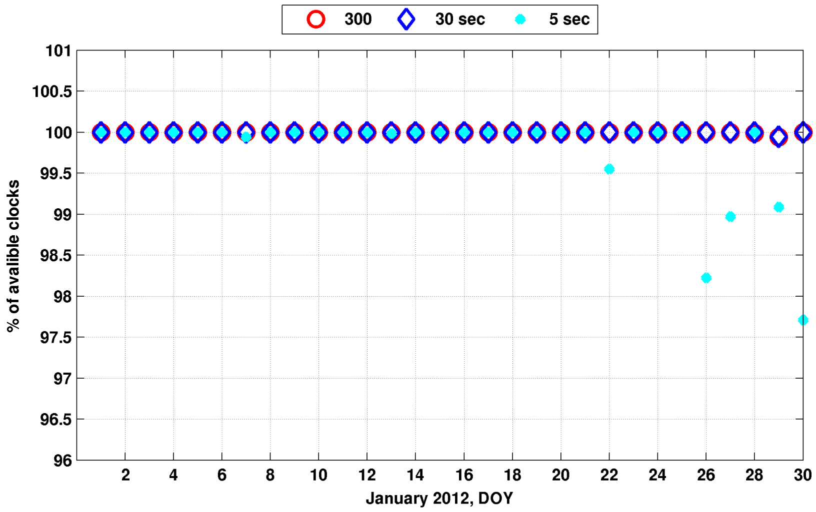


Figure 5: Percentage of available clock corrections in 300 second clock files (red), 30 second clock files (blue) and 5 second clock files (red) for GPS constellation.

3.Results

In this section we will summarize selected aspects from the quality control procedure established for the reprocessing. They start with some basic statistical elements, such as the number of satellites contained in the precise orbits. Furthermore the coordinate solution quality can be assessed by the number of accepted stations in the verification of the datum definition in a Helmert transformation process and the RMS of the Helmer transformation itself. The GNSS satellites orbits are validated using Satellite Laser Ranging (SLR) measurements. Last but not least, one month of GRACE Precise Orbit Determination (POD) is used to assess the quality and consistency of the Reference Frame product set provided within the EGSIEM project.

3.1 Comparison with Previous Reprocessing Activities

All products were compared with repro 02, performed at CODE. However, due to the fact that repro 02 finished in the end of 2013, the comparisons presented subsequently are referring to the period between the years 2003 and 2013.

Number of observations and parameters:
The number of observations is a general indicator to verify the quality of a GNSS solution series. It may indicate if a larger part of a network or of the satellite constellation is not available. The number of parameters may also indicate if the ambiguity resolution was not as successful as expected, because in that case more parameters have to be estimated as float ambiguities. As Figure 6 show this is not the case in the repro 03 series.

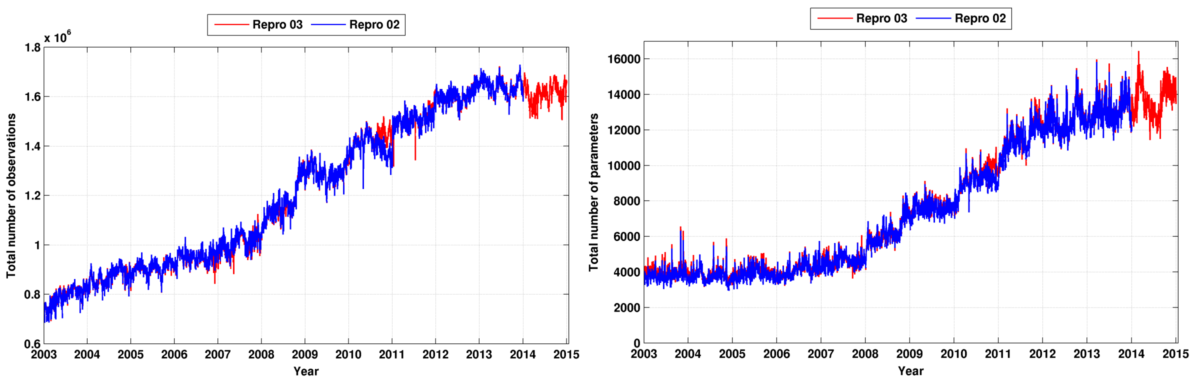


Figure 6: Left: Number of observations in 1-day solutions, (red represents current reprocessing campaign, and red repro 02. Right: Total number of parameters.

