Research on LEO Satellites Time Synchronization with GPS Receivers Onboard

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***Abstract*—Precise relative navigation of spacecraft is required for its critical movement, such as rendezvous and formation flying - key aspects of many current and future space missions. Potential applications of interest include the capabilities to detect and track slowly moving ground vehicles (ground moving target indication (GMTI)) and perform synthetic aperture radar (SAR) imaging, with the requirement to provide GMTI and SAR data to users in a timely manner. Extensive research has been carried out on terrestrial applications of Global Positioning System (GPS) time transfer. For low Earth orbit (LEO) satellites, such missions can use the GPS signals for relative positioning and data time tagging. This paper focuses on linking these two key applications - the use of GPS in LEO for relative navigation and precise formation flying, and time and frequency transfer between LEO satellites. As an example, the research investigates co-orbiting satellites A and B of Gravity Recovery and Climate Experiment (GRACE) at a separation of about 200 km. The observations of GPS receivers onboard both GRACE A and B satellites are transferred into Receiver Independent Exchange Format (RINEX) format (1 Sept. 2003). The orbit of both satellites is then computed using the zero-difference precise point positioning technique. The RMS orbital difference between the results obtained and the precise orbits from GFZ is below 0.07 m. Two methods are proposed to compute the time difference between GPS receiver onboard satellites A and B respectively.**

One uses onboard GPS RINEX observations and the GRACE orbit from GeoForschungsZentrum Potsdam (GFZ) which has a large relative latency, the times between A and B in multi-channel Common-View mode are compared. Another method computes the clocks of A and B by use of GPS observation onboard and the computed orbit. The times between A and B are then compared. Results indicate that a RMS accuracy of 2-3 nanoseconds (ns) can be achieved. This suggests that GPS has the capabilities of high-precision time transfer between LEO satellites.

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I. INTRODUCTION

Global Positioning System (GPS) is not only a navigation system; but also a time-transfer system. As a navigation system, GPS has proven it to be a reliable source of positioning for both the military and civilian communities. Besides，GPS is a versatile and global tool which can be used to both distribute time to an arbitrary number of users and synchronize clocks over large distances with a high degree of precision and accuracy. As a time-transfer system it provides stability very close to one part in ten to the fourteenth over one day (1 ns/day) [3]. Now more and more low Earth orbit (LEO) satellites are launched, and the satellites orbit is determining precisely by onboard GPS receivers, so the onboard GPS observation can also use for the time synchronization between LEO satellites. The Gravity Recovery and Climate Experiment (GRACE) mission is a joint project between the U.S. National Aeronautics and Space Administration (NASA) and the Zeutsches Zentrum für Luft und Raumfahrt (DLR).

A. GRACE mission

The two satellites of this mission were launched simultaneously on March 17, 2002 from the Russion Plesetsk cosmodrome. The primary goal of the GRACE mission is to obtain accurate global and high-resolution models for both the static and the time variable components of the Earth's gravity field. These gravity field estimates will provide, with unprecedented accuracy, integral constraints on the global mass distribution and its temporal variations. The main

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mission parameters of the two satellites are show as following [4]:

(1) Almost circular (eccentricity e<0.005) and near-polar ($i=89^0$) orbit,
(2) Initial altitude between 485km and 500km,
(3) The two satellites are some 220km apart (orbit maneuvers are required every one or two months to maintain the separation between the two spacecraft),
(4) Design lifetime of the mission is five years (but extended operation is envisaged),
(5) The weight of each satellite is about 480 kg and the length about 3 m.

B. GRACE payload

The following payload is on board of the two satellites:

(1) The K-band ranging system is the key instrument of GRACE to measure the range changes between both satellites using dual-band microwave signal (i.e., two one-way ranges) with a precision of about 1 μms^{-1}. The ranges are obtained at a sampling rate of 10Hz.
(2) The GPS receiver serves for the precise orbit determination of the GRACE spacecraft and provides data for atmospheric and ionospheric profiling. To achieve this satellite-to-satellite tracking between the GRACE satellites and GPS satellites is realized. A navigation solution comprising position, velocity, and a time mark is derived on board. The navigation solution is required for the attitude control system. The precise orbit based on code pseudoranges and carrier phase is determined on ground.
(3) The attitude and orbit control system comprise a cold gas propulsion system, three magnetic torque rods, star trackers, a three-axis inertial reference unit to measure angular rates, and a three-axis magnetometer.
(4) The accelerometer measures all nongravitational accelerations on the GRACE spacecraft, e.g., due to air drag or solar radiation pressure.

