A 30-year record of the time-variable gravity field from DORIS and SLR using a tailored parametrization via GRACE EOFs

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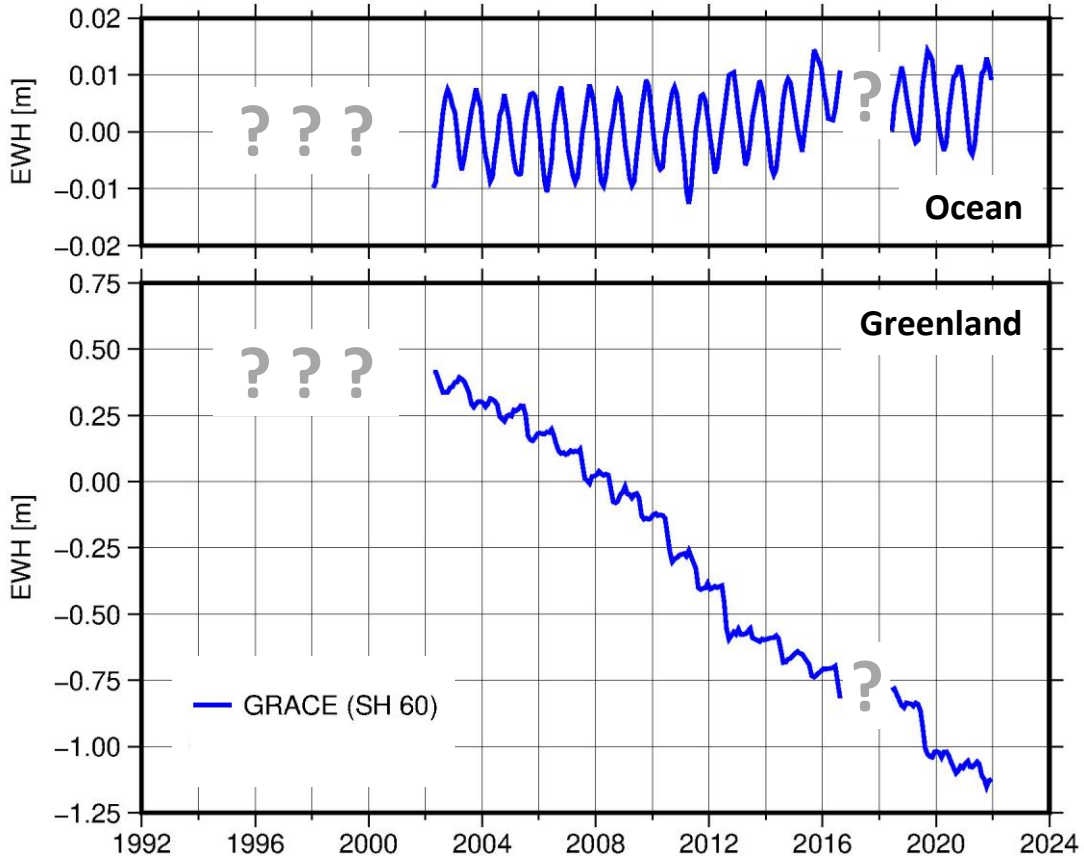
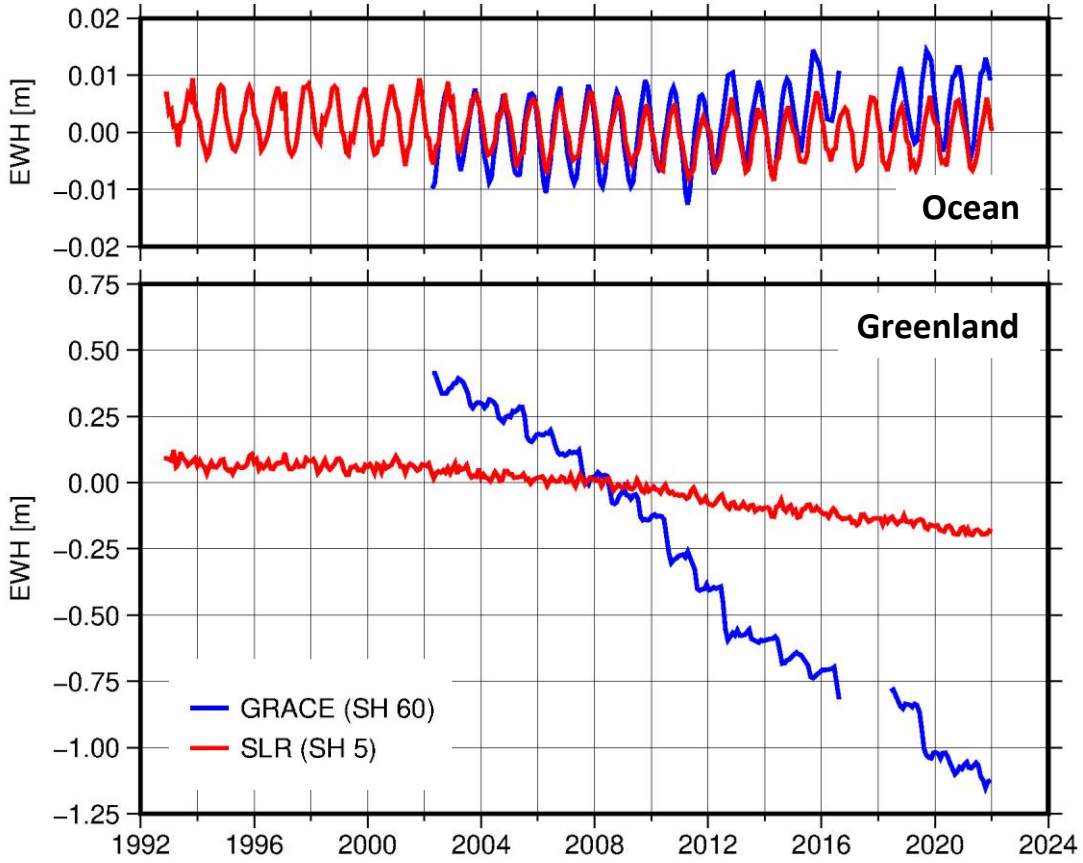
Introduction

