GPS-Based Real-Time Relative Orbit Determination for LEO Satellites

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Abstract: The GPS-based real-time relative orbit determination for Low-Earth Orbiting (LEO) satellites is very important for formation flying missions to satisfy the relative orbit accuracy requirements. Current methods need either reference stations or reference orbits using GPS Double-Differenced (DD) carrier phase measurements. That isn't convenient, particularly for real-time processing. For this reason, we investigated the GPS-based real-time relative orbit determination without any reference stations or reference orbits. The proposed method has been tested with the data from GRACE (Gravity Recovery and Climate Experiment). The relative orbit accuracy using this method is mainly dependent on the fixed real-time GPS satellite orbits. Therefore, different real-time GPS orbits (GPS satellite broadcast ephemeris, IGS ultra-rapid orbits, and one-day GPS orbit predictions from IGS CODE analysis center) were used to study the effects of GPS orbit errors on the relative orbit determination. The main purpose of this paper is to investigate how well the relative orbits of the LEO satellites can be determined in real-time using only GPS DD observations formed by GPS measurements from the LEO GPS onboard receivers. The relative orbit accuracy was assessed using orbital fits and GRACE K-Band Ranging (KBR) residuals. In addition, the absolute orbit accuracy was also evaluated using Satellite Laser Ranging (SLR) residuals and external orbit comparisons to know how well the absolute orbits can be determined using this method. The results show that the accuracy of the relative orbits can be improved from about 2 cm to 7 mm through the use of IGS real-time GPS orbits instead of navigation orbits.

Background and Motivations

•With the successful application of GPS-based Precise Orbit Determination (POD), more and more satellites are expected to carry onboard GPS receivers to support their absolute orbit accuracy requirements. When the GPS-based POD is used for the satellite formation flying (two or more satellites in a tightly-controlled spatial configuration), it could also satisfy different relative orbit accuracy requirements.

•Current methods for GPS-based relative orbit determination need either reference stations or reference orbits, which are not convenient, particularly for real-time data processing.

•For this reason, we investigated the GPS-based real-time relative orbit determination without any reference stations or reference.

Objectives

1) Analyze **different data processing scenarios** for GPS-based relative orbit determination of LEO satellites

2) Study the impact of **different real-time GPS orbits** on GPS-based relative orbit determination of LEO satellites

3) Investigate the GPS-based real-time relative orbit determination for LEO satellites without any reference stations and reference orbits **to see how well the relative orbit accuracy** can be achieved

Method and Data Processing Strategies

Method: dynamic orbit determination method, but with an aggressive force model parameterization (such as estimation of many empirical parameters in precise orbit determination) to reduce the effects of the force model errors. Using this method, one of the advantages is that the orbits can be better predicted.

Observation type: high-high GPS DD (two GPS satellites and two LEO satellites).

