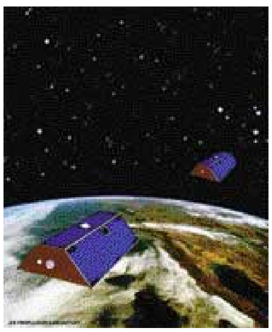
Instrument of Grace

GPS Augments Gravity Measurements

February 1, 2003
By:
Charles Dunn, Willy Bertiger, Yoaz Bar-Sever, Shailen Desai, Bruce Haines, Da Kuang, Garth Franklin, Ian Harris, Gerhard Kruizinga, Tom Meehan, Sumita Nandi, Don Nguyen, Tim Rogstad, J. Brooks Thomas, Jeff Tien, Larry Romans, Michael Watkins, Sien-Chong Wu, Srinivas Bettadpur, Jeongrae Kim
GPS World

E-mail This Page

Pages | 1 | 2 | 3 more



The Gravity Recovery and Climate Experiment (GRACE) mission uses high-precision GPS measurements, micron-level inter-satellite links, precision accelerometers, and accurate star cameras to produce gravity field maps of the Earth that are orders of magnitude more precise than current state-of-the-art. GRACE will also measure temporal variations in the Earth's gravity field over a 5-year period.

If the mission meets all of its goals, the knowledge of the gravitational field will be improved by a factor of well over 100, and changes in the field will be determined on a monthly basis. The improvement in the static (time-independent) gravity field will effectively eliminate the uncertainty in the height of the equipotential reference surface (referred to as the "geoid"), which is the largest error source for existing ocean altimetry missions such as TOPEX/Poseidon and Jason-1.

Beyond the static field, the time-varying gravity measurements have a huge potential to constrain mass motions in the ocean, cryosphere, and hydrosphere that are important to understanding the Earth's climate. Ultimately, the powerful combination of altimetry data over the ocean and ice sheets (for example from ICESat) and the time-varying gravity information from GRACE will have enormous impact on our understanding of climate change on Earth.

This article describes the design and on-orbit performance of the twin satellites' Instrument Processing Unit (IPU) that integrates most of the critical science functions required to perform the gravity science and atmospheric radio occultation tasks. The GPS ground data processing system is one of the key technologies enabling the micron-level inter-satellite link. We'll discuss the requirements and design of the IPU subsystems - GPS, 24/32 GHz-crosslink transceiver, star camera, accelerometer, and ultra-stable oscillator - along with the approach to ground testing, and results with data collected in Earth orbit during the first few months of the mission. Data validation includes GPS residuals, orbit overlaps, the K/Ka-band ranging, and satellite laser ranging.

Mission Design

An international collaboration, GRACE is the first mission launched by NASA's Earth System Science Pathfinder (ESSP) program. The twin satellites began their journey March 17, 2002, from Plesetsk, Russia, eventually entering a near-polar orbit about 500 kilometers in altitude, separated by about 200 kilometers.

Orbiting the Earth, the satellites experience very small accelerations as they pass across contours in the gravity field. Because of their along-track separation, these apply to first one spacecraft and then the other, continuously changing the distance between them.

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 satellites with dual-frequency data quality comparable to precision geodetic ground receivers.

K-band has a radio frequency of about 24 GHz and Ka is near 32 GHz. The GRACE K and Ka band frequencies are in an exact 3-to-4 ratio on each satellite.The K/Ka-band ranging system can measure the range (with a bias) to the micron level. A preview of the power of the calibrated K/Ka-band measurement to recover the Earth's gravity is shown by examining the high frequency content of this signal. An image of the Earth created using these measurements shows many geophysical features. (See magazine cover image.)

The accelerometer has a precision of 0.1 nanometer per second squared (10 to the minus 10th meters/second squared), and the star tracker measures attitude with a precision of 25 arcseconds (0.0075 degrees).

The mission processes GPS data to

- align K/Ka-band measurements between the two spacecraft to 0.1 nanoseconds (ns)
- contribute to the recovery of long-wavelength gravity field, and
- remove errors due to long-term onboard oscillator drift.

The timing functions of GPS are, of course, intimately connected with precision orbit determination (position and velocity as a function of time). Orbit accuracies are better than 2 centimeters in each coordinate. 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.

