

The role of Satellite Laser Ranging in terrestrial gravity field recovery

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Abstract

Satellite Laser Ranging (SLR) is a powerful technique for the estimation of the very long wavelengths of the Earth's gravity field. The most important parameter in this context is J_2. It represents the Earth's dynamic flattening, which is responsible for the largest deviation of the real (geometrical and physical) figure of the Earth from its spherical approximation. Despite of having available data from a number of recent dedicated gravity field missions, SLR is still superior for the determination of J_2. In addition, SLR is able to contribute to the estimation of further long-wavelength gravity field constituents. Therefore, (satellite-only) gravity field combination models usually comprise SLR data. One example is the latest release of the GOCO series: the GOCO03S model; for its compilation the Space Research Institute of the Austrian Academy of Sciences analysed ranging measurements to five geodetic satellites over a period of five years. In the meantime, we extended the analysis period to nearly 14 years. Furthermore, we refined parameterization and included observations to a sixth satellite. In this contribution we present the updated data processing strategies and the obtained results. We particularly address time-variability of the degree-2 spherical harmonic coefficients.

Keywords: Satellite Laser Ranging, J_2, gravity field, temporal variations, GOCO

Kurzfassung

Satellite Laser Ranging (SLR) liefert hochgenaue Messungen für die Bestimmung des sehr langwelligen Anteils des Erdschwerefeldes. Der bedeutendste Schwerefeldparameter ist J_2, welcher die dynamische Abplattung der Erde beschreibt. Er ist für die größte Abweichung der Erdfigur von einer Kugel verantwortlich. Trotz der Realisierung mehrerer dezidierter Schwerefeldmissionen kann die Abplattung am genauesten mit SLR bestimmt werden. Zusätzlich liefert SLR Informationen zu weiteren Koeffizienten des langwelligen Anteils. Aus diesen Gründen beinhalten kombinierte Schwerefeldmodelle SLR Daten. Ein Beispiel hierfür ist das letzte Release der GOCO Serie, GOCO03S. Das Institut für Weltraumforschung der Österreichischen Akademie der Wissenschaften hat bei der Erstellung dieses Modells mitgewirkt und SLR Messungen zu fünf geodätischen Satelliten über einen Zeitraum von fünf Jahren analysiert. Seit der Veröffentlichung von GOCO03S haben wir die Zeitreihe auf fast 14 Jahre erweitert und die Anzahl der Satelliten auf sechs erhöht. Im vorliegenden Beitrag wird auf die Prozessierung der Daten eingegangen sowie die Zeitvariabilität der Schwerefeldkoeffizienten vom Grad 2 präsentiert und diskutiert.

Schlüsselwörter: Satellite Laser Ranging, Schwerefeld, zeitliche Variationen, GOCO

1. Introduction

Satellite Laser Ranging (SLR) satellites (often referred to as geodetic satellites) are passive cannonball-like objects, free falling in the Earth's gravity field. They are of spherical shape and fully covered with Laser Retro-Reflectors (LRR, cf. Fig. 1). The sole objective of these satellites is to act as targets for ranging measurements. SLR provides unambiguous two-way time-of-flight observations between ground-based stations and the LRR; they are transferred to two-way distances. In post-processing, this so-called full rate data is compressed to Normal Points (NPs), i.e. time-averaged two-way distances. NPs are precise to about 1–3 mm [1].

Fig. 1: Illustration of the LAGEOS-1 satellite. The surface of the passive satellite is covered by 426 laser retro-reflectors (image credit: NASA).

Quantities derived from SLR data include positions and velocities of crust-bound stations, satellite orbits, and Earth orientation parameters.

	LAGEOS-1	LAGEOS-2	Ajisai	Starlette	Stella	Larets
Sponsor	US	US/Italy	Japan	France	France	Russia
Launch date	1976	1992	1986	1975	1993	2003
Diameter [cm]	60	60	215	24	24	24
Mass [kg]	407	405	685	47	48	23
Inclination [°]	109.8	52.6	50.0	49.8	98.6	98.2
Eccentricity [–]	0.0045	0.0135	0.0010	0.0206	0.0008	0.0002
Altitude [km]	5860	5620	1490	812	800	691

Table 1: Characteristics of geodetic satellites considered in this study.[1)]

