SLR in the framework of the EGSIEM project

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Abstract This contribution gives an overview of the Horizon 2020 project EGSIEM (European Gravity Service for Improved Emergency Management) where temporal gravity field solutions from different centers shall be combined. In particular, all aspects where SLR is involved are discussed. Namely, the GNSS orbits established in the framework of a reprocessing are validated using SLR data. We show that improved orbit modeling decreases systematic patterns in the residuals. Further, spherical harmonic coefficients of the Earth's gravity field were computed up to degree and order 3 using SLR data to five geodetic satellites (January 2003 to December 2013). The resulting SLR normal equations will be stacked with those of GRACE to optimally recover the very long wavelengths of the Earth's gravity field. The time series of the Earth's dynamic flattening term (C20) is compared against external solutions. Last, a workflow for establishing a reference frame is presented, which will be based on both GNSS and SLR data.

Introduction

The main objectives of EGSIEM are (1) to deliver the best gravity products for applications in Earth and environmental science research by combining the results from different institutions, (2) to reduce the latency and increase the temporal resolution of the gravity and therefore mass redistribution products, and (3) to develop gravity-based indicators for extreme hydrological events and demonstrate their value for flood and drought forecasting and monitoring services. The products evolving from EGSIEM will be based mostly on observations of the Gravity Recovery and Climate Experiment (GRACE) mission.

Validation of GNSS orbits

To ensure a consistent set of GNSS orbits over the mission life time of GRACE, a reprocessing campaign was initiated at the Astronomical Institute of the University of Bern. The reprocessed microwave-based products are based on the new Empirical CODE (Center for Orbit Determination in Europe) Orbit Model (ECOM; Arnold 2015), which is used for all orbit products generated at CODE from January 4, 2015 onwards (Dach et al., 2015). The kinematic orbits of GRACE will be based on these reprocessed products (i.e., orbits and clocks).

The principle of validating GNSS orbits is as follows: the SLR observations ('observed') are directly compared against the geometry based on the coordinates of the SLR stations and the microwave-based orbit ('computed') without estimating any parameter. The residuals ('observed minus computed') indicate how well the orbits agree with the SLR observations. Since the maximum angle of incidence of a laser pulse to a GNSS satellite does not exceed 14°, SLR data are mainly sensitive to the radial component of microwave-based GNSS orbits. Note that all GLONASS satellites and two GPS satellites are equipped with laser retroreflector arrays.