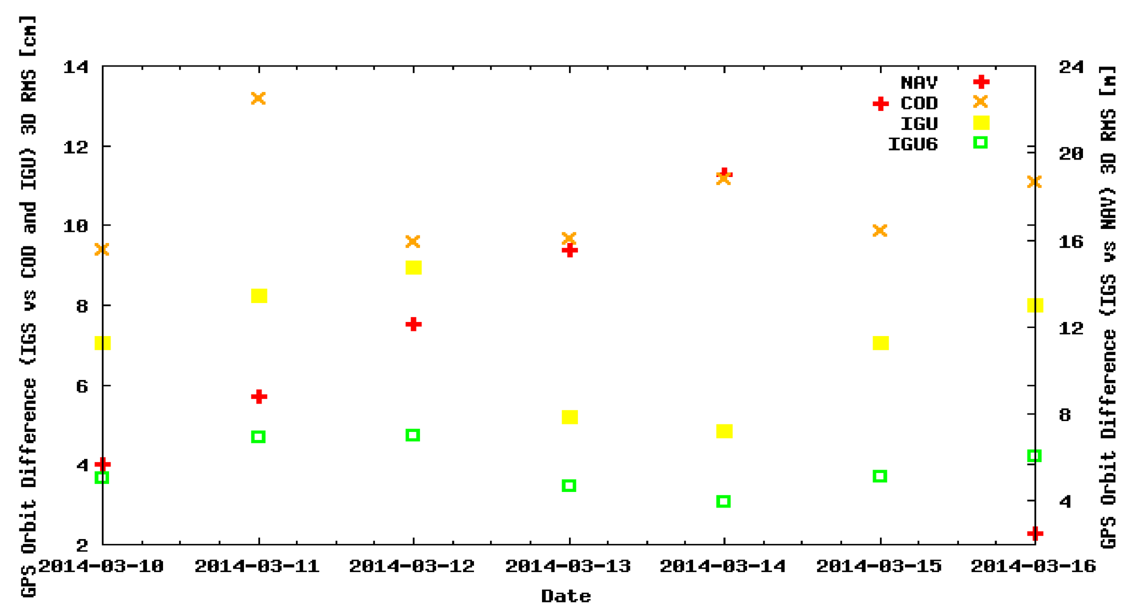
Test Data and Test Cases

Test data: one week (March 10-16, 2014) GRACE data

Test cases:

1) **NAV:** high-high GPS DD observations with GPS satellite broadcast ephemeris
2) **COD:** high-high GPS DD observations with one-day GPS orbit predictions from IGS CODE analysis center
3) **IGU:** high-high GPS DD observations with one-day IGS ultra-rapid orbits predictions
4) **IGU6:** high-high GPS DD observations with 6-hour IGS ultra-rapid orbit predictions

Fig. 1. GPS Orbit Comparison