Number of satellites:
The number of satellites , was also compared with repro 02. Figure 7 (left) shows the time series of all (GPS+GLONASS) satellites in the 1-day precise orbit files, Figure 7 (right) the corresponding histogram (current reprocessing campaing - repro 02).

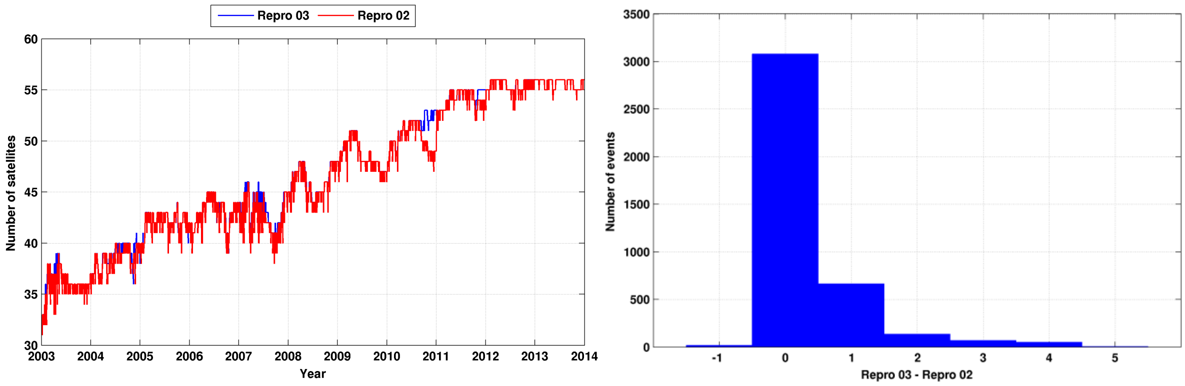


Figure 7: Left: time series of the total number of satellites available in 1-day precise orbits, (blue represents current reprocessing campaign, and red repro 02). Right: corresponding histogram of distribution.

As can be noticed from Figure 7, there are short periods when the current reprocessing campaign has more avalible satellites than repro 02. For instance a period between 2007 and 2008, i.e, for the main period selected in the EGSIEM to re-process the GRACE gravity field solutions, or in 2010 and 2011. The picture becomes even clearer when looking at the corresponding histogram (Figure 7, right). It shows that there are more than 500 days, where the current reprocessing campaing has 1 satellite more in the 1-day precise orbit files. A closer look into the mentioned period's revealed that repro 02 had a lower number of satellites considered for the processing itself, than the current reprocessing campaign. The main reason for this is that for the current reprocessing a special effort has been made to have a complete set of a priori orbits to the extent possible.

A posteriori RMS:

The a posteriori RMS of unit weight is a measure of the consistency of the functional model (here GNSS observation model and parametrization) and the real measurements. An increase of this parameter indicates model deficiencies. For that reason it is one of the most important quality measure for the repro 03 series. **Error! Reference source not found.** shows the a posteriori RMS of unit weight of the 1-day solutions from our current reprocessing campaign and from repro 02 for comparison.

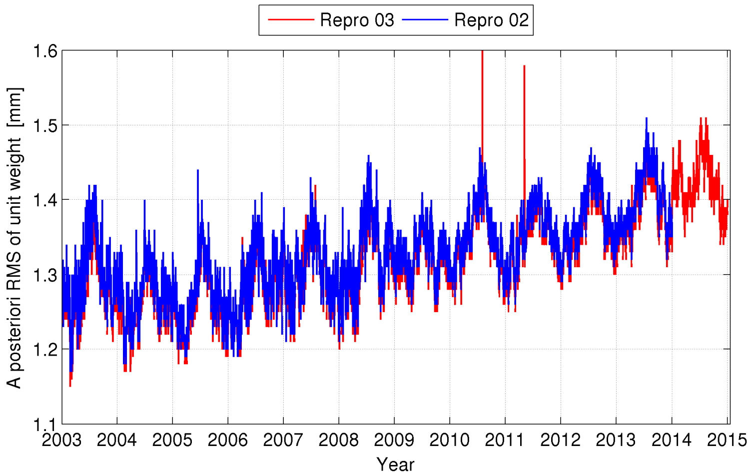


Figure 8: A posteriori RMS of unit weight, where blue color denotes repro 02 values and red current reprocessing campaign (denoted as repro 03).

