Flight performance analysis of GRACE K-band ranging instrument with simulation data

Jeongrae Kim\textsuperscript{a,*}, Seung Woo Lee\textsuperscript{b}

\textsuperscript{a}Korea Aerospace University, School of Aerospace and Mechanical Engineering, Goyang City 412-791, Republic of Korea
\textsuperscript{b}Korea Research Institute of Standards and Science, Division of Physical Metrology, Daejeon 305-340, Republic of Korea

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Abstract

A dual one-way ranging (DOWR) system provides very high accuracy range measurements between two satellites. The GRACE satellite mission implements the DOWR, called KBR (K-band ranging), to measure very small inter-satellite range change in order to map the Earth gravity field. The flight performance of the KBR is analyzed by using a hybrid software simulator that incorporates actual satellite orbit data into a comprehensive KBR simulator, which was earlier used for computing the GRACE baseline accuracy. Three types of experiments were performed. First is the comparison of the flight data with the simulated data in spectral domain. Second is the comparison of double differenced noise level. Third is the comparison of the range-rate difference with GPS clock estimates. The analysis shows a good agreement with the simulation model except some excessive high frequency noise, e.g. $10^{-4}$ m/$\sqrt{\text{Hz}}$ at 0.1 Hz. The range-rate difference shows 0.003 cyc/s discrepancy with the clock estimates. These analyses are helpful to refine the DOWR simulation model and can be benefit to future DOWR instrument development.

Keywords: Dual one-way ranging; K-band ranging; GRACE; Inter-satellite ranging; Gravity mapping

1. Introduction

The accuracy of microwave ranging systems is mainly limited by the instability of the oscillator that derives the microwave signal. A dual one-way ranging (DOWR) system minimizes the oscillator effect by combining the one-way microwave range measurements from two microwave ranging instruments. With identical transmission and reception subsystems, each instrument transmits a carrier-phase signal to the other instrument. The received signal at each instrument is recorded and later transmitted to a control segment [1,2]. The frequency fluctuations due to oscillator instability have nearly equal and opposite effects on each instrument’s measurement, and summation of these two phases cancels most of the oscillator noise. The combined phase measurement is converted to the biased range between the two instruments with very high precision.

The DOWR instrument was first implemented on the Gravity Recovery and Climate Experiment (GRACE) satellite mission as an inter-satellite ranging system. The GRACE mission is a dedicated spaceborne mission designed to map the gravity field with high accuracy. It is a joint project by NASA and the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The GRACE mission consists of two co-orbiting low-Earth-orbit satellites...
separated in orbit by about 200 km [3]. The orbit inclination is close to 90° and the initial altitude is 500 km. The mission is implemented under the overall direction of The University of Texas/Center for Space Research (UT/CSR). NASA Jet Propulsion Laboratory (JPL) has been assigned responsibility for the development of the science instrument and satellite system in partnership with Space Systems/Loral (SS/L) and Dornier Satelliten Systeme (DSS). The DLR German Space Operation Center (GSOC) with its ground tracking facilities is responsible for the operation of the GRACE satellites. The observation data collected by GSOC is processed in a cooperative approach by UT/CSR, JPL, and GeoForschungsZentrum (GFZ) in Germany.

Accurate Earth gravity model is essential for a wide variety of geophysical applications, including oceanography, hydrology, glaciology, geodesy, and the solid Earth sciences. The gravity model is usually expressed as a sum of spherical harmonics, and the signal strength and accuracy varies with frequency or wavelength. Gravity model accuracy is mainly described by geoid accuracy that represents equipotential surface height from the Earth reference ellipsoid. The orbit of any satellite in a near-Earth orbit is dependent on the globally integrated effect of the mass distributions in the Earth system. The orbits of the two GRACE satellites, sensing these effects at slightly different locations, will be perturbed differentially. This difference in perturbations is manifested in the inter-satellite range change and can be observed by a DOWR instrument, called K-band ranging (KBR) system. The KBR, developed by Jet Propulsion Laboratory, provides a micron level accuracy using carrier phase measurements in the K (26 GHz) and Ka (32 GHz) frequencies [4]. The satellite orbits and their relative positions are affected not only by the gravitational accelerations but also by non-gravitational accelerations, and their effects must be accurately measured to utilize the gravitational information in the range change measurements. For this purpose, each GRACE satellite carries a high precision three-axis accelerometer. Each satellite also carries a geodetic quality GPS receiver to ensure that the orbits for the satellites can be continuously and accurately determined and that the gravity field estimates can be correctly registered in a terrestrial reference frame.