Furthermore, SLR plays a crucial role in the computation of International Terrestrial Reference Frames (ITRFs) as it contributes to the origin and scale of the datum definition [2, 3]; to date, SLR is the best single technique to estimate geocenter motion, i.e. the translational shift between the Earth's center of mass and the Earth's center of figure (or center of network) [4, 5]. As far as the Earth's gravity field is concerned, the contribution of SLR is twofold. First, the technique has been proven to be a highly valuable source of information for the determination of static long-wavelength gravity field features. As a consequence, nowadays (satellite-only) combination solutions typically contain SLR; examples include GO_CONS_GCF_2_DIR_R4 [6], EIGEN-6S [7] and GOCO03S [8]. Secondly, SLR is powerful to detect temporal changes in gravity caused by very large-scale mass variations on and near to the Earth's surface [9, 10]. This holds particularly true for the C_{20} spherical harmonic gravity field coefficient (or J_2, recalling the relation $J_2 = -C_{20}$). For this reason, the C_{20} terms of time-variable gravity fields derived from dedicated space missions – such as GRACE (Gravity Recovery and Climate Experiment) – are routinely replaced (or augmented) by values derived from SLR [11, 12].

This contribution summarizes the strategy and results of the Space Research Institute in SLR-based gravity field research, with particular emphasis on C_{20} and the further degree-2 gravity field coefficients. It is an extension to the work by [13] with regard to refinements in parameterization, analysis period prolongation, and the inclusion of a sixth satellite.

2. Data

The International Laser Ranging Service (ILRS) provides SLR data acquired by a global network of tracking stations [14]. We analysed observations – on the level of NPs – to six geodetic satellites: LAGEOS-1, LAGEOS-2, Ajisai, Stella, Starlette, and Larets; their main characteristics are summarized in Table 1. The analysis period covers January 2000 to October 2013, i.e. almost 14 years. Our intention is to continuously prolong the analysis period beyond October 2013 as the reliability of long-term trends, for instance, increases with increasing length of the time series.

One of the main challenges (and limiting factors) in SLR data processing is the spatially and temporally inhomogeneous acquisition of ranging information. As exemplarily shown for January 2007 in Fig. 2, the number of observations per tracking station varies considerably. Observatories located in climatically favoured regions – such as Yarragadee, Australia – typically collect more observations than stations with restricted satellite visibility (see also http://ilrs.gsfc.nasa.gov/). It becomes obvious from Fig. 2 that the satellites are given different priority; in January 2007, Ajisai has been tracked most often, followed by LAGEOS-1/2 and Starlette.

Fig. 3 shows the spatial distribution of the NPs in January 2007. The figure illustrates the importance of highly inclined satellites orbiting at high altitude – such as LAGEOS-1 – for expanding the data coverage to the polar regions where no tracking facilities exist. Furthermore, it should be emphasized that due to the spatially inhomogeneous distribution of SLR stations, the spatial coverage on the southern hemisphere is considerably poorer compared to that one on the northern hemisphere.

During January 2000 to October 2013 – the time span investigated in this study – in total about 6.4 million NPs are available for the six considered satellites. The distribution on the individual satellites is as follows: Ajisai 34 %, Starlette 19 %, LAGEOS-1 17 %, LAGEOS-2 16 %, Stella 9 %, Larets 5 %.

1) All information retrieved from the ILRS website (ilrs.gsfc.nasa.gov, last access: Mar 19, 2014) except for the diameter of Larets retrieved from http://cddis.nasa.gov/lw14/docs/presnts/tar3a_vbp.pdf.

