GPS Solutions

CODE's new ultra-rapid orbit and ERP products for the IGS

--Manuscript Draft--

Manuscript Number:	GPSS-D-14-00070R2
Full Title:	CODE's new ultra-rapid orbit and ERP products for the IGS
Article Type:	Original Article
Keywords:	IGS ultra-rapid; GNSS orbits; earth rotation parameters; orbit prediction
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Response to Reviewers:	To reviewer #1: The description of the procedures at NRCan has been integrated into the manuscript. To the editor: All suggestions have been accepted. Figure 3 have been recreated with a larger font size. Unfortunately, no alternative reference concerning the NRCan procedure could be found.

CODE's new ultra-rapid orbit and ERP products for the IGS

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Abstract

The International GNSS Service (IGS) issues four sets of so-called ultra-rapid products per day, which are based on the contributions of the IGS Analysis Centers. The traditional ("old") ultra-rapid orbit and earth rotation parameters (ERP) solution of the Center for Orbit Determination in Europe (CODE) was based on the output of three consecutive 3-day long-arc rapid solutions. Information from the IERS Bulletin A was required to generate the predicted part of the old CODE ultra-rapid product. The current ("new") product, activated in November 2013, is based on the output of exactly one multi-day solution. A priori information from the IERS Bulletin A is no longer required for generating and predicting the orbits and ERPs. This article discusses the transition from the old to the new CODE ultra-rapid orbit and ERP products and the associated improvement in reliability and performance. All solutions used in this article were generated with the development version of the Bernese GNSS Software. The package was slightly extended to meet the needs of the new CODE ultra-rapid generation.

Keywords

IGS ultra-rapid; GNSS orbits; earth rotation parameters; orbit prediction

Introduction

The Center for Orbit Determination in Europe (CODE) is a joint venture of two Swiss and two German institutions: the Astronomical Institute of the University of Bern (AIUB), the Federal Office of Topography swisstopo in Wabern, the Federal Agency for Cartography and Geodesy (BKG) in Frankfurt am Main, and the Institut für Astronomische und Physikalische Geodäsie (IAPG) of the Technische Universität München. Since the start of the International GNSS Service (IGS, where GNSS stands for Global Navigation Satellite Systems, Beutler et al. 1999, Dow et al. 2009) as an official service of the International Association of Geodesy (IAG) in 1994, CODE (Dach et al. 2013b) is contributing to all post-processing IGS product lines, namely the final, the rapid, and the ultra-rapid products (Dach et al. 2009). All these solutions are generated with the development version of the Bernese GNSS Software (Dach et al. 2007). As opposed to other IGS Analysis Centers (AC), CODE includes as many GNSS satellites as possible in its processing schemes: CODE in particular rigorously combines GPS and GLONASS observations, and it includes observations from satellites set unhealthy or satellites undergoing repositioning or maintenance events.

The IGS ultra-rapid products consist of two parts covering a total of 48 hours: the first 24 hours are supported by observations and the second 24 hours stem from orbit, clocks, and ERP prediction (Griffiths and Choi 2013). CODE provides "only" rigorously combined GPS and GLONASS orbit and ERP products to the IGS (Dach et al. 2013b), whereas the IGS generates separate GPS-only and GLONASS-only ultra-rapid orbit products. For this purpose the CODE orbit files are split up into a GPS and a GLONASS part by the IGS Analysis Center Coordinator (IGS ACC).

We first briefly review the strategy for generating the IGS combined ultra-rapid orbit and ERP products and we discuss the length of the observation data span for prediction. The next section explains the old CODE ultra-rapid orbit and ERP products. Afterwards, we describe the update of the ultra-rapid product generation at CODE in general and the orbits in particular. The performance of the new CODE ultra-rapid orbits and ERPs is then documented. At the end the new procedure is summarized, followed by some general aspects which could be derived from updating the CODE ultra-rapid orbit procedure.

Ultra-rapid AC contributions and their use

The IGS ultra-rapid products are based on contributions of individual IGS ACs, which have to be produced in near real-time. This task is most demanding. Fully automated procedures are required because the products are not only due during office hours, but also during night time. Subsequently we briefly characterize the AC contributions, make some remarks concerning the IGS combination, and conclude the section with a discussion about the arc-length used for the orbit generation.

AC contributions to the IGS ultra-rapid products

Five software packages, the Bernese GNSS Software (CODE, NRCan, GOP, USNO), EPOS (GFZ), NAPEOS (ESOC), pages (NGS), and PANDA (WHU), are used for generating the contributions to the IGS ultra-rapid products. Six IGS ACs, namely CODE, NRCan, ESOC, GFZ, GOP, and WHU, include GLONASS in their solutions. All ACs combine normal equation constituents (NEQs) referring to adjacent time intervals. Since the contributions have to be delivered four times per day, the generation of an AC ultra-rapid product is easy, provided that at least four 6-hour NEQs are available per day.

Let us mention three examples based on NEQ stacking procedures: (1) A convincingly simple solution is delivered by ESOC (Springer et al. 2012). Apart from the selection of the particular NEQs the ESOC ultra-rapid contribution is procedurally identical with ESOC's 1-day IGS final and rapid products and thus fully consistent with the latter products. (2) The contribution of GOP (Dousa 2012), based on the Bernese GNSS Software, combines eight 6-hour NEQs. It thus represents a long-arc analysis based on the combination of 6-hour NEQs. (3) The contribution of NRCan, also based on the Bernese GNSS Software, is documented in Mireault et al. (2008) in the frame of the Precise Point Positioning Service. A 30-hour preliminary orbit is first generated using the last ten 3-hour NEQs. To further improve orbit prediction, it is followed by a long-arc orbit refit using the most current IGS/NRCan orbit products and part of this 30-hour preliminary orbit.

Our processing scheme results in a long-arc analysis, as well, but it is based on the readily available most recent 24-hour NEQs of the CODE rapid processing and on the possibly incomplete NEQ of the current day. Details of the AC ultra-rapid processing schemes of all contributing ACs as well as the full AC and software names can be found in Meindl et al. (2012) and Dach et al. (2013a).

IGS combination of ultra-rapid contributions

The contributions of the individual IGS ACs are combined for the IGS product following a weighted average scheme originally developed by Beutler et al. (1995). More information concerning the IGS combination can be found on the IGS ACC homepage (http://acc.igs.org).

For the ultra-rapid products, 48 hours of 15 minute orbit positions and satellite clock corrections are submitted by the IGS ACs, starting 24 hours prior to the last observation epoch (at t_{last}) of the particular ultra-rapid, and two sets of ERP values (x- and y-pole coordinates, UT1-UTC) and their rates, referring to the centers (t_{last}-12 h) and (t_{last}+12 h) of the observed and predicted parts, respectively. The two IGS combined ERP values are marked by green crosses in Figure 3. CODE does not submit satellite clock corrections for the ultra-rapid yet due to limited computing resources.

Length of data span used for the AC contributions

The appropriate length of the observation data span for orbit prediction (contained in the IGS ultra-rapid product) was recently investigated by Choi et al. (2013), who tested two versions of the Empirical CODE Orbit Model (ECOM, Beutler et al. 1994) to derive the optimum length of geocentric satellite position time series, spaced by 15 minutes, to predict GPS satellite orbits up to 24 hours.

The empirical orbit parameters of the ECOM refer to the D-, Y-, and X-system, where D represents the direction satellite-Sun, Y is the solar panel axes of the satellites, and X (called B in Choi et al. 2013) completes the right-handed orthogonal system. The full ECOM includes nine parameters: constant and periodic once-per-revolution components for each of the coordinate axes. For more details concerning this parameterization and the CODE orbit model, consult Beutler et al. (1994). The first version of the CODE model solves for the six initial osculating elements, which are equivalent to the initial position and velocity vectors, and all nine parameters of the ECOM. The second one solves only for the six initial osculating elements and five of the nine parameters of the ECOM: the three constant offsets and the two once-per-revolution parameters in X. This second version, documented by Springer et al. (1999), is also referred to as reduced ECOM parameterization. It is widely used in the IGS, for example, by CODE, ESA, and other ACs. Choi et al. (2013) found that a 40-45 hour observation data span is best suited for subsequent orbit prediction up to 24 h.

The old CODE ultra-rapid orbit procedure

The CODE ultra-rapid orbits and ERPs were continuously developed since the early days of the IGS. A first step of the developments performed in 2013 therefore had to consist of a review of the CODE ultra-rapid performance over the last decade. The orbit model is crucial for prediction. The orbits should be based on parameters, which can be well predicted. This is why orbit representation is discussed subsequently in some detail. Eventually, we focus on problems of the CODE orbit and ERP representations in use until mid 2013. This analysis provides the basis for the 2013 developments.

Performance of the CODE ultra-rapid orbits with respect to the combined IGS ultra-rapid orbits

Figure 1 compares the ultra-rapid orbits from CODE since May 2001 with the combined IGS product through a 7-parameter Helmert transformation. Three regimes may be distinguished: GPS weeks 1100-1228, 1229-1764, 1765-present.

1. The CODE contributions prior to GPS week 1229 were pure orbit predictions based on the three most recent complete CODE rapid orbit products.
2. Since GPS week 1229, the observations available up to 6, 12, 18, and 24 UTC of the current day have been included for the generation of the corresponding CODE ultra-rapid orbits (IGS Mail 4530 at http://igscb.jpl.nasa.gov/pipermail/igsmail/2003/004604.html).
3. A profound review of the CODE ultra-rapid orbits took place in 2013 and led to the remarkable improvement from GPS week 1765 onwards.

Leaving out the time period before GPS week 1229, we note: whereas the rotation angles about the x- and y-axes of the earth-fixed geocentric equatorial system and the variations in the scale of the CODE submissions with respect to the combined values are rather small, frequent excursions exceeding 1 mas in absolute value occur in the rotation about the z-axis. Since the submissions with excessively large rotation angles are automatically rejected from the IGS orbit combination by the IGS ACC, many exclusions of CODE ultra-rapid contributions took place before November 2013.

The change in scale at around GPS week 1765 in Figure 1 results from the implementation of the Albedo model (Rodríguez Solano et al. 2012), the inclusion of an antenna thrust model, and the skipping of the a priori Radiation Pressure model. The decrease of the excursions in the z-rotation angles to values well below 1 mas around the same time is, however, entirely due to the submission of the new CODE ultra-rapid orbits starting in November 2013.

Orbit representation

Each orbital arc is based on background orbit models, including the earth gravity field, lunar, solar, and planetary gravitational attraction. The same background models are used at CODE for the final, the rapid, and the ultra-rapid products (Dach et al. 2013b). The CODE orbit model allows us to estimate the following parameters for each orbital arc:

- Set of six osculating orbital elements.
- At maximum nine empirical orbit parameters, three constant acceleration terms in three orthogonal directions, three once-per-revolution periodic acceleration terms in the same directions, of the ECOM.
- Pseudo-stochastic pulses in radial direction R, in along-track S, and in out-of-plane W at 12 hour intervals, at noon and at midnight of each calendar day.

The CODE final, rapid, and ultra-rapid orbit contributions to the IGS make use of the six osculating elements, the reduced ECOM parameterization, and the pseudo-stochastic pulses in R, S, and W setup at noon and at midnight (for 3-day solutions). These pulses $\Delta v_{R,S,W}$ are constrained to zero by pseudo-observation equations of the type $\Delta v_{R,S,W} = 0$ using the weights $(\sigma_{obs}/\sigma_{\Delta vR,S,W})^2$. σ_{obs} is the RMS error a priori of the observations, $\sigma_{\Delta vR,S,W}$ are the user-defined RMS errors associated with the pulses in R, S, or W. The values $\sigma_{\Delta vR,S,W} = (1 \cdot 10^{-6}, 1 \cdot 10^{-5}, 1 \cdot 10^{-8})$ m/s are used in the CODE analysis.

The old CODE ultra-rapid orbits are based on the orbital positions of 72 hours stemming from two or three different parameter estimation procedures, where the positions of each day refer to a particular 3-day solution. The selection of the positions for the old ultra-rapid orbit is illustrated by the black arrows in Figure 2. The four-day interval on top represents the time interval from which the 72 hours of the resulting ultra-rapid orbit are selected. The orbital positions of the first two days are those of the central days of the two most recent complete 3-day solutions used to generate the CODE rapid orbits. The orbital positions of days 3 and 4 stem from the third 3-day arc (magenta line). This last 3-day orbit is given the attribute “pseudo-rapid”, because it ends at the last observation epoch used for the corresponding ultra-rapid generation at 6, 12, 18, or 24 UTC.

Orbital positions referring to different days are separated by tick marks in Figure 2. In the interval [t_{last}-72 h, t_{last}], stemming from the two to three 3-day arcs (green and magenta lines), 288 orbital positions (3x96 positions/day) are used as pseudo-observations in an orbit determination process to generate an orbital arc of 72 hours length ending at the epoch of the last observation. The parameters of this orbit determination process differ from those of the green and magenta 3-day solutions: the six osculating elements referring to the first observation epoch and the full nine empirical parameters of the ECOM are estimated, but no pulses are set up. The resulting orbits in the time interval [t_{last}-24 h, t_{last}+24 h] are stored and made available in the SP3-format of the IGS.

Problems related to the ERP representation of the old CODE ultra-rapid product

Figure 2 also illustrates the ERP extraction for the old CODE ultra-rapid product. The ERPs referring to the last day are in general of inferior quality as they are based on an observation time span of only a fraction of the day. This assessment is illustrated by Figure 3, which shows in de-trended form the estimated x-coordinates of the pole corresponding to the 6 UTC ultra-rapid product of September 23, 2013. The general shape is similar to the 6 UTC ultra-rapids of other days and for the other pole coordinate. Note that the ERPs of the old CODE ultra-rapid product (blue line) are continuous at the boundary of days 3 and 4, because the corresponding ERP values stem from the same 3-day solution, represented by the magenta line in Figure 2. They are not continuous at the other two internal day boundaries by construction though. The solid magenta line represents the IERS Bulletin A pole available at the time of the CODE ultra-rapid generation and the dash-dot magenta line represents the IERS Bulletin A pole, which became available one day after the ultra-rapid product.