Fig. 1 illustrates a system block diagram of the KBR. Both the KBR and GPS receiver are driven by the same oscillator. The GRACE has two types of measurement data, Level 1A (L1A) and Level 1B (L1B). The L1A data contains the raw measurements from the instruments and the data sampling time is 0.1 s for the KBR. The L1B data is generated by filtering the L1A data with corrections. The data sampling time of the L1B is 5 s for the KBR. The L1A data is available to only CSR,
Due to the extremely high precision of the KBR, it is impossible to evaluate its flight performance directly with external data, e.g. GPS. Some of indirect ways should be used for evaluating its flight performance in part. Several researches were performed to evaluate the GRACE KBR performance by comparing the KBR measurement power spectral density (PSD) level (not the measurement noise level) with the design noise level [12–14]. However, the KBR measurements have a strong gravity signal and it is better to compare the KBR PSD with consideration of the signal contribution. The gravity signal varies with the satellite orbits, and the orbit condition for interested KBR measurements should be considered for a proper analysis.

This paper evaluates the KBR flight performance by comparing the flight data with the simulation data that was used for predicting the baseline accuracy during mission design period. It is to find out the difference from the baseline (simulation). Three types of experiments were performed. First is the comparison of the flight data with the simulated data in spectral domain. Second is the comparison of double differenced noise level. Third is the comparison with GPS clock estimates. Since the onboard GPS receiver and the KBR system are both driven by the same oscillator, the correlation between the two measurements is analyzed. Since the KBR measurements are mainly affected by satellite orbit, the actual flight orbit data, estimated from onboard GPS measurements, was implemented into the simulation. The gravity estimate accuracy varies with frequency, i.e. the accuracy degrades as the frequency increases. Although the direct correlation between the KBR noise PSD and the gravity error PSD does not exist, they have some correlation in spectral domain, and it is better to evaluate the KBR noise spectrum instead of simple noise statistics.

2. Concept of the DOWR system

The following description briefly reviews the concept of the DOWR instruments. It shows how the oscillator noise from the individual DOWR instrument is canceled out. Each DOWR instrument transmits a carrier phase signal to the other instrument. Carrier phase received at the two instruments at a specified nominal time \( t \) can be modeled as follows [4,11]:

\[
\phi_A^B(t) = [\phi_A(t)+\delta\phi_A(t)]- [\phi_B(t)+\delta\phi_B(t)] + E_A
\]

\[
\phi_B^A(t) = [\phi_B(t)+\delta\phi_B(t)]- [\phi_A(t)+\delta\phi_A(t)] + E_B
\]

where \( \phi_A^B \) and \( \phi_B^A \) represent the phases measurements at the receiver \( A \) and \( B \), respectively, which are the
difference between received ($\varphi^A$ and $\varphi^B$) and reference phases ($\varphi_A$ and $\varphi_B$). $\delta \varphi_i$ represents the phase noise due to oscillator instability. The error term $E_A$ or $E_B$ includes phase bias ambiguity, ionosphere delay, other noise etc. The received phase, $\varphi'(t)$, is transmitted before the time-of-flight of the phase, $\tau$, and $\varphi'(t)$ can be replaced with $\varphi_i(t - \tau)$.

Dual one-way phase is defined as the summation of the two one-way phases of Eq. (1):

$$\Theta(t) \equiv \varphi^B_A(t) + \varphi^A_B(t)$$

(2)

Substitution of the one-way phase of Eq. (2) yields

$$\Theta(t) = \left[\varphi_A(t) - \varphi_A(t - \tau) + \varphi_B(t) - \varphi_B(t - \tau)\right] + \left[\delta \varphi_A(t) - \delta \varphi_A(t - \tau) + \delta \varphi_B(t) - \delta \varphi_B(t - \tau)\right] + \left[E_A + E_B\right]$$

(3)

The first term represents the true phase measurements that can be converted to range measurements. The second term represents the phase noise cancellation process. The two phase noises from the same satellite have opposite signs, $\delta \varphi_1(t)$ and $-\delta \varphi_1(t - \tau)$, and they are generated at slightly different times $t$ and $t - \tau$. If the phase noise is constant over $\tau$, the subtraction removes the phase noise. However, the generation time is different by $\tau$, and the short period phase noise having duration $< \tau$ remains after the dual one-way process. In the case of the GRACE, the signal time-of-flight time is $< 1$ ms and it effectively removes the phase noise in the mid and low frequency. The dual one-way phase is converted to a dual one-way range by multiplying with a wavelength. Since the ionosphere delay is not removed by the DOWR, dual frequency band signals (as like the GPS L1 and L2) are required to remove the ionosphere delay effect. Fig. 2 illustrates the phase noise cancellation process with the DWOR system. Detailed derivations can be found in the literature [1,2,4,11].

