GRACE-FO Real-Time POD with Onboard GPS and Inter-Satellite Ranging Measurements Based on DIA Quality Control Algorithm

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Shengjian Zhong[12], Xiaoya Wang[123], Min Li[4], Jungang Wang[5], Yabo Li[1]

[1]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China;
[2]University of Chinese Academy of Sciences, Beijing, China;
[3]Shanghai Key Laboratory of Space Navigation and Positioning Techniques, Shanghai 200030, China;
[4]School of Space Science and Technology, Shandong University, Weihai, China;
[5]Institut für Geodäsie und Geoinformationstechnik, Technische Universität Berlin, Berlin, Germany.

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ABSTRACT

Real-Time Precise Orbit Determination (RTPOD) of Low Earth Orbit (LEO) satellites relies primarily on onboard GNSS observations and may suffer from degraded performance when observation geometry weakens or tracking conditions deteriorate within satellite formations. To enhance the robustness and accuracy of RTPOD under such conditions, a cooperative Extended Kalman Filter (EKF) framework that fuses onboard GNSS and inter-satellite link (ISL) range measurements is established, integrated with an iterative Detection, Identification, and Adaptation (DIA) quality control algorithm. By introducing high-precision ISL range measurements, the POD increases observation redundancy, improves the effective observation geometry, and provides strong relative position constraints among LEO satellites. This constraint strengthens solution stability and convergence, while simultaneously enhancing the sensitivity of the DIA-based quality control to observation outliers. The proposed strategy is validated in a simulated real-time environment using Centre National d'Etudes Spatiales (CNES) real-time products and onboard observations of the GRACE-FO mission. The results demonstrate comprehensive performance enhancements for both satellites. For the GRACE-D satellite, which suffers from about 17% data loss and a cycle slip ratio several times higher than that of GRACE-C, the orbit accuracy improves by 39% (from 13.1 cm to 8.0 cm), and the convergence time is shortened by 44.3%. In comparison, the GRACE-C satellite achieves a 4.2% accuracy refinement and a 1.3% reduction in convergence time. These findings reveal a cooperative stabilization mechanism, where the high-precision spatiotemporal reference is transferred from the robust node to the degraded node via inter-satellite range measurements. This study demonstrates the effectiveness of the proposed method in enhancing the robustness and stability of formation orbit determination and provides algorithmic validation for future RTPOD of LEO satellite formations or large-scale constellations.

INTRODUCTION

- RTPOD of LEO satellites mainly depends on onboard GNSS.
- Weak geometry and poor observation quality can degrade accuracy and stability.
- ISL ranging can strengthen geometry and provide rigid relative constraints.
- GRACE-FO offers an ideal RT test with onboard GPS and high-precision ISL.

METHODS

- **Data:** GPS1B observations, KBR1B ranges, CNES RT products, JPL PSO reference.
- **Filter:** EKF implemented based on the PANDA platform.
- **Schemes:** GPS-only and GPS + ISL.
- **QC:** Iterative DIA based on standardized post-fit residuals.

OBJECTIVE

Evaluate whether high-precision inter-satellite ranging can improve real-time orbit determination robustness and accuracy under asymmetric GPS observation conditions. Specifically, we aim to:

- build an EKF-based cooperative RTPOD model for GRACE-FO;
- integrate an iterative DIA quality control strategy into the sequential filter;
- quantify the contribution of ISL measurements to orbit accuracy and convergence;
- explain the enhancement mechanism from the perspective of geometric stabilization and information transfer.

RESULT

(1) GPS observation quality:

- GRACE-D has 17% fewer GPS observations than GRACE-C.
- GRACE-D also shows much higher GF/MW cycle-slip ratios.
- This leads to a more challenging RTPOD scenario for GRACE-D.

