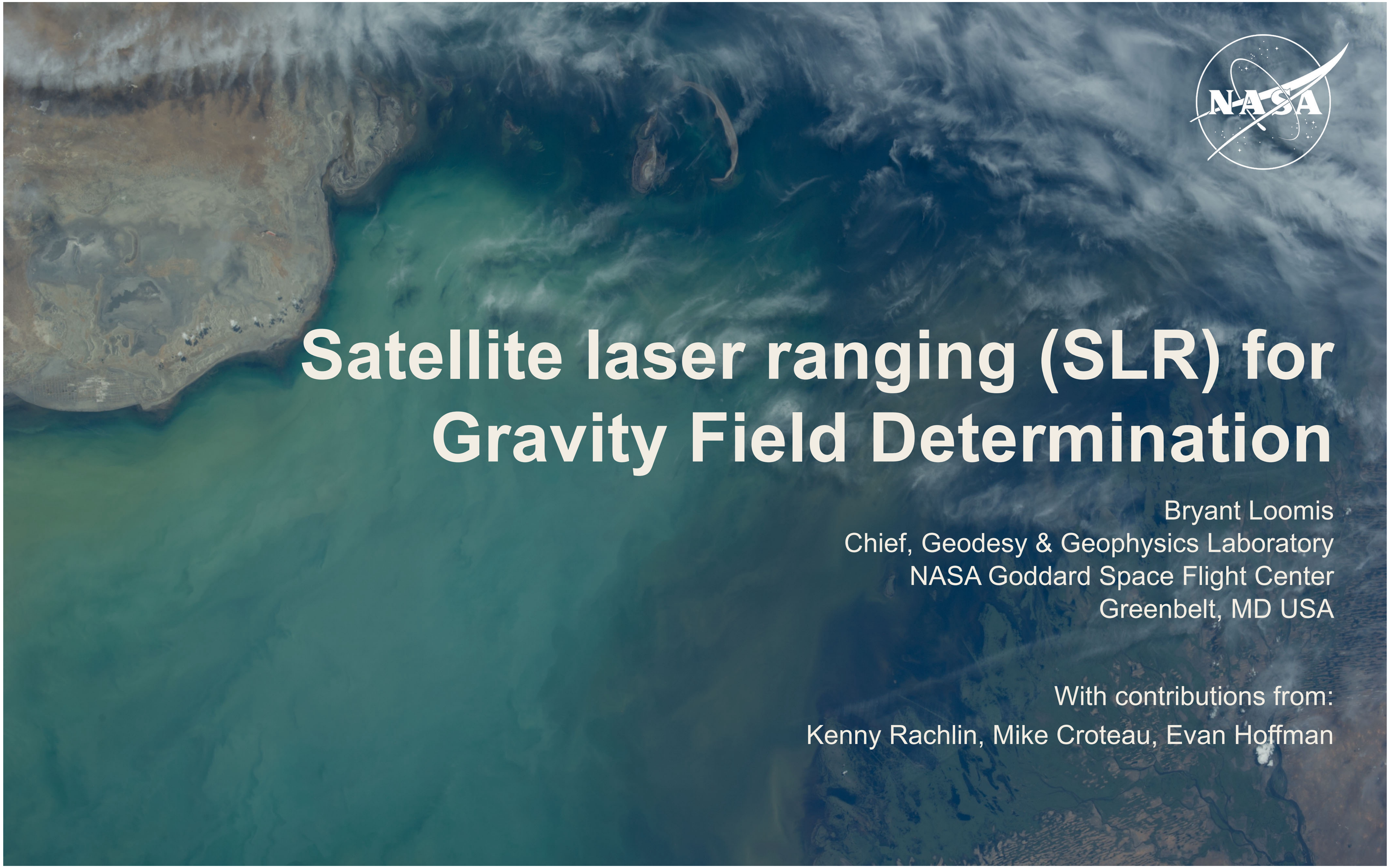

Satellite laser ranging (SLR) for Gravity Field Determination

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With contributions from:
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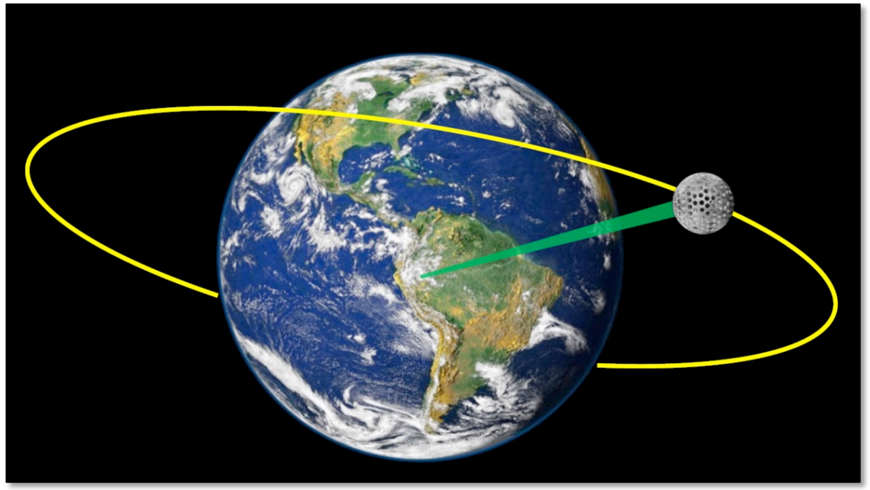
Outline

- SLR overview
- SLR data processing summary
- Gravity field determination (with focus on GSFC contributions)
- Combined SLR + GRACE gravity estimation
- Space Geodesy SLR (SGSLR) – the next generation SLR system

SLR Overview

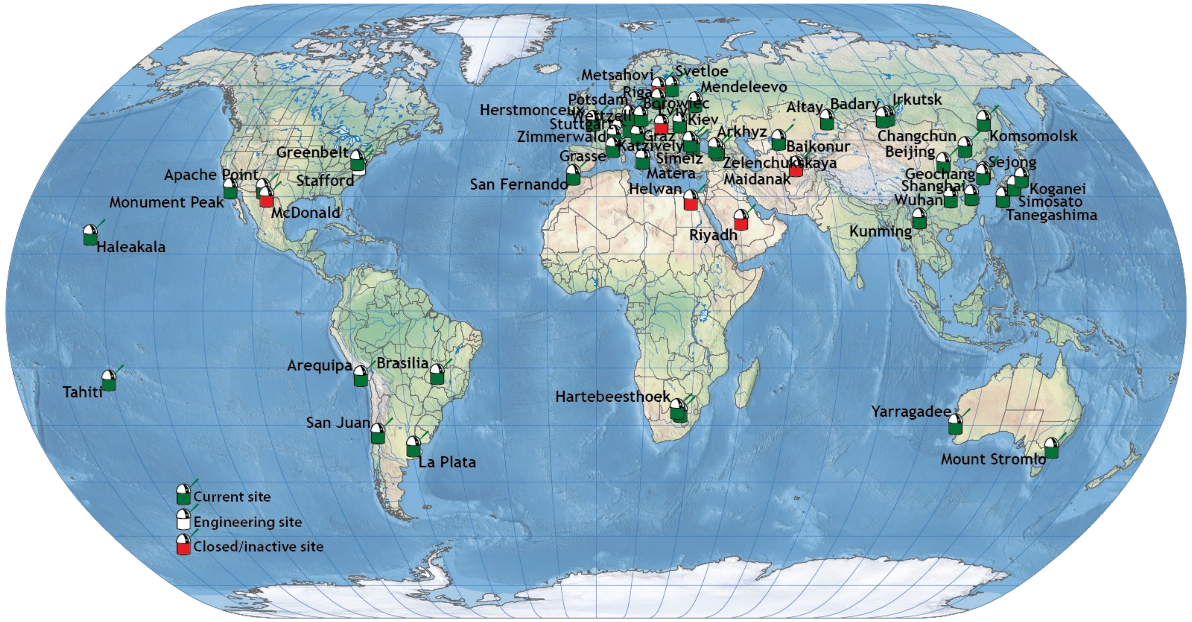
SLR provides range measurements:

- Fire a short laser pulse to a satellite equipped with a retro-reflecting mirror
- Time when the laser pulse leaves the station
- Laser pulse reflects off the mirror back towards the station
- Time when the laser pulse is received
- Correct for atmospheric delay
- Modern stations have 1-2 mm measurement precision
- SLR satellites have ~1 cm level orbit accuracy
- Full-rate (10 Hz – kHz) tracking measurements are converted to normal point data (~30 sec – 2 min) distributed by NASA's Crustal Dynamics Data Information System (CDDIS) and the EUROLAS Data Center (EDC) at DGFI-TUM

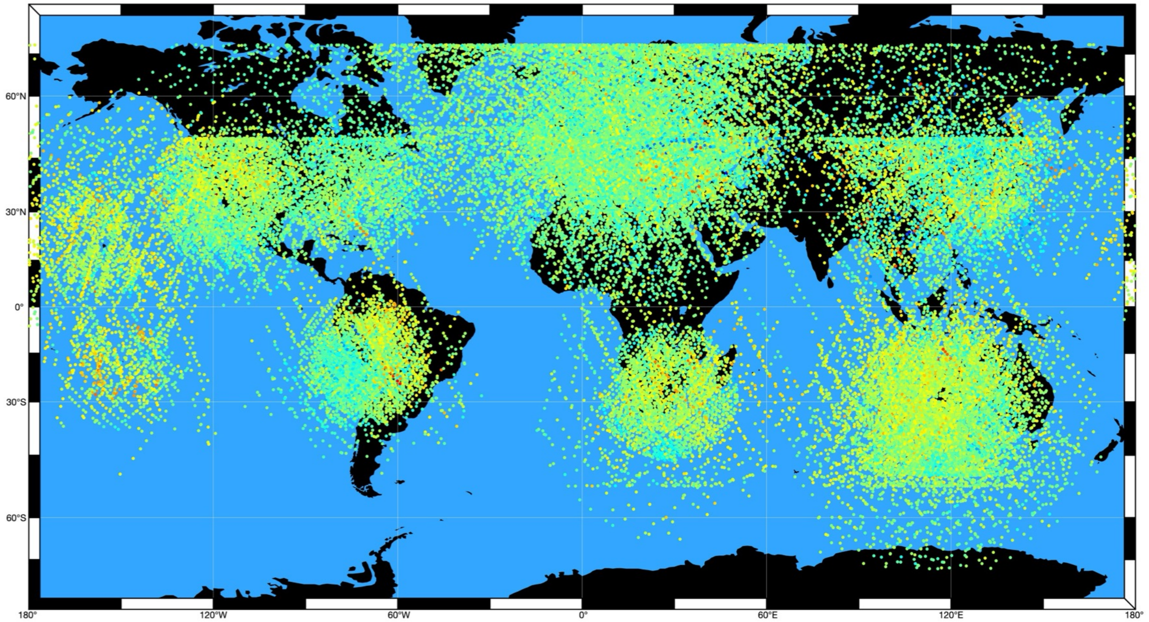


SLR Overview

Map of SLR stations



Tracking residuals (one month)



SLR Overview

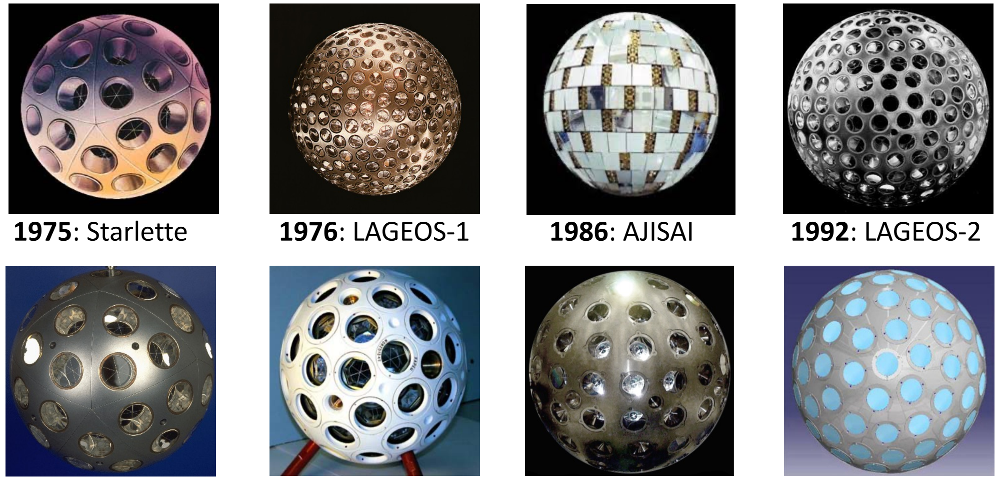
International Laser Ranging Service (ILRS) overview:

- Organizes laser ranging activities and provides global satellite and lunar laser ranging data to support research in geodesy, geophysics, Lunar science, and fundamental constants
- Includes data products that are fundamental to the International Terrestrial Reference Frame (ITRF), which is established and maintained by the International Earth Rotation and Reference Systems Service (IERS)
- Develops the necessary global standards and specifications for laser ranging activities
- Analysis Centers (AC) operationally contribute to the ITRF, but not to gravity estimation
- Website: https://ilrs.gsfc.nasa.gov/

SLR Overview

- SLR is one of four fundamental space geodesy measurement systems (SLR, VLBI, DORIS, GNSS) that contribute to the determination of Earth Orientation Parameters (EOP) and the International Terrestrial Reference Frame (ITRF)
- Of these techniques, SLR can best resolve changes in the low degree gravity field

