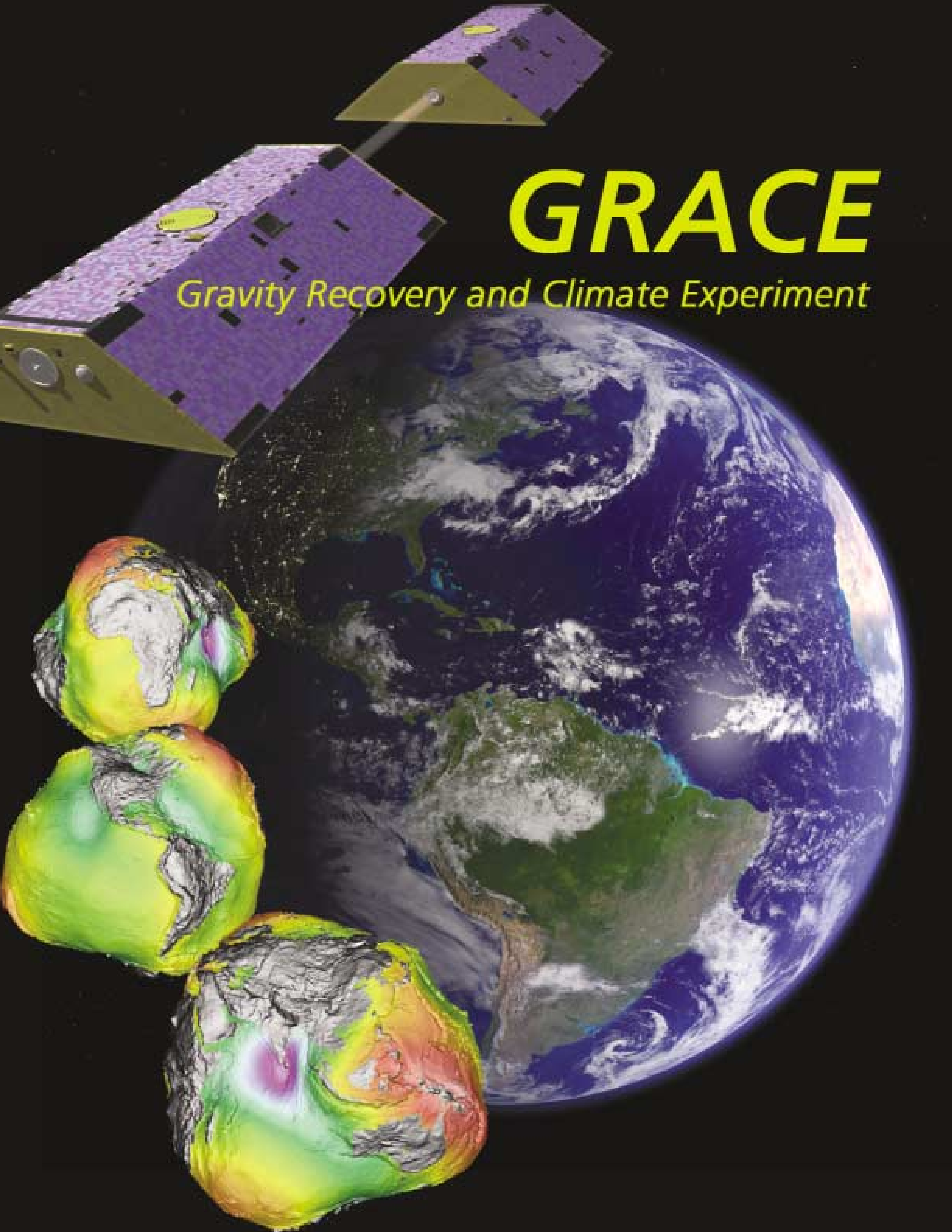
GRACE MISSION

Twins in orbit fly
linked by microwaves reveal
Earth mass in motion
— Ab Davis, GRACE Project Manager, JPL

