Regularized GRACE monthly solutions by constraining the difference between the longitudinal and latitudinal gravity variations

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Introduction

The existing unconstrained Gravity Recovery and Climate Experiment (GRACE) monthly solutions, e.g. CSR RL05 from Center for Space Research (CSR), GFZ RL05a from GeoForschungsZentrum (GFZ), JPL RL05 from Jet Propulsion Laboratory (JPL), DMT-1 from Delft Institute of Earth Observation and Space Systems (DEOS), AIUB from Bern University, and Tongji-GRACE01 as well as Tongji-GRACE02 from Tongji University, are dominated by correlated noise (such as north-south striping errors) at high degree coefficients. To suppress the correlated noise of the unconstrained GRACE solutions, one typical option is to use post-processing filters such as decorrelation filtering and Gaussian smoothing , which are quite effective to reduce the noise and convenient to be implemented. Unlike these post-processing methods, the CNES/GRGS monthly GRACE solutions from Centre National d'Etudes Spatiales (CNES) were developed by using regularization with Kaula rule (Bruinsma et al. 2010), whose correlated noise are reduced to such a great extent that no decorrelation filtering is required. Actually, the previous studies demonstrated that the north–south stripes in the GRACE solutions are partly caused by poor sensitivity of gravity variation in east-west direction (Liu et al. 2010). In other words, the longitudinal sampling of gravity signal is very sparse but the latitudinal sampling is quite dense, indicating that the recoverability of the longitudinal gravity variation is poor or unstable, leading to the ill-conditioned GRACE monthly solutions. To stabilize the monthly solutions, we constructed the regularization matrices by minimizing the difference between the longitudinal and latitudinal gravity variations and applied them to derive a time series of regularized GRACE monthly solutions named RegTongji RL01 for the period Jan. 2003 to Aug. 2011 in this research. To our best of knowledge, this is the first time to constrain the gravity variations. The distinction of signal losses between filtered solutions and our regularized ones was analyzed, demonstrating that the signal powers of RegTongji RL01 monthly models are obviously stronger than those of the filtered ones.

Regularization method

According to the modified short-arc approach (Chen et al. 2015), the observation equation for the unconstrained GRACE solution can be written as:

$$\boldsymbol{Ax} + \boldsymbol{Bv} = \boldsymbol{l} \qquad (1)$$

in which $\boldsymbol{x}$ is the unknown vector to be estimated, containing the geopotential coefficients and the accelerometer parameters; $\boldsymbol{x}$ is the correction vector for the measurements of the twin GRACE satellites' orbits and the inter-satellite range-rates. The matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ are the partial derivatives with respect to the unknown vector and the correction vector; and $\boldsymbol{l}$ is the residual vector.
In this research, the regularized solution is achieved by minimizing the following cost function:

$$\Phi = \boldsymbol{v}^T \boldsymbol{Q}^{-1} \boldsymbol{v} + \alpha \Delta \boldsymbol{g}^T \boldsymbol{Q}_{\Delta g} \Delta \boldsymbol{g} + 2\boldsymbol{K}^T \left(\boldsymbol{Ax} + \boldsymbol{Bv} - \boldsymbol{l} \right) \qquad (2)$$

where $\boldsymbol{Q}_{\Delta g}$ stands for the noise variance-covariance matrix of the gravity difference $\Delta \boldsymbol{g}$; $\boldsymbol{Q}$ is the variance-covariance matrix of observations (orbits and range-rates).