Ranging. Satellite-to-satellite tracking (SST) for making gravity field measurements has been studied for several decades. In the mid-1990s, the emergence of GPS as a technology capable of precise sub-nanosecond time determination and centimeter-level spacecraft orbit determination enabled a much lower cost approach to SST called dual-one-way-ranging (DOWR). In this approach, each of the two satellites transmits a carrier signal and measures the phase of the carrier generated by the other satellite relative to the signal it is transmitting. The sum of the phases generated is proportional to the range change between the satellites, while the phase variation due to long-term instability in each clock cancels out.

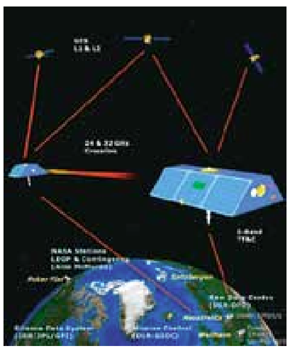


Figure 1: GRACE System Overview. Each spacecraft carries a codeless dual-frequency GPS receiver, a K/Ka band ranging instrument (KBR), an ultra-stable oscillator (USO), an accelerometer and two star trackers.

Figure 1 shows the main system components. The two spacecraft, GRACE A and GRACE B, each carry a codeless dual-frequency GPS receiver, a K/Ka band ranging instrument (KBR), an ultra-stable oscillator (USO), an accelerometer, and two star trackers. 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 determine the gravitational forces due to the earth's mass distribution.

To detect the gravitational field components at the scale of a few hundred kilometers, the range must be measured to an accuracy of a few microns (1026 meters). For the 32 and 24 GHz signals used on GRACE, this is approximately 1024 cycle. A timing error, Dt, results in a phase error, DF, according to the relation DF5fbp3Dt, where fbp is the difference in frequency.

On GRACE, the nominal values of fbp are 502 kHz and 670 kHz. In order to hold the phase error to 1024 cycle, Dt must be smaller than 1024/670 kHz5150 picoseconds (ps).

This time tag alignment could be maintained with stable onboard clocks. However, 150 ps over an orbit would require an Allan deviation better than 2.4310214 at 6,000 seconds, which would be very difficult with present technology. GPS time transfer, using the precise GPS receivers already carried on GRACE, provides an easier solution.

In addition to precise range, a large variety of error sources must be calibrated or controlled in order to make the micron-level range measurements. These include the effects of the ionosphere, atmospheric drag, and satellite attitude. Ground processing must remove confounding factors such as lunar and solar tides and atmospheric mass changes. The ionosphere is removed through a linear combination of the measurements at the two frequencies. The star tracker images processed in the IPU measure the attitude. The accelerometer measures atmospheric drag and other non-gravitational forces.

Pages | 1 | 2 | 3 more

Instrument of Grace

GPS Augments Gravity Measurements

February 1, 2003
By:
Charles Dunn, Willy Bertiger, Yoaz Bar-Sever, Shailen Desai, Bruce Haines, Da Kuang, Garth Franklin, Ian Harris, Gerhard Kruizinga, Tom Meehan, Sumita Nandi, Don Nguyen, Tim Rogstad, J. Brooks Thomas, Jeff Tien, Larry Romans, Michael Watkins, Sien-Chong Wu, Srinivas Bettadpur, Jeongrae Kim
GPS World

E-mail This Page

back Pages | 1 | 2 | 3 more

Timing GRACE

The four measurements of phase (two frequencies at two 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. This DOWR combination that eliminates long-term clock error can be explained briefly as follows; let

$$\phi_A = C_A(t_r) - C_B(t_t) = R + C^e_A(t_r) - C^e_B(t_t)$$

be the measurement of phase at spacecraft A, fA, which is the difference of the clock (USO) at GRACE A at receive time and clock at GRACE B 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 (including relativistic effects) represented by the superscript e-terms above.

