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 satellites of the Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR) observations to the pairs of LAGEOS and Etalon 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 conducted in the past (e.g. [3], [8]). [3] concluded that the effect of SLR in the combination was insignificant as this 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 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.

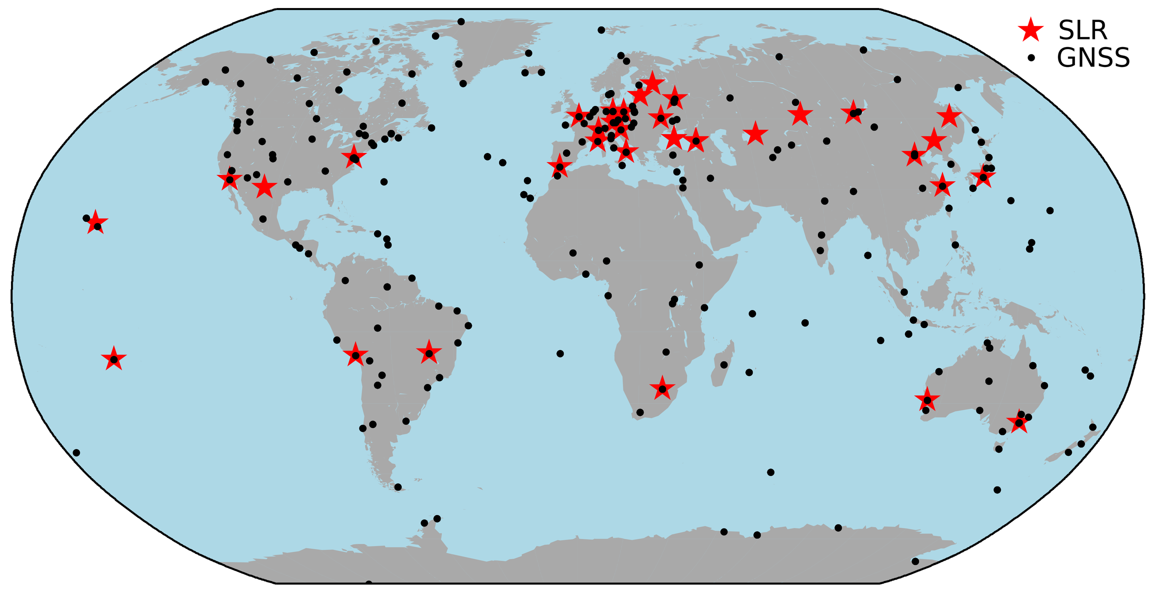

Figure 1: Distribution of the GNSS and SLR stations in 2014 used for this study.

The MW-NEQ used in this work were provided by REPRO 15 [7] and contain observations of about 250 GNSS stations of the International GNSS Service (IGS, [5]) distributed all over the globe while only about 40 SLR stations of the International Laser Ranging Service (ILRS, [6]) with a limited geographical distribution (Fig. 1) may be used. SLR stations are only able to track one target at a time and they depend on sufficient weather conditions for taking measurements. These facts lead to a significant difference in the availability of observations from the two techniques because GNSS station track about 10 targets per epoch and are weather independent. While the number of MW observations per 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 per day 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 GNSS (NEQ_{GNSS}) satellites provided by REPRO 15 and the NEQ generated from simulated SLR observations to GLONASS (NEQ_{SLR}).

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 by creating sets of simulated NPs with different random noise.

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

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

With a ratio of 2,500 between MW and SLR observations this might not be 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 the scale

The scale is expected to be transferred from the SLR into the MW solution. In order to identify the necessary weighting ω we have established the following experiment: The height of each SLR station was increased by 10 cm for the combination. Applying a no net rotation (NNR), no net translation (NNT) and no net scale (NNS) minimum constraint condition on these sites the scale discrepancy is expected to be transferred into the resulting GNSS station coordinates. Since the orbits of the GNSS satellites contain a strong information on the scale in the GNSS solution it can not be expected to transfer the full amount of 10 cm into the GNSS coordinates. Range biases, GNSS satellite antenna offsets (SAO) and SLR light reflector array (LRA) offsets were fixed in this setup.

