Contribution of LARES SLR Data to Co-estimated Earth Geopotential Coefficients

Linda Geisser, Ulrich Meyer, Daniel Arnold, and Adrian Jäggi

Abstract

The Satellite Laser Ranging (SLR) processing at the Astronomical Institute of the University of Bern (AIUB) is currently extended from the geodetic satellites LAGEOS-1/2 and Etalon-1/2 to also include LARES. The orbits are determined in 7-day arcs together with station coordinates, low-degree spherical harmonic (SH) coefficients of the Earth's gravity field, Earth Rotation Parameters (ERP), geocenter variations and range biases for selected stations. Due to the lower orbital altitude, LARES experiences a more variable environment such that the orbit parametrization has to be adapted. In this paper, we present SLR solutions for 5 years with different orbit parametrizations for LARES, i.e., LARES 7-day arcs are either determined from one set of orbit parameters and stochastic pulses at fixed time-intervals, or by stacking of seven daily arcs with continuity conditions at the day boundaries, so-called long-arcs. Including LARES does slightly improve the ERP and does not degrade the quality of the estimated SH coefficients and station coordinates. Additionally, it allows co-estimating the SH coefficient C_{30} and further low-degree SH coefficients.

Keywords

Earth rotation parameters · Gravity field coefficients · LAGEOS · LARES · Long-arc computation · SLR

1 Introduction

The Astronomical Institute of the University of Bern (AIUB) is an associated analysis center of the International Laser Ranging Service (ILRS, Pearlman et al. 2019) and collaborates with the analysis center at the Federal Agency for Cartography and Geodesy (BKG) in Germany to generate products for the ILRS from measurements to the geodetic SLR satellites (Pearlman et al. 2019) in the frame of the analysis center activities at BKG. The existing SLR processing at AIUB is based on the geodetic, i.e., spherical SLR satellites LAGEOS-1/2 and Etalon-1/2. According to the ILRS the orbits of these SLR satellites are determined in 7-day arcs. Additionally, station coordinates, low-degree spherical harmonic (SH) coefficients of the Earth's gravity field, Earth Rotation Parameters (ERP), geocenter variations and range biases for selected stations are co-estimated. Initially, it was planned that the ILRS contribution to ITRF2020 (Altamimi et al. 2018) should be based on LAGEOS-1/2, Etalon-1/2 and additionally on LARES (LAser RElativity Satellite). This motivated to extend the SLR processing at AIUB to also include LARES. With a mean semi-major axis of only 7820 km LARES is a low Earth orbiting (LEO) satellite and therefore experiences a more variable orbit environment, i.e., Earth's time-variable gravity field and upper atmosphere density variations, which has to be taken into account in the orbit parametrization. But the higher sensitivity on the SH coefficients of the Earth's gravity field from LARES also allows co-estimating SH coefficients up to degree 6 (e.g., Bloßfeld et al. 2018; Bloßfeld et al. 2019). Even if nowadays the determination of the Earth's time-variable gravity field is

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mostly based on dedicated gravimetry satellite missions, i.e., the Gravity Recovery And Climate Experiment (GRACE) (Tapley 2004) and GRACE Follow-on (Landerer et al. 2020), the geodetic technique of SLR is best suited to determine some low-degree gravity field coefficients, especially the zonal SH coefficients C_{20} and C_{30} (e.g., Bianco et al. 1998, Maier et al. 2012, Loomis et al. 2020). In this paper, we study the optimal orbit parametrization for LARES by either using 7-day true-arcs, or by so-called long-arcs (Beutler et al. 1996), which are created by stacking daily normal equations with continuity conditions for the orbit parameters at the day boundaries. The long-arc computation is already regularly and successfully used in the GNSS processing (Lutz et al. 2016) at the Center for Orbit Determination in Europe (CODE, Dach et al. 2009). The quality of the combined SLR solution is validated by comparing all parameters with internal and external quality metrics.

2 SLR Processing at AIUB

The SLR data provided by the ILRS used for this study are processed with the Bernese GNSS Software (BSW, Dach et al. 2015). In a first step each satellite group (i.e. A: LAGEOS-1/2, B: Etalon-1/2, C: LARES), is individually analyzed using the same background models (see Table 1). In addition, the corresponding Normal Equation Systems (NEQs) are set up. The satellite orbits are generally characterized in the BSW by six osculating orbital elements referring to the beginning of the arc and up to nine dynamical parameters (Beutler et al. 1994). Section 2.1 describes the different orbit modeling approaches for the satellite groups. Finally, the satellite-group-specific NEQs are combined for generating the multi-satellite solution (Sect. 2.2). The satellite orbits are determined together with station coordinates, range biases for selected stations as recommended by the ILRS, and the global geodetic parameters of interest, i.e., ERP, geocenter variations and SH coefficients of the Earth's gravity field.