Goddard Space Flight Center
Greenbelt, Maryland

NP-2002-2-427-GSFC


GRACE
Gravity Recovery and Climate Experiment

Acknowledgements

Content Developed By:	Alan Ward
Designed By:	Winnie Humberson
Edited By:	Margaret Baguio, Bill Bandeen, Charlotte Griner, Michael King, Margaret Srinivasan.
Technical Input Provided By:	Christoph Reigber, Rick Fitzgerald, Frank Flechtner, Bob Garnett, Marc Imhoff, Byron Tapley, Srinivas Bettadpur, John Ries, Don Chambers, Ab Davis, Mike Watkins.
Front Cover Foreground:	These images show three different views of the Earth's geoid—a surface of equal gravitational potential that, over the ocean, closely follows the sea surface. The geoid was determined from data collected by previous satellite missions. Among these satellites is the Challenging Minisatellite Payload (CHAMP), the forerunner to GRACE, launched by the German Georesearch Center GeoForschungsZentrum Potsdam (GFZ). Similar products will be developed using data from GRACE with an expected improvement in accuracy of several orders of magnitude. These images were provided courtesy of GFZ. The illustration of the GRACE satellites was provided by Chris Meaney.
Front Cover Background:	This day/night image of the Earth was produced using a combination of data from the Moderate Resolution Imaging Spectrometer (MODIS) sensor aboard NASA's Terra satellite (daytime portion), and the city lights image produced using Operational Line Scan (OLS) data from the Defense Meteorological Satellite. The daytime side of the Earth in this image was made using surface reflectance data from MODIS. The data was composited over a period of several months during the Northern Hemisphere of summer 2001. (Image courtesy of Robert Simmon and the MODIS Science Team.)
Back Cover:	This is a photograph of the two identical spacecraft in the environmental test facility at Industrieanlagen-Betriebsgesellschaft GmbH (IABG) in Ottobrun, Germany. When deployed into space, the two craft will be upright inside the launch vehicle. After launch, they will fly 500 km above the Earth and will be separated by 220 km. The photograph was provided courtesy of Astrium GmbH.

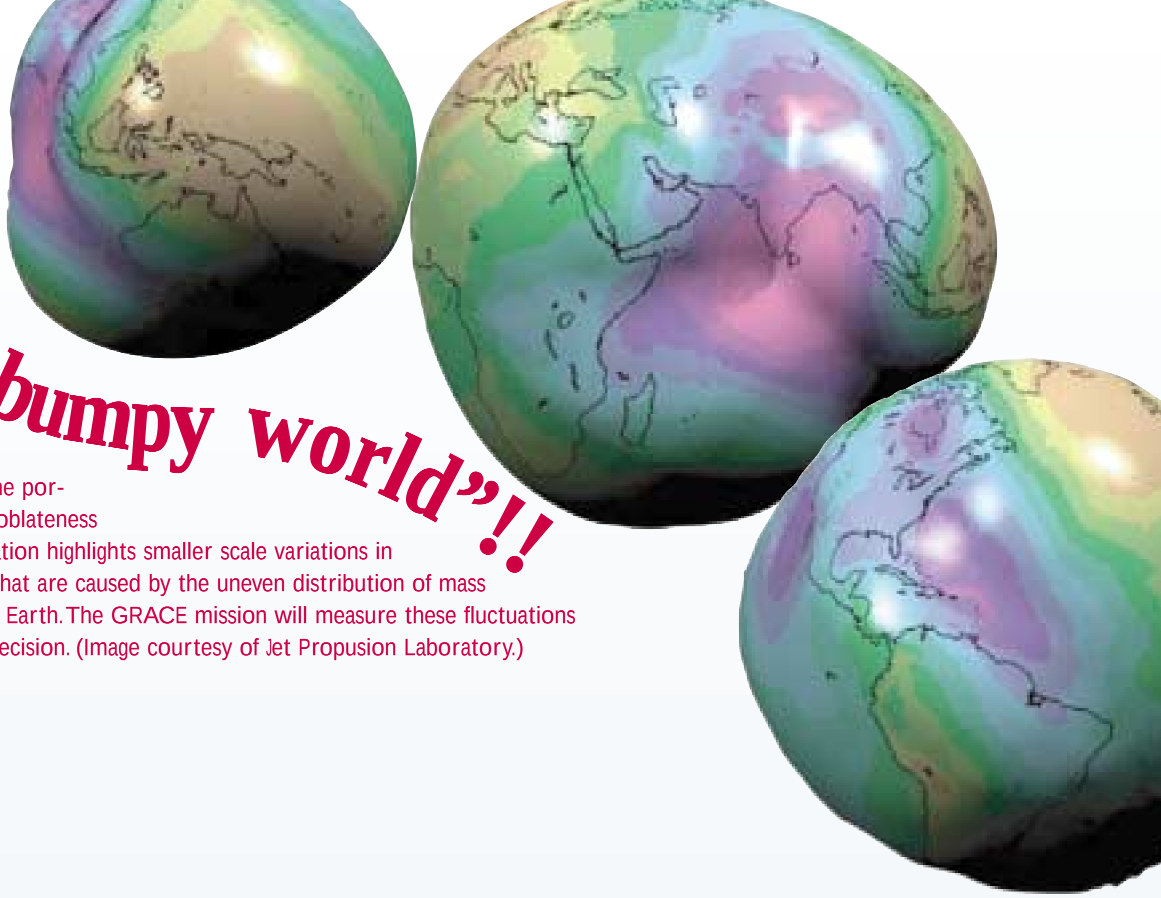
Gravity!