A key requirement for the KBR system is the measurement time synchronization; as the measurement epoch of the two satellites’ phases should be very close to maximize the noise cancellation. In other words, the time-tag error (difference between actual measurement time and the nominal time) should be small. In case of the GRACE, an onboard GPS receiver provides this time-tag information, and ground post-processing with external data, e.g. the International GNSS Service (IGS) [15–17] results in a high accuracy of the relative clock estimate between the two satellites, usually $< 100$ ps level. Using these clock estimates, the KBR one-way phases are interpolated toward the nominal epoch $t$, and then combined.

3. Simulation data

The GRACE DOWR software simulator, developed by the Kim [10,11], generates one-way phase measurements with the comprehensive error sources. The simulation process starts with simulating two satellites’ orbit with comprehensive dynamic models, i.e. Earth gravity, atmospheric drag, radiation pressure etc. From the simulated satellite orbits, the truth inter-satellite range is computed and it contains the gravity signal. Oscillator noise is simulated according to specified Allan variance and then converted into phase noise. In addition to the oscillator noise, measurement time-tag error, system noise, multipath noise, Analog Modulation/Phase Modulation conversion error, and attitude determination error from the star cameras are added into the phase noise. Structure distortion due to thermal variation is modeled as well but not included for the simulation since its magnitude is not very significant. Misalignment of the KBR with the satellite body is incorporated in the attitude error. From the truth range and phase noise, the one-way phase measurements from the two DOWR instruments are generated. The inter-satellite range measurements are obtained by the combination process described earlier section. The error level of the inter-satellite range was predicted from the simulated phase measurements and then used for the prelaunch analysis. The simulated parameters are shown in Table 1. Details on the error models can be found in Refs. [10,11]. In comparison with the flight data quality, the simulation models have some limitations; simple multipath model, no assumption on data loss/gap.
Table 1
Simulation parameters.

<table>
<thead>
<tr>
<th>Category</th>
<th>Type</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data description</td>
<td>Measurement type</td>
<td>One-way carrier phases</td>
</tr>
<tr>
<td></td>
<td>Phase frequency bands</td>
<td>Dual one-way inter-satellite range</td>
</tr>
<tr>
<td></td>
<td>Frequency offset:</td>
<td>K (26 GHz), Ka (32 GHz)</td>
</tr>
<tr>
<td></td>
<td>Sampling interval</td>
<td>0.5 MHz for K and Ka</td>
</tr>
<tr>
<td></td>
<td>Data span</td>
<td>0.1 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 day</td>
</tr>
<tr>
<td>Dynamic model</td>
<td>Earth gravity</td>
<td>Spherical harmonics</td>
</tr>
<tr>
<td></td>
<td>Atmospheric drag</td>
<td>Cannon ball model</td>
</tr>
<tr>
<td></td>
<td>Solar and Earth radiation pressure</td>
<td>Box-model</td>
</tr>
<tr>
<td></td>
<td>Third body gravity</td>
<td>Sun–Moon</td>
</tr>
<tr>
<td></td>
<td>(Actual orbit data replaces the dynamic models)</td>
<td></td>
</tr>
<tr>
<td>Measurement error</td>
<td>Oscillator noise</td>
<td>Allan variance $2 \times 10^{-13}$ for 100 s</td>
</tr>
<tr>
<td></td>
<td>Time-tag error</td>
<td>$200 \text{ps relative variation (}1\sigma)$</td>
</tr>
<tr>
<td></td>
<td>System noise</td>
<td>$C/N_0 = 69 \text{dBHz at 220 km}$</td>
</tr>
<tr>
<td></td>
<td>Multipath error</td>
<td>$3 \mu m/\text{mrad attitude variation}$</td>
</tr>
<tr>
<td></td>
<td>AM/PM error</td>
<td>$0.01 \text{cyc/rev}$</td>
</tr>
<tr>
<td></td>
<td>Attitude control error</td>
<td>$0.5 \text{mrad (yaw, pitch)}$</td>
</tr>
<tr>
<td></td>
<td>Attitude knowledge error</td>
<td>$0.05 \text{mrad}$</td>
</tr>
<tr>
<td></td>
<td>Thermal variation</td>
<td>Sum of harmonics or input time-series</td>
</tr>
</tbody>
</table>

Fig. 3. Simulated range error time series.