Similarly for phase measurement at GRACE B:

$$\phi_B = C_B(t_r) - C_A(t_t) = R + C^e_B(t_r) - C^e_A(t_t)$$

Adding these two equations, 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.

$$\phi_A + \phi_B = 2R + C^e_A(t_r) - C^e_A(t_t) + C^e_B(t_r) - C^e_B(t_t)$$

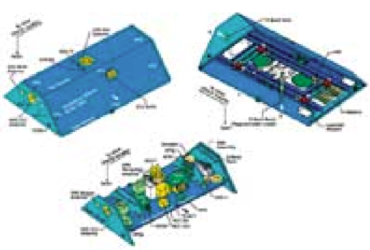


Figure 2: Above, below, and panels open views of GRACE.

In the above argument, we are assuming near-simultaneous sampling of the phase at both GRACE A and GRACE B. To achieve this near-simultaneous sampling, we use GPS to align time between the two spacecraft to better than the required 150 ps. 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 centimeters and that the absolute time is determined relative to a ground reference to about 100 ps. 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 spacecraft.

Satellites and Processing Unit

The GRACE mission developed from the German CHAMP mission, with a JPL BlackJack GPS receiver to do gravity recovery (at a much lower level) and atmospheric occultation measurements. Building the GRACE structure with carbon-fiber reinforced plastic body panels provided the micron-per-degree level of thermal expansion required by the demanding ranging mission. The GPS receiver was already making GPS carrier phase measurements at the millicycle level, so for GRACE, the K-Band ranging instrument was designed with a signal-to-noise ratio to allow 1024 cycle phase measurements. Combined with frequencies having wavelengths near 1 centimeter, the required micron-level range measurements were in reach.

GRACE Spelled Out

ACC	Accelerometer
BUP	Backup GPS antenna
CCD	Charge-coupled device
DI	Differential ionosphere
DOWR	Dual one-way ranging
IPU	Instrument processing unit
IS	Instrument system
KBR	K/Ka band ranging instrument
MWA	Microwave assembly
OBDH	On-board data-handling computer
OCC	Occultation GPS antenna
POD	Precision orbit determination
SCA	Star camera assemblies
SLR	Satellite laser ranging
SPU	Signal processing unit
SST	Satellite-to-satellite tracking
USO	Ultra-stable oscillator

GRACE Spelled Out

For GRACE, the CHAMP GPS receiver design was evolved to allow it to track the carrier phase from the K-Band ranging system and to read out two charge-coupled device (CCD)-based star cameras. CHAMP used commercial off-the-shelf parts. The Grace IPU modified this design to use high-reliability parts wherever possible. Because of extensive use of low-voltage (3.3 V and 2.5 V) digital logic and limited amount of space available, this was not possible in many cases. Because of the high fraction of commercial parts, the GRACE instrument processing unit incorporates full redundancy, with analysis to show no single point of failure to the parts level.

TABLE 1 GRACE instrument performance specs

IPU	CPU	200 MHz PowerPC 603e
	RAM	8M
	EEPROM	8M
	FPGA	36,000 Gates, fixed program
		36,000 Gates, programmable
SPU	GPS	3 dual frequency inputs
	Baseband	redundant dual freq.
	Clock	redundant 38.656 MHz inputs
KBR	Transmit Freq	24.527232 GHz
	GRACE A	32.702976 GHz
	Transmit Freq	24.527336 GHz
	GRACE B	32.703446 GHz
	Tx Power	23 dBm, each freq.
	Antenna	26 dBi K-band 29 dBi Ka-band
USO	Allan Variance	.2 s: 1.5×10^{-11}
		2 s: 2.6×10^{-13}
		10s: 1.9×10^{-13}
		100s: 1.8×10^{-13}
		1000s: 3.2×10^{-13}
SCA	Field of View	18.4° — 13.8°
	Accuracy	10 μr (1 σ) LOS
		120 μr (1 σ) Roll
	Rate	1 Hz
ACC	Sensitivity	10^{-10} m/s^2

Table 1: GRACE instrument performance specs.

Table 1 lists IPU and other component capabilities. The signal processing unit (SPU) down-converts and digitizes the signals received by the three GPS antenna - precise orbit determination (POD), occultation (OCC) and back-up (BUP), and the K-band ranging assembly (KBR). The SPU is clocked by the USO. The USO signal is also used to generate the transmit signal of the KBR.

