Long Term Analysis of Precise Orbit Determination for the GRACE and CHAMP missions

Y. Yoon
## Document Change Record

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Acronyms and Abbreviations

JPL  Jet Propulsion Laboratory
GFZ  GeoForschungZentrum
GPS  Global Positioning Systems
POD  Precise Orbit Determination
RSO  Rapid Science Orbit
SLR  Satellite Laser Ranging
Scope

This document presents the results from the precise orbit determination processing for the GRACE and CHAMP missions since January 01, 2006. The post-processed GPS-based orbits described here primarily target the long term (1 year) analysis of the science level quality orbits. The CHAMP rapid quality orbits are also estimated but the results will not be part of the discussion. This analysis will include discussions of the effects on the estimated orbits and measurement residuals due to the activation of the occultation antenna and the transition to the new reference frame, ITRF05.

The assessment of the GPS-based orbit quality includes the orbit overlap, comparison with an external orbit product (JPL) and using the SLR range measurements. For the CHAMP mission, the orbit verification also includes orbit comparison with the Rapid Science orbit (RSO) products from GFZ.

Precise orbit determination (POD) for the GRACE and CHAMP are performed using the 21/07/2007 version of the GPS High Precision Orbit Determination Software Tool (GHOST) package. A mathematical description of the fundamental models used in the software can be found in [1][2].
1. Introduction

1.1 CHAMP

A routine post-processing of the CHAMP GPS measurements was first initiated in late 2005 on the Flight Dynamics Systems. The generation of the rapid orbits is realized in less than 2 days after the reception of the BlackJack GPS data and the ultra-rapid GPS orbit and clock products from the IGS. The rapid orbits are generated twice a day, each with 18-hour orbital arc. These arcs are fixated according to the following:

- 05:00:00 - 23:00:00
- 17:00:00 - 11:00:00 (next day)

With this, there is always a 6-hour overlap between 2 consecutive arcs. It may happen that the predicted part of the ultra-rapid GPS products is used in the generation of the rapid orbit for CHAMP.

The science level orbits, which has slightly better quality, is generated when the CODE rapid GPS orbit and clock products become available. These orbits are always generated using a 30-hour orbital arc. This also allows an overlap period of 6 hours between consecutive orbits.

The presentation of the CHAMP results in this document only focuses on the science quality orbits. External orbit comparison are performed relative to JPL quick-look and GFZ Rapid Science orbit (RSO) products. The SLR range bias analysis is inclusive of JPL and GFZ orbit assessment.

1.2 GRACE

The post-processing of GRACE involves the reconstruction of the orbits at the science quality level. A 30-hour orbit arc is generated everyday for both GRACE 1 and 2 independently. The GPS RINEX, the attitude quaternion and the GRACE precise ephemerides are provided by JPL. Any missing days are patched by the GRACE L1B products obtained from the PO-DAAC web access. The CODE rapid GPS orbits and high-rate clocks are used in the processing.

For quality assessment, the post-processed orbits are compared to those of JPL. In addition, the absolute orbit accuracy assessment through the use of SLR ranging measurements is presented for both the DLR and JPL reconstructed orbits.
2. Orbit Assessment – GRACE

2.1 GPS Measurement Residuals

The ionosphere-free pseudorange and carrier phase measurement residuals for GRACE for the year 2006 are shown in Fig. 1 and 2 respectively. The daily RMS of the pseudorange for GRACE 2 gives a median of 39.5 cm and the RMS stayed below 41 cm throughout the entire year. The switch from the ITRF2000 to ITRF2005 reference frame on November 5, 2006 has no effects on the pseudorange residuals. The handling of the GPS antenna center offset values for each PRNs is in accordance with the recommendation described within the CODE rapid GPS products after November 5, 2006. No GPS antenna phase center variation with elevation is considered in the orbit estimation.

