Eight years of temporal gravity changes observed by the Swarm satellites

J. Encarnação[1,2] D. Arnold[3] A. Bezděk[4] C. Dahle[5] J. Guo[7] J. van den IJssel[1] A. Jäggi[3] J. Klokočník[4] S. Krauss[8] T. Mayer-Gürr[8] U. Meyer[3] J. Sebera[4] CK Shum[7] P. Visser[1] Y. Zhang[7]

[1]Delft University of Technology [2]Center for Space Research, The University of Texas at Austin [3]Astronomical Institute of the University of Bern [4]Astronomical Institute of the Czech Academy of Sciences [5]GFZ German Research Centre for Geosciences [6]Royal Netherlands Meteorological Institute [7]School of Earth Sciences of The Ohio State University [8]Institute of Geodesy of the Graz University of Technology

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Context and objectives

- ESA/DISC funded project (since 9/2017)
- Provide highest-quality monthly-independent Swarm gravity field models
- Combine individual gravity solutions, computed with:
  - different kinematic orbit solutions
  - different inversion approaches
- Monthly combined Swarm gravity field models:
  - period length set by the calendar month (first to last day)
  - from 2013-12-01 to 2021-12-31
  - available from:
    - ICGEM `icgem.gfz-potsdam.de/series/02_COST-G/Swarm`
    - ESA `swarm-diss.eo.esa.int` > *Level2longterm* > *EGF*

Kinematic Orbits

Institute	Software	Reference
AIUB	Bernese v5.3	Jäggi et al. (2016)[1]
IfG	Gravity Recovery Object Oriented Programming System (GROOPS)	Zehentner and Mayer-Gürr (2016)[2]
TUD	GPS High precision Orbit determination Software Tool (GHOST)	IJssel et al. (2015)[3]

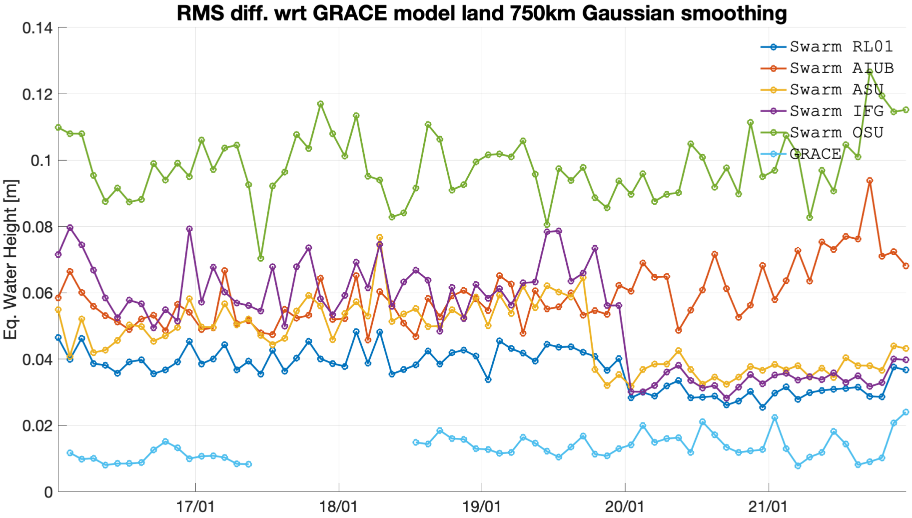
[1] ftp://ftp.aiub.unibe.ch/leo_orbits/swarm
[2] ftp://ftp.tugraz.at/outgoing/ITSG/tvgogo/orbits/Swarm
[3] http://earth.esa.int/web/guest/swarm/data-access

Individual Gravity field models

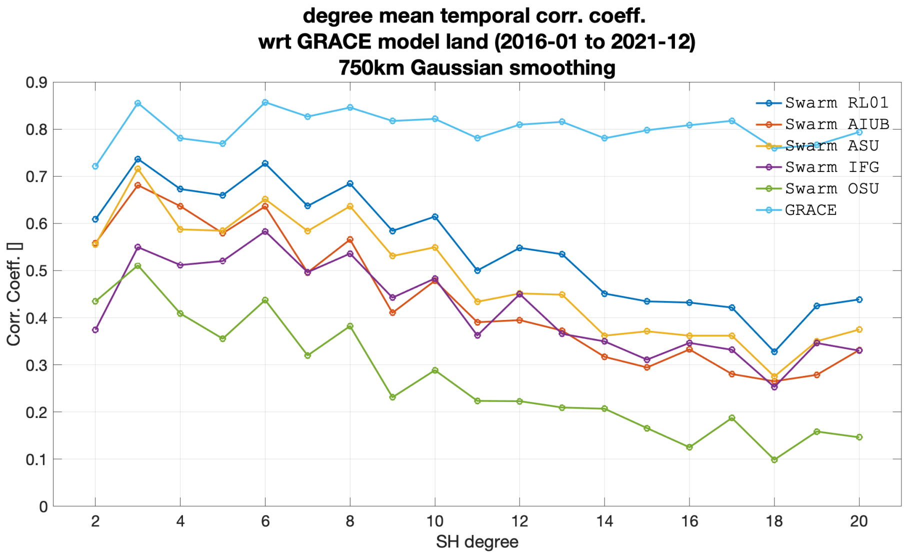
Inst.	Approach	Reference
AIUB	Celestial Mechanics Approach	Jäggi et al. (2016)
ASU	Decorrelated Acceleration Approach	Bezděk et al. (2016)
IfG	Short-Arcs Approach	Zehentner and Mayer-Gürr (2016)
OSU	Improved Energy Balance Approach	Guo et al. (2015)

