GRACE: Millimeters and Microns in Orbit

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Biography

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

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Srinivas Bettadpur received his Ph.D. in Aerospace Eng. from The University of Texas at Austin, in 1993. Since that time, he has continued to work at the Center for Space Research, where he is currently employed as a Research Scientist. His work has focused on the use of satellite techniques for global geodesy, including the Earth gravity field models, ocean tides, Earth orientation, and precision orbit determination.

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Charles Dunn received his Ph.D. in Physics from Cornell University in 1990, when joined the GPS systems group at JPL. At JPL he has focused on using GPS to perform and enable precise measurements of the earth. Recently he has served as instrument manager on the GRACE mission.

Bruce Haines received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the Topex/Poseidon and Jason-1 Science Working Teams, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

Gerhard Kruizinga received his Ph.D. in Aerospace Engineering from The University of Texas at Austin in 1997. He joined the Satellite Geodesy and Geodynamics Group at JPL in 1997. He is a member of the Topex/Poseidon and Jason-1 Science Working Teams, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry. Furthermore he is a member of the science team for the Gravity Recovery And Climate Experiment (GRACE) team and a member of the CHAMP Orbit Gravity Sensor Evaluation (OGSE) team.

Da Kuang received his Ph.D. in Aerospace Engineering from the University of Texas at Austin in 1995. He joined JPL's Orbiter and Radio Metric Systems Group in 1996. His work has been focused on analyzing GPS and GPS-like tracking data for precise orbit determination and precise relative positioning.

Sumita Nandi is presently a Senior Member of Technical Staff in the Orbiter and Radiometrics Systems Group at JPL. Her work focuses on radiometrics in support of navigation for Earth and deep space spacecraft. She holds a PhD in physics from Cornell Universityearned in 1991.

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1985. He has been a Member of the Technical Staff at JPL since 1993, mostly working on various applications of GPS, including remote sensing, geodesy, orbit determination, and wide area differential systems.

Michael Watkins is the Manager of the Navigation and Mission Design Section at JPL and is also the Project Scientist of the GRACE mission. He received his Ph.D. in Aerospace Engineering from the University of Texas in 1989. His areas of interest are precision orbit determination, geodesy, and applications to Earth and planetary sciences

Sien-Chong Wu received his Ph.D. degree in Electrical Engineering from the University of Waterloo, Canada. He is currently a Principal Engineer in the Tracking Systems and Applications Section at JPL. He has been involved with the development of various tracking systems for deep-space as well as near-Earth space vehicles, and their applications to precision geodesy. His current interest is in the space applications of GPS technology

Abstract

The Gravity Recovery and Climate Experiment (GRACE) was launched March 17, 2002. The experiment, intended to improve models of the Earth's gravity field, consists of two almost identical spacecraft, separated by approximately 200 km, in a near polar, near co-planar orbits, at about 500 km altitude. Each spacecraft carries four instruments, a GPS receiver, a K/Ka-band ranging system, and star camera (all integrated with a common processor), and a precision accelerometer. The GPS receiver can track up to 14 GPS with dual-frequency data quality comparable to precision geodetic ground receivers. The K/Ka-band ranging system can measure the range (with a bias) to the micron level. The accelerometer has a precision of 1 nm/s^2 and the star tracker measures attitude with a precision of 10 arcsec.

The GPS data are processed to (1) contribute to the recovery of long wavelength gravity field, (2) remove errors due to long term on-board oscillator drift, and (3) align K/Ka-band measurements between the two spacecraft to 0.1 ns. Scale and bias parameters for the accelerometer are determined through a combination of GPS data and modeling. This paper will concentrate on the use of GPS for these timing and calibration functions and will not address the recovery of the gravity field. The timing functions of GPS are, of course, intimately connected with precision orbit determination. Orbit accuracies are better than 2 cm in each coordinate. Validation results are presented, that include GPS residuals, orbit overlaps, the K/Ka-band ranging, and Satellite Laser Ranging. All GPS data processing for orbit and clock parameters is accomplished by a data driven, automated system, designed for constellations of spacecraft carrying GPS receivers.

Introduction

Both the GRACE satellites were launched on board a single ROCKOT launch vehicle on March 17, 2002, from Plesetsk (62.7° N, 40.3° E), Russia. They are in a near polar orbit at about 500 km in altitude separated by about 200 km. Its primary mission is to recover both the static and time varying nature of the earth's mass distribution [*Watkins et al*., 1995; *Watkins et al*., 2000]

Fig. 1 shows the main components of the GRACE mission system. There are two GRACE spacecraft, referred to as GRACEA and GRACEB. Each spacecraft carries a codeless dual–frequency GPS receiver, a K/Ka band ranging instrument (KBR) [*Dunn et al*., 2002], an ultra-stable oscillator (USO), an accelerometer and two star trackers [*Jorgensen et al*., 1997]. The accelerometer is used to remove the non-gravitational effects from the spacecraft positions. K/Ka band measurements aided by GPS measurements of the residual effects are used to determine the gravitational forces due to the earth's mass distribution.