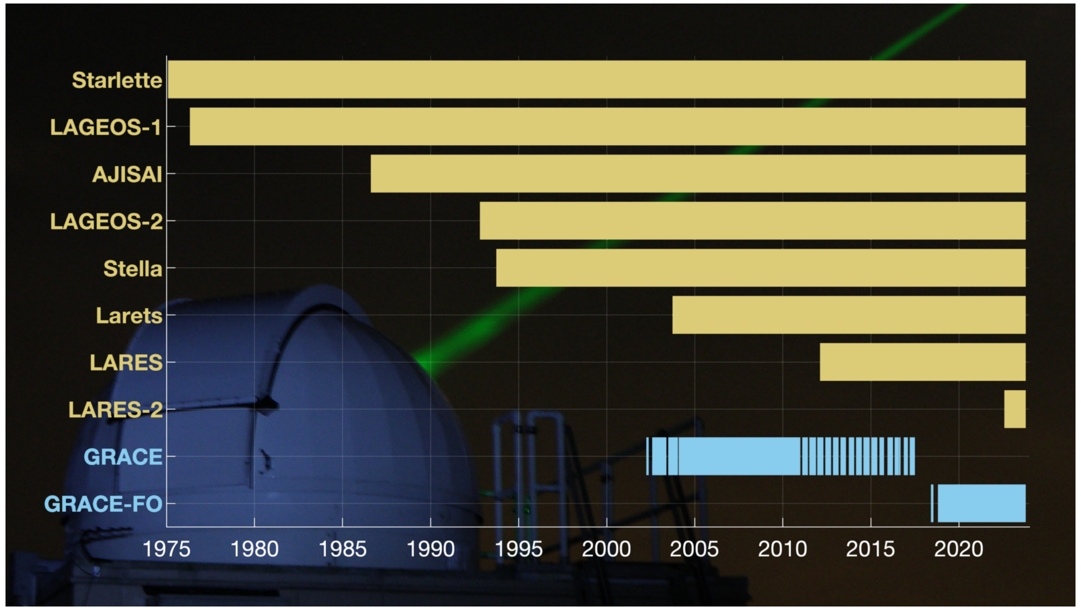
Dedicated SLR satellites used for time-variable gravity



1975: Starlette
1976: LAGEOS-1
1986: AJISAI
1992: LAGEOS-2
1993: Stella
2003: Larets
2012: LARES
2022: LARES-2

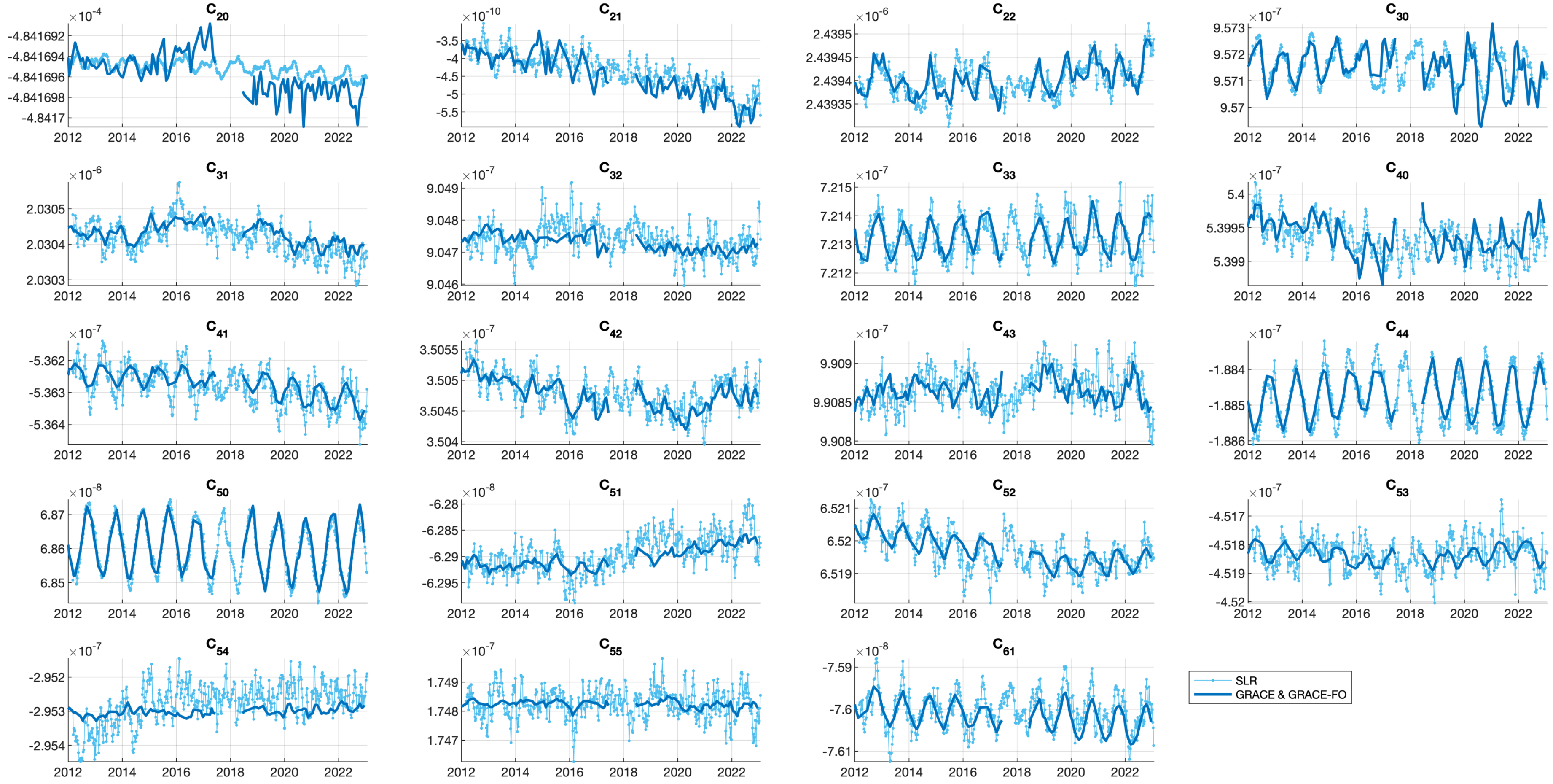
SLR Overview

- The earliest studies on SLR time variable gravity were from the University of Texas Center for Space Research (UT-CSR), largely led by Minkang Cheng and John Ries
- Other centers with history of SLR gravity estimation include NASA GSFC, CNES-GRGS, GFZ, AIUB/Wroclaw, DGFI-TUM, U. Bonn (apologies to any I have missed!)
- Various SLR gravity products:
  - 1976 – Present: C_{20} only
  - 1992 – Present: Low degree expansion (e.g., 5x5, 10x10)
  - 1992 – Present: Novel methods (e.g., EOF, large mascons, stacked normal equations)
  - 1992 – Present: SLR + DORIS
  - 2002 – Present: SLR + GRACE/-FO + LEO/GNSS

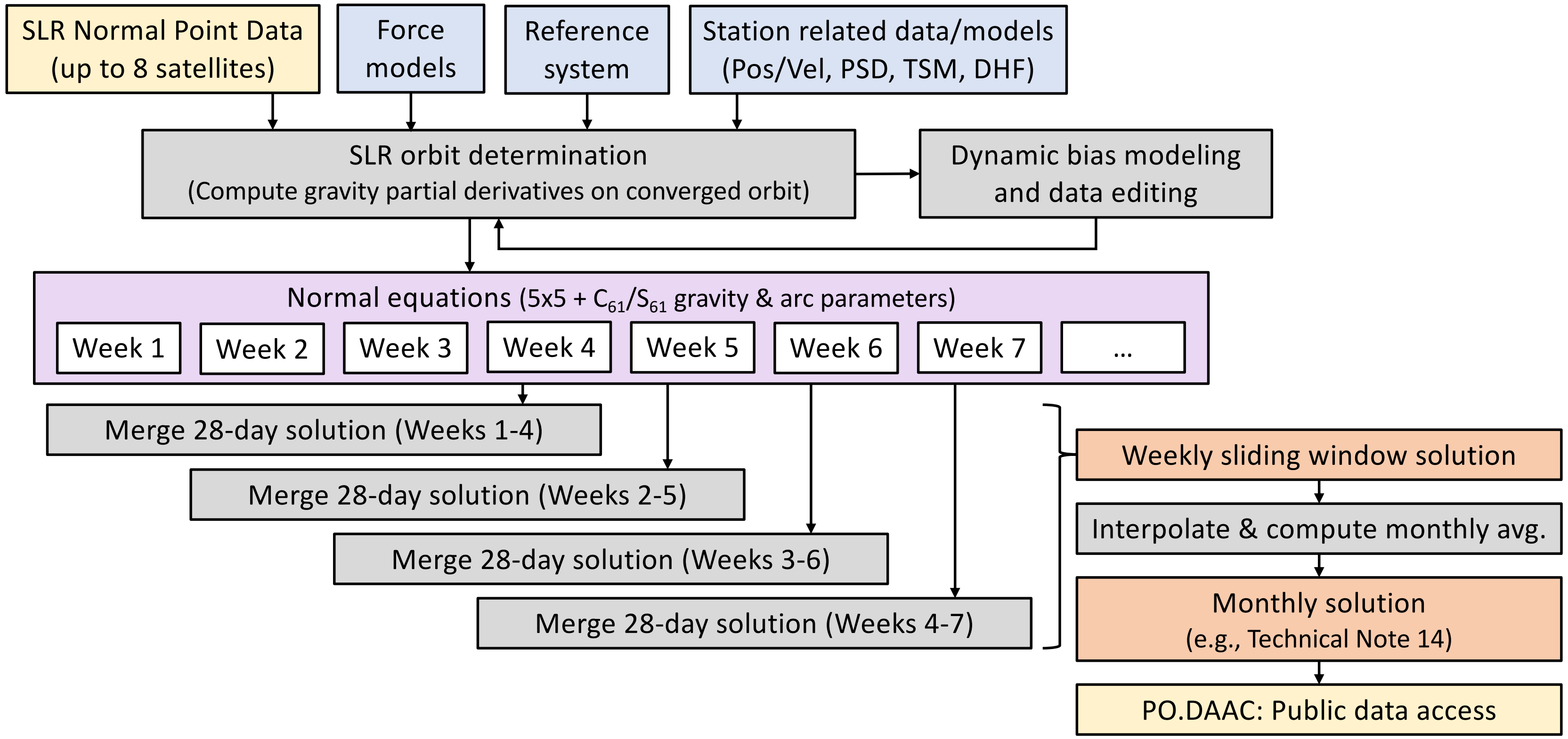


SLR Overview

- For unregularized solutions, SLR is sensitive to some low degree/order coefficients; high correlations are a major challenge



SLR Processing



SLR Normal Point Data (up to 8 satellites)

Force models

Reference system

Station related data/models (Pos/Vel, PSD, TSM, DHF)

SLR orbit determination (Compute gravity partial derivatives on converged orbit)

Dynamic bias modeling and data editing

Normal equations (5x5 + C_{61}/S_{61} gravity & arc parameters)

Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | …

Merge 28-day solution (Weeks 1-4)

Merge 28-day solution (Weeks 2-5)

Merge 28-day solution (Weeks 3-6)

Merge 28-day solution (Weeks 4-7)

Weekly sliding window solution

Interpolate & compute monthly avg.