2.1 Orbit Modeling

For LAGEOS and Etalon 7-day "true"-arcs are generated, which are represented by the six initial osculating orbital elements and three dynamical orbit parameters, i.e., a constant acceleration S_0 and once-per-revolution (OPR) sine and cosine accelerations (S_S resp. S_C) in along-track as a function of the satellites' argument of latitude. OPR accelerations in cross-track (W) are avoided, because of the strong correlation between the OPR sine acceleration in W and the zonal SH coefficient C_{20}, e.g., Jäggi et al. (2012) and Bloßfeld et al. (2014). Due to the more variable orbit environment at the low altitude of LARES, a more sophisticated orbit parametrization is needed than for the higher orbiting LAGEOS and Etalon satellites. Air drag is modeled using the model NRLMSISE-00 (Picone et al. 2002).

In this study, two different approaches are investigated. On the one hand, the orbit of LARES is parametrized in analogy to the orbit parametrization used for LAGEOS. On the other hand, daily LARES arcs are generated in a first step according to the orbit parametrization of LAGEOS. This means that daily normal equations with one set of osculating and dynamical orbit parameters are set up. Then the long-arc computation allows combining the daily arcs into a 7-day arc by transforming the initial osculating elements of the daily NEQs into one set of osculating elements referring to the beginning of the 7-day arc (Beutler et al. 1996). The dynamic orbit parameters may be kept in the NEQ as daily parameters or, alternatively, be stacked to one parameter for the entire arc. The former strategy provides more flexibility to account for modeling deficiencies. The long-arc computation realizes a continuous arc over several days by stacking daily arcs with continuity conditions at the day boundaries.

Additionally, daily pseudo-stochastic pulses in along-track (S) can partially absorb possible air drag mismodeling. Table 1 lists the background models used for the SLR data processing. All SLR solutions are based on the static Earth gravity field GGM05S (Ries et al. 2018).

In addition to the above mentioned orbit parameters also the geodetic and instrument parameters listed in Table 2 are

Table 1 A priori background models for SLR data processing

Models	Description
Reference frame	SLRF2014[1]
ERP	IERS-14-C04[2]
Nutation model	IAU2000 (Mathews et al. 2002)
Subdaily pole model	DESAI: IERS conventions 2010 (Petit and Luzum 2010)
Ocean tide model	FES2014b: d/o 30 (Lyard et al. 2021) + admittances
Earth Tides	Solid earth tides, Pole tides and Ocean pole tides: IERS 2010 (Petit and Luzum 2010)
Loading corrections	Ocean tidal loading: FES2014
	Atmospheric tidal loading: Ray and Ponte (Ray and Ponte 2003)
De-aliasing products	Atmosphere + Ocean RL06: d/o 30 incl. S1- and S2-atmosphere tides (Dobslaw et al. 2017)
Earth gravity field	GGM05S: d/o 90 (Ries et al. 2018)

[1] https://cddis.nasa.gov/archive/slr/products/resource/SLRF2014_POS+VEL_2030.0_200325.snx.

[2] https://hpiers.obspm.fr/eoppc/eop/eopc04/.

Table 2 Estimated parameters

Parameters	LAGEOS/Etalon	LARES
Osculating elements	1 set per 7 days	
Dynamical parameters	1 set per 7 days	1 set per 7 days (7d true-arc)
		1 set per day (7d long-arc)
Stochastic pulses	None	None
		Twice per day: along-track (S) cross-track (W)
Station coordinates	1 set per 7 days	
	NNR/NNT minimal constraint	
Geocenter coordinates	1 set per 7 days	
Range biases	1 set per 7 days	
	Selected stations	All stations
ERP	Daily	
	Piecewise linear	
SH coefficients	1 set per 7 days	
	Up to degree and order (d/o) 4	