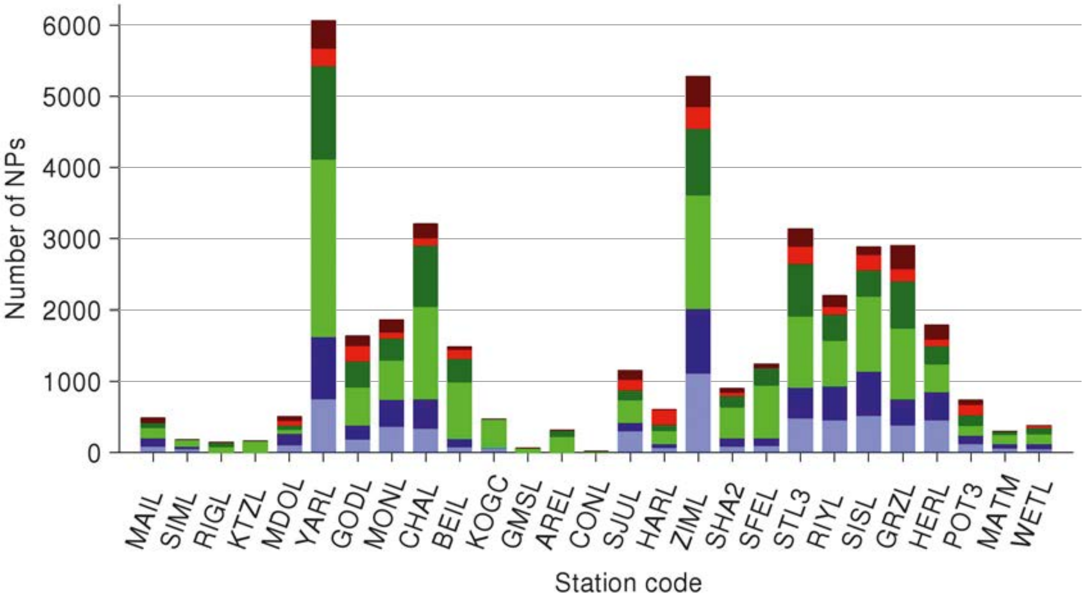

Fig. 2: *SLR data acquisition (NPs) per laser station in January 2007. LAGEOS-1: light blue, LAGEOS-2: dark blue, Ajisai: light green, Starlette: dark green, Stella: light red, Larets: dark red.*

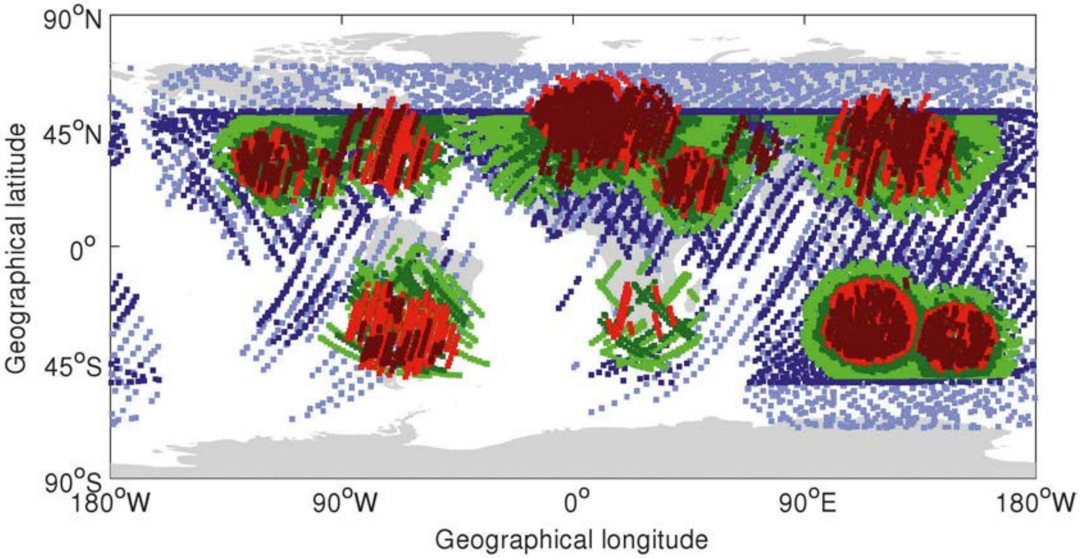

Fig 3: *Spatial distribution of NPs per satellite in January 2007 (the colour scheme is the same as in Fig. 2)*

3. Precise orbit determination

Dynamic Precise Orbit Determination (POD) is a prerequisite for the recovery of gravity field parameters from SLR measurements. It is based on the solution of Newton's equation of motion in the inertial space. In a least-squares sense, the sum of squared residuals between observed and computed (i.e. forward-evaluated) ranges is iteratively minimized. Typically, the total investigation period is subdivided into shorter time spans (called arcs) to minimize possible degradation of the determined orbit due to imperfect force modelling. For each arc, arc-specific parameters such as the initial state vector are iteratively determined. In a second step, the global parameters (i.e. gravity field coefficients, station positions) are estimated by reducing the overall normal equations system (comprising both arc-specific and global parameters) by the arc parameters; correlations between global parameters and arc