The use of the estimated ERPs referring to the last day for the next 24 hours may lead to unrealistic results for prediction, which actually is the case for the example of Figure 3. Therefore, the a priori ERPs from the most recent IERS Bulletin A, represented by the solid magenta line, were used in the old CODE ultra-rapid for ERP prediction after some point in time. This caused, however, some problems:

- IERS Bulletin A is not necessarily better than a linear extrapolation when the prediction for one or two days is made in an operational environment.
- The a priori ERPs need to be shifted in parallel to make the transition from the estimated to the a priori ERPs continuous at some point in time, compare solid and dash-dot magenta lines in Figure 3.

Eventually, after 10-Jul-2013, the estimated and shifted a priori ERPs were made to coincide at the beginning of the last day, represented by the solid magenta and blue lines in Figure 3, but the shifted a priori ERPs were used only after the end of the last day. This measure slightly improved the CODE ultra-rapid orbits and ERPs. The impact of the change is barely visible in the x- and y-rotations of the CODE orbit estimates with respect to the IGS ultra-rapid product, whereas a clear improvement is visible in the rotations about the z axis (Figure 1).

Figure 3 also shows the IERS Bulletin A pole available one day after the time of generating the ultra-rapid orbit (dash-dot magenta line). Both a priori pole curves, the solid and the dash-dot lines, agree well at the beginning of the time interval shown in Figure 3, but they substantially differ around the last observation and later on. As the figure shows, the use of the IERS Bulletin A pole for prediction is questionable at times. The sizable offset of the later IERS Bulletin A pole at the time of the prediction does not really cause a problem as the a priori positions are shifted anyway. Yet, the difference in slope for the time interval of the prediction may be problematic.

Problems related to the representation of the old CODE ultra-rapid orbit

A pseudo-stochastic pulse represents a velocity change at a particular epoch in a given direction. Pulses are constrained by user-defined weights as specified above. Pseudo-stochastic pulses are important elements to compensate for potential orbit model deficiencies, particularly in the long-arc solutions based on observations. There are typically five pulse epochs associated with each 3-day arc, at noon of each day and at the day boundaries of the middle day. For the ultra-rapid orbits the quality of the pulses may become a problem on the last day:

1. For the two ultra-rapid solutions with t_{last}=6 UTC and 18 UTC, only 6 instead of 12 hours of data are available after the pulse epoch at midnight and noon, respectively. This may degrade the last part of the orbit solution and seriously affect orbit prediction.
2. Pulses cannot be predicted for the predicted part of the orbit.

The second problem was actually circumvented in the old CODE ultra-rapid orbit by the use of the original satellite positions as pseudo-observations, as explained above and visualized in Figure 2.

The new CODE ultra-rapid orbit procedure

Based on the recommendations by Choi et al. (2013), the experiences gained with the old CODE ultra-rapid orbit product, the limitations due to the daily NEQs covering calendar days, and the degrees of freedom offered by the actual parameterization of the NEQs, the following principles for the new CODE ultra-rapid orbit products were adopted:

1. The observed part of the new ultra-rapid product does not refer to three different 3-day solutions, but to exactly one, where three NEQs of three consecutive days are used. This 3-day solution is represented by the magenta line in Figure 2.
2. Weakly determined orbit and ERP parameters referring to the last 24 hours of the observed part of the ultra-rapid products are avoided.
   a. A pulse determination is considered as weak, if the time interval covered by observations to the left or to the right of the pulse epoch is shorter than 12 hours.
   b. An ERP determination is considered as weak, if the time interval covered by observations to the right of an ERP vertex is shorter than 24 hours.
3. The ERPs in the predicted part of the ultra-rapid product are defined by the two ERP parameters referring to the last 24 hours covered by observations.
4. Apart from the unavoidable fact that UT1-UTC has to be anchored to an a priori value for one particular epoch, the a priori information from IERS Bulletin A is not used for creating the new CODE ultra-rapid product.
5. Four complete sets of observed and predicted ERPs and orbits are issued and made available to the IGS ACC and other users every day.

Table 1 summarizes the characteristics and the representation of the key parameters for the four ultra-rapid orbits and ERPs issued every day. The first column labels the ultra-rapid product. For practical reasons, the parameterization in all ultra-rapid solutions refers to a nominal arc-length of three days. Column 2 provides the start and end epoch with respect to t_{last}. The third column shows that the time interval actually covered by observations varies between 54 hours for the 6 UTC and 72 hours for the 24 UTC ultra-rapid solutions.

Principle 1 of the new CODE ultra-rapid asks to avoid the pulses closer than 12 hours to t_{last}. The number of pulse epochs therefore increases from 3 for the 6 UTC to 5 for the 24 UTC ultra-rapid products. This way of handling weak pulses is the only option available, when only daily NEQs referring to calendar days are available, as there are no “hidden” pulses set up in the 24-hour NEQs.

Principle 1 also asks for a modification of the ERP parameterization. The reference point for the ERP vertices with 1-day resolution is made to coincide with the last observation epoch t_{last}, that is, 6, 12, 18, or 24 UTC of the current day. The input NEQs contain one set of ERPs, namely offset and drift, every 6 hours. It is therefore possible to derive ERP parameters for all required ERP vertices via a parameter transformation instead of reprocessing all individual observations. Note that t_{last} is not an ERP vertex. According to Table 1 the right-most ERP vertex is set to $+\infty$ h, where in practice “$+\infty$ h” is defined to contain the entire requested prediction interval. For IGS purposes, we therefore set “$+\infty$ h = +24 h”. For the purposes of the International Laser Ranging Service (ILRS, Pearlman et al. 2002) CODE makes predictions available for five days. With this treatment of the ERPs the x- and y-coordinates of the pole and UT1-UTC, actually UT1R-UTC, are represented by straight lines in the interval $[t_{last}\text{-}24\text{ h}, t_{last}+\infty\text{ h}]$.

The ERP vertices for the observed part of the 3-day interval are set to -72 h, -48 h, and -24 h. The first ERP vertex (-72 h) lies outside the interval covered by the three NEQs for the first three daily ultra-rapid products. This is, however, not important as a straight line may be characterized by its function values at any two epochs, inside or outside the interval of interest.

The red line in Figure 3, representing the new CODE ultra-rapid, illustrates that the new procedure avoids unrealistic drifts of the ERPs in the last 24 hours covered by observations and in the first 24 hours of the prediction time period. The epoch of the last observation, which corresponds to the version of the ultra-rapid product, is half way between the green “+” tick marks corresponding to the IGS epochs of ERP comparison for the observed and the predicted part, respectively.

As mentioned before, the ERP modeling was slightly modified in summer 2013 by the transition of estimated to shifted a priori ERPs. These changes were implemented in July 2013 and activated for the CODE submissions to the IGS on 11-Jul-2013. The in-depth redesign of the CODE ultra-rapid orbit was developed and tested between August and October 2013. The new CODE ultra-rapid orbits have been submitted to the IGS since 12-Nov-2013.

Consistency of the orbits with and without pulses

We are still left with the problem that the stochastic pulses in the orbit parameterization are not well suited for orbit prediction. The orbits obtained from one ultra-rapid solution according to the description in the previous section, which are based on a 3-day arc with 3 to 5 sets of stochastic pulses, and represented by the magenta line in Figure 2, may be used to extract satellite positions every 15 minutes in the earth-fixed reference frame. The satellite positions in the time interval [$t_{las\ t}$-48h, t_{last}] are introduced into an orbit determination process without pulses, implying that we closely follow the recommendation by Choi et al. (2013). The orbits in this process are described by 15 parameters, 6 initial osculating elements and the 9 parameters of the full ECOM.

To study the consistency of these two orbits, the CODE ultra-rapid orbit of 13-Apr-2014, 18 UTC, is used here as a typical example. The residuals of the orbit determination process, which represent the difference between the orbits, are only provided for the last 48 hours. Figure 4 illustrates the residuals in the radial, along-track, and out-of-plane components R, S, and W. The GPS results are represented in green, the GLONASS results in red. The consistency is best, better than 1 cm RMS, in W and worst in S, where about 2 cm RMS are achieved for GPS and 3 cm for GLONASS. This consistency is sufficient to justify the use of the orbits fitting the original satellite positions with the orbits based on the full ECOM without pulses. Figure 4 also shows that the residuals for GLONASS are in general slightly larger than for GPS.

Figure 5 shows the plain differences in R, S, and W of the two orbits underlying Figure 4, where the same pattern is seen as in Figure 4 in the observed part – before 13-April-2014, 18 UTC. Note, however, the different scale in the S component. The time arguments in Figure 5 are shifted by 24 hours with respect to Figure 4. Figure 5 thus covers the time interval of the IGS ultra-rapid orbit: one day is covered with observations and one day contains the predictions. Not unexpectedly, the two predictions agree best in out-of-plane W, and least in along-track prediction S, where the differences are substantial.

Figure 5 does not tell which of the two predictions is better. Figure 6, showing the differences of the two predictions with respect to the CODE rapid orbit of April 10, answers this important question. Whereas there are no substantial differences for the R and W components, which are not shown here, the prediction based on the ECOM is clearly superior to the standard CODE model based on the reduced ECOM parameterization including the pulses at a 12-hour spacing (Table 1) as it was obtained from the parameter estimation step. Figure 6 represents the ultimate justification of the somewhat artificial orbit determination procedure using the satellite positions of the magenta 3-day orbit in Figure 2 as pseudo-observations. It also justifies the orbit determination problem based on satellite positions used in the old CODE ultra-rapid procedure. The illustrations of this section are typical for other ultra-rapid orbits.

Quality of the new CODE ultra-rapid orbit and ERP products

The new CODE ultra-rapid orbits were compared to the CODE rapid and final orbits. Moreover, different ultra-rapid solutions were mutually compared during the development phase. Yet, the real quality can only be assessed by a comparison with independent products. Therefore, we confine ourselves here to the comparisons extracted from the combination protocols provided by the IGS ACC and from the combined orbit and ERP products. The orbit comparisons are based on the entire 48 hours, 24 hours adjusted and 24 hours predicted, of the submitted products. The information is available under http://www.igs.org/components/prods.html. As the orbits of the GPS and GLONASS satellites are treated separately in the IGS combination, the corresponding comparisons are provided here separately for the two satellite systems, as well.

GPS orbits

The impact of the first change made on 11-Jul-2013 can barely be recognized in the translation parameters in x, y, and z of the Helmert transformation in Figure 7. Note, however, that the excursions in the z translations are clearly larger than those in x and y. In the rotation about the z-axis a clear improvement can be seen in Figure 8 after 10-Jul-2013. The implementation of the full new CODE ultra-rapid procedure further reduced the excursions in the z-rotation in Figure 8. It moreover improved the consistency to the other ultra-rapid contributions, visible in the decrease of the RMS and the weighted RMS of the CODE solution compared to the combined IGS ultra-rapid product in Figure 9.

GLONASS orbits

Figures 10 and 11 show the transformation parameters of the GLONASS orbits with respect to the combined GLONASS-only IGS ultra-rapid product. Keep in mind that this GLONASS combination is strictly experimental as fewer ACs are contributing to it than to the GPS combined product.

Exactly as in the case of GPS, the most obvious improvement refers to the rotation parameter z of the Helmert transformation (Figure 11). As opposed to GPS, only marginal improvements are seen in the RMS and weighted RMS values in Figure 12 after the implementation of the new procedure. The RMS and WRMS values are on a substantially higher level than the corresponding GPS values. This might be due to a different handling of GLONASS ambiguities at the contributing IGS ACs. CODE performs a partial ambiguity resolution for GLONASS.

Earth rotation parameters

Two sets of ERPs, consisting of pole coordinates and their rates, are submitted to the IGS and compared with the combined solution. The first set is assigned to the epoch of the last observation, corresponding to the epoch of the ultra-rapid product minus 12 hours and representing the observed part of the ultra-rapid and the second set to the same epoch plus 12 hours, representing the predicted part of the ultra-rapid.

The differences in the ERP estimations derived for the observed part have not changed much with the implementation of the new ultra-rapid procedure. Only the length of day (LOD) parameter has improved, which is documented by Figure 13. The scatter is reduced because all ERPs used to construct one ultra-rapid product are based on exactly one parameter estimation step. The predictions of the ERPs in Figure 14 clearly improved with the introduction of the new CODE ultra-rapid product. Both, the amplitudes of the differences with respect to the combined IGS solution and the systematic patterns, were substantially reduced.

The formal errors of the x- and y-components of polar motion did not change as a consequence of the two parts of the redesign. The formal errors of the polar motion rates in x and y did, however, significantly decrease after the implementation of the complete new CODE ultra-rapid (Figure 15). This improvement is due to the consistency of the ERP parameters, which all stem from exactly one 3-day analysis.

Summary

Prior to GPS week 1229, the CODE ultra-rapid product was based on a prediction of the most recent CODE rapid orbits and ERPs. Its performance is partly illustrated in Figure 1. It was not further analyzed in this article.

Between GPS weeks 1229 and 1764 the CODE ultra-rapid products were based on the most recent 3-day solutions from which the CODE rapid products were derived, and on a fourth “pseudo-rapid” 3-day solution analyzing the two most recent complete daily NEQs and the NEQ of the current day containing observations until 6, 12, 18, and 24 UTC, respectively. The three 3-day solutions and the four days relevant for the CODE ultra-rapid are illustrated in Figure 2.

The ERPs for the CODE ultra-rapid product between GPS weeks 1229 and 1765 corresponding to the computed part of the ultra-rapid were extracted from the last, the magenta 3-day solution in Figure 2, where the UT1-UTC values of different solutions had to be aligned to one and the same a priori value. The ERPs for the predicted part after midnight of the fourth day were taken from IERS Bulletin A, where the a priori ERP curves were shifted to coincide with the corresponding estimated ERP values at a particular epoch of the last day. Before summer 2013, this epoch coincided either with noon of day 4 or with midnight separating days 4 and 5. Afterwards, the epoch was made to coincide with midnight separating days 3 and 4. The satellite positions from three days, spaced by 15 minutes and ending at the epoch of the last observation, were used to generate the computed and the predicted part of the CODE ultra-rapid orbits. They were used as pseudo-observations in an orbit determination process, where the six initial osculating elements and the nine parameters of the ECOM were estimated.