simultaneously estimated. In the special case of the long-arc computation for LARES, daily station coordinates, geocenter coordinates, range biases and SH coefficients are combined into a weekly solution. Hence, these solutions cover all 'three pillars' of geodesy, i.e., geokinematics, Earth rotation and the Earth's gravity field (Rummel et al. 2005), and ensure a highest possible level of consistency. The datum is defined by the no-net-rotation (NNR) and no-net-translation (NNT) minimum constraint conditions for the verified ILRS core stations,[3] which have more than 30 observations available per week. A station contributes to the weekly solution if it provides more than 9 normal points to both LAGEOS satellites or more than 2 normal points to LARES. Etalon observations are only included if the station also observed one of the LAGEOS satellites during the week. The ERP are estimated based on a daily piecewise linear model, where the 4th offset of UT1-UTC is fixed to the a priori series and the length of day is constrained with 2 ms/day. The pole coordinates are constrained with 30 mas, which corresponds to the 1 m constraint recommended by the ILRS. Since the geocenter is estimated as a geometric offset, only the SH coefficients from d/o 2 up to d/o 4 are co-estimated.

2.2 Combination

In the SLR solution, the combination of different satellites reduces the correlation between orbit parameters, geodetic parameters, and SH coefficients (e.g. Sośnica et al. 2014; Bloßfeld et al. 2019). The lower altitude and therefore the higher sensitivity of LARES on the Earth's gravity field also allows it to co-estimate SH coefficients up to degree 4.

The NEQs are set up satellite-specific and contain all relevant parameters. These NEQs are then combined, where common parameters are stacked. The Etalon data are rescaled with a variance factor of 3^{-2}, which corresponds to the standard value within the ILRS Analysis Standing Committee. The variance factor of LARES data is currently set to 1.5^{-2} and was determined empirically by checking the quality of the geodetic parameters.

3 Validation of the SLR Solutions

The quality of the generated SLR solutions are validated by comparing the estimated geodetic parameters, i.e.,

- Gravity field coefficients with the external model CSR_Monthly_5x5_Gravity_Harmonics[4] (Cheng et al. 2011) labelled as CSR, which is comparable with the Technical Note 14 (Loomis et al. 2020),
- ERP with IERS-14-C04[2] (Bizouard et al. 2019) at 12-h epochs,
- Station coordinates through the RMS of the Helmert transformations w.r.t. SLRF2014.

Figure 1 (top) shows the time series of weekly co-estimated SH coefficients C_{20} for five years covering 2015–2019. The LAGEOS-only solution, where only C_{20} is co-estimated, is capable to estimate a reliable C_{20}. This is expected, Sosnica (2014) already pointed out the high sensitivity of combined LAGEOS solutions to C_{20}. If LARES is included the gravity field parameters have to be co-estimated up to d/o 4, to properly account for the additional sensitivity gained from the significantly lower LARES orbit. Both for including LARES as 7d true-arc or as a 7d-arc based on the long-arc computation, the time series of C_{20} is very similar to the LAGEOS-only solution. All solutions show a semi-annual and annual signal (Fig. 1, bottom). Nevertheless, all solutions have a small offset $1.1 \cdot 10^{-10}$ (resp. $0.85 \cdot 10^{-10}$ with LARES) with respect to the reference series of CSR (see Table 3). The variability of the gravity field coefficients is described by the RMS of the weekly SLR solutions w.r.t. the corresponding 4-weeks solutions, which are generated by stacking 4 weekly multi-satellite SLR solutions with pre-eliminating all parameters besides the gravity field coefficients. The lower LARES orbit altitude and consequently higher sensitivity to the Earth's gravity field, together with the orbit inclination different to the LAGEOS satellites, allow it to estimate C_{30}. Due to the strong correlation between the OPR accelerations in along-track and C_{30} (Bloßfeld et al. 2018), a meaningful

[3] https://ilrs.dgfi.tum.de/fileadmin/data_handling/.

[4] https://download.csr.utexas.edu/pub/slr/degree_5/.