Reference system/frame	
Inertial reference frame	J 2000.0
Earth rotation parameters	IERS 08 C04 [21]
Polar motion	IERS conventions 2003 [22]
Precession and nutation	IERS conventions 2003
Solid Earth tides	IERS conventions 2003
Ocean loading	IERS conventions 2003, GOT4.8 [20]
Solid Earth pole tide	IERS conventions 2003
A priori station coordinates	SLRF2008 [23]
Gravity	
A priori gravity field model	EIGEN-5S up to degree and order 150 [24]
Solid Earth tides	IERS conventions 2003
Solid Earth pole tide	IERS conventions 2003
Ocean tides	GOT4.8 up to degree and order 20
Third bodies	DE-403: all planets, Sun, and Earth's Moon [25]
Relativistic corrections	Applied (light time corrections, point mass accelerations, Coriolis force, Lense-Thirring effect)
Surfaces forces	
Atmospheric density model	MSIS-86 [26]
Earth radiation pressure (albedo)	Applied
Data editing criteria	
Rejection level of NPs	3.5 sigma
Elevation cut-off angle	12°
Minimum number of NPs per station and month	30
Measurement corrections	
Center of mass corrections	0.251 m (LAGEOS-1, LAGEOS-2), 0.993 m [27] (Ajisai), 0.078 m (Stella, Starlette), 0.0562 (Larets)
Tropospheric refraction model	Mendes-Pavlis [28]
Weighting	
NP weighting	1
Weighting of satellite-dependent normal equations	all 1
Estimated arc parameters	
Atmospheric drag coefficient	1 per day
Empirical accelerations	1/rev along track, constant cross track (1 set per day)
Measurement bias	1 per station and arc
Satellite state vector	1 per arc
Estimated global parameters	
Gravity field coefficients	up to spherical harmonic degree and order 4
Station coordinates	3-d position

Table 2: Standards and models used for orbit determination and parameter estimation

parameters are thus taken into account. For more details on the technique, we refer to [15]. For our computations, we used the NASA/GSFC software packages GEODYN-II [16] and SOLVE [17] for POD and gravity field recovery, respectively. We processed the SLR data in "weekly" batches; each calendar month was subdivided into three 7-day arcs plus a fourth arc of variable length according to the number of days within the month.

Table 2 summarizes the standards and models used for POD. The adopted standards are motivated by the compilation of the gravity field models of the GOCO (Gravity Observation COmbination) series. The objective of the GOCO initiative is to compute high-accuracy and high-resolution global gravity field combination models from complementary gravity data sources; the Space Research Institute of the Austrian Academy of Sciences is responsible for the SLR part (please visit www.goco.eu for more information). The GOCO consortium agreed to data processing in consistency with the GOCE High-level Processing Facility (HPF) standards [18]. Thus, the processing of SLR data entering GOCO02S and GOCO03S (the SLR part is the same for both models) is consistent with the GOCE HPF standards. For the 14-year time span presented here, however, the ocean tide model FES2004 [19] was replaced by the more recent GOT4.8 model [20].

Furthermore, Table 2 lists the estimated arc (or local) parameters and global parameters. As far as the gravity field parameters (in terms of spherical harmonic coefficients) are concerned, earlier simulations have shown that their recovery from SLR is limited to about degree and order 5 [13]. A higher resolution could not be achieved because the normal equations become ill-conditioned, which can mainly be traced back to the non-global data coverage (cf. Fig. 3), but is also due to the high altitudes of the geodetic satellites (cf. Table 1). SLR has particular strength for the determination of the degree-2 terms, as will be focused on in Sects. 4 and 5. For this reason and in order to avoid any regularization to overcome ill-conditioning, we chose the maximum gravity field resolution to degree and order 4. The coordinate system has been chosen such that it coincides with the Earth's centre of mass implying that the degree-1 coefficients are fixed to zero.

Table 3 shows Root Mean Square (RMS) values of the post-fit residuals that give an indication for the quality of the POD process. The high precision of the LAGEOS trajectories is due to orbital altitude; at about 6000 km above the Earth's surface, the influence of the atmosphere on the motion of the satellite is negligible. The RMS values for the further (lower-orbiting) satellites point to deficiencies in the modelling of non-gravitational perturbing forces such as atmospheric drag and solar radiation pressure. A further shortcoming might come from the fact that we treated the centre of mass corrections as constant values. [27] showed, however, that a constant value for Ajisai is only an approximation as the correction actually varies up to 45 mm among different stations.