Fig. 4. Simulated range error PSD-dual vs. single ranging.

Fig. 3 shows the range error time series of the simulated data, difference between truth and noisy simulated data. Since the measurement bias, including the integer ambiguities, can be corrected during the estimation process, the bias level is not important. The standard deviation of the error is $< 5 \mu m$. Fig. 4 shows the power spectral density (PSD) of the range error. The range error PSD with a single instrument is also presented for comparison. It is clear that the DOWR effectively removes the phase noise, especially in low and mid frequency. The high frequency noise level, which is mainly due to the system noise, is about $1 \mu m/\sqrt{\text{Hz}}$. Range-rate and range-acceleration can be obtained by applying differentiation filter to the range measurements. In case of the GRACE, a N self-convolutions of a rectangular time-domain window function, called CRN digital filter, is implemented to filter 0.1 s dual one-way range into 5 s range, range rate, and range acceleration [4].

Unlike the simulated data, the truth data is not available for the flight data and the measurement itself (instead of noise level) should be compared for evaluation. Since the measurement is highly dependent of the satellite orbits, direct comparison between the flight and simulated measurements are not possible. In order
to resolve this problem, the simulator was modified to use the actual flight data as well as the simulated orbit. Fig. 5 illustrates the hybrid DOWR simulation procedure developed for the flight data comparison. In case of using the actual orbit, the dynamic models used for generating the simulated orbit is not used.

The precision orbit determination is performed using the onboard GPS measurements and the orbit estimates are provided as a L1B product. Since GPS does not detect high frequency orbit variation and the orbit accuracy is usually centimeter level [18,19], the orbit estimates have low and mid frequency gravity signals only. The orbit estimates are feed into the DOWR simulator to generate the hybrid one-way phase whose low and mid frequency, e.g. below 0.01Hz, is the same as the flight measurements. Without matching the low frequency PSD, even the high frequency PSD is distorted and unable to compare. Although the high frequency gravity signal is still different from the flight data, the noise component is dominant at the high frequency and it is possible to compare the measurement signal level. If the actual orbit data is not used, the PSD difference between the simulation and flight data at the low frequency affects the high frequency PSD, and the PSD comparison is not possible.

4. Measurement comparison in spectral domain

GRACE L1A data contains the raw measurements from the instruments, including the one-way phase measurements. The data sampling time of the L1A phase is 0.1 s. The one-way phases are combined into a dual one-way phase, and then it is converted to a dual one-way range by multiplying the wavelength. L1B data contains the dual one-way range and corrections. The data sampling time of the L1B range data is 5s. A low-pass filter is implemented to filter 0.1 s range data to 5s range, range-rate, and range-acceleration data. Since L1A data is not available for public, the data of selected dates, which were received from the University of Texas at Austin, were used for the analysis.

Fig. 6 shows the inter-satellite range variation on August 2, 2005. The separation distance is about 184km and the range variation is 2km. Orbit adjustment for changing the separation distance is not performed frequently, and the orbit condition varies for the mission period and affects the PSD variation. It is why the orbit condition should be considered for the signal comparison.

Because the simulation conditions are not exactly the same as the flight condition, the flight and simulated data are compared in spectral domain instead of time domain. The PSD of the flight data is compared with the PSD of simulated data that represents the design specifications. Fig. 7 compares the one-way phase PSD of the flight and simulated measurements. Data of August 2, 2005 is compared. The largest peak at 0.00018Hz corresponds to the orbit period of 5500s or 1 cyc/rev. The second peak at 0.00036Hz corresponds to twice-per-revolution, which is due to orbit eccentricity. These peak levels vary with time since the satellite orbit formation is changing. Since the flight data was used for the satellite orbit of the simulation, the two measurements show an identical PSD in the low frequency. Even at the high frequency above 1Hz, the two PSD levels are almost same except some peaks in the flight data. These
peaks level is different for other dates. One candidate for the causes of the peaks is the multipath error due to attitude variation. The analysis of other dates showed the same level of agreement (not shown in this paper). These results support that the one-way phase noise level is close to the design (simulated) noise level.

