Temporal Earth's Gravity Variations Derived from GPS, GLONASS, and SLR Satellites

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Introduction

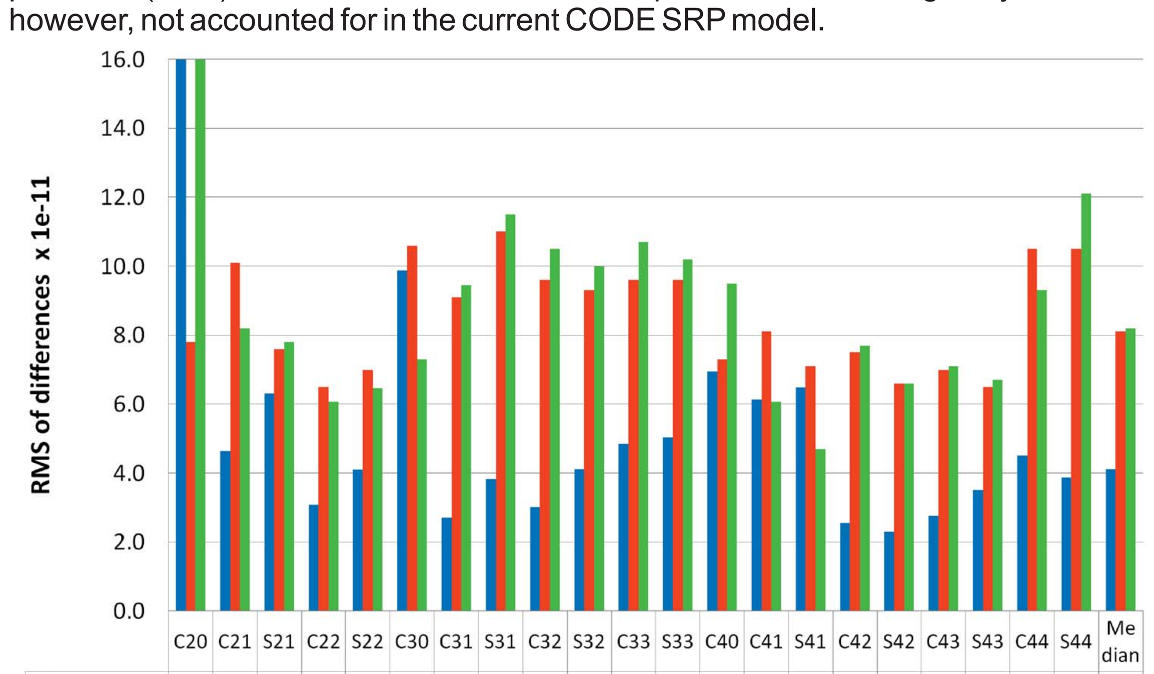
The sensitivity of high-orbiting GNSS satellites to medium and high degree gravity field coefficients is low due to their orbital altitude. GPS satellites are, however, particularly sensitive to specific coefficients of the Earth's gravity field, because of the deep 2:1 orbital resonance with Earth rotation (two revolutions for the GPS satellites per sidereal day). The resonant coefficients cause, among other, a "secular" drift (actually very long periodic variations) of the semi-major axes of up to 5.3 m/day of GPS satellites.
We processed 10 years of GPS and GLONASS data using the standard orbit models from the Center of Orbit Determination in Europe (CODE) with a simultaneous estimation of the Earth gravity field coefficients and other parameters, e.g., satellite orbit parameters, station coordinates, Earth rotation parameters, troposphere delays, etc. (see Tab. 1). The weekly GNSS gravity solutions up to degree and order 4 are compared to weekly SLR gravity field solutions and to monthly GRACE results (namely, AIUB-GRACE RL01 generated with the Celestial Mechanics Approach).
Figure 1 shows that the median difference of low degree gravity field coefficients is 4.1×10^{-11}, 8.1×10^{-11}, and 8.2×10^{-11} between SLR-GRACE solutions, GNSS-SLR solutions, and GNSS-GRACE solutions, respectively. There is, however, a relatively good agreement between C_{20} estimates derived from GNSS and SLR, whereas the GRACE-derived C_{20} is typically affected by alias with S2 tide constituent.