Figure 2 shows the estimated scale parameter when performing a seven parameter Helmert transformation between the a priori GNSS station coordinates and the 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. Increasing the weight also increases the scatter between the estimated scale parameters due to a larger influence of the uncertainties within the NPs and their varying availability.

Furthermore the inner consistency of the MW-only solution is degraded more and more with an increasing weight for the SLR measurements representing the contaminated geometry.

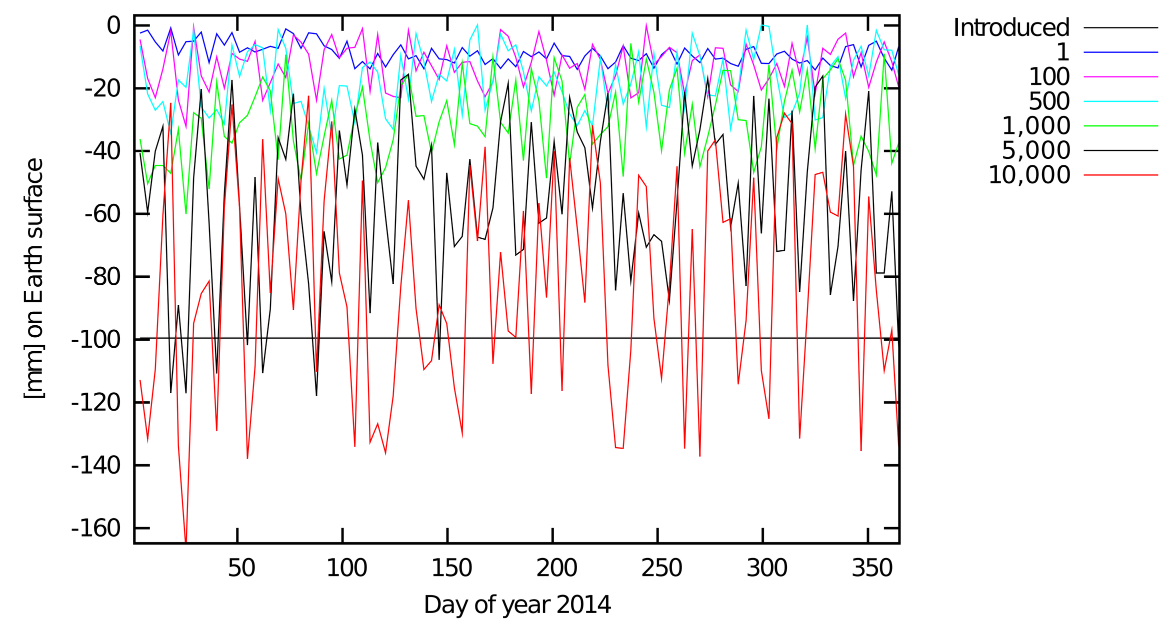

Figure 2: Estimated scale for different weights.

Estimating satellite antenna offsets

When simultaneously estimating GNSS SAO in Z direction (SAO-z) the effect of these artificial 10 cm is distributed between the scale and the SAO-z. For each satellite the SAO-z was estimated and the difference to the a priori offsets was averaged over all satellites per day. Figure 3 shows the estimated scale and average SAO-z correction.