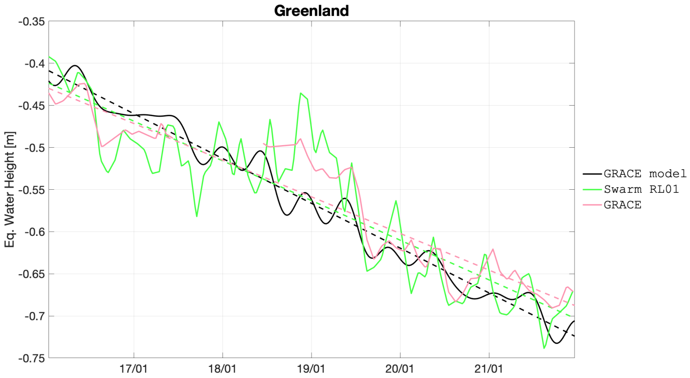
Combined Gravity field models

- Combination at the level of solutions, up to degree 40
- Weights applied to individual solutions derived from Variance Component Estimation (VCE)
- Degrees 2-20 considered in VCE
- João Teixeira da Encarnação and Pieter Visser (2019). *TN-03: Swarm models validation*. Tech. rep. TU Delft. DOI: 10.13140/RG.2.2.33313.76640



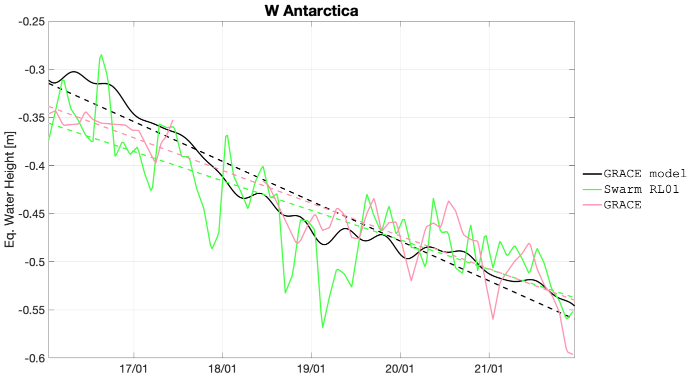
swarm SWARM DISC COST-G UNIVERSITÄT BERN Astronomical Institute of the Czech Academy of Sciences GFZ Helmholtz Centre POTSDAM The Ohio State University TU Delft TU Graz TEXAS The University of Texas at Austin


degree mean temporal corr. coeff.
wrt GRACE model land (2016-01 to 2021-12)
750km Gaussian smoothing
Corr. Coeff. []
SH degree
Swarm RL01
Swarm AIUB
Swarm ASU
Swarm IFG
Swarm OSU
GRACE
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
2
4
6
8
10
12
14
16
18
20



solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
GRACE MODEL	-56.63	0.00	-5.32	0.00	1.00
Swarm RL01	-56.29	0.34	-4.71	0.61	0.91
GRACE	-57.31	-0.68	-4.35	0.97	0.95

latitude 60 to 85 degrees, longitude -60 to -37 degrees

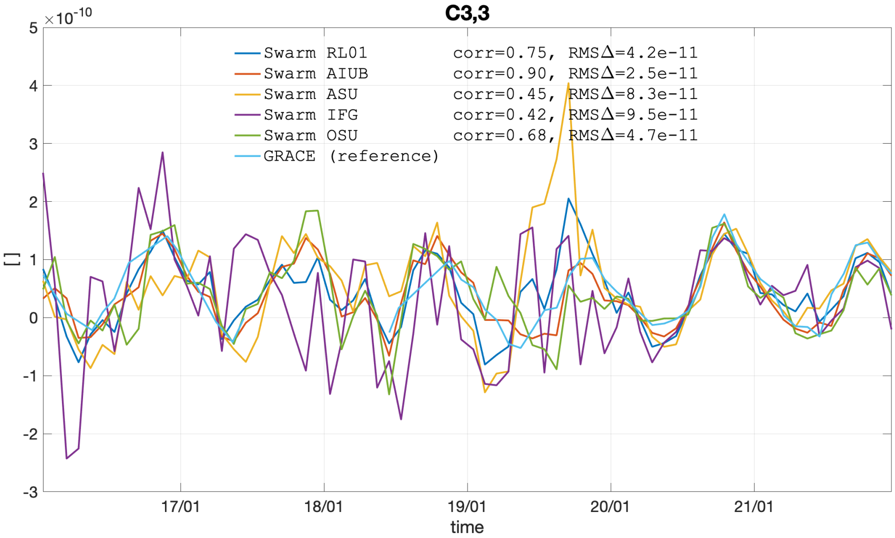


solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
GRACE MODEL	-43.71	0.00	-4.14	0.00	1.00
Swarm RL01	-44.66	-0.95	-3.06	1.07	0.89
GRACE	-45.25	-1.54	-3.40	0.74	0.95

latitude -80 to -70 degrees, longitude -140 to -85 degrees

Statistics from all 18 analysed basins

solution	constant term Δ RMS [cm]	linear term Δ RMS [cm/year]	corr. coeff. mean [ ]
GRACE model	0.00	0.00	1.00
Swarm RL01	1.23	0.75	0.76
GRACE	0.92	0.78	0.88



