Determination of hydrological signal in polar motion variations from gravity field models obtained from kinematic orbits of LEO satellites

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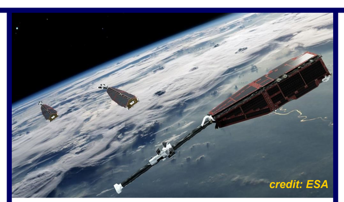
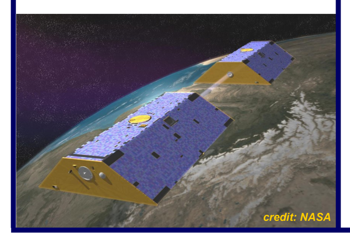
I. INTRODUCTION

- The temporal variations of polar motion are caused by changes in the mass distribution of the atmosphere, ocean, land hydrosphere. These variations can be determined from the observations of Earth's gravity field. Such data were delivered from 2002 to 2017 by the Gravity Recovery and Climate Experiment (GRACE) mission.
- Here, we examine the usefulness of several temporal gravity field models determined from kinematic orbits of Low Earth Orbit (LEO) satellites (GRACE, non-dedicated satellites, and combined solutions) in determining polar motion variations. All of these solutions are based only on orbit positions (high-low satellite-to-satellite tracking, SST-hl).
- Our investigations are focused on comparison of hydrological polar motion excitation functions HAM (*Hydrological Angular Momentum*) obtained from LEO satellites.
- The reference data for an evaluation of the models are: (1) hydrological signal in observed polar motion excitation derived from precise measurements of the pole coordinates (geodetic residuals - GAO), (2) hydrological signal obtained from GRACE gravity field solution ITSG 2018 (low-low satellite-to-satellite tracking, SST-ll).
- We consider overall time series and also decompose them into trends, seasonal and nonseasonal oscillations.

II. SATELLITE MISSIONS

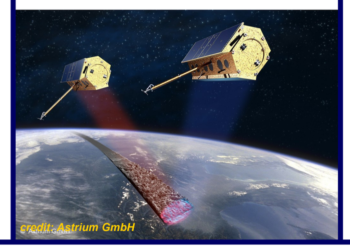
GRACE A & B
- Gravimetry satellites
- Altitude 485 km
- Inclination 89°





TanDEM-X & TerraSAR
- SAR satellites
- Altitude 515 km
- Inclination 97.4°

Swarm A, B & C
- Magnetic field
- Altitude 450 km (A,B), 550 km (C)
- Inclination 87.4° (A,B), 88° (C)



Jason 2
- Altimetry satellite
- Altitude 1336 km
- Inclination 66°

MetOp-A & MetOp-B
- Weather satellites
- Altitude 817 km
- Inclination 98.7°

III. DATA SOURCES AND METHODS

1) Gravity field models - each in the form of geopotential coefficients C_{nm}, S_{nm}

- **GRACE ITSG 2018** solution provided by the Institute of Theoretical Geodesy and Satellite Geodesy of the Graz University of Technology (ITSG TUG); *Mayer-Gürr et al., 2018;*
- **Gravity field models from kinematic orbits of GRACE A & B and non-dedicated satellites** provided by the ITSG; *Zehentner and Mayer-Gürr, 2016;*
- **Gravity field models from kinematic orbits of GRACE A & B and Swarm A, B & C satellites** provided by Astronomical Institute, Czech Academy of Sciences (ASU CAS); *Bezdek et al., 2016;*

2) Data and models used for determination of geodetic residuals (GAO)

- **Geodetic Angular Momentum (GAM)** - observed geodetic polar motion excitation functions (χ_1, χ_2) obtained from EOP C04 series provided by the International Earth Rotation and Reference System Service (IERS);
- **Atmospheric Angular Momentum (AAM)** time series (χ_1, χ_2) based on ECMWF (European Centre for Medium-Range Weather Forecasts) model and provided by the GeoForschungsZentrum (GFZ);
- **Oceanic Angular Momentum (OAM)** time series (χ_1, χ_2) based on MPIOM (Max Planck Institute Ocean Model) model and provided by the GFZ.