The flight and simulated dual one-way ranges are compared in Fig. 8. The size of the peaks at once and twice per revolution of the flight data is close to those of the simulated data. The flight data PSD level at the high frequency above 0.001 Hz is higher than the simulated data PSD level. The high frequency PSD discrepancy is partly due to a low-pass filter loss. The 5s flight data is obtained from 0.1s data by applying a low-pass filter and there are some signal distortion due to aliasing. However, the simulated data is obtained from 5s data directly and it is equivalent to using a perfect low-pass filter. Another discrepancy may come from unmodeled noise components that are not canceled during the dual one-way combination process. More aggressive low-pass filter can be helpful to improve the gravity estimation [13,14]. Selection of the low-pass filter may affect the PSD shape and signal loss at the high frequency, and Kalman filter is one of candidates for the range-rate and range-acceleration computation. Since evaluating the new filter performance requires comprehensive gravity estimation and evaluation process, the refinement of the low-pass filter can be a future research topic.

The high frequency noise is more significant in the range-rate PSD of Fig. 9. The differentiation process in generating the range rate magnifies the high frequency noise. Since the range-rate is the major data type for the GRACE gravity estimation, this high frequency noise can explain the gravity accuracy discrepancy from the baseline accuracy.

5. Double differenced measurements comparison

Dunn et al. used the following double differenced one-way phases to evaluate the GRACE KBR noise level [16]:

\[
DD = \left[ \phi_B^B(t)_K - \frac{3}{4} \phi_A^B(t)_K a \right] - \left[ \phi_B^A(t)_K - \frac{3}{4} \phi_A^B(t)_K a \right] 
\]  

Since the ratio between the K (26GHz) and the Ka (32GHz) is exactly \( \frac{3}{4} \), this combination of the four one-way measurements removes the gravity signal component and reflects part of noise components, mainly ionosphere difference between the two satellites. Detailed derivation of the equation is not covered in this paper. Although this DD value does not fully reflect the DOWR noise level, it is closely related to the noise level. The simulated DD time series were generated from the simulated one-way measurements with actual orbit data.
GRACE satellite carries a geodetic-grade GPS Blackbox receiver built by the Jet Propulsion Laboratory (JPL). It is capable of receiving codeless dual-frequency P-code range and carrier phase data. The GRACE onboard clock is free running with limited number of clock steering. The onboard clock error is estimated by the GPS measurements. The onboard GPS receiver and the KBR system are both driven by the same Ultra Stable Oscillator (USO) so that the effect of the oscillator noise is common on both phase measurements. Given this fact, the following phase-rate difference equation is derived by modifying Bertiger’s equation [17]:

\[
\dot{\phi}_B^A(t) - \dot{\phi}_A^B(t) = D_1 - D_2 - D_3 + D_4 + D_5
\]  

where

\[
D_1 = (1 - \dot{t}/2)(f_A + f_B)(\Delta t_A(t) - \Delta t_B(t))
\]

\[
D_2 = (1 - \dot{t}/2)(f_A - f_B)(\Delta t_A(t) + \Delta t_B(t))
\]

\[
D_3 = (f_B \dot{t}_A^B - f_A \dot{t}_A^B)
\]

\[
D_4 = 2(f_A - f_B)
\]

\[
D_5 = (f_A \Delta t_A \dot{t}_B^A - f_B \Delta t_B \dot{t}_A^B)
\]

The left side is obtained from the KBR one-way phase measurements, and the right side is obtained from the clock offset estimates, \(\Delta t_i(t)\), and the time-of-flights, \(\dot{t}_i^j(t)\). \(f_A\) and \(f_B\) are the two satellites’ carrier frequencies. The time-of-flights are computed from the orbit estimates. \(D_1\) term represents the clock offset rate difference while \(D_2\) does the summation of the clock rate offsets. If the clock offsets drift with a large difference, \(D_1\) becomes significant. \(D_3\) term is related with the time-of-flights and determined by the orbit characteristics. The authors refined Bertiger’s equation by including the \(D_3\) term which represents a high frequency time-tag error.