![Figure 1](image.png)

Figure 1 Time series of GPS ionosphere free pseudorange residuals for Grace

The pseudorange residuals for GRACE 1 differ slightly whenever the occultation antenna is activated. The jumps are noticeable in Figure 1, an indication of interference of the active occultation antenna on the pseudorange noise.
The scatter of the carrier phase residuals shows a consistent variation below 1.4 cm before the switch to the new reference frame. The measurement fit seemed to improve after the reference frame switch on November 5, 2006. The residuals are reduced by 2 mm on the average. Both GRACE 1 and 2 have a median daily residual RMS of 9 mm. The scatter for GRACE 1 is not shown as the orbits are of similar quality.

### 2.2 Orbit Overlap

An internal orbit assessment is also performed to evaluate the stability of the filter in estimating a consistent set of orbit solutions based on a pre-determined set of parameter estimates.
Figure 3 Time series of daily 3D orbit overlap statistics for Grace

Figure 3 displays the distribution of the overlap statistics. The median of the overlap agreement between consecutive arcs is shown to be 8.3 mm and 1.15 cm for GRACE 1 and 2 respectively.

2.3 External Orbit Comparison with JPL

In the GRACE L1B level product distribution, the GRACE precise ephemerides are also provided and are computed by JPL. Figures 5 and 6 illustrate the time series variation of the orbit fit with JPL precise ephemeris product. The orbit fit on DOY 214 somehow shows significant degradation in the along-track component for both spacecraft. There is not enough indication, at least in this analysis, to conclude which orbit causes the anomaly. The same goes to DOY 336 and 337. The overlap statistics between these two days in Fig. 3 did not reveal a poor fit. The median of the 3D orbit agreement between the two products is less than 4 cm for both GRACE 1 and 2. The largest orbit difference shows in the along-track component.

Figure 5 Grace 2 orbit variation with JPL orbit solutions
2.4 SLR Range Residuals

The GRACE orbit solutions are also assessed using an independent and unbiased SLR tracking systems. This verification offers an absolute accuracy of the reconstructed GRACE trajectory. If only the high elevation SLR measurements are considered, an estimate of the radial orbit accuracy can be deduced. The unmodeled orbit errors in the cross- and along-track components may partially show themselves if lower elevation SLR passes are taken into account.

The following ground stations are not included in the SLR range residuals statistics due to the measurement collection sparseness over the year and lack the normal distribution trend (thus considered as unreliable):

- Beijing
- Maidanak-1
- Katsively
- Riyadh
- Simeiz

Based on the annual station-wise statistics (see Appendix A), the SLR range residuals editing level is set to 20 cm. A compilation of the mean and RMS values for each station is tabulated in Table 1.
Table 1 Annual station-wise SLR range statistics for Grace 2 excluding the aforementioned SLR stations for all elevation angles.

<table>
<thead>
<tr>
<th>Ground station</th>
<th>Mean (cm)</th>
<th>RMS (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boroweic</td>
<td>-1.20</td>
<td>4.0</td>
</tr>
<tr>
<td>Chang Chun</td>
<td>0.97</td>
<td>5.3</td>
</tr>
<tr>
<td>Graz</td>
<td>-1.10</td>
<td>2.1</td>
</tr>
<tr>
<td>Greenbelt</td>
<td>-0.98</td>
<td>1.7</td>
</tr>
<tr>
<td>Herstmonceux</td>
<td>-1.55</td>
<td>2.4</td>
</tr>
<tr>
<td>Matera</td>
<td>-2.16</td>
<td>2.8</td>
</tr>
<tr>
<td>Postdam</td>
<td>-0.32</td>
<td>2.3</td>
</tr>
<tr>
<td>Riga</td>
<td>0.00</td>
<td>4.4</td>
</tr>
<tr>
<td>San Fernando</td>
<td>2.10</td>
<td>2.8</td>
</tr>
<tr>
<td>Simosato</td>
<td>0.92</td>
<td>2.7</td>
</tr>
<tr>
<td>Tahiti</td>
<td>0.92</td>
<td>3.1</td>
</tr>
<tr>
<td>Wettzell</td>
<td>-1.56</td>
<td>2.3</td>
</tr>
<tr>
<td>Yarragadee</td>
<td>0.19</td>
<td>1.9</td>
</tr>
<tr>
<td>Zimmerwald</td>
<td>-0.64</td>
<td>2.1</td>
</tr>
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</table>

The overall statistics for 2006 are shown in Figures 7 through 10. When including low elevation passes, the orbit agreement has a RMS of approximately 2.3 cm and an average bias of -7 mm for GRACE-1 and 2.2 cm and -5 mm for GRACE-2. For higher elevation passes (above 50°), the GRACE-1 range bias and RMS of the daily range residuals are at -1 cm and 2.0 cm respectively. GRACE-2 shows only slightly better statistics with the daily RMS averaged at 1.9 cm and a bias of -8 mm.