What is it?
You can't see it!
You can't smell it!
You can't touch it!
But it's there. In fact, it's everywhere.

While gravity is much weaker than other basic forces in nature, such as magnetism and electricity, its effects are ubiquitous and dramatic. Gravity controls everything from the motion of the ocean tides to the expansion of the entire Universe. To learn more about the mysteries of gravity, twin satellites named GRACE—short for the Gravity Recovery and Climate Experiment—are being launched to make detailed measurements of Earth's gravity field. This experiment could lead to discoveries about gravity and Earth's natural systems, which could have substantial benefits for society and the world's population.

The GRACE mission will be the inaugural flight of NASA's Earth System Science Pathfinder Program (ESSP). A component of NASA's Earth Science Enterprise (ESE), the ESSP missions are intended to address unique, specific, highly focused scientific issues and provide measurements required to support Earth science research.

The ESSP missions are an integral part of a dynamic and versatile program consisting of multiple Earth system science space flights. The ESSP program is characterized by relatively low- to moderate-cost, small-to medium-sized missions that are capable of being built, tested and launched in short-time intervals. Each mission is led by a Principal Investigator (PI), who is responsible for all elements of the mission, from ensuring the science accuracy to making sure the mission stays on budget and on time. ESSP missions are capable of supporting a variety of scientific objectives related to Earth science, including the atmosphere, oceans, land surface, polar ice regions and solid Earth. Investigations include development and operation of remote sensing instruments and conducting research using data returned from these missions. Subsequent satellite launches are planned over the next few years, all of them focusing on the atmospheric sciences.



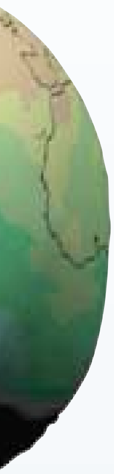
"It's a bumpy world"!!

This is a three dimensional rendering of the Earth's geoid magnified a thousand times, with the portion due to the Earth' oblateness removed. The magnification highlights smaller scale variations in gravitational potential that are caused by the uneven distribution of mass over the surface of the Earth. The GRACE mission will measure these fluctuations with unprecedented precision. (Image courtesy of Jet Propusion Laboratory.)

