Combined SLR and GNSS solution using co-locations in space

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Introduction

The International Terrestrial Reference Frame (ITRF, 1) combines microwave (MW) based observations to Global Navigation Satellite Systems (GNSS) satellites and Satellite Laser Ranging (SLR) observations to the pairs of LAGEOS satellites using local ties at the stations.

Experiments using SLR observations to GNSS satellites that are equipped with both techniques (mainly GLONASS) as space ties for the combination were studied in the past (3, 8). The goal is to prevent GNSS-draconic signals into the center of mass of the Earth as determined by the spherical SLR satellites. At the same time the quality of the ERP series should not be degraded by the considerably noisier SLR measurements. (3) concluded that the effect of including SLR in a combined solution was insignificant as the combined solution remained within small margins equal to the MW-only solution. (8) concluded that co-locations in space are more effective and less prone to calibration errors of the system ties than local ties. Both of them conducted a combination on the normal equation (NEQ) level and determined the relative weighting of the MW-NEQ and the SLR-NEQ by the ratio $\sigma^2_{GNSS}/\sigma^2_{SLR}$ of standard deviations of the specific observations.

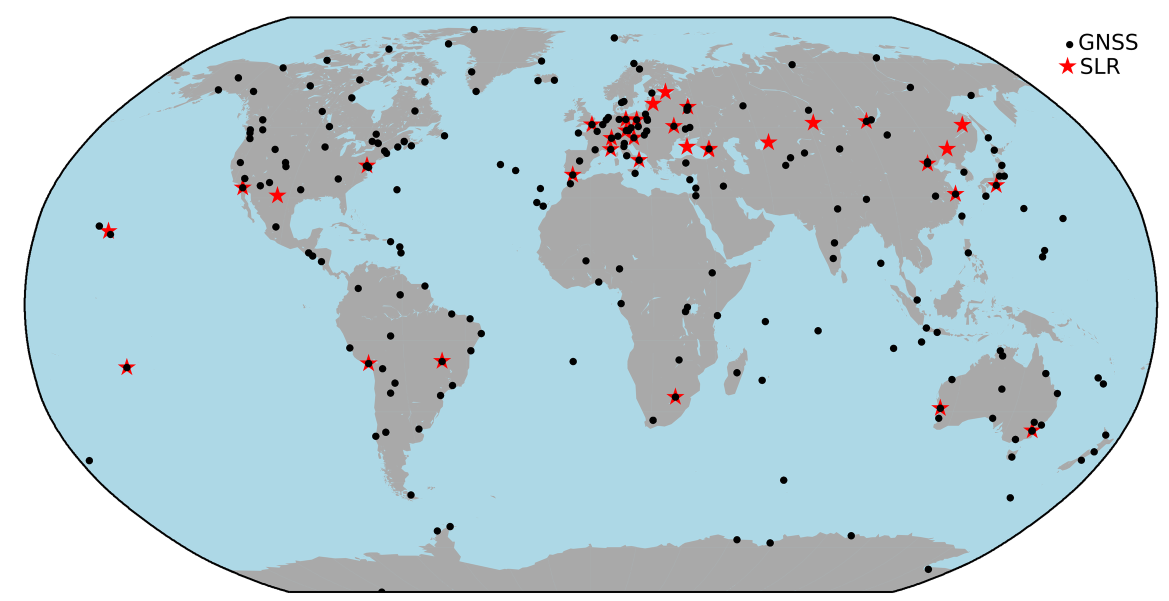

Figure 1: Distribution of the GNSS and SLR stations in 2014 used for this study.

