BKG's Contribution to the ILRS Pilot Project on Systematic Errors

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1. Introduction

In the context of the ILRS Pilot Project (PP) on Systematic Errors, BKG, as one of the ILRS Analysis Centers, contributed a solution. As opposed to ILRS pos+eop standard procedure pursued so far for the operational Terrestrial Reference Frame (TRF) products, this pilot project only incorporates LAGEOS-1/-2 data, and range biases were to be estimated separately for LAGEOS-1 as well as -2 for each station involved. We extended the time span of the Pilot Project and generated these special type solutions for 17 years. This presentation aims at investigating the effect of the additional range biases estimated on the TRF parameters.

2. Solution Setup

In order to assess the effect of the additional RB estimated two solutions have been computed, one called "PP" following the provisions of the PP, and another one named "STAND" meeting standard ILRS parameterization. Both solutions cover the time span 2000.0-2017.5 in order to gain reliable results with a long-term perspective. The main characteristics of both solutions are listed in Table 1.

Table 1 Main characteristics of the processings carried out (differences w.r.t. ILRS pos+eop standards are typeset italic; "ERP": Earth Rotation Parameters, "RB": Range Biases).

Parameter Group	Setup PP	Setup STAND
Satellites	*LAGEOS-1, LAGEOS-2*	*LAGEOS-1, LAGEOS-2*
Arc length	7 days	7 days
Station positions	Global XYZ per arc	Global XYZ per arc
ERP	Daily	Daily
RB	*Separately for LAGEOS-1, LAGEOS-2* *Per station* Per arc	Combined for LAGEOS-1, LAGEOS-2 For pre-defined list of non-core stations only Per arc
Time span	2000.0-2017.5	2000.0-2017.5
Datum definition	Loose constraints (1 m on station positions in X, Y, Z)	Loose constraints (1 m on station positions in X, Y, Z)

The only difference of the "STAND" solution w.r.t. to ILRS pos+eop standards is that SLR data of only LAGEOS-1 and -2 are processed, whereas Etalon-1 and -2 data were excluded. As opposed to the "STAND" characteristics, within the "PP" procedure the RB are set up separately for LAGEOS-1 and -2 for each station. In this, it is expected to absorb remaining systematic errors inherent in the normal point (NP) data into these parameters. Comparing the results of these two solutions will reveal the effect of the additional RB estimated. Concerning station positions it has to be noted that the parameters actually estimated are corrections to the a priori coordinates. The datum is defined by constraining the estimated position corrections to their a priori values at a sigma of 1 m, thus resulting

in a loose constraints solution. The a priori reference frame chosen for all solutions is SLRF2014 respectively ITRF2014 including the Post-Seismic Deformation (PSD) model.

3. Results

In the following time series are presented for station positions, RB, Earth Rotation Parameters (ERP), and the scale. Station position as well as RB parameters are shown only for a subset of the ILRS list of core stations (7090-Yarragadee, 7110-Monument Peak, 7501-Hartebeesthoek, 7810-Zimmerwald, 7840-Herstmonceaux, 7941-Matera, 8834-Wettzell).

- 3.1 Station positions

First of all, it is interesting to see how the additional RB influence the station positions. For better interpretation the estimated corrections to the position coordinates are transformed to respective values dU, dN, and dE in Up, North, and East. In Fig. 1 these transformed position corrections are displayed for both the PP as well as the STAND solution.

