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PRECISE MANEUVER CALIBRATION FOR REMOTE SENSING SATELLITES

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Abstract

Orbit maintenance maneuvers are performed as necessary to maintain the spacecrafts trajectory to within a specified tolerance relative to a set of predefined reference orbital parameters as depicted by the mission objectives. After each executed maneuver, the rate of change in velocity is calibrated to deduce the thruster's performance and to assist with future maneuver planning.

For the GRACE mission, the maneuver performance can be independently deduced from the in-flight telemetry data and by processing the GPS navigation messages. Alternatively, one can also exploit the precise GPS observables for maneuver calibration. This precise calibration approach is implemented in the precise orbit determination and has been successfully demonstrated using the GPS data from the GRACE spacecraft. The analysis not only yields remarkable improvement and consistency in the calibration performance but also in the GPS measurement residuals and the reconstructed orbits of GRACE in the vicinity of the maneuver.

1. Introduction

In every remote sensing satellite mission, maneuver planning, maneuver calibration and prediction are performed to maintain the spacecraft orbit configuration. Maneuvers are usually designed in such a way as to minimize fuel consumption and to prolong the satellite's lifetime for scientific data collection. Depending on the objectives of the mission, some satellites require more orbit maneuvers than others. For example, TOPEX/POSEIDON and Jason-1 require orbit maneuvers once every few months to maintain its near 10-day repeat cycle ground tracks to within ±1km, whereas the GRACE twin spacecraft requires 2-4 orbit maneuvers per year to maintain their relative position of 220±50km. A more extreme example is the upcoming DLR-EADS joint TerraSAR-X mission. Here the frequency of orbit maintenance maneuvers varies from once every ten days (at the beginning of the mission) to once per day at the end of the mission's lifetime in order to stay within a predefined boundary relative to the reference trajectory.

For routine operation, the thruster performance for the GRACE spacecraft is deduced from the in-flight telemetry data and from operational orbit determination. The in-flight telemetry data provides the tank pressure (and thus the propellant mass flow rate) information from the pressure sensor. The operational orbit determination processes the GPS navigation messages to deliver operational orbit products which include maneuver calibration information for the planning of future maneuvers.

The precise maneuver calibration approach introduced in this paper serves as the 3rd independent method in evaluating the propulsion system performance. This latest approach is adopted in the precise orbit determination (POD) software package developed at DLR/GSOC. The software has the unique capability to simultaneously calibrate single/multiple maneuvers over an orbit arc length and generate a continuous precise ephemeris. The functionality of this method has been investigated using the dual frequency GPS observation data from GRACE.

Descriptions of the GRACE orbit and satellite characteristics, the different maneuver calibration strategies and implementation, the calibration performance assessment and validation, and the impact of the precise calibration method on the reconstructed orbit of the GRACE spacecraft are represented in the following sections.

2. GRACE Orbit Configuration

The GRACE mission consists of two spacecraft

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flying in formation in a near polar near circular orbit with a nominal separation distance of 220km. Both were injected into a 500km altitude. Their relative distance is allowed to drift within a ±50km window about the nominal before an orbit maintenance maneuver is initiated. The altitude will decrease over the mission lifetime due to atmospheric drag. After achieving the operational orbit, the pitch angle for each spacecraft is adjusted so that the inter-satellite radar link can be established between the K-band horns. GRACE A has been the leading satellite until the recent switch maneuver on December 3rd, 2005 [1]. This maneuver was performed to prevent degradation of the K-Band range data caused by the atomic oxygen induced erosion of the K-Band horn of the trailing satellite.

2.1 Orbital Maneuvers

The GRACE orbit maintenance strategy is to maximize the time between two maneuvers based on the characteristics of the relative separation, semi-major axis and ballistic coefficient of the spacecraft. At the beginning of the mission phase, each of the GRACE spacecraft has initiated two calibration maneuvers for science instruments calibration. The failure of the Inertial Measurement Unit (IMU) on GRACE A has placed the spacecraft in safe mode which requires higher fuel consumption. Therefore, all subsequent orbit maintenance maneuvers were performed on GRACE B to reduce the relative spacecraft mass.