Estimated parameters		GNSS solutions	SLR solutions
		up to 32 GPS and 24 GLONASS satellites	LAGEOS-1/2, Starlette, Stella, Ajisai
Orbits	Osculating elements	$a, e, i, \Omega, \omega, u_0$ (1 set per 3 days)	$a, e, i, \Omega, \omega, u_0$ (1 set per 7 days)
	Dynamical parameters	D_0, Y_0, X_0, X_S, X_C	LAGEOS-1/2: S_0, S_C, S_S (1 set per 7 days) Sta/Ste/Aji: C_D, S_C, S_S, W_C, W_S (1 set per day)
	Pseudo-stochastic pulses	R, S, W (once per revolution)	LAGEOS-1/2: no pulses Sta/Ste/Aji: S (once per revolution)
Earth rotation parameters		X_P, Y_P, UT1-UTC (1 set per day)	X_P, Y_P, UT1-UTC (1 set per day)
Geocenter coordinates		1 set per 7 days	1 set per 7 days
Earth gravity field		**Estimated up to d/o 4/4** (1 set per 7 days)	**Estimated up to d/o 4/4** (1 set per 7 days)
Station coordinates		1 set per 7 days	1 set per 7 days
Other parameters		Troposphere ZD (2h), gradients (24h), GNSS-specific translations and ZTD biases	Range biases for selected stations

Tab: 1: List of estimated parameters in the weekly GNSS and weekly SLR gravity field solutions. The modeling standards follow the IERS 2010 Conventions in the both solutions. Weekly GNSS solutions are generated by stacking seven 3-day NEQs with overlapping orbits (stacking all parameters with except for the orbits). Both, SLR and GNSS solutions are generated with no-net-translation and no-net-rotation minimum conditions applied on SLRF2008 and IGb08 fiducial stations, respectively. GNSS dynamic orbit parameters estimated in the standard CODE solutions read as follows (for the explanation of the orbital directions see Fig. 2):

$$D = D_0 \qquad Y = Y_0 \qquad X = X_0 + X_S \sin \Delta u + X_C \cos \Delta u.$$

This set of parameter was designed for absorbing the impact of solar radiation pressure (SRP) on GNSS satellites. The temporal variations of gravity field are, however, not accounted for in the current CODE SRP model.



	C20	C21	S21	C22	S22	C30	C31	S31	C32	S32	C33	S33	C40	C41	S41	C42	S42	C43	S43	C44	S44	Median
GRACE-SLR	84.4	4.7	6.3	3.1	4.1	9.9	2.7	3.8	3.0	4.1	4.9	5.0	7.0	6.1	6.5	2.6	2.3	2.8	3.5	4.5	3.9	4.1
SLR-GNSS	7.8	10.1	7.6	6.5	7.0	10.6	9.1	11.0	9.6	9.3	9.6	9.6	7.3	8.1	7.1	7.5	6.6	7.0	6.5	10.5	10.5	8.1
GNSS-GRACE	81.8	8.2	7.8	6.1	6.5	7.3	9.5	11.5	10.5	10.0	10.7	10.2	9.5	6.1	4.7	7.7	6.6	7.1	6.7	9.3	12.1	8.2

Fig. 1: RMS of differences for low degree gravity field parameters derived from weekly SLR, weekly GNSS, and monthly GRACE solutions. Note the good agreement between C_{20} derived from the GNSS and SLR solutions as compared to the GRACE solutions, which are strongly affected by deficiencies in S2 tide.