The review of the CODE ultra-rapid product in summer 2013 solved three problems: (1) By extracting the ERPs and orbits from exactly one 3-day solution, represented by the magenta solution in Figure 2, full consistency between ERPs and orbits is achieved. (2) By anchoring the daily vertices of the piece-wise linear ERPs to the nominally last observation epoch, ERPs based on short data spans as seen in Figure 3 are avoided. This measure removed unrealistic drifts of the ERPs towards the end of the observed period and allows using the last daily set of ERPs for prediction, as well. The new CODE ultra-rapid orbit and ERP strategy also removes large rotations of the orbits (Figures 1 and 5). In addition, the new CODE ultra-rapid generates substantially better ERP rates. (3) By using the satellite positions from one 3-day solution discontinuities in the pseudo-observations could be removed.

The new CODE ultra-rapid product as well as its predecessors avoids storing NEQs more frequently than once per calendar day. If partial NEQs are for example available at least at six hour intervals, simpler procedures to generate ultra-rapid orbits may be achieved as done, for example, by NRCan (Mireault et al. 2008), ESA (Springer et al. 2012), and GOP (Dousa 2012).

The mild improvement of the old CODE ultra-rapid product in July 2013 concerned the orientation of the submitted orbits with respect to the combined IGS ultra-rapid products, in particular the rotation of the orbits about the z axis. The implementation of the complete new orbit model substantially improved the orientation of the orbits. This is also reflected by the RMS of the combination of the GPS orbits. The new CODE ultra-rapid orbits only have a minor impact on the translation parameters.

The predicted ERPs are much more consistent with the combined product after the implementation of the full new CODE ultra-rapid procedure, which avoids the use of the IERS Bulletin A.

The new CODE ultra-rapid product, based on 2.25 to 3 days of observations, meets the requirements of a high-accuracy contribution to the IGS combined orbit product. It also meets the demands of the user community for an accurate, reliable, and robust real-time orbit product.

Conclusions

The ultra-rapid product is the most challenging one for the ACs because of the stringent restrictions concerning production time. Only three hours are available for data distribution, processing, and combination, implying that the procedure at the AC should not take longer than one hour of processing time. The predicted part of the orbit is the basis for many real-time or near real-time applications. The key points are:

- A fully consistent multi-day solution for orbits and ERPs is the basis for a successful orbit prediction over a period of 24 or more hours.
- The orbit parameterization is different for parameter estimation and orbit prediction. Stochastic pulses, introduced to absorb potential deficiencies of the dynamic orbit model, should be avoided for orbit prediction.
- As the deadlines of the IGS ultra-rapid products are not synchronized with the update schedule of IERS Bulletin A, a simple linear extrapolation of the ERP parameters is generally more appropriate for a one day prediction. Over longer intervals the sophisticated background models of IERS Bulletin A may be preferable for ERP prediction.

Acknowledgements The work regularly performed by the IGS ACC, in particular the routine comparisons of the IGS AC contributions with the official IGS products, was extremely helpful when developing the new CODE ultra-rapid products. This invaluable material, supported by the quick feedback to our questions provided by the IGS ACC, is gratefully acknowledged.

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Figure 1 Evolution of scale and rotations of the submitted CODE ultra-rapid orbits with respect to the combined IGS ultra-rapid product (GPS-only) since 2001 (http://acc.igs.org/media/Gmt_sum_ultra_cen_rot_cou_ALL.gif)

Figure 2 Origin of orbit positions in the old CODE ultra-rapid product (here a solution for t_{last}=18 UTC). Green: orbital positions originating from most recent two complete CODE rapid 3-day solutions; Magenta: most recent long-arc orbit solution based on the two most recent daily rapid normal equation files and the normal equation file from the (un-)complete current day; Red: composed orbit arcs from parameter estimation processes (green and magenta) used as the basis to fit the long arc; Black: orbit arc fitted into the orbit positions from the recent rapid and ultra-rapid solutions (red) used to extract the submitted ultra-rapid orbit including the beginning of the orbit prediction

Figure 3 Estimated and a priori x-coordinate of the pole (de-trended). Blue: old CODE ultra-rapid; Red: new CODE ultra-rapid; Magenta solid: IERS Bulletin A available at the time of generating the ultra-rapid; Magenta dash-dot: IERS Bulletin A available one day after generation of the ultra-rapid; Green “+”: IGS ultra-rapid pole positions (estimated, predicted)

Figure 4 Residuals in R, S, and W of the orbit determination over 48 hours for the GLONASS (GLO) and GPS satellites from an 18 UTC ultra-rapid analysis using the new CODE ultra-rapid model

Figure 5 Differences in R, S, and W of 24 hours of adjusted and 24 hours of predicted orbits using the full ECOM model and the standard reduced ECOM model plus the 12 UTC pulses in R, S, and W

Figure 6 Differences of the 24 hours of predicted GLONASS and GPS orbits from a 24 UTC ultra-rapid solution with respect to the corresponding CODE rapid orbits in along-track S using the standard CODE orbit model with pulses (top) and the full ECOM without pulses (bottom)

Figure 7 Translation parameters in x-, y-, and z of the Helmert transformation between CODE's submitted ultra-rapid orbits and the combined IGS product (GPS-only)

Figure 8 Rotation parameters for the z-, x-, and y-rotations of the Helmert transformation between CODE's submitted ultra-rapid orbits and the combined IGS product (GPS-only)

Figure 9 RMS and weighted RMS (WRMS) of the CODE ultra-rapid orbits derived from the combination of the IGS ultra-rapid product (GPS-only). On November 12, 2013 the first results from the new ultra-rapid procedure were submitted.

Figure 10 Translation parameters in x-, y-, and z of the Helmert transformation between CODE's submitted ultra-rapid orbits and the combined IGS product (GLONASS-only)

Figure 11 Rotation parameters for the rotations about the z-, x-, and y-axes of the Helmert transformation between CODE's submitted ultra-rapid orbits and the combined IGS product (GLONASS-only)

Figure 12 RMS and weighted RMS (WRMS) of the CODE ultra-rapid orbits derived from the combination of the IGS ultra-rapid product (GLONASS-only)

Figure 13 Observed part of the polar motion in x and y, their rates, and LOD of the submitted ERPs with respect to the combined IGS product

Figure 14 Predicted part of the polar motion components in x and y, their rates, and LOD of the submitted CODE ERPs with respect to the combined IGS product

Figure 15 Formal errors of the polar motion in the x- and y-coordinates, their rates, and LOD of the submitted CODE ultra-rapid ERP product

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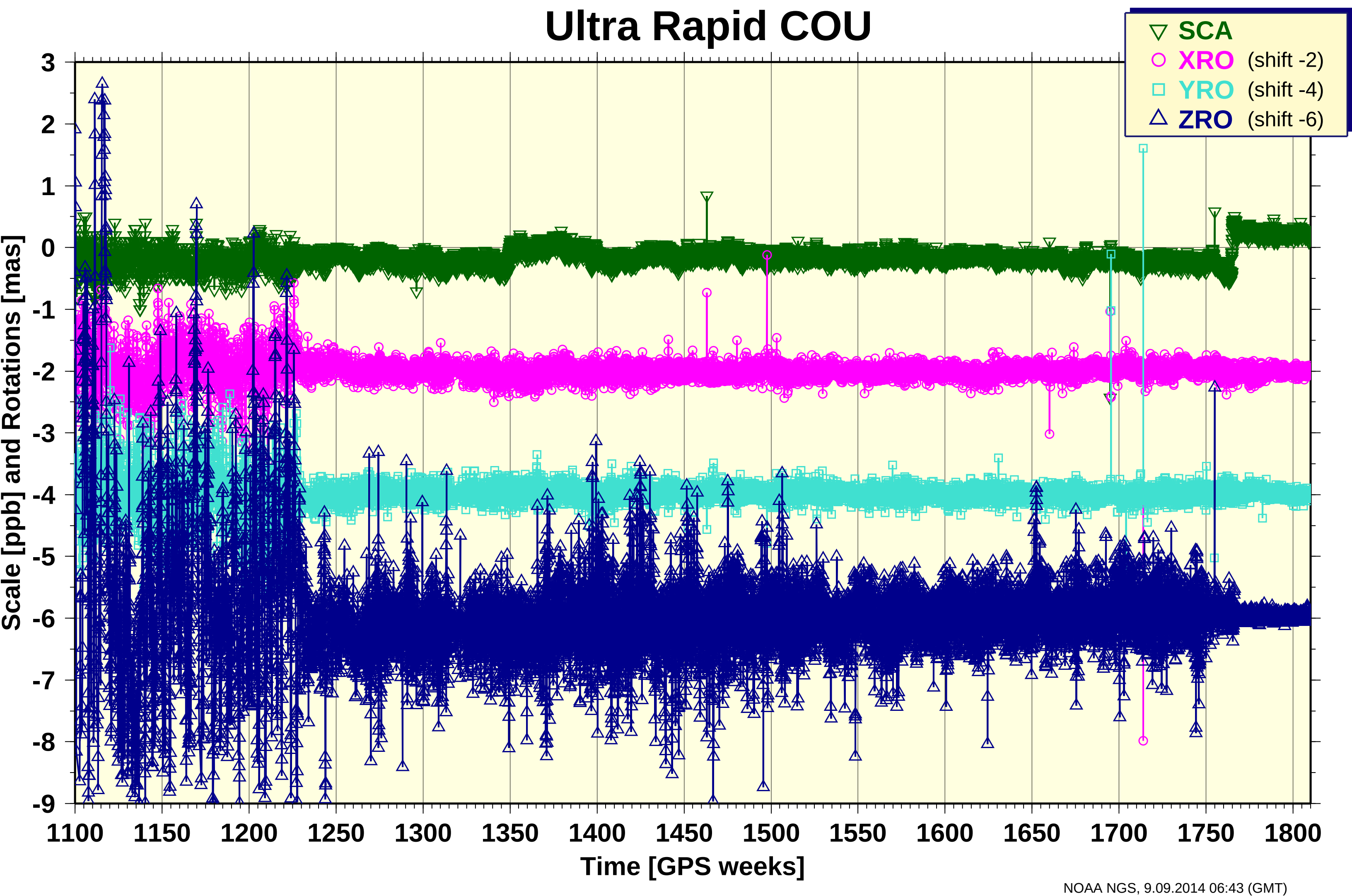

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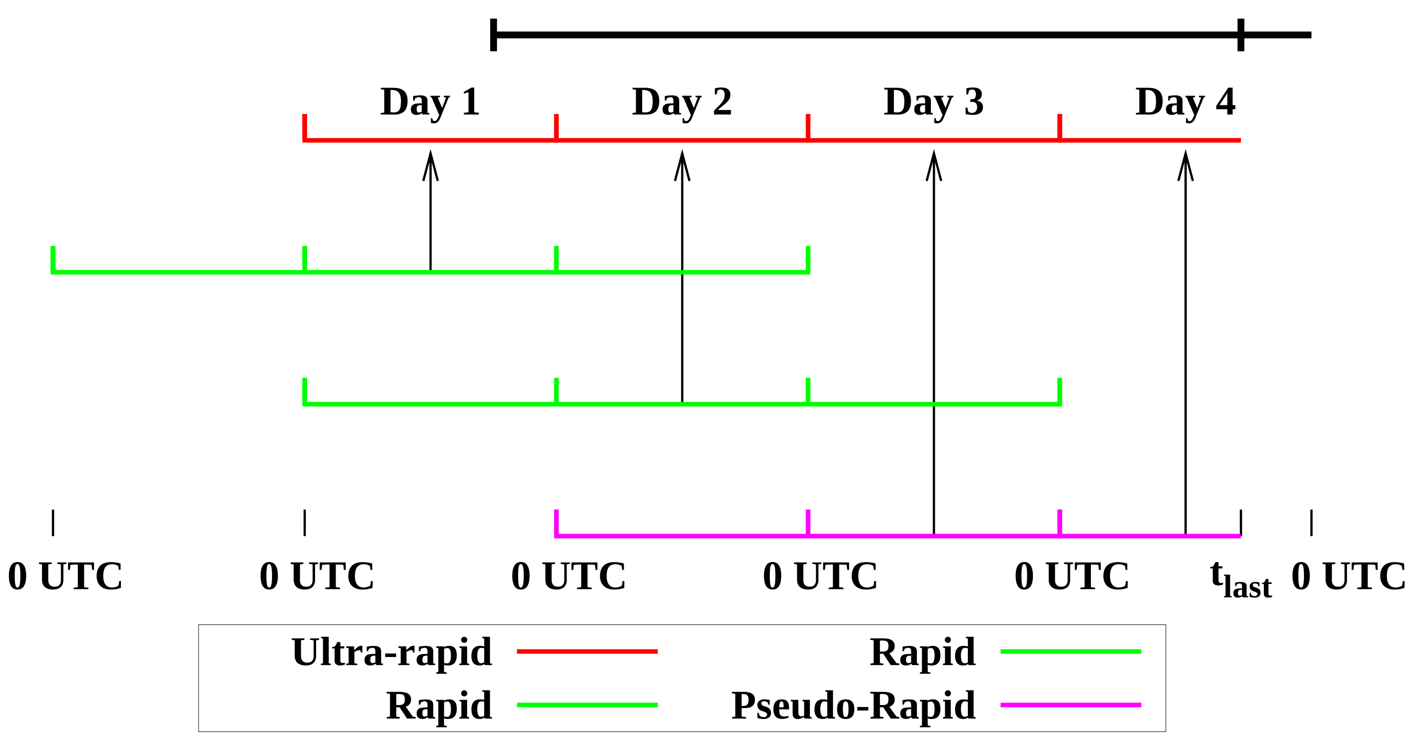