The MW-NEQs used in this work were provided by REPRO 15 (7) and contain observations of around 250 GNSS stations of the International GNSS Service (IGS, 5) distributed all across the globe while are only roughly 40 SLR stations in the International Laser Ranging Service (ILRS, 6) with limited geographical distribution (Fig. 1). The different number of stations, SLR station only being able to track one target at a time and their dependency on clear skies leads to a significant difference in available observations from the two techniques. While the number of MW observations each day is fairly stable throughout the year, the number of available SLR normal points (NP, binned full rate data) is subject to large variations. The ratio of MW observations to SLR observations to all GLONASS satellites collected during 2014 is varying between 1,000 and 5,000 with an average of roughly 2,500.

Combination of SLR and MW observations

We created daily combined NEQ (NEQ_{COMB}) by stacking the individual NEQ from MW data to GLONASS (NEQ_{GNSS}) satellites provided by REPRO 15 and the NEQ generated from simulated SLR observations to GLONASS (NEQ_{SLR}). The common parameters are ERPs, GCCs and the satellite orbit parameters. All SLR observations were replaced by simulated NPs (2) using the consistent set of station coordinates and satellite orbits from REPRO 15. Therefore the truth is known and we can distinguish between the influence of the observation noise and the effect of the SLR station/observation distribution in the solution.

(3) and (8) used a weight $\omega = \sigma^2_{GNSS}/\sigma^2_{SLR} \approx 0.2 - 1$ in the combined NEQ:

$$NEQ_{COMB} = NEQ_{MW} + \omega \cdot NEQ_{SLR}.$$

With a ratio of 2,500 between MW and SLR observations this was not enough for the comparably few SLR observations to influence the combined solution significantly. We therefore tested larger weights ranging from 1 to 10,000..

Transferring scale

We studied whether it is possible to transfer information about the scale from the SLR observations onto the GNSS network. To do so we used an virtual SLR station network where the height of each station was increased by 10 cm for the combination. We then studied how well this information can be forced upon the GNSS stations when applying a no net rotation (NNR), no net translation (NNT) and no net scale (NNS) minimum constraint condition on the SLR station network in the combination. If the scale can be transferred using the SLR observations to the GNSS satellites as space ties the GNSS station heights should react accordingly. Because the GNSS orbits are estimated at the same time, their information on the scale is kept in the solution.

Figure 2 shows the estimated scale parameter when performing a seven parameter Helmert transformation between the a priori GNSS station coordinates and their coordinates from the combined solution using different ω ranging from 1 to 10,000. It indicates that ω has to be at least 500 to have a significant effect explaining the results by (3).

Increasing the weight also increases the scatter between the estimated scale parameters due to a to a larger influence of the uncertainties within these observations. Furthermore the inner consistency of the MW-only solution is influenced increasingly. A weight of $\omega = 10,000$ gives an average scale of almost 90 mm on the Earths surface.