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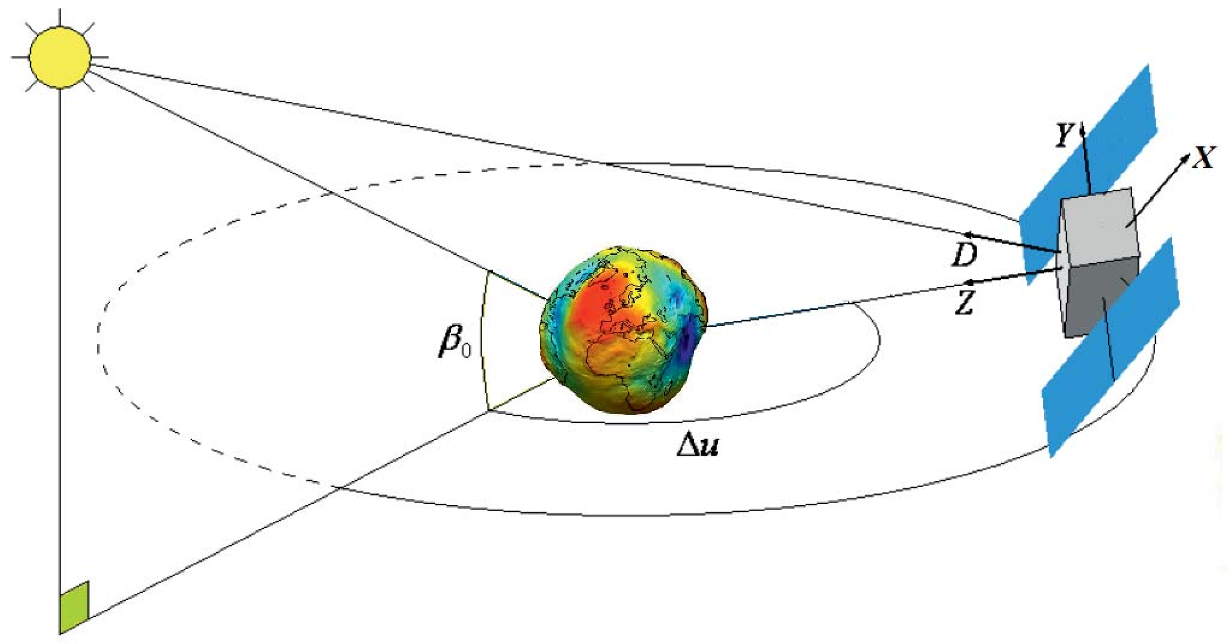
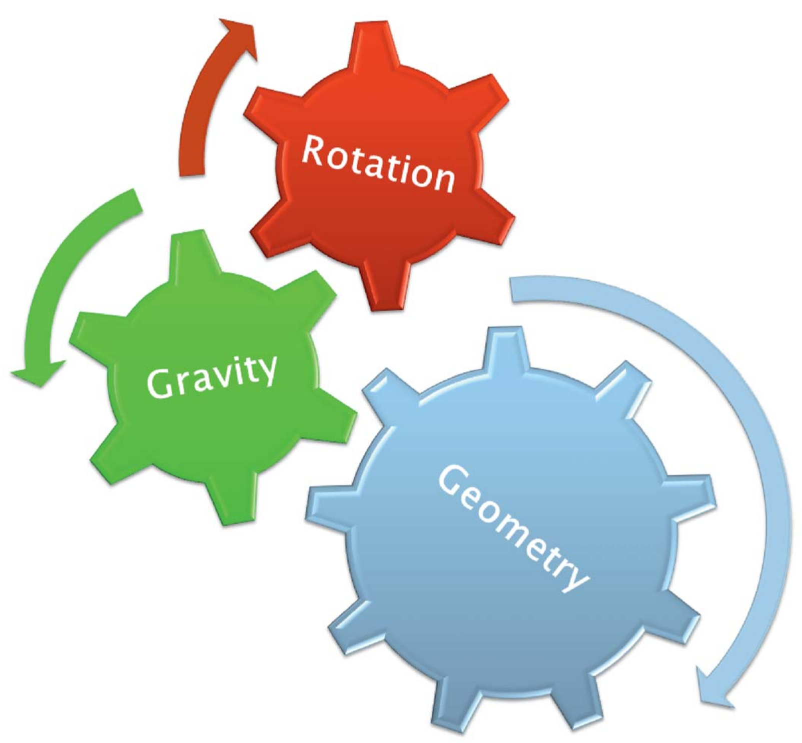