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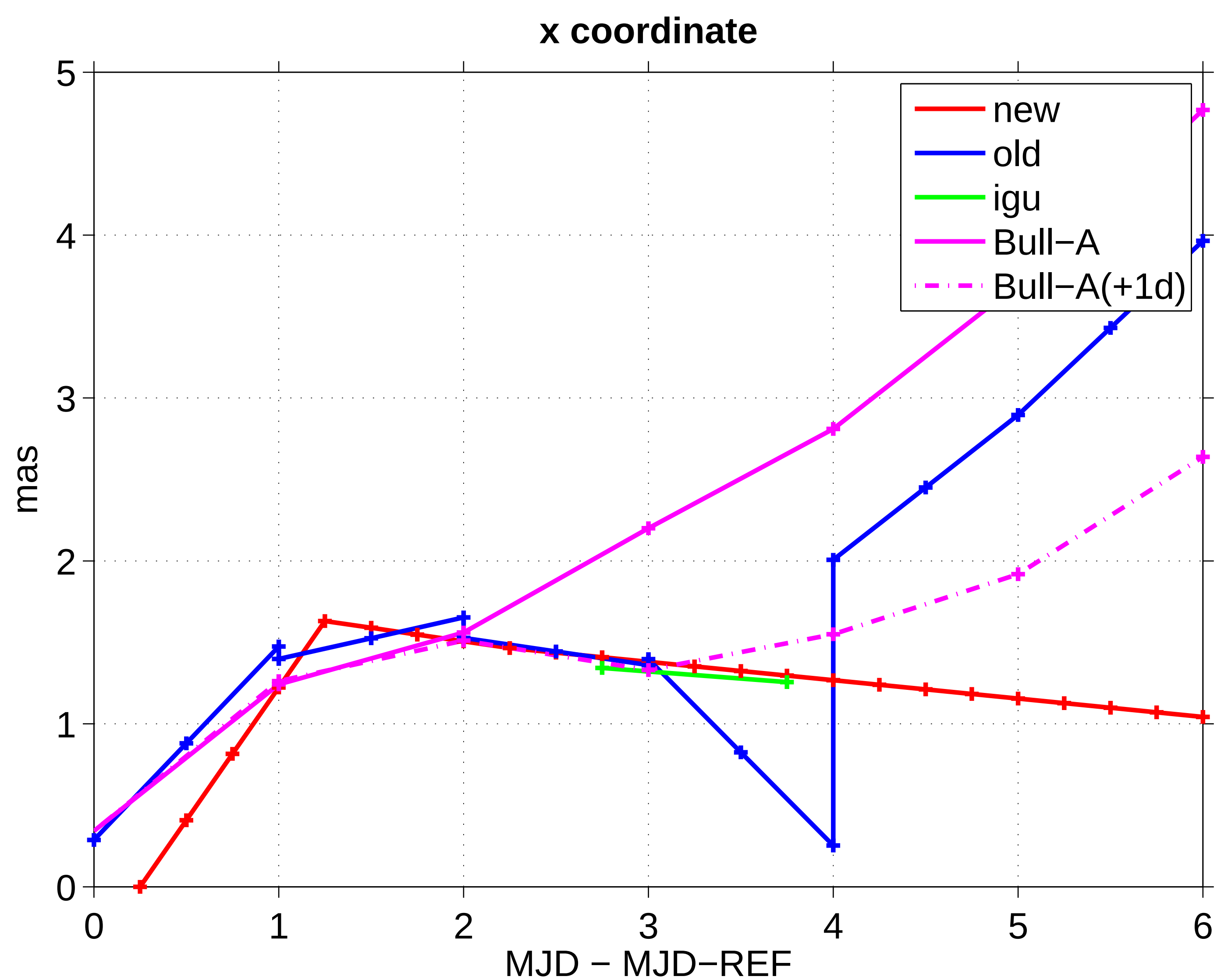

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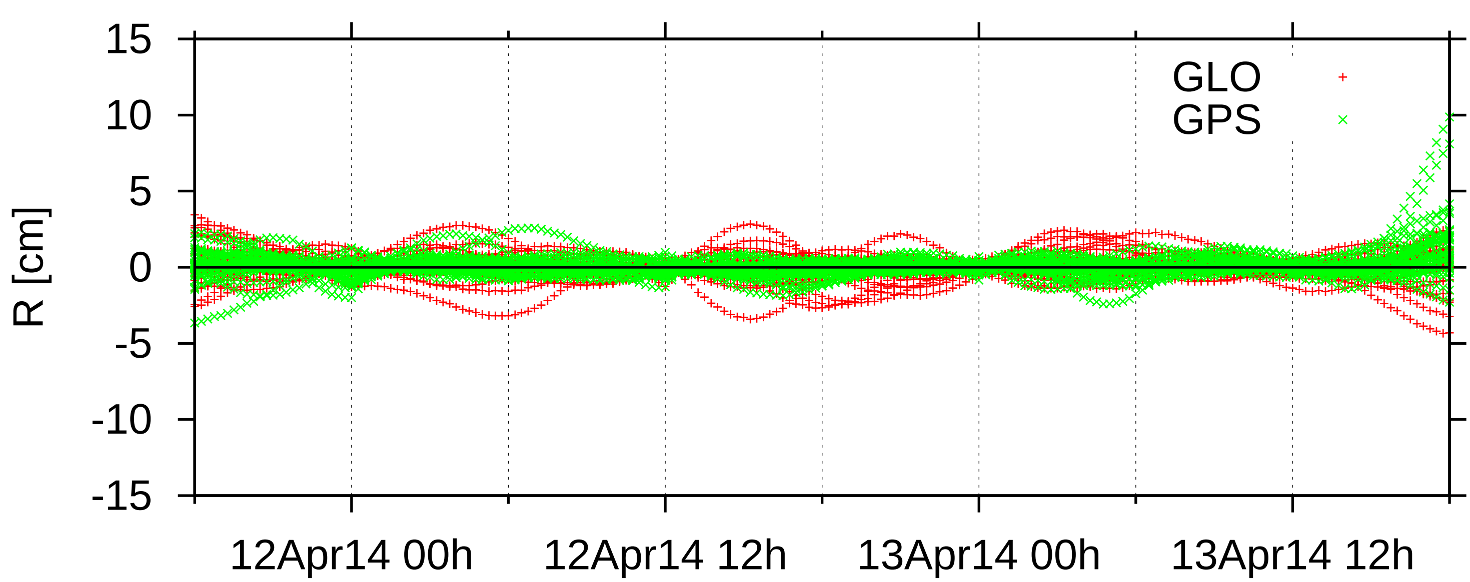

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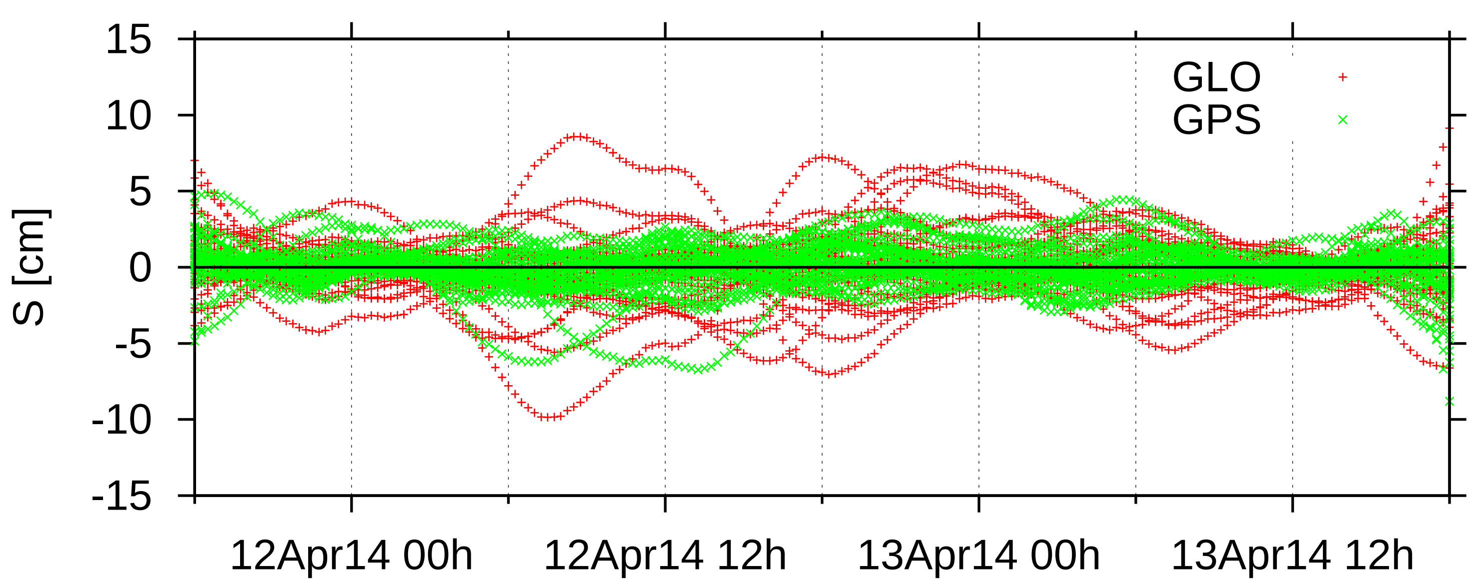

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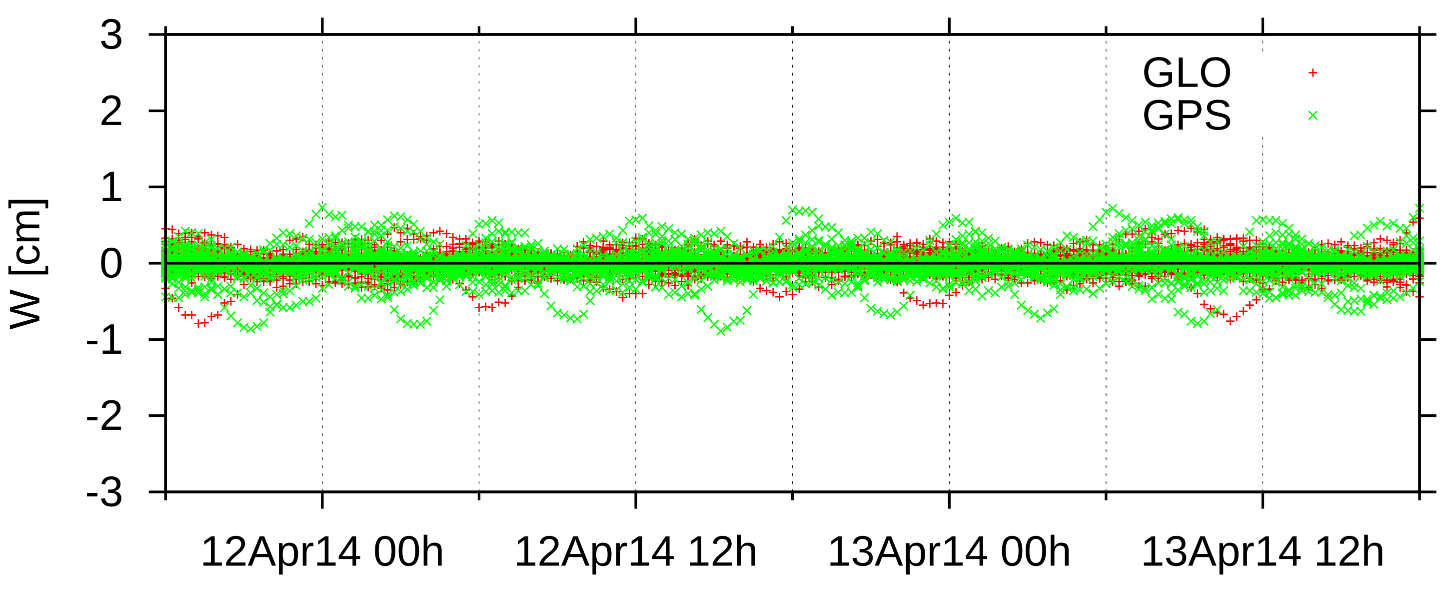

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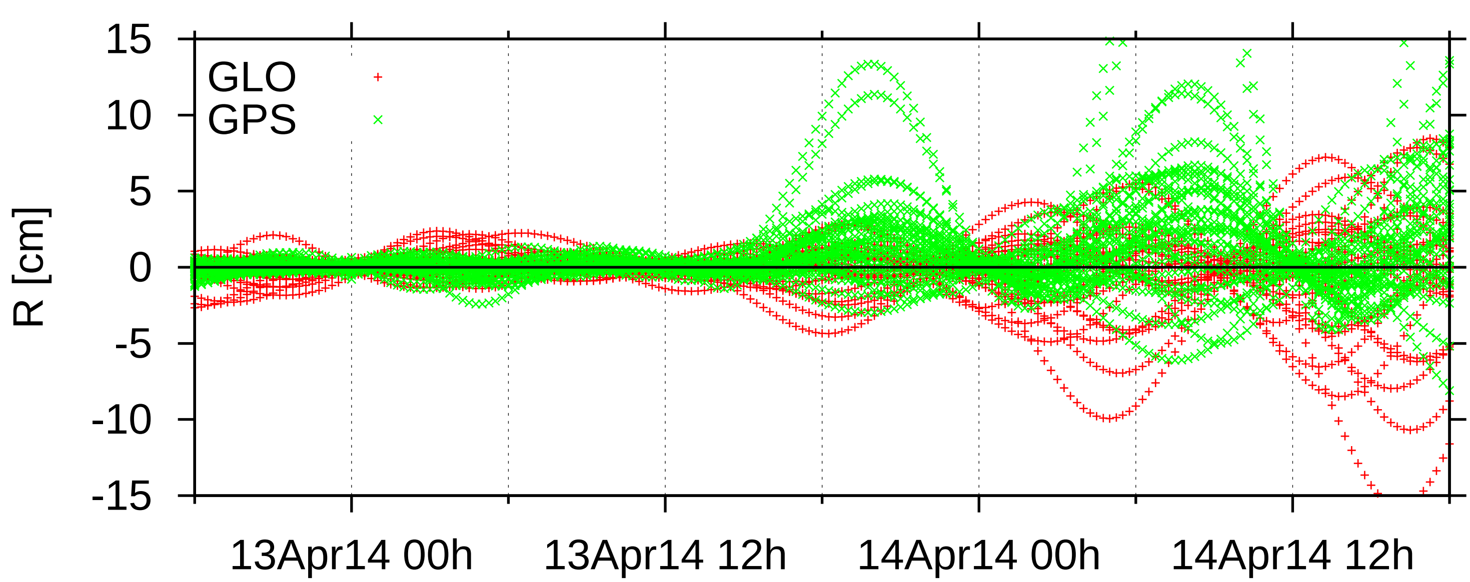

