The Instrument on NASA's GRACE Mission: Augmentation of GPS to Achieve Unprecedented Gravity Field Measurements

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BIOGRAPHY

Charles Dunn received his PhD in Physics from Cornell University in 1990. He went on to join the GPS systems group at JPL, where 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.

Willy Bertiger received his PhD 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.

Garth Franklin received his BS from California Polytechnic University Pomona in 1992. He is an engineer in the GPS Systems Group and Advanced Radiometric Instruments Group at JPL, where he has built high precision GPS receivers for scientific applications and more recently for precise orbit determination of low earth orbiters including Jason, Champ, Sac-C, and Grace.

Ian Harris holds a BSc in Astrophysics and a PhD in Astronautics. He joined JPL from Oxford in 1997 to work on ionospheric remote sensing and other scientific applications of GPS. He was an instrument system engineer on GRACE.

Gerhard Kruizinga received his PhD 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 GRACE and a member of the CHAMP Orbit Gravity Sensor Evaluation (OGSE) Team.

Thomas Meehan was the Task Manager for the GPS-on-a-Chip development effort that directly led to the BlackJack instrument for CHAMP. He is the Cognizant Engineer for the BlackJack receivers on both the CHAMP and SAC-C spacecraft. He was the Co-PI for the GPS/MET instrument on the Micro-Lab spacecraft and the Task Manager for the TurboRogue GPS receiver development. He received his B.S. in Electronic Engineering from Cal Poly San Luis Obispo in 1982.

Sumita Nandi is presently a senior member of the Technical Staff in the Orbiter and Radiometric Systems Group at JPL. Her work focuses on radiometrics in support of navigation for Earth and deep space spacecraft. She holds a Ph.D in physics from Cornell University earned in 1991.

Don Nguyen was the Electronic Packaging Engineer for the Grace IPU. His responsibilities included design, packaging, and manufacturing for Grace flight assembly. He has been working at JPL for 20 years and in the GPS systems group for five years.

Tim Rogstad served as the software cognizant engineer for the IPU on the GRACE mission. He received his M.S. degree in Electrical Engineering from Cal Poly, Pomona in 2000 and has been with the JPL GPS systems group since 1998.

Jeffrey Tien received a BSEE from California Polytechnic University, Pomona in 1990, and a MSEE from University of Southern California in 1993. He joined the GPS systems group at JPL in 1989 where he worked on the hardware design of flight GPS receivers for various space missions including GPSMET, SNOE, Oersted, SRTM, JASON, CHAMP/SAC-C, and GRACE. Recently he served as lead instrument engineer for the Autonomous Formation Flying sensor on the StarLight Mission.

ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) mission is an international collaboration that uses high-precision global positioning system (GPS) measurements, augmented by micron-level inter-satellite links, in combination with a precision accelerometer, to produce gravity field maps of the Earth that are orders of magnitude more precise than current state of the art. GRACE also measures temporal variations in the Earth's gravity field. The mission is an international collaboration between NASA and Deutsches Zentrum für Luftund Raumfahrt eV (DLR). NASA supplied the twin GRACE satellites and the instrumentation. The DLR supplied the launch services and mission operations. JPL manages the Project for NASA, and the Principal Investigator is from the University of Texas at Austin. JPL provided the satellites and instrumentation with principal support from Astrium, Gmbh, Space Systems / Loral, Technical University of Denmark, Office National d'Éstudes et de Recherches Aérospatiales and Johns Hopkins University Applied Physics Laboratory. This paper will describe the design and on-orbit performance of the GRACE Instrument Processing Unit (IPU) that integrates most of the critical science functions required by the GRACE mission to perform its gravity science and atmospheric radio occultation tasks. Requirements and design of the IPU subsystems (GPS, K/Ka-band cross link transceiver, star camera, accelerometer, and ultra-stable oscillator) will be discussed along with the approach to ground testing of the high performance instrument and comparisons with data collected in Earth orbit during the first few months of the mission.