Geodetic residuals (GAO):

$$GAO = GAM - AAM - OAM$$

Hydrological excitation functions (HAM):

$$\chi_1/\chi_2 = -\sqrt{\frac{5}{3}} \cdot \frac{1.608 \cdot R_e^2 \cdot M}{C - A'} \Delta C_{21}/\Delta S_{21}$$

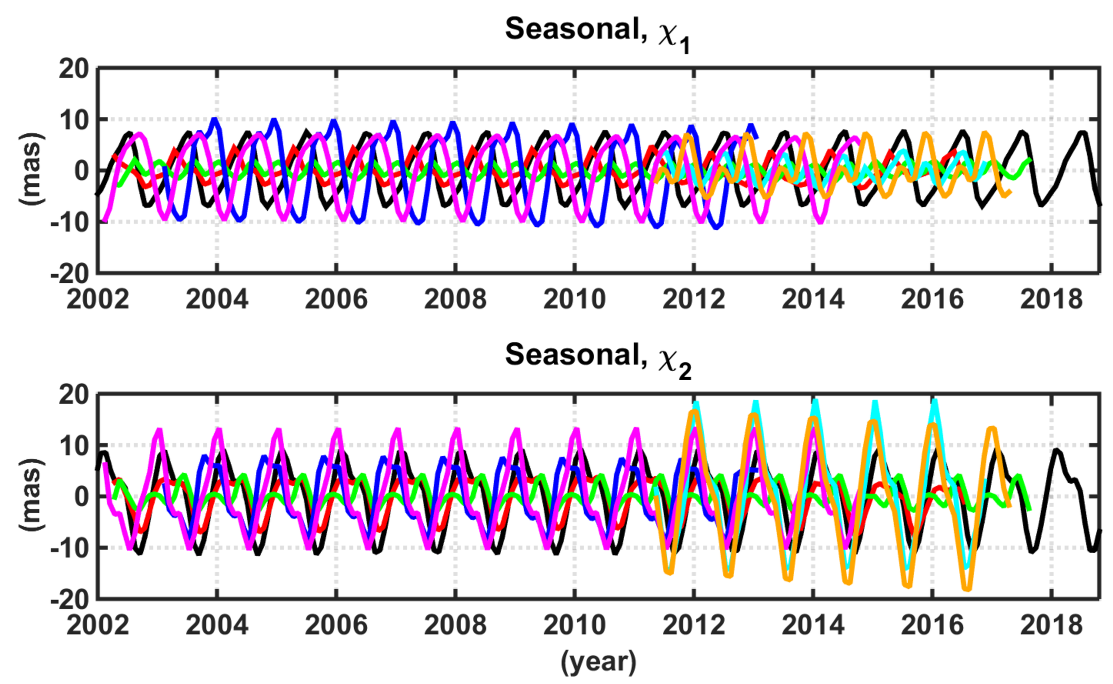
- R_e, M are the Earth's mean radius and mass,
- A, B, C are the Earth's principal moments of inertia,
- A' = (A+B)/2 is an average of the equatorial Earth's principal moments of inertia.

IV. OVERALL TIME SERIES AND TRENDS

Table 1. Standard deviation and linear trends of χ_1 and χ_2 components of GAO and HAM. The GRACE A, B CAS and Swarm A-C CAS series are provided by ASU CAS while the rest of them – by ITSG TUG. Because the series were available in different time periods and with different length (shown in columns 2 and 3, respectively), the trends of reference series were computed for all periods of available series.