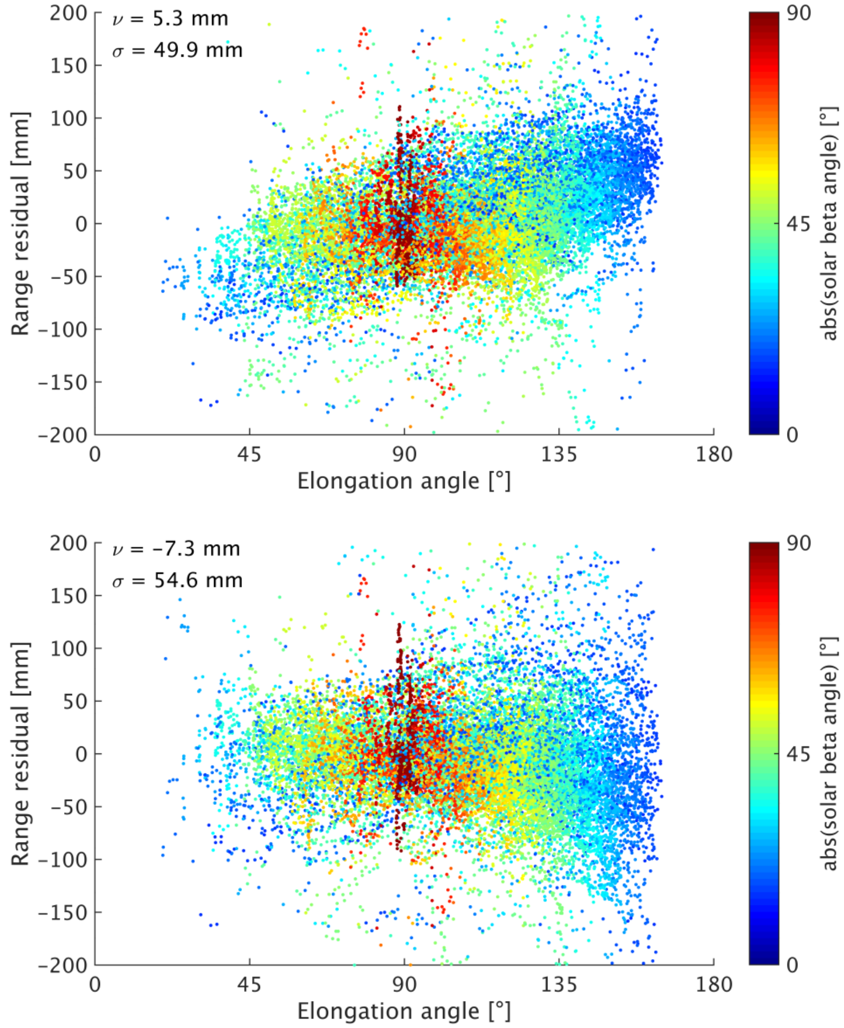

Figure 1. SLR residuals w.r.t. GLONASS-M orbits using the original ECOM (top) and the extended ECOM (bottom). Mean value (ν) and standard deviation (σ) are based on all residuals whose absolute value is smaller than 150 mm. Observations to four GLONASS satellites (SVN 723, 725, 736, 737) have been excluded due to anomalous patterns. Furthermore, all residuals having an absolute beta angle smaller than 15° have been not taken into account due to unmodeled attitude during eclipses.

The SLR residuals w.r.t. all GLONASS-M orbits from 2003 to 2014 are shown in Figure 1 as a function of the elongation angle (i.e. the angle Sun-geocenter-satellite angle) and the solar beta angle (i.e. elevation of the Sun above the orbital plane). The systematic pattern of the residuals, which is evident for orbits generated with the original ECOM, has been successfully reduced in case the extended ECOM is used. On the other hand, mean value and standard deviation are slightly larger for the new ECOM. The larger standard deviation can be mainly contributed to the 4-cycles per revolution term estimated in the satellite-Sun direction.

Gravity field coefficients from SLR

The Earth's dynamical flattening, i.e. the spherical harmonic coefficient C20, cannot be well determined from GRACE data due to aliasing issues. On the other hand, SLR observations to geodetic satellites are perfectly suitable to derive high-quality estimates of this coefficient. In particular, the two LAGEOS satellites are highly sensitive to C20 as they orbit the Earth at an altitude of nearly 6000 km. At this altitude the influence of the atmosphere on the satellite, which is difficult to model, is negligible. The superiority of SLR data concerning the very long wavelengths of the Earth's gravity field is the reason why combined satellite-only gravity field models such as GO_CONS_GCF_2_DIR_R5 (Bruinsma et al., 2013), EIGEN-6S2 (Rudenko et al., 2014), and the Gravity Observation Combination (GOCO) model GOCO05S (Mayer-Gürr et al., 2015) include SLR data.

For the time being, the SLR data to LAGEOS 1/2, Ajisai, Stella, and Starlette have been analyzed from January 2003 to December 2013 (compare also Sośnica et al., 2015). For the LAGEOS satellites, 10-day arcs are set up. For the other three lower orbiting satellites, which are perturbed by the atmosphere, shorter arcs (1-day) are generated to prevent unmodeled effects from degrading the estimated orbit (cf. Figure 2). The atmosphere and ocean de-aliasing product (AOD, Flechtner et al., 2015), RL05, is used for de-aliasing; the corrections are applied at the observation level. Spherical harmonic coefficients are estimated up to degree and order (d/o) 3 (cf. Table 1). Moreover, geocenter coordinates, Earth rotation parameters, and station coordinates are retrieved (cf. Table 1). Figure 2 illustrates the processing scheme for the stacking of normal equations (NEQs) to derive the monthly gravity field coefficients.