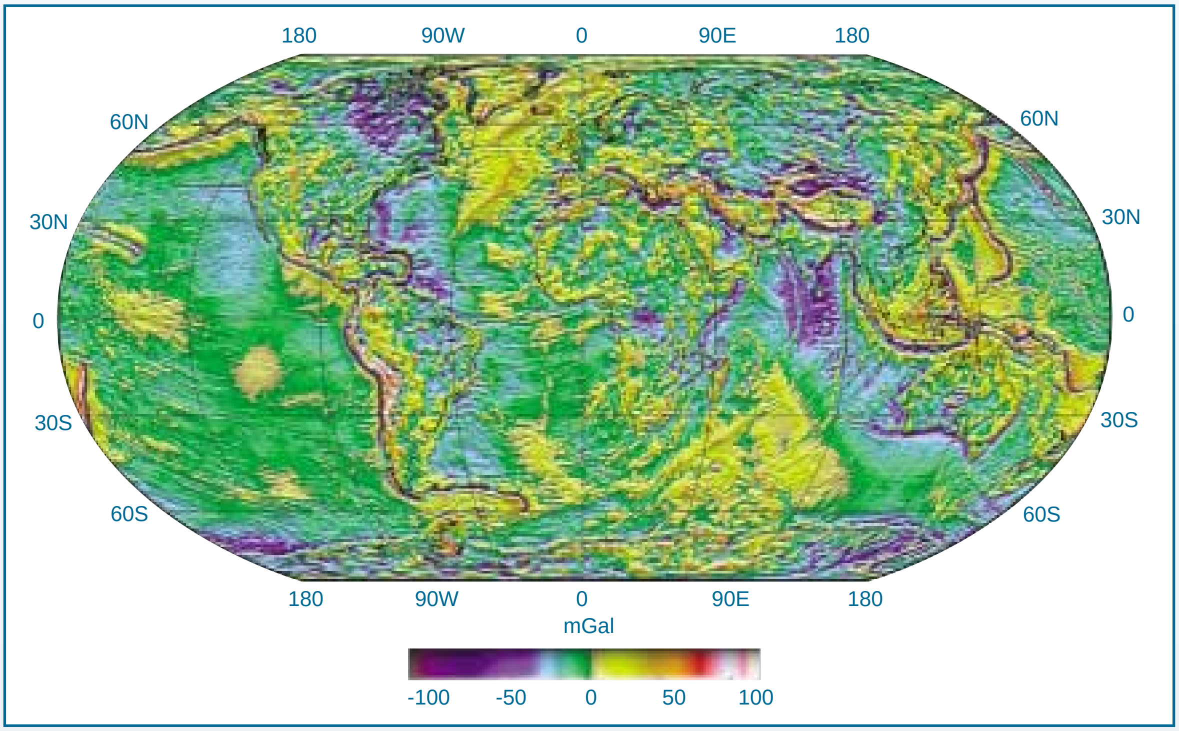
WHY
A Mission To Study Gravity?

If Earth were a smooth sphere composed of similar elements or ingredients, there would be no need for a GRACE mission; the assumption made in most introductory physics courses that the acceleration due to Earth's gravitational field has a constant value would indeed be correct—end of story. However, previous observations have clearly demonstrated that our Earth isn't smooth and homogeneous and it really isn't even a sphere! What's more, the images shown above are just instantaneous snapshots from one moment in time. The reality is that the gravity field is continually changing, mostly due to variations in water content as it cycles between the atmosphere, oceans, continents, glaciers, and polar ice caps. By far the largest "lump" is the flattening observed at the poles—the Earth's oblateness. The above profiles have removed the portion of the response due to oblateness in order to focus on the smaller anomalies that exist. GRACE will reveal the broad features of the Earth's gravitational field over land and sea; it will also allow for these smaller scale features to be identified and studied with unprecedented accuracy, and it will show how the Earth's gravity field varies with time.