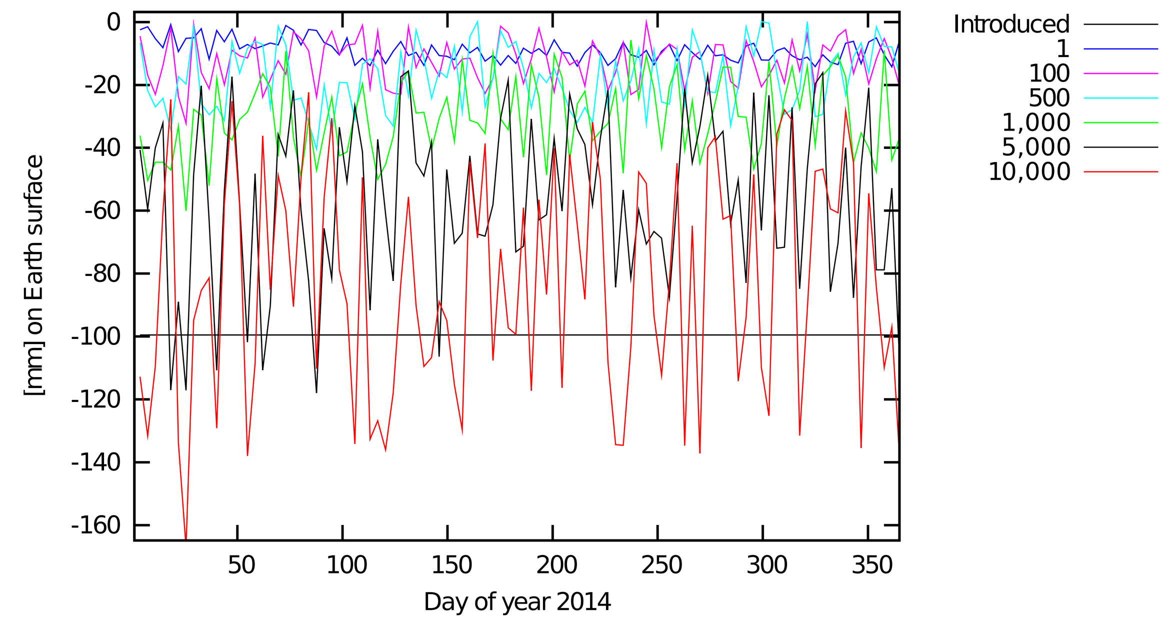

Figure 2: Estimated scale for different weights.

Estimating satellite antenna offsets

When estimating satellite antenna offsets in Z direction (SAO-z) at the same time the effect of these artificial 10 cm is distributed between the scale and the SAO-z. Figure 3 shows the estimated scale and SAO-z.

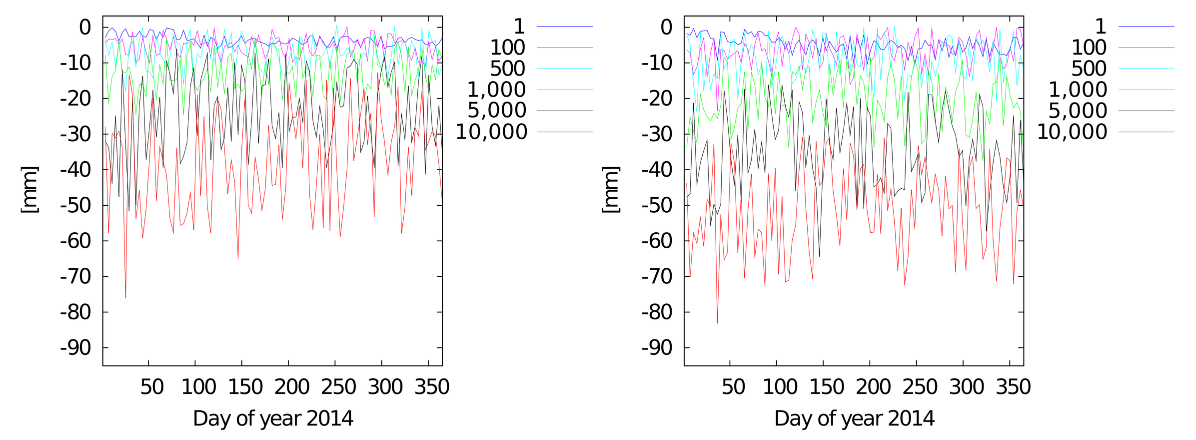

Figure 3: Left: Scale when simultaneously estimating SAO-z for different weights. Right: Estimated SAO-z difference from the a priori offsets for different weights.

We can see that more than 50% of the scale in Fig. 2 is now estimated as SAO-z and again ω needs to be at least 500 to significantly differ from solution with $\omega = 1$. The scatter between the days remains on the same level.

Influence of SLR observation noise

To asses the influence of the simulation noise on the scatter between the days in Fig. 2 we created multiple set observations with a varying initialization of the random number series used for the noise simulation. Increasing the weight increases the scatter between solutions for the different sets of observations. For ω up to $\approx 4{,}000$ the scatter between the different solutions remains smaller than the one given by the variation in available observations. For weights of $\omega \approx 5{,}000$ the scatter between different initializations of the random simulation noise reaches the same level as the scatter given by the variation in the distribution of available observations. For higher weights the noise dominates the scatter.