- Time-variable gravity field precisely known since 2002 from GRACE and GRACE Follow-On
- **Goal**: Extend the GRACE time series backward (and close the gap between GRACE and GRACE Follow-On)



Introduction

- Time-variable gravity field (TVG) precisely observed since 2002 by GRACE and GRACE Follow-On
- **Goal**: Extend the GRACE time series backward (and close the gap between GRACE and GRACE Follow-On)
- Solutions from non-dedicated techniques restricted to the lowest SH degrees
- **Idea**: Use base functions tailored to the expected signal



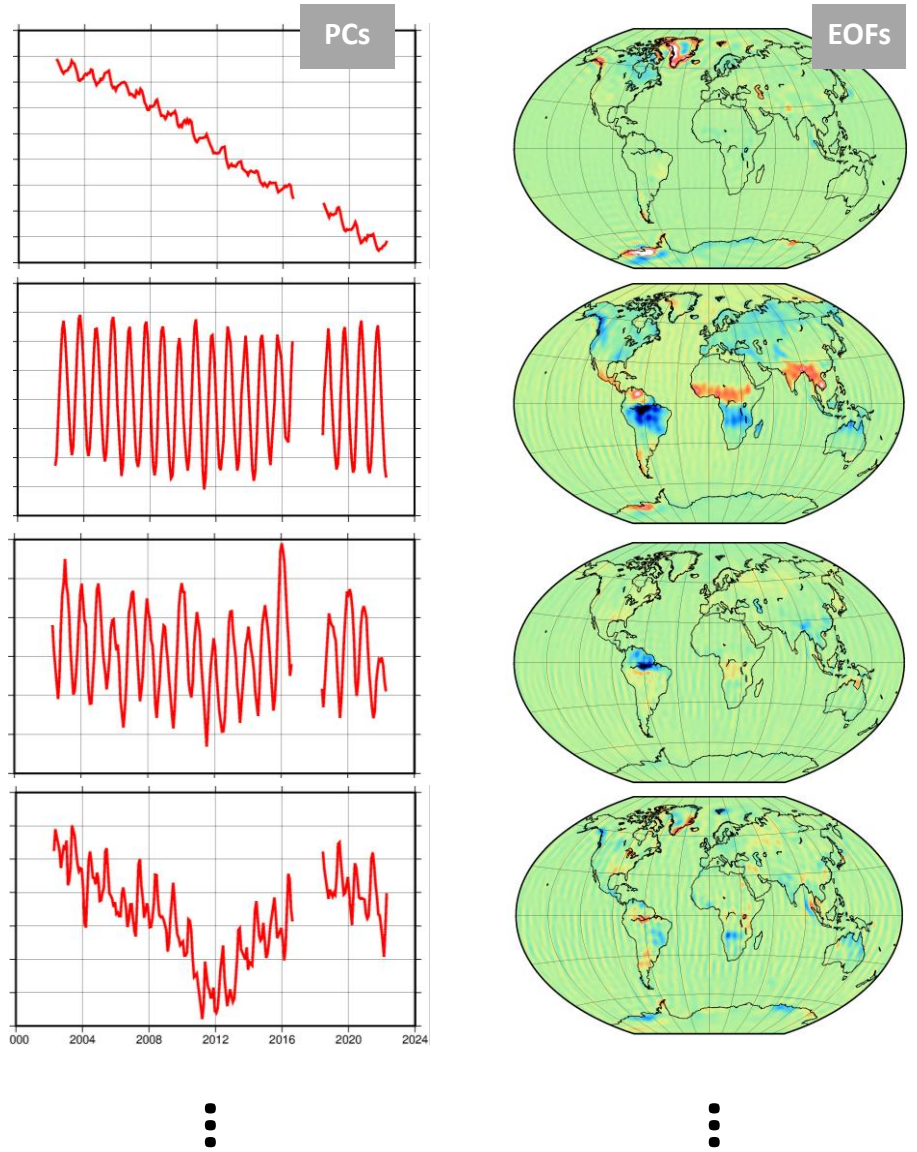
Tailoring the base functions

- Principal component analysis (PCA) decomposes the GRACE time series into temporal and spatial modes ordered by their significance
- PCA performed by singular value decomposition

$$\mathbf{A} = \mathbf{P}\mathbf{\Lambda}\mathbf{E}^T$$

- $\mathbf{E}$: EOFs (spatial modes)
- $\mathbf{\Lambda}$: Singular values
- $\mathbf{P}$: PCs (temporal modes)
- $\mathbf{A}$: GRACE solutions