Error! Reference source not found. shows that the value of the a posteriori RMS is overall slightly lower for the current reprocessing campaign than for repro 02. However, it can be noticed that in the case of current reprocessing campaign there are two visible outliers (30.06.2010 and 03.05.2011). The high RMS for these days may be caused by mismodeled repositioning events, but further investigations are needed for clarification. Repro 2, which does not have the two outlying RMS peaks, did not include the corresponding satellites for these days. Besides the mentioned outliers, also seasonal variations of the a posteriori RMS of unit weight can be seen with maximum values in summer and minimum values in winter. This is a typical effect for GNSS data processing. The magnitude has been, e.g., reduced when the troposphere model has improved (e.g., when switching from GPT/GMF to ECWMF/VMF1, Böhm et al., 2006, 2004). For that reason it is assumed that limitations in the troposphere modelling significantly contribute to this effect.

Verification of the Datum Definition:
Another product of great importance are the coordinates of the GNSS ground station network. They transfer the terrestrial reference frame (ITRF) into the GNSS satellite orbits. If the GRACE orbits will be consistently computed, they will share this frame and transfer in that way the geometrical reference frame into the gravity field solution to ensure the full consistency.

Two aspects are of importance in this context: if more stations are allowed to contribute to the datum definition it indicates that the solution agrees better with the assumption of a secular reference frame (station coordinate series are represented by coordinates and linear velocities only). Typically the number of stations accepted by the criteria is decreasing in time after the end of the interval, where the reference frame is computed from (in that case after the end of the year 2008). Reasons are discontinuities in the coordinate series due to earthquakes or equipment changes. This is clearly visible in Figure 9 (left). It is noticeable that the decrease of the acceptance of stations goes quicker than for the repro 02 than for the repro 03 series indicating a better quality of the coordinate series of the repro 03 series. In particular the problems in some of the coordinate solutions (indicated by the spikes in the blue curve) seems to be solved, likely by fixing a bug in the grid handling to compute the VMF1 (Vienna Mapping Function 1) troposphere correction coefficients.

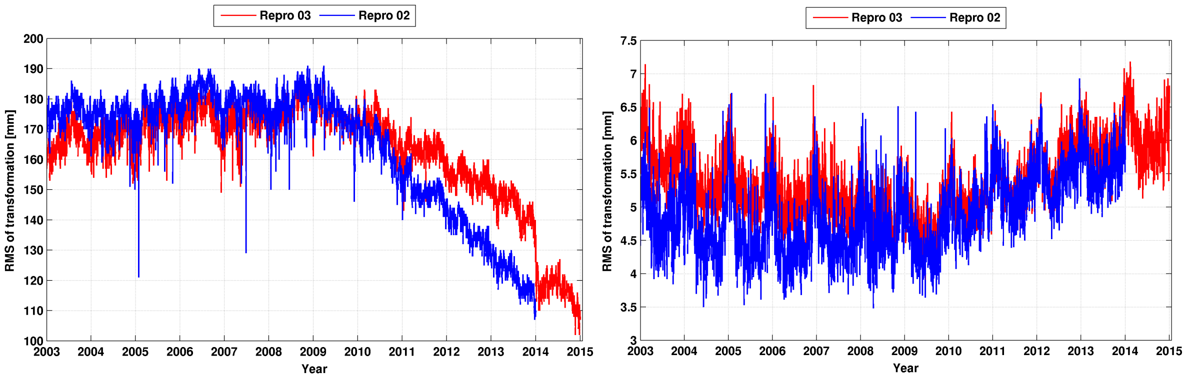


Figure 9: Left: time series of the number of the accepted stations for the verification of the datum definition. Right: corresponding RMS of transformation. On both figures blue represents current reprocessing campaign, and red repro 02.