	Data	Time period	Period length (yr)	X_1 trend (mas/year) LEO /GAO/ ITSG2018	X_2 trend (mas/year) LEO /GAO/ ITSG2018	X_1 STD (mas)	X_2 STD (mas)
reference data	GAO	2000.00–2019.14	19.14	4.84	–0.72	8.08	9.76
	ITSG 2018	2002.28–2016.54	14.26	6.88	–2.29	5.56	8.12
GRACE models	GRACE A, B CAS	2002.28–2016.49	14.21	8.91 /5.32/ 6.90	0.69 /–0.17/ –2.29	15.06	14.47
	GRACE A, B TUG v2	2003.12–2012.98	9.86	4.88 /5.62/ 7.59	–0.70 / 0.44/ –1.18	28.47	23.59
	GRACE A, B TUG v3	2011.37–2016.46	5.09	14.20 /4.65/ 5.99	–2.80 /–0.60/ –5.49	23.37	20.04
Combined models	Combined v2	2002.29–2014.77	12.48	5.07 /5.43/ 6.87	–1.83 /–0.31/ –2.08	19.93	20.51
	Combined v3	2011.37–2016.46	5.09	12.59 /4.65/ 5.99	–2.40 /–0.60/ –5.49	17.93	17.57
Swarm models	Swarm A-C CAS	2013.95–2016.42	2.46	16.84 /1.83/ 9.64	3.18 / 3.16/ 1.25	18.49	15.85
	Swarm A-C TUG v1	2013.87–2015.35	1.48	–5.22 /2.72/ 9.74	–31.46 / 1.09/ –5.43	28.79	47.46
	Swarm A-C TUG v2	2013.87–2016.42	2.55	5.82 /2.21/ 9.61	–27.68 / 2.96/ 1.04	21.87	35.75
	Swarm A-C TUG v3	2013.87–2016.42	2.55	22.49 /2.21/ 9.61	9.02 / 2.96/ 1.04	60.99	95.38
Other models	TanDEM-X	2011.87–2016.47	4.60	31.78 /4.28/ 5.76	–26.96 / 0.03/ –4.88	68.28	88.66
	TerraSAR-X	2011.37–2016.46	5.09	7.36 /4.65/ 5.99	11.56 /–0.60/ –5.49	54.10	60.62
	Jason 2	2011.37–2016.46	5.09	–103.54 /4.65/ 5.99	–120.27 /–0.60/ –5.49	1078.70	960.27
	MetOp-A	2011.37–2016.46	5.09	–254.74 /4.65/ 5.99	–68.57 /–0.60/ –5.49	1320.95	729.69
	MetOp-B	2013.12–2016.49	3.37	118.10 /3.01/ 7.15	544.35 / 3.39/ –1.06	1088.38	1183.26

V. SEASONAL CHANGES

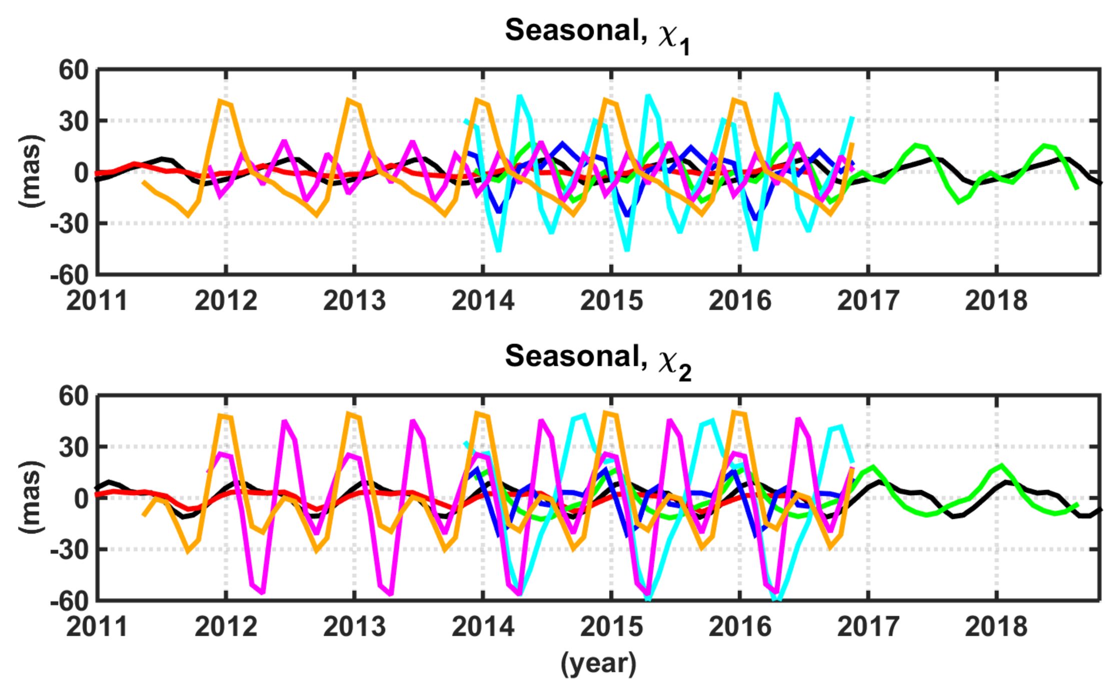


for χ_1 only ITSG 2018 and GRACE AB TUG v3 provide good phase agreement with GAO; the best amplitude agreement with GAO for Combined v3;

for χ_2 good phase agreement between all series; the best amplitude agreement with GAO for GRACE AB TUG v2;

the newest solutions from TUG (v3) noticeably overestimates amplitudes of GAO in χ_2.