Fig: 2: Satellite-Sun-oriented reference frame



Dynamical Oblateness from GPS and GLONASS

Figure 3 shows that the variations of C_{20} are not fully recovered from GNSS applying the standard CODE orbit parameterization, which is reflected in substantially smaller amplitudes of annual and semiannual signals as compared to the SLR solutions. Figure 4 shows that C_{20} can be much better determined from the GNSS solutions if the constant and once-per-revolution parameters in the X direction are not estimated: the semi-annual signal is well reproduced, the secular drift w.r.t. SLR is reduced, the 3rd harmonic of 118 days disappears, and the correlation coefficient between the SLR and GNSS series increases from 0.02 to 0.28. A very good agreement between SLR and GNSS solutions is observed in particular for the period after 2008 when the contribution of GLONASS satellites becomes stronger and the GLONASS-observing network becomes more global.
It is important to avoid the estimation of both, constant X and once-per-revolution orbit parameters in the X direction, because both parameters are correlated with C_{20} and all solutions with estimating one or both of these parameters result in inappropriate C_{20} estimates (as in Fig. 3).
The spectral analysis shows the 2nd, 3rd, 5th, 6th, and 7th harmonics of the draconitic year in most of the GNSS-derived coefficients (Fig. 3-5). The amplitudes of these harmonics can be reduced for some parameters when not estimating X_0, X_S, X_C (see Fig. 4). The quality of other estimated parameters, e.g., ERPs and station coordinates, are, however, slightly degraded when X_0, X_S, X_C are not estimated (e.g., the RMS of the X pole coordinate from 54.3 to 61.7 µas).

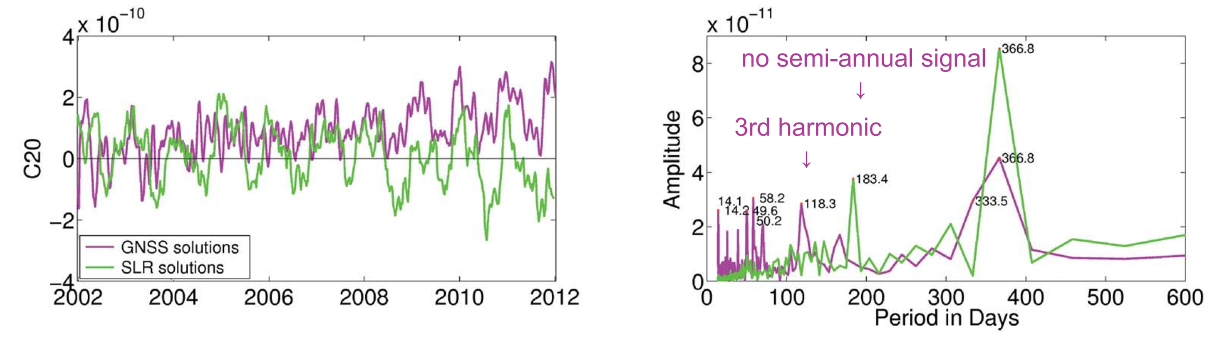


Fig: 3: Variations of C_{20} w.r.t. EGM2008 from the GNSS solutions with standard CODE modeling, and from the SLR solutions for the time span 2002-2011

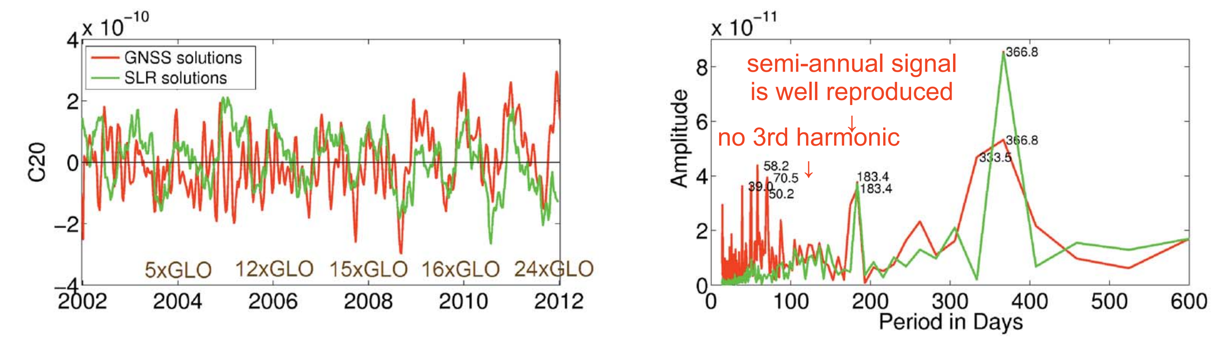


Fig: 4: Variations of C_{20} w.r.t. EGM2008 from the GNSS solutions without estimating constant and once-per-rev dynamical orbit parameters in the X direction, and from the SLR solutions for the time span 2002-2011

