Preliminary GRACE-FO gravity field solutions

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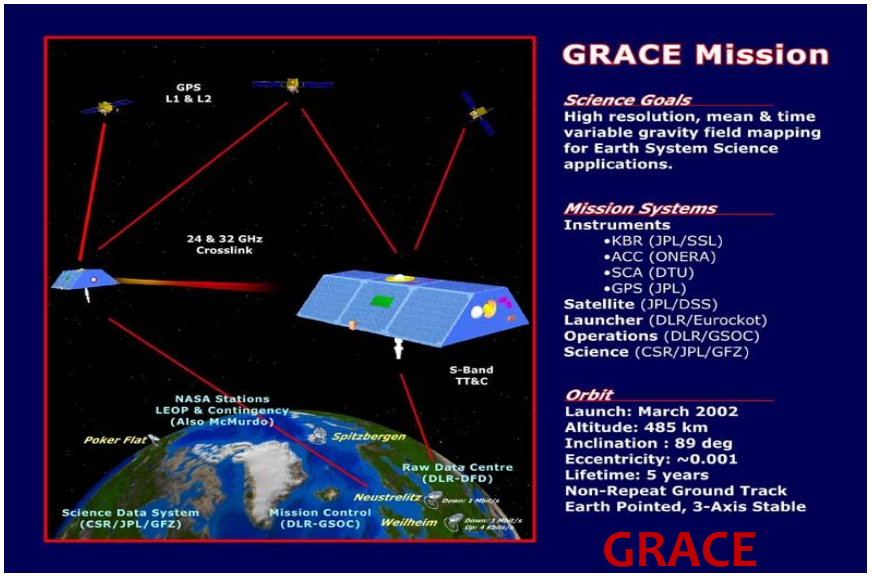
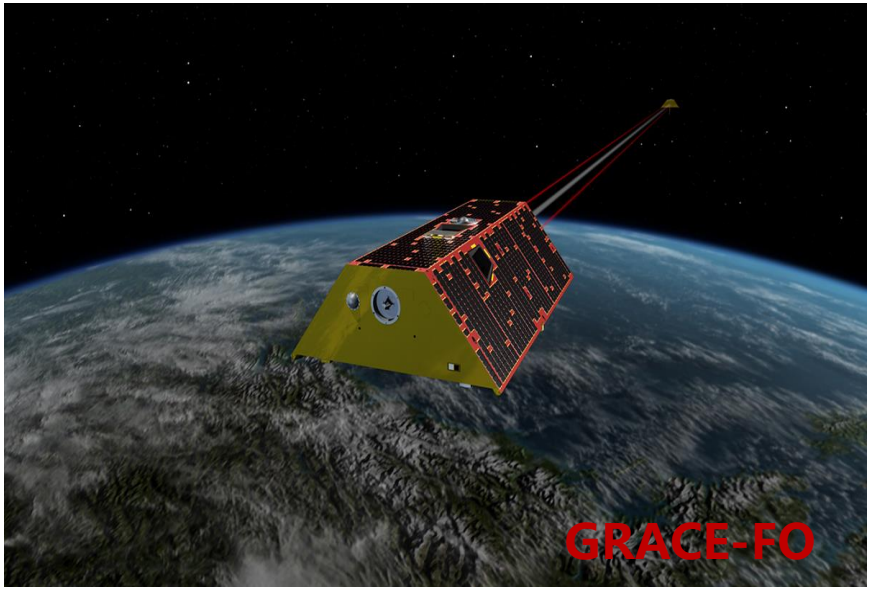
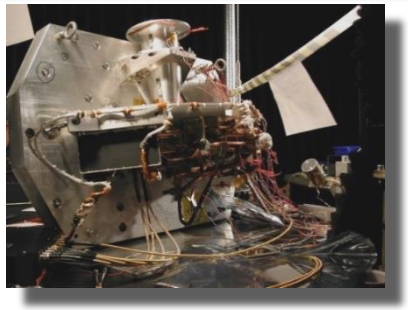
Outline

1. Introduction of GRACE/GRACE-FO mission
2. Gravity Field Estimation Methods
3. GRACE static/monthly solutions
4. Preliminary GRACE-FO monthly models
5. Concluding Remarks

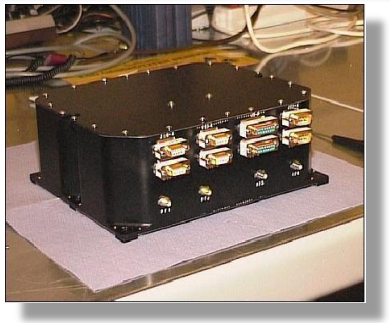
Introduction — GRACE & GRACE-FO



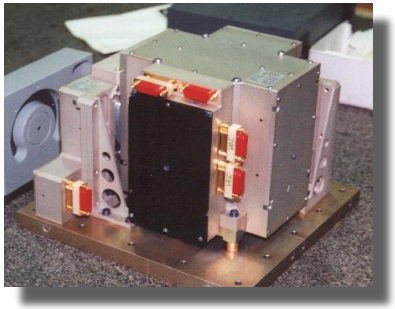




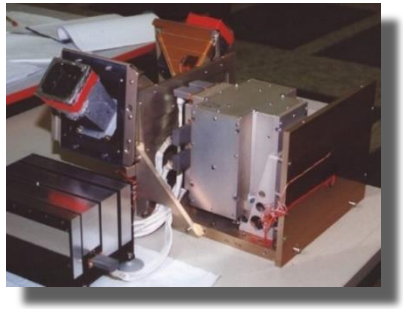
K-Band Ranging



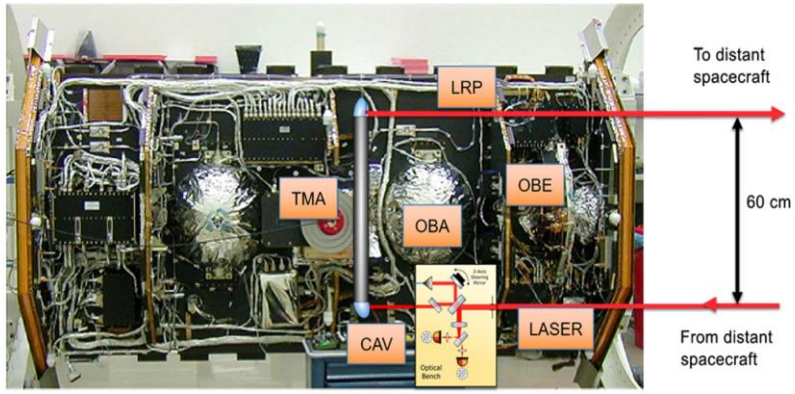
GNSS Receiver



Accelerometer



Star Camera



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Introduction — GRACE/GRACE-FO Solutions

GRACE monthly solutions

Monthly model	Spatial / time res.	Time span
CSR RL06	(60 96) / 30	04/02-06/17
GFZ RL06	(60 96) / 30	04/02-06/17
JPL RL06	(60 96) / 30	04/02-06/17
ITSG-Grace2016	(60 90 120) / 30	04/02-06/17
ITSG-Grace2018	(60 96 120) / 30	04/02-06/17
CNES/GRGS RL05	90 / 30	04/02-06/17
DMT-1	120 / 30	02/03-12/09
DMT-2	120 / 30	02/03-04/12
Tongji-RL01*	60 / 30	01/03-08/11
Tongji-RL02*	60 / 30	01/03-09/15
Tongji-Grace2018*	96 / 30	04/02-06/17
HUST-Grace2016	60 / 30	01/03-04/15
IGG RL01	60 / 30	04/02-07/16
WHU RL01	(60 90 120) / 30	04/02-07/16

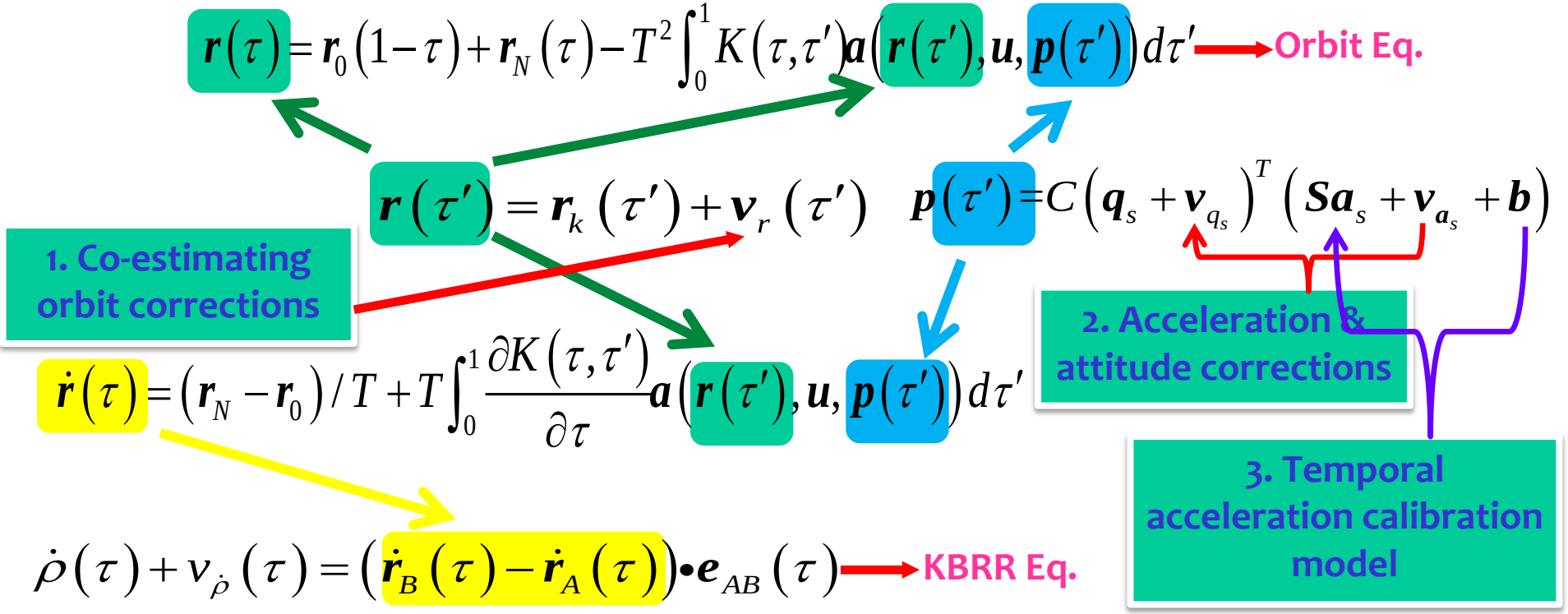
GRACE-FO monthly solutions

Monthly model	Spatial / time res.	Time span
CSR RL06	(60 96) / 30	06/18-11/19
GFZ RL06	(60 96) / 30	06/18-11/19
JPL RL06	(60 96) / 30	06/18-11/19
ITSG-Grace2018 (opt.)	(60 96 120) / 30	06/18-10/19