Fig.1. χ_1 and χ_2 seasonal (sum of annual, semiannual and terannual) components of geodetic residuals (GAO) and hydrological polar motion excitation functions (HAM) obtained from: (1) ITSG 2018 GRACE solution (SST-ll), (2) solutions based on kinematic orbits of GRACE satellites (SST-hl) and (3) combined solutions (SST-hl). The combined solutions are based on kinematic orbits of both gravimetry and non-dedicated satellites (see *Zehentner & Mayer-Gürr, 2016).*



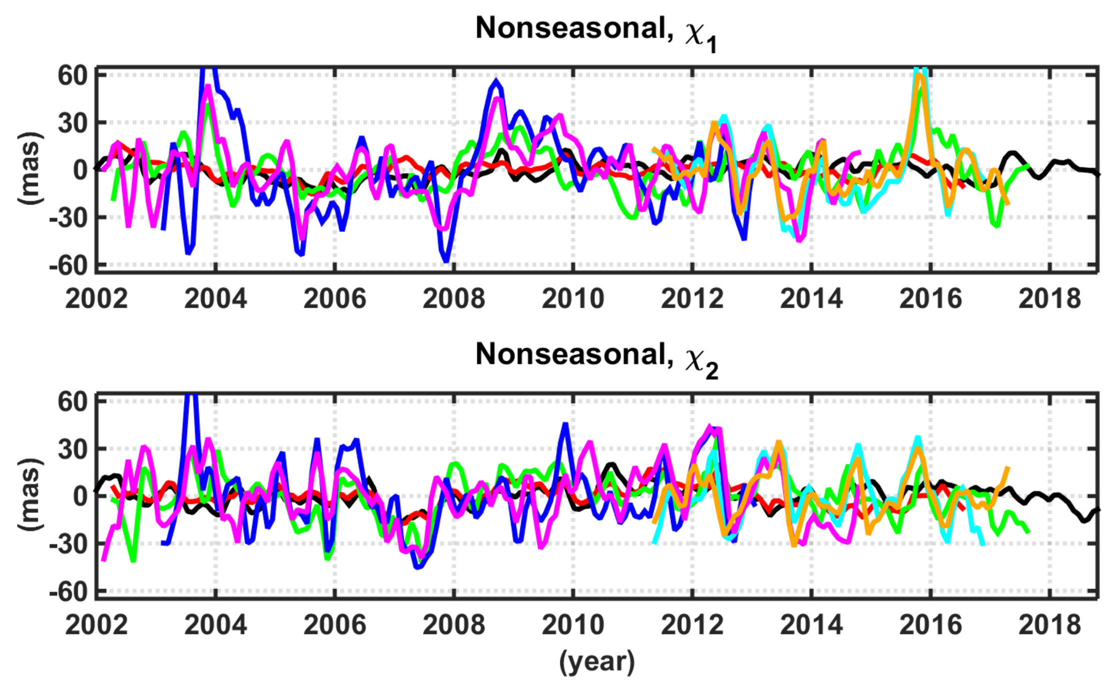
for χ_1 and χ_2 the best amplitude and phase agreement with GAO and ITSG 2018 provides Swarm A-C from CAS;

series from other satellites noticeably overestimate amplitudes of GAO and ITSG 2018-based HAM;

Swarm TUG v2 provides better amplitude agreement with GAO than Swarm TUG v3.

Fig. 2. χ_1 and χ_2 seasonal components of GAO and HAM obtained from: (1) ITSG 2018 GRACE solution (SST-ll), (2) solutions based on kinematic orbits of Swarm A–C, TanDEM-X and TerraSAR-X satellites (SST-hl).