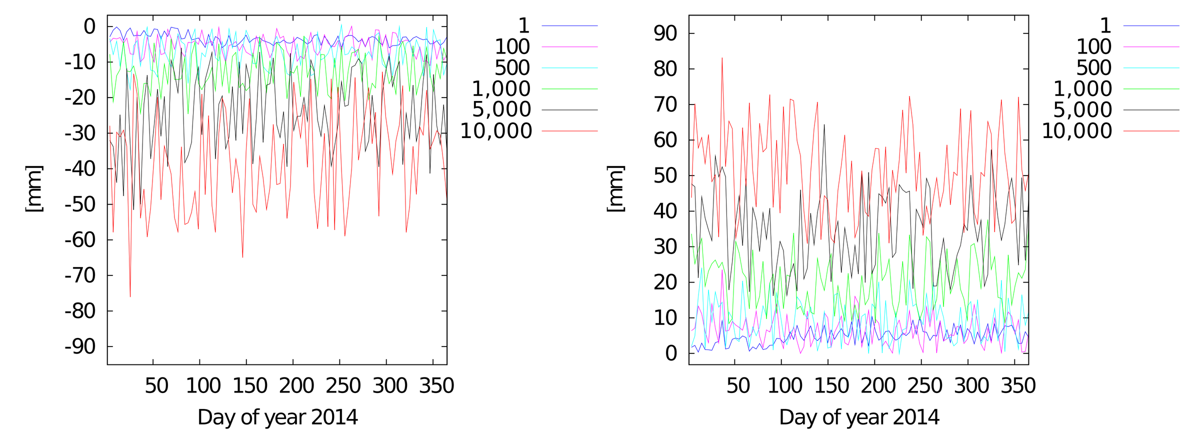

Figure 3: Left: Scale when simultaneously estimating SAO-z for different weights. Right: Estimated average SAO-z correction to the a priori offsets for different weights.

We notice that more than 50% of the scale in Fig. 2 is now estimated as correction to the SAO-z. ω again needs to be at least 500 to significantly differ from solution with $\omega = 1$. It seems that the scatter between the days is dominated by the number and geographical distribution and not the noise of the single NPs.

Influence of SLR observation noise

An advantage of using simulated NPs is that the experiment can be repeated with different initializations for the random noise function. In this way, the impact of the observation noise itself and the geographical and temporal distribution of the SLR measurements in Fig. 2 can be separated.

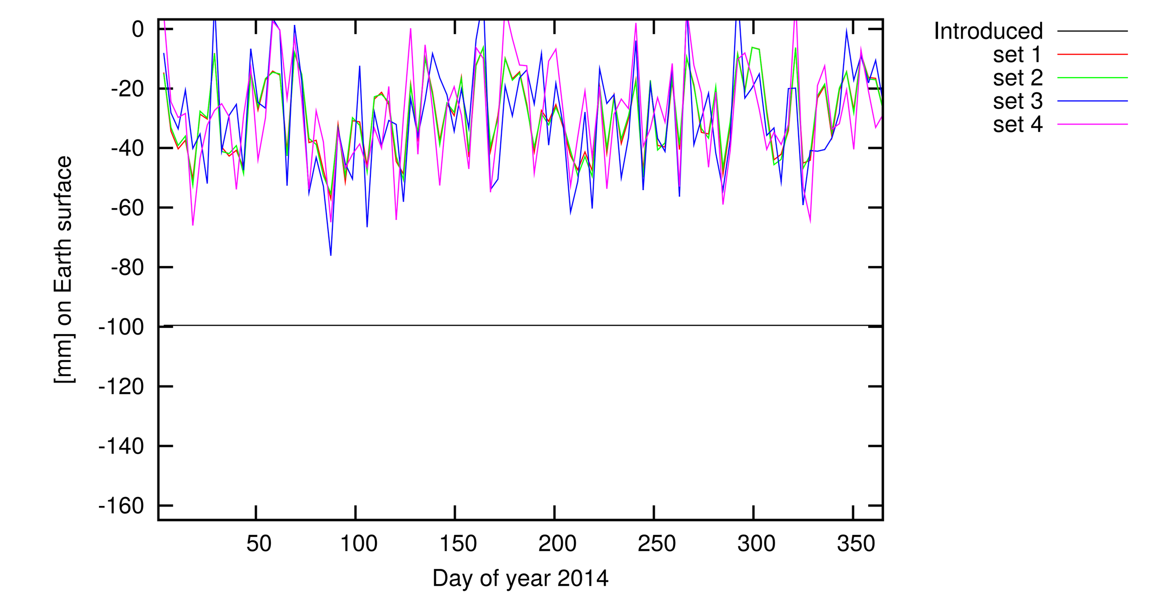

Figure 4: Estimated scale for different initialization of the random noise time series and fixed weight ω = 2,000. The scaling is the same as in Fig. 2.