INTRODUCTION

GRACE is the first mission to be launched by NASA's Earth System Science Pathfinder (ESSP) program. The ESSP program is designed to provide valuable information about the Earth at a low cost to the public. The GRACE mission is doing this by using GPS as an enabling technology to sense the gravitational field of the Earth using one-way radio-frequency carrier links between two nearly identical spacecraft. The GRACE project also explored ways of reducing space flight costs without incurring uncontrolled risk.

The purpose of the GRACE mission is to measure the gravitational field of the Earth to an accuracy at least an order of magnitude better than the prior best determination. If the mission meets all of its goals, the knowledge of the gravitational field will be improved by a factor of ~1000 and changes in the field will be determined every 15–30 days. The improvement in the static gravity field will instantaneously remove the largest error source for existing and future altimetry missions such as TOPEX/Poseidon and Jason. Time varying gravity measurements have a huge potential to determine mass motions in the ocean and hydrosphere which are important to the climate of the Earth.

The central component of the GRACE instrument system is the Instrument Processing Unit (IPU), which performs the observable extraction for the cross-link signals, the GPS receiver, and the star cameras. We will discuss the development and operation of the GRACE IPU.

DUAL-ONE-WAY RANGE

When the GRACE mission was proposed in 1996, the concept of determining the Earth's gravity field using satellite-to-satellite tracking (SST) had been discussed for 30 years [Wolff, 1969], but had never resulted in a space mission. In the mid-1990s, the emergence of GPS as a technology capable of precise sub-nanosecond time determination and sub-centimeter spacecraft orbit determination enabled a much lower cost approach to SST called "Dual-One-Way-Ranging" (DOWR) [MacArthur, 1985; Thomas, 1999]. 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 transmitter clock cancels out. To detect the gravitational field components at degree 100, the range must be measured to an accuracy of a few microns. For the 32 and 24 GHz signals used on GRACE, this is ~10^{-4} cycle. Since a timing error, Δt, results in a phase, $\Delta\phi$, error according to the relation $\Delta\phi = f_{bp} * \Delta t$, where f_{bp} is the difference in frequency between the carriers transmitted on each satellite, the time at which the phase of the signal is measured must be determined to better than 100 ps in order to achieve the required accuracy in DOWR.

On GRACE, the nominal values of f_{bp} are 502 kHz and 670 kHz. In order to hold the phase error to 10^{-4} cycle, Δt must be smaller than 10^{-4}/670 kHz = 150 ps.

This time tag alignment could be maintained with stable on-board clocks. However 150 ps over an orbit would require an Allen deviation better than 2.4 x 10^{-14} at 6000 seconds, which would be very difficult with present technology. GPS time transfer, using the precise GPS receivers already carried on GRACE, is an easier solution. Carrier phase-based GPS time transfer near this level was demonstrated in the early 1990s [Dunn, 1992].

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. In addition, ground processing must remove confounding factors such as lunar and solar tides and atmospheric mass changes. For most of these, we refer the reader to the bibliography [Bertiger, 2002; Davis, 1999; Watkins, 1995 & 2000]. However, the ionosphere and satellite attitude are measured by the IPU.

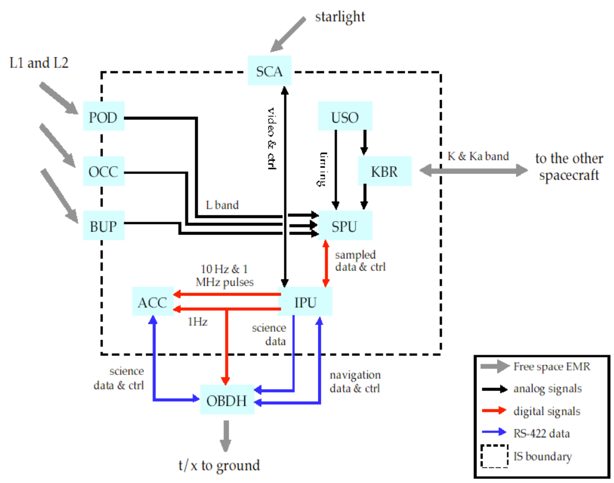

Figure 1. A schematic drawing of the GRACE instrument system. The IPU, SPU, KBR and ACC are internally redundant, and the ultra-stable oscillator (USO) is redundant. See text for definitions.