GRACE static solutions

Static model	Spatial res.	Data span
GGM05S	180	~10 yrs.
Tongji-Grace02s*	180	~13.5 yrs.
Tongji-Grace02k*	180	~13.5 yrs.
ITSG-Grace2018s	200	~15 yrs.
AIUB-GRACE03S	160	~6 yrs.
Tongji-GRACE01*	160	~5 yrs.
HUST-Grace2016s	160	~13 yrs.

Method — Modified Short-arc Algorithm



Tongji-GRACE01 Model: Modelling Orbit and KBR Obs. Errors

Tongji-GRACE02 model: Further Modelling Acc. and Attitude Obs. Errors

Method — Optimized Short-arc Algorithm

➢ Boundary Conditions

$$\boldsymbol{r}_k(\tau_0)+\boldsymbol{v}_r(\tau_0)=\boldsymbol{r}_0+\delta\boldsymbol{r}_0$$

$$\boldsymbol{r}_k(\tau_N)+\boldsymbol{v}_r(\tau_N)=\boldsymbol{r}_N+\delta\boldsymbol{r}_N$$

➢ Obs. Eq. for One Arc

Sat. A: $\boldsymbol{C}_k^A\boldsymbol{x}_k+\boldsymbol{D}_k^A\boldsymbol{v}_k^A=\boldsymbol{y}_k^A,\ \boldsymbol{D}_k^A\text{->Sq. Mat.}$

Sat. B: $\boldsymbol{C}_k^B\boldsymbol{x}_k+\boldsymbol{D}_k^B\boldsymbol{v}_k^B=\boldsymbol{y}_k^B,\ \boldsymbol{D}_k^B\text{->Sq. Mat.}$

KBRR: $\boldsymbol{C}_k^{\dot\rho}\boldsymbol{x}_k+\boldsymbol{D}_k^{\dot\rho A}\boldsymbol{v}_k^A+\boldsymbol{D}_k^{\dot\rho B}\boldsymbol{v}_k^B-\boldsymbol{v}_k^{\dot\rho}=\boldsymbol{y}_k^{\dot\rho}$

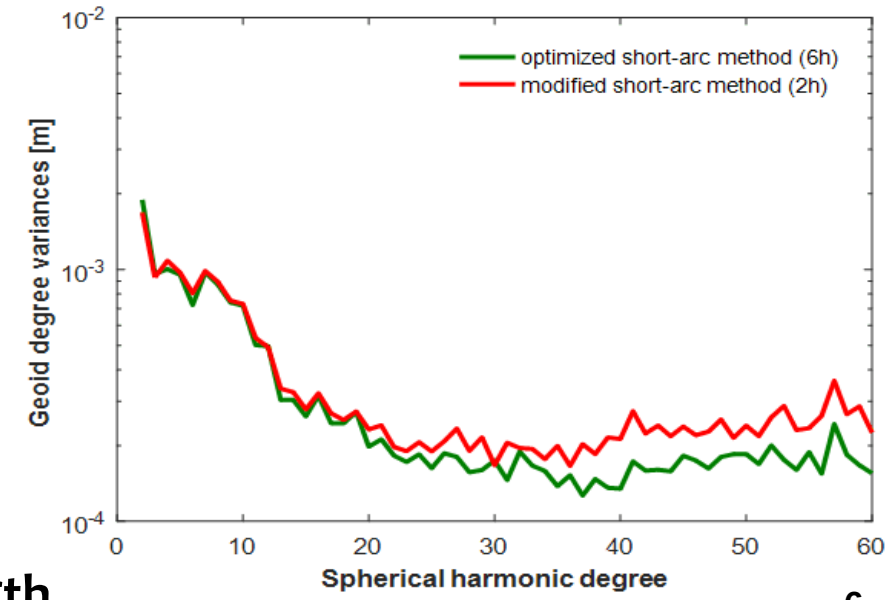
➢ Re-Organized Obs. Equation

$$\boldsymbol{v}_k^A=-\left(\boldsymbol{D}_k^A\right)^{-1}\boldsymbol{C}_k^A\boldsymbol{x}_k+\left(\boldsymbol{D}_k^A\right)^{-1}\boldsymbol{y}_k^A$$

$$\boldsymbol{v}_k^B=-\left(\boldsymbol{D}_k^B\right)^{-1}\boldsymbol{C}_k^B\boldsymbol{x}_k+\left(\boldsymbol{D}_k^B\right)^{-1}\boldsymbol{y}_k^B$$

$$\boldsymbol{v}_j^{\dot\rho}=\overline{\boldsymbol{C}}_j^{\dot\rho}\boldsymbol{x}_j-\overline{\boldsymbol{y}}_j^{\dot\rho}$$

Arc Length	Cond. Num. [log10]	Cond. Num. [log10]
	Mod. Algorithm	Opt. Algorithm
	$\mathbf{D_kQ_kD_k^T}$	$\mathbf{D_k^s(s=A,B)}$
2	15.3	3.3
4	15.8	4.2
6	16.4	4.8
8	16.8	5.5
12	*	9.9



Tongji-GRACE2018 model: 6 hour Arc Length

Tongji-GRACE Gravity Field Solutions

Gravity Field Models
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Calculation Service
Regular grids
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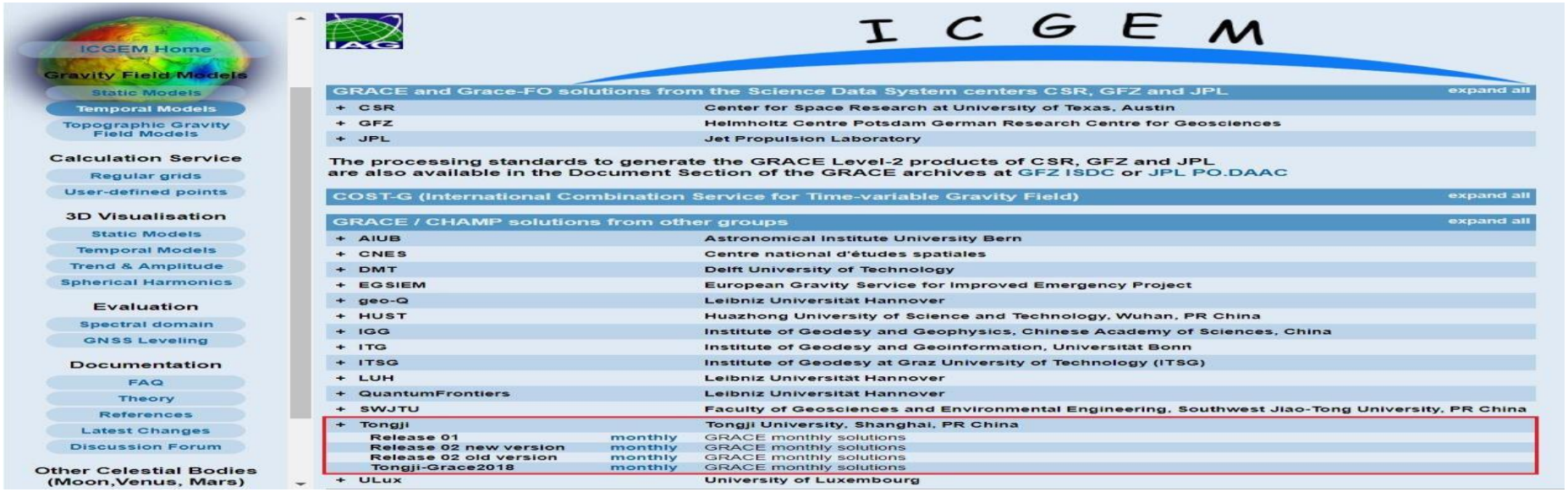
ICGEM