Monthly solution (e.g., Technical Note 14)

PO.DAAC: Public data access

SLR Processing

Data inputs/definitions for the SLR processing system:

- Force models
- Earth Orientation Parameters
- Station-related values
  - Positions & rates, including distance from laser “center” to survey point
  - Post-seismic deformation model
  - Geocenter variability
  - Target Signature Model (e.g., satellite center-of-mass offset) by station for most satellites
  - Data Handling File:
    - Long-term range biases estimated from LAGEOS-1/2 that are assumed stable over a given time interval
    - List of data to be deleted
    - List of recommended biases to be estimated

SLR Processing

Arc parameterization:

MEO satellites (LAGEOS-1, LAGEOS-2, LARES-2):

- Satellite position & velocity
- Empirical accelerations 1 cycle-per-rev along-track & cross-track, along-track constant, every 3.5 d
- Range measurement bias
- Solar radiation coefficient (constrained)

LEO satellites (AJISAI, LARES, Larets, Starlette, Stella):

- Satellite position & velocity
- Empirical accelerations – 1 cycle-per-rev along-track & cross-track, every 3.5 d
- Drag coefficient
- Range measurement bias
- Solar radiation coefficient (constrained)

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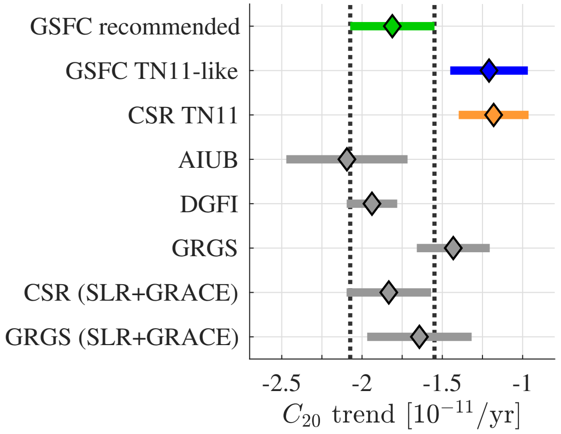
Gravity field determination: GSFC's perspective

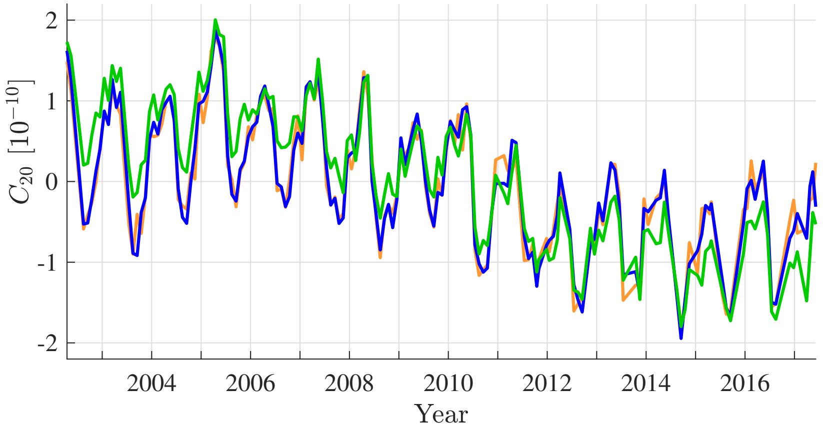
- Starting point for current GSFC SLR gravity estimation in 2018:
  - Zelensky et al. (2014) – GSFC's institutional knowledge of SLR processing for orbit determination and ITRF contributions
  - Sośnica et al. (2015) – Relative contribution for different SLR satellites determines GSFC's relative weighting
  - Cheng and Ries (2016) – Optimization of selected gravity parameters: 5x5 + C_{61}/S_{61}
- While validating our SLR gravity estimates, we identified large discrepancies between various solutions in the reported C_{20} rates, leading to Loomis et al. (2019) – next chart:

Gravity field determination: GRACE era C_{20}

Summary of Loomis et al. (2019):

- Demonstrated impact of background time variable gravity model on the recovery of C_{20}
- C_{20} rate increased by ~38% for 2005–2015
- Improved global mean sea level budget agreement: Total (altimetry) = Mass (GRACE/SLR) + Steric (Argo)
- Improved agreement of C_{20} seasonal variability to independent length-of-day (LOD) observations





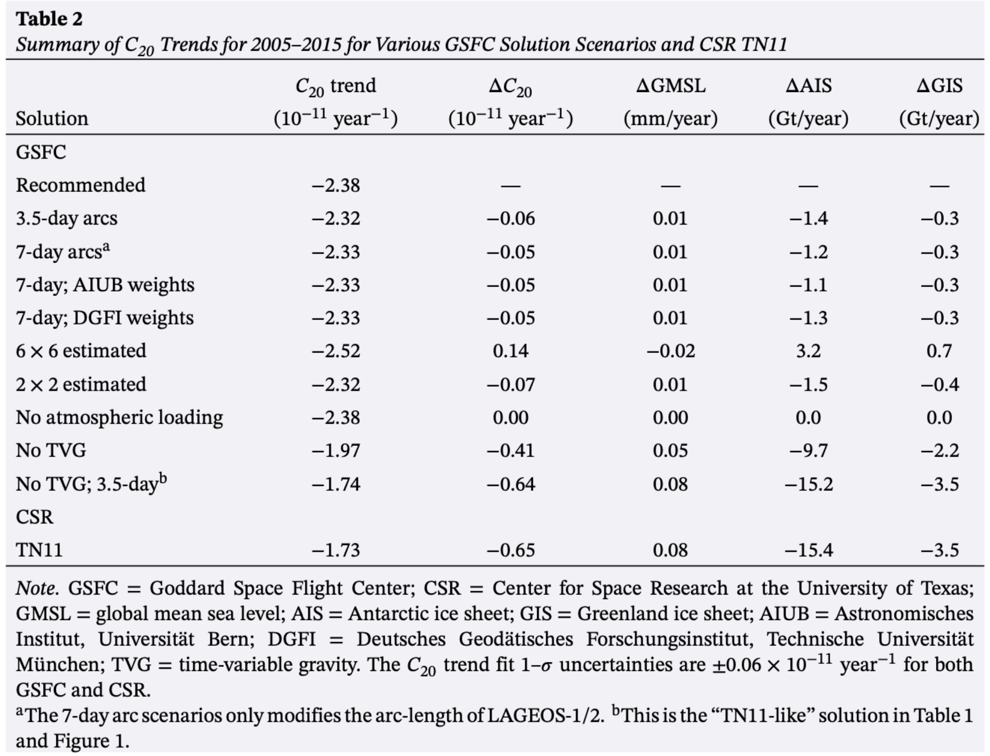


Table 2

Summary of C_{20} Trends for 2005–2015 for Various GSFC Solution Scenarios and CSR TN11

Solution	C_{20} trend (10^{-11} year^{-1})	ΔC_{20} (10^{-11} year^{-1})	ΔGMSL (mm/year)	ΔAIS (Gt/year)	ΔGIS (Gt/year)
GSFC					
Recommended	−2.38	—	—	—	—
3.5-day arcs	−2.32	−0.06	0.01	−1.4	−0.3
7-day arcs[a]	−2.33	−0.05	0.01	−1.2	−0.3
7-day; AIUB weights	−2.33	−0.05	0.01	−1.1	−0.3
7-day; DGFI weights	−2.33	−0.05	0.01	−1.3	−0.3
6 × 6 estimated	−2.52	0.14	−0.02	3.2	0.7
2 × 2 estimated	−2.32	−0.07	0.01	−1.5	−0.4
No atmospheric loading	−2.38	0.00	0.00	0.0	0.0
No TVG	−1.97	−0.41	0.05	−9.7	−2.2
No TVG; 3.5-day[b]	−1.74	−0.64	0.08	−15.2	−3.5
CSR					
TN11	−1.73	−0.65	0.08	−15.4	−3.5

Note. GSFC = Goddard Space Flight Center; CSR = Center for Space Research at the University of Texas; GMSL = global mean sea level; AIS = Antarctic ice sheet; GIS = Greenland ice sheet; AIUB = Astronomisches Institut, Universität Bern; DGFI = Deutsches Geodätisches Forschungsinstitut, Technische Universität München; TVG = time-variable gravity. The C_{20} trend fit 1–σ uncertainties are ±0.06 × 10^{-11} year^{-1} for both GSFC and CSR.

[a] The 7-day arc scenarios only modifies the arc-length of LAGEOS-1/2. [b] This is the "TN11-like" solution in Table 1 and Figure 1.

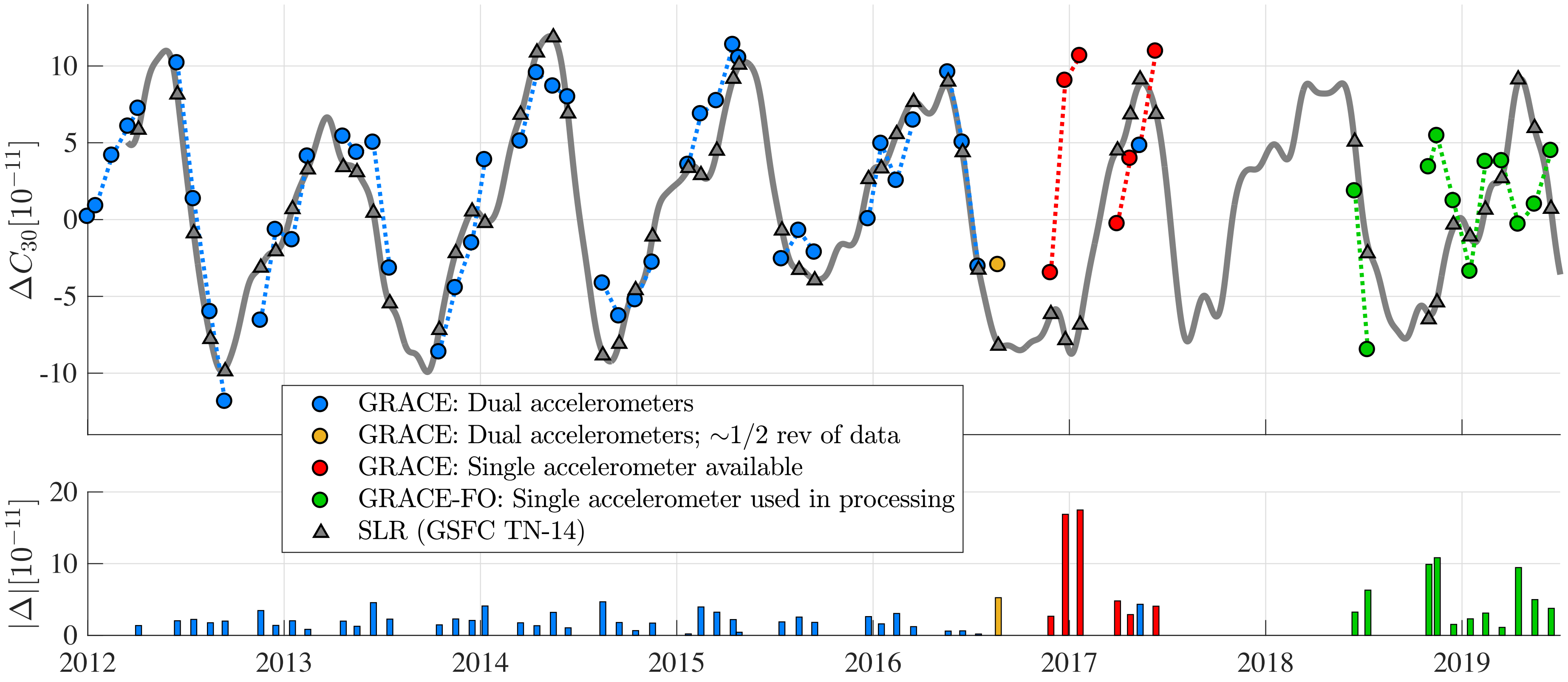
Gravity field determination: C_{30}

Discovering the importance of C_{30}:

- Loomis et al. (2019) used the same 5 SLR satellites as Cheng and Ries (2016)
- While updating our SLR processing to include new satellites Larets (2003) and LARES (2012), we discovered that the inclusion of LARES significantly improves the recovery of C_{30} and C_{50}
- The sensitivity of LARES to C_{30} was first reported by Sośnica et al. (2015)
- The significance of this result became apparent when discussing early GRACE-FO gravity estimates with David Wiese (JPL)
- GRACE & GRACE-FO estimates of C_{30} have reduced accuracy when only one accelerometer is unavailable (late GRACE) or underperforming (all of GRACE-FO), which has major impacts on the application of the GRACE/-FO products, especially on the Antarctic Ice Sheet
- GSFC's new 7-satellite solution for C_{30} was presented in Loomis et al. (2020) – next chart

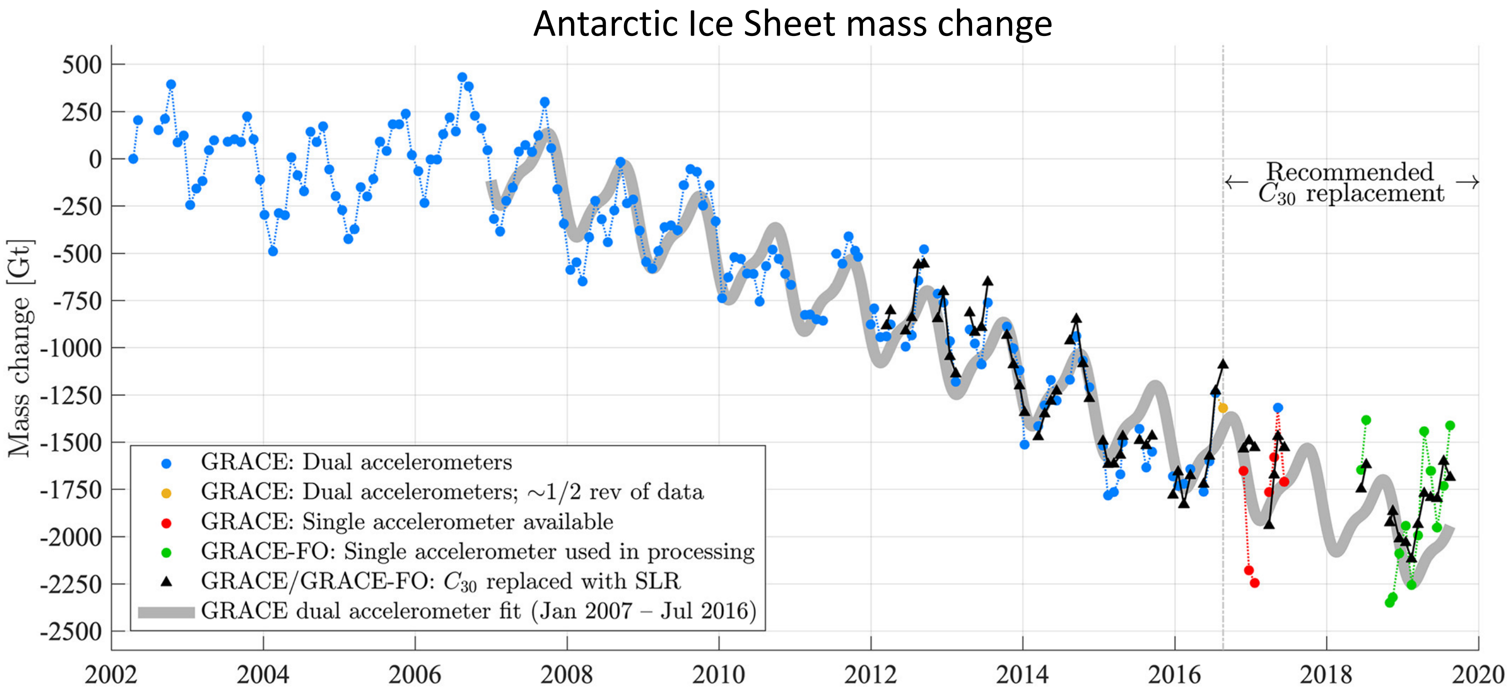
Gravity field determination: C_{30}

Results from Loomis et al. (2020):