Comparisons of unconstrained and regularized solutions

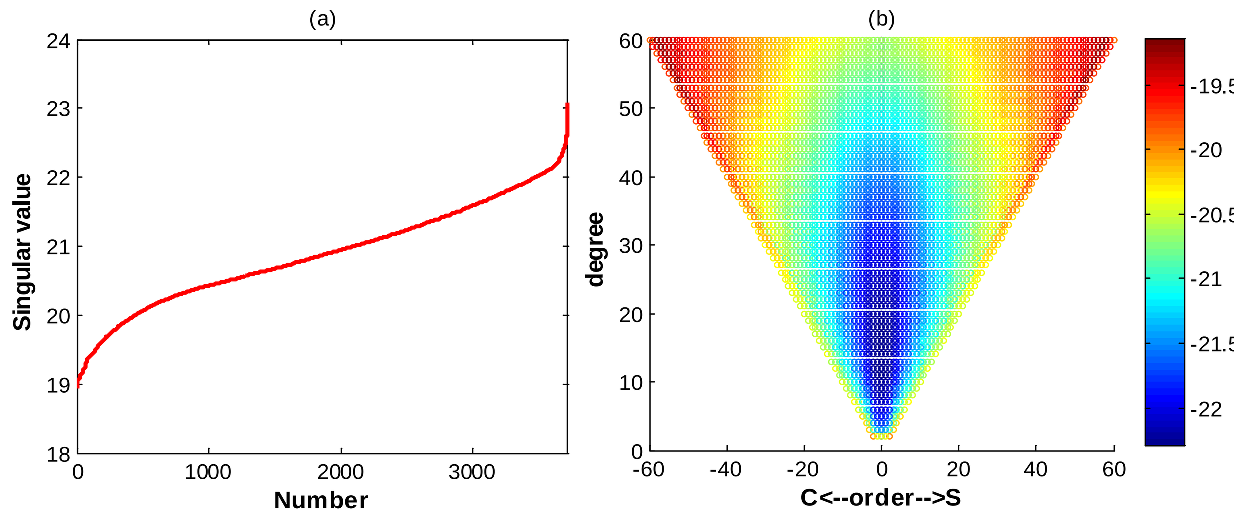

Figure 1 (a) the singular values (log10 scale) of the unconstrained normal equation matrix in Feb. 2004; (b) diagonal elements (log 10 scale) of variance-covariance matrix in Feb. 2004 for different degrees and orders

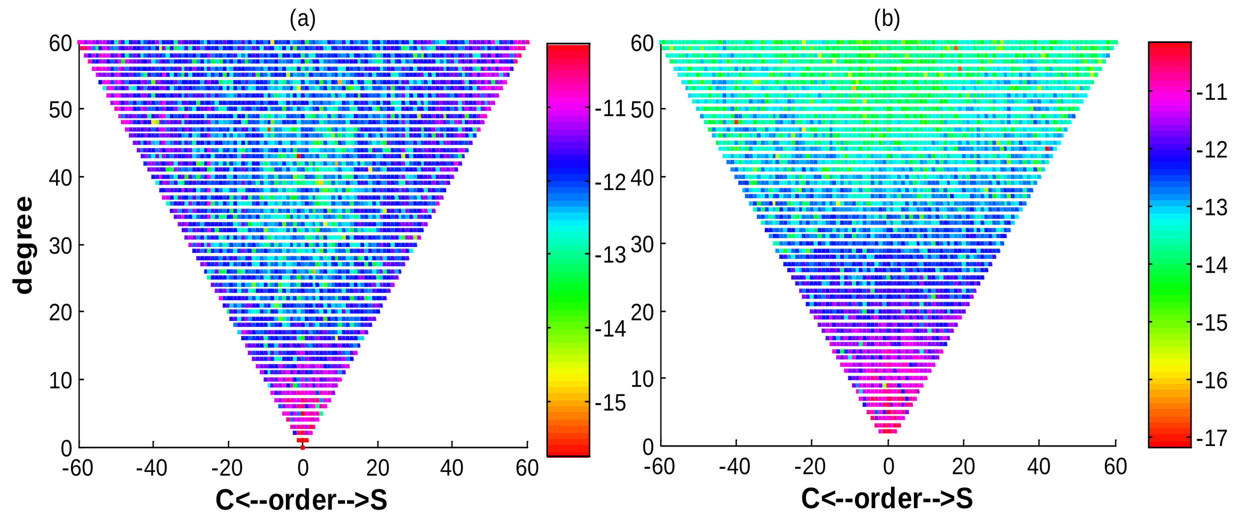

Figure 2 Geopotential coefficient variations (log10 scale) of the unconstrained (a) and regularized (b) solutions in Feb. 2004 with respect to the mean field (EIGEN6C2)