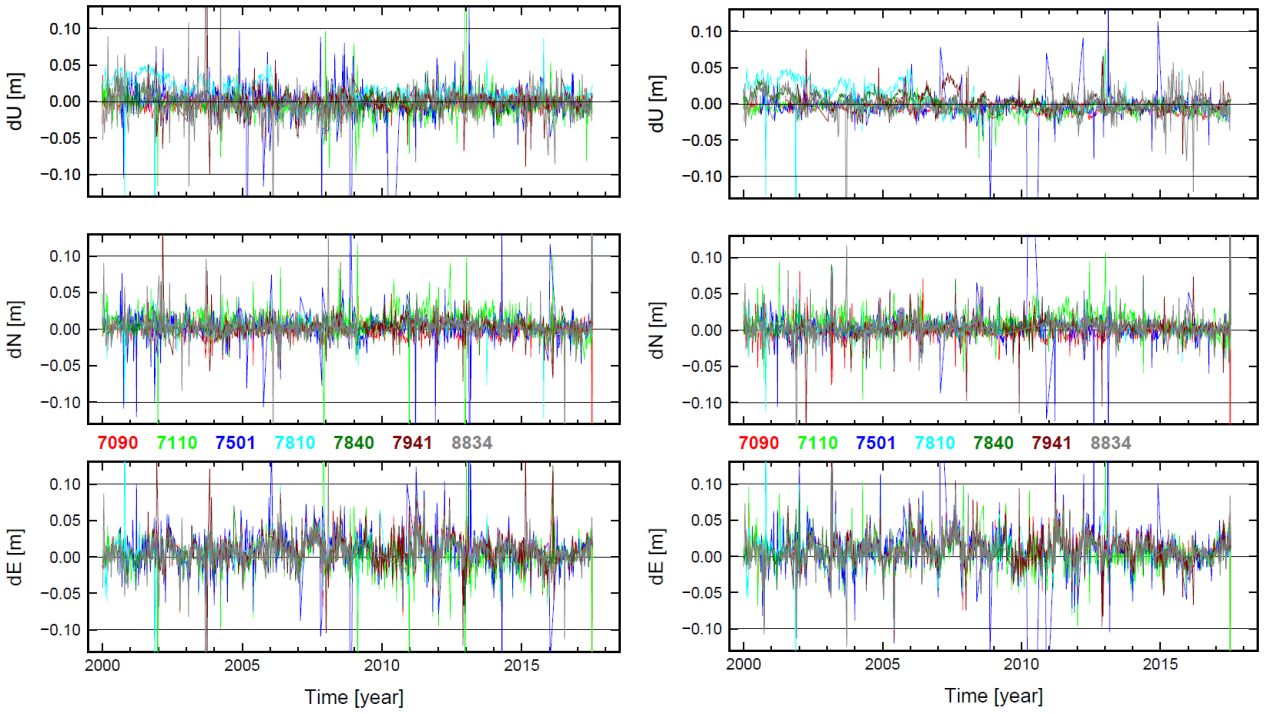


Fig. 1 Time series of estimated corrections to station positions transformed to local horizontal UNE-frames for selected stations (left: PP solution, right: STAND solution).

It is well revealed that none of the three components exhibits a significant mean or trend meaning that the additional RB do not contradict the a priori TRF. While the scatter of the time series in dN and dE is roughly the same between both solutions it is obvious that the scatter of the series in dU is higher in the PP than in the STAND solution. This behavior is expected as the RB parameters are correlated with the station height component. However, for the PP case the scatter in dU is just on the same level as in dN and dE what is certainly reasonable. Moreover, it should be noted that a strange pseudo-

systematic structure present between 2007-2008 in dU of 7941 is no more present in the PP solution, indicating possible problems for that station.

- 3.2 Range biases

Before proceeding to the other TRF parameters it is important to have a look at the RB themselves. For LAGEOS-1 and -2, for the same subset of stations, the RB estimated within the PP solution are displayed in Fig. 2. On the one hand, in case of either LAGEOS-1 as well as -2 the time series do neither exhibit a significant mean nor a trend, and they are on the same noise level. Naturally, the correlations of the time series between LAGEOS-1 and -2 are quite high (7090: 0.78, 7110:0.47, 7501:0.71, 7810:0.86, 7840: 0.78, 7941: 0.73, 8834: 0.88) indicating that the calibration of the SLR systems is stable when tracking any satellites that are comparable. Currently, there is no explanation for the smaller value for station 7110.