Nr	Model	Year	Degree	Data	References	Download	Calculate	Show	DOI
176	XGM2019e_2159	2019	2190 5540 760	A, G, S(GOCO06s), T	Zingerle, P. et al, 2019	gfc zip gfc zip gfc zip	Calculate	Show	✓
175	GO_CONS_GCF_2_TIM_R6e	2019	300	G (Polar), S(Goce)	Zingerle, P. et al, 2019	gfc zip	Calculate	Show	✓
174	ITSG-Grace2018s	2019	200	S(Grace)	Mayer-Gürr, T. et al, 2018	gfc zip	Calculate	Show	✓
173	EIGEN-GRGS.RL04.MEAN-FIELD	2019	300	S	Lemoine et al, 2019	gfc zip	Calculate	Show	✓
172	GOCO06s	2019	300	S	Kvas et al., 2019	gfc zip	Calculate	Show	✓
171	GO_CONS_GCF_2_TIM_R6	2019	300	S(Goce)	Brockmann, J. M. et al, 2014	gfc zip	Calculate	Show	✓
170	GO_CONS_GCF_2_DIR_R6	2019	300	S	Bruinsma, S. L. et al, 2014	gfc zip	Calculate	Show	✓
169	IGGT_R1C	2018	240	G, S(Goce), S(Grace)	Lu, B. et al., 2019	gfc zip	Calculate	Show	✓
168	Tongji-Grace02k	2018	180	S(Grace)	Chen, Q. et al, 2018	gfc zip	Calculate	Show	
167	SGG-UGM-1	2018	2159	EGM2008, S(Goce)	Liang, W. et al., 2018 & Xu, X. et al. (2017)	gfc zip	Calculate	Show	✓
166	GOSG01S	2018	220	S(Goce)	Xu, X. et al., 2018	gfc zip	Calculate	Show	✓
165	IGGT_R1	2017	240	S(Goce)	Lu, B. et al, 2017	gfc zip	Calculate	Show	✓
164	IfE_GOCE05s	2017	250	S	Wu, H. et al, 2017	gfc zip	Calculate	Show	✓
163	GO_CONS_GCF_2_SPW_R5	2017	330	S(Goce)	Gatti, A. et al, 2016	gfc zip	Calculate	Show	✓
162	GAO2012	2012	360	A, G, S(Goce), S(Grace)	Demianov, G. et al, 2012	gfc zip	Calculate	Show	✓
161	XGM2016	2017	719	A, G, S(GOCO05s)	Pail, R. et al, 2017	gfc zip	Calculate	Show	✓
160	Tongji-Grace02s	2017	180	S(Grace)	Chen, Q. et al, 2016	gfc zip	Calculate	Show	✓
159	NULP-02s	2017	250	S(Goce)	A.N. Marchenko et al, 2016	gfc zip	Calculate	Show	✓
158	HUST-Grace2016s	2016	160	S(Grace)	Zhou, H. et al, 2016	gfc zip	Calculate	Show	✓



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Other Celestial Bodies (Moon,Venus, Mars)

ICGEM

GRACE and Grace-FO solutions from the Science Data System centers CSR, GFZ and JPL — expand all

+ CSR	Center for Space Research at University of Texas, Austin
+ GFZ	Helmholtz Centre Potsdam German Research Centre for Geosciences
+ JPL	Jet Propulsion Laboratory

The processing standards to generate the GRACE Level-2 products of CSR, GFZ and JPL are also available in the Document Section of the GRACE archives at GFZ ISDC or JPL PO.DAAC

COST-G (International Combination Service for Time-variable Gravity Field) — expand all

GRACE / CHAMP solutions from other groups — expand all

+ AIUB		Astronomical Institute University Bern
+ CNES		Centre national d'études spatiales
+ DMT		Delft University of Technology
+ EGSIEM		European Gravity Service for Improved Emergency Project
+ geo-Q		Leibniz Universität Hannover
+ HUST		Huazhong University of Science and Technology, Wuhan, PR China
+ IGG		Institute of Geodesy and Geophysics, Chinese Academy of Sciences, China
+ ITG		Institute of Geodesy and Geoinformation, Universität Bonn
+ ITSG		Institute of Geodesy at Graz University of Technology (ITSG)
+ LUH		Leibniz Universität Hannover
+ QuantumFrontiers		Leibniz Universität Hannover
+ SWJTU		Faculty of Geosciences and Environmental Engineering, Southwest Jiao-Tong University, PR China
+ Tongji		Tongji University, Shanghai, PR China
Release 01	monthly	GRACE monthly solutions
Release 02 new version	monthly	GRACE monthly solutions
Release 02 old version	monthly	GRACE monthly solutions
Tongji-Grace2018	monthly	GRACE monthly solutions
+ ULux		University of Luxembourg

Static Solutions — Data input and Model Output

➢ Data Input:

- JPL RL02 KBRR (5s)
- JPL RL02 Acceleration Data(5s)
- JPL RL02 Attitude Data (5s)
- Graz Kinematic Orbit (10s)

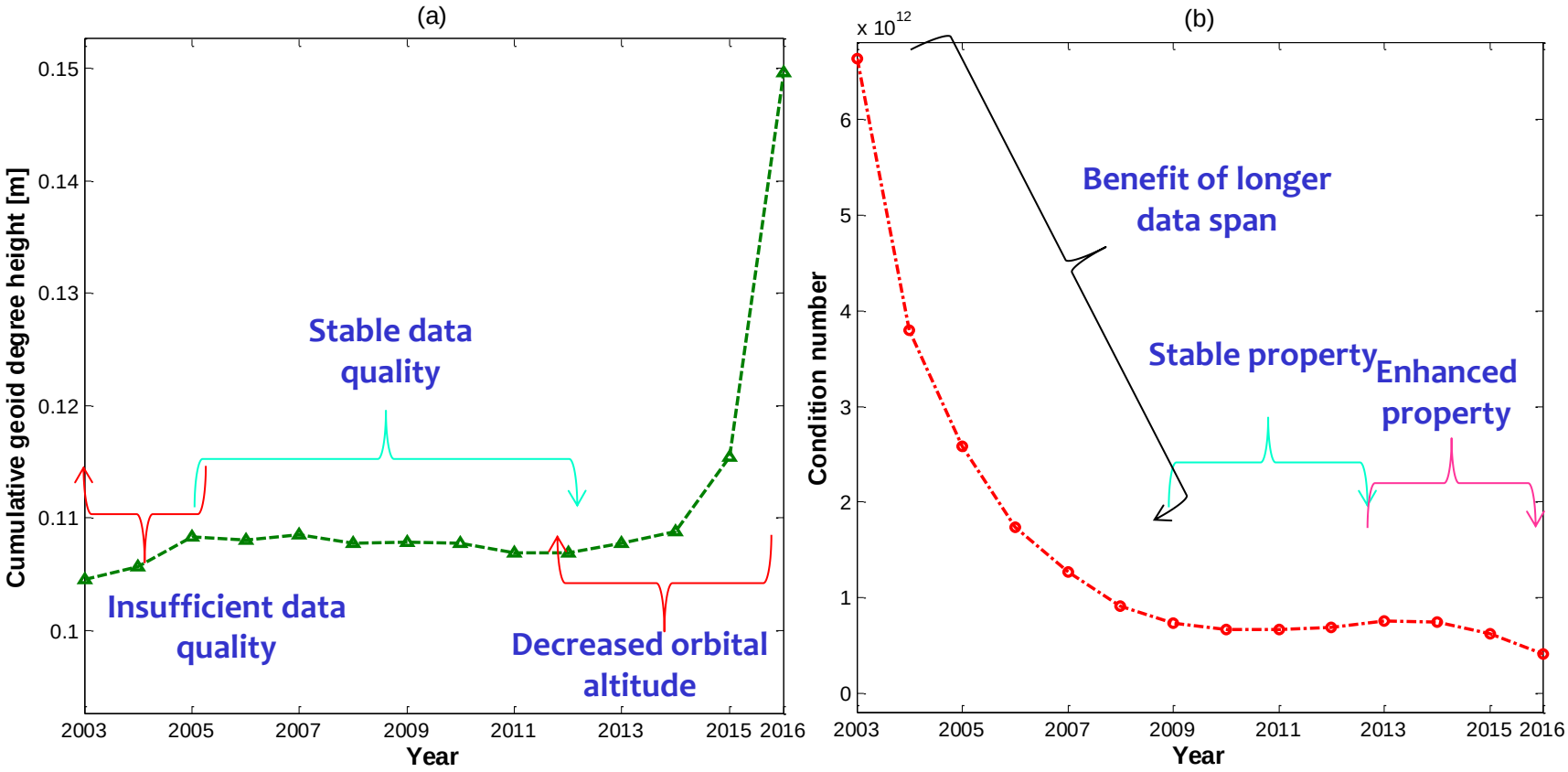
➢ Spatial/Temporal Resolution:

- Temporal Resolution： ~13.5 years (01/2003-03/2016)
- Spatial Resolution： 180 d/o

➢ Model Output:

- Tongji-Grace02s Model, Unconstrained Solution
- Tongji-Grace02k Model, Regularized Solution

Static Solutions — Data Contribution



(a) Contributions of GRACE Data

(b) Cond. Num. of Normal Eq.