If all the KBR error sources are properly modeled and the clock and orbit estimates by the GPS data are accurate, the left and right sides of (5) should be identical and the difference between the two values should be close to zero:

\[
P_{KBR} - P_{GPS} = [\dot{\phi}_B^A(t) - \dot{\phi}_A^B(t)] \\
- [D_1 - D_2 - D_3 + D_4 + D_5] \\
\approx 0
\]

For orbit maintenance and scientific purposes, each GRACE satellite carries a geodetic-grade GPS Blackbox receiver built by the Jet Propulsion Laboratory (JPL). It is capable of receiving codeless dual-frequency P-code range and carrier phase data. The GRACE onboard clock is free running with limited number of clock steering. The onboard clock error is estimated by the GPS measurements. The onboard GPS receiver and the KBR system are both driven by the same Ultra Stable Oscillator (USO) so that the effect of the oscillator noise is common on both phase measurements. Given this fact, the following phase-rate difference equation is derived by modifying Bertiger’s equation [17]:

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\]  

where

\[
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\]

\[
D_2 = (1 - \dot{t}/2)(f_A - f_B)(\Delta t_A(t) + \Delta t_B(t))
\]

\[
D_3 = (f_B \dot{t}_A^B - f_A \dot{t}_A^B)
\]

\[
D_4 = 2(f_A - f_B)
\]

\[
D_5 = (f_A \Delta t_A \dot{t}_B^A - f_B \Delta t_B \dot{t}_A^B)
\]

The left side is obtained from the KBR one-way phase measurements, and the right side is obtained from the clock offset estimates, \(\Delta t_i(t)\), and the time-of-flights, \(\dot{t}_i^j(t)\). \(f_A\) and \(f_B\) are the two satellites’ carrier frequencies. The time-of-flights are computed from the orbit estimates. \(D_1\) term represents the clock offset rate difference while \(D_2\) does the summation of the clock rate offsets. If the clock offsets drift with a large difference, \(D_1\) becomes significant. \(D_3\) term is related with the time-of-flights and determined by the orbit characteristics. The authors refined Bertiger’s equation by including the \(D_3\) term which represents a high frequency time-tag error.

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\[
P_{KBR} - P_{GPS} = [\dot{\phi}_B^A(t) - \dot{\phi}_A^B(t)] \\
- [D_1 - D_2 - D_3 + D_4 + D_5] \\
\approx 0
\]

Bertiger used his equation to evaluate the onboard clock estimation accuracy, but it can be used to evaluate the KBR performance as well. In order to validate this formulation, the simulated measurements, both clock errors and phase measurements, are applied. The size of Eq. (7) computed with the simulated value is close to zero.
to zero. That is, the formulation is validated as long as all the KBR error sources are properly modeled.

JPL provides GRACE precise clock estimates as a part of the GRACE Level 1B data. To determine the spacecraft position, a detailed set of force models is used to propagate the spacecraft position in time along with a set of stochastic accelerations to account for errors in the force models. Adjusted parameters include the initial spacecraft state, stochastic accelerations and a white-noise error in the clock every five minutes [20–22]. GPS-based orbits and clocks are fixed to JPL’s FLINN estimates, which are used for IGS solutions, for the GPS constellation. The orbits are typically determined at the 5cm level. The GPS clocks are determined relative to a ground reference clock chosen from the IGS network. Details on the estimation process are found in Refs. [20,22].

The onboard clock offsets estimated by JPL on October 1, 2004 are shown in Fig. 12. In order to avoid a large discrepancy due to the clock offset, the onboard controller frequently steers the clock toward a true time using real-time GPS clock solutions.

When the actual clock estimates and KBR phases were applied to the formulation, small difference was found as much as 0.004cyc/s. This level of difference is also reported by Bertiger. Although the inclusion of $D_5$ term in Eq. (6) helps the high frequency clock error, the difference level is nearly the same. There are several possibilities on the cause of the difference:

1. Incompleteness in the formulation.
2. Error in the JPL’s clock estimates.
3. Un-modeled error sources in the KBR.

The agreement with the simulation measurements reduces the first possibility as long as the measurement precision is better than the considered accuracy. In order to validate the second possibility, another independent clock estimate was tested. In the framework of GRACE gravity field generation, GeoForschungsZentrum Potsdam (GFZ) produces routinely GRACE orbit and clock solutions (which are not provided to the user community) using also un-differenced GPS data [23]. Since both JPL and GFZ clock estimates came from the same GPS measurements, the two estimates are inherently correlated. However, different data processing strategy provides certain level of independence on the clock estimation error.