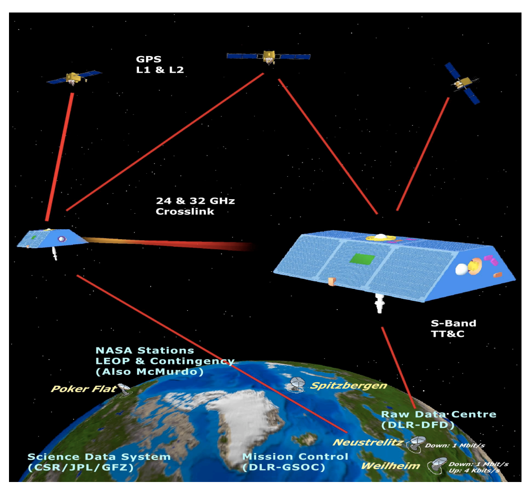

Fig. 1, GRACE System Overview

The GPS receiver and the KBR are both driven by the same USO. The KBR transmits and receives signals at K band (about 24 Ghz) and Ka band (about 32 Ghz). The four measurements of phase 2-frequencies at 2-spacecraft) are combined to measure range up to a bias in such a way that long term (longer than the light time between the two spacecraft) clock errors cancel and first order ionosphere effects are eliminated. The combination that eliminates long-term clock error is referred to as dual-one way range [*MacArthur et al.,* 1985, *Thomas*, 1999] and can be explained briefly as follows; let

$$\phi_A = C_A(t_r) - C_B(t_t) = R + C_A^e(t_r) - C_B^e(t_t)$$

be the measurement of phase at spacecraft A, ϕ_A, which is the difference of the clock(USO) at GRACEA at receive time and the clock at GRACEB at transmit time including any clock errors (and relativistic effects). This clock difference can further be expanded into the actual range, *R*, and a difference of clock error terms represented by the superscript e-terms above. Similarly for the phase measurement at GRACEB:

$$\phi_B = C_B(t_r) - C_A(t_t) = R + C_B^e(t_r) - C_A^e(t_t)$$

Adding these two equations together, we see that if the clock errors were constant over the light time (difference between transmit and receive times) that the errors cancel in the sum.

$$\phi_A + \phi_B = 2R + C_A^e(t_r) - C_A^e(t_t) + C_B^e(t_r) - C_B^e(t_t)$$

In the above argument, we are assuming near simultaneous sampling of the phase at both GRACEA and GRACEB. To achieve this near simultaneous sampling, we use GPS to align time between the two spacecraft to better than 0.1 nano-seconds (ns). Since the USO drives both the GPS receiver and the KBR instrument, precision orbit determination (POD) can be performed to determine the absolute time tag of KBR measurements and the spacecraft position. We will show that the spacecraft position is determined to about 2 cm and that the absolute time is determined relative to a ground reference to about 0.1 ns. Relative time between the two spacecraft should be better than the absolute time due to cancellation of some common mode GPS constellation errors. Tests include KBR range measurements compared to the GPS determined range and satellite laser ranging (SLR) of the GRACE spacecraft.

Precision Orbit Determination, Position and Clock Procedures

Each GRACE spacecraft's GPS data is processed independently using GPS orbits and clocks fixed to FLINN [*Heflin et al*., 2002]. FLINN is JPL's most precise determination of the GPS orbits and clocks. 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. The ground reference clock is always chosen to be some high quality atomic clock with good GPS data for the data arc. The GPS data for GRACE are processed in 30-hour arcs centered on noon of each day to match the FLINN processing arcs. This means each solution has a 6-hour data overlap from 21:00 on the day before to 3:00 on the current day. During these overlapping periods the orbital positions and clock corrections can be compared from the different solution arcs as a first measure of solution precision and accuracy. The solutions are performed with GIPSY-OASIS II software set using automated constellation processing software typically running for weeks at a time without need of human intervention. The GRACE GPS data are dual-frequency carrier phase and pseudorange measurements. The receiver samples the GPS data and returns phase at 1 Hz to the ground and range measurements every 10 seconds. For the POD process, the phase data are sampled every 5 minutes and the range data are carrier smoothed to 5 minute points.