The laser retroflector is a passive payload instrument used to reflect short laser pulses transmitted by ground stations. The distance between a ground station and a GRACE satellite can be retroreflector data are primarily used together with the GPS receiver data for the precise orbit determination.

The GRACE has been proven that it is effectual for strengthen the understanding of earth's inner structure and to provide a better reference for the study of ocean and atmosphere [6]. The research investigates the applications of the GRACE onboard GPS observation for LEO satellites time comparison.

II. Methods of Compute

A. Common-View mode

The standard method of using GPS to compare the times of distant clocks is called the common view technique, by which two or more ground stations simultaneously observe a single GPS space vehicle (SV). The resulting clock offsets between the laboratory clock and GPS time are obtained from a fixed procedure defined by the CCTF (Consultative Committee for Time and Frequency). The classical time transfer method used to realize the TAI (International Atomic Time) is based on the common view technique, with GPS observations collected by C/A code receivers. The potential of GPS carrier-phase and dual-frequency geodetic receiver for time transfer has been recognized [8]. The research proposes to use the Satellite-to-Satellite Tracking in High-Low (SST-hl) GRACE onboard GPS observation in common-view mode. Because the data of GRACE onboard GPS observation are in **A**dvanced **S**tellar **C**ompass (ASC) format, first the data are transformed into general Receiver Independent Exchange Format (RINEX) format, then according to the CCTF Group on GNSS Time Transfer Standards (CGGTTS) format program to compute clock error [9]. The data of RINEX GRACE onboard GPS observations and the GRACE orbit from GFZ are used. The processing flow is as Fig. 1.

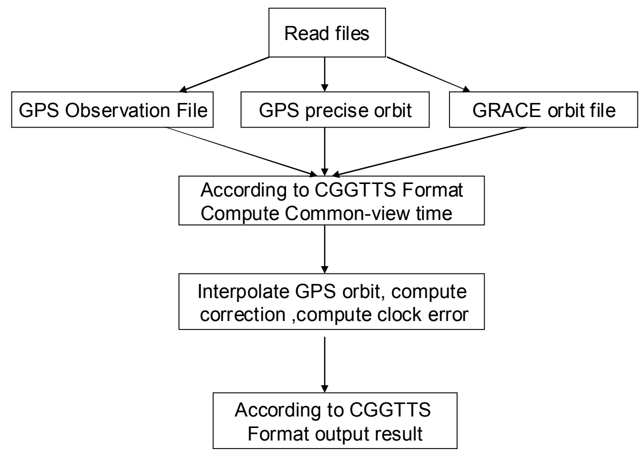

Figure 1. Clock error computing in CGGTTS Format

According to CGGTTS Format every 13 minutes observation divides a group. The clock error unit is nanosecond (ns). The compare interval is 30 second. It is relative to all common-view satellite. The part of Pseudo-Random Noise (PRN)'s GPS relative clock error between GRACE A and B is show the table 1.

Table I. Part of relative Clock error between GRACE A and B

A-B m/s	1	2	3	11	13	27	31	Σ/n
3/0	0.4	−0.8	−0.8	4.6	3	0.1	0.3	0.9
3/30	−1.8	−0.1	−0.6	1.0	1.2	0.5	−0.1	0.0
4/0	1.7	−0.2	−0.4	−0.3	−2	−0.3	0.1	-0.2
4/30	−0.3	−0.8	−0.6	−3	2	0.3	−0.2	-0.3
5/0	−7.2	−0.2	−0.9	−6.1	0.6	−0.6	0.5	-1.9
5/30	−1.7	−0.2	0	−6.6	1.6	−0.1	0.1	-0.9
6/0	−0.8	−0.6	−1.2	−4.1	5.6	−0.1	0.4	-0.1
6/30	0.5	−0.4	−0.2	0.8	1.3	0.3	0.3	0.3
7/0	−0.2	−0.5	-12.2	9.5	1.2	−0.6	0.6	-0.3
7/30	−0.8	−0.5	1.3	−0.4	4.9	−0.5	0.4	0.6
8/0	10.5	−0.8	0.6	7.4	6	0.1	0.5	3.4
8/30	4.5	−0.4	0.5	2.9	6.9	−1.2	0.5	1.9
9/0	6.2	−0.5	−5.1	7.1	4.6	0.8	0.8	1.9
9/30	−0.1	−0.5	0	−6.7	3.2	0.5	0.4	-0.4
10/0	0.5	−0.8	3.7	4.7	2.1	1.1	0.5	1.6
10/30	−0.6	−0.4	3	2.4	−8.5	1.4	0.3	-0.3