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 ω = 2,000. The variation between the different sets of ≈ 20 mm is only 25% of the scatter between different days. Since the different sets of observations are mainly following the variation from day to day most of the variation is introduced by the geometry effects in the SLR measurements. If the weighting ratio ω is increased further (>4,000) the noise of the observations start to dominate the variation in time. This indicates that the SLR-measurements are over-weighted to an extent that they start to degrade the solution. We therefore choose ω = 2,000 as an appropriate weight since it also resembles the ratio of observations.

Combination with LAGEOS

The combination of SLR and MW observations to GNSS satellites using the proper SLR station coordinates was further combined with the seven-day solution from simulated SLR observations to LAGEOS. The weight ω = 2,000 was used for the SLR observations to the GNSS satellites as well as the SLR observations to LAGEOS following the approach of [8]. A NNR condition was applied for the GNSS stations while a NNT condition was applied for the SLR stations.

Geocenter coordinates

The SLR observations to LAGEOS are supposed to deliver the strongest contribution to the geocenter coordinates (GCC). 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.

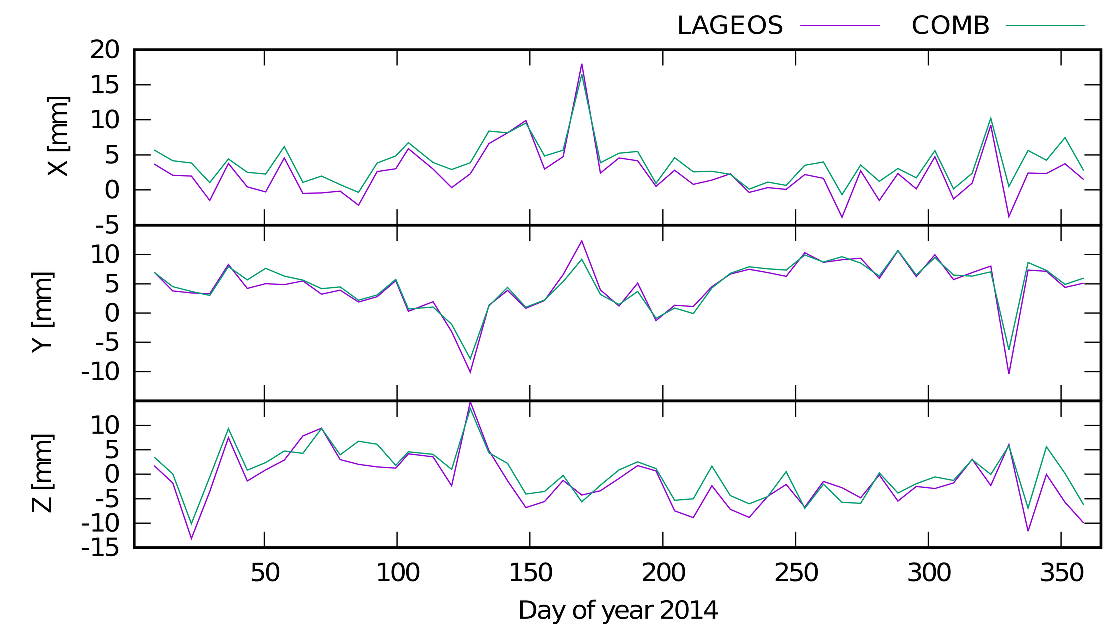

Figure 5: Solutions for GCC from LAGEOS only (LAGEOS), SLR and MW to GLONASS combined with LAGEOS (COMB).