Figure 7 Grace-1 orbit assessment using SLR evaluated at elevation angle above 10°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.
Figure. 8 Grace-1 orbit assessment using SLR evaluated at elevation angle above 50°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.

Figure. 9 Grace-2 orbit assessment using SLR evaluated at elevation angle above 10°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.
Thus, the absolute radial orbit accuracy can be said to be at the 2 cm level for both the GRACE spacecraft. The 3D orbit accuracy can be said to be better than 10 cm on the average.

The same computation is made for the JPL L1B precise orbits and they are illustrated in Figures 11 through 14. With the inclusion of low elevation pass down to 10 degrees, JPL’s orbit agreement with the SLR measurement has a RMS of 2.6 cm and a relatively smaller bias of -4 mm for GRACE-1. The GRACE-2 ephemeris has a computed daily RMS median of 2.5 cm and also a relatively smaller bias of -3 mm.

The absolute radial orbit accuracy (Figures 12 and 14) is at 1.9 cm for both GRACE spacecraft. The orbits have a good fit with the SLR range with relatively small averaged range biases of -4.5 mm and 1 mm for GRACE-1 and GRACE-2 respectively.

Analyzing the two sets of statistics (DLR and JPL), one may conclude that both orbit solutions have the same quality in the radial component. However, the orbits computed at DLR are somehow slightly biased as shown in the plots.
Figure. 11 JPL Grace-1 orbit assessment using SLR evaluated at elevation angle above 10°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.

Figure. 12 JPL Grace-1 orbit assessment using SLR evaluated at elevation angle above 50°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.
Figure. 13 JPL Grace-2 orbit assessment using SLR evaluated at elevation angle above 10°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.

Figure. 14 JPL Grace-2 orbit assessment using SLR evaluated at elevation angle above 50°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.
3. Orbit Assessment - CHAMP

3.1 GPS Measurement Residuals

The ionosphere-free pseudorange and carrier phase measurement residuals for CHAMP for the year 2006 are shown in Figure 15. The daily RMS of the pseudorange gives a median of 63.4 cm and the RMS stayed below 70 cm throughout the entire year. This value is indeed higher than that obtained for the GRACE spacecraft as the data editing criteria for CHAMP is set differently. A drop in the daily RMS between DOY 180 until 220 is unclear. This effect is also observed for the carrier phase residuals. The switch from the ITRF2000 to ITRF2005 reference frame on November 5, 2006 has no effects on the pseudorange residuals. However, this does not hold for the ionosphere-free carrier phase. The handling of the GPS antenna center offset values for each GPS PRNs is in accordance with the recommendation described within the CODE rapid GPS products after November 5, 2006. No GPS antenna phase center variation with elevation is considered in the orbit estimation.

Contrary to the GRACE GPS carrier phase residuals scattering in Figure 2, the reference frame switch and the introduction of the GPS antenna phase center offset causes an increase in the carrier phase residuals for CHAMP.
3.2 Orbit Overlap

An internal orbit assessment is also performed to evaluate the stability of the filter in estimating a consistent set of orbit solutions based on a pre-determined set of parameter estimates.

![Figure 16 Time series variation of the daily 3D overlapping orbit arcs of CHAMP](image)

The overlap analysis is based on a 4-hour overlapping arc between 2 consecutive orbit solutions centered at midnight. The median of the 3D orbit overlap statistics is approximately 7.6 mm and the scatter is consistently below the 2.2 cm mark.