In the event of the switch maneuver sequence, an inclination maneuver was initiated on GRACE B as it crosses the ascending node on April 6, 2005 to help induce a drift in the cross-track direction. The switch sequence started on December 3rd, 2005 and comprises a drift-start and two drift-stop orbital maneuvers over a period of 40 days. This is the latest maneuver occurrence as of this writing.

2.2 Thruster Characteristics

GRACE uses the cold gaseous nitrogen propulsion system for orbit and attitude control. The thruster configuration on each spacecraft consists of two 40mN orbit trim and twelve 10mN attitude control thrusters. The orbit thrusters can operate individually or in pairs. Each spacecraft has two propellant tanks and a high pressure transducer is mounted to each tank to monitor the mass flow of the propellant and burn time during thruster firing. This information is noted in the in-flight telemetry data and is later used for thruster performance calibration.

The configuration of the orbit thrusters (OT) is shown in Fig. 1. The OTs are located on the x-y plane of the satellite reference frame with a distance offset of 275mm from the x-axis [2]. This is equivalent to ~9.1° angle offset of the thrust vector pointing through the satellite center of mass and the x-axis.

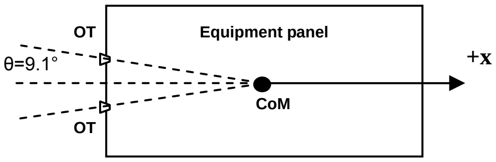

Fig. 1 Orientation of the orbit thrusters for orbit trim maneuvers onboard GRACE (as seen from above). Figure is drawn not to scale. The +x axis coincides with the flight/anti-flight direction.

3. Maneuver Calibration Methods

3.1 In-Flight Telemetry

With the knowledge of the propellant mass flow rate from the in-flight telemetry data, the maneuver performance can be predicted by applying the Tsiolkovsky rocket equation [3]. Using the thruster characteristics and introducing the maneuver performance scale factor, f, the velocity increment is given by:

$$\Delta v = \pm I_{\mathrm{sp}} \cos\theta \times \ln\left(\frac{fM_0}{M_0 - \dot{m}\Delta t}\right) \qquad (1)$$

where

I_{sp} = specific impulse

Θ = offset angle of the thruster wrt to the x-axis

M_0 = spacecraft mass before thruster activation

$\dot{m}$ = propellant mass flow rate

Δt = burn duration

Eq (1) uses the scale factor to model the efficiency of the thruster during the maneuver. The scale factor for the first maneuver is always 1 with the assumption that energy is conserved. The scale factor for the subsequent maneuver is then derived from an accumulated average of all previously calibrated thruster performances. The “±” sign is dependent upon the direction of the thruster/s activation. In order to achieve a negative Δ*v* on the trailing spacecraft, a 180° yaw maneuver has to be performed prior to the orbit maneuver. Another 180° yaw turn is also required after the orbit maneuver to bring the spacecraft back to its original formation flying configuration. The resultant ∆v is expressed in m/s.

3.2 Operational Maneuver Calibration

The operational orbit determination produces orbit parameters for mission planning, command generation, maneuver planning and evaluation, and tracking pass evaluation [4]. The operational maneuver calibration is evaluated using the Orbit Determination for Extended Maneuvers (ODEM) software package [5]. The GPS navigation solutions are used as tracking data in the orbit determination. ODEM is a general orbit determination software for LEO, highly elliptical and GEO Earth satellite missions. It is also designed to model series of impulsive or extended maneuvers for LEO orbit acquisition and maintenance, and for GEO station keeping operations. The filter algorithm is based on a sequential least squares filtering technique.

The maneuver calibration involves processing a 6-hr orbit arc center at the maneuver. The thrust is characterized as a constant acceleration over the maneuver burn time.

3.3 Precise Maneuver Calibration

The precise calibration approach exploits the precision of the GPS observables in predicting the maneuver performance. This maneuver calibration functionality has been implemented in the precise orbit determination (POD) software package, GPS High Precision Orbit Determination Software Tools (GHOST), developed at DLR/GSOC. GHOST offers two types of filtering techniques for reduced-dynamic orbit determination: the batch weighed least squares and extended Kalman filter. The POD and maneuver calibration for GRACE adopts the former filtering technique.