Gravity field determination: C_{30}

Results from Loomis et al. (2020):



Data span	C_{30} replacement?	Antarctic Ice Sheet trend	Equiv. ocean mass trend
Jan 2007 – July 2016:	N/A	−167 ± 10 Gt yr^{-1}	+0.46 ± 0.03 mm yr^{-1}
Aug 2016 – Aug 2019:	Yes	−170 ± 34 Gt yr^{-1}	+0.47 ± 0.09 mm yr^{-1}
Aug 2016 – Aug 2019:	No	−92 ± 47 Gt yr^{-1}	+0.26 ± 0.13 mm yr^{-1}

Gravity field determination: TN-14

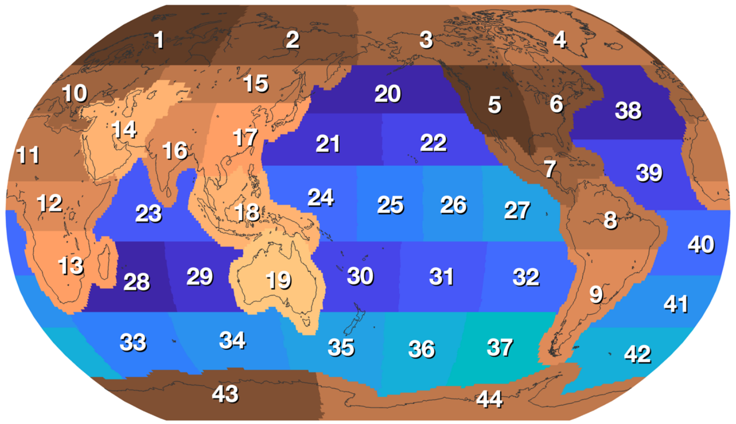
Technical Note 14:

- (Loomis et al., 2019 & 2020) led the GRACE-FO SDS to recommend the new TN-14
- C_{20} replacement recommended for all GRACE & GRACE-FO months
- C_{30} replacement recommended for all GRACE months after August 2016 and all GRACE-FO months
- GRACE-FO estimates of C_{30} have improved significantly with improved accelerometer transplant products, but for now, replacement with TN-14 is still recommended
- We have continued to improved the accuracy of TN-14 over the original version with monthly updates of the background TVG models

Gravity field determination: SLR mascons

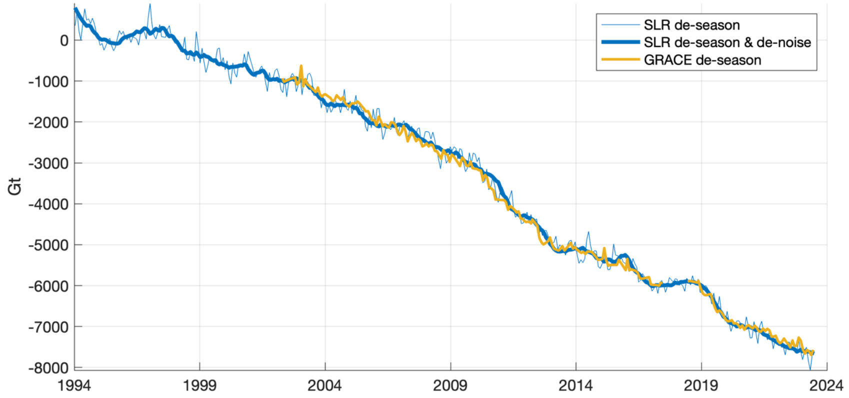
Continental-sized mascons from SLR to extend mass change record to 1990’s:

SLR mascon definitions

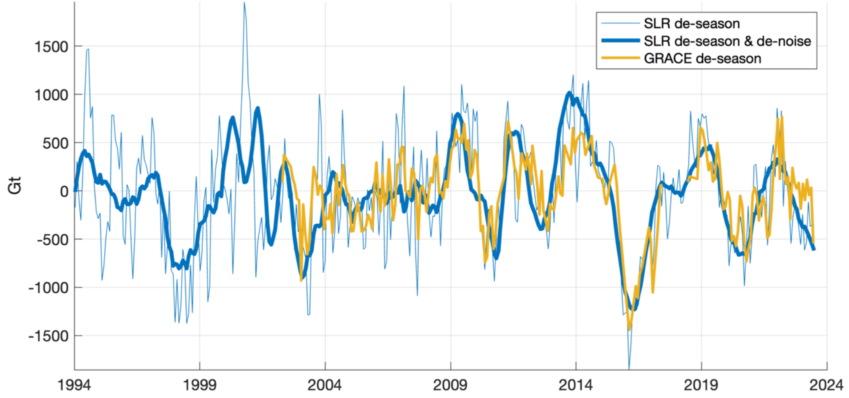


- Large mascons estimated from SLR tracking data
- Partial derivatives computed to 10x10
- Simple diagonal regularization tuned to best agree with GRACE/-FO estimates (JPL RL06.1 shown)
- Trends are calibrated to match GRACE/-FO (tests revealed that inter-annual estimates are not sensitive to background model, while trends are)

Greenland + Canadian Arctic (Mascon 4)



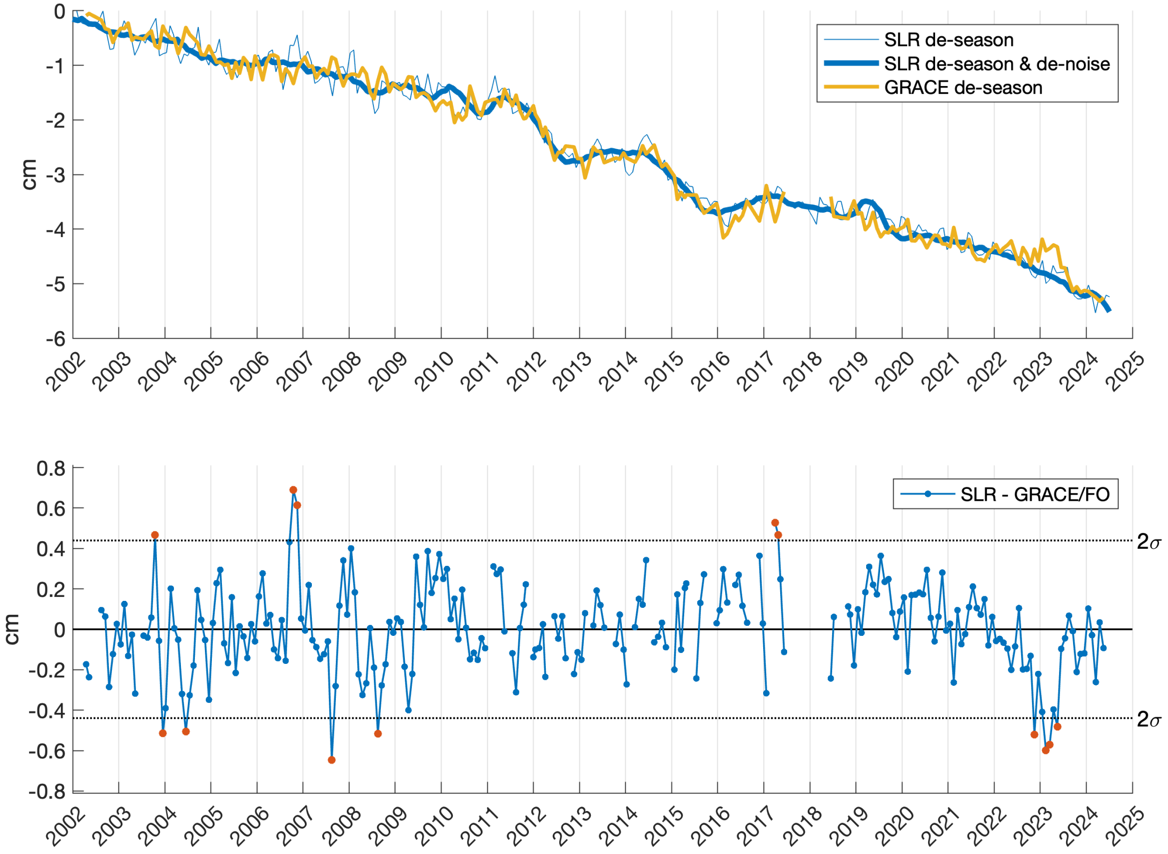
South America (Mascons 8 & 9)



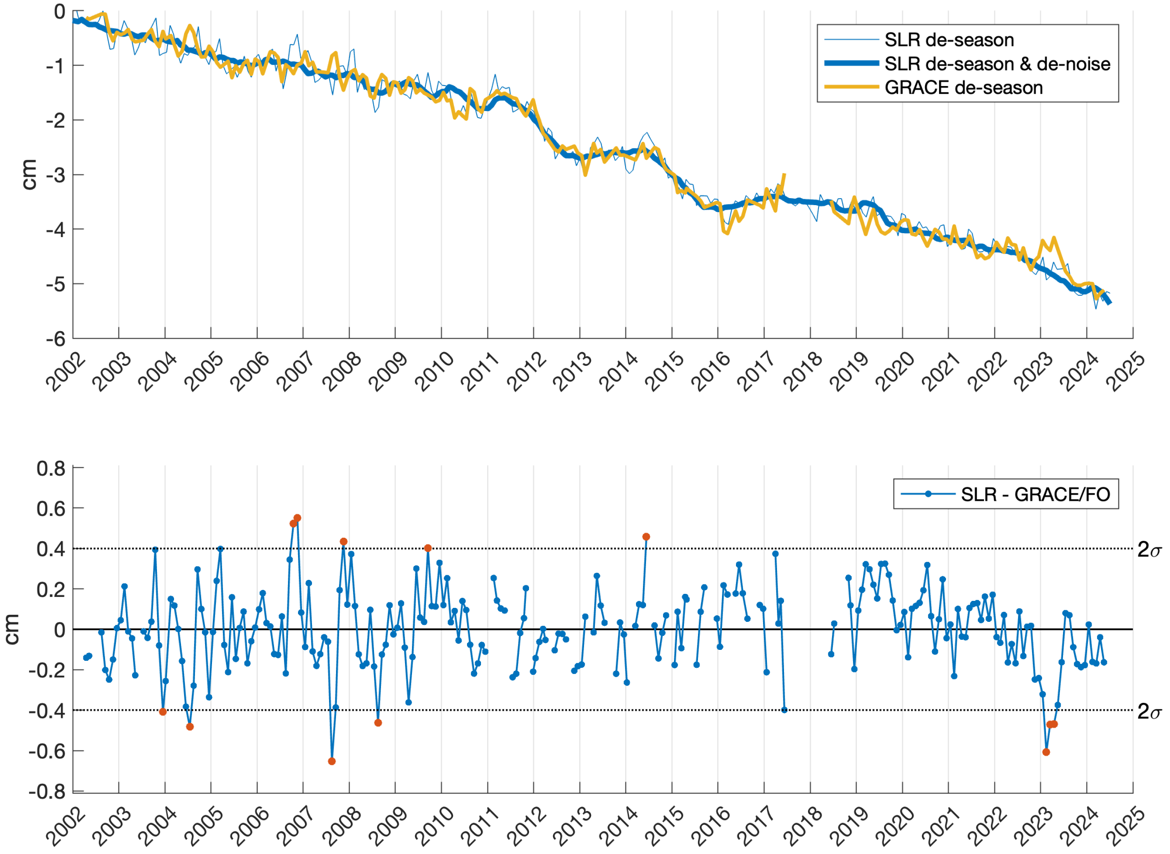
Gravity field determination: SLR mascons

Application of SLR mascons: GRACE-FO SDS validation of Level 2 products

Global TWS: SLR mascons vs. JPL RL06.3



Global TWS: SLR mascons vs. CSR RL06.3



Gravity field determination: Long-term C_{20}

Long-term C_{20}, or J_2 (1976 – Present):

- Time history of C_{20} from SLR is a unique climate data record, spanning 1976-Present
- Recent work has shown that the accurate recovery of C_{20} during the GRACE era (2002-Present) requires the use of time-variable gravity (TVG) information from GRACE & GRACE-FO when processing the SLR data
- This leads to these key questions:
  1. How reliable are the C_{20} estimates from 1976–2002?
  2. Can we develop a methodology to accurately recover C_{20} without TVG modeling?
- GSFC has developed a new approach for estimating C_{20} that eliminates the need to model TVG, resulting in an accurate and consistent time history of C_{20} from 1976-Present

New paper: Loomis, B.D., T.J. Sabaka, K.E. Rachlin, M.J. Croteau, F.G. Lemoine, R.S. Nerem, A. Bellas (2025). “Optimized J_2 recovery for multi-decadal geophysical studies,” *Geophys. Res. Lett.* doi:10.1029/2024GL114472

Note:
- $J_2 = -\sqrt{5}C_{20}$
- Time series shown as C_{20}
- Fits/trends reported for J_2

Gravity field determination: Long-term C_{20}

- UT-CSR has provided the only long-term time history of C_{20} derived from satellite laser ranging (SLR), most recently described by (Cheng et al., 2013)

- The UT-CSR C_{20} data set has been extensively applied to various geophysical and climate-related studies including glacial isostatic adjustment (GIA), length-of-day (LOD) variations, ice melt, sea level rise, etc. (See e.g., Mitrovica et al., 2015; Agnew 2024; Shahvandi et al., 2024)

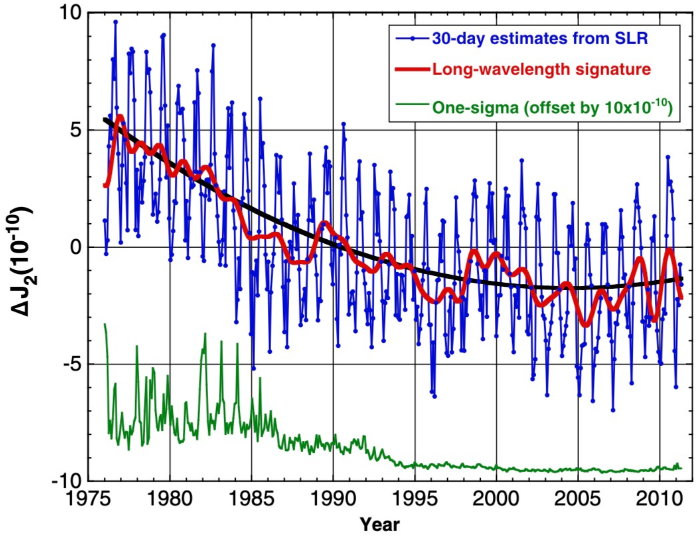


Figure from (Cheng et al., 2013)

ΔC_{20} (observed by SLR) = GIA + mass change (ice + sea level + hydrology + non-tidal ocean/atm.)