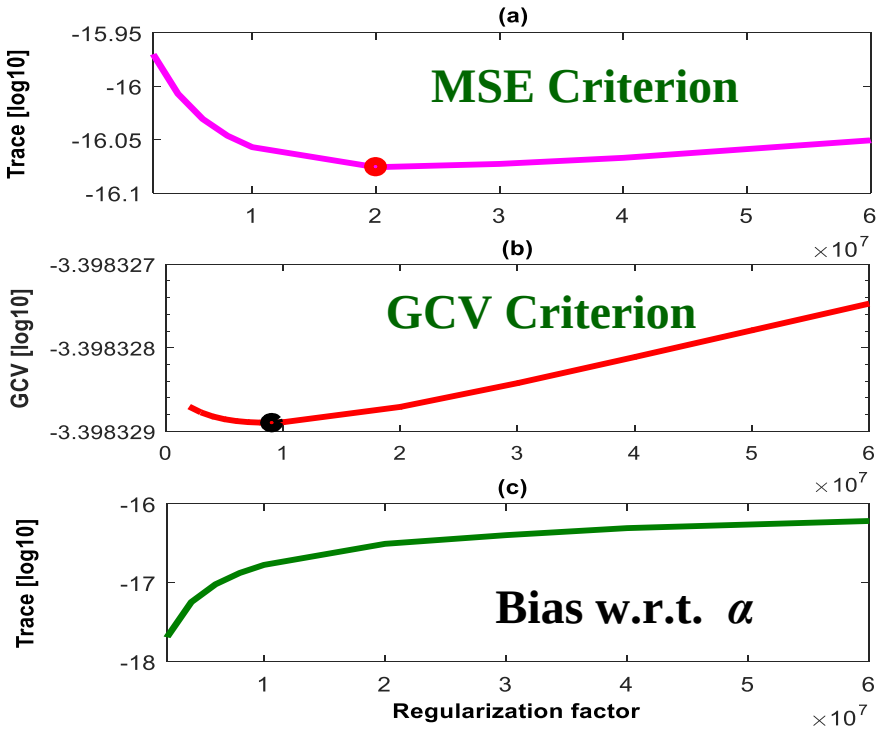
Static Solutions — Regularization Method

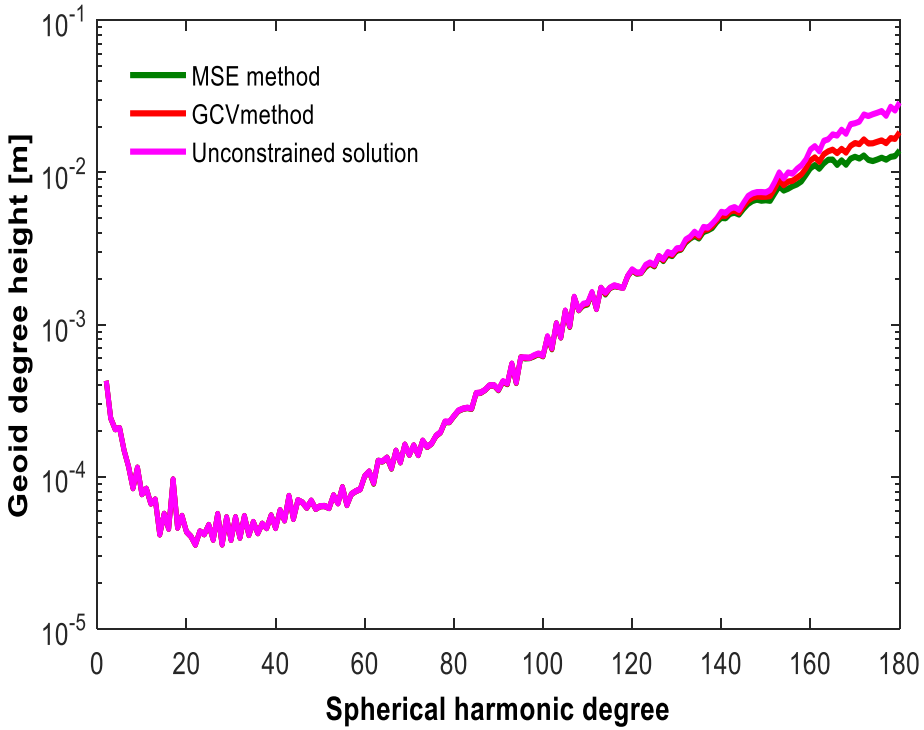
➢ Regularization Method

$$\delta \boldsymbol{u}_\alpha = \left(\boldsymbol{N}_{\boldsymbol{uu}} + \alpha \boldsymbol{K}\right)^{-1} \boldsymbol{W}_{\boldsymbol{u}}$$ **K -> Kaula constraint**

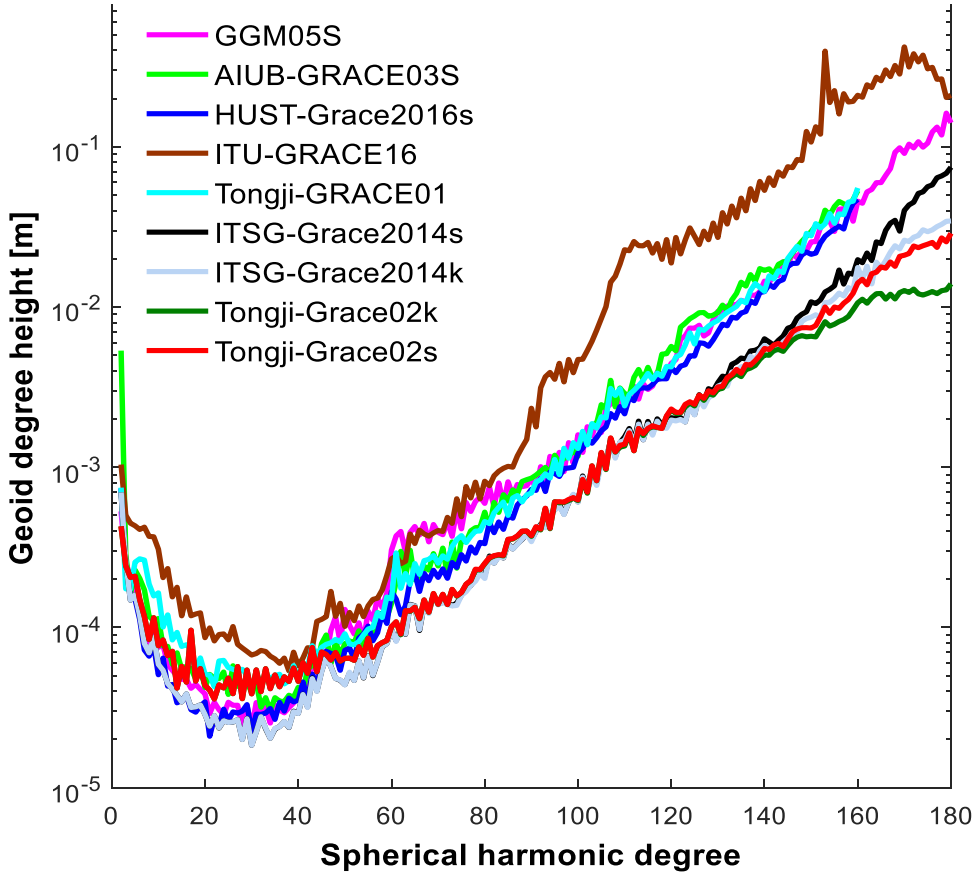
Criterion to Est. α :

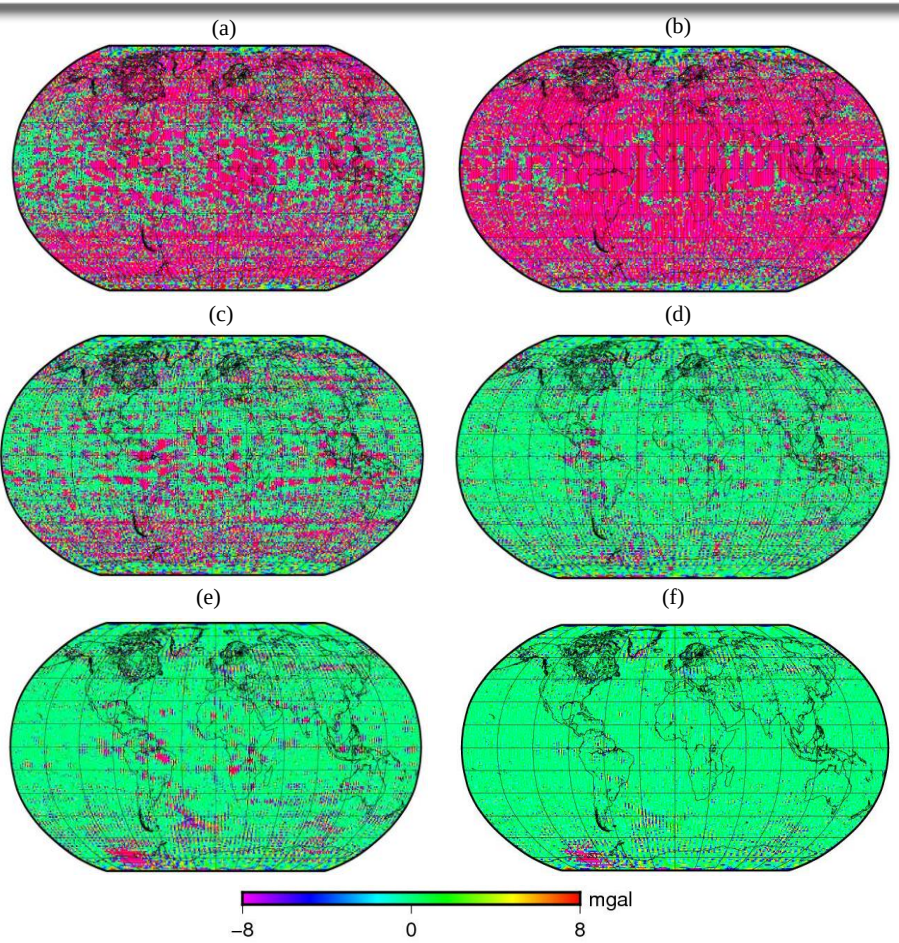
$$\min: \operatorname{trace}\left[\operatorname{MSE}\left(\delta \boldsymbol{u}_\alpha\right)\right] = \sigma_0^2 \operatorname{trace}\left[\boldsymbol{Q}_\alpha \boldsymbol{N}_{\boldsymbol{uu}} \boldsymbol{Q}_\alpha\right] + \alpha^2 \operatorname{trace}\left[\boldsymbol{Q}_\alpha \boldsymbol{K} \delta \boldsymbol{u}_L \delta \boldsymbol{u}_L^T \boldsymbol{K} \boldsymbol{Q}_\alpha\right]$$