Figure 4 shows the scale that is transferred onto the GNSS station coordinates for four different initializations of the simulation noise for a fixed weight $\omega = 2000$.

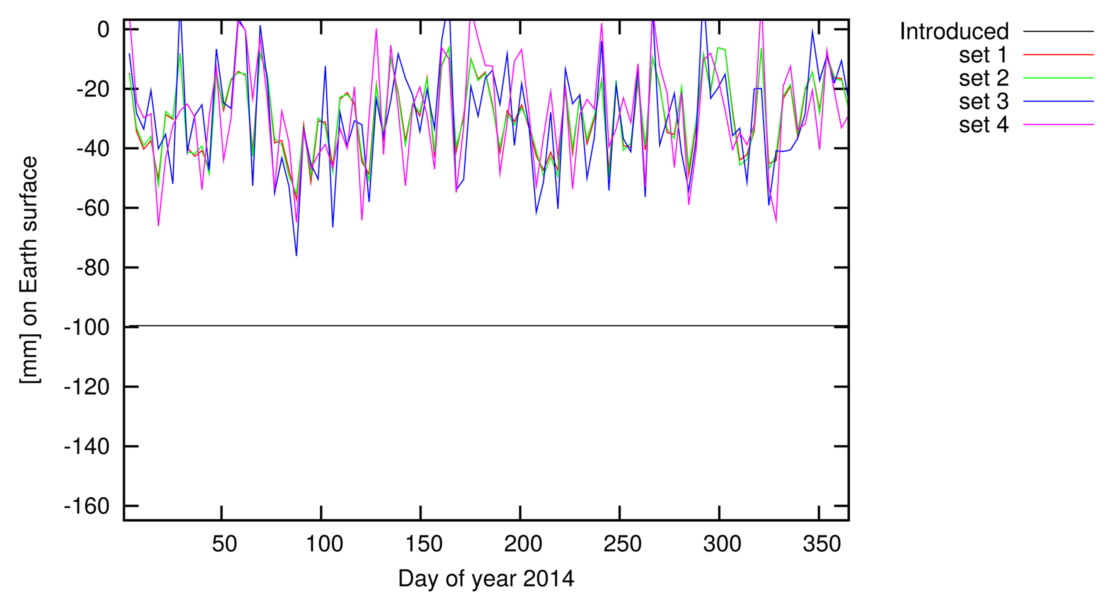

Figure 4: Estimated scale for different initialization of the random noise time series and fixed weight $\omega = 2{,}000$. The scaling is the same as in Fig. 2

The variation between the different sets of ≈ 20 mm is only 25% of the scatter between different days. We therefore choose $\omega = 2{,}000$ as an appropriate weight since it also resembles the ratio of observations.

Combination with LAGEOS

The combined solution of SLR and MW observation to GNSS satellites using the proper SLR station coordinates was further stacked with the seven-day solution from SLR observations to LAGEOS. The same weight $\omega = 2{,}000$ was used for the SLR observations to the GNSS satellites as well as the SLR observations to LAGEOS. A NNR condition was applied for the GNSS stations while a NNT condition was applied for the SLR stations.

The SLR observations to LAGEOS are supposed to define the GCC series. However The GCC of the combined solution remains closer to the MW-only solution unless the GCC parameters are pre-eliminated in the MW-NEQ before stacking. Because of the simulation setup, the GCC parameters of the MW observations is kept separate. Figure 5 compares the GCC of the combination with the one determined from LAGEOS only. The differences are below 2 mm on most days never exceeding 4 mm at maximum. They solely come from the additional SLR observations to the GNSS satellites.