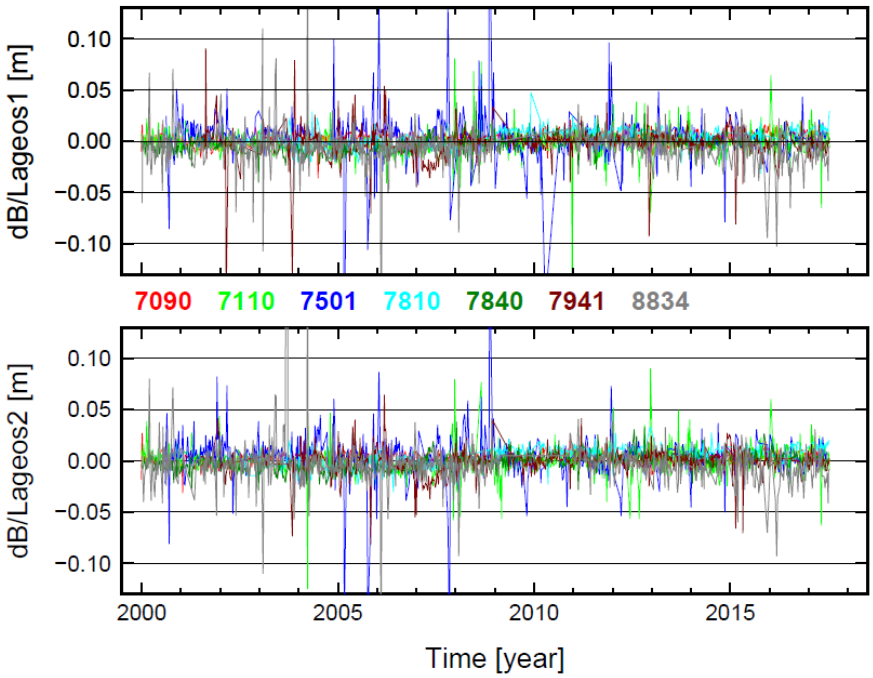
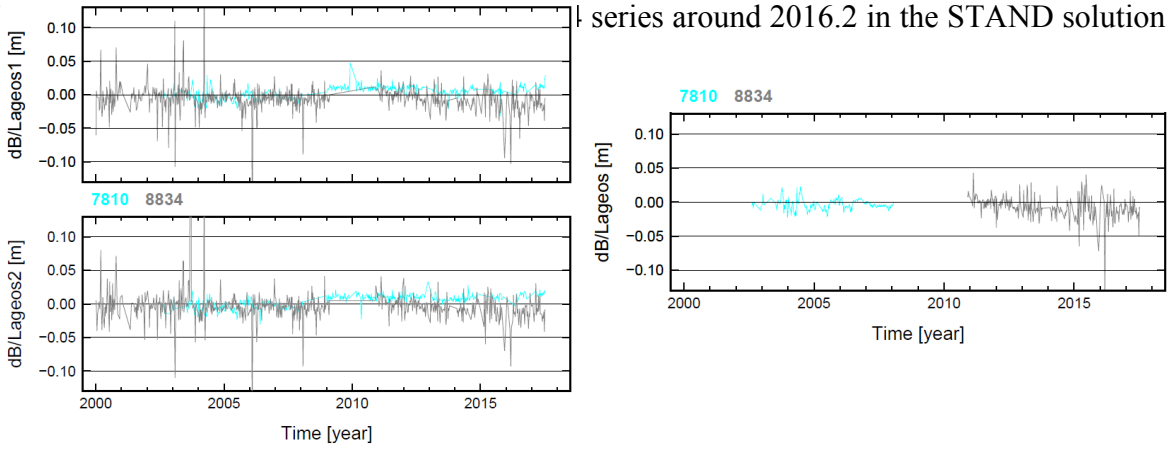


Fig. 2 Time series of RB estimated within the PP solution for selected stations.

A direct comparison of the RB estimated within each solution is only possible for the intersection between the set of stations chosen for the PP solution (see above) and the set of stations where a RB is estimated for in the STAND solution. This intersection contains the two stations 7810 (Zimmerwald) as well as 8834 (Wettzell) whose RB time series are displayed in Fig. 3. It has to be noted that in case of the STAND solution the RB are only set up for the limited time intervals specified by the ILRS official list whereas they are estimated within the PP solution whenever the corresponding station is involved. For the overlapping periods (7810: 2003-2008, 8834: 2011-2017) the time series of both solutions are quite similar indicating that both solutions do not produce significantly different estimates for such high-quality stations. On the other hand, the PP solution seems to have some



series around 2016.2 in the STAND solution is largely

Fig. 3 Time series of RB estimated for stations 7810 (Zimmerwald) and 8834 (Wettzell) (left: PP solution, right: STAND solution)

- 3.3 Earth Rotation Parameters

Though it is not expected that the RB having an impact on the ERP it is mandatory to inspect them. The time series of the ERP for the PP processing are given in Fig. 4 as well as the differences between the PP and the STAND solution.