- GRACE PCA usually applied to gridded data, EOFs returned as gridded values



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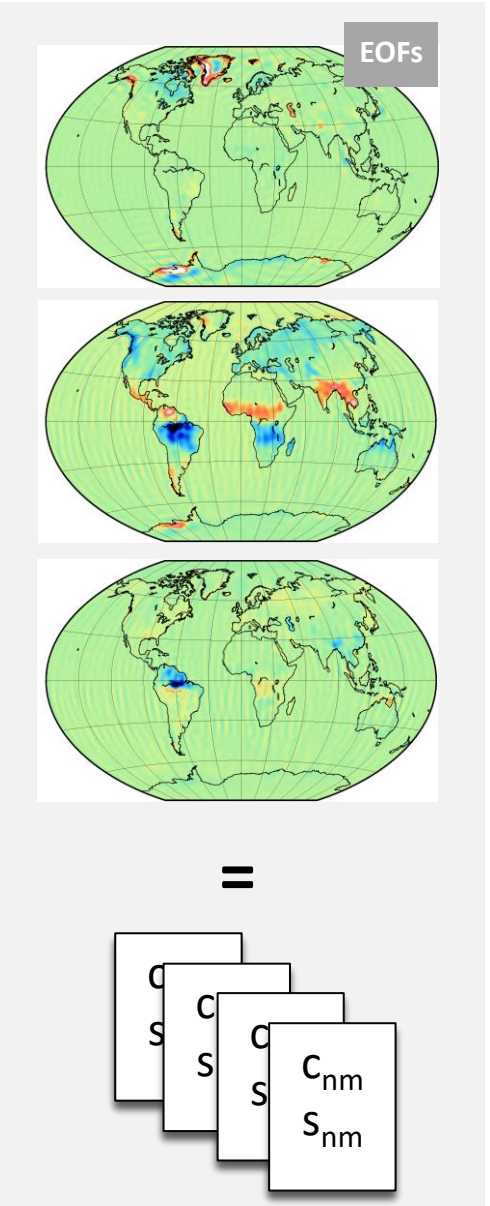
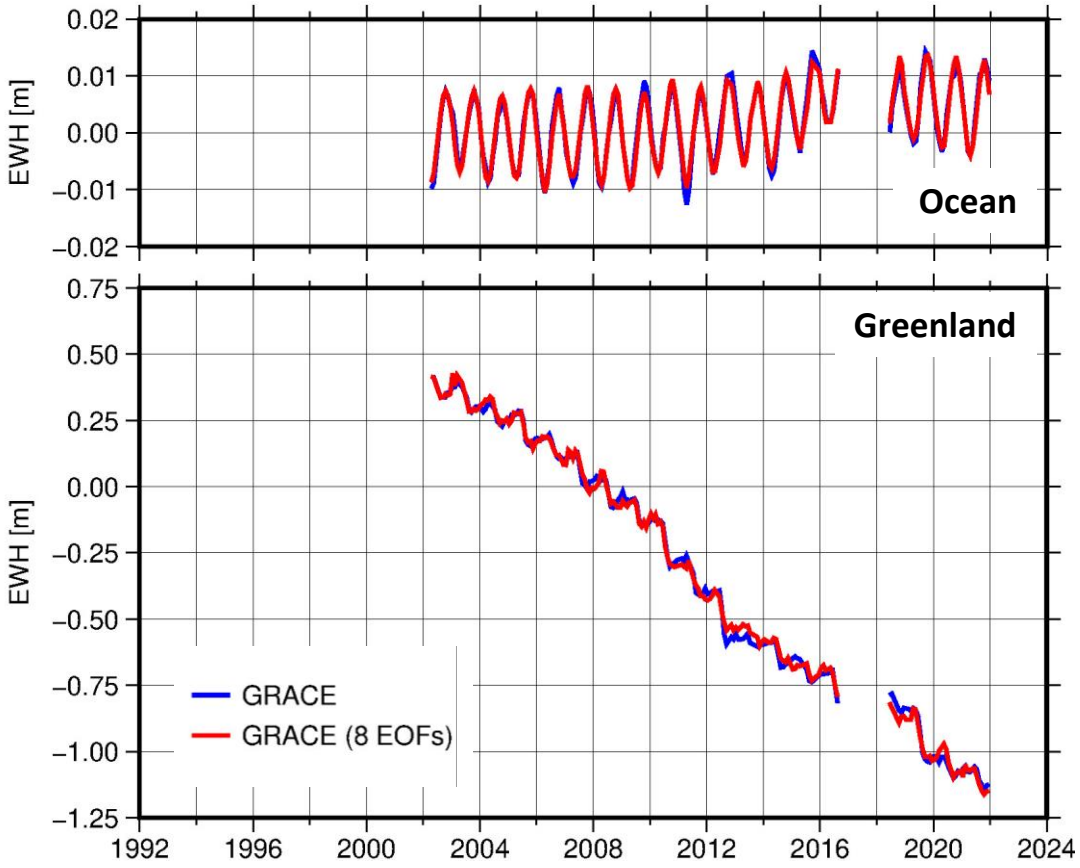
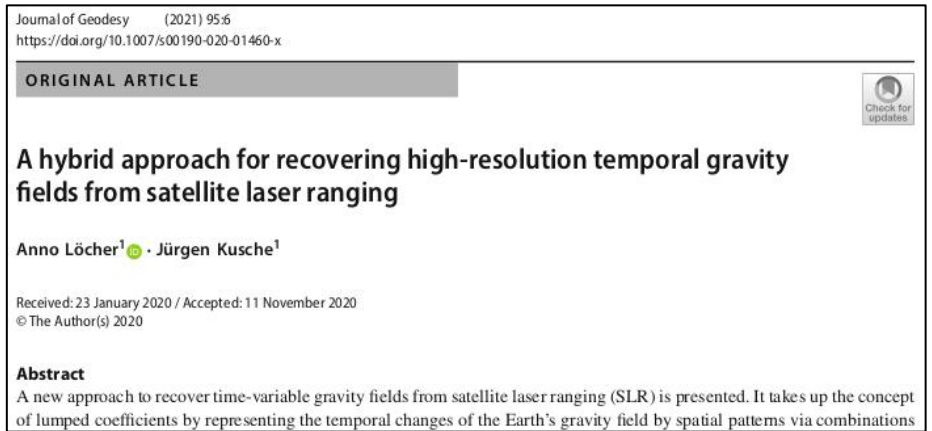
- GRACE PCA usually applied to gridded data, EOFs returned as gridded values
- More appropriate here: submit SH coefficients, get back EOFs also in SH domain