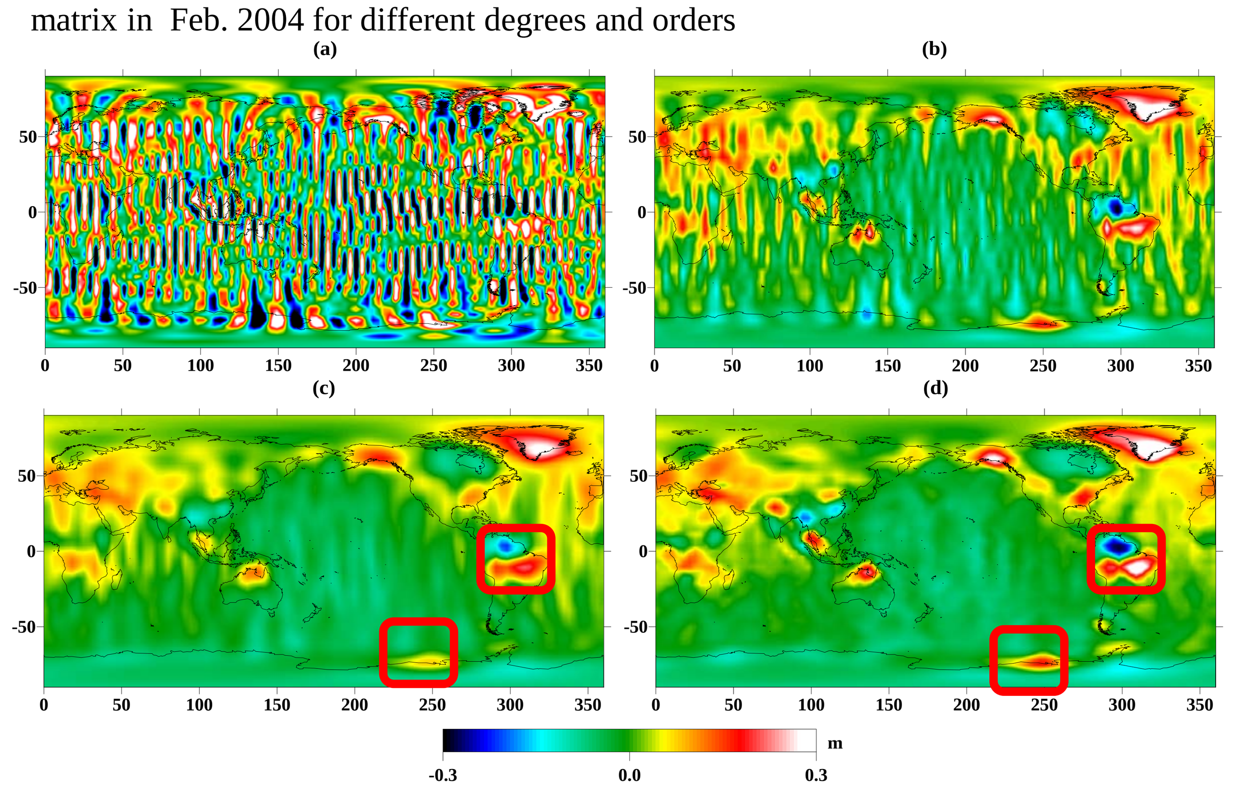

Figure 3 Global mass variations (in EWH) in Feb. 2004 from: (a) Tongji-GRACE01 without any smoothing and filtering; (b) Tongji-GRACE01 processed with 300 km Gaussian smoothing; (c) Tongji-GRACE01 processed with 500 km Gaussian smoothing; (d) RegTongji RL01 without post-filtering.