The calibration and orbit estimation are carried out simultaneously using a 100x100 GGM01S gravity field model. The initial state vector, the drag and solar radiation coefficients, the empirical accelerations, the receiver clock offsets and the carrier phase ambiguities are estimated given the a-prior information. When recognizing a maneuver execution at a specified epoch within the orbit arc, the software reorganizes the estimation interval of the empirical acceleration parameters around the maneuver. The instantaneous change in velocity is treated as a constant acceleration over the burn time whereby Δv is simply converted to Δa using the knowledge of the burn time. The GPS orbit and high rate clock products from the Center of Orbit Determination in Europe (CODE) are used in this calibration analysis.

4. Maneuver Performance Assessment

The thruster performance for GRACE is assessed using the three aforementioned calibration methods. The results presented are in terms of the efficiency of the respective calibration performances with respect to the derived values from the telemetry.

The calibration performance as a function of the burn time for the GRACE spacecraft is shown in Fig. 2. Calibrated maneuvers from GHOST show better overall consistency relative to ODEM except for the two values with maneuver burn durations between 500 and 600s. The two maneuvers occurred during the calibration maneuver phase on March 28, 2002 where no GPS measurements were collected for more than 11 hours. The two maneuvers were implemented approximately 9 hours apart and occurred within the missing GPS observation time period.

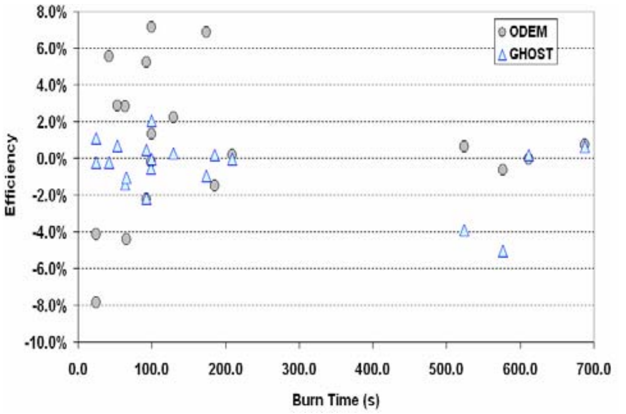

Fig. 2 Maneuver calibration performance for GRACE as a function of maneuver burn duration.

The rest of the calibration performances from GHOST illustrate close agreement of 2.5% or better. The calibration performance evaluated from ODEM tends to have better agreement for long/extended maneuvers. This is a good alternative at least for long maneuvers when no GPS measurements are available for precise calibration.

Ignoring the two maneuvers on March 28, 2002 due to the large GPS data gap, the overall calibration performance from GHOST is about 0.96%. ODEM produces an overall performance (inclusive of the maneuvers on March 28, 2002) of approximately 3.81%.

5. Software Performance Validation

The validation of the GHOST software reliability and efficiency in calibrating the maneuvers is demonstrated by analyzing the GPS measurement residuals and the estimated empirical accelerations. With the dual frequency GPS observables from GRACE, the ionosphere-free linear combinations of the phase and pseudorange are used in resolving the orbit determination problem and in calibrating the maneuvers. The residuals of the linear combinations without maneuver calibration are shown in Fig. 3a and the residuals obtained with calibration are in Fig. 3b.

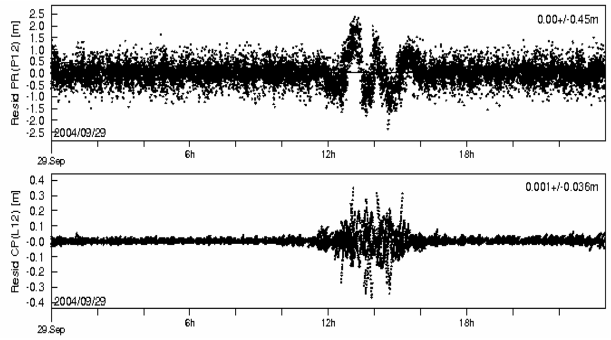

Fig. 3a Scatters of the ionosphere-free linear combinations of pseudorange (top) and carrier phase (bottom) without accounting for the maneuver on GRACE B on September 29, 2004 13:52:33 UTC.