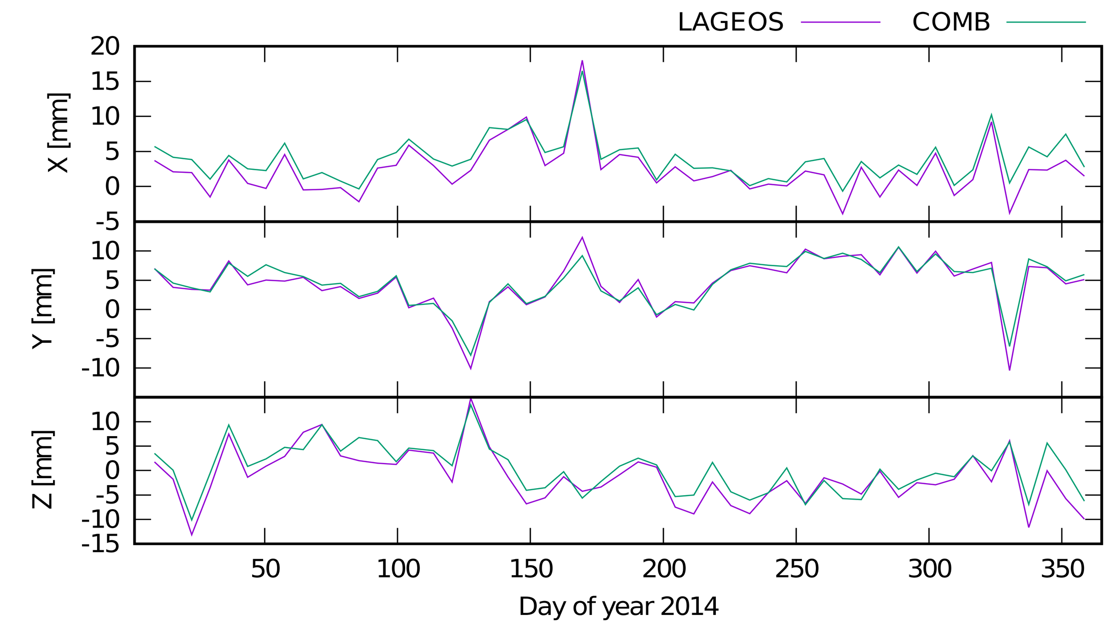

Figure 5: Solutions for GCC from LAGEOS only (LAG), SLR and MW to GLONASS combined with LAGEOS (COMB). GCC pre-eliminated in the MW NEQ before stacking combination.

The variations in Fig. 5 are dominated by the inhomogeneous geographical distribution of the SLR NPs. This is reflected in the cofactor matrix, i.e., in the formal errors of the resulting GCC parameters displayed in Fig. 6. Taking a look at the formal errors of the LAGEOS only GCC components we can see large weekly variations typical for a SLR solution The sparse station network is subject to weather conditions and other limiting operational factors which result in a big differences of the geographical distribution and number of NPs each week.