Within the KBR, this transmit signal is mixed with the signal received from the other satellite, with the resulting quadrature baseband signals presented to the SPU. In order to calibrate the ionosphere between the satellites, a dual-frequency approach is used. The RF frequencies used by the KBR are 32.7 and 24.5 GHz. The difference frequencies between satellites are nominally 670,032 Hz and 502,524 Hz. The only hardware difference between the two satellites is the frequency of the USO crystal, which is offset by 99 Hz in order to achieve the desired baseband frequencies.

The GRACE IPU determines the relative phase of the K and Ka-band signals received from the other satellite compared to the K and Ka band signals produced by the local KBR. In the SPU, the baseband signals from the KBR are one-bit sampled in quadrature at 19 Mega-samples/second, and the resulting digital stream is mixed with a three-level model at this rate using a JPL-designed signal processing application-specific integrated circuit (ASIC).The cross-correlated data stream is then accumulated for 20 milliseconds (ms) and used to drive a second-order phase-locked loop (PLL) implemented in the software. The software implementation of the PLL permits flexibility to accommodate changes in the tracking algorithm. In addition to phase and phase rate, signal to noise ratio (SNR) is also determined and recorded. Because the digital signal processing hardware and CPU host are shared with the GPS function on the IPU, the K-band data can be time-aligned with GPS data with picosecond accuracy.

An important feature is the ability to upload nearly all of the IPU software in dynamically linked libraries. Uploads to date have focused on improving the star camera performance, fixing some K-Band tracking anomalies, and improving the operational reliability of the instrument system.

Figure 3 shows the GRACE IPU in the context of the GRACE instrument system. The IPU and SPU constitute the heart of the instrument system. The IPU and SPU form a system that extracts the observables from the various RF links (GPS and K-band) and the spacecraft attitude from the analog images recorded by the star cameras. The IPU also handles the data interface to the On-Board Data Handling computer (OBDH), which is the primary spacecraft bus computer.

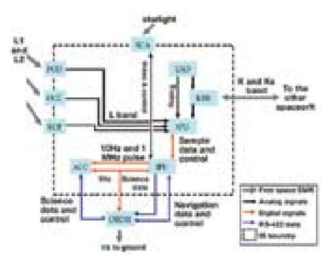


Figure 3: A schematic drawing of the GRACE instrument system. The IPU, SPU, KBR and ACC are internally redundant, and the USO is redundant.

The range measured by the KBR is also affected by the pointing direction of the satellite. In order to remove this error source, the satellite attitude is measured by a pair of star cameras. The star camera assemblies (SCA) consist of a stray light baffle, optics, and a CCD camera. The analog pixel values are sent to the IPU which contains a "frame grabber" that digitizes the pictures.

The attitude data resulting from the SCA is also used by the OBDH for attitude determination and control.

Accelerometer (ACC) data is used to remove the effect of non-gravitational forces from the cross link. To be useful, the data from the ACC must be time tagged relative to the other data types to within 100 microseconds. The IPU generates timing signals for this purpose.

IPU operational tasks include controlling the KBR waveguide switches that select the redundant electronics within the KBR, selecting between the redundant USO clocks, and recording 41 temperatures and voltages for housekeeping purposes. It sends data to be telemetered to the ground to the OBDH and receives commands from the OBDH.

The IPU is capable of receiving codeless dual-frequency 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.

Orbit, Position. and Clock Procedures

Each spacecraft's GPS data is processed independently using GPS orbits and clocks fixed to FLINN, JPL's most precise determination of the GPS orbits and clocks. The orbits are typically determined at the 5-centimeter level. The GPS clocks are determined relative to a ground reference clock chosen from the International GPS Service (IGS) network. The ground reference clock is always chosen to be some high-quality atomic clock with good GPS data for the data arc.

GPS data for GRACE are processed in 30-hour arcs centered on noon of each day, to match the FLINN processing arcs, giving a 6-hour data overlap from 21:00 day prior to 03:00 on current day. During these overlaps, orbital positions and clock corrections can be compared from the different solution arcs as a first measure of solution precision and accuracy. Solutions are performed with GIPSY-OASIS II software set using automated constellation-processing software typically running weeks at a time without human intervention.

Force Models. In the POD process, accelerometer data were not initially used, so that possible errors from various instruments could be isolated in the commissioning phase. Simulation, covariance analysis, and experience with other craft indicated that GPS could perform the positioning and timing requirements without accelerometer data.