The presence of the maneuver clearly disrupts the measurement residuals as the error induced by the change in velocity cannot be compensated for in the dynamical modeling of the spacecraft motion. The empirical acceleration in the along-track component seemed to have absorbed a good portion of the mismodeled force error as shown in Fig. 4.

When the velocity change is accounted for in the orbit determination, the unusually large scatter of the measurement residuals around the maneuver vanished. As can be seen in Fig. 3b the carrier phase and pseudorange residuals gave a much better orbit fit. The residuals RMS have decreased to 35cm and 1cm for the pseudorange and carrier phase respectively. These statistics are in compliance with measurement residuals obtained from a normal day (with no maneuver) processing of the GRACE data [6].

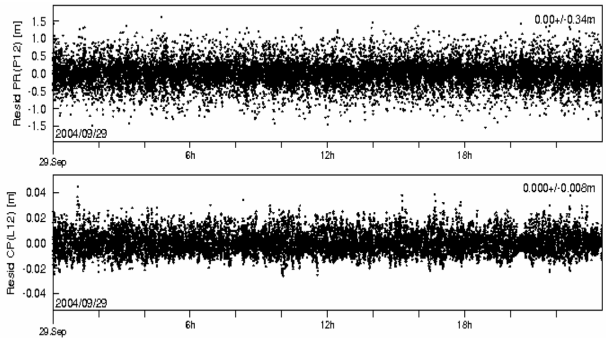

Fig. 3b Scatters of the ionosphere-free linear combinations residuals of pseudorange (top) and carrier phase (bottom) without accounting for the maneuver on GRACE B on September 29, 2004 13:52:33 UTC.

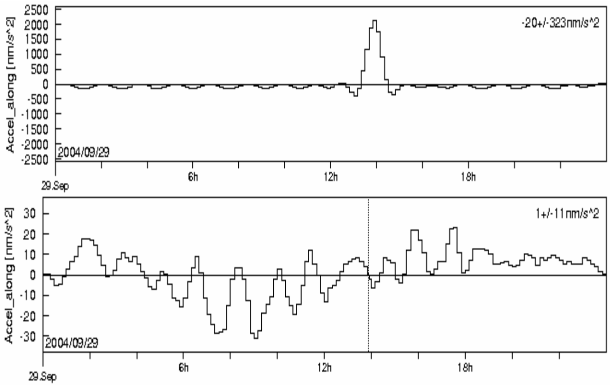

Fig. 4 Modeled empirical accelerations in the along-track component without (top) and with (bottom) maneuver calibration.

The calibration of the maneuvers acknowledges the instantaneous change in velocity and avoids misrepresentation of the instantaneous velocity in the along-track empirical acceleration.

6. Orbit Accuracy Assessment

In order to quantify the accuracy of the orbit solutions after maneuver calibration, the orbits are assessed using different approaches; comparison with GRACE B ephemerides provided by the University of

Texas/Center for Space Research (UT/CSR) [7] and JPL, and the Satellite Laser Ranging (SLR) range residuals analysis.

6.1 External Orbit Comparison

The GRACE B orbit (with maneuver calibration) generated for September 29, 2004 is evaluated using UT/CSR and JPL orbits. When compared to the maneuver calibrated orbit solution, Fig. 5, the orbit fluctuation increases in the vicinity of the maneuver and the maximum peak of ~4.3m is observed in the along-track component. The impact of the maneuver on the orbit solution is spread over ~10 hours.

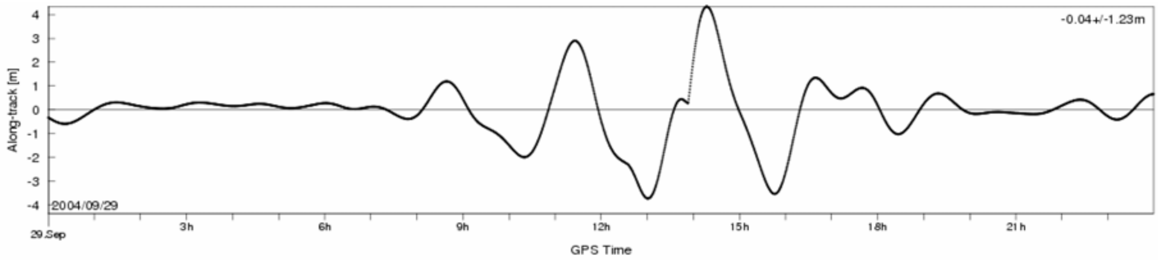

Fig. 5 GRACE B along-track orbit variation between GSOC maneuver calibrated and UT/CSR orbits on 29 September, 2004.