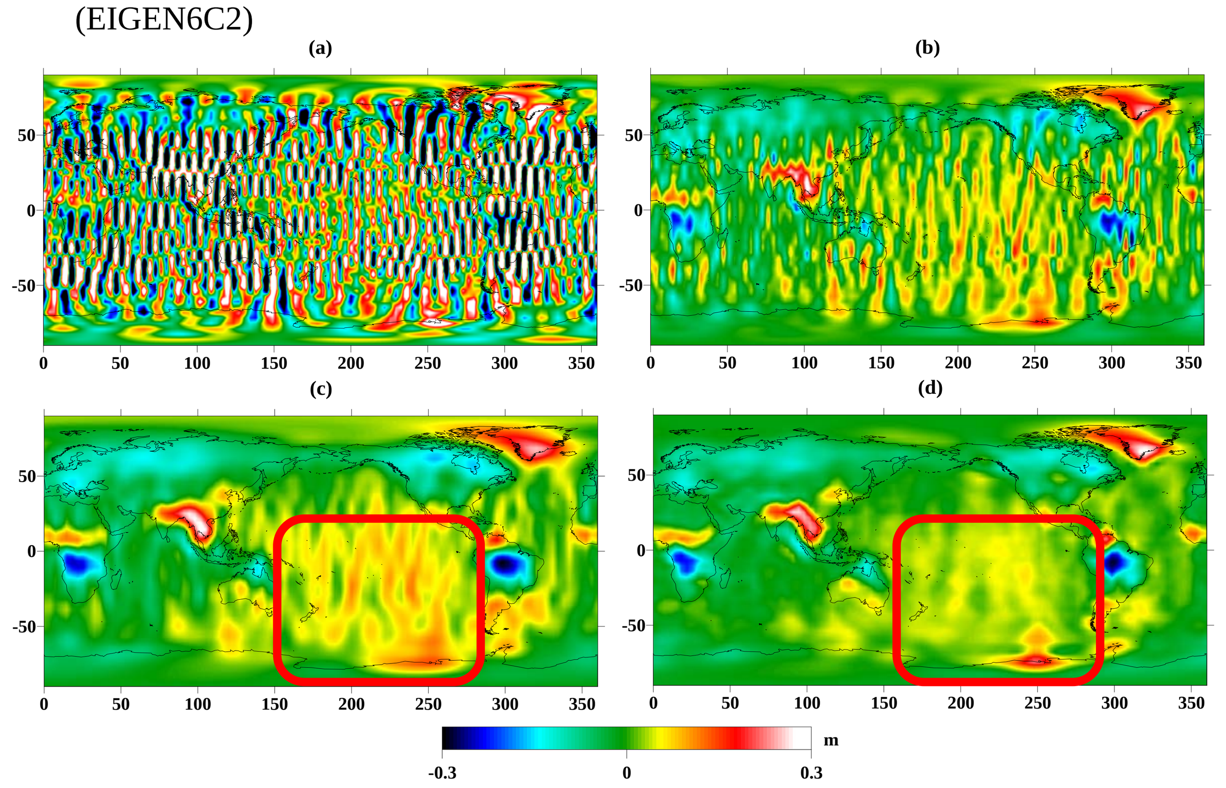

Figure 4 Global mass variations (in EWH) in Sept. 2004 (indicates poor ground track coverage) from: (a) Tongji-GRACE01 without any smoothing and filtering; (b) Tongji-GRACE01 processed with 300 km Gaussian smoothing; (c) Tongji-GRACE01 processed with 500 km Gaussian smoothing; (d) RegTongji RL01 without any smoothing and filtering.