Recovering TVG with EOFs

- EOFs in terms of SHs directly usable as base functions in force modelling. „PCs“ solved-for
- Large-scale mass variations well represented by a few EOFs
  - → massive reduction of parameter space
  - → stable solutions from non-dedicated missions
- Limitations:
  - Early truncation of EOF series might leave detected signal unmodelled
  - GRACE EOFs probably not perfect for other periods
- Concept proved with SLR, now applied to DORIS

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ORIGINAL ARTICLE

A hybrid approach for recovering high-resolution temporal gravity fields from satellite laser ranging

Anno Löcher[1] · Jürgen Kusche[1]

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Abstract
A new approach to recover time-variable gravity fields from satellite laser ranging (SLR) is presented. It takes up the concept of lumped coefficients by representing the temporal changes of the Earth's gravity field by spatial patterns via combinations

DORIS processing at IGG

- In-house software, DORIS capabilities developed from SLR → **Observation equations consistently set up for (biased) ranges**

DORIS 1.0/2.1/2.2	**Unchained observations**: Range-rates each split into two biased ranges (0 m and range rate x 7 sec) **Chained observations**: Range-rates integrated to biased ranges as long as possible
DORIS RINEX	Phase observations

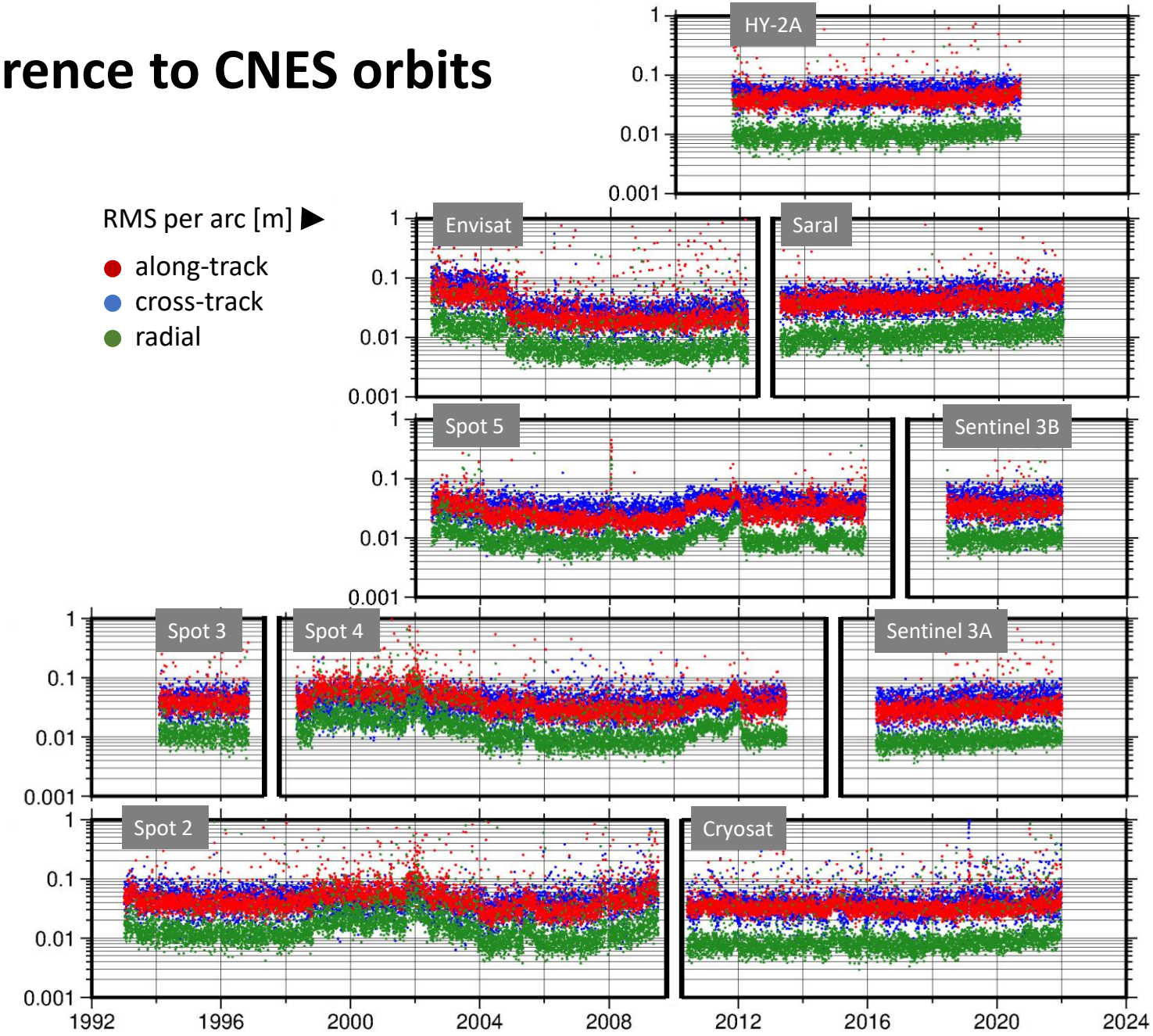
DORIS processing at IGG

- In-house software, DORIS capabilities developed from SLR → **Observation equations consistently set up for (biased) ranges**
- 10 satellites (altitude < 1000 km) processed in daily arcs
- Orientation and macromodels from IDS document
- Stations and Earth orientation fixed (DPOD2014, IERS C04)
- Force models and force parameters comparable to CNES