Static Solutions — Tongji-Grace02s/k





(a) GGM05S; (b) ITU-GRACE16; (c) ITSG-Grace2014s

(d) ITSG-Grace2014k; (e) Tongji-Grace02s; (f) Tongji-Grace02k

Geoid degree height and gravity anomaly relative to Eigen6C4

Static Solutions — Validation by DTU13 data

A: $[26^\circ N, 36^\circ N], [255^\circ E, 265^\circ E]$; B: $[30^\circ \mathrm{N}, 40^\circ N], [165^\circ \mathrm{E}, 175^\circ E]$ (mGal)

Region	Degree	GGM 05S	ITU-GRACE 16	AIUB-GRACE 03S	Tongji-GRACE 01	HUST-Grace 2016s	ITSG-Grace 2014s	ITSG-Grace 2014k	Tongji-Grace 02s	Tongji-Grace 02k
A	60	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
	90	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
	120	0.81	1.28	0.82	0.85	0.85	0.81	0.81	0.82	0.82
	160	3.94	34.74	3.51	3.74	3.27	2.31	1.41	2.31	1.39
	180	10.52	72.80	*	*	*	6.79	4.06	4.18	2.42
B	60	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
	90	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
	120	2.25	2.29	2.28	2.27	2.25	2.25	2.25	2.26	2.26
	160	3.17	10.62	4.84	4.09	3.29	2.60	2.57	2.47	2.30
	180	10.74	15.07	*	*	*	4.83	4.44	3.05	2.61

Monthly Solutions — Data input and Model Output

➢ Data Input:

- JPL RL03 KBRR (5s)
- JPL RL02 Acceleration Data(5s)
- JPL RL02 Thruster Data(30s)
- JPL RL03 Attitude Data (5s)
- Graz Kinematic Orbit (10s)

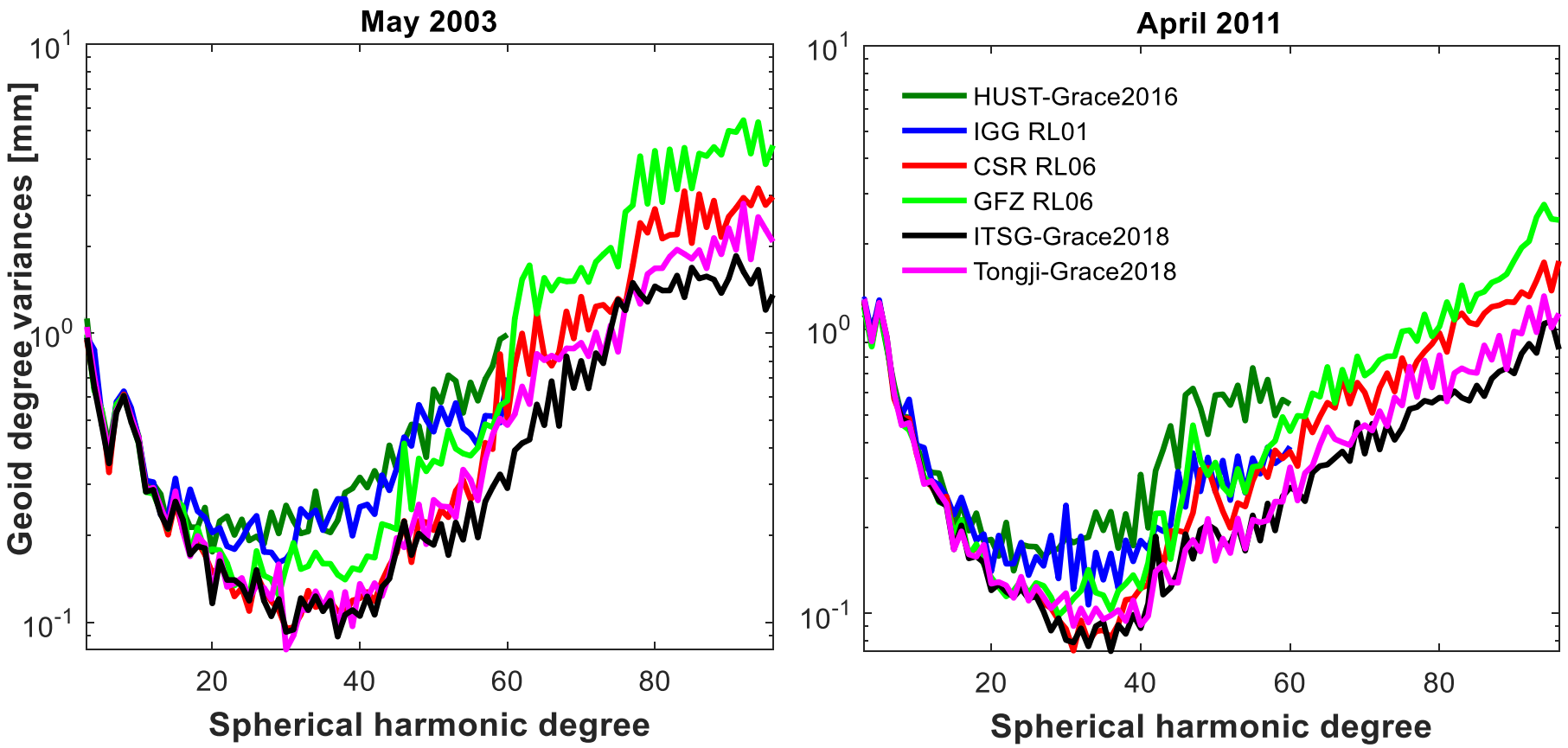
➢ Spatial/Temporal Resolution:

- Temporal Resolution： One month (04/2002-06/2017)
- Spatial Resolution： 96 d/o

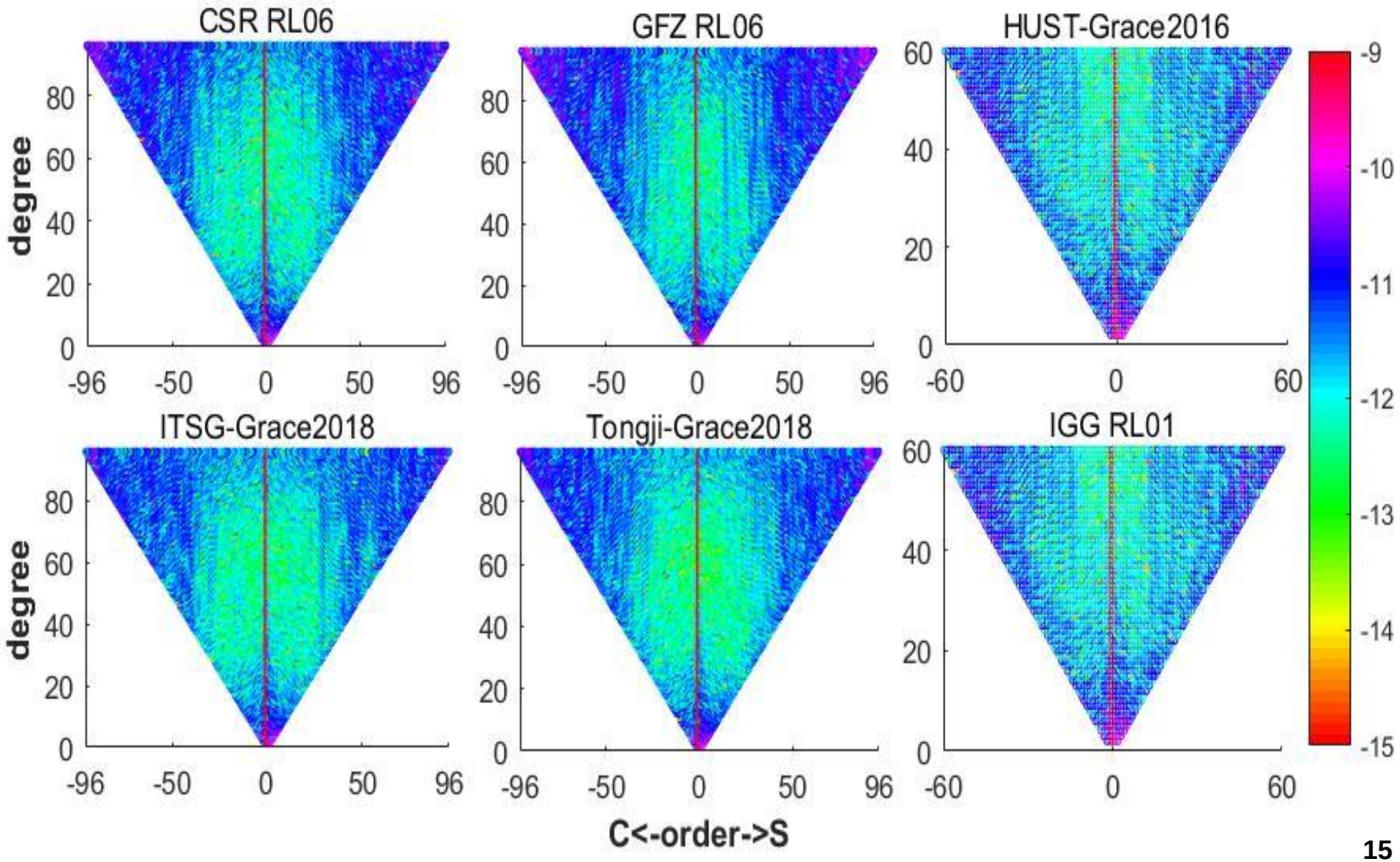
➢ Model Output:

- Tongji-Grace2018s Model, Unconstrained Solution

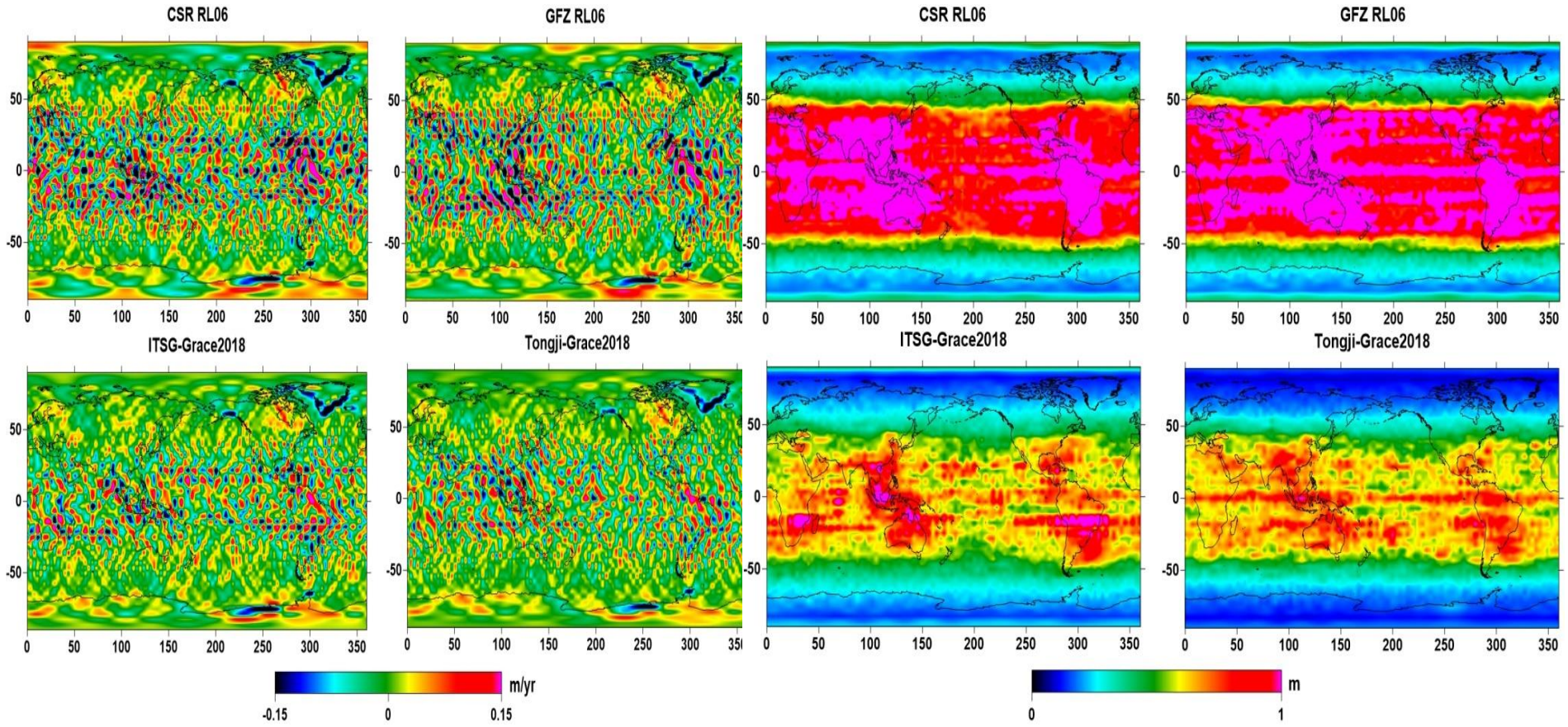
Monthly Solutions — Geoid Degree Variances



Monthly Solutions — Coefficient Difference



Monthly Solutions — Global Trend Comparison

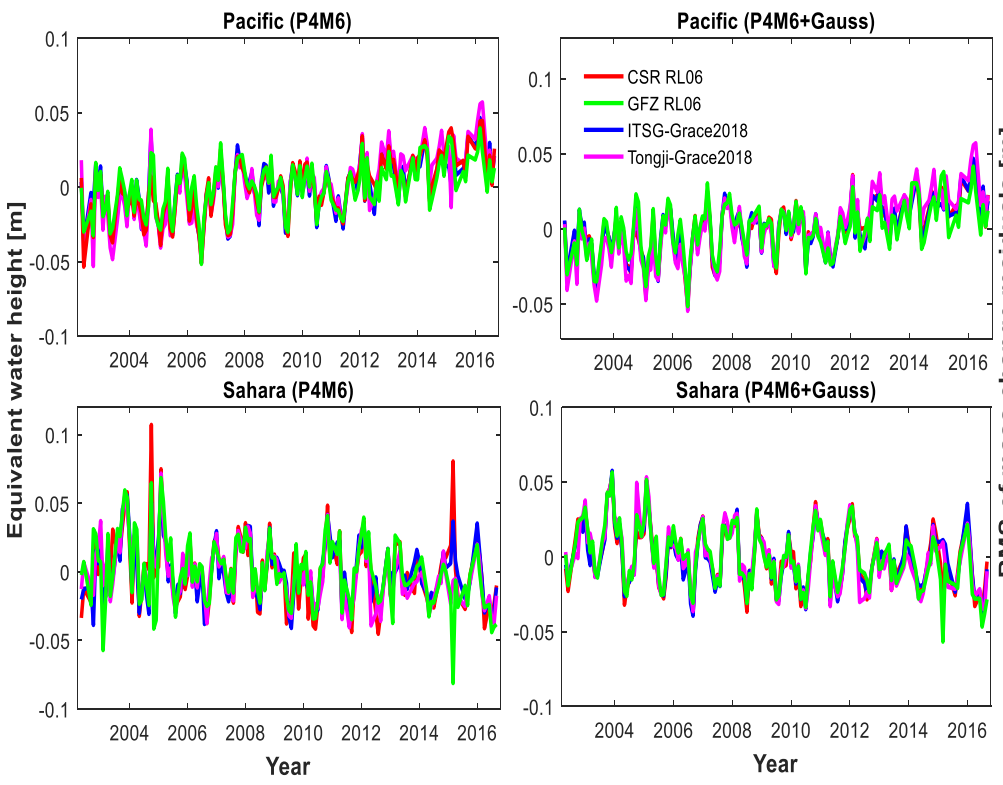


Global Trend **Global RMS**

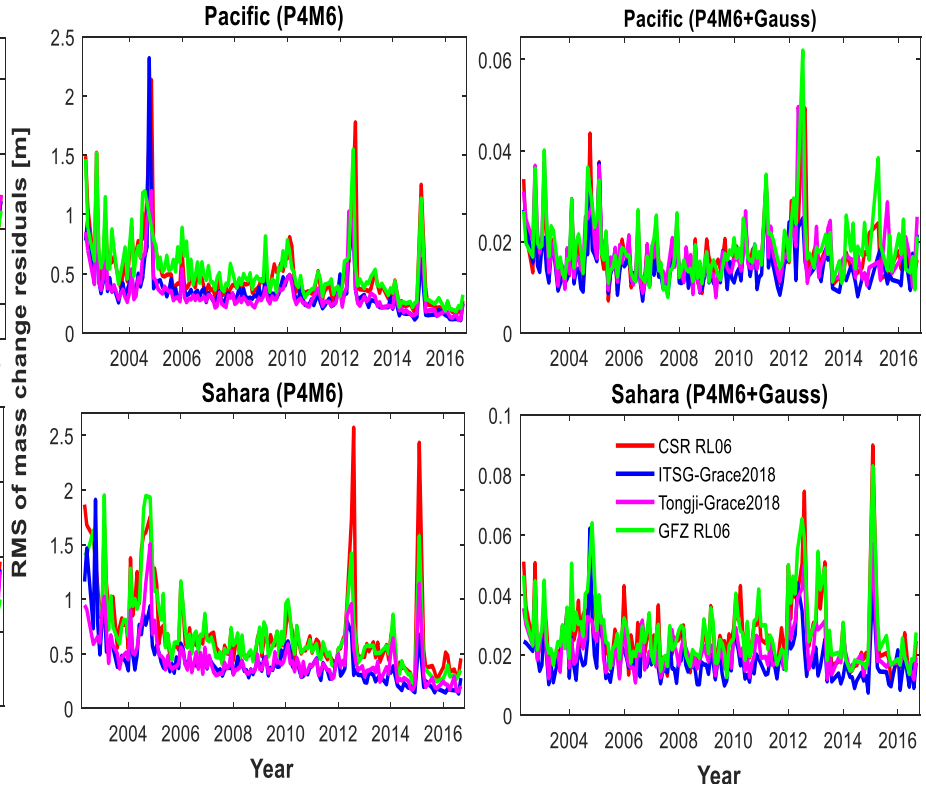
P4M6 Decorrelation

Monthly Solutions — Noise Analyses

Pacific (28N~51°N, 170°E~220°E), Sahara (15°N~35°N, 0°E~35°E)