The relative orbit accuracy related to our method is mainly dependent on the used GPS orbits. Figure 1 shows the daily RMS of GPS satellite orbit differences between the IGS final and navigation, CODE, and IGU solutions. You can see that the CODE and IGU orbits are much better than the navigation orbits. The navigation orbit accuracy is about **12 meters**; the orbit accuracies for CODE (24 hour prediction), IGU (24 hour prediction) and IGU6 (6 hour prediction) are about **11, 7 and 4 cm**, respectively.

Fig. 2. GRACE Orbit Fits

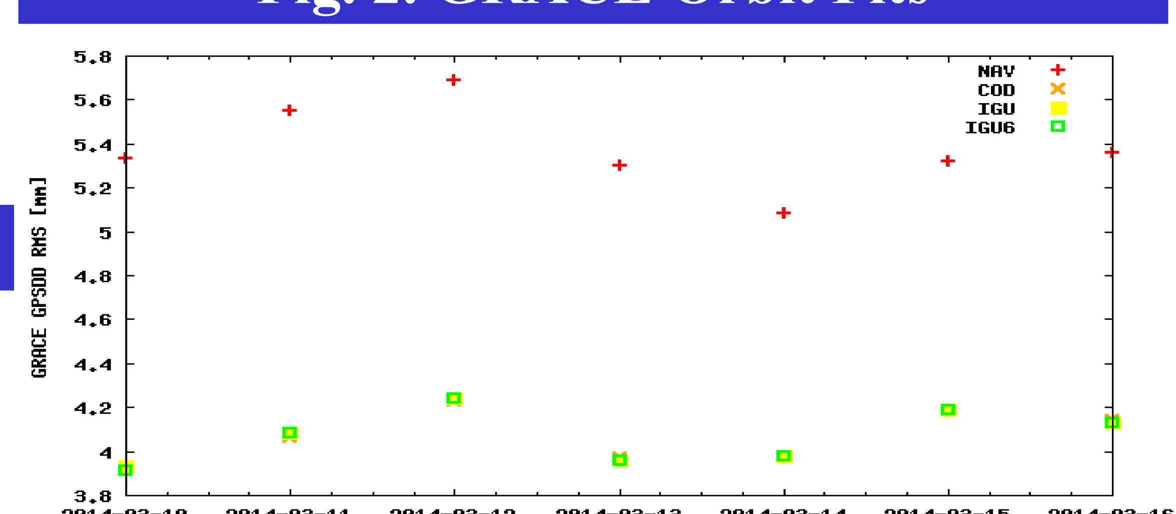
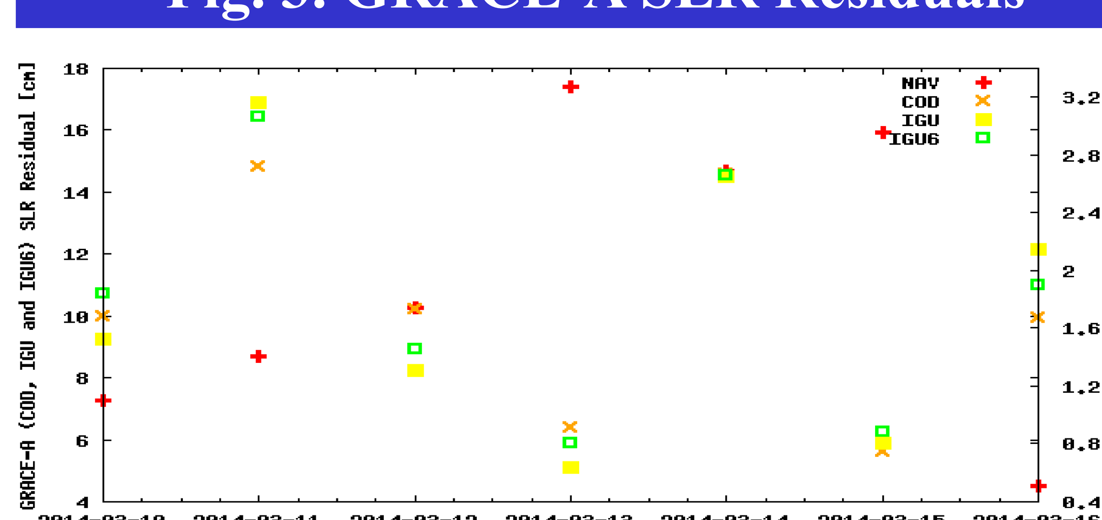