Initial values	1 set per arc
Range bias (integration constant)	1 per range sequence
Range drift (for station frequency offset)	1 per pass
Troposphere zenith bias	1 per pass
Troposphere gradient	1 per pass **(only Spot 5 and Envisat)**
Once-per-rev along-track	1 per arc
Scale factor solar radiation	1 per arc
Scale factor atmospheric drag	1 per 3 hrs

DORIS processing: difference to CNES orbits

	Mean RMS per arc [cm]		
	along	cross	radial
Spot 2	4.7	4.4	1.6
Spot 3	4.0	4.1	1.2
Spot 4	4.4	4.0	1.5
Spot 5	2.9	3.4	1.0
Envisat	3.2	3.8	0.9
Cryosat	3.7	4.4	1.2
Saral	4.4	4.8	1.2
HY-2A	4.4	4.9	1.1
Sentinel 3A	3.2	3.9	0.9
Sentinel 3B	3.4	4.1	1.0



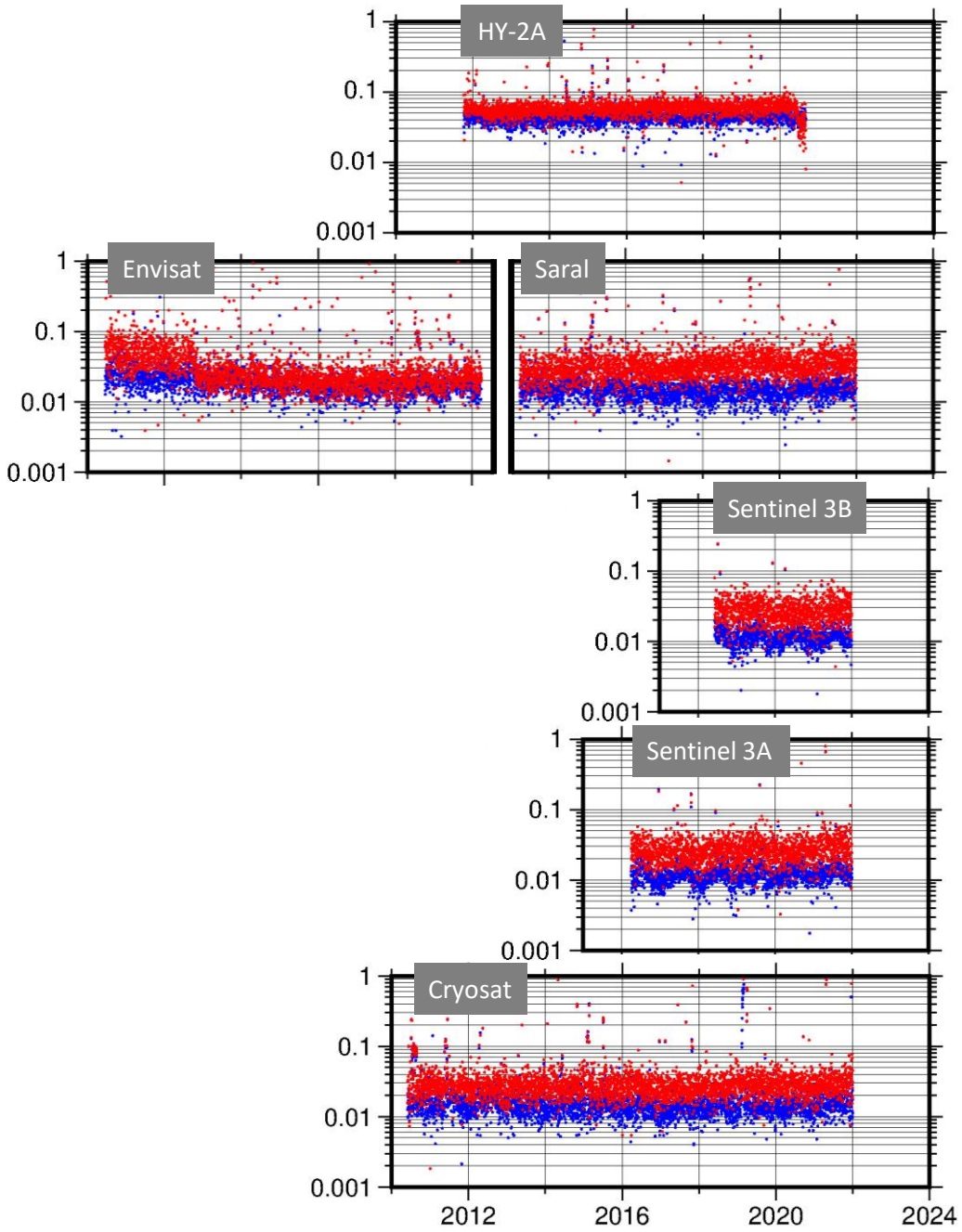
DORIS processing: SLR residuals

	Mean RMS per arc [cm]	
	IGG orbits	CNES orbits
Envisat	3.0	2.1
Cryosat	2.9	1.6
Saral	3.4	1.6
HY-2A	5.9	4.4
Sentinel 3A	2.7	1.3
Sentinel 3B	2.8	1.2