In the future, folding in the accelerometer data should improve results. Instead of the accelerometer, non-gravitational force models include drag, 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 one of the best pre-launch models. Once GRACE data are used to improve the knowledge of the Earth's gravitational force, we should realize additional 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. Using the almost continuous GPS 3-dimensional geometric information, three 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/second2.

back Pages | 1 | **2** | 3 more

Instrument of Grace

GPS Augments Gravity Measurements

February 1, 2003
By: Charles Dunn, Willy Bertiger, Yoaz Bar-Sever, Shailen Desai, Bruce Haines, Da Kuang, Garth Franklin, Ian Harris, Gerhard Kruizinga, Tom Meehan, Sumita Nandi, Don Nguyen, Tim Rogstad, J. Brooks Thomas, Jeff Tien, Larry Romans, Michael Watkins, Sien-Chong Wu, Srinivas Bettadpur, Jeongrae Kim
GPS World

E-mail This Page

back Pages | 1 | 2 | 3 more

On-Orbit Experience: Raw Data Performance

The GRACE satellites each have two redundant microwave assemblies (MWAs) within the KBR. All four of these units have been exercised in orbit. The received SNRs with the satellites in science mode have been between 55 and 72 dB-Hz, representing phase precision between 0.6 and 4 microns (micrometers). A good K-band SNR measurement indicates the health of a number of instrument components, including the USOs, the KBR components, and the satellite pointing.

$DI5\ (K_{GR\ A}2\ 3/4Ka_{GR\ A})2\ (K_{GR\ B}2\ 3/4Ka_{GR\ B}).$ Systematic variation of the intersatellite signal phase can result in an erroneous gravity signature and therefore must be assessed. It can be studied by forming some of the K- and Ka-band links into combinations other than the DOWR. In particular, the combination of differential ionosphere (DI) produces a quantity that is free of clock noise from both satellites, intersatellite range, and most of the ionospheric delay between satellites. The remaining signature in DI is due to differential ionospheric delay along the inter-satellite line of sight and phase instabilities on one or more link due to the transmitting system aside from the clock (that is, RF components or the antenna).

Figure 4 shows that DI has a variation of 10 microns with a period of one orbit for many hours. The excursions are correlated with the intersatellite ionosphere, and may be mostly attributable to differential ionosphere. In any case, this indicates a systematic phase variation of 10 microns or better for the individual K- and Ka-band links. For comparison, 10 microns is about the diameter of a human red blood cell.

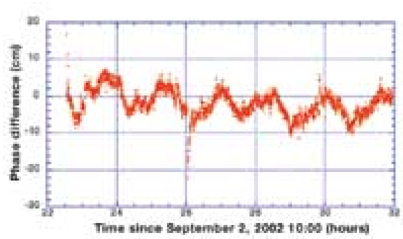


Figure 4: KBR double difference. Data plotted is the difference between satellites of the phase of received 24 GHz signal minus 3/4 of the 32 GHz signal phase. Remaining quantity is free of clock and range variation, but contains differences between phase delay in the two satellites and higher order ionospheric delay.

GPS. Currently each IPU is configured to track a maximum of 10 GPS satellites. The time average number of tracks is 8.03 for GRACE A and 7.69 for GRACE B. The voltage SNR in a one-second integration of the C/A code at the maximum of the antenna pattern is 900 for GRACE A and 850 for GRACE B. The peak codeless SNRs are 650 and 700 for P1 and P2 on GRACE A respectively, and 580 and 780 on GRACE B.

TABLE 2 RMS residual statistics for 106 30-hour arcs, May 1– August 17

	Avg. # 5 min. measurements/30 hr arc, range	Avg RMS Range Residual (cm)	Avg. # 5 min. measurements/30 hr arc, phase	Avg RMS Phase Residual (mm)
GRACE A	2507	30.5	2507	0.4
GRACE B	2338	22.1	2384	0.3

Table 2: RMS residual statistics for 106 30-hour arcs, May 1 - August 17.