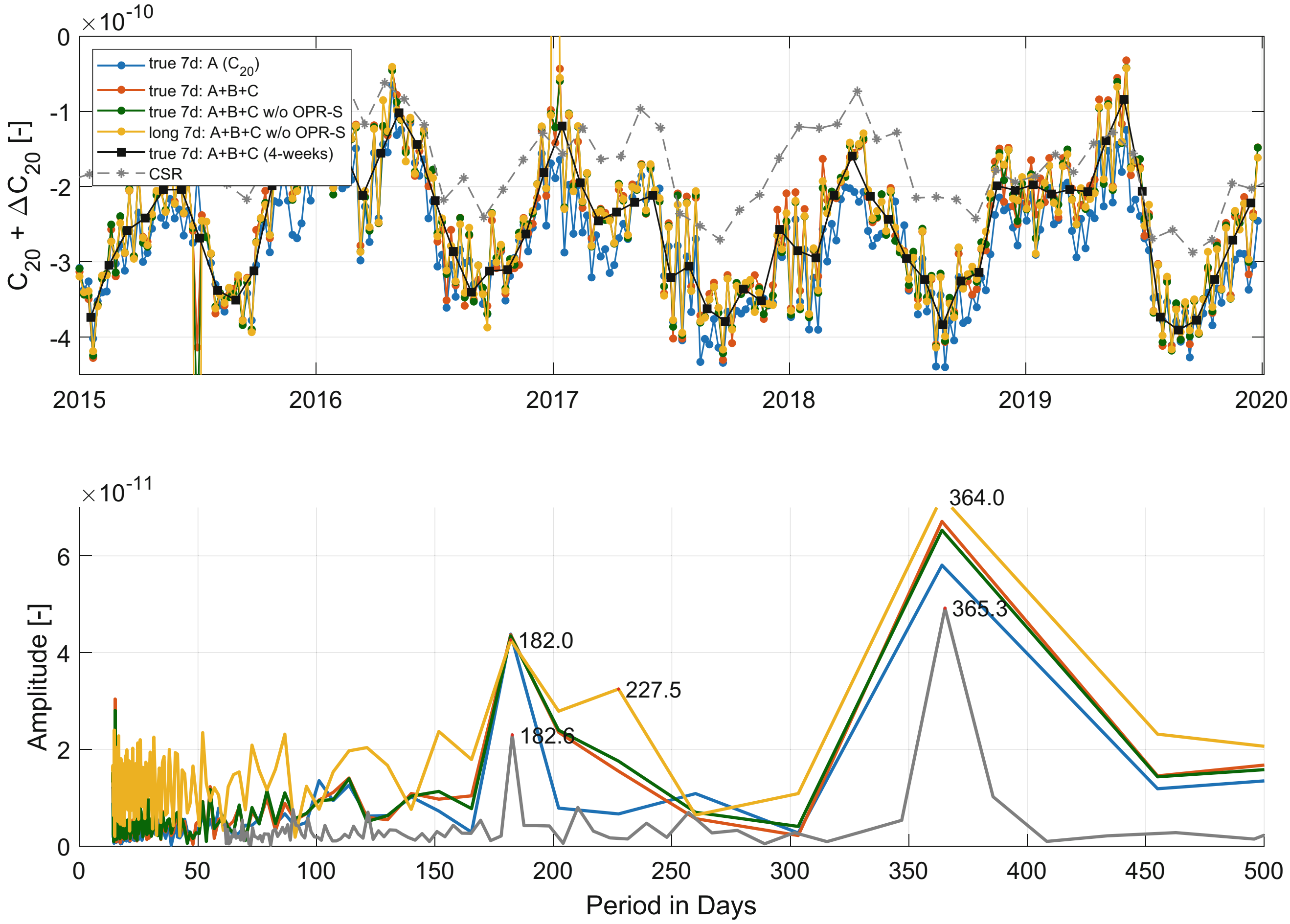


Fig. 1 Time series of weekly resp. monthly co-estimated gravity field coefficients C_{20} (with $\Delta C_{20} = 0.48416945732 \cdot 10^{-3}$) (*top*) and the spectral analysis (*bottom*) for different SLR solutions

estimation of C_{30} is only possible if the OPR accelerations in along-track are not set up (Fig. 2). The C_{30} series shows again an offset with respect to the reference series of CSR. In addition the annual and semi-annual signals are noticeably larger than for the reference series. The RMS of C_{30} can be slightly reduced by estimating additional stochastic pulses in along-track and cross-track.

The comparison of the estimated ERP, i.e., polar motion (x-pole and y-pole) and UT1-UTC shows that including LARES as a 7d true-arc without estimating stochastic pulses increases the WRMS of the polar motion by 24% in x-direction resp. 19% in y-direction (see Table 4). However, if the orbit parametrization of LARES is extended with additional parameters, i.e., twice per day stochastic pulses in cross-track and along-track, the WRMS and the mean biases can again be significantly reduced.