Comparisons of signal losses

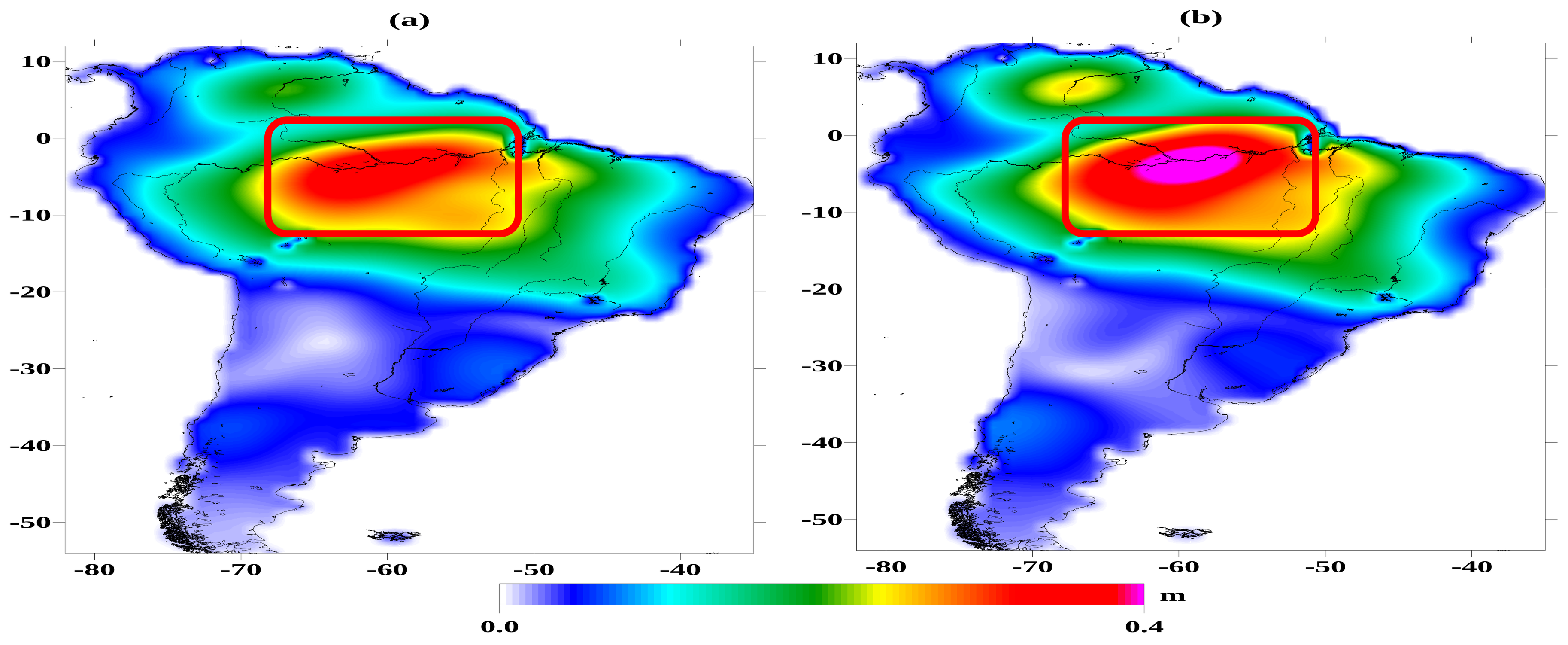

Figure 5 Amplitudes of mass changes over the South America (in EWH) derived from:
(a) Tongji-GRACE01 processed with 300 km Gaussian smoothing and P4M6 decorrelation filtering; and (b) RegTongji RL01 without any smoothing and filtering.

To investigate the signal losses caused by filtering and regularization, the GLDAS solution of Sept. 2004 is treated as a true gravity solution. Then the GLDAS solution is processed by using the regularization method presented in this study and filtering method (P4M6+300 km Gaussian smoothing), respectively.