GRACE 2002:
A Scientific Geodesy

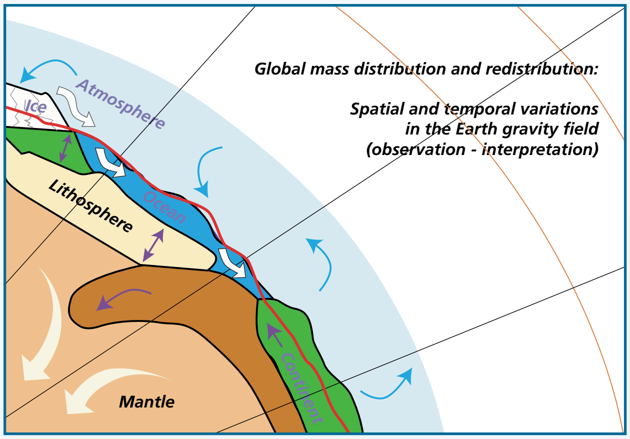


Gravity is the invisible force that pulls two masses together. The branch of science dealing with obtaining precise measurements of the Earth, mapping points on the surface, and studying its gravitational field is known as *geodesy*. Producing a precise model of the fluctuations in gravity over the Earth's surface has proven to be a formidable task. Currently, data from several dozen satellites must be combined to produce a model of Earth's gravitational field. These models do a good job at replicating the large-scale features of Earth's gravitational field but cannot resolve finer-scale features or accurately describe the small month-to-month variations associated with the hydrologic cycle. The unique design of the GRACE mission (twin satellites flying in formation) is expected to lead to an improvement of several orders of magnitude in these gravity measurements and allow much improved resolution of the broad-to finer-scale features of Earth's gravitational field over both land and sea.



This is a plot of the Earth's geoid (surface of equal gravitational potential) produced by the Earth Gravitational Model (EGM96), one of many models used for gravity studies. The Space Geodesy Branch of NASA Goddard Space Flight Center worked in collaboration with the National Imagery and Mapping Agency (NIMA) and The Ohio State University (OSU) to develop this model. Data from GRACE is expected to allow for a quantum leap of several orders of magnitude in the precision and resolution of the geoid. The improved rendering of the geoid will have benefits for many disciplines that rely directly or indirectly on precise measurements of the gravity field, including disciplines that study the Earth's climate.

The distribution of mass over the Earth is non-uniform. GRACE will determine this uneven mass distribution by measuring changes in Earth's gravity field. The term mass refers to the amount of a substance in a given space, and is directly correlated to the density of that substance. For example, a container filled with a more dense material, like granite, has more mass than that same container filled with water. Because mass and density are directly related, there is also a direct relationship between density and gravity. An increase in density results in an increase in mass, and an increase in mass results in an increase in the gravitational force exerted by an object. Density fluctuations on the surface of the Earth and in the underlying mantle are thus reflected in variations in the gravity field. As the twin GRACE satellites orbit the Earth together, these gravity field variations cause infinitesimal changes in the distance between the two. These changes will be measured with unprecedented accuracy by the instruments aboard GRACE leading to a more precise rendering of the gravitational field than has ever been possible to date.



This schematic diagram illustrates the different forces that redistribute mass on the surface of the Earth. Since mass changes and gravity changes are correlated, the data retrieved by the GRACE satellite should help scientists better quantify these movements and their impact on the Earth's climate. (Image provided by GFZ.)