The variations in Fig. 5 are likely dominated by the inhomogeneous geographical distribution of the SLR NPs. This is reflected 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.

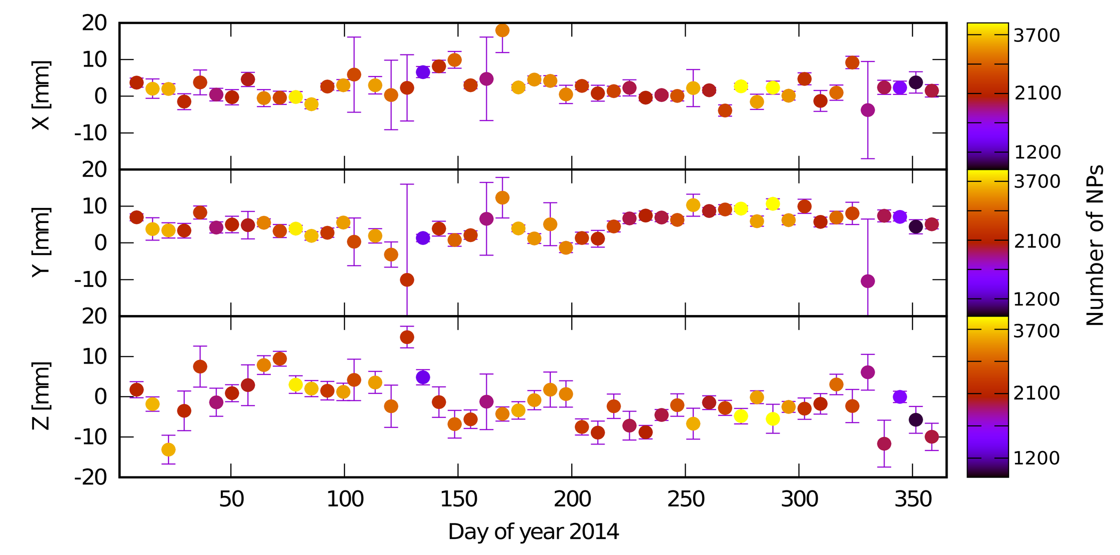

Figure 6: Formal errors of GCC components from LAGEOS only solution. The color code represents the total number of observations to LAGEOS-1 and LAGEOS-2 for each week, a darker color means less observations.

If there is 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 a smaller number of observations can still be sufficient to get to a similar level in the formal errors as in weeks with more observations.

Earth rotation parameters

We compare the resulting Earth rotation parameters (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 formal errors are smaller than the formal errors of the LAGEOS only solution by a factor of 4 but about 20 times larger than in the MW-only solution. This is expected because of the larger noise in the SLR observations and the better ERP estimation capability using MW-only.