B. Compute orbit mode

Generally, it is need precise determinate GRACE satellite orbit for time comparison between the LEO satellites. Commonly, for LEO satellites orbit determination, two step's method is used. First, the GPS satellites orbit is determined by ground IGS GPS stations. Second, LEO satellites orbit and other gravity parameters are determined by use of onboard GPS receiver's observation and precise orbit of GPS. The GeoForschungsZentrum (GFZ) of Germany already completed the one-step's method, it is simultaneity computes all the parameters, that including GPS satellites orbit, LEO satellites orbit, gravity of Earth, Earth Orientation Parameters (EOP), and GPS stations coordinates. The processing data included ground GPS tracking coordinates, Satellite Laser Ranging (SLR) ground tracking coordinates, data of SLR tracking LEO satellites, onboard GPS observation of GRACE, accelerometer data of GRACE, ranging data and it's rate of K wave band, the altitude of GRACE and data of orbit maneuver.

In this paper, the Bernese5.0 program is used for GRACE satellites orbital determination and clock error resolving. Similarly, because the format of GRACE onboard GPS observation [5], which is ASC format, was not recognized by Bernese5.0, the GRACE onboard GPS data are transformed to RINEX format. In order to obtain precise time synchronization between the LEO satellites, some key steps are taken into account. First, the reference frame must be consistent. It is that the orbit and clock error of GPS satellites must came from same analysis center. Second, because the altitude of GRACE satellites, the troposphere delay is slide over in the processing. Third, in order to obtain centimeter accuracy orbit, both geometer and dynamic information will fall together. The processing steps follow the below flow [1, 3]:

First the primary GRACE orbit is determined. Then the data of onboard GPS observation are preparative editing processing and cycle slip detect carefully [4, 7]. Second the GRACE orbit is determinate. It is an iterative process in the orbit determination. Final, the clock error of GRACE satellites were resolved. The sample of GRACE onboard GPS observation is 10 second. The JPL GPS satellites clock error that it sample is 30 second and orbit correspondingly is used. The clock error resolving flow is show Fig. 2.

III. RESULT ANALYSIS

The onboard GPS observation on Sept. 1 2003 is computed. According to Fig. 2 processing flow, two satellites orbit of GRACE A and B are computed, then the computed orbit is compared to the standard orbit provided by GFZ. This comparing is in radial, tangential and normal respectively. The residual bias is shown in Fig. 3.

It is shown that for the GRACE satellite A the orbit radial residual is 0.056 m, tangential orbit residual is 0.089 m and normal orbit residual is 0.045 m, a day average RMS of GRACE orbit is 0.067 m. For the GRACE satellite B the orbit radial residual is 0.057 m, tangential orbit residual is 0.092 m and normal orbit residual is 0.032 m, a day average RMS of GRACE orbit is 0.066 m. It is shown that there is systemic error in the computed orbit relative to the orbit of GFZ. It is a part of reason that caused by the orbit and clock error of GPS. The main reason is that only onboard GPS observation is used for orbit determination. The data of SLR and ranging and ranging rate are not used. Using the computed orbit, the clock error is computed. It included satellite clock error of GRACE A and B respectively, and relative clock error between GRACE A and B. The sample is 10 second. It is shown in Fig. 4.