ΔLOD = ΔC_{20} impacts (GIA + mass change) + Lunar tidal friction + Core-mantle exchange + Ocean-atm.

- Following the publication of (Loomis et al., 2019), UT-CSR began using TVG modeling for 2002–Present to better match TN-14 over that span only, resulting in an **inconsistent long-term C_{20}** product with large changes in the trend and annual amplitude beginning in 2002

Gravity field determination: Long-term C_{20}

Key assumptions in Loomis et al. (2025):

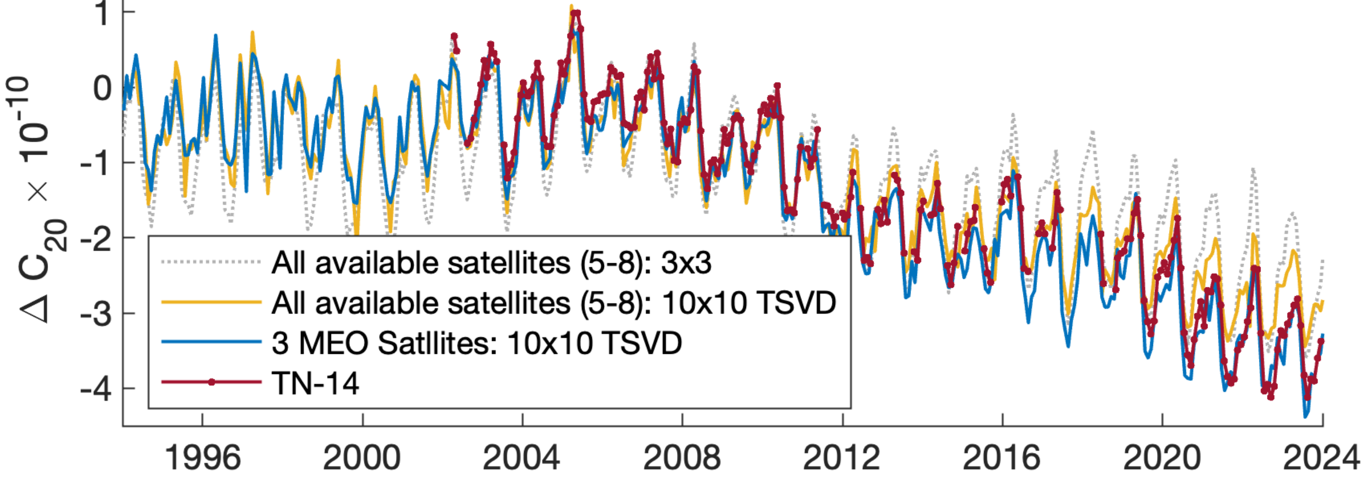
1. TN-14 is an accurate representation of C_{20}, and we treat it as the truth during GRACE era for comparing to candidate solutions
    - TVG modeling using GRACE data
    - Estimation of 5x5 + C_{61}/S_{61} gravity coefficients (Figures labeled “5x5”)
    - Uses 5-8 SLR satellites (available 1993 and later)
    - Agrees well with CSR’s long-term C_{20} solution 2002-Present (which also uses TVG for 2002-Present)
2. We can assess (Cheng et al., 2013) methodology by replicating their procedures:
    - No TVG modeling
    - Estimation of 3x3 + C_{40} gravity coefficients (Figures labeled “3x3”)
    - Performance tested for 2-satellites (available in 1976) and 5-8 satellites (available 1993 and later)
3. The stochastic behavior of C_{20} should be similar throughout the full record (1976-Present)
    - Stochastic defined as residual to regression fit (bias, trend, annual, semi-annual)

Gravity field determination: Long-term C_{20}

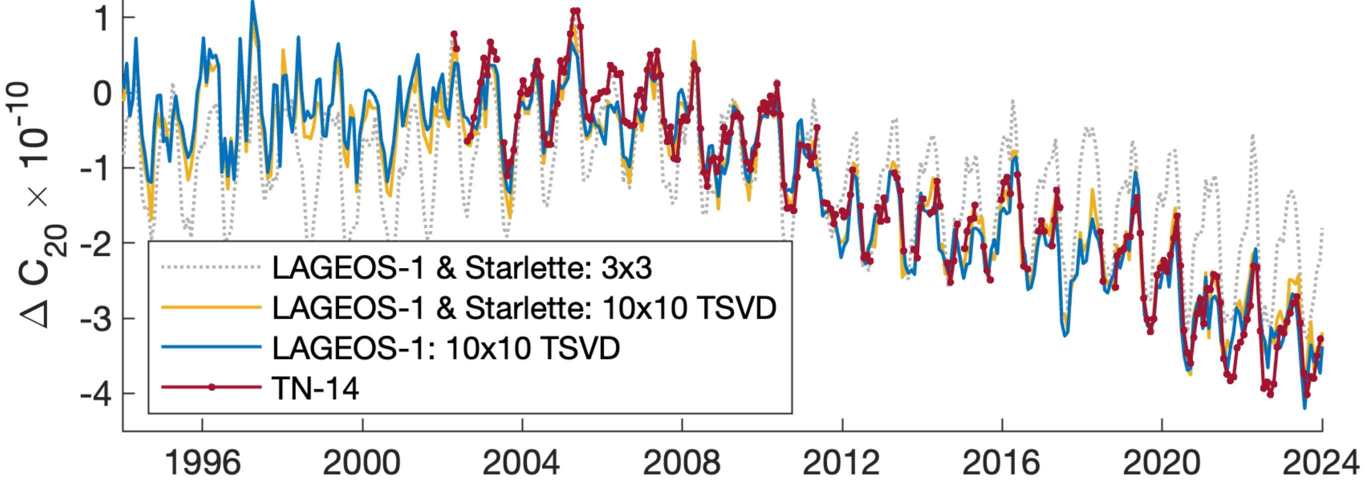
Key finding: Combination of two strategies provides accurate C_{20} without TVG:

1. Truncated Singular Value Decomposition (**TSVD**) applied to 10x10 normal equations
2. Use of all Medium Earth Orbit (**MEO**) SLR satellites only, which are the highest altitude SLR satellites:
    - LAGEOS-1 (1976 launch)
    - LAGEOS-2 (1992 launch)
    - LARES-2 (2022 launch)

***All plotted scenarios exclude TVG except for TN-14**



SLR satellites available 1993 - Present



SLR satellites available 1976 - Present

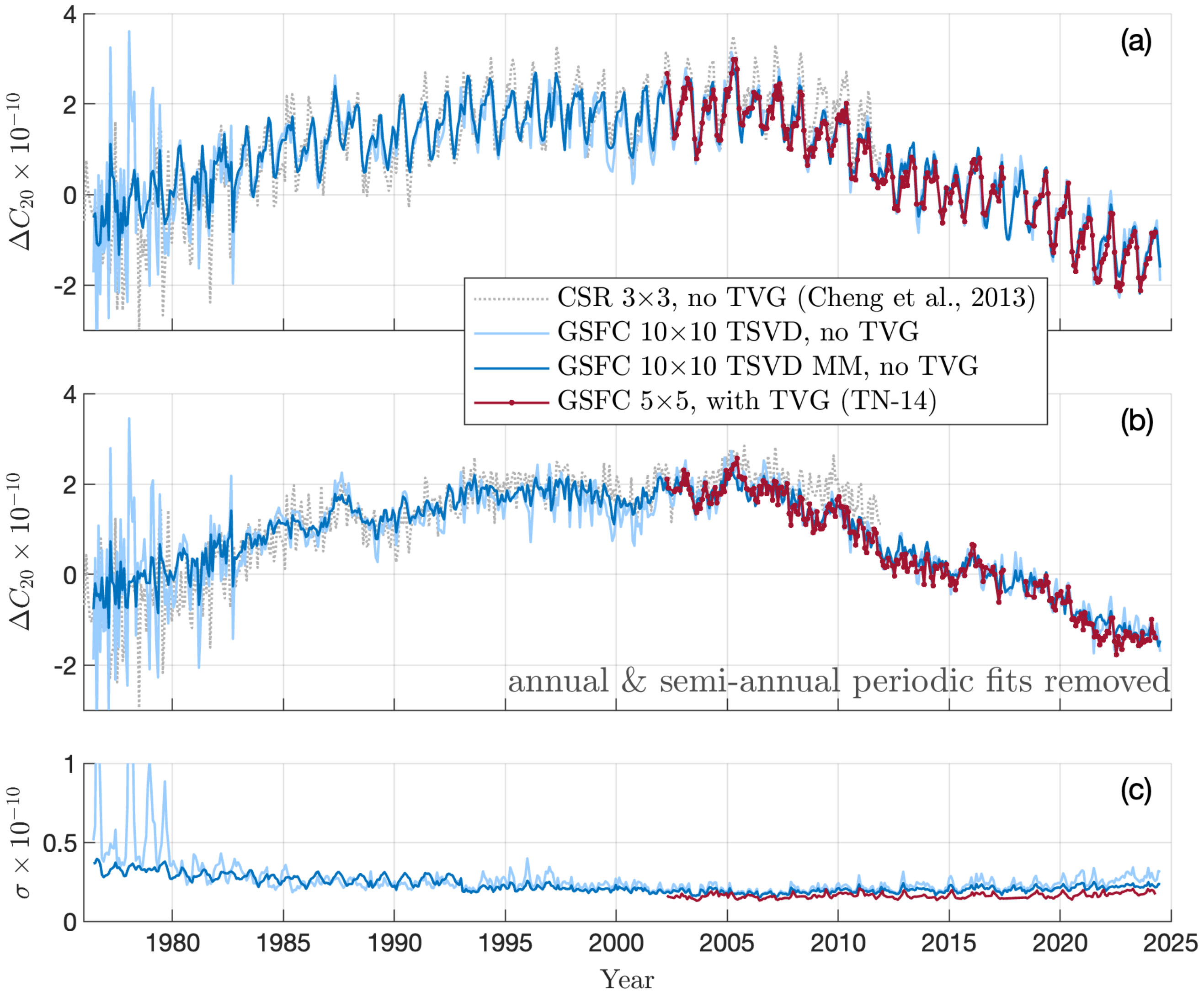
Gravity field determination: Long-term C_{20}

Earliest SLR data has reduced signal-to-noise:

- Sparse network
- Early generation hardware
- Fewer satellites (1 MEO until 1992)

Strategies to improve C_{20} estimation pre-1993:

1. 56-day processing arcs instead of 7-day (sliding window solution to provide 28-day sampling)
2. Simple station bias modeling
3. Truncated Singular Value Decomposition with Mixed Modeling (**TSVD MM**) – MM represents fixed effects, including 2nd order polynomial, annual, semi-annual