Orbit/Clock Results

The first test of orbit and clock solution quality is the residuals to the fit of the GPS data. **Table 2** 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 GRACE A tracking significantly more GPS than GRACE B. The typical GRACE B pseudorange residual of 22.1 centimeters versus GRACE A's value of 30.5 centimeters is probably partly related to the fewer spacecraft tracked and indicates that we may do better on GRACE A by more judicious data editing. Of course, you are always better off with more data to edit, and even without the further editing on GRACE A, other tests indicate that GRACE A's orbit is better determined (see overlap and SLR tests further on).

Orbit/Clock Overlap Tests

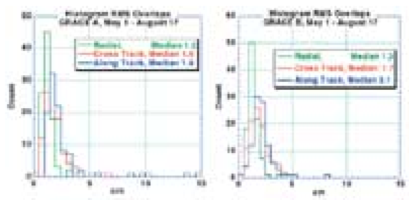


Figure 5: GRACE A RMS overlap statistics, 21:30 - 02:30. Figure 6: GRACE B RMS overlap statistics, 21:30 - 02:30.

The differences in orbit positions during the overlapping data period from one 30-hour arc to the next provide a good test of orbit precision and a good indicator of orbital accuracy. 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 5 and 6** 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 centimeters respectively for GRACE A and 1.3, 1.7, and 2.1 centimeters for GRACE B.

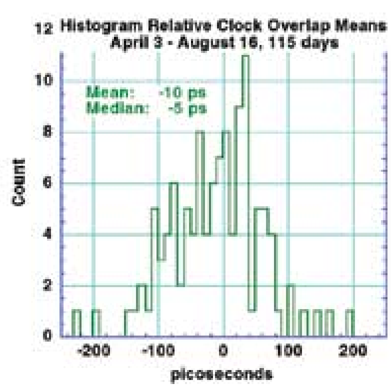
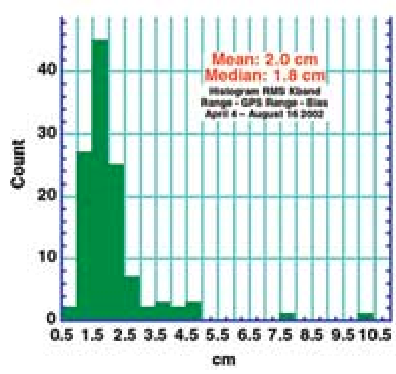


Figure 7: Relative clock overlaps.

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 GRACE A and GRACE B. In **Figure 7**, we plot a histogram of overlap difference of mean clock correction for GRACE A during the 5-hour period minus mean clock correction for GRACE B during this period. Almost all points are well within the 100-ps relative clock requirement.



Since the dual-one way range measurement (K-band range) measures the biased range between the spacecraft independently of GPS, we can examine the difference between the K-band range and the range determined by the GPS orbit determination process (subtracting one bias in a continuous K-band arc). **Figure 8** 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 centimeters. We should expect a little cancellation of common mode errors due to the GPS constellation in the determination of the GRACE A to GRACE B range.

Figure 8: Dual one-way range - GPS determined range-bias.

As a final test on orbit accuracy, we examine SLR measurements differenced with the range determined by the GPS determined orbits and the known laser station locations. These tests used only a subset of the better-performing SLR stations. No adjustment for timing biases is made.

TABLE 3 GRACE A SLR mean pass statistic 0.0 degree elevation cut, April-June

Station	Mean (cm)	Stnd. Dev. (cm)	RMS (cm)	Min (cm)	Max (cm)	No. 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	54
Potsdam	4.0	3.0	4.9	±1.3	8.8	34
Monument	3.6	2.0	4.1	±0.2	8.8	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 4 GRACE B SLR mean pass 0.0elevation

Station	Mean (cm)	Stnd. Dev. (cm)	RMS (cm)	Min (cm)	Max (cm)	No. 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 3: GRACE A SLR mean pass statistic 0.0 degree elevation cut, April-June. Table 4: GRACE B SLR mean pass 0.08 elevation.

Tables 3 and 4 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 an error in the GPS phase center location on GRACE. Both 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 5 and 6**, we see standard deviations of 2.4 centimeters on GRACE A and 3.5 centimeters on GRACE B. GRACE B has significantly less coverage by the SLR stations.