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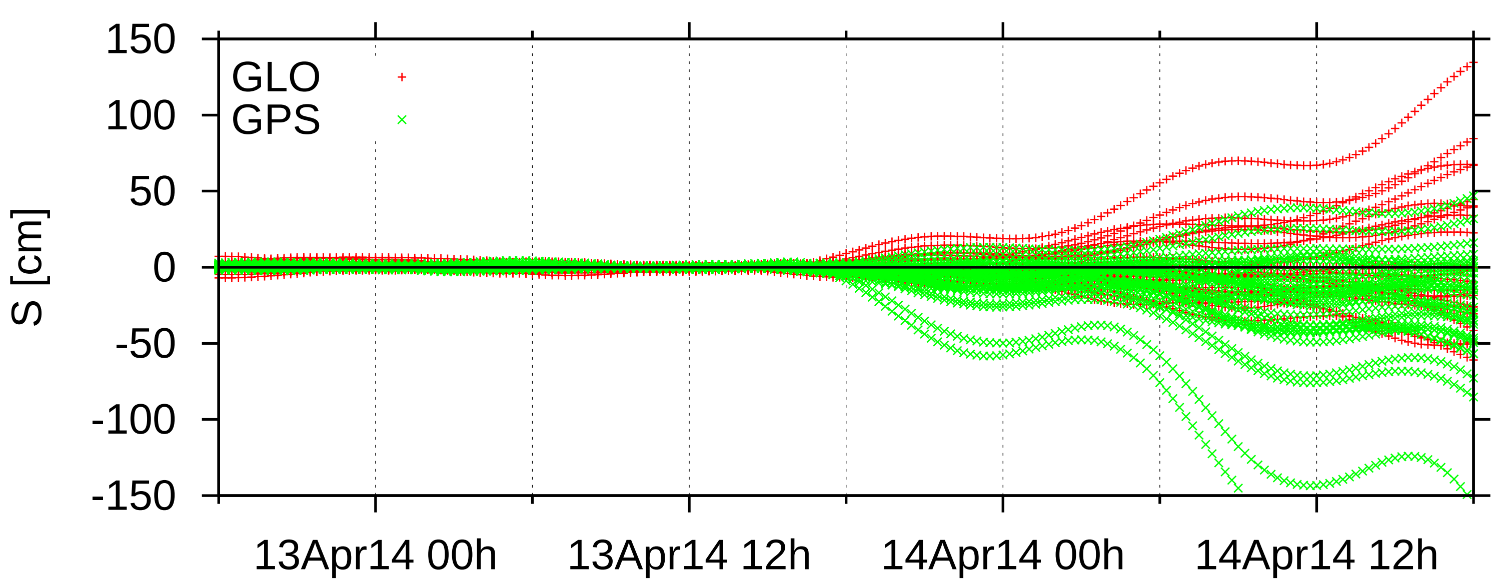

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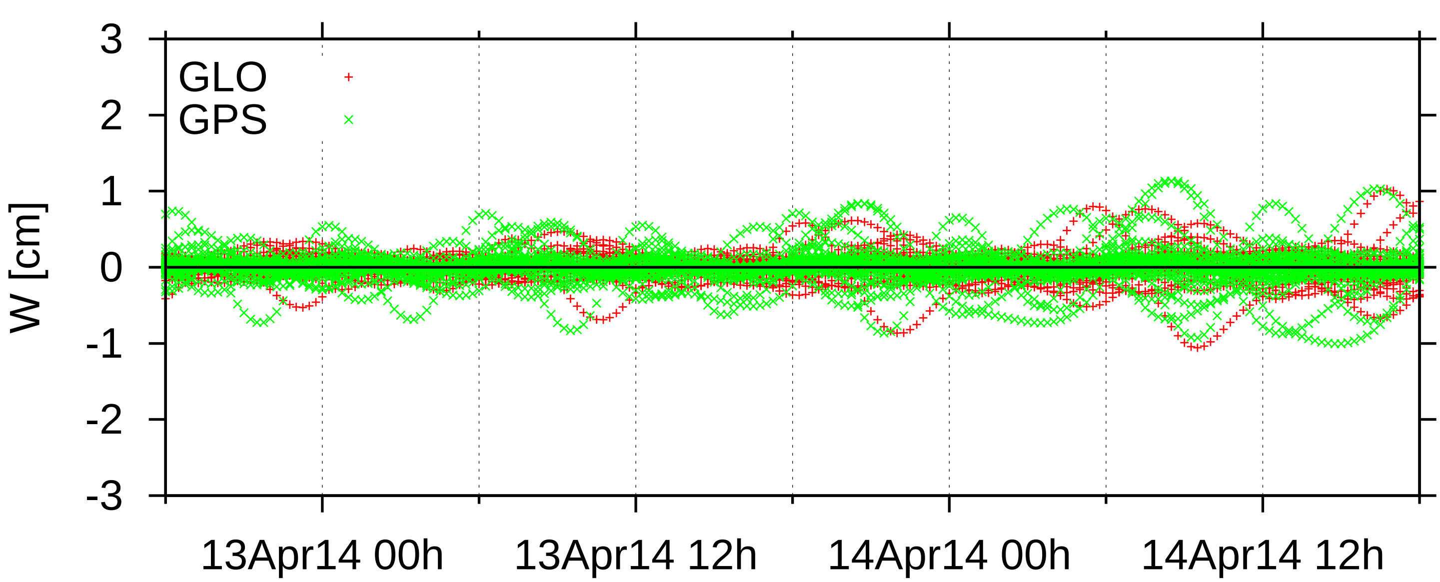

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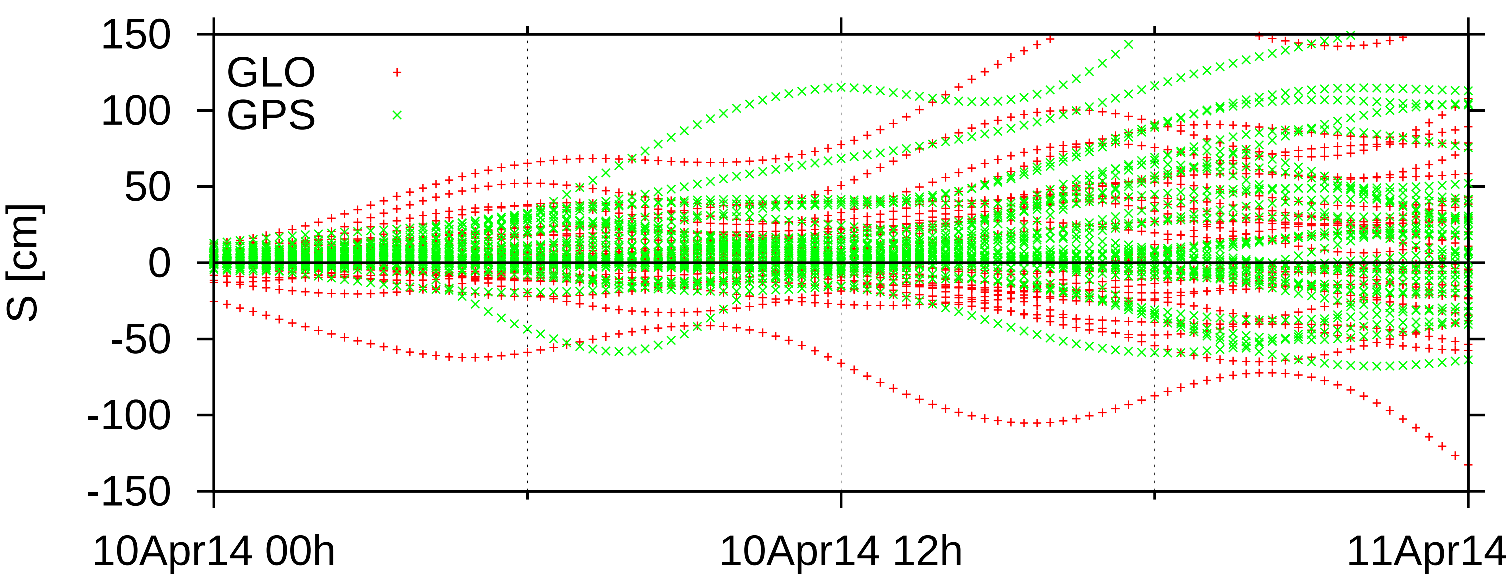

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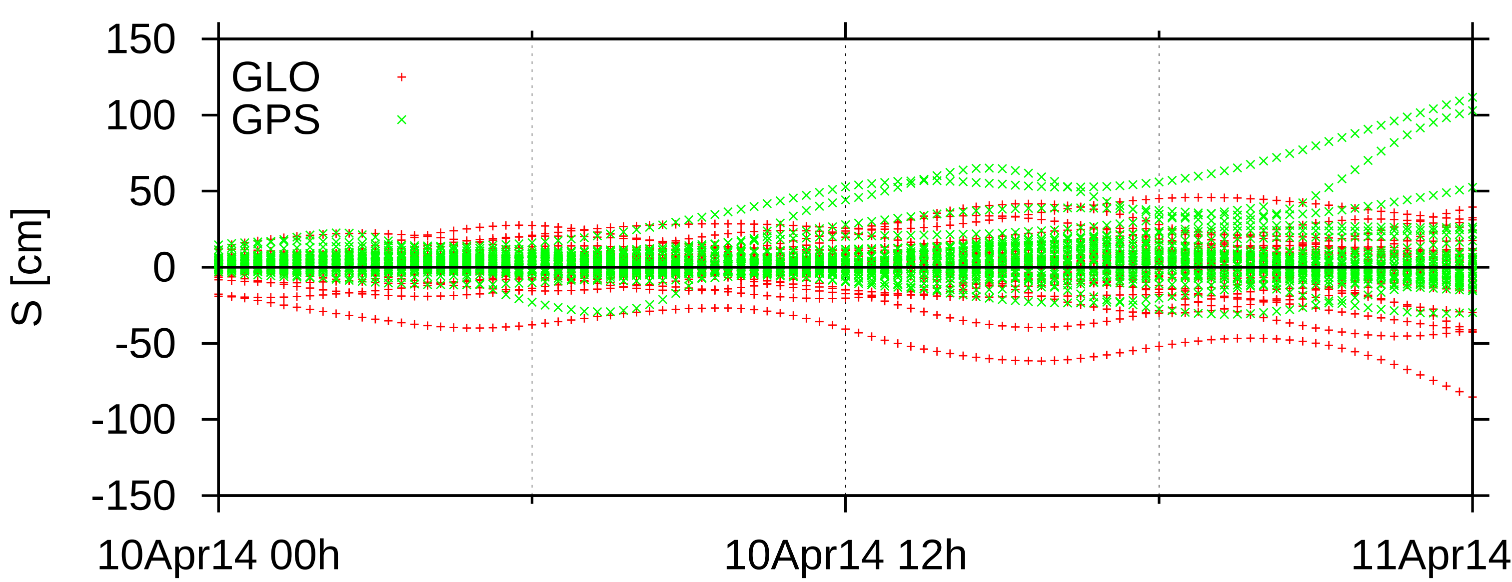

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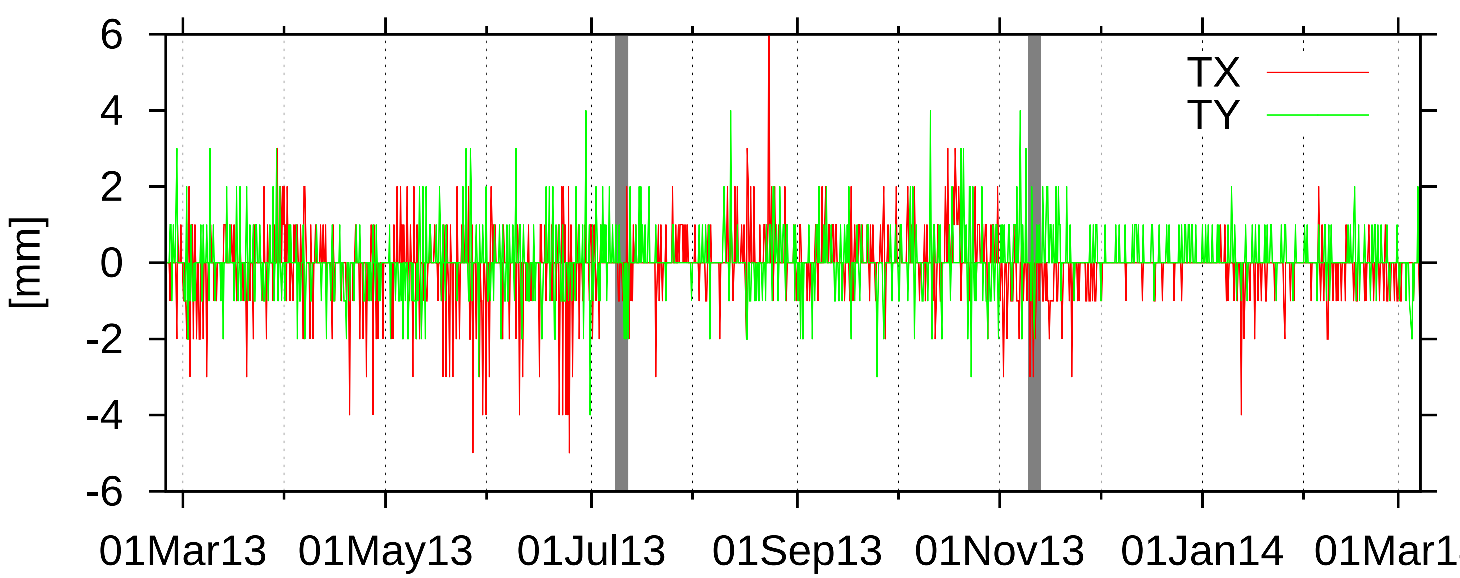