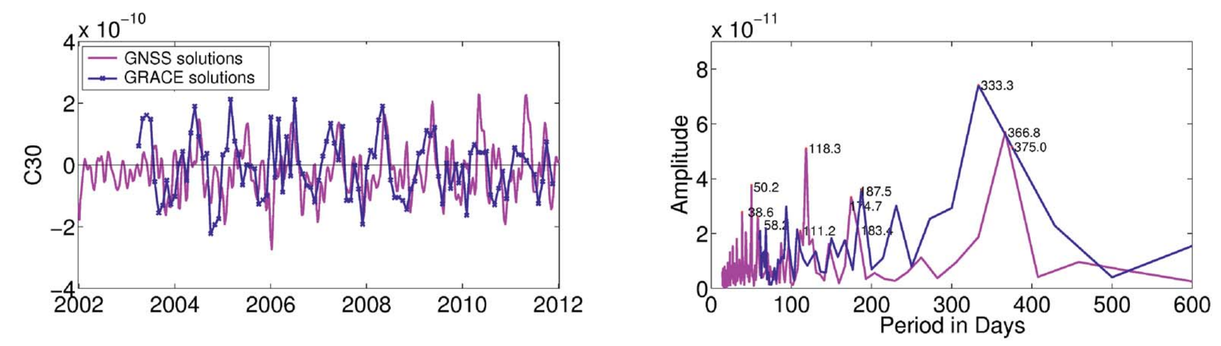


Fig: 5: Variations of C_{30} w.r.t. EGM2008 from the GNSS solutions with standard CODE modeling, and from the GRACE solutions for the time span 2002-2011

Three Pillars of Satellite Geodesy

The 'three pillars' of satellite geodesy are typically understood as:
1. **Geometry**: precise determination of geometrical three-dimensional positions and velocities in the reference frames,
2. **Rotation**: modeling and observing of the rotation and orientation of the figure Earth,
3. **Gravity**: determination of the Earth's gravity field and its temporal variations.
Even though all three pillars describe geodetic and geodynamic phenomena within the system Earth, the gravity has typically been treated separately from the geometry and rotation. E.g., in the official solutions of the International Association of Geodesy (IAG) serives, e.g., in the International Laser Ranging Service (ILRS) and in the International GNSS Service (IGS) products, the gravity field parameters are not estimated, as yet. In this study we derive the geodetic parameters belonging to all three pillars from the GNSS and SLR solutions.

Three Pillars from SLR Solutions

The simultaneous estimation of the gravity field parameters along with other geodetic parameters (e.g., pole coordinates, LoD, station coordinates):

(1) reduces the offset of LoD estimates w.r.t. IERS-08-C04 series (Fig. 6, left), which is mostly due to absorption of the C_{20} variations by LoD estimates,

(2) reduces peaks in the spectrum analysis (Fig 6, right), which correspond, e.g., to orbit modeling deficiencies (peaks of 222 days, i.e., a draconitic year of LAGEOS-2, 280 days, i.e., an eclipsing period of LAGEOS-1),

(3) substantially reduces the a posteriori error of estimated LoD (Fig. 7, right, notice a logarithmic scale for the y axis). The mean a posteriori error of LoD is 1.3, 16.9, 7.1, and 44.6 µs/day in the multi-SLR solution with gravity, multi-SLR solution without gravity, LAGEOS-1/2 solution without gravity, and SLR-LEO solution without gravity field parameters, respectively. The RMS of pole coordinates is, however, slightly increased in the multi-SLR solution with estimating gravity as compared to the multi-SLR solution without gravity estimation.