To include a station into the datum definition the residuum must be below a certain threshold. A more complete view provides the RMS over the residuals of all stations accepted for the datum definition as shown in the right hand plot of Figure 9

The RMS shows again a seasonal variation what is consistent to the overall a posteriori RMS of the parameter adjustment shown in **Error! Reference source not found.**. Here an additional reason are loading effects that (in agreement with the IGS processing conventions) are not considered in the solution but that have an influence on the station coordinates because of crustal deformations.

3.2 SLR Validation

Since all GLONASS and two GPS satellites are equipped with retro-reflector arrays, Satellite Laser Ranging (SLR) provides an independent tool to validate microwave-based GNSS orbits. Because the maximum angle of incidence of a laser pulse to a GNSS satellite does not exceed 14°, SLR residuals indicate mainly the radial accuracy of microwave-based GNSS orbits (Sośnica et al., 2014, Fritsche et al., 2014, Maier et al., 2015).

Figure 11 and Figure 12 show SLR residuals w.r.t. the 1-day GLONASS-M orbits computed at CODE -- once using the old ECOM and once using the new ECOM. The residuals are depicted depending on the elongtion angle *E'*, which is the Sun-Earth-satellite angle (see Figure 10), and the solar beta angle Δu, which is the elevation of the Sun above the orbital plane (β_0). When the old ECOM model is used (Figure 11), there is a clear dependency of the SLR residuals on the elongation angle: whereas the residuals to the satellite positions near solar beta angle 90° are scattered around zero, those to satellite positions of smaller absolute solar beta angle show a significant offset to zero. The dependency of the SLR residuals on the elongation angle is significantly reduced in the case of the new ECOM (Figure 12).

$$\cos E' = \cos\beta_0 \cos\Delta u$$

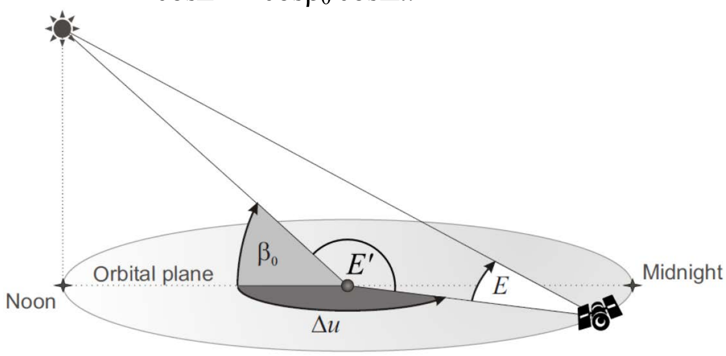


Figure 10: Geometry spanned by the Sun, the geocenter, and the satellite.

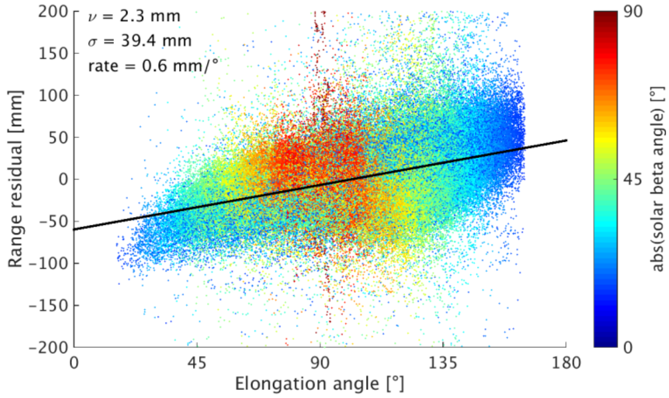


Figure 11: SLR residuals w.r.t. 1-day GLONASS-M orbits between 2003 and 2014 using the old ECOM. Mean value (ν), standard deviation (σ), and the rate of the linear trend per degree of elongation angle are computed w.r.t. all residuals whose absolute value is smaller than 150mm. Furthermore, all residuals having an absolute beta angle smaller than 15° have been not taken into account due to uncontrolled attitude during eclipses.