DORIS-only, laser ranges not used

RMS per arc [m] ▶

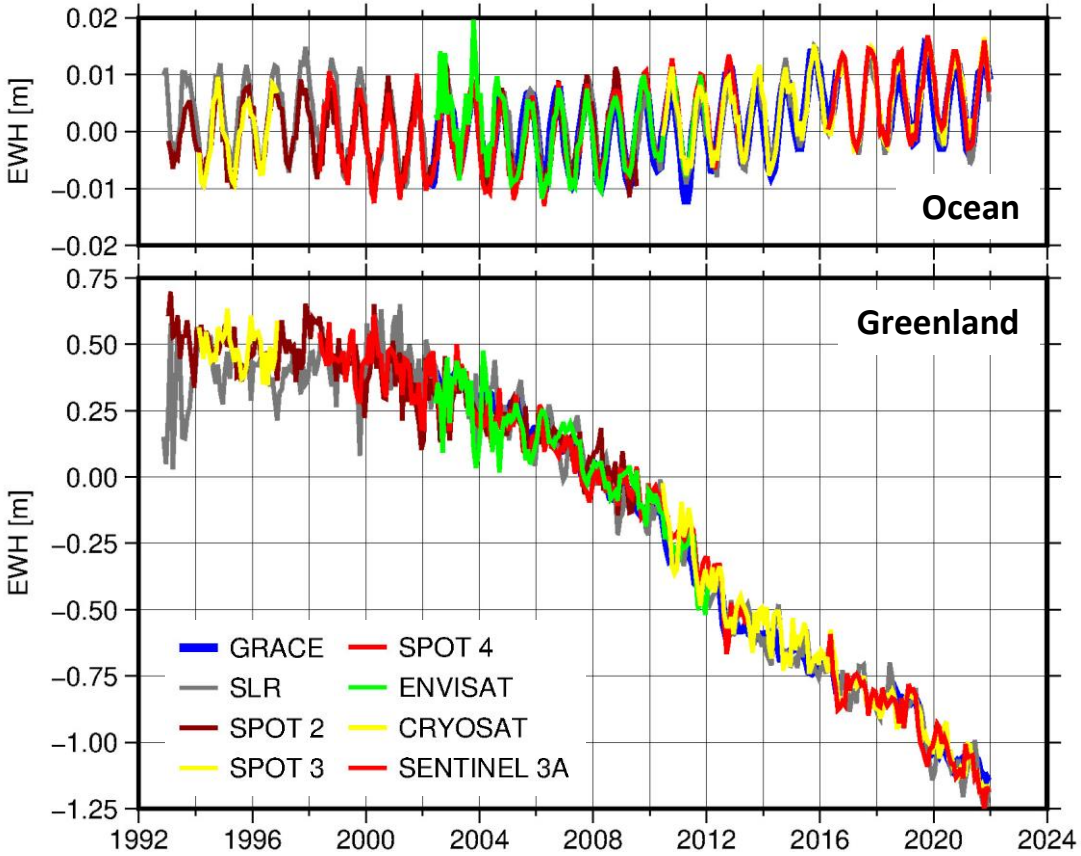
- IGG orbits
- CNES orbits



Monthly gravity field solutions

- EOFs from ITSG2018 and ITSG-operational (GRACE-FO)
- Monthly solutions from daily normal equations combined with VCE
- For DORIS/SLR solution, daily NEQs from DORIS combined with monthly NEQs from SLR

Single-satellite solutions (8 EOFs)



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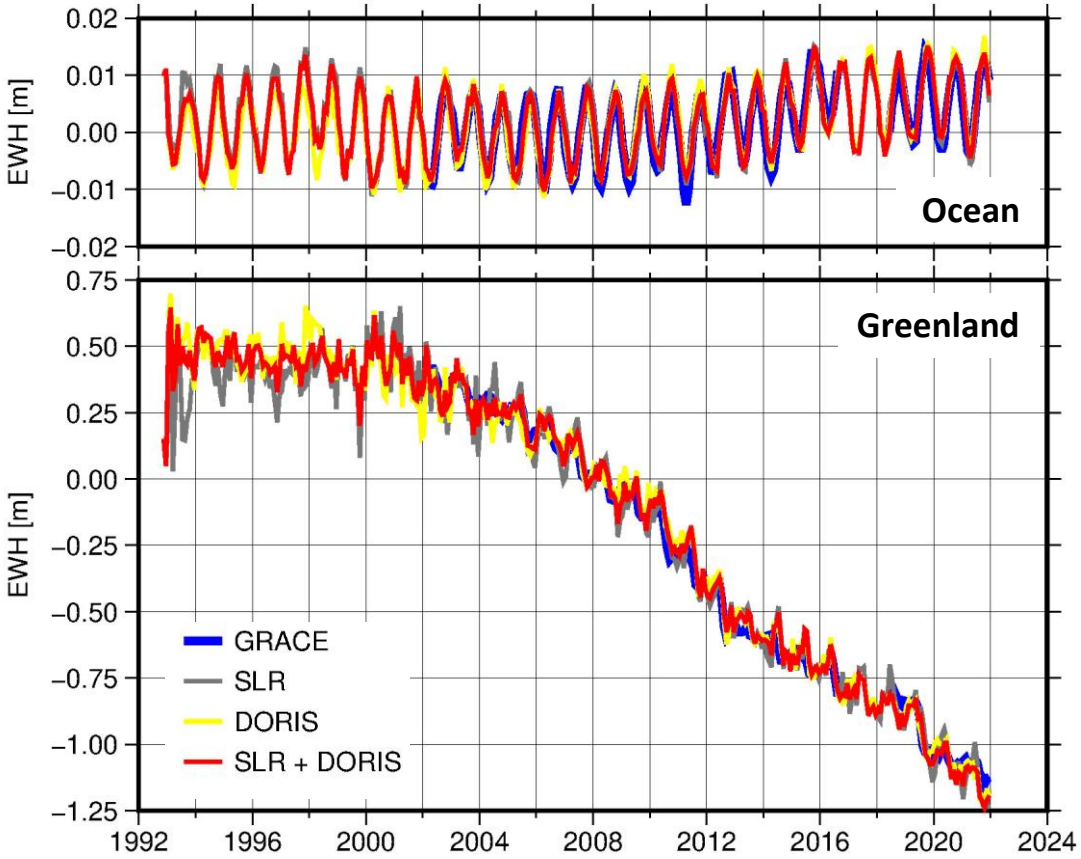
Combined solutions (8 EOFs)