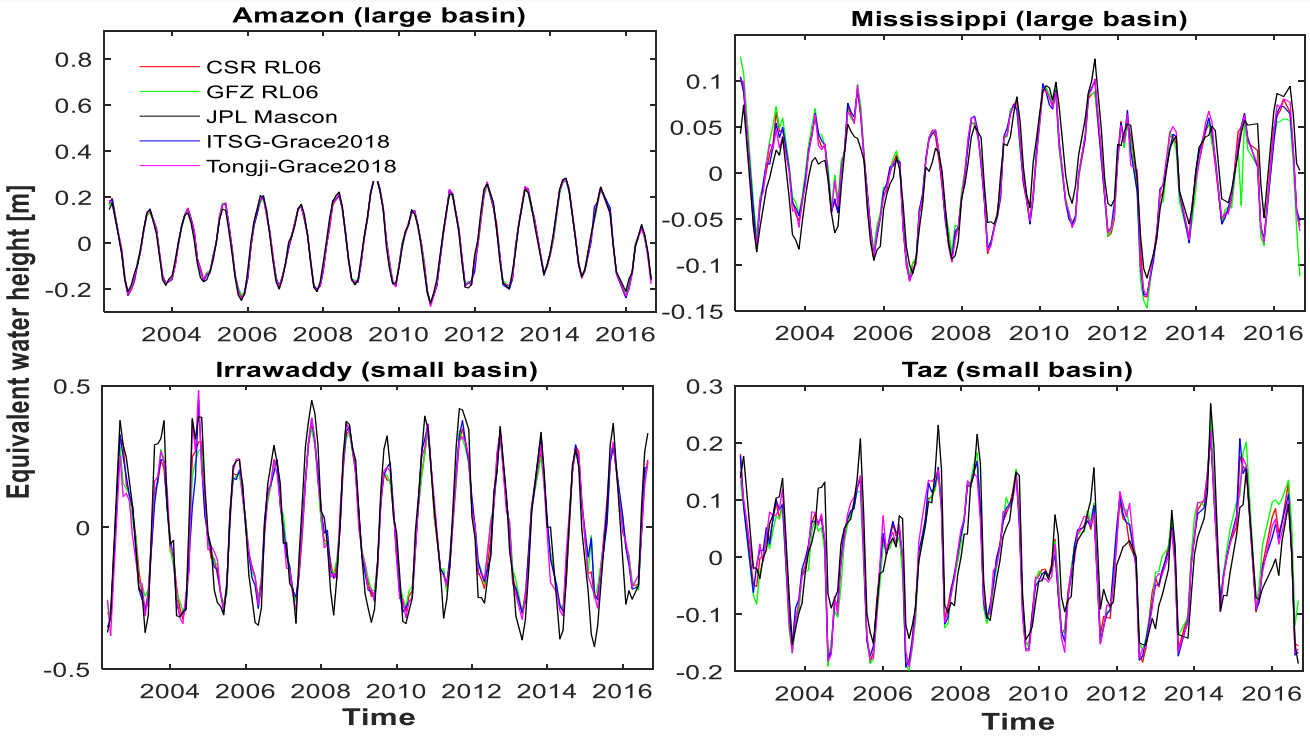


Mean Mass Variation Series



Mean RMS Series

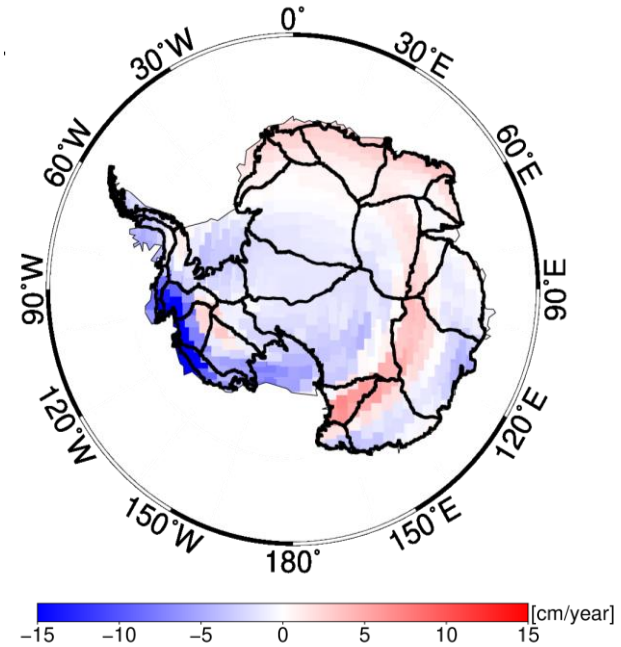
Monthly Solutions — Signal Comparison



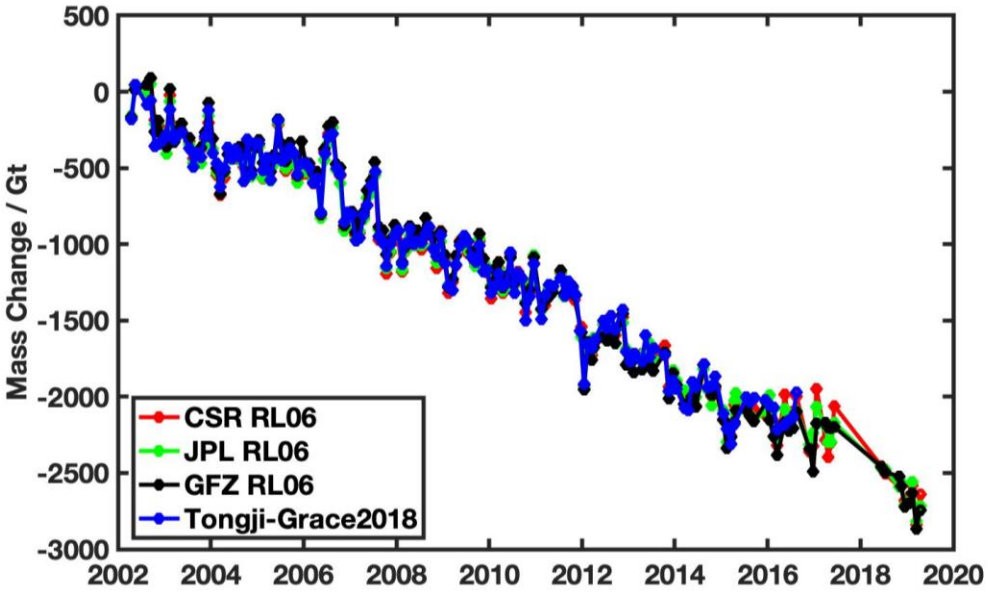
⟨Amp|Pha⟩

River Basin	CSR RL06	GFZ RL06	ITSG-Grace2018	Tongji-Grace2018	JPL Mascon
Amazon	⟨22.8cm|96°⟩	⟨22.5cm|96°⟩	⟨23.4cm|98°⟩	⟨23.3cm|96°⟩	⟨24.7cm|111°⟩
Mississippi	⟨6.5cm|112°⟩	⟨6.4cm|111°⟩	⟨6.5cm|113°⟩	⟨6.6cm|111°⟩	⟨6.0cm|100°⟩
Irrawaddy	⟨26.6cm|291°⟩	⟨25.3cm|291°⟩	⟨27.3cm|290°⟩	⟨27.0cm|292°⟩	⟨34.8cm|296°⟩
Taz	⟨10.4cm|126°⟩	⟨10.6cm|126°⟩	⟨10.5cm|128°⟩	⟨10.7cm|128°⟩	⟨10.3cm|103°⟩

Monthly Solutions —Signal in Antarctica by Mascon Modelling



Secular trend in equivalent water height (cm/year)



Time series of Antarctica mass change.

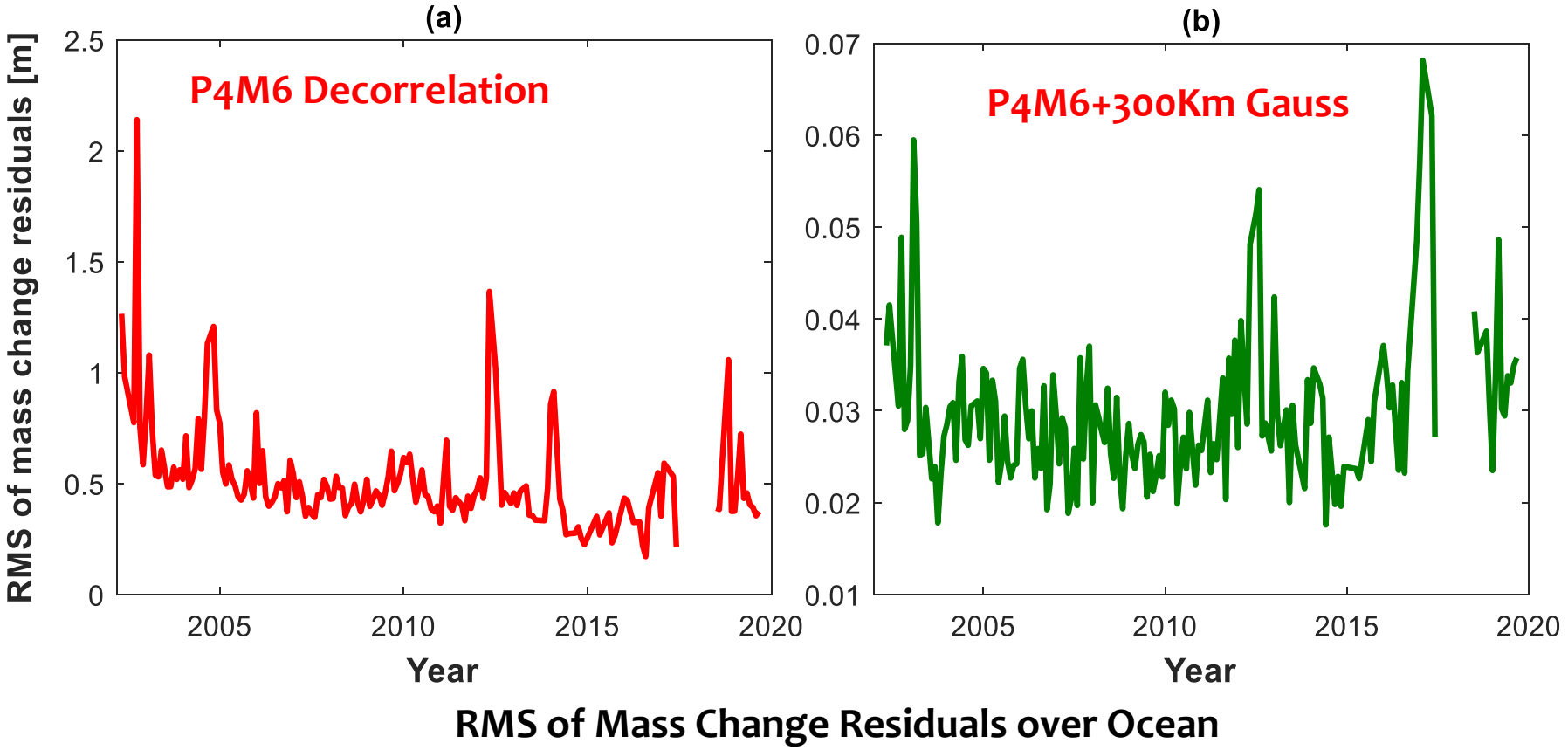
Mass Variations in Antarctica	Trend(Gt/year)	Annual		Semiannual	
		amplitude(Gt)	phase(°)	amplitude(Gt)	phase(°)
CSR Release 06	-151 ±17	84 ±27	126 ±17	15 ±8	234 ±78
JPL Release 06	-150 ±17	73 ±27	125 ±21	9 ±7	228 ±86
GFZ Release 06	-157 ±18	89 ±29	134 ±21	11 ±9	243 ±92
Tongji-Grace2018	-150 ±18	84 ±29	131 ±20	12 ±8	230 ±89

secular trends and seasonal signals (significant at 2-σ level)