Data

Each GRACE GPS receiver is capable of receiving codeless dual-frequencey P-code range and phase data from up to 14 GPS satellites. Currently the maximum number of GPS observed is set to 10, but will be increased with future versions of the software. The pseudorange data are sampled every 10 seconds and the phase data are recorded at 1-Hz. On the ground, the pseudorange data are carrier smoothed to 5 minutes and the phase data are decimated to 5 minutes. Some improvements can probably be realized if the data are processed at a higher rate. Since we are fixing the GPS clocks and orbits, higher rate processing requires higher rate fixed GPS clock values. Initially these were not available routinely, and thus the 5-minute rate was chosen. Five minute data rates, also allowed for very rapid turn around early in the mission. Processing 30-hours of data, currently takes less than 5 minutes elapsed time on a 2-Ghz Pentium 4 processor running LINUX.

Force Models

In the POD process the accelerometer data were not initially used, so that possible errors from the various instruments could be isolated in the commissioning phase of the GRACE mission. Simulation, covariance analysis, and experience with other spacecraft indicated that GPS could perform the positioning and timing requirements without use of the accelerometer data. In the future, folding in the accelerometer data should improve the results. Instead of the accelerometer, non-gravitational force models include the DTM94 drag model [*Berger et al.,* 1998] , solar radiation pressure, and Earth albedo. All these models account for the shape and surface properties of the GRACE spacecraft. The earth's gravitational force was modeled using TEG4 [*Tapley et al.,*2001]. Again, once the GRACE data are used to improve the knowledge of the Earth's gravitational force, we should realize improvements in the position and clock solutions.

Reduced Dynamic Parameters

Since there are errors in the force models and the GPS data strength is so great, the reduced dynamic technique was used [*Bertiger et al.,* 1994; *Wu et al.,* 1991; *Yunck et al.*, 1990, 1994]. Using the almost continual GPS 3-dimensional geometric information, 3 orthogonal stochastic accelerations are adjusted in the radial, cross-track, and along-track directions as colored process noise with a 15-minute time constant and process noise values of 100, 100, and 50 nano-meters/sec^2.

Orbit and Clock Solution Results

Residuals

The first test of orbit and clock solution quality is the residuals to the fit of the GPS data. Table 1 shows statistics for the dual-frequency phase and range residuals for each spacecraft. The RMS residual is calculated for each 30 hour arc and the average of these RMS values are shown. The variation from these averages is quite small. There are clear differences in the two spacecraft, with GRACEA tracking significantly more GPS than GRACEB. The typical GRACEB pseudorange residual of 22.1 cm versus GRACEA's value of 30.5 cm is probably partly related to the fewer spacecraft tracked and indicates that we may do better on GRACEA by more judicious data editing. Of course, you are always better off with more data to edit and even without the further editing on GRACEA, the tests below would indicate that GRACEA's orbit is better determined (see overlap and SLR tests below).

Table 1 RMS residual statistics for 106 30-hour arcs, May 1 – August 17

	Av. # 5 min. measurements/30 hr arc, range	Av RMS Range Residual (cm)	Av. # 5 min. measurements/30 hr arc, phase	Av RMS Phase Residual (mm)
GRACEA	2597	30.5	2567	64
GRACEB	2378	22.1	2384	63

Orbit/Clock Overlap Tests

A good test of orbit precision and a good indicator of orbital accuracy are the differences in orbit positions during the overlapping data period from one 30-hour arc to the next. The RMS difference in position is computed over central 5 hours of the 6 hour overlapping data period. A half hour on each end, is eliminated to remove edge effects from the statistics. Figures 2 and 3 show histograms of the RMS overlaps for each spacecraft. As usual, since dynamics supply significant constraints in the radial direction, the radial component (direction from the center of the earth to the spacecraft) is the best determined. Along track is roughly in the direction of the velocity vector and cross track completes the local orthogonal coordinate system. The statistics peak around the median values and are not normally distributed. The median RMS overlap values in radial, cross-track and along track directions are 1.2, 1.6, and 1.9 cm respectively for GRACEA and 1.3, 1.7, and 2.1 cm for GRACEB.