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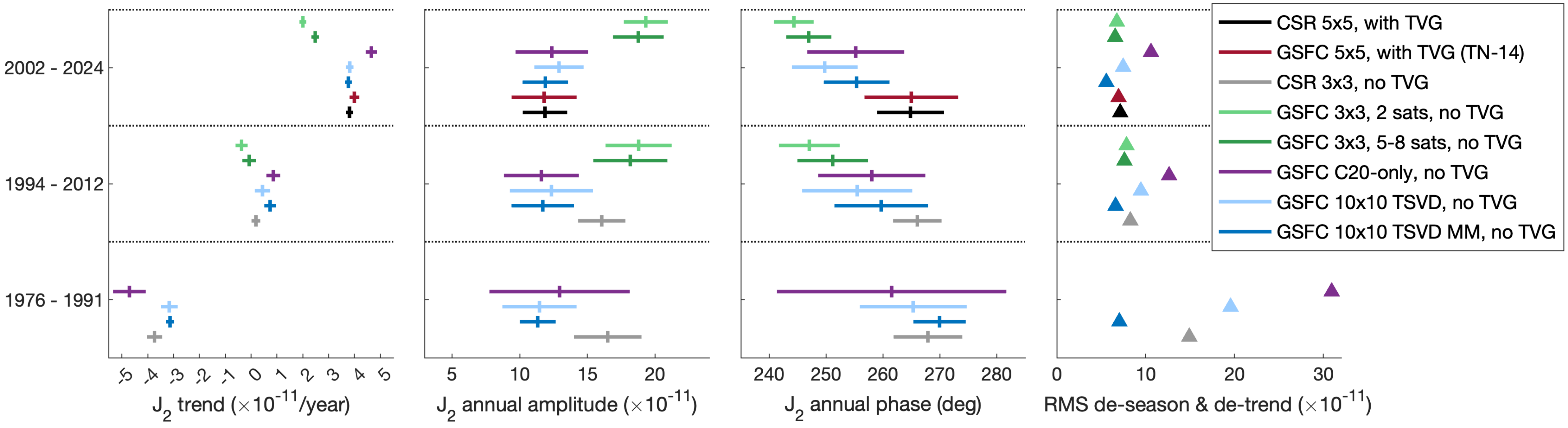
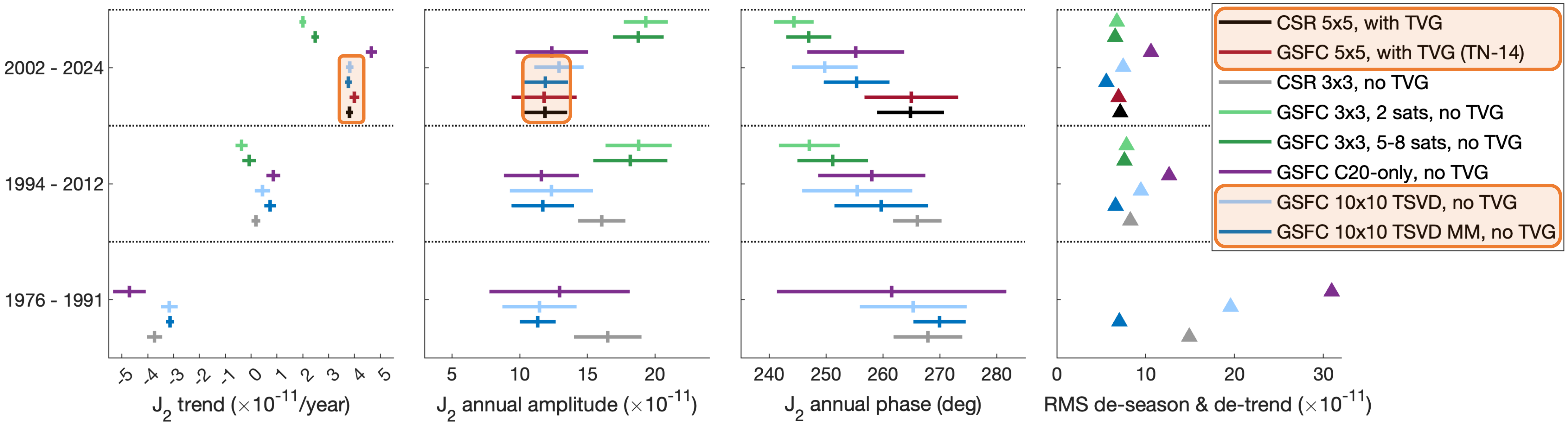
Gravity field determination: Long-term C_{20}

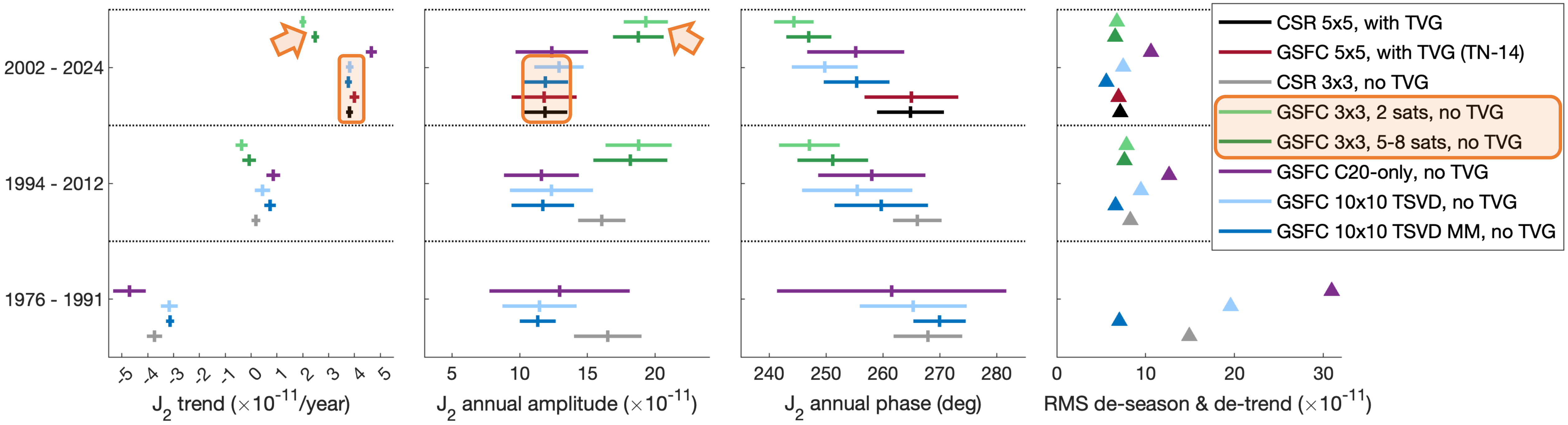


Gravity field determination: Long-term C_{20}



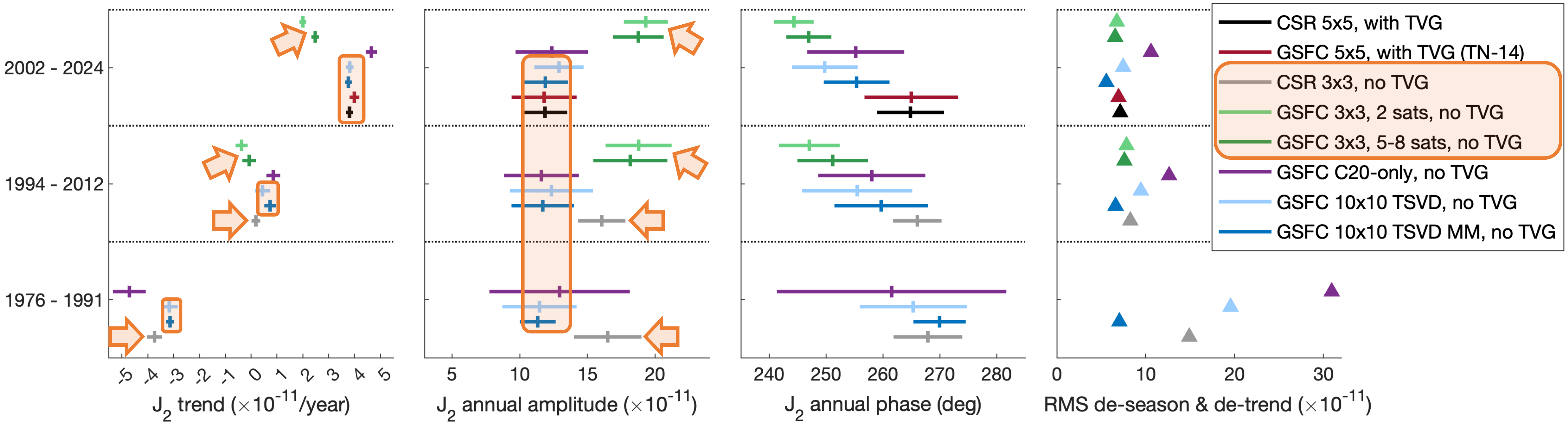
- GSFC TSVD J_2 solutions with no TVG (**dark blue** & **light blue**) agree very well with GRACE-era J_2 solutions (**black** & **dark red**) that use TVG modeling to mitigate correlations.

Gravity field determination: Long-term C_{20}



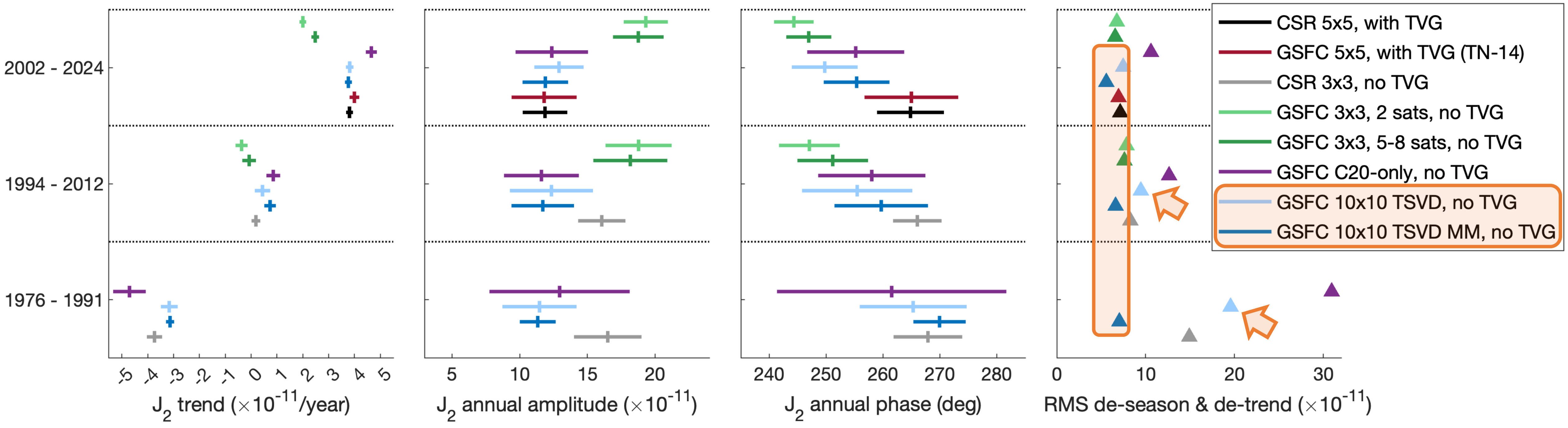
- During the GRACE era, the (Cheng et al., 2013) approach to estimate 3x3 with no TVG (**green**) produces large differences with the established solutions (**black** & **dark red**).
- Note that the CSR solution following (Cheng et al., 2013) procedures (**gray**) is not available for 2002-2024, only our attempt to replicate it (**green**).

Gravity field determination: Long-term C_{20}



- Disagreements between 3x3 (**green** & **gray**) and TSVD (**blue**) is persistent across time.
- Impact of 3x3 deficiency in trend recovery is likely smaller earlier in the time series due to smaller TVG signals (i.e., less ice melt).
- 1976-1991 GSFC trend: $\mathbf{-3.1 \pm 0.1 \times 10^{-11}/yr}$ disagrees with CSR trend: $\mathbf{-3.7 \pm 0.1 \times 10^{-11}/yr}$

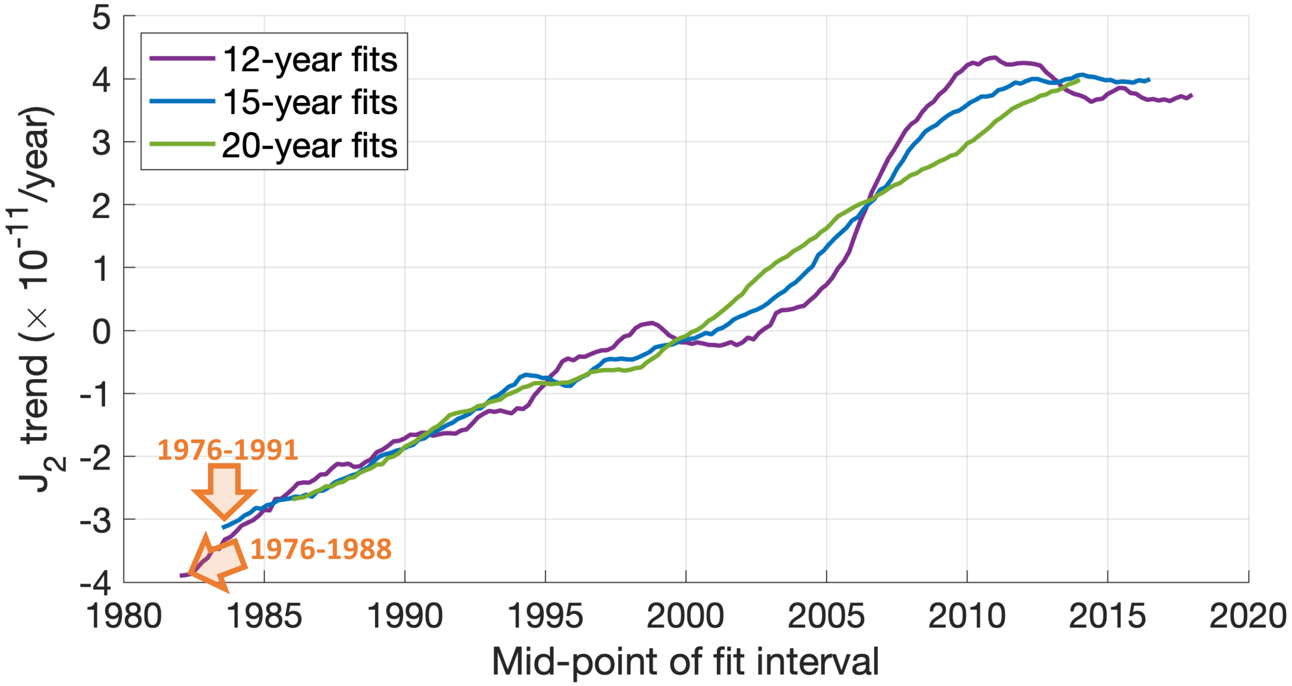
Gravity field determination: Long-term C_{20}



- The Mixed Model (MM) approach (**dark blue**) provides consistent J_2 regression parameter fits, while also providing consistent stochastic behavior.
- By contrast, the TSVD without MM (**light blue**) has significantly more noise for the earliest time intervals.