Preliminary GRACE-FO Solutions: Data Input and Model Output

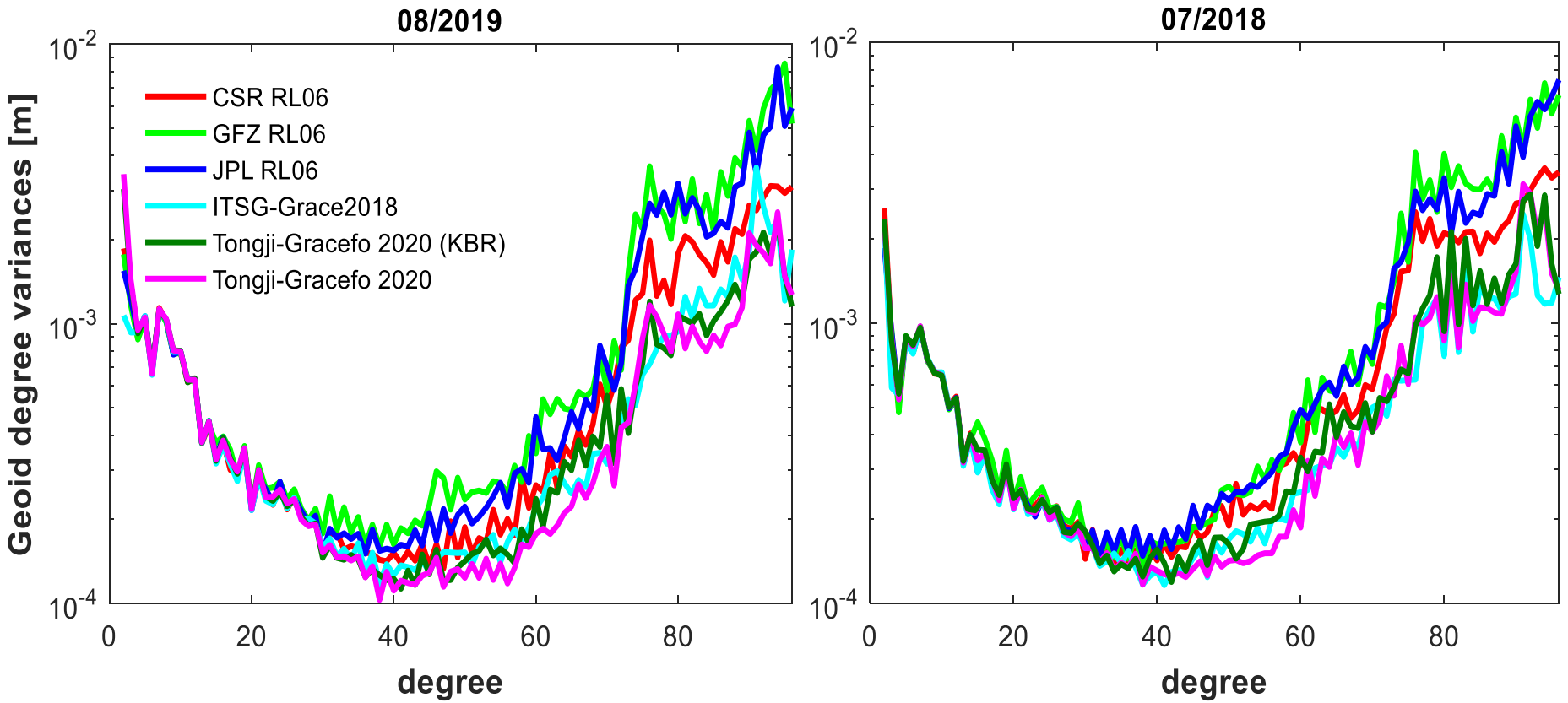
- **Data Input:**
  - JPL RL04 KBRR (5s) / LRIRR (2s)
  - JPL RL04 Acceleration Data(1s)
  - JPL RL04 Thruster Data(30s)
  - JPL RL04 Attitude Data (1s)
  - Tongji Kinematic Orbit (10s)
- **Spatial/Temporal Resolution:**
  - Temporal Resolution： One month (06/2018-10/2019)
  - Spatial Resolution： 96 d/o
- **Model Output:**
  - Tongji-Gracefo2020 Model, Unconstrained Solution

Preliminary GRACE-FO Solutions: KBR-based Models

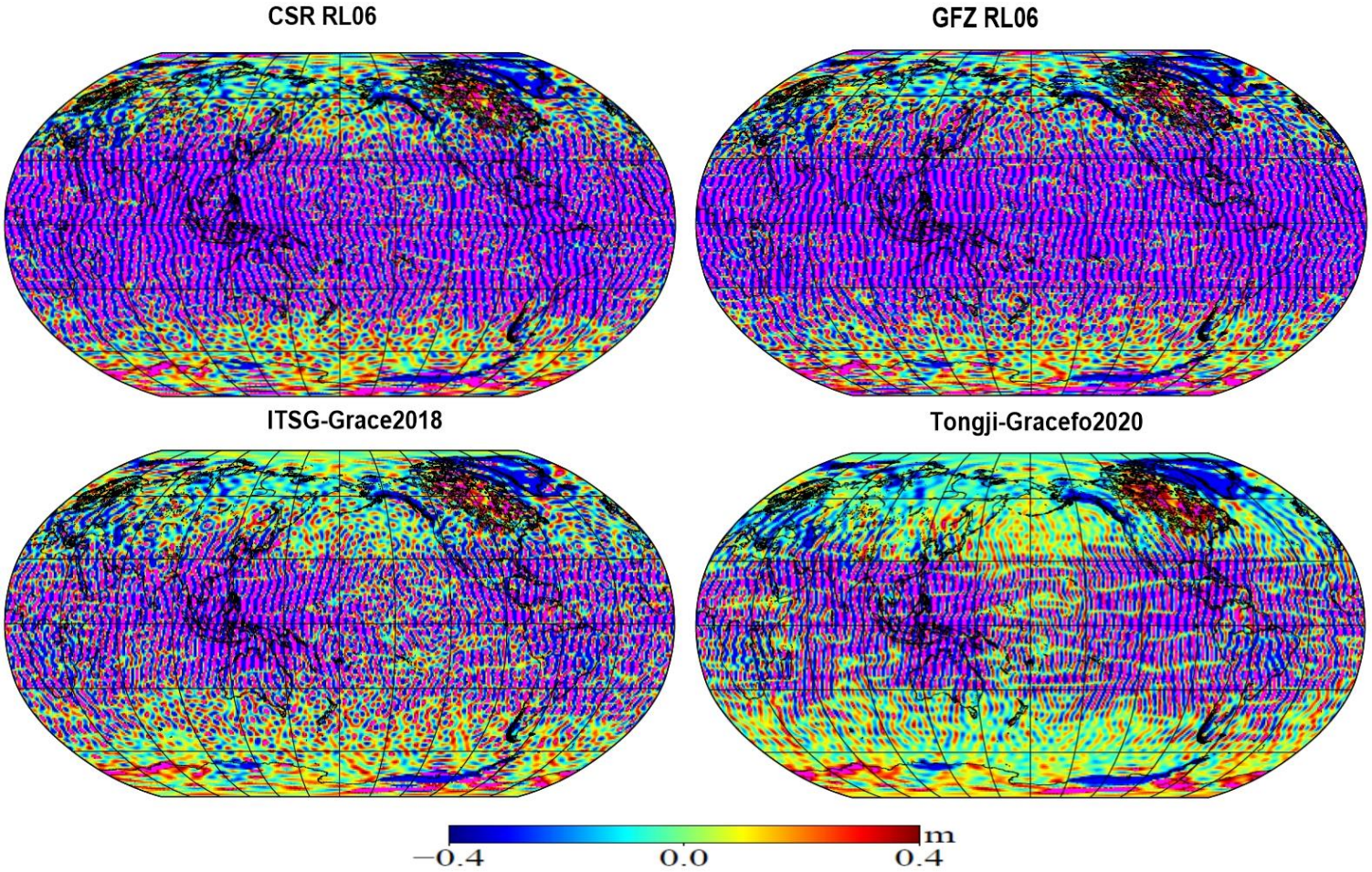


RMS of Mass Change Residuals over Ocean

Preliminary GRACE-FO Solutions: Degree Variances



Preliminary GRACE-FO Solutions: Spatial Noise



P4M6-Decorrelation

Concluding remarks

1. High-frequency noise in Tongji-Grace02s/k static gravity field solutions has been reduced.
2. Compared to the officially released RL06 models, Tongji-Grace2018 has comparable signals and improved noise level. Tongji-Grace2018 is closer to ITSG-Grace2018.
3. The noise of preliminary GRACE-FO gravity field solutions from Tongji Uni. has been further reduced. Additional work is still going on...

Thank You for Your Attention!