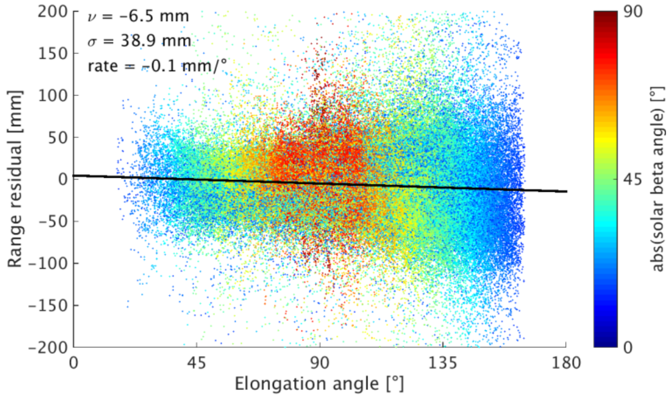


Figure 12: SLR residuals w.r.t. 1-day GLONASS-M orbits between 2003 and 2014 using the new ECOM. Mean value (ν), standard deviation (σ), and the rate of the linear trend per degree of elongation angle are computed w.r.t. all residuals whose absolute value is smaller than 150mm. Furthermore, all residuals having an absolute beta angle smaller than 15° have been not taken into account due to uncontrolled attitude during eclipses.

Note that for both, Figure 11 and Figure 12, the SLR residuals to the GLONASS-M satellites with SVN 723, 725, 736, and 737 have been excluded as they show anomalous behavior. An example of the exceptional behavior of GLONASS satellites is given in Figure 13 where the old satellite (SVN 725) in the slot R21 is replaced by a new satellite (SVN755). In the first phase the extended version of the ECOM (green dots) is a degradation whereas for the new satellite it improves the solution with respect to the classical ECOM (black dots). The reason for that behavior is under investigation.

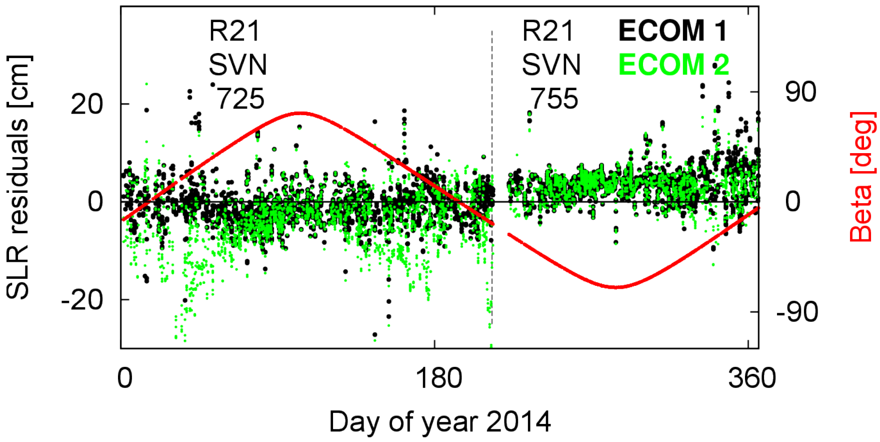


Figure 13: SLR residuals during the year 2014 for two different GLONASS satellites in the slot R21.

3.3 Validation by GRACE Orbit Determination

As we have already processed both, GNSS orbits and high-rate clock corrections, first validation tests of the results using precise orbit determination for low Earth orbiting satellites are underway. Figure 14 (left) shows the χ^2 value for the kinematic orbit determination of GRACE-A over the January 2012 period when using the operational orbits and clocks (shown in red) and the current reprocessing products (shown in green). One can see that in general the fit is slightly better when using the repro 03 products. The number of used observations (and hence the degrees of freedom) are almost identical in both cases, see Figure 14 (right).