Gravity field determination: Long-term C_{20}

- Multiple studies have used 1976-1991 as the “steady state” J_2 rate
- However, J_2 rates are dynamic and highly dependent on the selected fit span and time interval:



- This dependence is much larger than the reported uncertainties of $0.1{\times}10^{-11}/yr$
- This should be considered when using early J_2 data, e.g., GIA & length-of-day studies

Combined SLR+GRACE gravity estimation

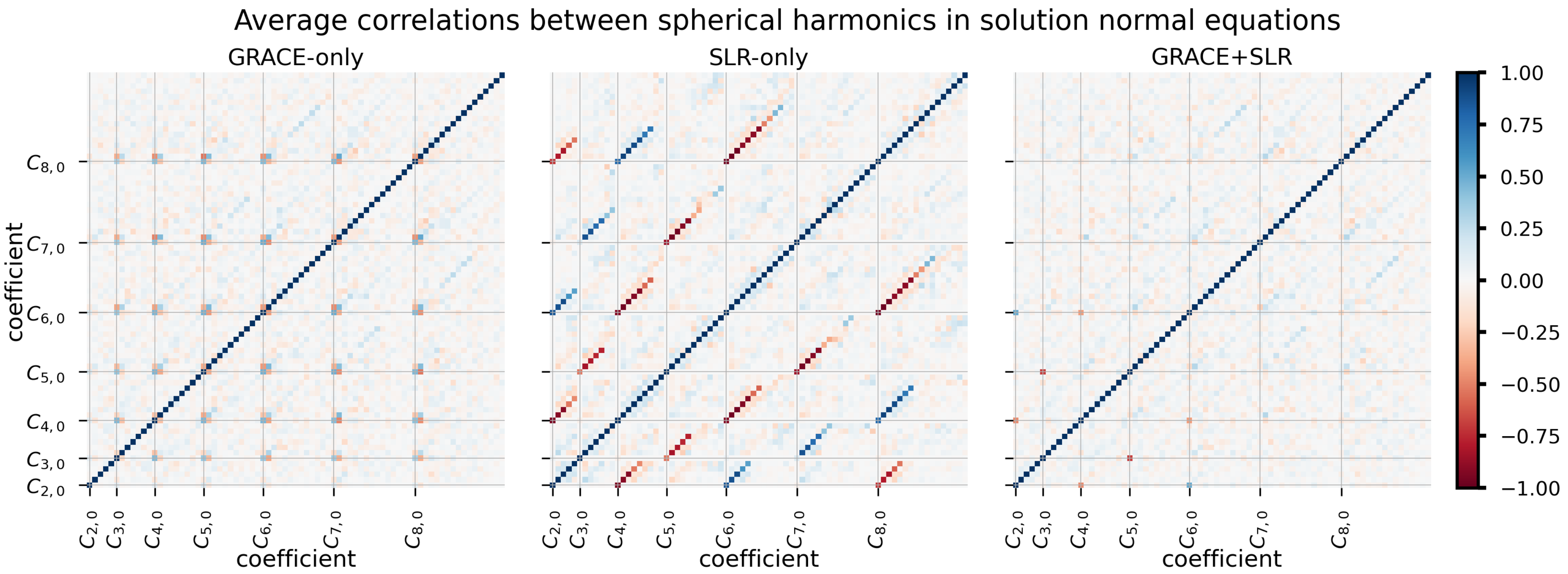
- Unregularized monthly GRACE+SLR combination solutions:
  - CNES-GRGS (Lemoine et al., 2019)
  - DGFI-TUM (Haberkorn et al., 2015)
  - UT-CSR (Kang et al., 2022)
- High-resolution static field with regression model from some combination of SLR, LEO GNSS, GRACE, GOCE:
  - GOCO-06s, TU Graz (Kvas et al., 2020)
  - EIGEN models, CNES-GRGS (Lemoine et al., 2019)
- Croteau et al. (2025) is first published study quantifying impact of SLR on SLR+GRACE mascon estimation – next charts

(apologies to any I've missed!)

Combined SLR+GRACE gravity estimation

Results from Croteau et al. (2025):

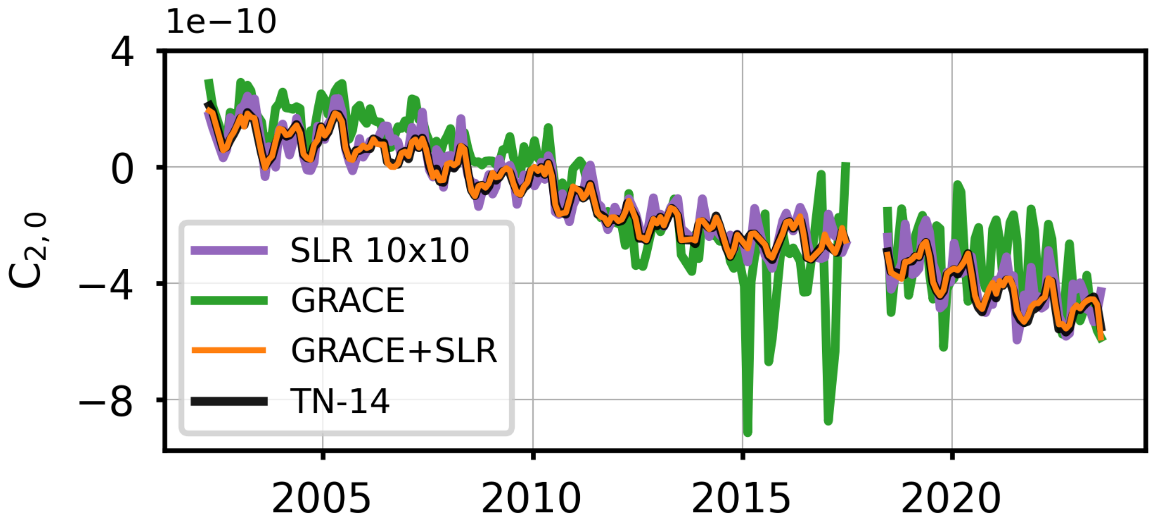
- Formal correlations between gravity coefficients are greatly reduced in the combination

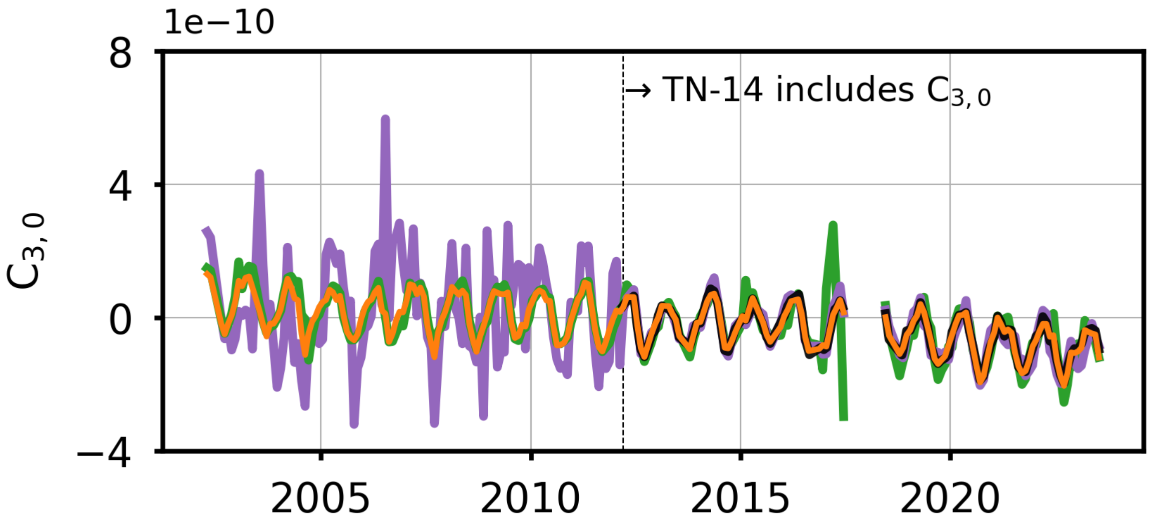


Combined SLR+GRACE gravity estimation

Results from Croteau et al. (2025):

- GRACE (60x60) + SLR (10x10) combination shows excellent agreement to Technical Note 14
- This is strong validation of the parameter selection for TN-14 (5x5 + C_{61}/S_{61})