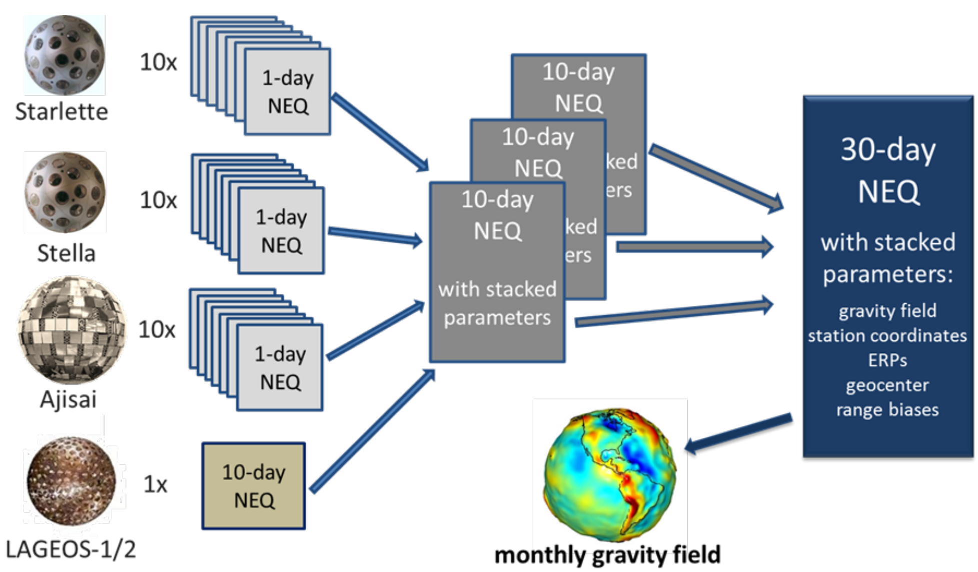

Figure 2. Processing scheme for stacking normal equations (NEQs) to derive monthly gravity field coefficients.

Table 1. Orbit modeling and list of estimated parameters.

	LAGEOS-1/2	Stella, Starlette, Ajisai
Arc-specific parameters:		
Osculating elements	1 set per 10 days	1 set per day
Dynamical parameters	const. and 1/rev along track (1 set per 10 days)	const. and 1/rev along track, 1/rev cross track (daily)
Pseudo-stochastic pulses	–	1/rev in along track
Common parameters:		
Earth rotation parameters	X_P, Y_P, UT1-UTC (piecewise linear, 1 set per day)	
Geocenter coordinates	1 set per 30 days	
Gravity field coefficients	up to d/o 3 (1 set per 30 days)	
Station coordinates	1 set per 30 days	
Range biases	for selected stations (1 set per 30 days)	for all stations (1 set per 30 days)

We compare our monthly sets of coefficients with two external solutions, both computed at the Center for Space Research (CSR) at Austin, Texas. One is based on SLR measurements[1] (Cheng et al., 2011) and the second one is estimated from GRACE data[2] (Bettadpur, 2012). To ensure consistency of the time series that shall be compared, the CSR estimates are adjusted as follows: for both the SLR and GRACE time series, the monthly C20 coefficients are transferred from the zero-tide system to the tide-free system. Further, the monthly average of the atmosphere and ocean de-aliasing product[3] (Flechtner et al., 2015) is added to the GRACE series and to our SLR-based estimates. Finally, all spherical harmonic coefficients are scaled to the same reference radius (6378.1363 km).

The seasonal annual variations due to mass redistribution in the atmosphere, ocean, and continental water, are well distinguishable in the two series that are based on SLR data (cf. Figure 3). In the GRACE time series, in contrast, the annual variations are less pronounced. This is also evident in the amplitude spectrum of the three different C20 time series (cf. Figure 4). Whereas for GRACE the amplitude of the semiannual signal is larger than the one of the annual signal, the amplitudes of the SLR series contain a distinct annual signal and a smaller semiannual signal. The offset between our solution and the SLR series from CSR (cf. Figure 3), which amounts to approximately 1*10^-10, is under investigation. Further, it is intended to extend the time series and to include more satellites such as Beacon-C, Lares, and Larets. Including more satellites of different inclination angles will help to decorrelate spherical harmonic coefficients (Sośnica 2015). A higher resolution (for example up to d/o 6) might be achievable.

[1] retrieved from ftp://ftp.csr.utexas.edu/pub/slr/degree 2/RL05/
[2] release 05 gravity field solutions; retrieved from http://isdc.gfz-potsdam.de
[3] retrieved from http://isdc.gfz-potsdam.de