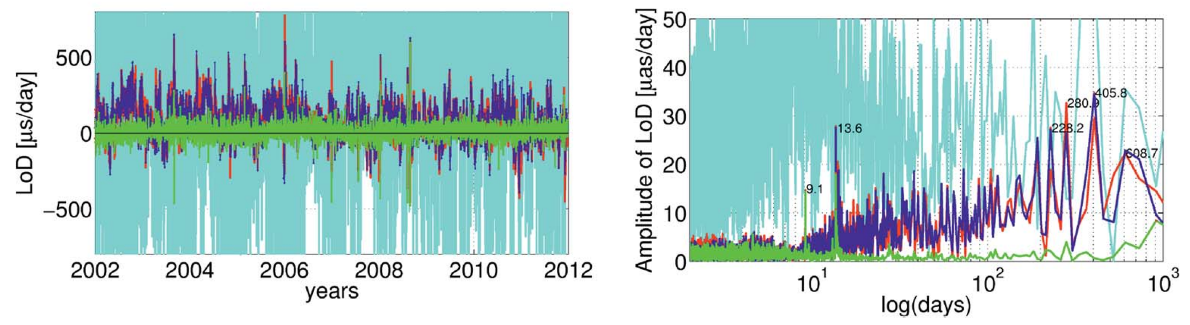


Fig: 6: Differences of SLR-derived LoD estimates w.r.t. IERS-08-C04 series (left) and spectral analysis of LoD differences (right). Following solutions are compared: Starlette+Stella+AJISAI (SLR-LEO), LAGEOS-1+LAGEOS-2, (both without esimating gravity field) Starlette+Stella+AJISAI+LAGEOS-1+LAGEOS-2 without estimating gravity (multi-SLR) and with estimating gravity field (multi-SLR)

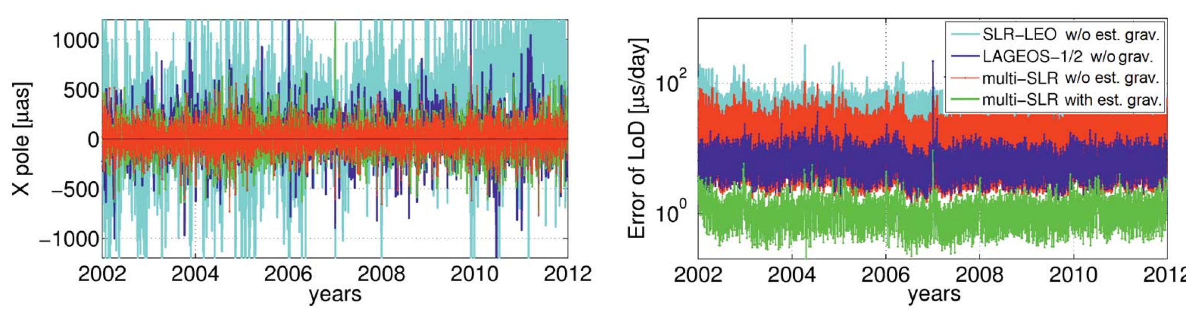


Fig: 7: Differences of SLR-derived pole coordinates w.r.t. IERS-08-C04 series (left) and formal errors of SLR-derived LoD estimates (right).

Three Pillars from GNSS Solutions

The simultaneous estimation of the gravity field parameters along with other geodetic parameters in the GNSS solutions:

(1) slightly reduces the variations of pole coordinates w.r.t. IERS-08-C04 series (Fig. 8). When the gravity field parameters are not estimated the pole coordinates are strongly affected by deficiencies in solar radiation pressure modeling (e.g., the period of 50.2 days related to the 7th harmonic of the GPS or GLONASS draconitic year). The mean RMS of differences between the GNSS-derived X pole coordinates and the IERS-08-C04 series is reduced from 55.7 to 54.3 µas in the solutions without and with estimating gravity field, respectively,

(2) remarkably reduces peaks in the spectrum analysis of pole rates (Fig. 9, Fig. 10, right), corresponding, e.g., to 7th, 6th, 4th harmonic of the draconitic year and to alias period of the S_1/S_2 tides and GNSS orbits (about 352 days and 176 days, respectively). The mean offset of the X pole rate is reduced from 10 to 4 µas/day for the GNSS solutions without and with estimating gravity field, respectively,

(3) slightly improves the estimates of LoD (not shown here),

(4) reduces the formal errors of ERP estimates, e.g., from 9 to 6 µas for the X pole coordinate (see Fig. 10, left).