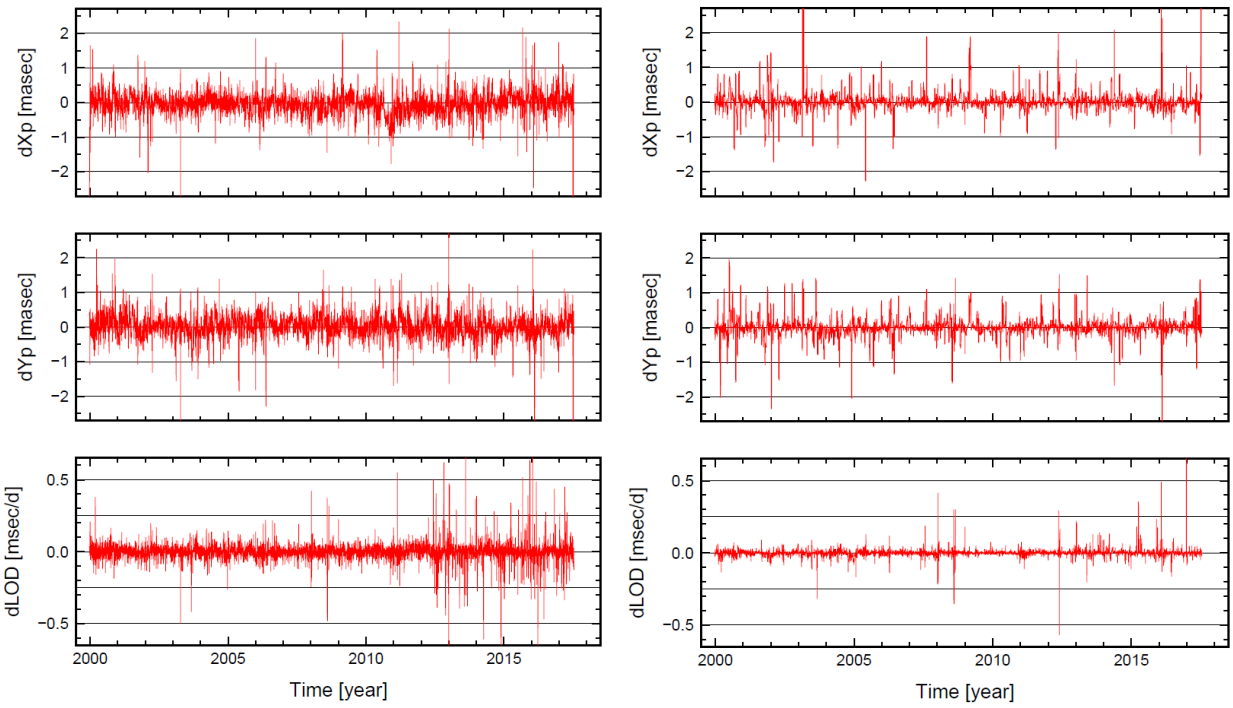


Fig. 4 Time series of ERP estimates from the PP solution (left) and differences between the PP solution and the STAND solution (right)

According to the left hand side graphs, the Polar Motion parameter corrections dXp (RMS: 0.428 mas) as well as dYp (RMS: 0.413 mas) stay mainly between +1 and -1 mas, and the LOD estimate (RMS: 0.0612 ms/d) between +0.15 and -0.15 ms/d what may well be expected from a loose-constraint solution. None of the three time series reveals a significant offset or trend (dXp: -0.045+/-0.426mas, +0.009+/-0.413mas, -0.002+/-0.061ms/d). As the right hand side graphs indicate there is only very small difference in the ERP between both solutions (RMS dXp: 0.362 mas, RMS dYp: 0.351 mas, RMS dLOD: 0.029 ms/d). These results show that the additional RB do not disturb the ERP estimated.

- 3.4 Scale

For each arc processed a seven-parameter Helmert transformation over the core stations is carried out between the estimated and the SLRF2014 station coordinates. In the context of this PP, the most important parameter derived is the scale as a correlation with the RB is natural. For both the PP as well as the STAND solution the resulting time series are shown in Fig. 5.