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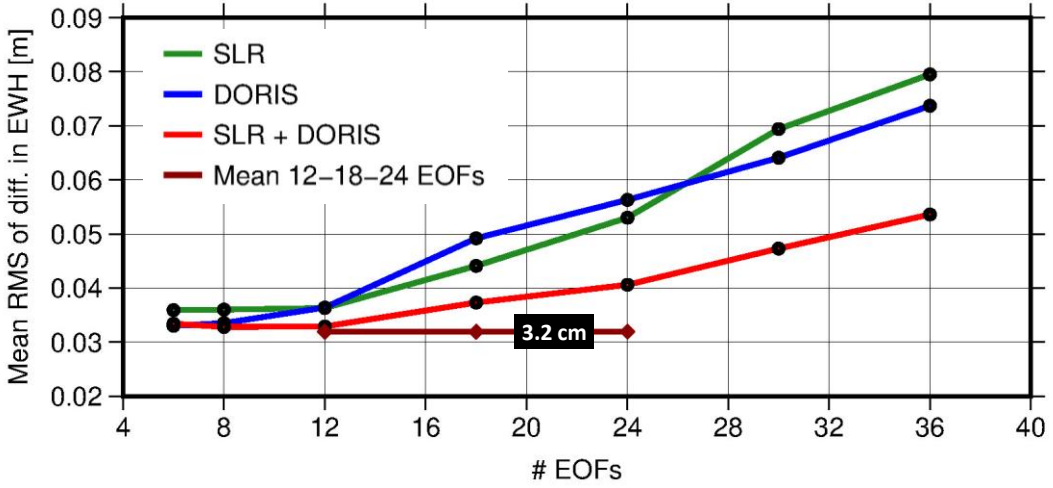
Difference to GRACE/GRACE-FO