Satellite	RMS [cm]
LAGEOS-1	1.63
LAGEOS-2	1.60
Ajisai	11.46
Starlette	11.91
Stella	16.56
Larets	20.27

Table 3: RMS values of post-fit residuals over 7-day arcs from January 2000 to October 2013

4. Time-variable gravity field

We estimated monthly sets of gravity field coefficients to be able to compare our results with two solutions provided by the Center for Space Research (CSR) at Austin, Texas [29]. For this purpose, the normal equations of all six satellites over one calendar month (three 7-day arcs plus a fourth arc of variable length) were combined and inverted, yielding one set of coefficients per month. One of the external solutions is based on SLR data (retrieved from ftp://ftp.csr.utexas.edu/pub/slr/degree_2/RL05/) and one is based on GRACE (release 05 gravity field solutions). In order to ensure consistency, the CSR estimates were adjusted as follows: for both the SLR and GRACE time series, the C_{20} coefficients were transferred from the zero-tide system to the tide-free system. Further, the monthly average of the atmosphere and ocean de-aliasing product [30] was added to the GRACE series. Finally, we scaled all spherical harmonic coefficients to the reference radius of 6378.1363 km.

The variability of C_{20} reflects changes in the Earth's oblateness [31, 32, 33]; it is dominated by an annual signal and – to a smaller extent – a semi-annual signal (Fig. 4, top) caused by mass redistribution in the atmosphere, in continental water reservoirs, and in the oceans. Inter-annual variability is clearly recognizable. The periodic

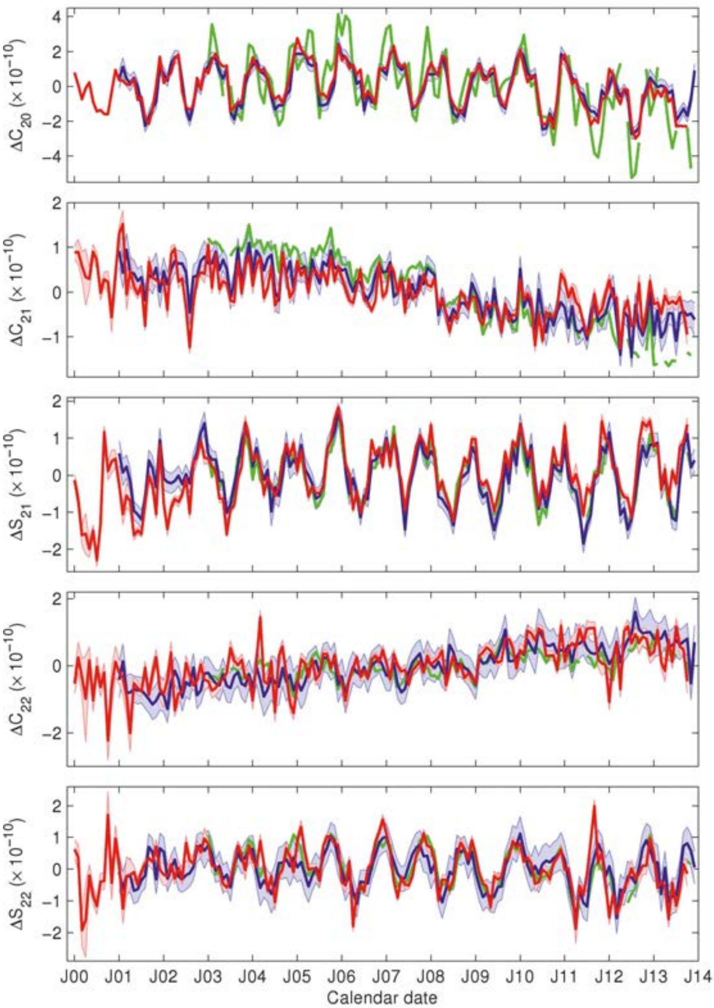

Fig. 4: Monthly degree-2 gravity field coefficients reduced by mean values. Our solution is depicted in red (formal errors in light red). The SLR-based solution by the CSR is shown in blue (formal errors in light blue); data availability from January 2001 to December 2013. The GRACE-based estimates by the CSR are shown in green; data availability from January 2003 to November 2013 (gaps: June 2003, January 2011, June 2011, May 2011, October 2012, March 2013, August 2013, September 2013).

effects are superposed by a secular trend, which is explained in the first instance by land uplift due to the Post-Glacial Rebound (PGR) signal, but has also contributions from the ablation of mountain glaciers and changes in water reservoirs [34], as well as the deceleration of the Earth's rotation (mainly caused by tidal friction).