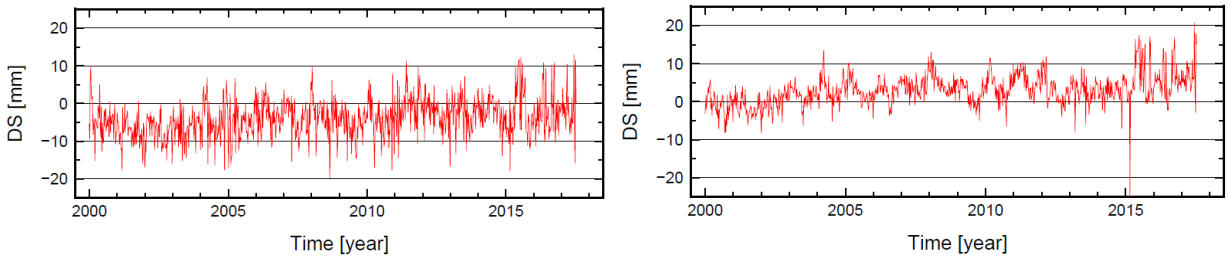


Fig. 5 Time series of differential scale DS from Helmert transformations between estimated station positions and ITRF2014 (rescaled to arc length on Earth surface; left: PP solution, right: STAND solution).

Visual inspection suggests that the scale time series of the PP solution has higher scatter. This is well expected as the additional RB parameters in the PP solution correlate with station height and scale. Concerning the long-term behavior some numerical measures have to be considered since the time series of the STAND solution is inhomogeneous. On the one hand, the trend over the whole time span is +0.30 mm/y for the PP and +0.34 mm/y for the STAND solution. This difference of 0.04 mm/y is quite tiny. On the other hand, dividing the whole time span into yearly subintervals and computing the mean value for each of them (c.f. Table 2) shows another picture. In case of the PP solution, the mean values all stay negative and the difference between the maximum and the minimum is 7.00 mm. By contrast, for the STAND solution the mean values are negative at the beginning and reach high positive values towards the end, and the difference between the maximum and the minimum is 8.45 mm. This shows that the time series of the scale parameter stemming from the PP solution is more stable though the day-by-day scatter is higher.

Table 2 Mean values [mm] of differential scale DS for yearly subintervals. The outlier at 2015.2 in the STAND time series is excluded; the minimum and maximum values are typeset bold.

Time Interval	PP	STAND
2000	-4.66	-1.04
2001	**-7.62**	**-1.43**

2002	-7.46	-0.20
2003	-6.36	+1.57
2004	-4.28	+3.01
2005	-5.52	+2.81
2006	-3.43	+2.75
2007	-3.83	+4.13
2008	-3.60	+4.75
2009	-5.72	+1.99
2010	-4.43	+3.77
2011	**-0.62**	+5.59
2012	-2.85	+2.53
2013	-2.42	+2.80
2014	-2.16	+2.87
2015	-2.44	+6.07
2016	-2.23	+5.56
2017	-1.49	**+7.02**

4. Conclusions

The solution provided by BKG to the ILRS PP on Systematic Errors and its extension, covering the time span of 2000.0-2017.5, was taken as an opportunity to have a detailed look at the impact of the Range Biases additionally estimated by comparison to a solution following standard procedure.

In view of station coordinates the results reveal that there is no significant change in the estimates in North and East direction but that the scatter in Up increases just to the level of North and East components. This effect is quite reasonable as the height component is highly correlated with the range biases additionally estimated in the PP solution.

Concerning the RB there is a high correlation between the estimates for LAGEOS-1 and -2. This underlines that the RB are estimated reliably as it is expected that they should be the same for similar satellites tracked. This is also confirmed by the RB estimated for the two sample stations 7810 (Zimmerwald) and 8834 (Wettzell) which do not show significant overall change between either solution.

The time series of the ERP estimated reveal quite reasonable behavior as expected. Small differences to the corresponding estimates of the standard solution indicate that the additional RB do not disturb these important reference frame parameters.

Finally, the additional RB estimated exert beneficial influence on the scale. The time series of this parameter gains more long-term stability, becoming evident especially within certain time subintervals. On the other hand, the time series' scatter increases just on a level to be expected for a loose-constraints weekly solution. As a consequence, reliable values for the range biases should be determined from a long-term solution (instead of weekly level), and the weekly solutions should use these range biases as given corrections.