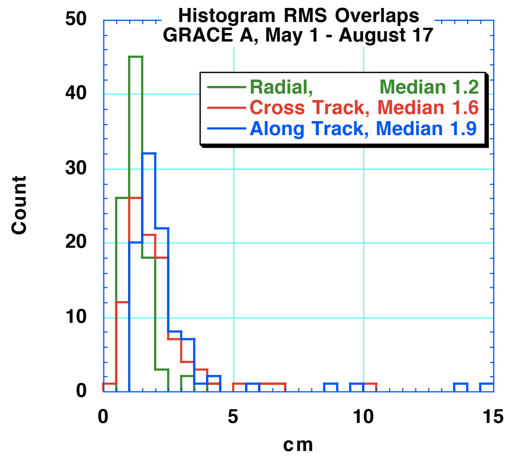

Fig. 2 GRACE A RMS Overlap Statistics, 21:30 to 02:30

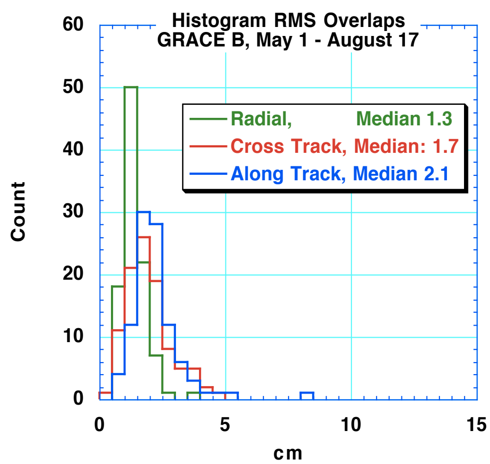

Fig. 3 GRACE B RMS Overlap Statistics, 21:30 to 02:30

Similar to looking at orbit overlaps, we can examine clock overlaps as a measure of precision and approximate accuracy of the relative clock alignment between GRACEA and GRACEB. In Fig. 4, we plot a histogram of overlap difference of the mean clock correction for GRACEA during the 5-hour period minus the mean clock correction for GRACEB during this period. Almost all points are well within the 100-ps relative clock requirement.

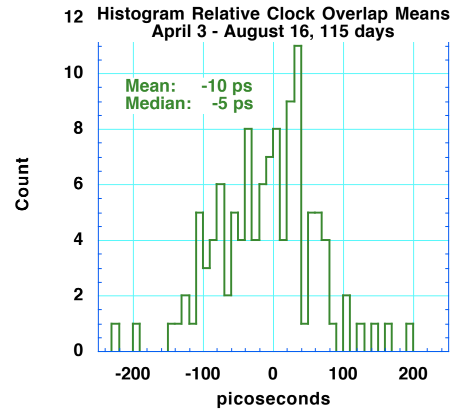

Fig. 4 Relative Clock overlaps

Kband Residual Tests of Orbit Accuracy

Since the dual-one way range measurement (Kband range), measures the biased range between the spacecraft independently of GPS, we can examine the difference between the Kband range and the range determined by the GPS orbit determination process (subtracting 1 bias in a continuous Kband arc). Fig. 5 shows the histogram of these differences from April 4 – August 16, excluding a few days where there are known problems (planned satellite maneuvers for instance). This measure of accuracy should be compared to the along track overlaps. It is somewhat better than the along track overlaps with a median value of 1.8 cm. We should expect a little cancellation of common mode errors due to the GPS constellation in the determination of the GRACEA to GRACEB range.

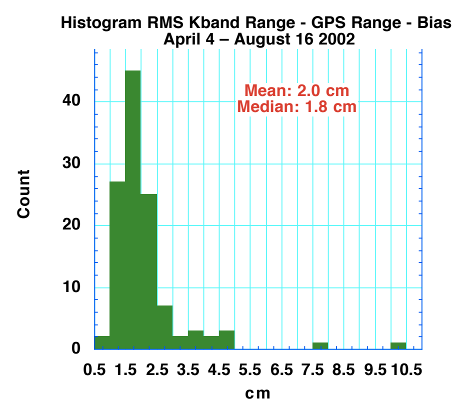

Fig. 5 Dual 1-way range –GPS determined range–bias

SLR Residual Tests

As a final test on orbit accuracy, we examine satellite laser ranging (SLR) measurements differenced with the range determined by the GPS determined orbits and the known laser station locations. In these tests, only a subset of the better performing SLR stations were used. The data were obtained from the quick look CDDIS data repository. No adjustment for timing biases is made. Tables 2 and 3 show the statistics with 0 degree elevation cutoff for 3 months. These statistics sample the orbit error in all components. There is a clear bias in the SLR residuals indicating a possible error in either the SLR reflector location on GRACE or a error in the GPS phase center location on GRACE. Both of these possibilities are under investigation. There are also some points that may be SLR outliers in these statistics. Looking at only high elevation passes, in Tables 4 and 5, we see standard deviations of 2.4 cm on GRACEA and 3.5 cm on GRACEB. GRACEB has significantly less coverage by the SLR stations.