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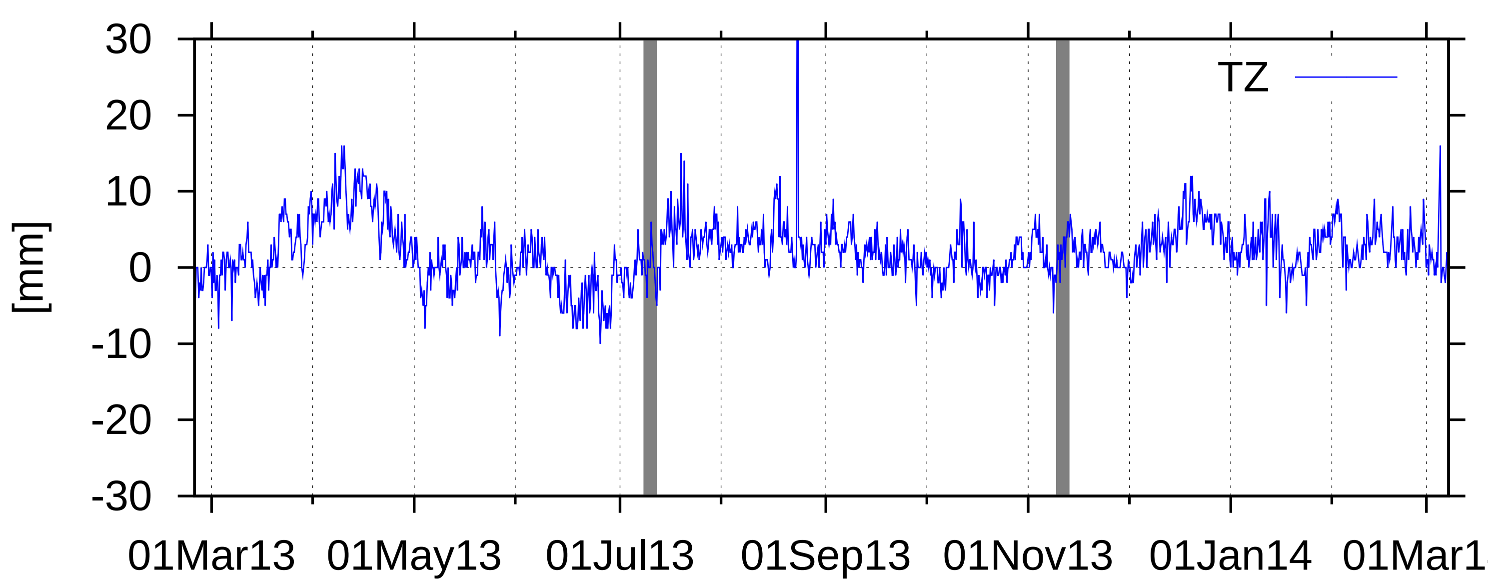

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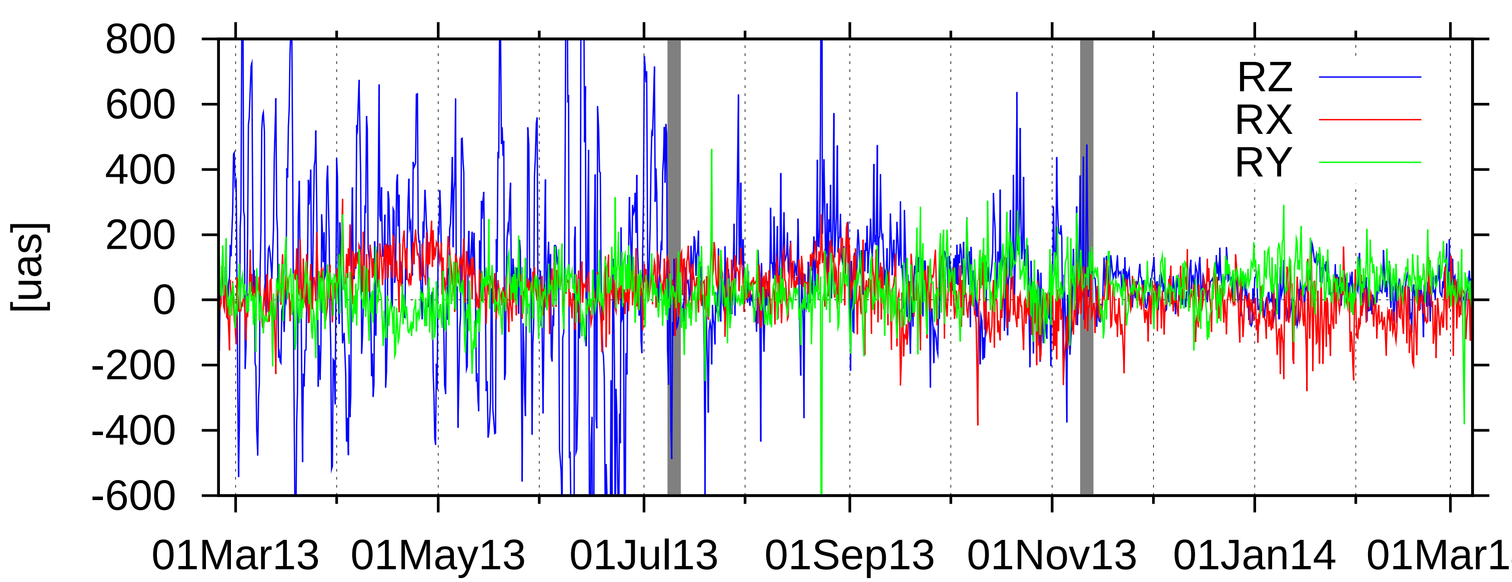

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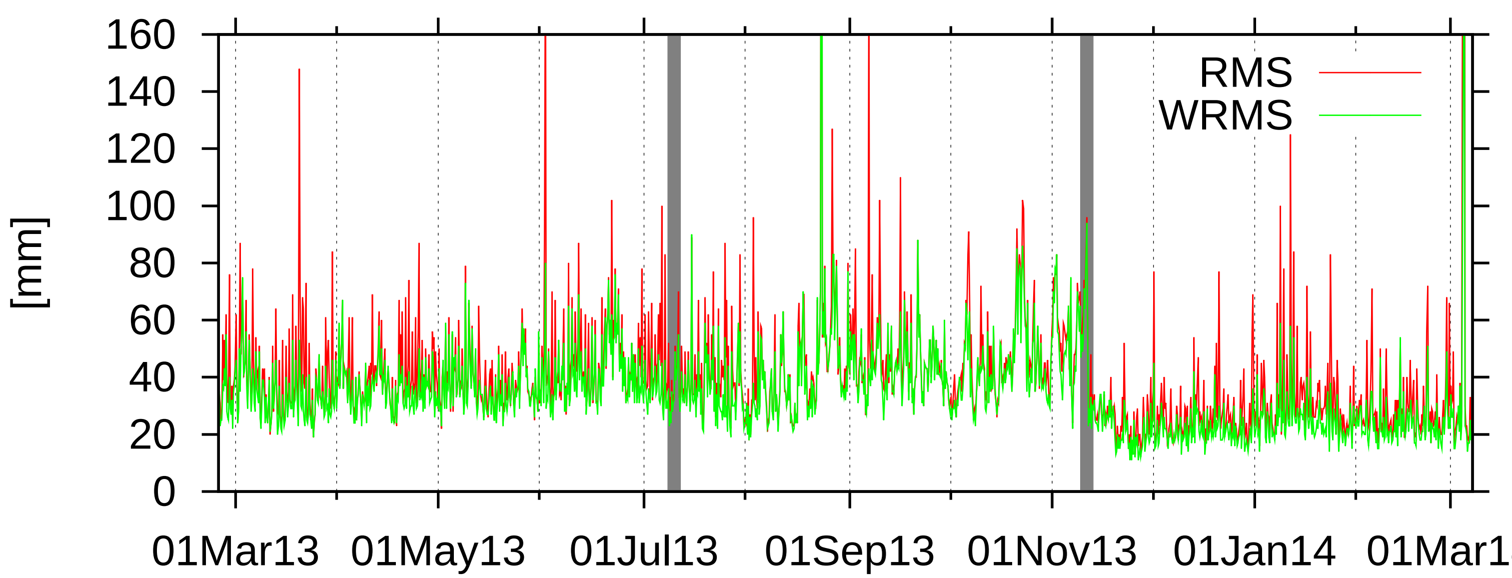

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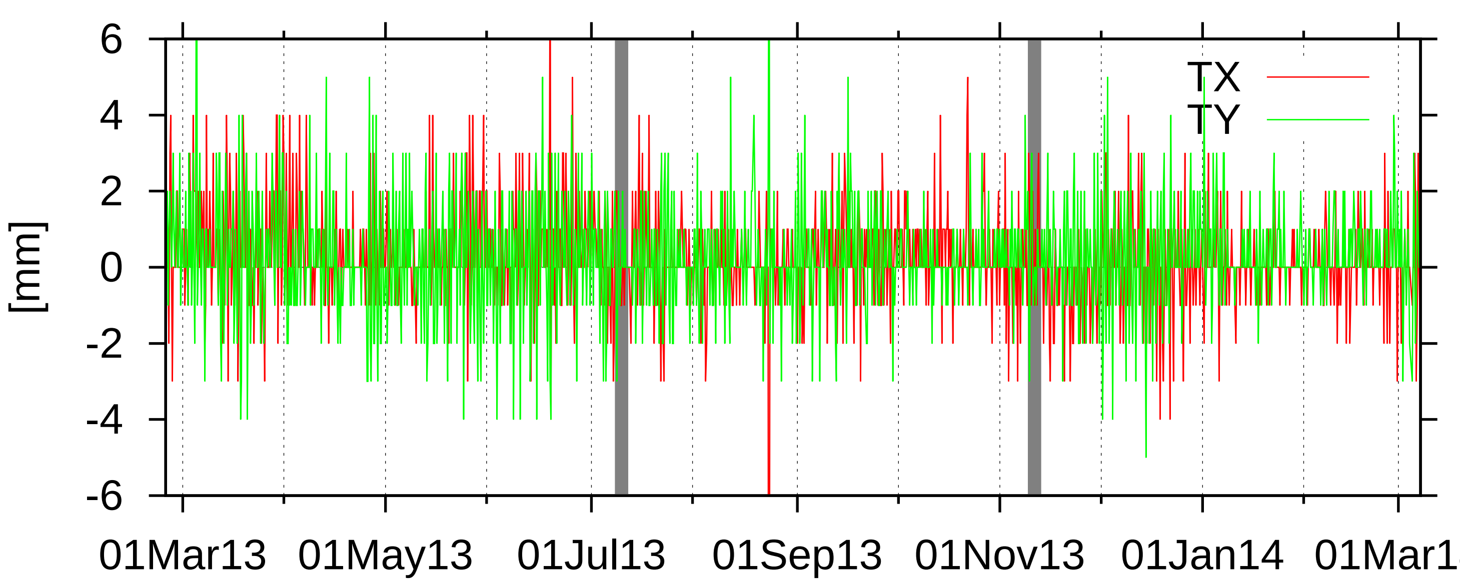

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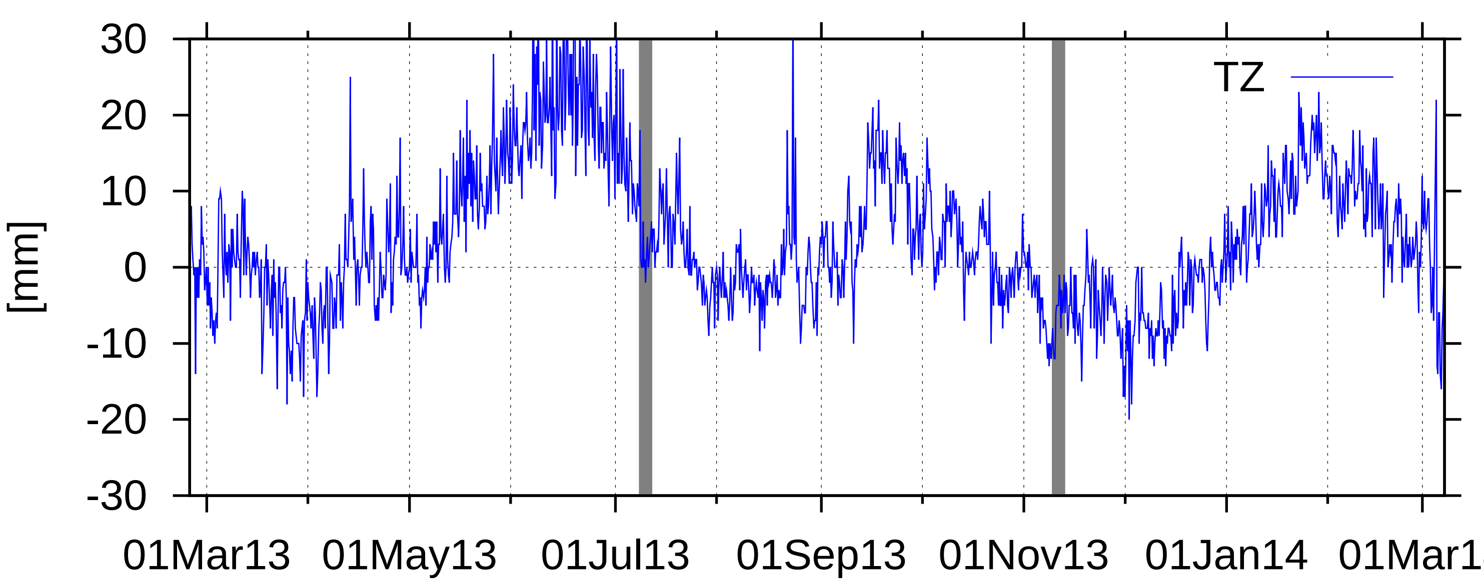

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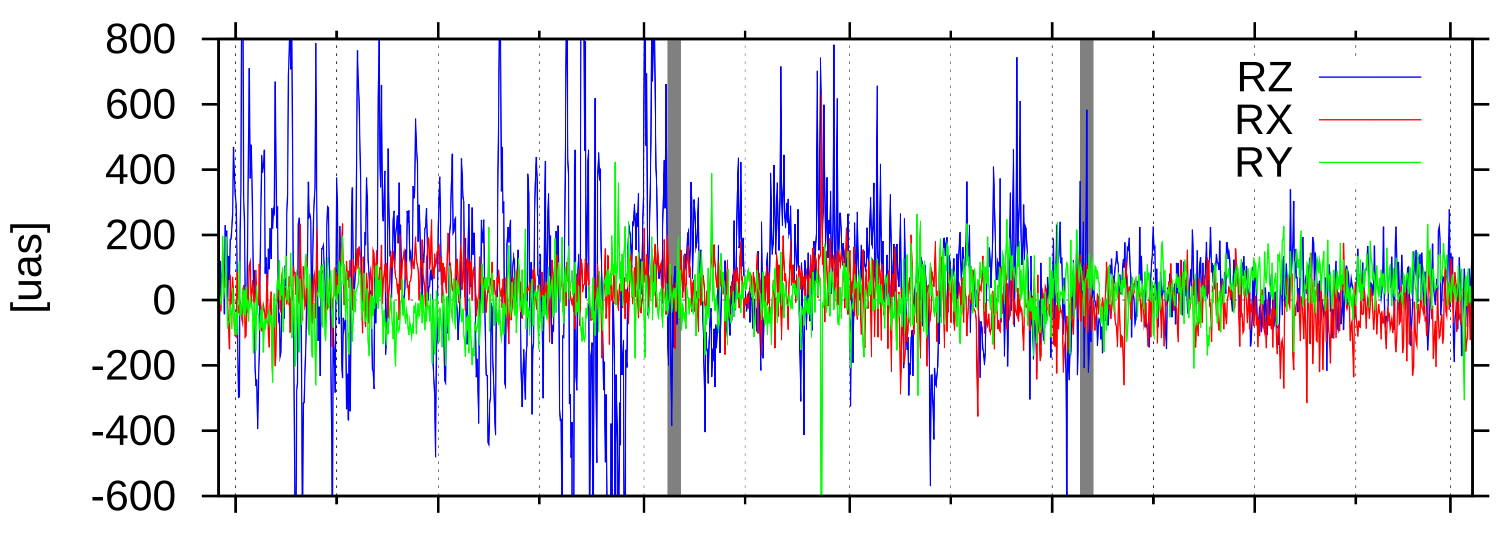