THE GRACE IPU

Figure 1 shows the GRACE IPU in the context of the GRACE instrument system. The IPU and the signal processing unit (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.

The capabilities of the IPU and other instrument system components are listed in Table 1. The SPU performs the function of down converting and digitizing 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, produced by Johns Hopkins Applied Physics Laboratory. 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 electronics in the KBR were produced by Space Systems/Loral. The waveguide feed network and antenna were produced at JPL, and the mechanical support for the KBR was produced by Astrium, Gmbh.

The GRACE IPU is used to determine the relative phase of the K and Ka-band signals received from the other satellites 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 Ms/s and the resulting digital stream is mixed with a three-level model at this rate using a JPL-designed signal processing ASIC. The cross-correlated data stream is then accumulated for 20 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, if desired. In addition to phase, and phase rate, 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.

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 charge-coupled device (CCD) camera. The analog pixel values are sent to the IPU which contains a “frame grabber” that digitizes the pictures. Danish Technical University fabricated the SCA heads and provided the IPU software which determines the attitude from the SCA pictures. Astrium fabricated the stray light baffles for the star cameras.

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.

In addition to the science tasks described above, the IPU also controls the waveguide switches in the KBR, which select the redundant electronics within the KBR, as well as select between the redundant USO clocks and measure 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.

Table 1. GRACE Instrument System Performance Specification

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. GR-1	24.527232 GHz 32.702976 GHz
	Transmit Freq. GR-2	24.527735 GHz 32.703646 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 80 µr (1 σ) Roll
	Rate	1 Hz
ACC	Sensitivity	10^{-9} m/s^2

DEVELOPMENT APPROACH

In order to reduce costs, the GRACE project sought methods to ensure mission success which were less expensive than traditional JPL flight practices. In each instance, though, a mitigating practice was used to contain risk.

The most significant deviations were in the area of parts and software. GRACE required that the “best possible” parts be used, but allowed unscreened commercial parts where a space-qualified replacement was not available. In order to mitigate the risk incurred by this policy, additional testing was required. To avoid infant mortality, 1000 hours of failure-free operation on each unit was required. To detect manufacturing defects, particle impact noise detection (PIND) testing or powered on vibration testing was required on cavity parts. Within the IPU, many parts were upgraded to space qualified or high reliability parts. However, because 2.5 V and 3.3 V logic is extensively used to control power consumption, many parts had no replacement. The majority of the parts in the IPU are commercial parts. The part failures experienced during development did not indicate lower reliability for the commercial parts.

As a further mitigation of the risk of commercial parts, the GRACE mission sought to limit single point failures, and required failure mode effect and criticality analysis (FMECA) to verify that this was achieved. Within the GRACE instrument system, the accelerometer sensor unit, which must be on the center of mass of each satellite, and the passive K/Ka-band horn are the only potential single-point failures.

An additional cost savings was achieved by conducting a voltage, temperature, frequency margin test (VTFMT) instead of performing a worst-case analysis. Because the IPU is a fairly mature design with a large number of parts, and there is a large existing testing infrastructure at JPL, verifying the integrity of the electronic design through test required significantly less labor than a worst-case analysis.

Traditional flight practices were used to ensure there were no fabrication or assembly errors in custom made portions of the instrument. These included quality assurance inspections and coupon testing of printed wiring boards.

TESTING AND VERIFICATION

Although the GRACE IPU receiver enjoys a successful heritage of over 10 flight BlackJack receivers, the additional features and requirements designed specifically for GRACE demanded an additional suite of verification tests. Early prototype testing included functionality over temperature, star camera noise levels, KBR sampler checks, SST performance in vacuum, and GPS tracking using representative flight hardware. Additionally, verification of the design though analysis was also performed and included single-point failures, thermal modeling, venting, radiation ray tracing, and a parts-stress analysis. Information gained from this was used to shape the final design of the instrument.