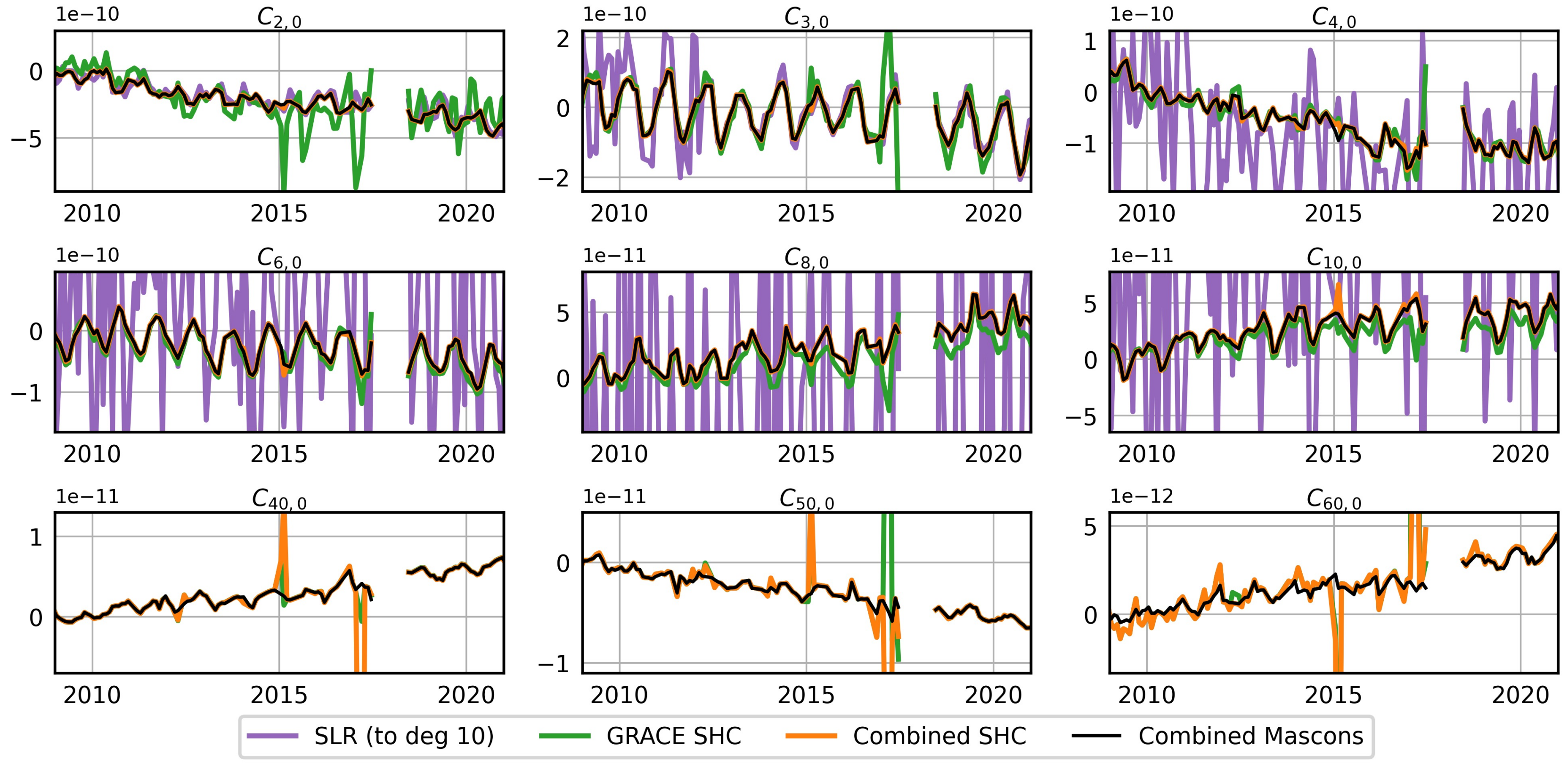




Combined SLR+GRACE gravity estimation

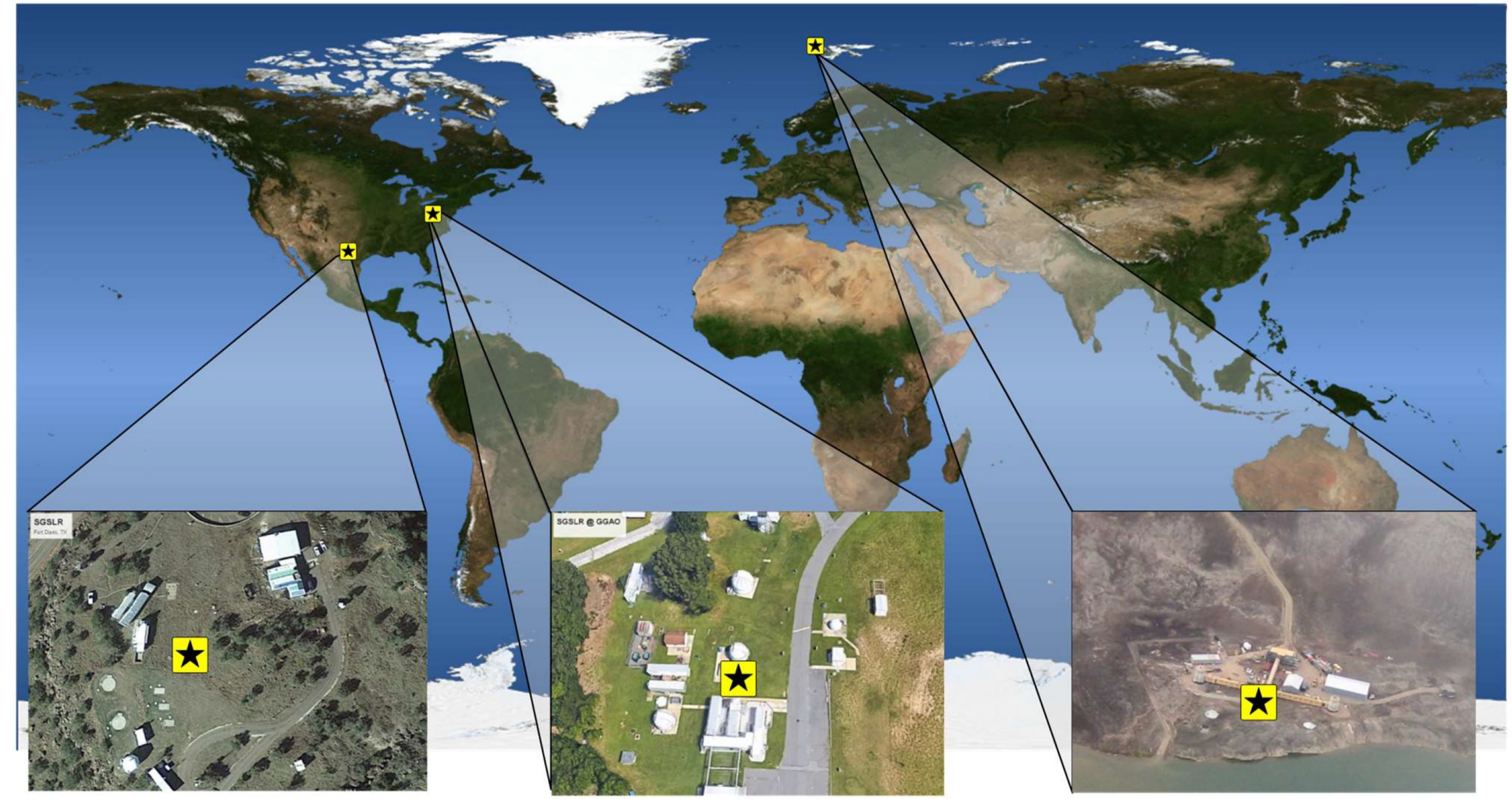
Results from Croteau et al. (2025):

- GRACE+SLR combination improves lower degree coefficients, while the mascon regularization improves higher degree coefficients and stabilizes challenging months



SGSLR: The next generation SLR system

- NASA's current legacy system is reaching end-of-life
- NASA's Space Geodesy Project (SGP) is working with the Norwegian Mapping Authority (NMA) on the installation and deployment of the first SGSLR station at Ny-Ålesund, Svalbard
- Much of the development and testing occurs at GGAO, NASA's space geodesy observatory at GSFC



McDonald Observatory, TX
(MGO)

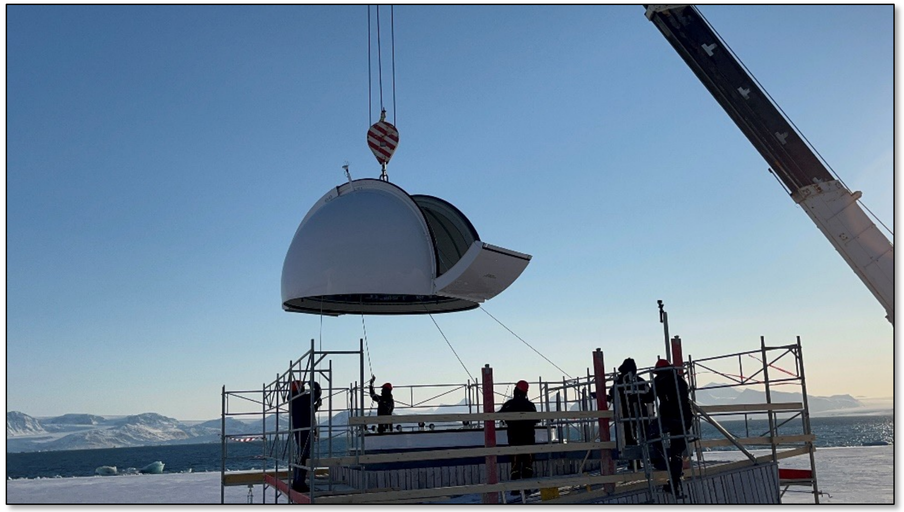
Greenbelt, MD
(GGAO)

Ny-Ålesund, Norway
(NGO)

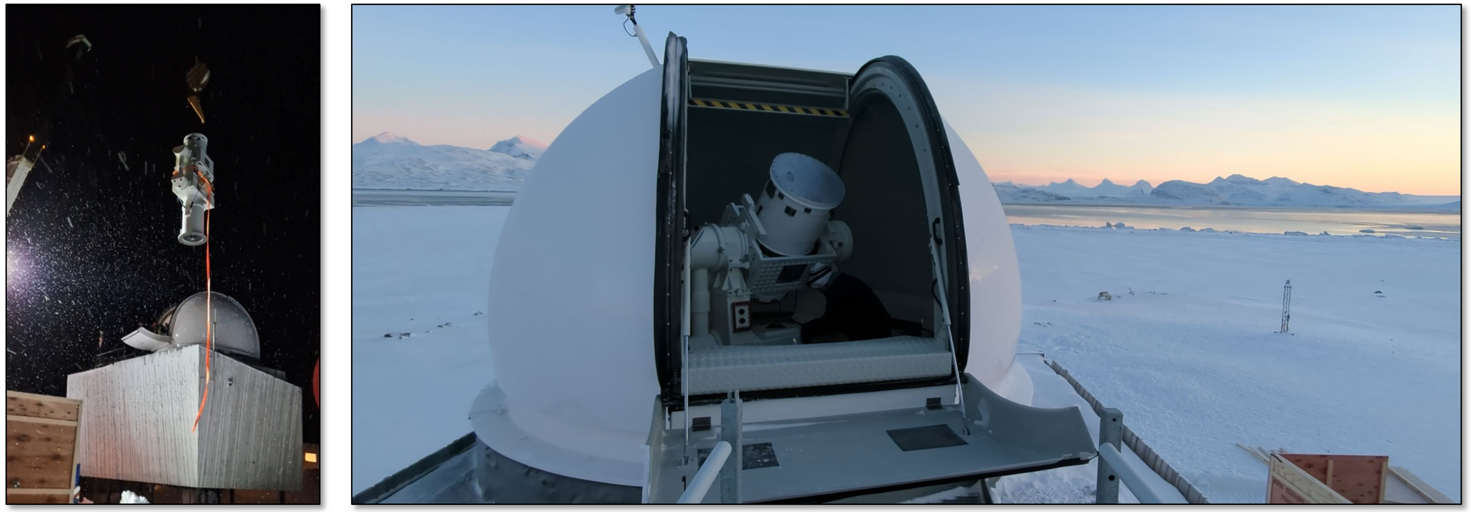
SGSLR: The next generation SLR system

2014: Casting SLR concrete pier.

2015: SLR building construction.



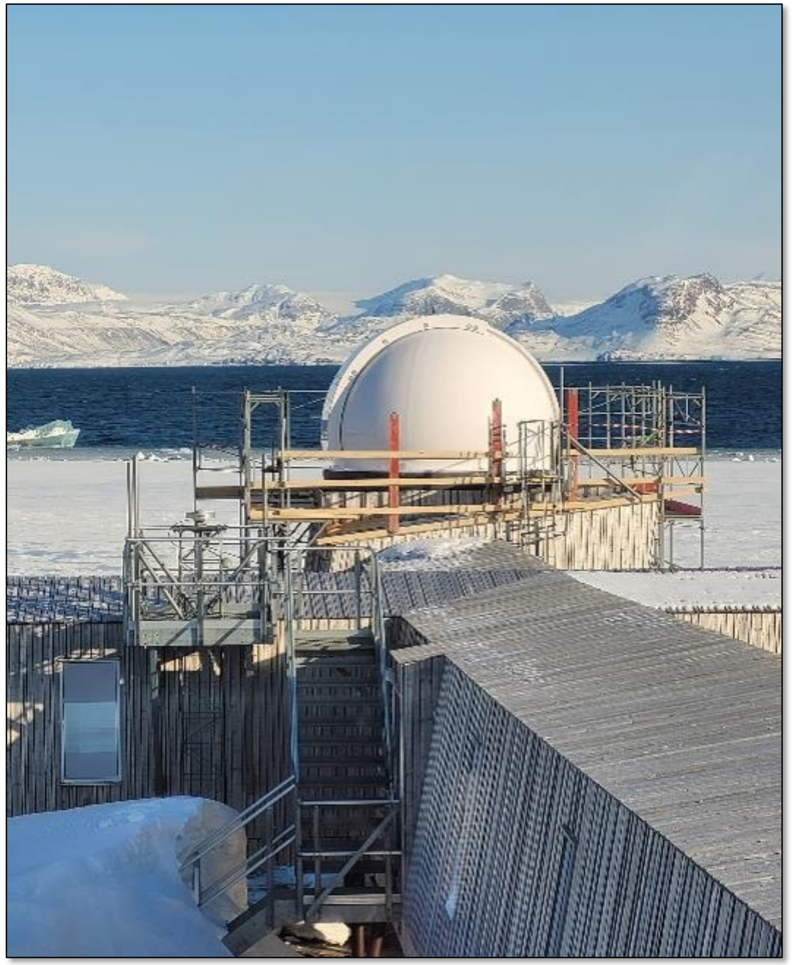
2022: Dome installation.



2024: Installing the gimbal and telescope assembly

SGSLR: The next generation SLR system

Ny-Ålesund, Svalbard (left to right): Ben Phillips (ESI lead at NASA HQ), Karen St. Germain (Division Director of the Earth Science Division, Science Mission Directorate at NASA HQ), Kim Hurst (NASA HQ), Stephen Merkowitz (NASA GSFC, Space Geodesy Program Manager)



2022 dome installation of SGSLR system in Ny-Ålesund, Svalbard.

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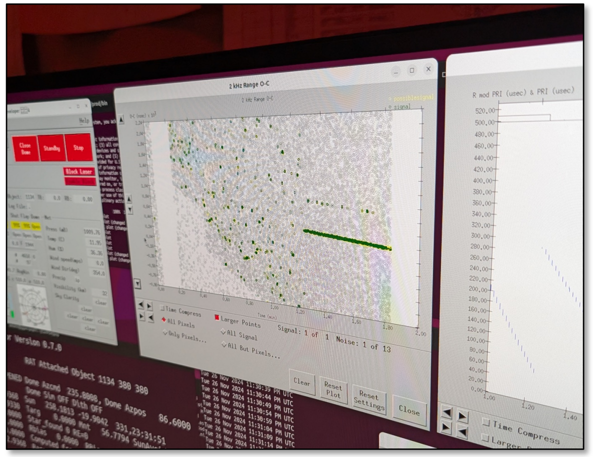
SGSLR: The next generation SLR system

SGSLR Achieves First Light!

- 26 November 2024 at 23:17 UTC, SGSLR at GGAO (NASA GSFC) acquired and tracked its first satellite: Starlette (eccentric orbit at 812-1114 km)
- First acquisition and tracking of a satellite is one of the most difficult points in SLR system development
- Integration & Testing ongoing at GGAO

Key next steps:

- Co-location comparison tests with GGAO legacy station MOBLAS 7
- Ny-Ålesund "ranging ready" July 2026
- Ny-Ålesund Operation Readiness Review Oct 2026



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Done Azcmd 235.8008, Done Azpos 86.6000
Tue 26 Nov 2024 11:30:39 PM UTC
Tue 26 Nov 2024 11:30:44 PM UTC
Tue 26 Nov 2024 11:30:49 PM UTC
Tue 26 Nov 2024 11:30:54 PM UTC
Tue 26 Nov 2024 11:30:59 PM UTC
Tue 26 Nov 2024 11:31:04 PM UTC
Tue 26 Nov 2024 11:31:09 PM UTC
Tue 26 Nov 2024 11:31:14 PM UTC
```

Thank you!