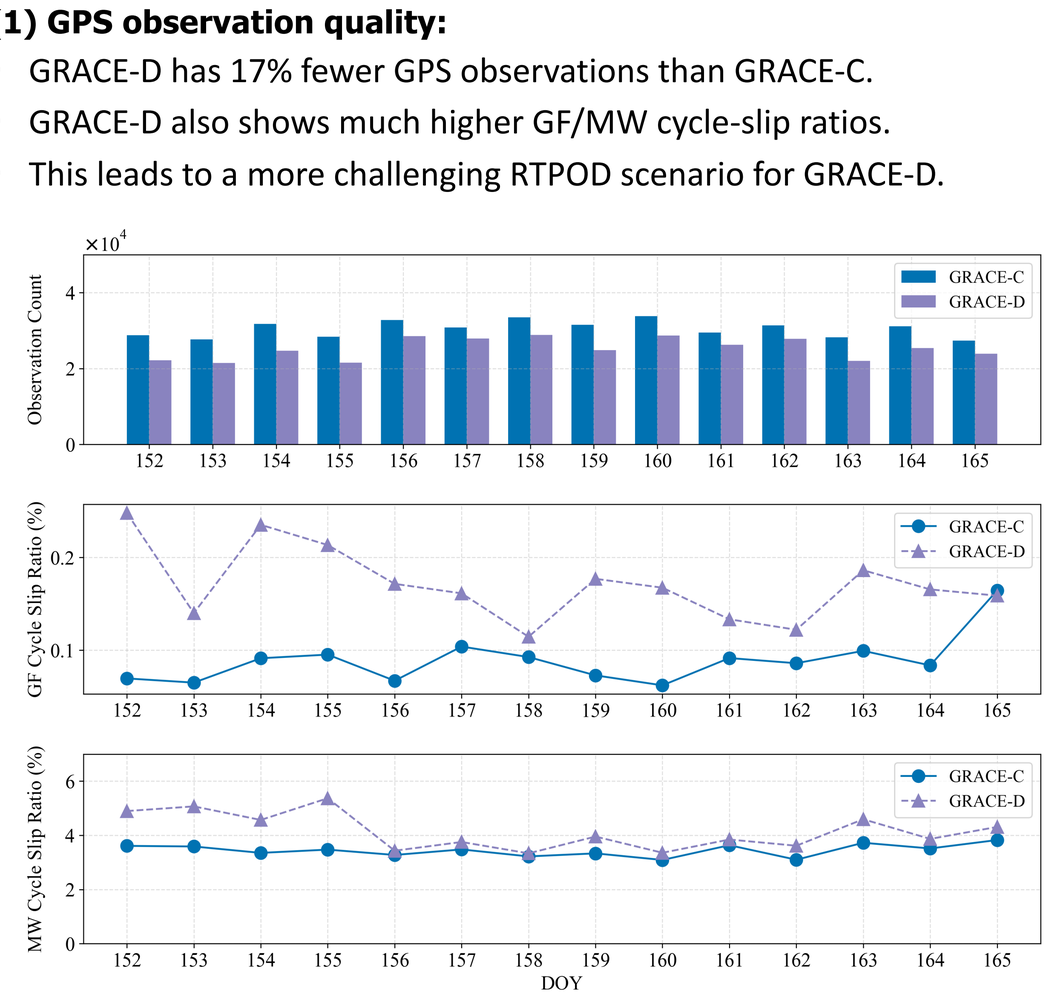

Figure 1. *Daily statistics of GPS data quality for GRACE-C (blue) and GRACE-D (purple) from DOY 152 to 165, 2021. The number of onboard GPS observations (top), GF cycle slip ratio (middle), and MW cycle slip ratio (bottom).*

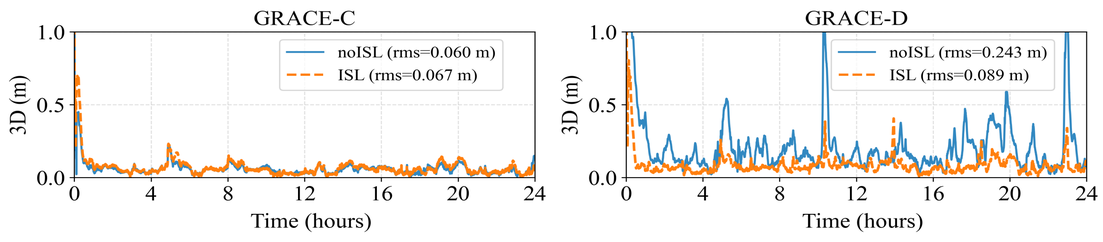

Figure 3. *Orbit error sequences in 3D for GRACE-C (left) and GRACE-D (right) at each epoch on 1 June 2021.*

Table 1. Mean RMS (unit cm) in and the convergence time (unit min) of the two schemes.

Scheme	GRACE-C		GRACE-D	
	3D	Conv. Time	3D	Conv. Time
GPS-only	7.3	46.9	13.1	77.8
GPS+ISL	7.0	46.3	8.0	43.4

(2) Effect of DIA quality control:

- GRACE-C: 8.2 cm → 7.3 cm.
- GRACE-D: 21.7 cm → 13.1 cm.
- DIA effectively suppresses abnormal observations and stabilizes the filter.