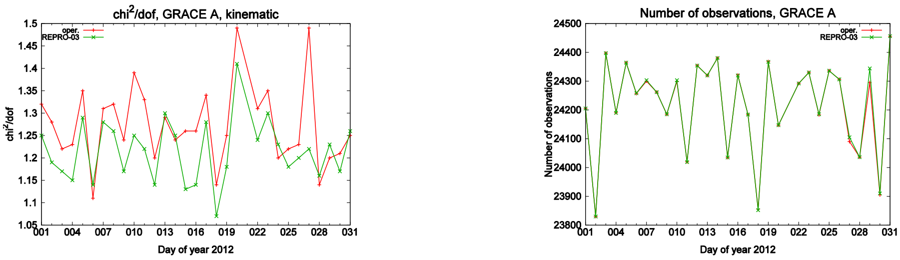


Figure 14: Left: χ^2 value of the kinematic orbit determination of GRACE-A for January 2012 when using the operational orbits and clocks and the current reprocessing products, respectively. Right: The number of used observations based on the operational (oper.) and the current reprocessing products, respectively.

Figure 15 shows daily mean values (left) and standard deviations (right) of the differences between the kinematic GRACE orbits based on operational orbit and clock products and from reprocessed products, respectively. Figure 15 (left) shows that systematic differences are generally small for the radial and the along-track direction, but slightly larger for the cross-track direction. In terms of standard deviation the differences are generally below the 1-cm level. Further validations are needed to verify which solution is better. For this purpose independent validations with SLR and inter-satellite K-Band data will be performed.

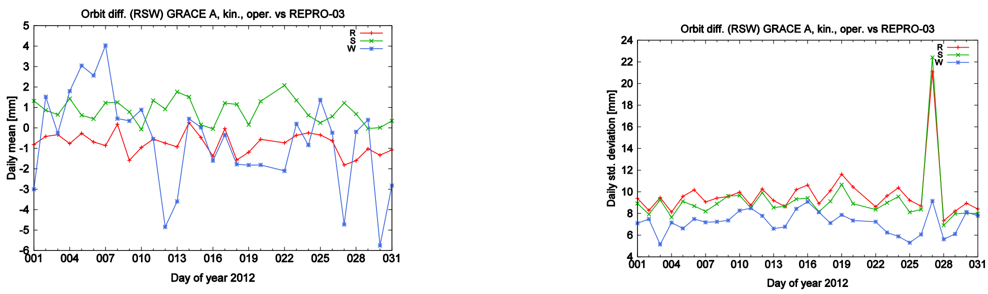


Figure 15: Left: The daily mean values of orbit differences in RSW system. Right: Corresponding daily standard deviations.

4.Summary and Conclusions

The objective of this document is to demonstrate the work carried out in the frame of the Reference Frame Products. We have presented the implemented processing scheme for the generation of the Reference Frame Products

Section 2 provides a detailed description of the GNSS orbit and clock products processing methodology. Additionally, in Section 2 we have presented first results regarding the completeness of the GNSS clock products. It was shown that for the period investigated the products have 100 % completeness. For the cases with incomplete clock corrections an investigation revealed the presence of a large number of stations with missing data.

In Section 3 a quality check of the products was presented, addressing the number of observation, parameters, satellites, verification of the datum definition, and the a posteriori RMS.
It was shown that the current reprocessing campaign overall has better products that repro 02. However, there are still some aspects (i.e. outliers in a posteriori RMS) that are currently under investigation.

Sections 3.2 and 3.3 presented independent validation results as obtained from SLR (Section 3.2) and Grace Orbit Determination (Section 3.3). In case of the SLR validation it was shown that the systematic dependency on the elongation angle could be clearly reduced for the new products than to the use of the new ECOM model..

Last, but not least, a first validation of the final GNSS orbit and clock production was performed by GRACE Orbit Determination. This “free-preview” confirmed that using the newest products the χ^2 values of GRACE orbit determination show a slightly better performance than when using the operational products.

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6.Glossary

CODE	Center for Orbit Determination in Europe
EGSIEM	European Gravity Service for Improved Emergency Management
GNSS	Global Navigation Satellite System
GRACE	Gravity Recovery and Climate Experiment
IGS	International GNSS Service
ITRF	International Terrestrial Reference Frame
SLR	Satellite Laser Ranging
LOD	Length of day
NEQ	Normal equations