VI. NONSEASONAL CHANGES

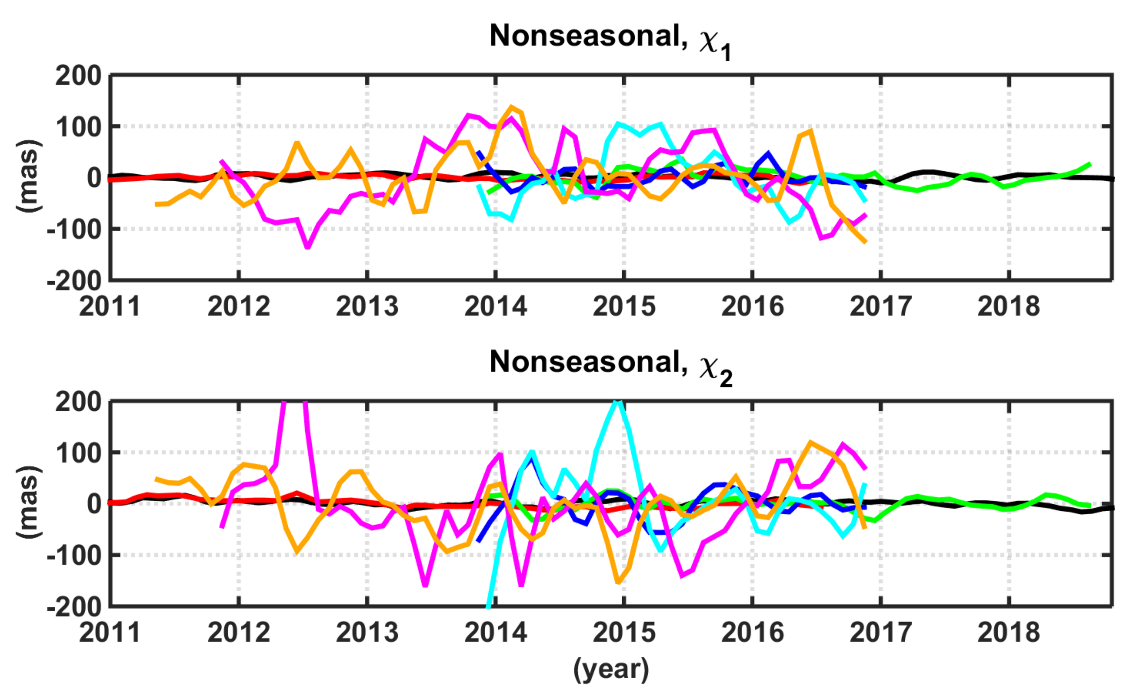


good phase and amplitude agreement between all series from kinematic orbits for both χ_1 and χ_2;

there are some periods where HAM series from SST-hl agree well in phase with GAO but they have amplitudes generally higher than those obtained from GAO and ITSG 2018 ;

it is hard to indicate the SST-hl solution that gives the best results.

Fig.3. χ_1 and χ_2 nonseasonal (after removing seasonal) components of GAO and HAM obtained from: (1) ITSG 2018 GRACE solution (SST-ll), (2) solutions based on kinematic orbits of GRACE satellites (SST-hl) and (3) combined solutions (SST-hl). The combined solutions are based on kinematic orbits of both gravimetry and non-dedicated satellites (see *Zehentner & Mayer-Gürr, 2016*).



for χ_1 and χ_2 the best amplitude and phase agreement with GAO and ITSG 2018 provides Swarm A-C from CAS;

series from other satellites noticeably overestimate amplitudes of GAO and ITSG 2018-based HAM.

Fig.4. χ_1 and χ_2 nonseasonal components of GAO and HAM obtained from: (1) ITSG 2018 GRACE solution (SST-ll), (2) solutions based on kinematic orbits of Swarm A–C, TanDEM-X and TerraSAR-X satellites (SST-hl).