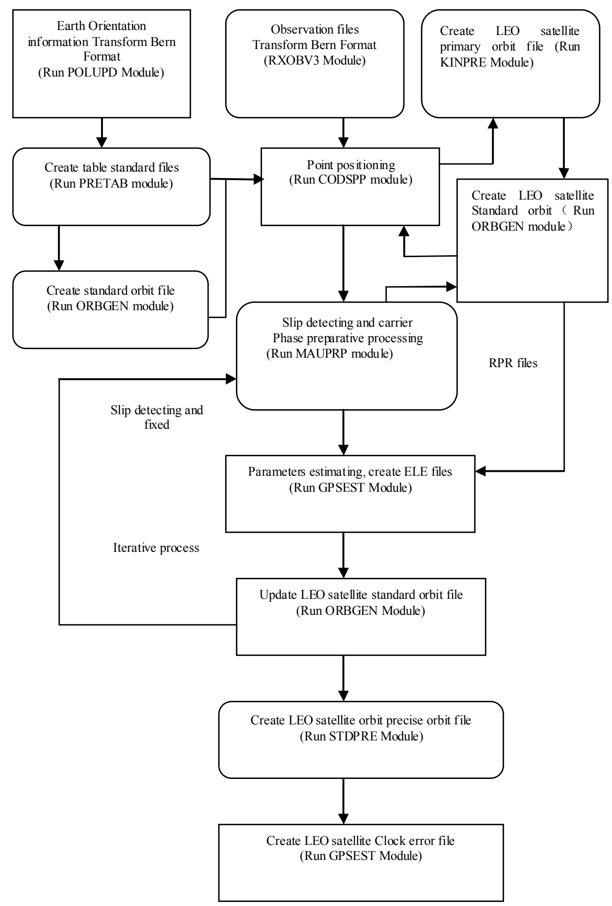

Figure.2.Processing flow of GRACE Satellite clock error

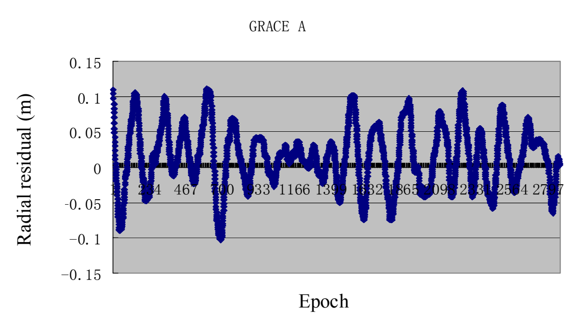

Figure 3a. GRACE A Radial residual

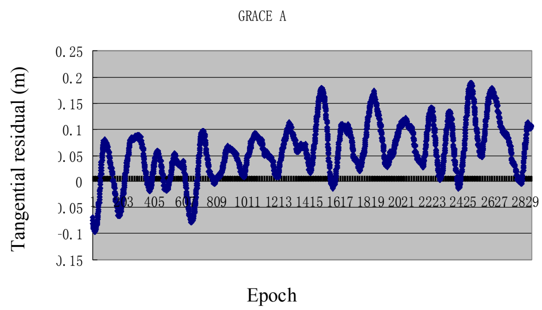

Figure 3b. GRACE A Tangential residual

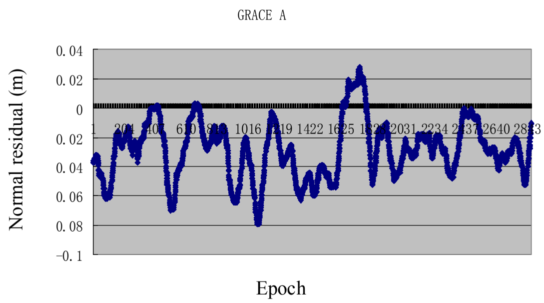

Figure 3c. GRACE A Normal residual

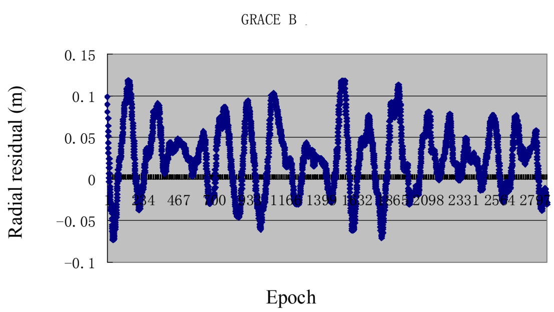

Figure 3d. GRACE B Radial residual

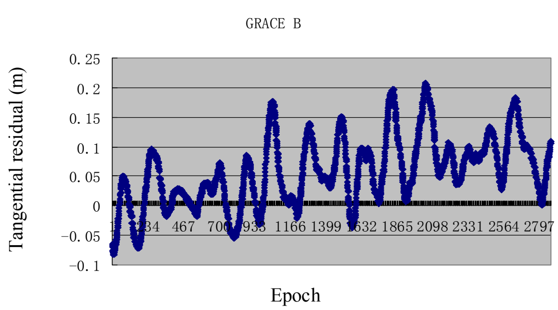

Figure 3e. GRACE B Tangential residual

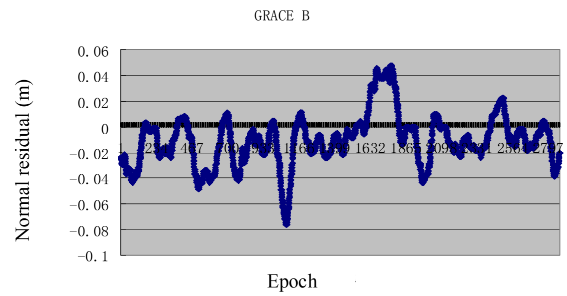

Figure 3f. GRACE B tangential residual

Figure 3. RMS of comparison between the computed results and the precise orbit by GFZ