Figure 2 shows the daily GRACE high-high GPS DD RMS for the four different test cases. In those tests, only different GPS orbits are used. Therefore, the values of the GPS DD RMS can indicate the quality of the used GPS orbits. The more accurate the GPS orbits are, the smaller the RMS's are. There are no significant differences of the RMS values for using CODE and IGU GPS orbits. But the GPS DD RMS for using navigation orbits is much larger than that for using other GPS satellite orbits.

Fig. 3. GRACE-A SLR Residuals



As an independent evaluation of the absolute orbit quality, SLR data were processed to compute laser range residuals relative to the fixed GRACE orbits. Figure 3 shows the GRACE-A SLR residuals for difference test cases, respectively. There are no significant differences for COD, IGU and IGU6 test cases. But there are big differences for the SLR residuals by using navigation and other GPS orbits. The average SLR RMS's are about 2 meters and 12 cm for using navigation and other GPS orbits, respectively.

Fig. 4. GRACE KBR Range Residuals

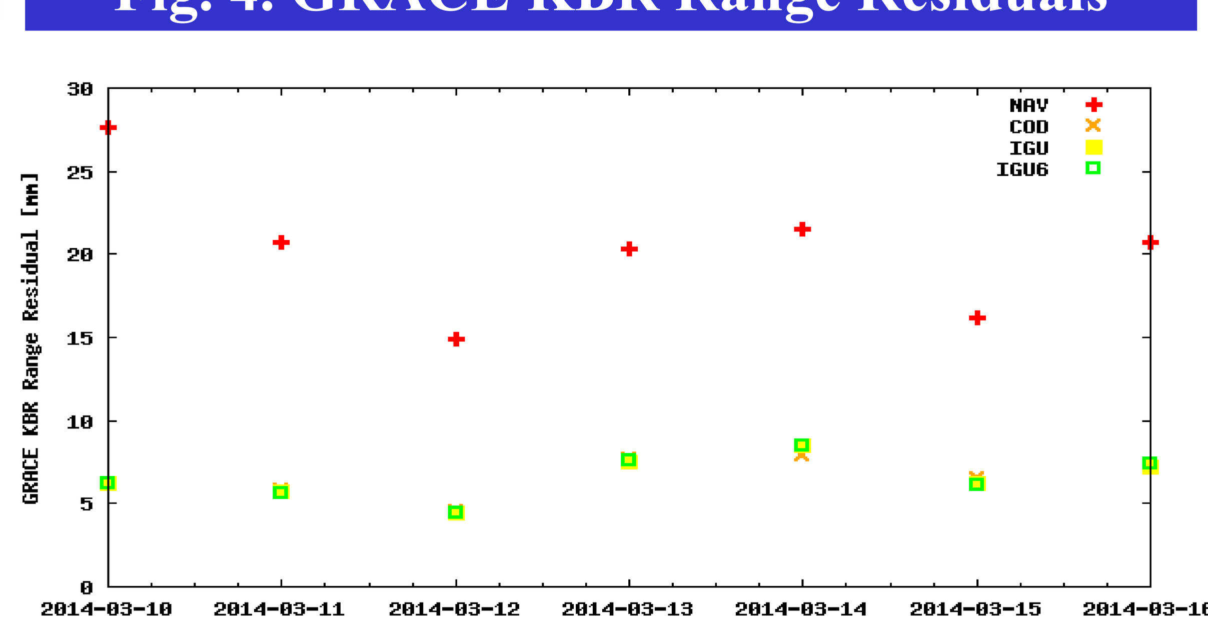


Fig. 5. GRACE KBR Range Rate Residuals

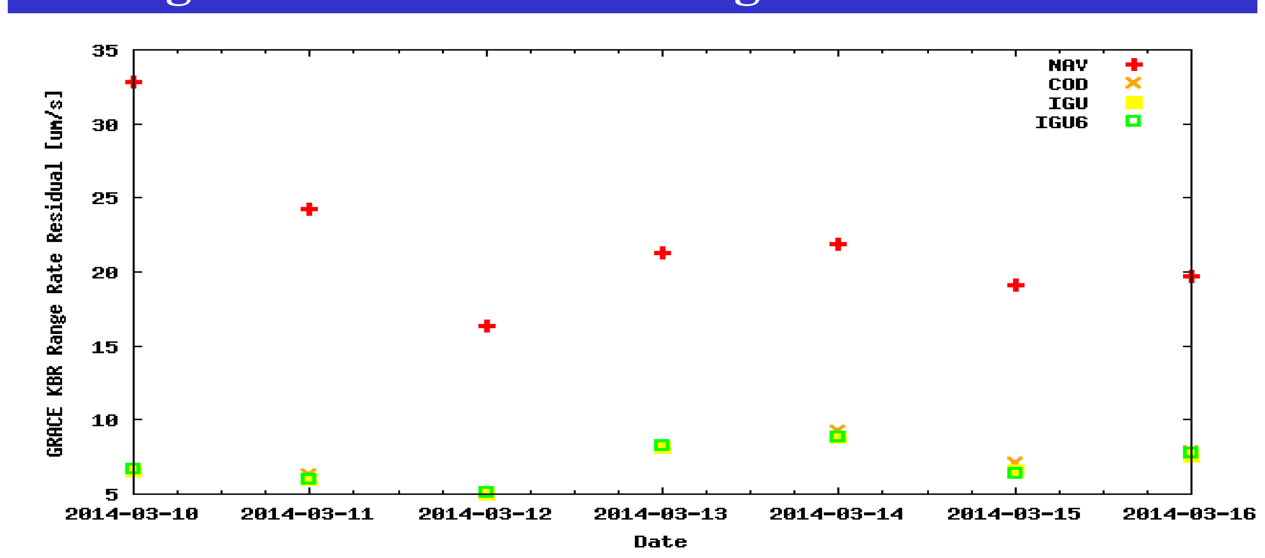


Table 1. KBR Range and Range Rate Residuals

Case	Range [mm]	Range Rate [um/s]
NAV	20.29	22.21
COD	6.55	7.18
IGU	6.55	6.95
IGU6	6.54	6.99

The GRACE KBR range and range rate residuals can be used for evaluating the relative orbit accuracy of the GRACE satellites. Figure 4 and 5 display the RMS of the KBR range and range rate residuals. Table 1 summarizes the average RMS of the GRACE KBR range and range rate residuals for different test cases. The results show that the improved relative orbit accuracy in position from 20 mm to 7 mm for the GRACE satellites is achieved through using CODE and IGU orbits instead of navigation orbits; the accuracy in velocity is from 22 to 7 μm/s.