VII. SEASONAL AND NONSEASONAL CHANGES – CORRELATION COEFFICIENTS WITH GAO

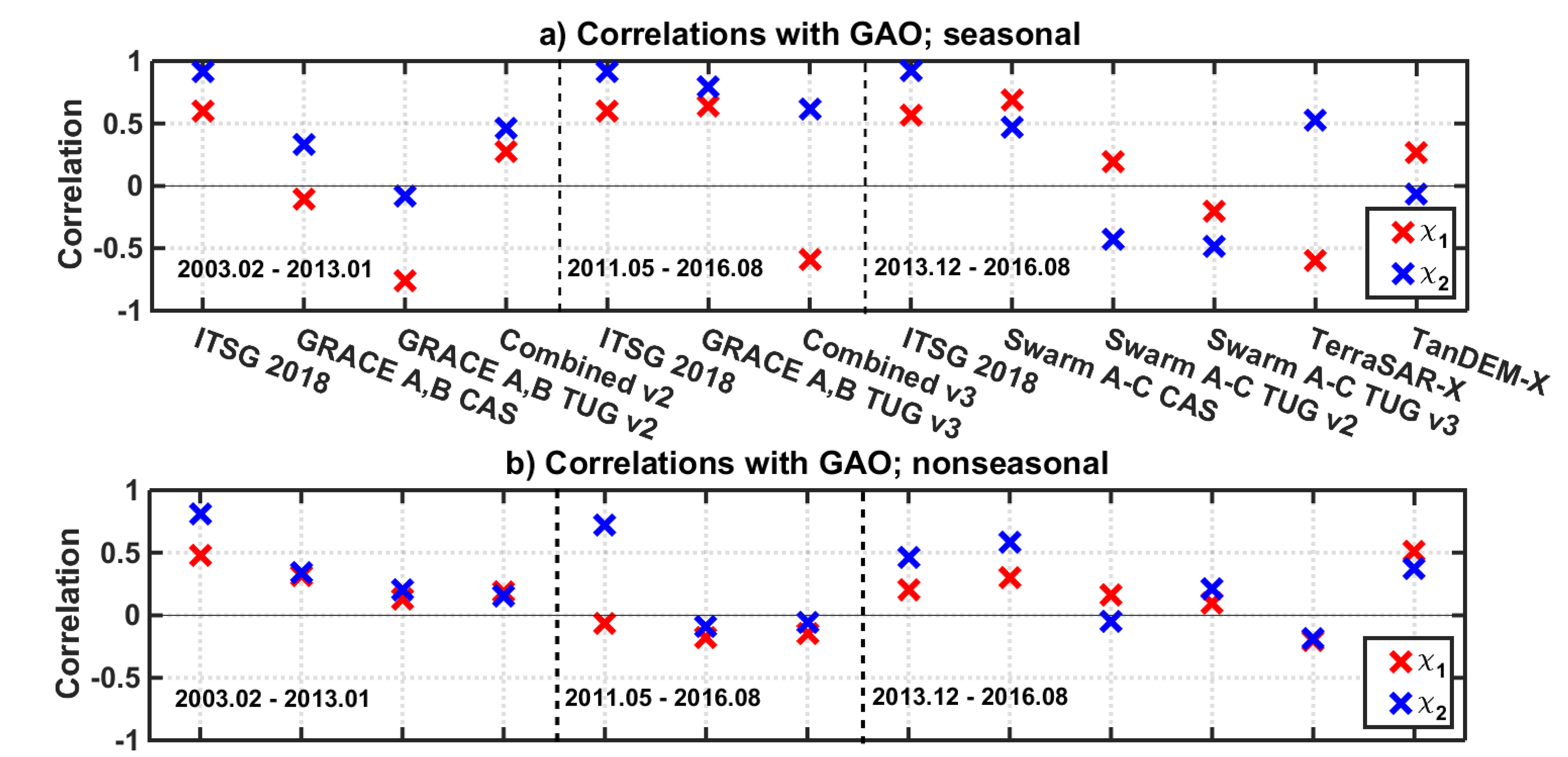


Fig. 5. Correlation coefficients between GAO and HAM obtained from ITSG 2018 GRACE solution (SST-ll) and solutions based on kinematic orbits of satellites (SST-hl). Because of different data length of series, we consider three periods. a) seasonal changes, b) nonseasonal changes.

VIII. CONCLUSIONS

- **Standard deviation:** The higher altitude of the satellite, the bigger STD of HAM. All SST-hl solutions overestimate STD of GAO.
- **Trends:** for χ_1 the most compatible trends with GAO provide series from kinematic orbits of GRACE from CAS and TUG v2, Swarm A-C from TUG v2, TerraSAR-X and combined solutions; for χ_2 – GRACE from TUG v3, Swarm from CAS and TUG v3 and combined solutions. Other satellites noticeably overestimates these values. The size of trends of GAO and ITSG 2018-based HAM depends on considered time period.
- **Seasonal oscillations:** Visibly better phase agreement with GAO for χ_2; for χ_1 there are many antiphases with GAO. Apart from GRACE SST-hl and combined solutions, high correlations are detected for Swarm A–C CAS.
- **Nonseasonal oscillations:** all HAM series from GRACE-based SST-hl and combined solutions are comparable with each other. For other satellites, only Swarm A–C CAS provides high amplitude agreement with GAO. For many cases the correlations with GAO are higher for non-seasonal variations. One of the highest correlations are obtained for series from TanDEM-X.
- **General remarks:** It is difficult to objectively assess the quality of all considered time series due to short joint data period. Of course, neither of considered missions provide full agreement with GRACE-based hydrological excitations and GAO. However, the combination of few solutions improves these results.
- The Swarm A–C CAS solution provides highest correlation and amplitude agreement with GAO than corresponding solutions derived from TUG.
- We observe a decrease of correlation with GAO for v3 series from TUG (both GRACE-only and combined) comparing to v2.

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