TABLE 5 GRACE A SLR mean pass 40.0elevation

Station	Mean (cm)	Stnd. Dev. (cm)	RMS (cm)	Min (cm)	Max (cm)	No. 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 6 GRACE B SLR mean pass 40.0elevation

Station	Mean (cm)	Stnd. Dev. (cm)	RMS (cm)	Min (cm)	Max (cm)	No. 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

Table 5: GRACE A SLR mean pass 40.08elevation. Table 6: GRACE B SLR mean pass 40.08 elevation.

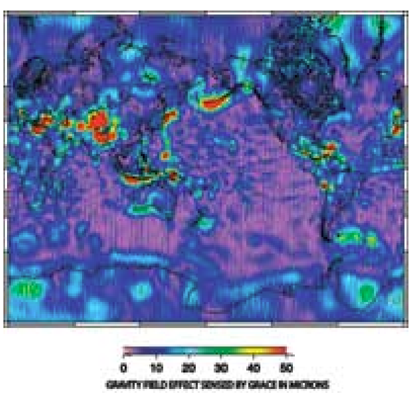


Figure 9: Mass features sensed by GRACE, in microns.

Imaging The Earth

We constructed an image of the Earth in **Figure 9** from the DOWR using six months of data. To do so, a spline fit (piece-wise smooth cubic function) to the DOWR is removed from the DOWR. The fit parameters are chosen to eliminate all the long period information. Figure 9 shows the remaining measurement of range in microns. Note the large signal in the Himalayas. Other features include the continental shelf around Antarctica, Hawaii, and Aleutian Trench off the coast of Alaska. The apparent lack of signal at these high frequencies in locations such as the Rocky Mountains is due to the satellites' polar orbit. The greatest high-frequency sensitivity to the gravity signal is in the north-south direction.

Conclusion

The ability of GPS to determine the clock offset between two orbiting clocks to better than 100 ps enabled a low-cost approach to determining Earth's gravitational field. By exchanging K- and Ka- band carrier signals and adjusting the timetags using GPS, GRACE is achieving a quantum leap in the knowledge of the Earth's gravitational field.

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 centimeter level and is supported by independent measurements of position accuracy using K-band range and SLR. The median K-band range minus the GPS-determined range is 1.8 centimeters and is sampled every 5 seconds over the entire data set. High elevation SLR range minus GPS determined range are at the 2.5 centimeter level for GRACE A and the 3.5 centimeter level for GRACE B. The SLR data samples are quite sparse over the mission.

Initial plots of the high-frequency ranging measurement for instrument check-out reveal many subtle features of the Earth's mass distribution. They provide an indication of the great potential of the GRACE data set to recover the Earth's full gravity field and its time variability.

Acknowledgements

We acknowledge the significant contributions of innumerable colleagues around the world who have made the GRACE project successful, including the principal investigators, Byron Tapley of the University of Texas, Christoph Reigber of GFZ Potsdam, and project manager Ab Davis of the Jet Propulsion Laboratory, California Institute of Technology (JPL). The work we describe was done in part by JPL under contract with the National Aeronautics and Space Administration (NASA).

NASA supplied the twin GRACE satellites and the instrumentation. The Deutsches Zentrum fur Luft- und Raumfahrt (DLR) supplied the launch services and mission operations. JPL manages the project for NASA.

Manufacturers

JPL supplied the satellites and instrumentation, including the *BlackJack* GPS receiver, waveguide feed network, and K-band antenna. **Astrium Space** (Freidrichshafen, Germany) provided the satellite bus, mechanical support for the KBR, and stray light baffles for star cameras. **Space Systems/Loral** (Palo Alto, California) handled KBR electronics. **Sensor Systems** (Chatsworth, California) supplied zenith and backup GPS antennas, with JPL ground planes. **Technical University of Denmark** (Copenhagen, Denmark) provided the star camera heads and IPU processing software to determine attitude from SCA pictures. **Office National d'etudes et de Recherches Aerospatiales (ONERA)** (Chatillon, France) made the SuperStar accelerometer. **Johns Hopkins University Applied Physics Laboratory** (Laurel, Maryland) contributed the ultra-stable oscillator. **Custom Microwave** (Longmont, Colorado) manufactured the K-Band feed network.

back Pages | 1 | 2 | **3** more

Home | Buyer's Guide | Contact Us | Privacy Policy