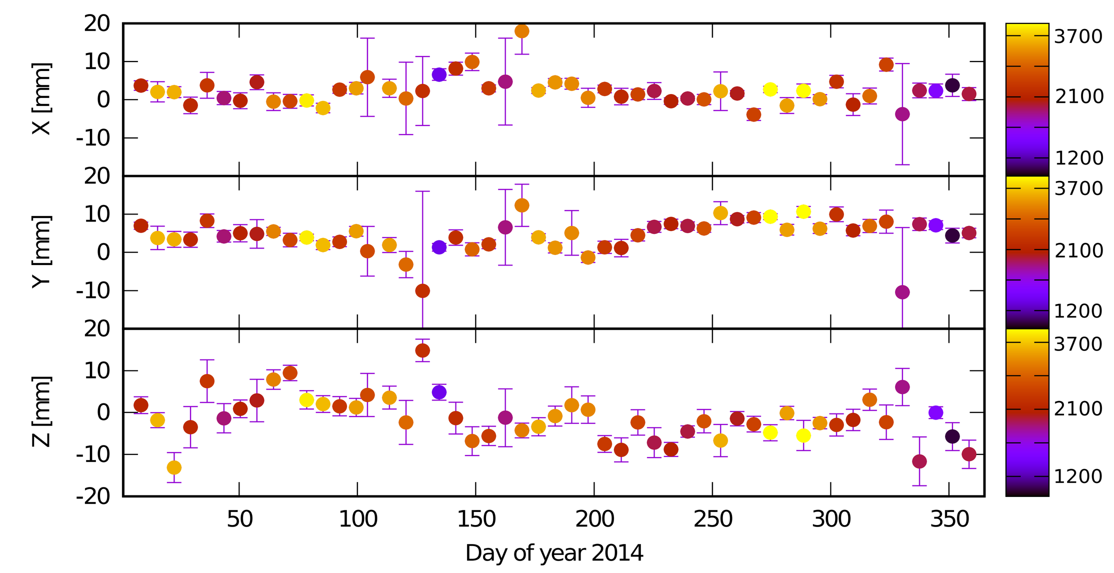

Figure 6: Formal errors of GCC components from LAGEOS only solution. The colorcode represents the total number of observations to LAGEOS-1 and LAGEOS-2 for each week, a darker color means fewer observations.

When theres a large number of observations in a certain week the formal errors remain small. The formal errors in weeks with a small number of NPs depend strongly on the geographical distribution of the observations. In some weeks fewer observations can still be sufficient to get to a similar level in the formal errors as in weeks with a larger number of observations.

We compare the resulting ERPs of the combination to the MW-only solution from REPRO 15 to see the influence of the SLR observations on the ERPs. The differences are displayed in Fig. 7. The average difference in the X component is 0.08 mas with a standard deviation of 0.1 mas. The average difference in Y component is 0.1 mas with a standard deviation of 0.12 mas.

The formal errors of the ERPs are displayed in Fig. 8. In the combination the errors are smaller than the formal errors of the LAGEOS only solution by a factor of 4 but larger than in the MW-only solution by a factor of ≈ 20. This is expected because of the larger noise in the SLR observations and the better ERP estimation capability using MW-only.

The SLR station coordinates remain on a roughly $10 - 15$ mm level at the coordinates used for the simulation while the MW station coordinates match on a $5 - 10$ mm level before and after the combination with the SLR NEQs.

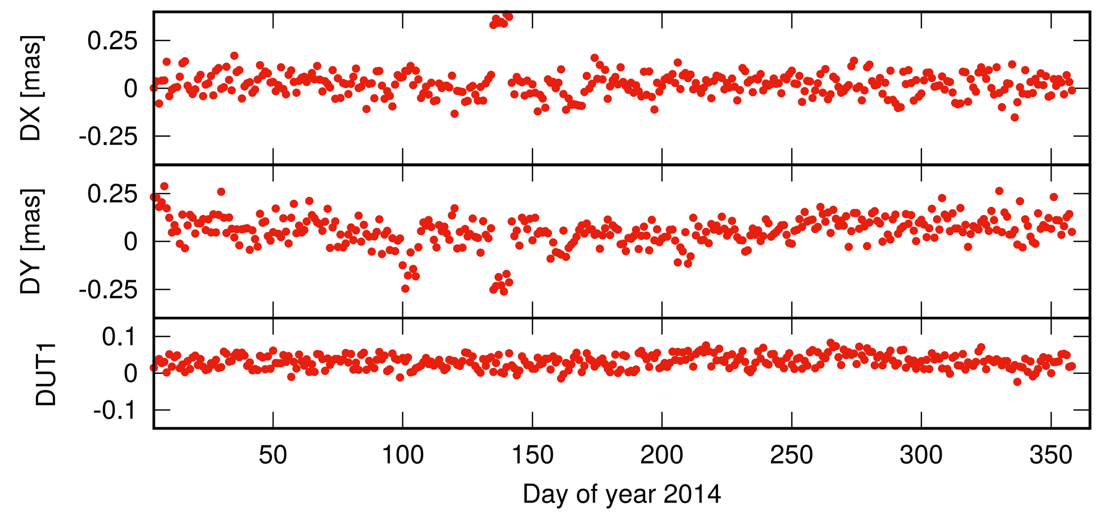

Figure 7: ERP differences between the MW-only ERPs from the REPRO 15 and the combination with SLR to GLONASS and LAGEOS with pre-elimination of the GCC parameters in the MW NEQ before stacking.