3.3 External Orbit Comparison

A more reliable method to assess the overall consistency and orbit quality is by differencing with orbit solutions generated by other centers whereby a different POD software package is utilized. This so-called external orbit comparison has been performed with reconstructed orbits from JPL and GFZ.

3.3.1 JPL

JPL’s CHAMP quick-look ephemeris is available to the public through the genesis web access [3]. The orbits are distributed in the ECI and JPL format. The latter is in the ECEF coordinates. These orbit files are then converted to the SP3 format for the purpose of this analysis.

The radial orbit agreement shows a median of about 5.2 cm with respect to JPL’s solution. The 3D component has an orbit fit of about 10 cm on the average. No information is available from the website regarding the accuracy of these quick-look orbits. Nonetheless, it is mentioned that this CHAMP orbit product is generated using the JPL GPS quick-look ephemerides.
3.3.2 GFZ

The GFZ RSO products can be obtained at GFZ CHAMP data center through a registered account [4]. The original CHAMP orbit format files are then converted to the SP3 format for orbit analysis. Figure 18 illustrates the statistics of the orbit variation over the year with radial and 3D orbit agreement at 3.4 cm and 9.0 cm respectively. With reference to Figure 17, the orbit fit seems to have a better overall agreement with the GFZ RSO products.

Information on the latest activities of the CHAMP spacecraft is not too transparent, so it is difficult to discern anomalies (if any) in the statistics.
3.4 SLR Range Residuals

The CHAMP orbit solutions are also assessed using an independent and unbiased SLR tracking systems. This verification offers an absolute accuracy of the reconstructed satellite trajectory. If only the high elevation SLR measurements are considered, an estimate of the radial orbit accuracy can be deduced. The unmodeled orbit errors in the cross- and along-track components may partially show themselves if lower elevation SLR passes are taken into account.

The following ground stations are not included in the SLR range residuals statistics due to the measurement collection sparseness over the year and lack the normal distribution trend (thus considered as unreliable):

- Concepcion
- Maidanak-1
- Katsively
- Matera
- Riyadh
- Simeiz
- Tahiti
- Tokyo

Based on the annual station-wise statistics (see Appendix B), the SLR range residuals editing level is set to 20 cm. A compilation of the mean and RMS values for each station used in the analysis is tabulated in Table 2.
### Table 2

Annual station-wise SLR range statistics for CHAMP excluding the aforementioned SLR stations for all elevation angles.

<table>
<thead>
<tr>
<th>Ground station</th>
<th>Mean (cm)</th>
<th>RMS (cm)</th>
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<td>Beijing</td>
<td>4.52</td>
<td>7.08</td>
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<td>Borowiec</td>
<td>-1.75</td>
<td>5.61</td>
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<td>Chang Chun</td>
<td>-1.83</td>
<td>4.54</td>
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<tr>
<td>Graz</td>
<td>-1.88</td>
<td>3.33</td>
</tr>
<tr>
<td>Greenbelt</td>
<td>-2.03</td>
<td>4.29</td>
</tr>
<tr>
<td>Hartebeesthoek</td>
<td>0.23</td>
<td>3.18</td>
</tr>
<tr>
<td>Herstmonceux</td>
<td>-2.07</td>
<td>3.30</td>
</tr>
<tr>
<td>Monument Peak</td>
<td>-0.74</td>
<td>2.90</td>
</tr>
<tr>
<td>Postdam</td>
<td>-0.82</td>
<td>2.85</td>
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<tr>
<td>Riga</td>
<td>1.42</td>
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<td>San Fernando</td>
<td>1.48</td>
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<td>Zimmerwald</td>
<td>-0.85</td>
<td>2.94</td>
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The overall statistics for 2006 are shown in Figures 19 and 20 for elevation masks at 10 degrees and 50 degrees respectively. When including low elevation passes, the orbit agreement has a RMS of approximately 3.3 cm and an average bias of -7 mm. Note that this -7 mm bias is also present for GRACE-1. For higher elevation passes (above 50°), the averaged range bias increases to -1 cm. Nonetheless, the absolute radial orbit accuracy for CHAMP is less than 3 cm in the RMS sense.