The quality of the station coordinates is validated by comparing the RMS of the Helmert transformation w.r.t. SLRF2014 (see Fig. 3). Only stations that were used for the datum definition were considered in this analysis. Including

Table 3 Offset to CSR solution and RMS of Earth's gravity field coefficients C_{20} and C_{30} w.r.t. 4-weeks gravity field solutions

Solutions			C_{20}		C_{30}	
			Offset $[10^{-10}]$	RMS $[10^{-11}]$	Offset $[10^{-10}]$	RMS $[10^{-11}]$
7d true-arc	(blue)	A	1.10	3.26	–	-
	(orange)	A+B+C	0.82	4.27	−2.02	96.41
	(green)	A+B+C: a	0.82	4.11	−1.06	4.15
	(turquoise)	A+B+C: $a+b$	0.82	4.04	−1.06	3.91
7d long-arc		A+B+C	0.81	4.04	−0.31	41.97
	(yellow)	A+B+C: a	0.81	4.20	−1.03	4.04
	(purple)	A+B+C: $a+b$	0.85	4.59	−1.06	3.86

A: LAGEOS-1/2
B: Etalon-1/2
C: LARES
a: w/o OPR-S for C
b: w/ stoch. pl. in S and W for C

LARES with OPR accelerations in along-track increases the RMS by around 18% in North, 26% in East and 4% in Up compared with the LAGEOS-only solution. If for

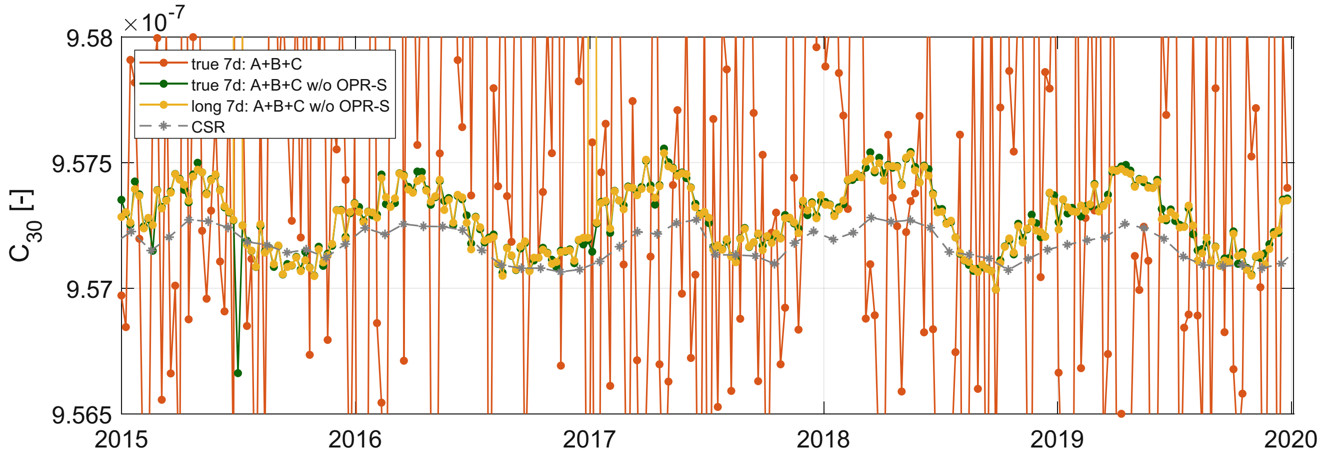


Fig. 2 Time series of weekly co-estimated gravity field coefficients C_{30} for different SLR solutions

Table 4 Comparison of ERP for different SLR solutions

Solutions		Mean bias			WRMS		
		x-pole [µas]	y-pole [µas]	UT1-UTC [µs]	x-pole [µas]	y-pole [µas]	UT1-UTC [µs]
7d true-arc	A	89.2	24.8	−0.6	161.1	135.1	23.1
	A+B+C	70.2	9.6	1.1	199.7	161.3	25.9
	A+B+C: a	70.5	12.7	0.3	209.4	167.5	25.0
	A+B+C: $a + b$	55.9	20.5	0.6	136.3	125.1	23.1
7d long-arc	A+B+C	69.1	18.8	1.6	189.5	161.4	24.2
	A+B+C: a	70.7	13.8	1.1	202.6	164.6	23.5
	A+B+C: $a + b$	56.3	18.6	0.1	144.3	132.1	23.5

A: LAGEOS-1/2
B: Etalon-1/2
C: LARES
a: w/o OPR-S for C
b: w/ stoch. pl. in S and W for C

both orbit parametrizations, i.e., 7d true-arc and 7d long-arc of LARES, stochastic pulses in along-track and cross-track are set up, the RMS of the Helmert transformation can be reduced. In the case of the 7d true-arc, it is even possible to get smaller RMS than for the LAGEOS-only solution.