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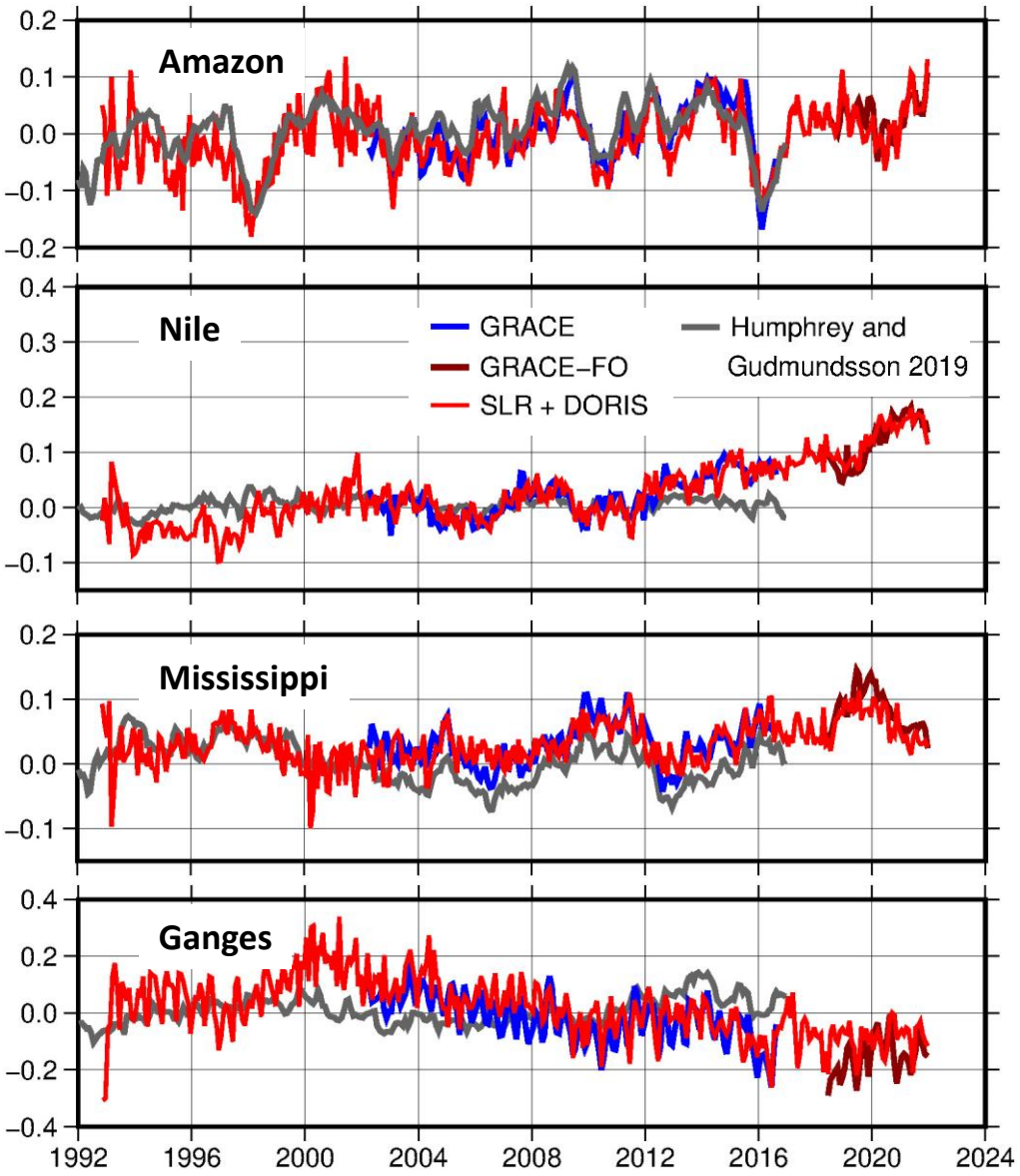
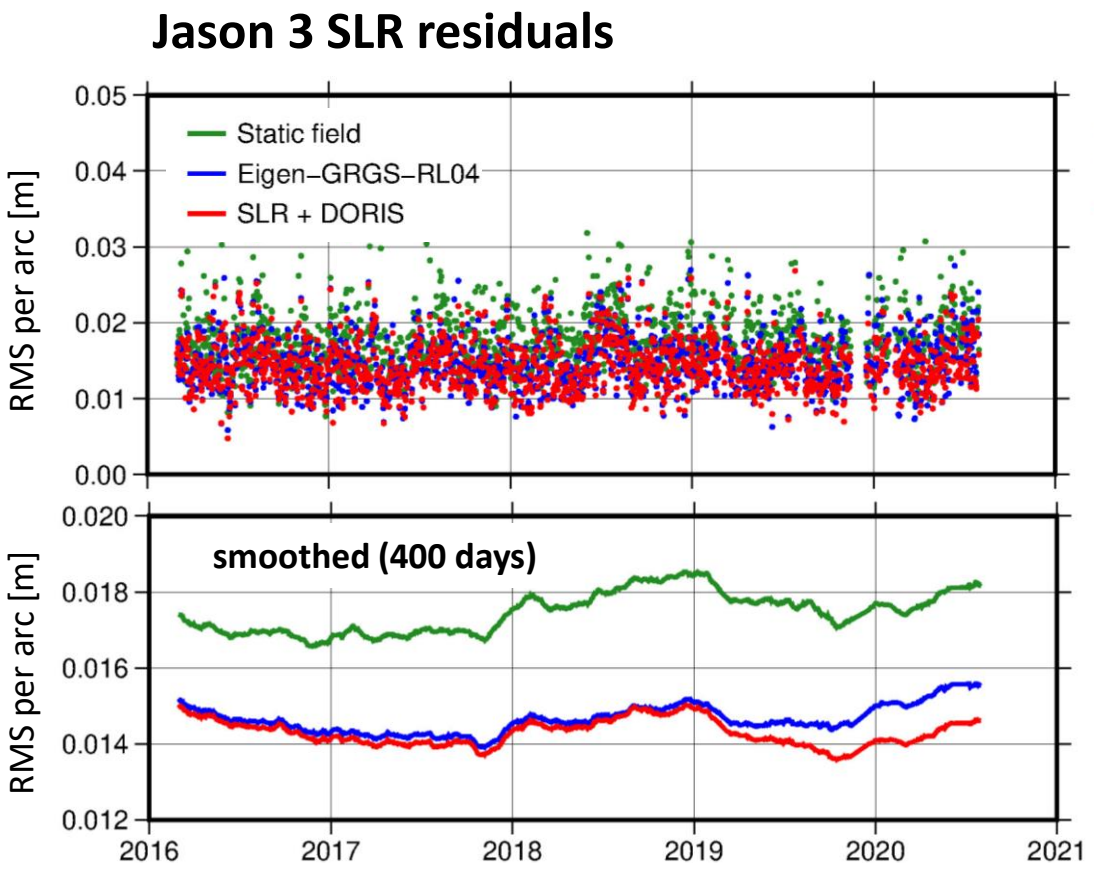
River basins

(Mean 12-18-24 EOFs, annual signal removed)



Application as force model in POD

- Monthly solutions from SLR and DORIS should be accurate enough to be used as force models in POD at higher altitudes (Topex, Jason, …)
- Test: Dynamical reconstruction of Jason 3 orbits from GNSS
  - Observations: Kinematical orbits from TU Graz
  - Parametrization as above (without biases). Orientation from quaternions
  - Three solutions: static field, Eigen-GRGS-RL04, SLR+DORIS
  - Orbit accuracy assessed by SLR residuals



Summary

- EOF representation for TVG recovery well suited for DORIS
- Reasonable results for large-scale mass variations even from single satellites including early Spot missions
- SLR solution substantially improved by combination with DORIS
- SLR/DORIS solution equivalent to Eigen-GRGS-RL04 as force model at higher altitudes. Slight advantage when Eigen model provides only extrapolated values