Fig. 6. GRACE-A Orbit Comparison with JPL

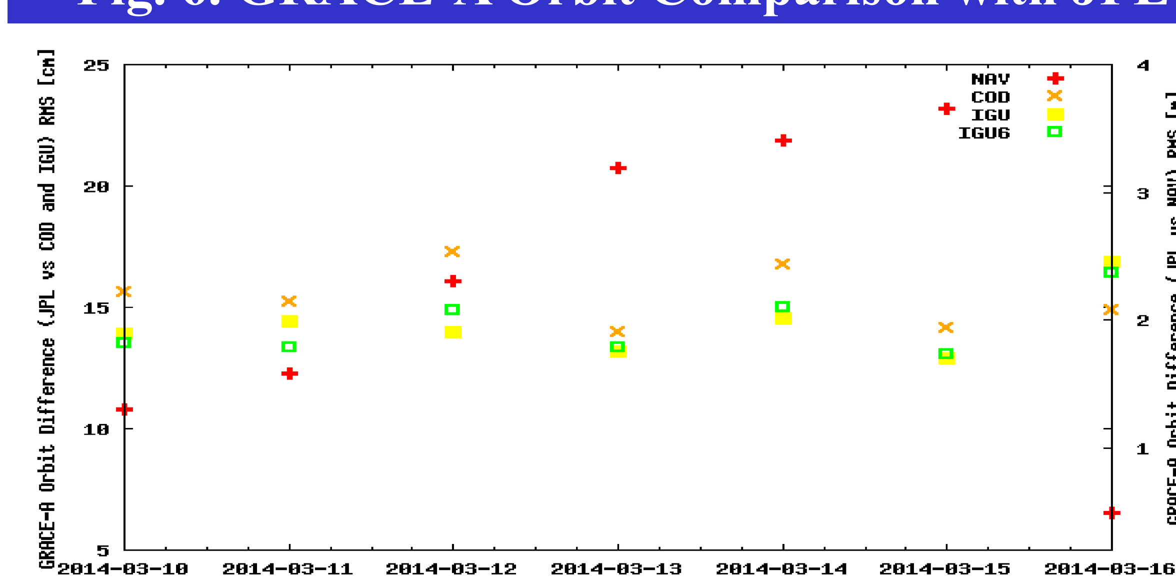


Table 2. GRACE Orbit Comparison with JPL [mm]

Case	GRACE-A	GRACE-B
NAV	2.274	2.278
COD	0.154	0.154
IGU	0.142	0.142
IGU6	0.142	0.142

The CSR determined GRACE orbits using different real-time GPS orbits were directly compared with GNV1B GRACE orbits from JPL. There were no any removing biases and similar transformations for the comparison. The comparison results can be used to evaluate the absolute orbit accuracy.

Summary and Conclusions

1. The main goal of this paper was to investigate how well the GRACE relative orbits can be determined using only high-high GPS DD observations without any reference stations or reference LEO orbits in real-time mode. The absolute and relative orbit accuracy using this method is mainly dependent on the quality of the used real-time GPS satellite orbits.
2. Both SLR residuals and external orbit comparison can be used to indicate the absolute orbit accuracy. The absolute orbit accuracy is from **14 cm to 2.3 meters,** which are dependent on the used real-time GPS orbits.
3. According to the GRACE KBR range and range rate residuals, the relative accuracy between two GRACE satellites is improved from **2 cm to 7 mm** in position and from **22 to 7 μm/s** in velocity through the use of IGS real-time GPS orbits instead of navigation orbits.
4. The proposed method for the GPS-based real-time relative orbit determination has been demonstrated for the GRACE satellites. Actually, the relative orbit accuracy is not only dependent on the used real-time GPS orbit quality, but also the satellite separation, satellite altitude, onboard receiver ….