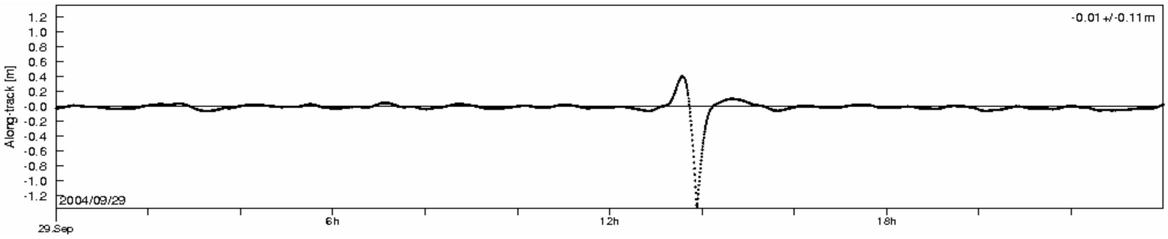

Fig. 6 GRACE B along-track orbit variation between GSOC maneuver calibrated and JPL orbits on 29 September, 2004.

Orbit comparison with JPL ephemeris for the same day is shown in Fig. 6. The impact of the maneuver on the orbit is less significant (max. peak is about -1.3m) and the degradation only starts about an hour before the maneuver. JPL orbit determination strategy is able to alleviate the effect of the velocity change on the orbit solution.

This analysis acknowledges the fact that the batch sequential modified Kalman filter (JPL) together with a processing data interval of more than 5mins can easily overshadow short maneuvers far better than a batch filter (UT/CSR). Furthermore, the characteristics of the empirical accelerations in the orbit estimation may also have played a vital part in such circumstances.

6.2 SLR Range Residuals

The GRACE B orbit is also evaluated using the satellite laser ranging measurements as an independent orbit quality assessment. Table 1 gives the range residuals of observations above 35 degrees elevation and that are found within a 4-hr window centered at the maneuver. Based on the statistics in Table 1, the SLR residuals decreased to less than 6cm when the maneuver is calibrated in the orbit determination. All statistics obtained are for GRACE B except the last. Huge fluctuations in the SLR residuals are apparent when maneuvers are not calibrated which signifies the

Table 1 SLR residuals statistics of GRACE in the vicinity of a maneuver with and without maneuver calibration.

Date (ddmmyy)	Δt (sec)	# of points	Residual RMS (cm)	
			No calib.	With calib.
12.12.05	611.2	12	>1000	1.8
07.06.05	24.5	11	52.6	5.4
06.04.05	129.6	5	9.1	0.5
29.09.04	64.3	10	47.0	0.7
30.01.03	24.5	27	24.6	2.7
30.09.02	174.5	18	215.5	4.3
		11	174.0	3.7
05.04.02 (GRA)	100.0	13	35.1	3.5

difficulty of the filter to accommodate the large velocity error.

The calibrated orbits show good consistency with RMS range residuals well below 6cm. The most distinct impact of the maneuver calibration is during the long maneuver on December 12, 2005 whereby the RMS range residual improved from ~460m to 1.8cm.

7. Conclusion

The precise maneuver calibration technique using GPS observations has shown approximately fourfold improvement in thruster calibration performance and yielded remarkable calibration consistency relative to the operational calibration method for GRACE. The 3D orbit quality after maneuver calibration also shows significant improvement and the radial accuracy is consistently below 6cm in the vicinity of the maneuver. The effect on the orbit solutions is most eminent especially for very long maneuvers. However, large data gaps and/or frequent short data gaps during the maneuver time span can easily degrade the calibration performance.

Nonetheless, this alternative approach can guarantee consistent and precise thruster calibration, and is still capable of achieving demanding orbit accuracy requirements. This is most beneficial for satellite missions with frequent maneuvers and also for automated routine operational orbit determination whereby the thruster performance and continuous precise orbit solutions can be obtained in a single step.

Acknowledgement

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