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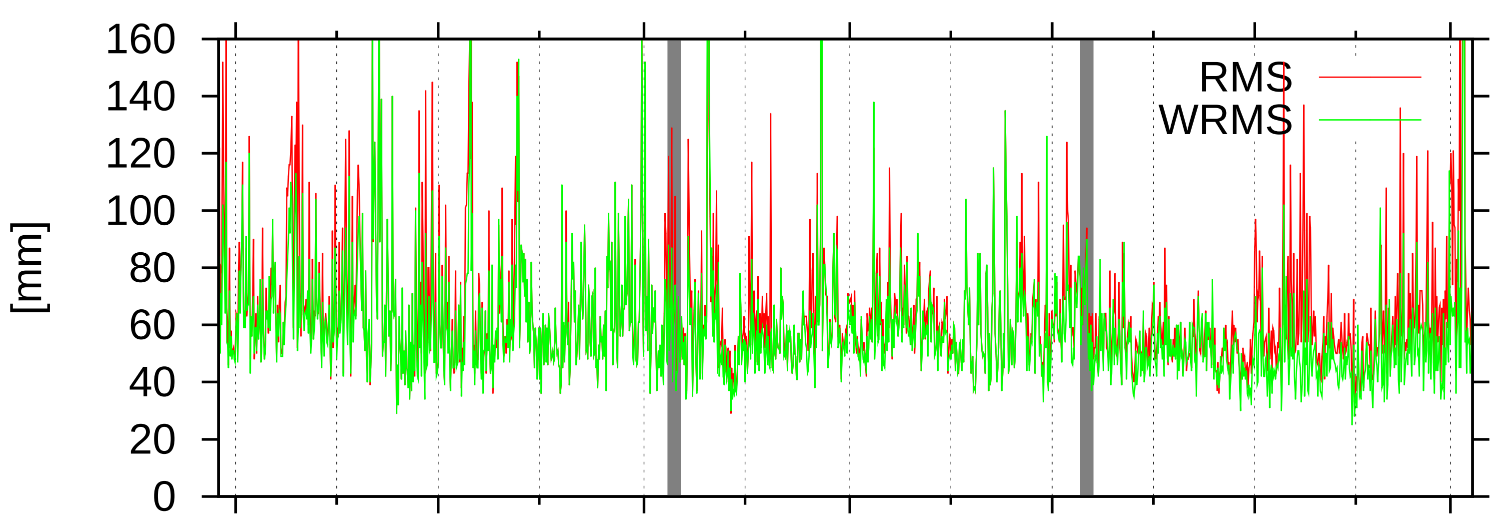

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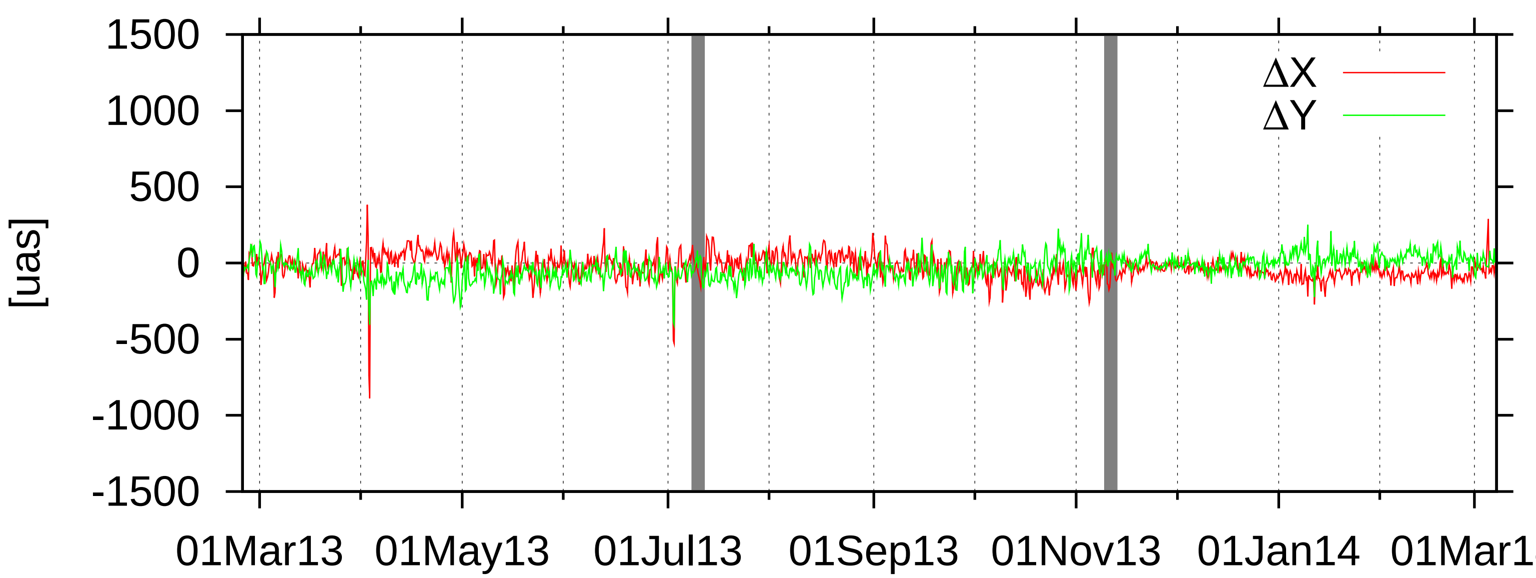

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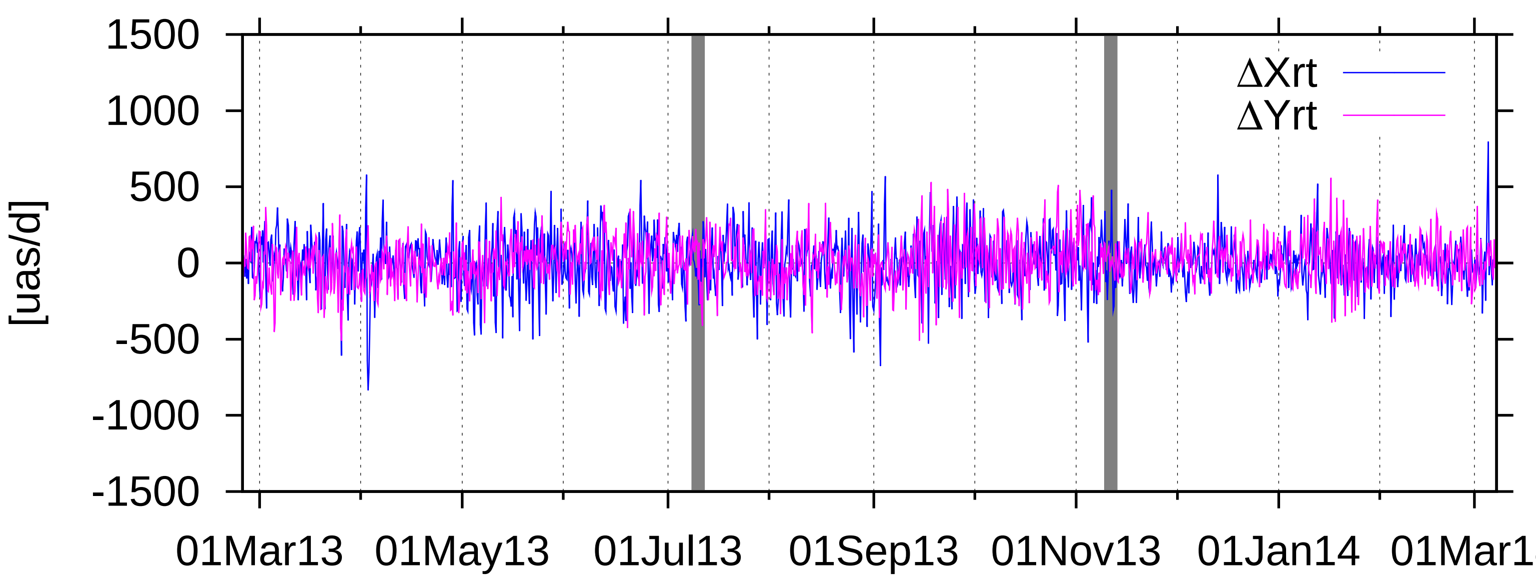

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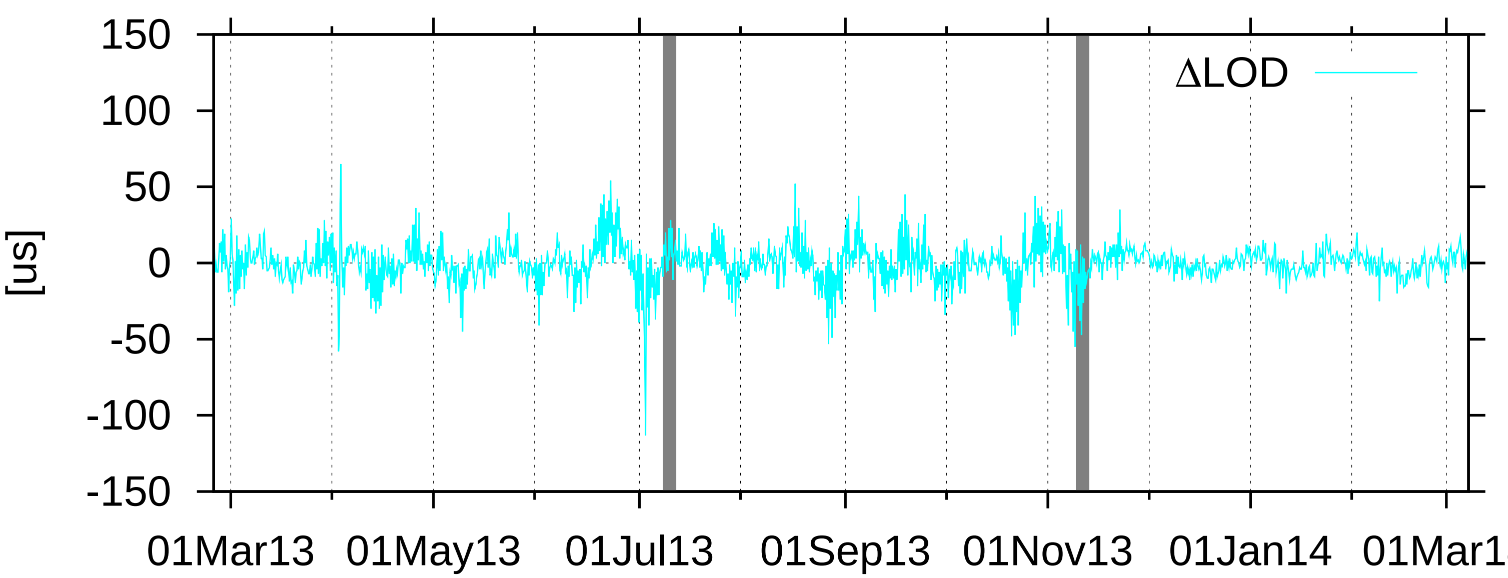

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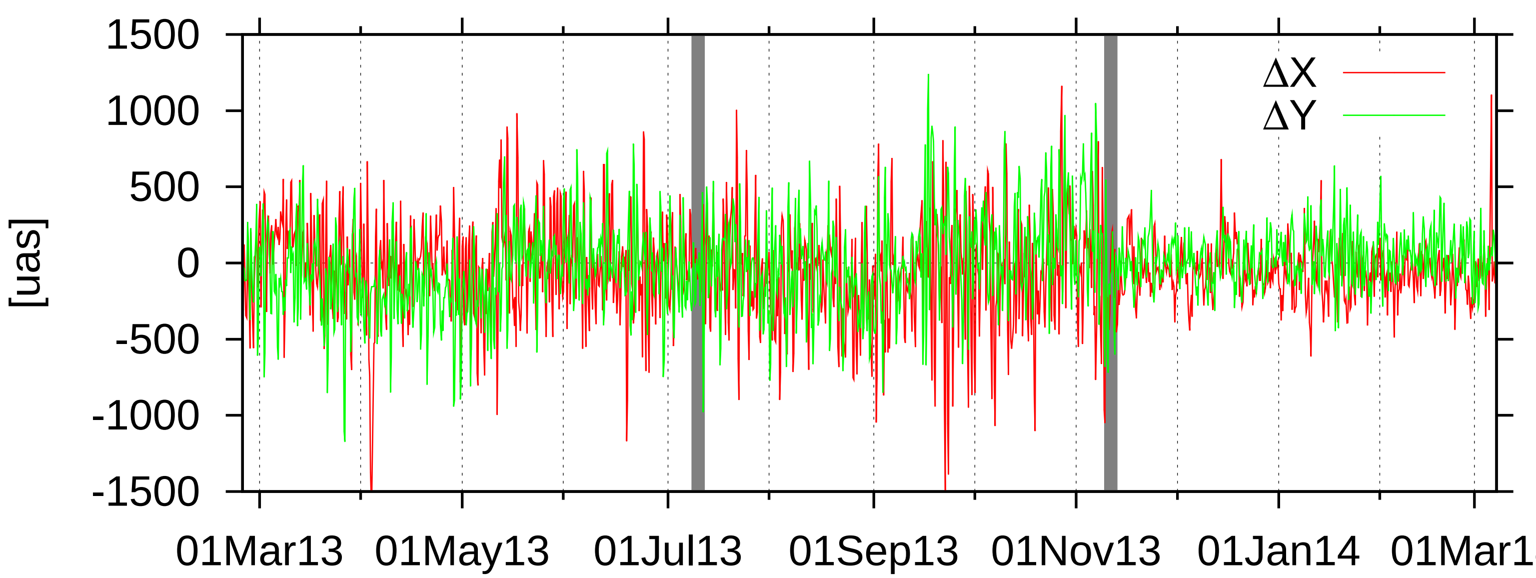