The comparison between our SLR and the GRACE C_{20} time series reveals unrealistically large amplitudes for GRACE (Fig. 4, top), underpinning the superiority of SLR when it comes to the determination of the zonal degree-2 coefficient. For the other degree-2 coefficients, on the other hand, the amplitudes of the GRACE- and SLR-derived time series are in the same range (cf. Fig. 4).

Variations in C_{21} and S_{21} (Fig. 4, middle) are caused by mass-induced excitations of polar motion. Besides seasonal variations, these coefficients experience a significant linear trend that is explained by PGR as well as present-day mass changes of glaciers and ice sheets [35]. The sectorial coefficients of degree two (C_{22} and S_{22}; Fig. 4, bottom) reflect the ellipticity of the equator and are characterized by mainly seasonal fluctuations.

Our results agree very well with the external SLR-based solution by the CSR. In particular, the variations in C_{20} almost coincide. Apart from a few peaks in our solution, also the S_{21} and S_{22} series show good agreement. The same (arguably to a slightly smaller extent) holds true for the C_{21} and C_{22} results, for which periodic variations are much less emphasized compared to the other coefficients.

5. Static gravity field

For the computation of a set of coefficients (up to degree and order 4) representing the static gravity field, we analysed the SLR data from January 2000 to October 2013 in a joint least-squares adjustment (superposition of arc-wise normal equation systems). The resulting static gravity field coefficients have to be seen as averaged values over the considered time span. The error amplitudes (formal errors) per degree of the static solution are approximately one order of magnitude smaller than those of the monthly estimates (Fig. 5). Note that – especially for the degree-2 coefficients – the error amplitudes of our combined solution are considerably smaller than that one of the adopted a priori gravity field model EIGEN-5S (a combination solution of GRACE and 14 years of LAGEOS data). We

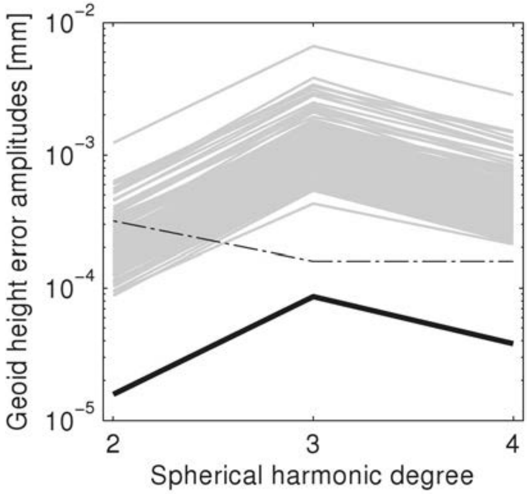

Fig 5: Degree-error amplitudes in terms of geoid heights. Grey lines: monthly solutions (SLR); solid black line: averaged solution (SLR); dashed black line: EIGEN-5S.

attribute this improvement to more convenient stochastic properties in general, and – to a lesser extent – taking into account ranges to six geodetic satellites instead of to LAGEOS only.

6. Discussion and conclusions

Although a number of dedicated gravity field missions were realized in the recent past, SLR is still an integral part in gravity field recovery. Therefore, global static (satellite-only) gravity field models comprise SLR data; the ranging information significantly supports the determination of very long-wavelength gravity field features.

As far as the temporal variations of the degree-2 terms are concerned, SLR is able to detect both seasonal changes and secular variations on (and near to) the Earth's surface. SLR-based C_{20} values are superior to the estimates from GRACE or any other space gravimetry mission. It should be emphasized that C_{20} is the most important gravity field parameter as it describes the flattening of the Earth and has the largest absolute value in the spherical harmonic expansion. The quality of the non-zonal degree-2 coefficients is similar for SLR and GRACE. Beyond degree two, the benefit of SLR over GRACE becomes less pronounced. However, due to the fact that GRACE might be decommissioned at any time, SLR is likely to gain more emphasis in future gravity field research.

The validation of our SLR-derived degree-2 time series with those provided by the CSR revealed a very good agreement. Our monthly estimates of degree-2 spherical harmonic coefficients can be retrieved from http://geodesy.iwf.oeaw.ac.at.

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