Fig. 13 shows the clock estimate difference between GFZ and JPL. Since the clock offset contains the relativistic effect due to the satellite motion, it should be compensated either in the clock estimates or in the gravity and orbit estimates. JPL clock estimate includes the relativistic effects while GFZ does not [17,22,24]. Therefore, the two clock estimates shows a large difference. This research used GFZ’s clock solution without applying the relativistic effect in order to find out if the KBR-GPS discrepancy still exists under such a large difference.

Fig. 14 shows the phase-rate difference of Eq. (7) using JPL’s and GFZ’s clock estimates. The simulation results are also shown in the figure. Both JPL’s and GFZ’s clock estimates yield the similar level of the difference; $-0.0040$ cyc/s with JPL and $-0.0036$ cyc/s with GFZ while the simulation results show near zero difference.

Other days’ data were processed as well and the discrepancies are listed in Table 2. Within 0.001 cyc/s variation, both the JPL and GFZ clock estimates show the same level of difference. These results partly support the existence of un-modeled KBR error sources. If the difference is caused by the un-modeled KBR error sources, it may be a linear drift error on the KBR phase measurements since the bias in the phase rate is equivalent to a drift in the phase (integration of the phase rate).
Fig. 14. KBR-GPS phase-rate difference with onboard clock estimates.

Table 2  
Phase-rate difference with JPL and GFZ clock estimates (cyc/s).

<table>
<thead>
<tr>
<th>Date</th>
<th>JPL clock</th>
<th>GFZ clock</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003.11.28</td>
<td>-0.0045</td>
<td>N/A</td>
</tr>
<tr>
<td>2004.10.01</td>
<td>-0.0040</td>
<td>-0.0036</td>
</tr>
<tr>
<td>2004.10.10</td>
<td>-0.0033</td>
<td>-0.0023</td>
</tr>
<tr>
<td>2004.10.20</td>
<td>-0.0035</td>
<td>-0.0033</td>
</tr>
</tbody>
</table>

The GRACE gravity estimation process mainly uses the range-rate measurements instead of the range measurements since the range-rate contains more high frequency gravity signals. The phase rate difference can be treated as a bias in the range-rate measurements. Since the range-rate bias and drift are adjusted during the gravity estimation process, the effect of the phase rate difference may not be significant on the gravity estimation. However, the characteristic of the un-modeled error should be further analyzed in order to improve the DOWR model for future inter-satellite ranging missions.

7. Conclusions

The concept of the DOWR system is described and the flight performance of the GRACE DOWR is evaluated using a pre-launch simulation model. Three types of experiments were performed. First is the comparison of the flight data with the simulated data in spectral domain. Second is the comparison of double differenced noise level. Third is the comparison with GPS clock estimates. The analysis shows a good agreement with the simulation model except some excessive high frequency noise, e.g. $10^{-4}$ m/$\sqrt{\text{Hz}}$ at 0.1 Hz. The high frequency noise can be used to explain the gravity accuracy degradation from the baseline accuracy. Improvement of the DOWR low pass filter may be helpful to reduce the noise. Reprocessing of the raw data with the improved filter may increase the gravity accuracy. Certain level of discrepancy was found when comparing the phase rate with the clock estimates by GPS, approximately 0.003 cyc/s. This discrepancy can be an un-modeled linear drift in the phase measurements, but it can be adjusted during gravity estimation process. In depth analysis of this drift can be a future research to refine the DOWR simulation model.

This research focuses on demonstrating the methodologies for evaluating the DOWR flight performance, and the time-dependent phenomena of the GRACE KBR are remained for further study. For example, the atmospheric density and ionosphere perturbation during geomagnetic storm may affect the KBR performance. Annual or seasonal variation of the KBR performance can be a further research. These analysis results can be used to update the simulation models and algorithm, which can be benefit to future DOWR instrument development. Although any DOWR missions are not planned yet, the DOWR can be a good candidate for inter-satellite ranging of forming flying missions (not only for gravity mapping) since high ranging accuracy can be obtained with relatively low cost. The DOWR can be applied for the gravity mapping of the Moon or Mars.

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