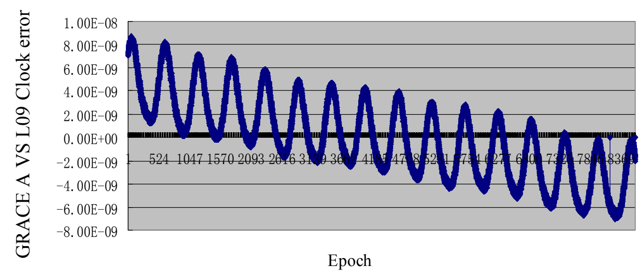

Figure 4a. GRACE A VS GPS 09 Clock error

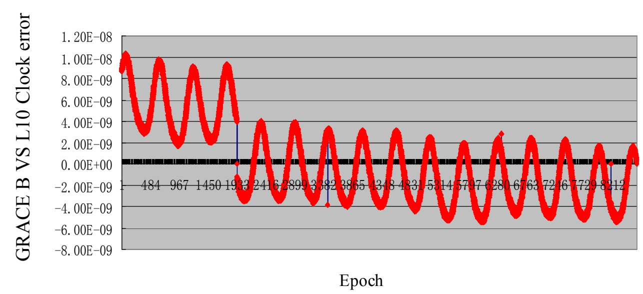

Figure 4b. GRACE B VS GPS 10 Clock error

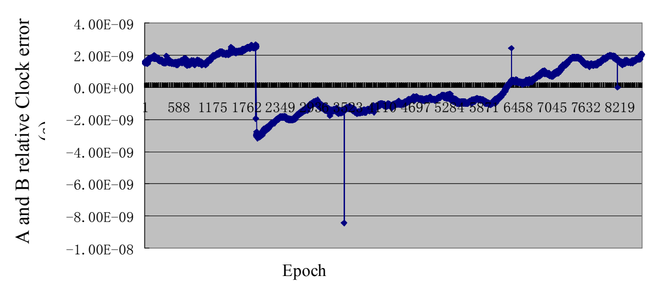

Figure 4c. Relatively clock error between GRACE A and B

Figure 4. GRACE Satellite VS. GPS clock error and relatively clock error between GRACE A and B

The information can be detected from clock error figure of GRACE A and B: most of clock errors are small change between neighborhood epochs. But there are skips at special epoch. In the relative clock error, the GPS satellite errors are eliminated and the other errors also are become lower, the change become smooth. The value almost is within a few ns. But those skips may be caused by cycle slips that are not detected and correct fixed. The accuracy of clock error computed by two methods is similar. But the second method is more convenience for real time application.

IV. POTENTIAL APPLICATIONS

Satellites operating and application based on the synchronization between the onboard clocks and ground clocks. Commonly, the precise synchronization of satellite and ground is controlled by ground monitoring station. Precise determination the time bias between satellite clock and ground clock is key point. The time bias between the satellites will lead to the relative distance change of formatting satellites constellation. It is important for time correction of satellite. Formatting small satellites precise time measurements are necessary for synchronizing control and communications facilities, for example. GPS provides an opportunity to measure time exactly on a global basis. Simultaneity, GPS is wide used for time and frequency transfer. The research investigates the capability of GRACE onboard GPS observation to participate in time and frequency transfer applications. The onboard GPS receivers can be use for precise orbit and relative clock error determinate. When the time synchronization of LEO satellites have established, it can provide precise moving target indication. Potential applications include the capabilities to detect and track slowly moving ground vehicles, providing synthetic aperture radar (SAR) imaging processing and information processing perform.

V. CONCLUSION

The main objectives of satellite carrying SST equipment are to obtain the gravity field and geoid model of the earth, to strengthen the understanding of earth's inner structure and to provide a better reference for the study of ocean and atmosphere. The research has also demonstrated that the use of the onboard GPS dramatically improves the stability of the time and frequency transfer. However, practical utilization will depend on the development of calibration methods that can be applied to geodetic receiver systems. Among the effects, which must be considered and controlled, in order to achieve the full potential of geodetic onboard GPS receiver time transfer is observation biases. It is shown about 2-3ns accuracy of inter clock error, by means of Bernese 5.0 program compute GRACE satellite relative clock error. So the onboard GPS can use for time synchronization between LEO satellites. The means of time synchronization link also can be provided for formatting satellites. This LEO satellites time synchronized means will be wide use in various aspects in future.

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