![Figure 19](image) **Figure 19** CHAMP orbit assessment using SLR evaluated at elevation angle above 10°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.
Figure 20 CHAMP orbit assessment using SLR evaluated at elevation angle above 50°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.

Figures 21 and 22 shows the SLR range residual statistics based on the JPL quick-look ephemerides. The orbit accuracies at both elevation masks are not as promising but the centering of the orbits are much better with average mean biases of -2 mm and -4.5 mm at elevation masks 10 and 50 degrees respectively.

The orbit assessment of GFZ RSO (Figures 21-22) products shows close agreement with those of JPL quick-look solutions. The centering of the orbit shows smaller range bias compared to DLR but slightly larger than JPL at high elevation.

Based on the SLR analysis for CHAMP and GRACE, it can be concluded that the orbits generated at DLR somehow introduced a consistent (radial) range bias of up to 1 cm on the average.
Figure 21 JPL CHAMP orbit assessment using SLR evaluated at elevation angle above 10°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.

Figure 22 JPL CHAMP orbit assessment using SLR evaluated at elevation angle above 50°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.
Figure 23 GFZ CHAMP orbit assessment using SLR evaluated at elevation angle above 10°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.

Figure 24 GFZ CHAMP orbit assessment using SLR evaluated at elevation angle above 50°: (a) distribution of daily RMS range residuals, (b) distribution of daily mean residuals, and (c) the daily number of SLR observations.
For simplicity, Table 3 summarizes the 2006 statistics of Figures 19-24 for each center and for different elevation masks.

<table>
<thead>
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<th>Center</th>
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<th>High Elevation Mask</th>
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<td>Mean (cm)</td>
<td>RMS (cm)</td>
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<td>DLR</td>
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<td>3.3</td>
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<td>JPL</td>
<td>-0.20</td>
<td>5.2</td>
</tr>
<tr>
<td>GFZ</td>
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<td>5.1</td>
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4. Conclusion

A long term (1 year) analysis of the precise trajectory estimation for GRACE and CHAMP has been carried out and the quality of the resultant precise orbits are found to be comparable with those of other centers such as JPL and GFZ.

The estimated orbits for both the GRACE spacecraft agree with the GRACE Level 1B orbit products (provided by JPL) at the 4 cm level (3D RMS). The radial component shows an agreement of less than 1.5 cm in the RMS sense. In comparison to the laser ranging at high elevation, the absolute accuracy in the radial component is approximately 2 cm and the absolute 3D accuracy can be said to be better than 8-10 cm RMS. The GRACE Level 1B precise orbits are also found to be of similar quality but the mean SLR range residual bias is less pronounce than DLR estimated orbits.

The overall statistics from CHAMP is less promising than those of GRACE. This can be attributed to the tracking performance of the BlackJack GPS receiver onboard CHAMP, the unknown quality of the publicly available product from JPL PO.DAAC [5] and the less accurate Rapid Science Orbit (RSO) product from GFZ [4]. The orbit agreement with JPL quick-look product demonstrates a 3D RMS fit of 10 cm and a radial fit of 5.2 cm (RMS). With those of GFZ RSO, the 3D and radial agreement are 9 cm and 3.4 cm respectively. Based on the SLR statistics at high elevation, DLR estimated orbit achieved an absolute radial orbit accuracy of 2.5 cm RMS with a mean range bias at -1 cm. Both the JPL and GFZ CHAMP products used in this SLR analysis illustrate a higher RMS of 4.2 cm and 4.1 cm respectively. Despite of this higher scatter, both products show a less biased orbit solution.
References


Appendix A


mean = −0.3 cm
Appendix B
CHAMP Precise Orbit Assessment Using SLR at Hartebeesthoek for 2006

Range residuals (cm)

Elevation (deg)

CHAMP Precise Orbit Assessment Using SLR at Herstmonceux for 2006

Range residuals (cm)

Elevation (deg)
CHAMP Precise Orbit Assessment using SLR at Katsively for 2006

CHAMP Precise Orbit Assessment using SLR at Maidanak-1 for 2006