In order to qualify the GRACE IPU Instrument for flight, a protoflight testing approach was used for all but the radiation and VTFMT. Previous part level radiation test knowledge was used to select parts for the prototype, which was tested at the subsystem level and exposed a "soft" part type which was subsequently replaced. This same board was later used for the VTFMT test to provide worst case parametric shifts in part specifications. No anomalous behavior was observed.

Once the flight builds were complete, thermal-vac, vibe, and shock tests were performed on the flight hardware in excess of expected flight levels. The vibe-thermal-vac combination proved most valuable when it weeded out a part failure that was systemic across an entire part lot. The whole lot was replaced in all the receivers with a part from a different manufacturer and the qualification test process was started over. An EMI/EMC test and burn in was also performed on each flight unit.

A performance verification table was created based on the GRACE system-level requirements and four tests were created to complete the verification. These formal tests included a 72-hour (performance) test, an overall functionality test, a 24-hour GPS simulator test, and a Table Mountain Observatory test of star camera performance. Any remaining items that could not be verified by test were done though analysis.

ON ORBIT EXPERIENCE—OPERATIONS

The GRACE satellites were launched into a 500-km altitude, 89.0-degree inclination orbit on March 17, 2002. GRACE-1 is leading GRACE-2. The satellites were allowed to separate to 300 km. Since that time, the on-board cold-gas propulsion system has been used to maintain the separation between 270 km and 175 km. Orbit maneuvers have been needed about every 50 days to do this.

Because the IPU is not hardened against single event upsets, the GRACE mission was planned to tolerate outages in IPU data for a short duration. Because the star camera data is used in the attitude control system (AOCS) of the satellites, the upset/reset frequency and the “time to first fix” became important design drivers. The AOCS is also required to coast for some amount of time when the geometry of the Sun, Moon, Earth system is such that the two star cameras are simultaneously blinded by the Sun and the Moon. Currently, the AOCS allows star camera outages of up to 500 seconds—long enough to accommodate both types of outage.

The reset frequency of the IPU was determined in ground testing with simulated inputs to be approximately one per six days and to be dominated by a "memory leak," which causes the software to slowly fill the available free random access memory. On-orbit, GRACE-1 has exhibited a reset rate which corresponds to the ground measurement. However, GRACE-2 has experienced resets at close to a 72-hour period. The reason for the higher rate on GRACE-2 is not currently understood.

The most significant operational problem to date has been the corruption of the parameter storage flash memory which causes the receiver to become un-configured. This is a serious problem because in the current software version, the receiver is then unable to select the correct USO input for operation. In three instances to date, this has caused the satellite to enter "coarse pointing mode," which results in higher cold-gas consumption than the normal, star camera-based, "fine-pointing" modes.

In order to correct data artifacts and improve operational reliability, an IPU software upload is planned for the month of October. The primary goals of the new software are to improve star camera operation, add GPS occultation capability, and set default parameter values to prevent data outages in the event of parameter memory corruption.

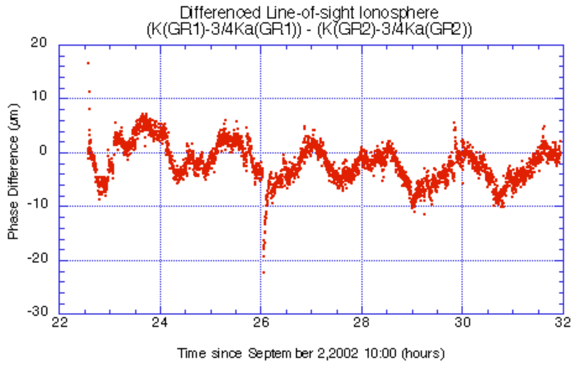

Figure 2. KBR double difference. The data plotted is the difference between satellites of the phase of the received 24 GHz signal minus 3/4 of the 32 GHz signal phase. The remaining quantity is free of clock and range variation, but contains differences between the phase delay in the two satellites and higher order ionospheric delay.