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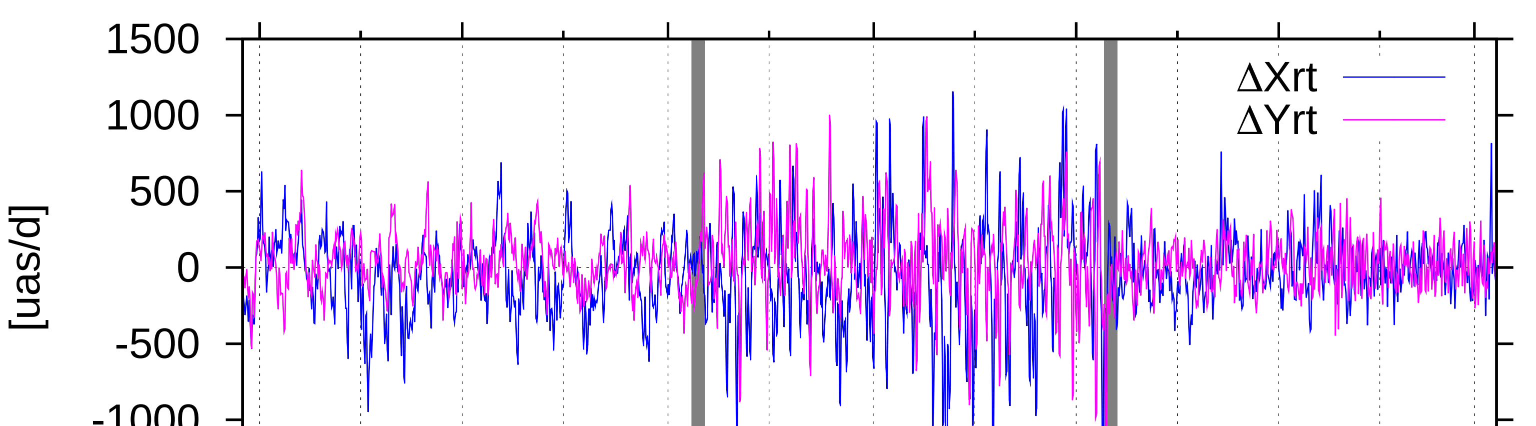

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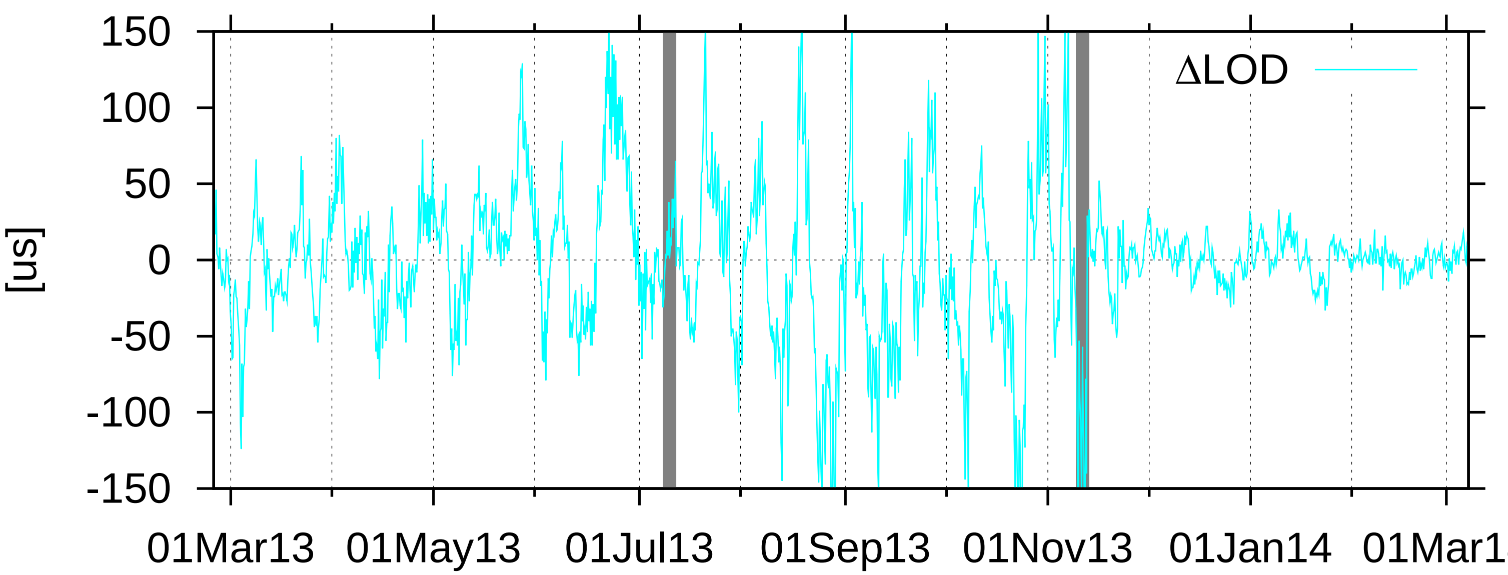

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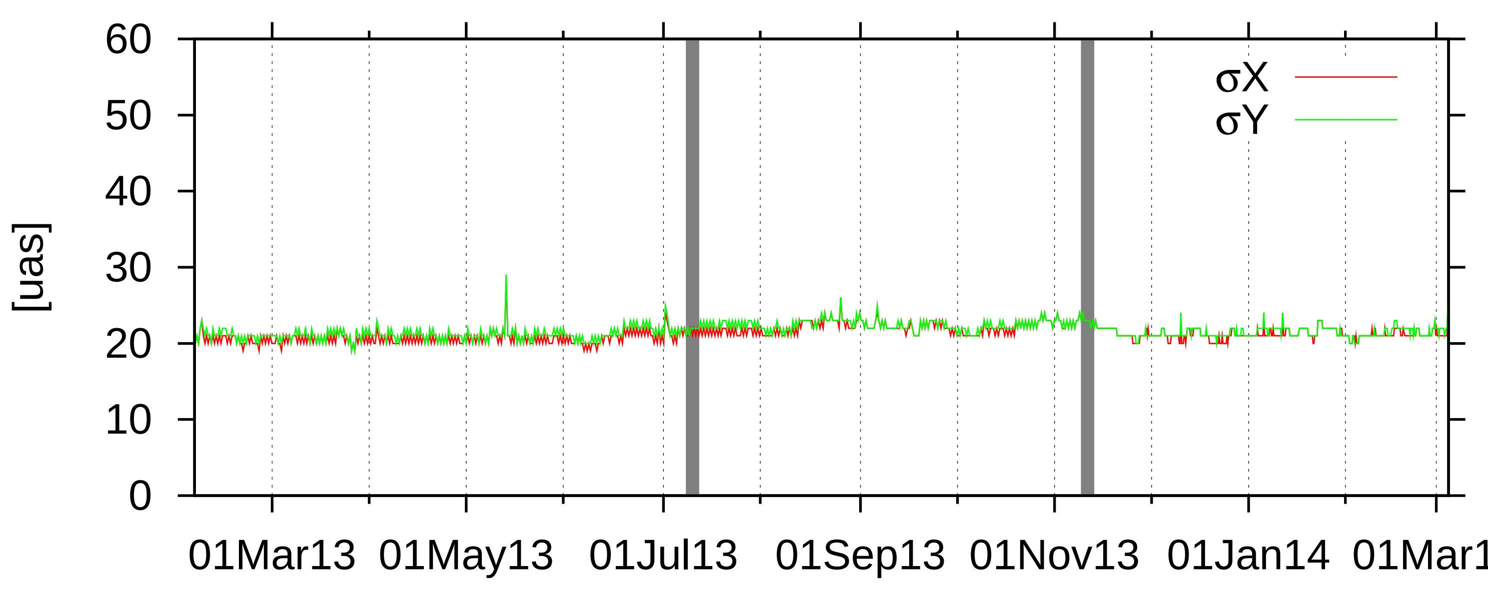

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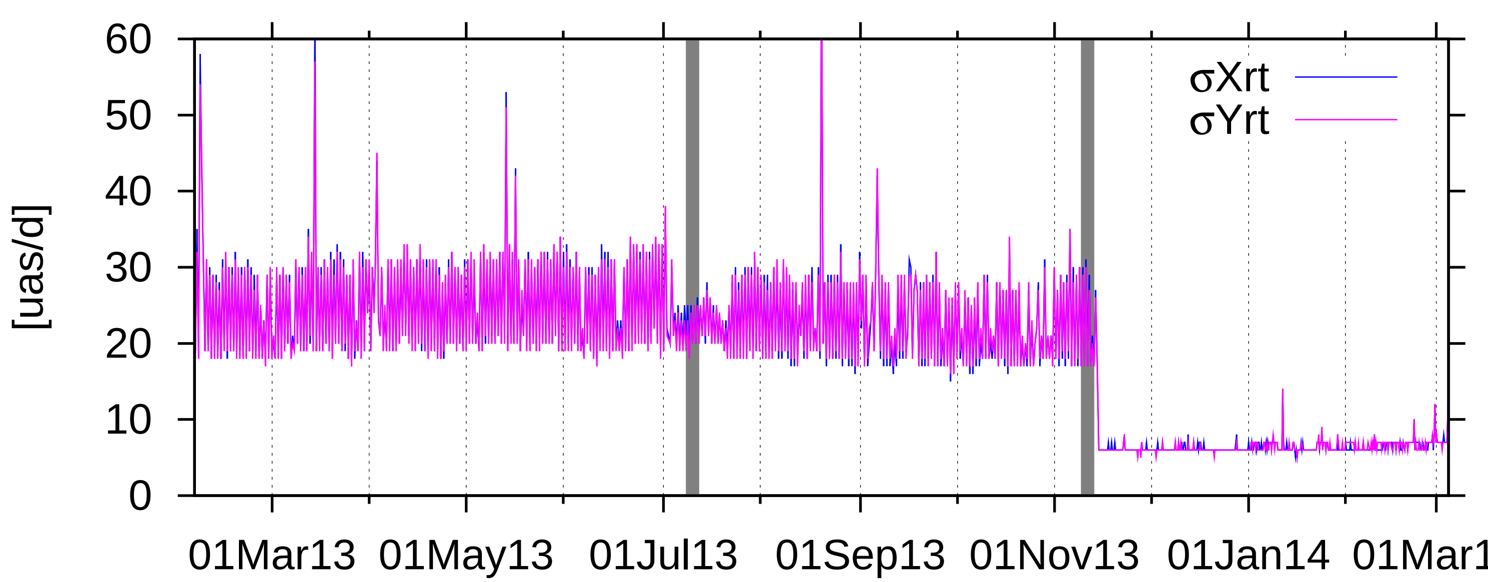

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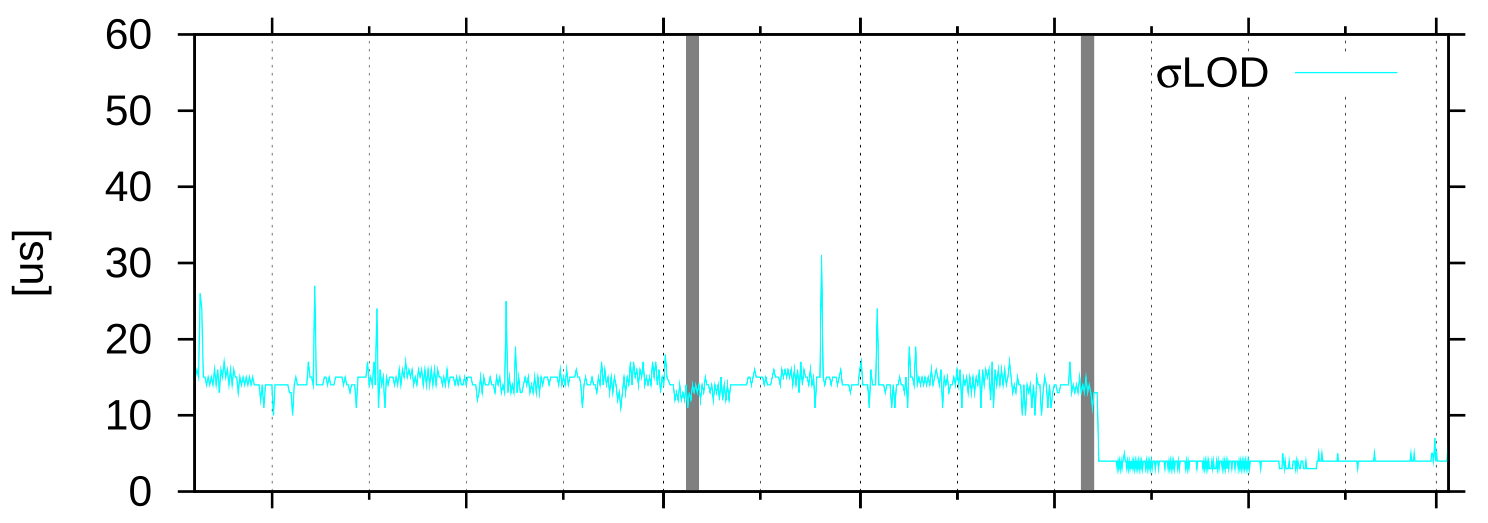

Table 1 Characteristics of the four update versions of the new ultra-rapid products at CODE. The epochs refer to t_{last} of the corresponding ultra-rapid product

Version	NEQ boundaries	Observations	ERP vertices	Stochastic pulses
06 UTC	-54 to +18 h	54 h	-72, -48, -24, +∞ h	-42, -30, -18 h
12 UTC	-60 to +12 h	60 h	-72, -48, -24, +∞ h	-48, -36, -24, -12 h
18 UTC	-66 to +6 h	66 h	-72, -48, -24, +∞ h	-54, -42, -30, -18 h
24 UTC	-72 to +0 h	72 h	-72, -48, -24, +∞ h	-60, -48, -36, -24, -12 h