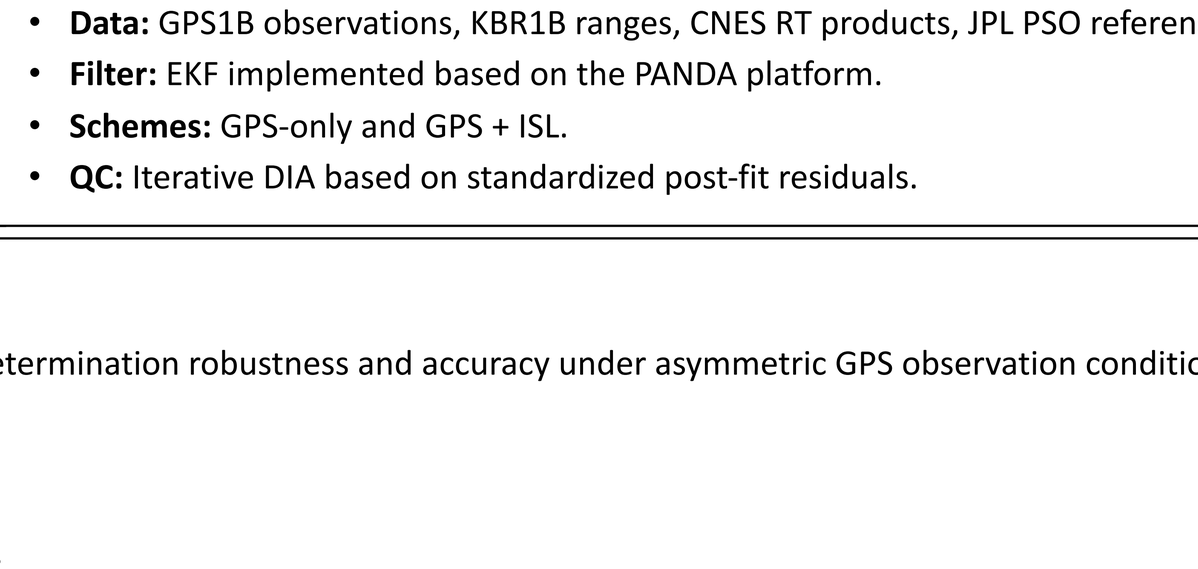

Figure 2. *Assessment of the impact of the iterative DIA quality control on RTPOD performance over DOY 152–165, 2021. Daily 3D RMS statistics for GRACE-C (left) and GRACE-D (right) with and without quality control.*

(3) Effect of inter-satellite ranging:

- GRACE-C: 7.3 cm → 7.0 cm.
- GRACE-D: 13.1 cm → 8.0 cm.
- Convergence time of GRACE-D is reduced by 44.3%.

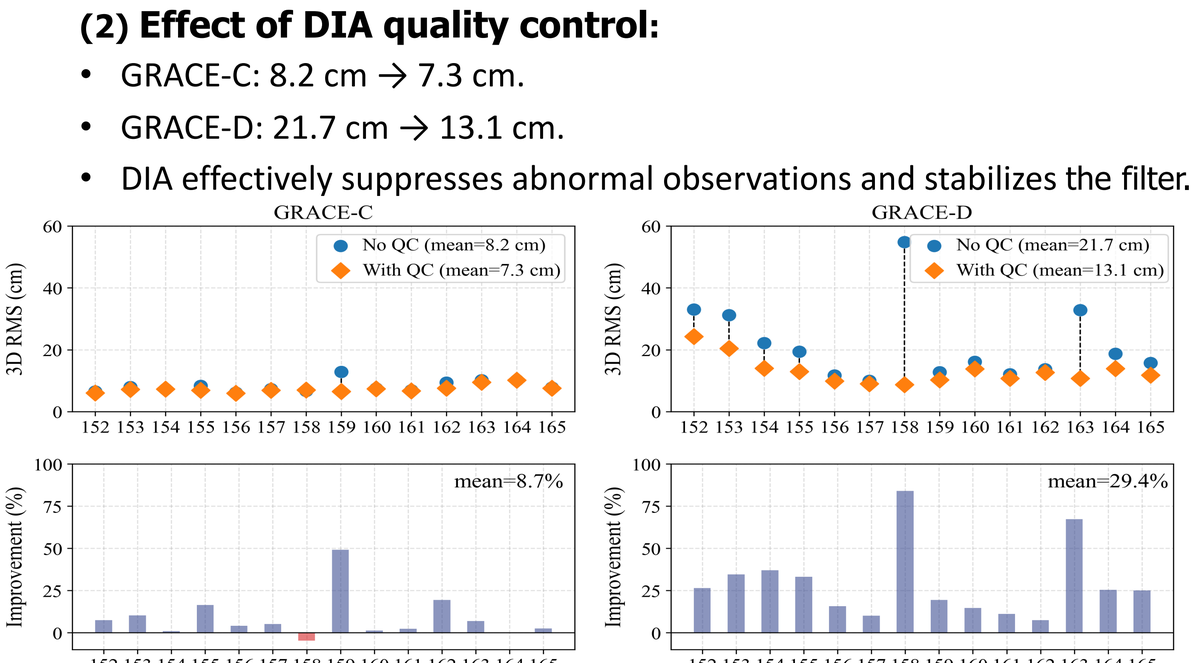

Figure 4. *Daily RMS values of orbit errors in the 3D directions obtained using GPS-only and GPS +ISL observations.*

(4) Key message

- ISL provides moderate improvement for the well-observed satellite.
- ISL is decisive for the degraded satellite, effectively recovering its solution to the level of the better node.

CONCLUSIONS

- A robust cooperative RTPOD framework was developed by combining GPS + ISL + DIA-QC.
- DIA improves filter robustness, especially under degraded observation conditions.
- ISL measurements significantly enhance orbit accuracy and convergence for the weak satellite.
- The main mechanism is rigid geometric constraint + spatiotemporal information transfer within the formation.

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