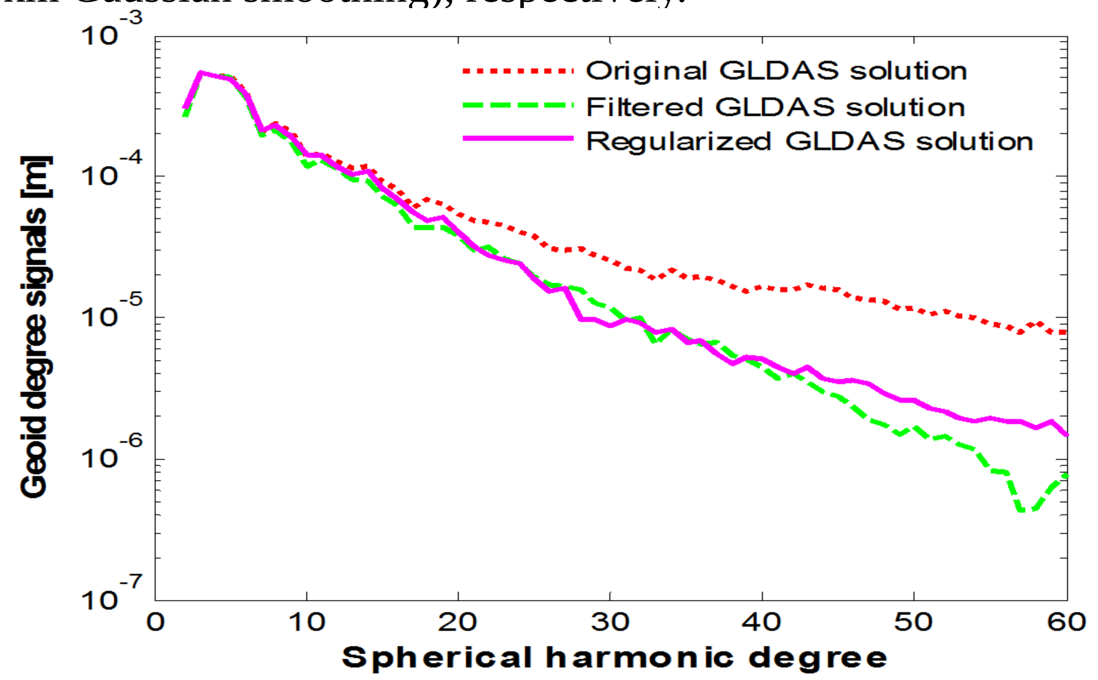

Figure 6 Geoid degree signals of GLDAS solutions. The comparisons between filtered and regularized solutions demonstrate that our regularized method achieves smaller signal attenuation than the filtered one.

Table 1 Significant signals (in EWH of cm) over river basins estimated from filtered and regularized solutions

Model	River basins	Annual amplitude	Semiannual amplitude	Octennial amplitude	Quadrennial amplitude	S2 alias amplitude	Amplitude
Tongji-GRACE01	Irrawaddy	15.7	2.6	8.7	2.6	0.2	18.3
	Fraser	9.9	1.1	7.1	3.5	1.0	12.7
	Taz	9.1	3.4	5.5	2.3	0.5	11.4
	Pearl	6.8	1.5	7.2	1.4	0.4	10.1
	Amazon	19.7	1.9	5.9	3.2	1.2	20.3
	Mississippi	6.5	0.7	4.8	2.1	0.6	8.4
	Zambezi	12.9	1.9	8.2	2.7	0.6	15.7
	Nile	6.4	1.4	3.0	1.5	0.4	7.4
RegTongji RL01	Irrawaddy	18.6	2.5	9.3	2.9	0.4	21.1
	Fraser	11.8	1.5	9.1	4.6	1.4	15.8
	Taz	9.4	4.0	6.7	3.0	0.4	12.6
	Pearl	6.8	1.5	6.9	1.9	0.6	10.1
	Amazon	20.1	2.3	7.3	3.6	1.3	22.3
	Mississippi	6.3	0.8	6.4	2.5	0.6	9.4
	Zambezi	14.4	2.5	10.3	3.1	0.7	18.2
	Nile	7.1	1.7	3.3	2.0	0.5	8.3

Concluding remarks

- ✓**A new method to stabilize monthly gravity field solutions was proposed for the first time.**
- ✓**Neither smoothing nor decorrelation filtering is necessary for our regularized monthly solutions.**
- ✓**Our regularized monthly solutions achieve smaller signal attenuation.**

References

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