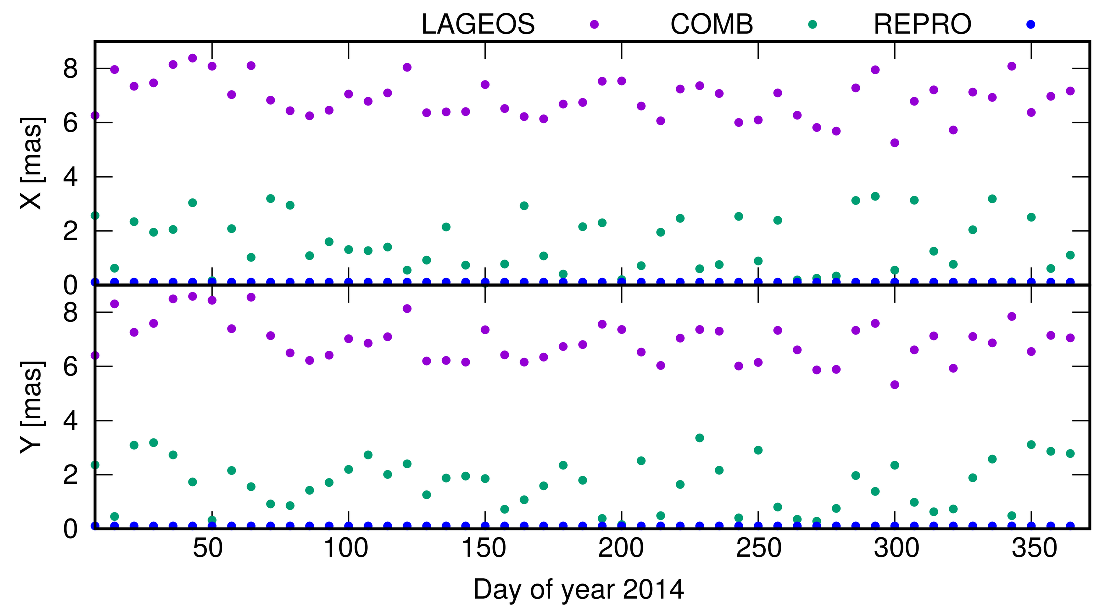

Figure 8: Formal errors ERP from LAGEOS only (LAGEOS), the MW-only ERPs from the REPRO 15 (REPRO) and the combination with SLR to GLONASS and LAGEOS with pre-elimination of the GCC parameters in the MW NEQ before stacking (COMB).

Summary

By using a virtual SLR station network which was inflated by 10cm in height we were able to study the transfer of scale information using different weights between MW and SLR in a combined solution. Fixing the SLR stations with a NNR, NNT and NNS condition a relative weight of $\omega \approx 2{,}000$ resembling the ratio of available observations allowed a transfer of of this inflation onto the GNSS station network mainly via the scale. The remainder of these 10cm is distributed among other parameters in the solution.

At this weighting the GCCs match the solution derived from SLR observations to LAGEOS on the level of $2mm$ and the ERPs remain ± 0.025 mas within the solution obtained from the MW observations.

It is possible to create a reasonable combined solution of MW observations to GNSS satellites and SLR observation to LAGEOS using SLR observations to GNSS satellites as space ties.

The simulation approach allows to distinguish between the effect of the observation noise and the availability and geographical distribution of the SLR observations in the solution.

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