Station coordinates

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

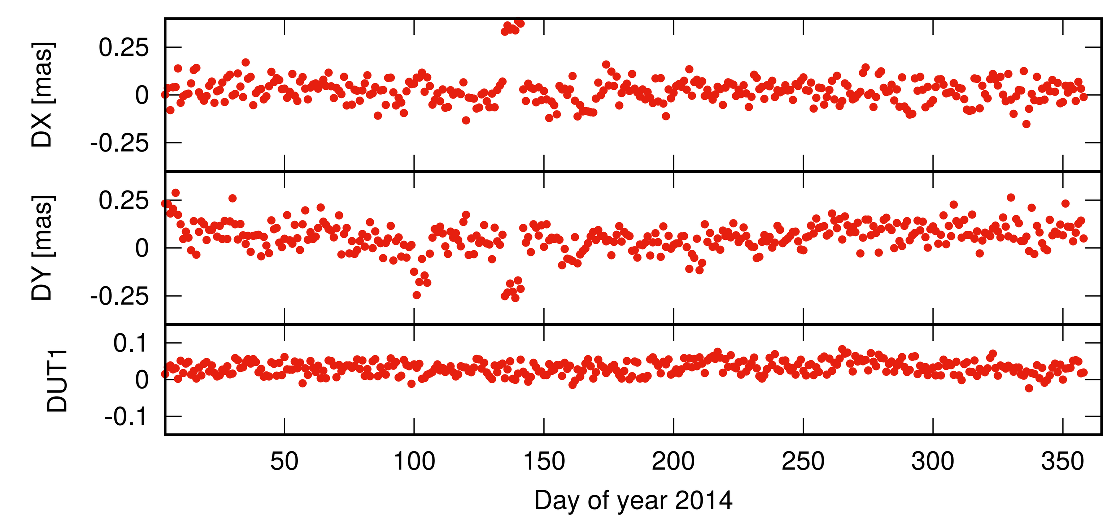

Figure 7: Differences between the MW-only ERPs and the ERPs of the combination with SLR to GLONASS and LAGEOS.

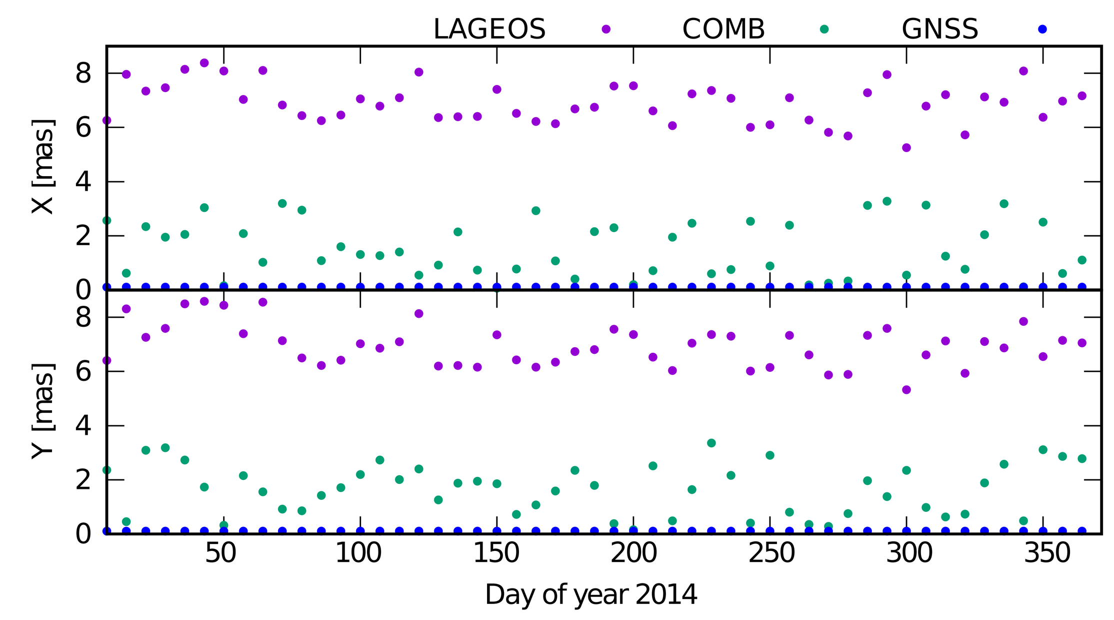

Figure 8: Formal errors of the ERPs from LAGEOS only (LAGEOS), MW-only (GNSS) and the combination with SLR to GLONASS and LAGEOS (COMB).

Summary and Conclusions

- 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 scale information can be transferred from SLR into the MW solution using space ties. A relative weight of $\omega \approx$ 2,000 should be chosen which is in the order of magnitude of the ratio of available observations (about 1:2,500) but not related to the observation noise.
- At this weighting the GCC match the solution derived from SLR observations to LAGEOS on the level of 2 mm and the ERPs remain ± 0.025 mas within the solution obtained from the MW observations.
- 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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