ON ORBIT EXPERIENCE—DATA

DOWR: 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 μm. 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.

Systematic variation of the SST 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=$(K_{SAT1}-3/4Ka_{SAT1})-(K_{SAT2}-3/4Ka_{SAT2})$, 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 (i.e., RF components or the antenna). Figure 2 shows that DI has a variation of 10 μm with a period of one orbit for many hours. The excursions are correlated with the inter-satellite ionosphere, and may be mostly attributable to differential ionosphere. In any case, this indicates a systematic phase variation of 10μm or better for the individual K- and Ka-band links. For comparison, 10μm is about the diameter of a human red blood cell.

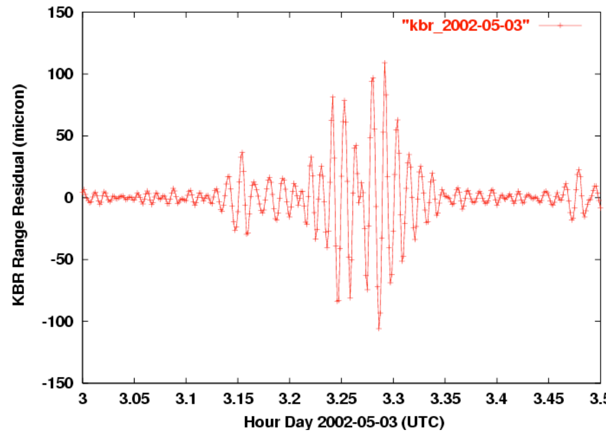

Figure 3. The inter-satellite range as measured by DOWR after removal of frequencies lower than 1/60s by a cubic spline fit, including the 4.5-km variation due to orbit eccentricity and low frequency gravity. The longitude of the ground track was 79 E. The large signal is due to the Himalayas.

Examination of the DOWR shows features that are clearly related to surface features on the Earth. The largest signal occurs over the Himalayas, as shown in Figure 3. This plot is from a ground track from south to north at 79 E. longitude. When the amplitude of this type of signal is plotted on the globe, geologically interesting features are clearly visible, with repeatability across hundreds of ground tracks.

Current progress in a full determination of the gravitational field shows DOWR residuals well below 1 μm/s.

GPS: Currently each GRACE IPU is configured to track a maximum of 10 GPS satellites. The time average number of tracks is 8.03 for GRACE-1 and 7.69 for GRACE-2. The voltage SNR in a one-second integration of the CA code at the maximum of the antenna pattern is 900 for GRACE-1 and 850 for GRACE-2. The peak codeless SNRs are 650 and 700 for P1 and P2 on GRACE-1 respectively, and 580 and 780 on GRACE-2.

Figure 4. A star camera frame taken by GRACE-1 over Antarctica.

Star Camera: Figure 4 shows a photograph taken by GRACE-1 with its star camera over Antarctica on May 7, 2002. The Technical University of Denmark Advanced Stellar Compass software determines the satellite attitude from frames like this using between 20 and 100 stars, depending on the portion of sky that is in view and a user-settable threshold value. Currently in the directions perpendicular to the line of sight, the star camera noise equivalent angle error appears to lie between 7.2 and 11.6 micro-radians, which is consistent with expectations. The accuracy in the "twist" axis is somewhat lower than desired, falling between 102 and 155 micro-radians. This should be significantly improved using an improved algorithm to be uploaded this October. This upload should also improve the automatic-gain-control performance, resulting in better performance when the Moon is in the field of view or the Sun is near the field of view.

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 the gravitational field of the Earth. By exchanging K- and Ka-band carrier signals and adjusting the time tags using GPS, the GRACE mission is achieving a quantum leap in the knowledge of the Earth's gravitational field.

ACKNOWLEDGMENTS

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