Table 2: GRACEA SLR mean pass statistic 0.0 degree elevation cut over 3 months, April-June

Station	*Mean (cm)*	*Standard Deviation (cm)*	*RMS (cm)*	*Min (cm)*	*Max (cm)*	*# Arcs*
Hartbeesthoek	6.2	2.5	6.7	2.2	9.7	9
McDonald	5.2	1.9	5.5	3.5	7.2	3
Yaragadee	3.6	2.4	4.3	-2.0	8.8	62
Grasse	3.4	2.3	4.1	-1.2	8.2	14
Potsdam	4.0	3.0	4.9	-1.3	8.8	14
Monument	3.6	2.0	4.1	-0.2	8.6	27
Graz	4.4	1.9	4.8	0.9	9.3	25
Goddard	3.2	9.4	9.7	-32.3	10.1	17
Haleakala	3.1	2.5	3.9	-1.0	5.9	8
ALL	3.8	3.6	5.3	-32.3	10.1	179

Table 3: GRACE B SLR mean pass statistic 0.0 degree elevation cut over 3 months, April-June

Station	*Mean (cm)*	*Standard Deviation (cm)*	*RMS (cm)*	*Min (cm)*	*Max (cm)*	*# Arcs*
Hartbeesthoek	4.4	3.3	5.4	0.3	10.8	13
McDonald	3.3	2.2	3.7	1.8	4.9	2
Yaragadee	2.3	7.4	7.7	-48.3	9.0	54
Grasse	3.9	2.5	4.5	-1.0	7.9	9
Potsdam	4.9	2.2	5.3	0.7	6.9	12
Monument	3.1	1.4	3.4	0.4	5.4	22
Graz	4.3	2.0	4.7	-0.4	8.7	18
Goddard	4.2	1.6	4.5	0.8	6.9	13
Haleakala	10.7	12.5	15.3	3.1	29.5	4
ALL	3.5	5.3	6.4	-48.3	29.5	147

Table 4: GRACE A SLR mean pass statistic 40.0 degree elevation cut over 3 months, April-June

Station	Mean (cm)	Standard Deviation (cm)	RMS (cm)	Min (cm)	Max (cm)	# Arcs
Hartbeesthoek	7.2	3.0	7.7	1.9	9.7	6
Yaragadee	6.0	2.4	6.4	2.3	9.4	21
Grasse	5.2	2.4	5.6	3.1	8.6	4
Potsdam	4.8	3.1	5.6	-1.3	8.8	10
Monument	4.6	1.7	4.9	0.2	8.2	18
Graz	4.6	1.5	4.8	2.1	6.7	6
Goddard	6.6	2.7	7.1	2.9	11.8	9
Haleakala	5.6	0.1	5.6	5.5	5.7	2
ALL	5.5	2.4	6.0	-1.3	11.8	76

Table 5: GRACE B SLR mean pass statistic 40.0 degree elevation cut over 3 months, April-June

Station	Mean (cm)	Standard Deviation (cm)	RMS (cm)	Min (cm)	Max (cm)	# Arcs
Hartbeesthoek	6.4	3.1	6.9	3.6	10.8	4
Yaragadee	4.6	5.7	7.1	-14.6	9.0	15
Grasse	6.3	2.4	6.5	4.6	7.9	2
Potsdam	6.0	1.2	6.1	3.9	7.4	11
Monument	4.8	1.4	5.0	3.3	6.3	6
Graz	4.9	2.1	5.2	3.2	7.2	3
Goddard	5.4	2.6	5.9	1.6	7.3	4
Haleakala	8.5	0.0	8.5	8.5	8.5	1
ALL	5.4	3.5	6.4	-14.6	10.8	46

Summary, Conclusions, Future Work

Current relative clock accuracy for GRACE is below the 100 ps mission requirement as supported by the clock overlap statistics with typical values of 5-10 ps. Related accuracy of orbital positions is at the 2-3 cm level and is supported by independent measurements of position accuracy using Kband range and SLR. The median Kband range – the GPS determined range is 1.8 cm and is sampled every 5 seconds over the entire data set. High elevation SLR range – GPS determined range are at the 2.5 cm level for GRACEA and the 3.5 cm level for GRACEB. The SLR data samples are quite sparse over the mission. There are several enhancements possible to the orbit and clock determination process including 1) use of the accelerometer data, 2) use of GRACE tuned gravity fields, 3) simultaneous processing of GRACEA and GRACEB data with integer ambiguity resolution, 4) use of higher rate GPS data, and 5) better data editing procedures.

We look forward to a long and satisfying science mission with the rest of the GRACE project.

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