The geocenter coordinates are very similar for all the discussed solutions and therefore they are not shown in this paper.

4 Conclusions

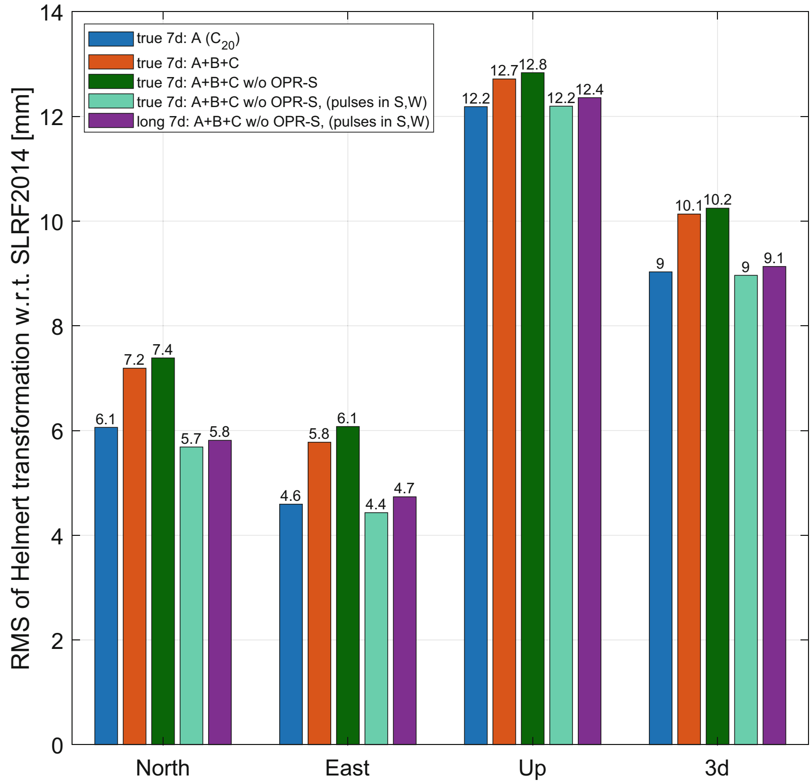
We extended our SLR processing based on LAGEOS-1/2 and Etalon-1/2 to also use normal points from the LEO satellite LARES. Due to its lower altitude, the orbit environment is more variable and the orbit modeling becomes more challenging. Therefore, we investigated two different orbit modeling approaches for LARES:

- 7d true-arc: one set of initial osculating orbital elements and one set of dynamical orbit parameters estimated for 7 days,
- 7d long-arc: one set of initial osculating orbital elements and daily dynamical orbit parameters estimated for 7 days.

The results showed that including LARES does not degrade the already well defined SH coefficient of Earth's gravity field C_{20} w.r.t. the LAGEOS-only solution. In addition it allows to precisely estimating C_{30}, if the OPR accelerations in along-track are not set up for LARES. Nevertheless, the larger amplitude of C_{30} requires further investigations.

The analysis of the ERP showed that including LARES without any additional stochastic pulses in along-track and cross-track, the WRMS of the polar motion increases significantly compared with the LAGEOS-only solution. In addtion, the comparsion of the RMS of the Helmert transformation w.r.t. SLRF2014 results in the same conclusion that additional stochastic pulses improve the quality of the station coordinates. This indicates that orbit modeling defi-

Fig. 3 RMS of the Helmert transformation w.r.t. SLRF2014 in North, East, Up and in 3D for different SLR solutions



ciencies for LARES can be reduced by setting up stochastic pulses in along-track and cross-track, without harming C_{20}.

Furthermore, the comparison of the ERP and the RMS of the Helmert transformation shows that the 7d true-arc is slightly better than the 7d long-arc for LARES, if the orbit parametrization of LARES is added with stochastic pulses. This research can now be used at AIUB as a basis for generating a multi-satellite SLR solution with, e.g., Starlette and Stella, where due to the low altitudes we expect to use the long-arc computation. As for example Bloßfeld et al. (2018) demonstrated, with a multi-satellite solution, we should be able to also co-estimate higher degrees of the gravity field than C_{30}. Since in combined solutions the relative weighting is very important, further studies, e.g. variance component estimation, to find the optimal variance factors to increase the quality of the SLR solution should be performed.

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