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Enhanced GPS-based GRACE baseline determination by using a new strategy for ambiguity resolution and relative phase center variation corrections

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ABSTRACT

Precise relative position determination is a prerequisite for radar interferometry by formation flying satellites. It has been shown that this can be achieved by high-quality, dual-frequency GPS receivers that provide precise carrier-phase observations. The precise baseline determination between satellites flying in formation can significantly improve the accuracy of interferometric products, and has become a research interest. The key technologies of baseline determination using spaceborne dual-frequency GPS for gravity recovery and climate experiment (GRACE) formation are presented, including zero-difference (ZD) reduced dynamic orbit determination, double-difference (DD) reduced dynamic relative orbit determination, integer ambiguity resolution and relative receiver antenna phase center variation (PCV) estimation. We propose an independent baseline determination method based on a new strategy of integer ambiguity resolution and correction of relative receiver antenna PCVs, and implement the method in the NUDTTK software package. The algorithms have been tested using flight data over a period of 120 days from GRACE. With the original strategy of integer ambiguity resolution based on Melbourne-Wübbena (M-W) combinations, the average success rate is 85.6%, and the baseline precision is 1.13 mm. With the new strategy of integer ambiguity resolution based on a priori relative orbit, the average success rate and baseline precision are improved by 5.8% and 0.11 mm respectively. A relative ionosphere-free phase pattern estimation result is given in this study, and with correction of relative receiver antenna PCVs, the baseline precision is further significantly improved by 0.34 mm. For ZD reduced dynamic orbit determination, the orbit precision for each GRACE satellite A or B in three dimensions (3D) is about 2.5 cm compared to Jet Propulsion Laboratory (JPL) post science orbits. For DD reduced dynamic relative orbit determination, the final baseline precision for two GRACE satellites formation is 0.68 mm validated by K-Band Ranging (KBR) observations, and average ambiguity success rate of about 91.4% could be achieved.

1. Introduction

Formation flying technique in low Earth orbit (LEO) has been widely used in geodesy in the last few decades, such as interferometric synthetic aperture radar (InSAR) imaging [1] and Earth gravity field recovery [2]. There are many satellite formation missions which have been or are going to be studied, such as GPS-based orbit estimation and laser metrology for inter-satellite navigation (Gemini) [3], GRACE [2], TerraSAR-X add-on for digital elevation measurement (TanDEM-X) [4], the prototype research instruments and space mission technology advancement (PRISMA) [5], shi jian-9 formation flight mission (SJ-9) [6], technology satellite of the 21st century (TechSat21) [7], interferometric cartwheel [8], and so on. The distributed SAR is a research hotspot, which combines formation-flying LEO satellites and interferometric SAR technology. The distributed SAR system fixes its SAR antennas on formation-flying satellites, and completes interferometric SAR mission through the cooperation of satellites and SAR antennas, which can be used for ground three-dimensional targets positioning, surface deformation, moving targets detection, satellite surveying and mapping [8]. Although the distributed SAR system has wide application prospects, it also faces many challenges. One of them is the precise inter-satellite baseline determination [9,10]. In order to obtain high quality global digital elevation model (DEM) products, the requirement of inter-satellite baseline accuracy for a distributed SAR system is very high. TanDEM-X is a distributed SAR mission developed by German Deutsches Zentrum für Luft und Raumfahrt (DLR), which consists of two twin satellites each provided with an X-band SAR instrument. The satellites, TerraSAR-X (TSX) and TanDEM-X (TDX), fly in a controlled helix formation with an

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altitude of 515 km and form a high resolution radar interferometer in space [4]. The relative position between TSX and TDX, which is typically separated by baseline lengths of 150–600 m, has to be determined down to an accuracy of better than 2 mm (1σ) [11]. Both TSX and TDX are equipped with tracking, and ranging device (TOR), which is composed by an integrated GPS and occultation receiver (IGOR) and a laser reflector. The IGOR, provided by the GeoForschungsZentrum Potsdam (GFZ) is a heritage of the BlackJack GPS receiver, which was successfully flown on GRACE mission [12].

Given its characteristics of all-weather availability, high precision and good continuity, spaceborne dual-frequency GPS has been successfully applied to the LEO satellite precise navigation. The precise baseline determination is based on the estimation of the relative orbit position with carrier phase differential GPS (CDGPS), which can eliminate the influence of some common errors and achieve 1 mm millimeter-level relative positioning accuracy [13]. As TanDEM-X has no direct measurement instrument for the baseline precision validation, many descriptions of TanDEM-X baseline precision are proved by inter-agency comparison [14] or referring to GRACE formation indirectly [12]. GRACE [15] is a satellite gravity field measurement system developed by German DLR and American National Aeronautics and Space Administration (NASA). It consists of two identical formation flying satellites GRACE A and B. On March 17, 2002, the twin satellites were launched into an almost circular, near polar orbit with an inclination of 89° and an altitude of 500 km. The initial distance between the two satellites is approximate 220 km. The payloads equipped on GRACE satellites mainly contain KBR, GPS receiver, accelerometer, star sensor, and so on. The KBR, which is mainly used to detect changes in Earth's gravity field, can be used to independently validate the inter-satellite baseline precision.