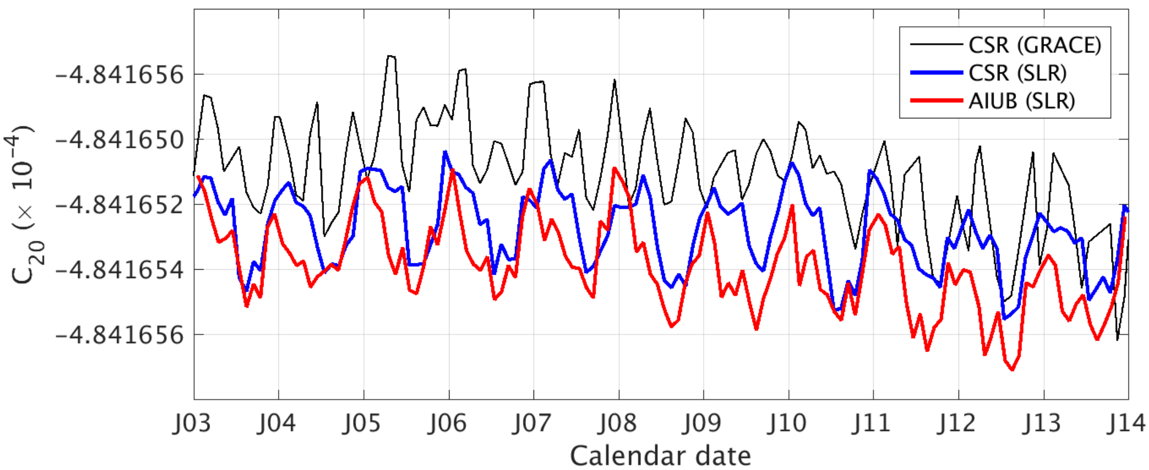

Figure 3. Monthly C20 gravity field coefficient. Red: estimated coefficients. Blue: SLR-based coefficients by CSR. Black: GRACE-based estimates by CSR (gaps: June 2003, January 2011, June 2011, May 2011, October 2012, March 2013, August 2013, September 2013).

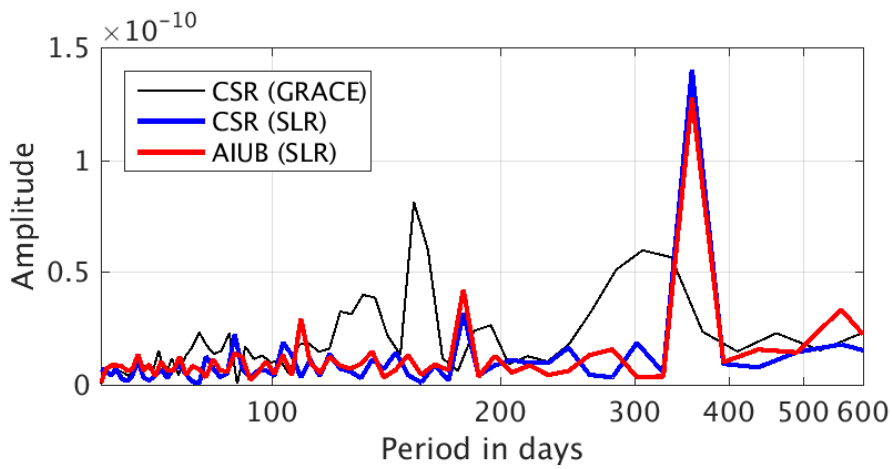

Figure 4. Spectral analysis of three C20 time series between January 2003 and December 2013.

Deriving a combined reference frame

The gravity field product delivered by the EGSIEM project will be based on GRACE and SLR data. It would be thus desirable to establish a reference frame based on both GNSS data and SLR observations. For this purpose we intend to analyze SLR measurements to GNSS satellites equipped with a retroreflector array and to estimate common parameters such as station coordinates and geocenter coordinates from a combined set of SLR and GNSS data (cf. Figure 5).

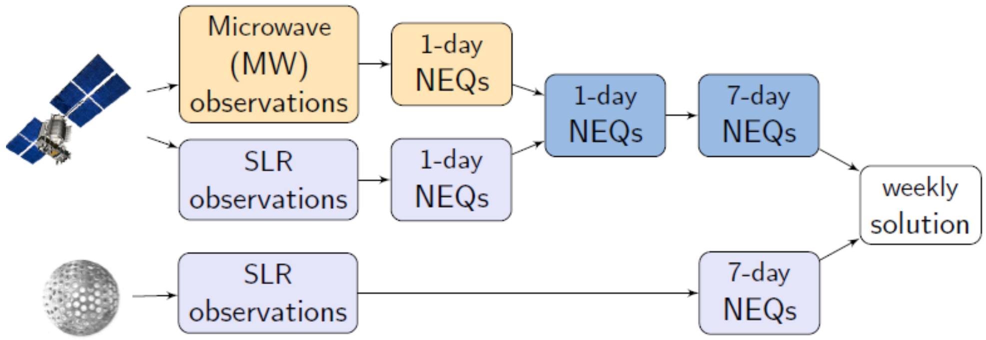

Figure 5. Workflow to derive a combined reference frame.

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