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Conclusions (I)

- Combined model better than individual models under any metric
- Swarm signal useful below degree 15 (750 km radius smoothing)
- Swarm gravity field model quality stable since 2016
- IfG KO orbit processing changes result in a slight improvement since 2020
- Ocean areas are $\approx$ 30-50% noisier than land areas

Conclusions (II)

- Seasonal land signal clearly resolvable by Swarm (compared to GRACE model):
  - Temporal correlations dip under 0.5 over degree 13
  - Global spatial agreement at $\approx$ 4 cm RMS EqWH (before 2020)
  - Over 18 analysed basins (of various sizes):
    - trends agree under 0.75cm/year EqWH
    - correlation is at 0.76
- Since early 2020:
  - Temporal correlations higher (below degree 13)
  - Global spatial agreement with GRACE model at $\approx$ 3 cm RMS EqWH
- Suitable for GRACE/GRACE-FO gap/outage filling (since 2016)

Extra slides

AIUB Processing strategy

Software: Bernese v5.3 (Dach et al., 2015)

Approach: Celestial Mechanics Approach (Beutler et al., 2010)

Reference GFM: AIUB-GRACE03S (Jäggi et al., 2011)

Empirical Parameters: Daily and 15 minutes, both piecewise-constant (constrained)

Temporal correlations: None

Drag Model: None

EARP and EIRP Models: None

Non-tidal Model: **Unti Nov 2017:** Atmosphere and Ocean De-aliasing Level 1B (Flechtner, 2011)
After Nov 2017: Atmosphere and Ocean De-aliasing Level 1B RL06 (Dobslaw et al., 2017)

Ocean Tidal Model: 2011 Empirical Ocean Tide model (Savcenko and Bosch, 2012)

Permanent Tide System: tide-free

ASU Processing strategy

Software: (developed in-house)

Approach: Decorrelated Acceleration Approach (Bezděk et al., 2014)

Reference GFM: ITG GRACE-only static model, 2010 (Mayer-Gürr et al., 2010)

Empirical Parameters: Daily constant-piecewise

Temporal correlations: Empirical decorrelation filter

Drag Model: Naval Research Laboratory Mass Spectrometer and Incoherent Scatter radar (Picone et al., 2002)

EARP and EIRP Models: Knocke, Ries, and Tapley (1988)

Atmospheric Tidal Model: Biancale and Bode (2006)

Ocean Tidal Model: 2004 Finite Element Solution (Lyard et al., 2006)

Permanent Tide System: tide-free

IfG Processing strategy

Software: GROOPS

Approach: Short-Arcs Approach (Mayer-Gürr, 2006)

Reference GFM: GOCO release 05 satellite-only gravity field model (Mayer-Gürr, 2015)

Empirical Parameters: Piecewise linear for each arc (ranging from 15 to 45 minutes)

Temporal correlations: Empirical covariance function

Drag Model: Jacchia-Bowman 2008 (Bowman et al., 2008)

EARP and EIRP Models: Rodriguez-Solano et al. (2012)

Ocean Tidal Model: 2014 Finite Element Solution (Carrere et al., 2015)

Permanent Tide System: zero tide

OSU Processing strategy

Software: (developed in-house)
Approach: Improved Energy Balance Approach (Shang et al., 2015)
Reference GFM: GRACE Intermediate Field 48 (Ries et al., 2011) up to Degree and Order (D/O) 200
Empirical Parameters: 2nd order polynomial every 3 hours, 1-Cycle Per Revolution (CPR) sinusoidal every 24 hours
Temporal correlations: None
Drag Model: Naval Research Laboratory Mass Spectrometer and Incoherent Scatter radar (Picone et al., 2002)
EARP and EIRP Models: Knocke, Ries, and Tapley (1988)
Ocean Tidal Model: 2011 Empirical Ocean Tide model (Savcenko and Bosch, 2012)
Permanent Tide System: tide-free

Common assumptions

Atmospheric Tidal Model: Biancale and Bode (2006)

Solid Earth Tidal Model: IERS2010

Pole Tidal Model: IERS2010

Ocean Pole Tidal Model: IERS2010

Third body perturbations: Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn, following the JPL Planetary and Lunar Ephemerides (Folkner et al., 2014)

$C_{2,0}$ **coefficient:** estimated alongside other coefficients

Non-tidal Model: Atmosphere and Ocean De-aliasing Level 1B RL06 (Dobslaw et al., 2017)

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