The feasibility of GPS-based GRACE baseline determination at millimeter or submillimeter levels using GPS carrier phase measurements with fixed integer ambiguities has been well demonstrated [16–19]. In 2005, the GRACE baseline solutions of 1.0 mm level precision were firstly obtained by Kroes using the GHOST software package with a Kalman filter [16], and the average ambiguity success rate was about 83%. In 2007, the Bernese software package with a batch least-squares estimator was used by Jäggi [17], the baseline precision for GRACE was 0.88 mm, and the average ambiguity success rate was 89.8%. In 2012, the strategy of integer ambiguity resolution in the GHOST software package was improved by van Barneveld with the subset approach [18], and the average ambiguity success rate reached 96%. In 2015, precise baseline determination for maneuvering GRACE was implemented by Ju using the national university of defense technology orbit determination toolkit (NUDTTK) software package [19], the daily baseline precision under maneuver condition for GRACE was 0.7 mm, and the average ambiguity success rate was 87%. Although the submillimeter levels of GRACE baseline determination have been achieved by some software packages, there are still some issues worthy to be discussed to improve baseline precision, such as improved integer DD ambiguity resolution and receiver antenna PCV estimation.

One of the key technologies of baseline determination is integer DD ambiguity resolution. Once the integer DD ambiguities are successfully fixed, the corresponding carrier phase observations will be transformed into precise relative ranges, thus allowing for a baseline solution with a comparable high precision. Due to the large separation of GRACE satellites, ionosphere delays do not cancel by CDGPS, and this makes integer ambiguity resolution more difficult. A common strategy of integer ambiguity resolution for long baseline is used by the Bernese software packages in early relative positioning between ground stations, which separately estimates the wide-lane and narrow-lane ambiguities. It has the shortcomings that the success rate of the wide-lane ambiguity resolution through M-W combinations will strongly depend on low-precision code observations. The subset approach presented by van Barneveld is a good way to improve the ambiguity success rate instead of the full set approach [18], but it still did not overcome the shortcomings. To overcome the shortcomings, a new strategy of integer ambiguity resolution based on a priori relative orbit is presented in this paper.

Furthermore, neglected or mismodeled antenna PCVs, which might be attributed to ground calibrations being performed with limited information related to the satellite environment, have gradually become the most important systematic error source in high-precision GPS positioning application. The decision to perform an in-flight calibration of receiver antenna PCVs is necessary. Most of the related studies have focused on the estimation of absolute receiver antenna PCVs for precise orbit determination (POD) of a single LEO satellite. In-flight calibration of absolute receiver antenna PCVs has been adopted for many satellites, such as Jason-1 [20], GRACE [21–23], TerraSAR-X [14,21], COSMIC [24], GOCE [25], and Haiyang 2A [26]. However, for baseline determination, the influence of antenna absolute PCVs from the reference LEO satellite can be weakened by difference, and the influence is mainly derived from the relative PCVs, which represent differential antenna PCVs between two LEO satellites. In POD, the estimation of absolute PCVs will be affected by GPS satellite ephemeris errors and transmitter antenna PCVs, and some PCV distortions may be absorbed by other estimation parameters, such as float carrier phase ambiguities [22,27]. This might limit the actual accuracy of absolute PCV estimation and therefore an estimation of relative PCVs based on differential carrier phase measurements with fixed DD ambiguities is expected to better reflect the magnitude of those systematic errors between two LEO satellites. Thus, we need to pay more attention to the estimation of relative receiver antenna PCVs for GRACE baseline determination. Note that the estimation of relative PCVs is not a direct differential map between two GRACE satellites, as GRACE B satellite is typically rotated 180° around the z-axis with respect to GRACE A.

A method based on a new strategy of integer ambiguity resolution and correction of relative receiver antenna PCVs is proposed in this paper to enhance GPS-based GRACE baseline determination, and is implemented in the NUDTTK [19,27,28] software package. The proposed method including a description of POD for single-satellite orbits, a description of precise baseline determination for two satellites, a description of integer DD ambiguity resolution and a description of relative PCV estimation, is validated by performing tests using data over a long period from GRACE. The obtained baseline solutions and the details of data and methods used for each of them are described.

2. Reduced dynamic orbit determination for a single satellite

2.1. ZD observation equation

In order to eliminate the first order ionosphere delay, dual-frequency ionosphere-free (IF) combination observations are adopted. For code and carrier phase observations, the ionosphere-free combination yields

$$\begin{aligned} P_{\mathrm{IF}}^{\mathrm{j}}(t_i) &= \frac{f_1^2}{f_1^2-f_2^2}P_1^{\mathrm{j}}(t_i) - \frac{f_2^2}{f_1^2-f_2^2}P_2^{\mathrm{j}}(t_i) = \rho^{\mathrm{j}}(t_i) + c\cdot(\delta t_r(t_i) - \delta t^{\mathrm{j}}(t_i)) + \delta\rho_{\mathrm{PIF}}^{\mathrm{j}}(t_i) + \varepsilon_{\mathrm{PIF}}^{\mathrm{j}}(t_i) \\ L_{\mathrm{IF}}^{\mathrm{j}}(t_i) &= \frac{f_1^2}{f_1^2-f_2^2}L_1^{\mathrm{j}}(t_i) - \frac{f_2^2}{f_1^2-f_2^2}L_2^{\mathrm{j}}(t_i) = \rho^{\mathrm{j}}(t_i) + c\cdot(\delta t_r(t_i) - \delta t^{\mathrm{j}}(t_i)) + \lambda_{\mathrm{IF}}A_{\mathrm{IF}}^{\mathrm{j}} + \delta\rho_{\mathrm{LIF}}^{\mathrm{j}}(t_i) + \varepsilon_{\mathrm{LIF}}^{\mathrm{j}}(t_i) \end{aligned}, \quad (1)$$