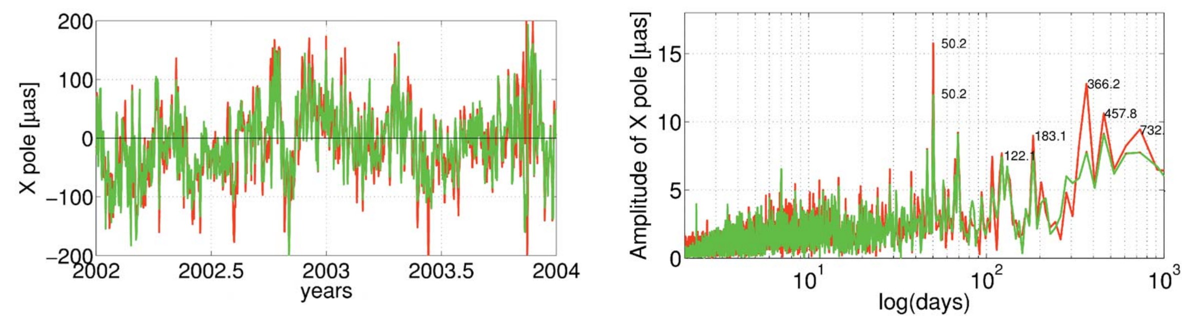


Fig: 8: Differences of the GNSS-derived X pole coordinates from the solutions without estimating gravity field parameters and with estimating gravity field w.r.t. IERS-08-C04 series (left) and the spectral analysis of the differences (right)

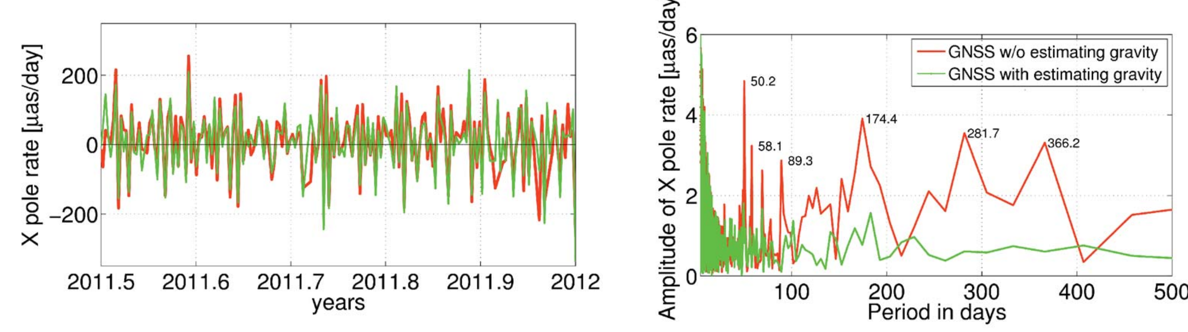


Fig: 9: Differences of the GNSS-derived rates of X pole coordinates from the solutions without estimating gravity field parameters and with gravity field w.r.t. IERS-08-C04 series (left) and the spectral analysis of these differences (right)

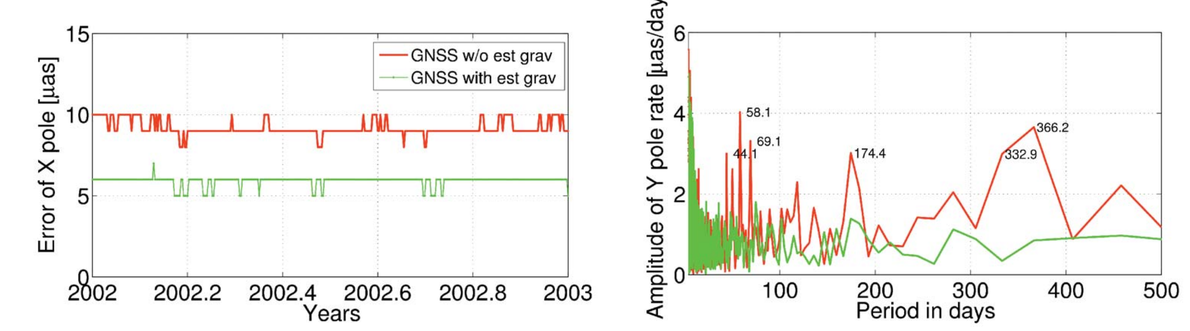


Fig: 10: Formal errors of the GNSS-derived X pole coordinates from the solutions without estimating gravity field parameters and with gravity field w.r.t. IERS-08-C04 series (left) and the spectral analysis of the differences of the GNSS-derived rates of Y pole coordinates (right)

Summary

1. The recovery of C_{20} from GPS and GLONASS satellites is feasible with a comparable quality to the SLR estimates after 2008.

2. Simultaneous estimation of the gravity field parameters along with station coordinates and Earth rotation parameters is possible. Moreover it is particularly beneficial for LoD estimates (in the SLR solutions) and for the pole coordinates and their rates (in the GNSS solutions).

References

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