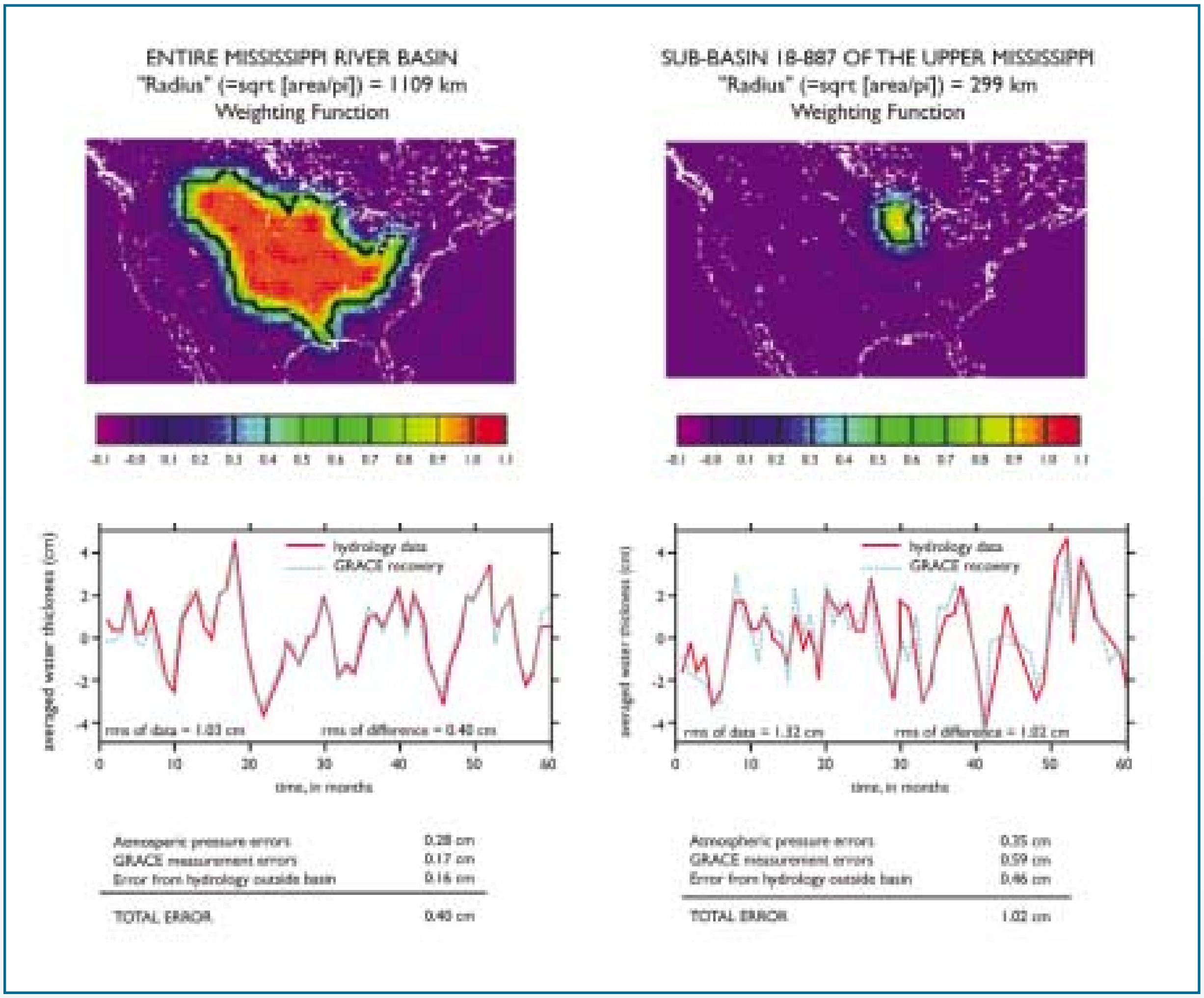
GRACE will do more than just produce a more accurate gravitational field plot, however. The measurements from GRACE have important implications for improving the accuracy of many scientific measurements related to climate change. Substantive advances in the interpretation of satellite altimetry, synthetic aperture radar interferometry, and digital terrain models, covering large land and ice areas used in remote sensing applications and cartography, will result from the improved gravitational field measurements provided by GRACE. These techniques provide critical input to many scientific models used in oceanography, hydrology, geology and related disciplines, and, for this reason, the Earth Science community eagerly anticipates the GRACE launch. The next few pages present some of the expected scientific applications.

Tracking water movement on and beneath Earth's surface

Perhaps the most interesting and least well-measured cause of fluctuations in the Earth's gravitational field is movement of water over the surface of the Earth. The gravitational data collected by GRACE will be combined with data from other NASA satellites, aircraft and ground-based measurements to study the movement of liquid water over our home planet with a level of detail never before possible. Water moves in significant quantities throughout the Earth's hydrologic cycle (see diagram), and at a rapid rate relative to other processes that redistribute mass over Earth's surface.

The gravitational variations observed by GRACE are primarily attributable to the seasonal and interannual movement of water throughout the hydrologic cycle. This means that by combining measurements from GRACE with measurements taken on the ground, scientists will be able to improve their models of water exchange between the ocean and land surfaces—through rainfall, deep soil moisture, and runoff. This can be done from continental scales down to regional scales of a few hundred kilometers.

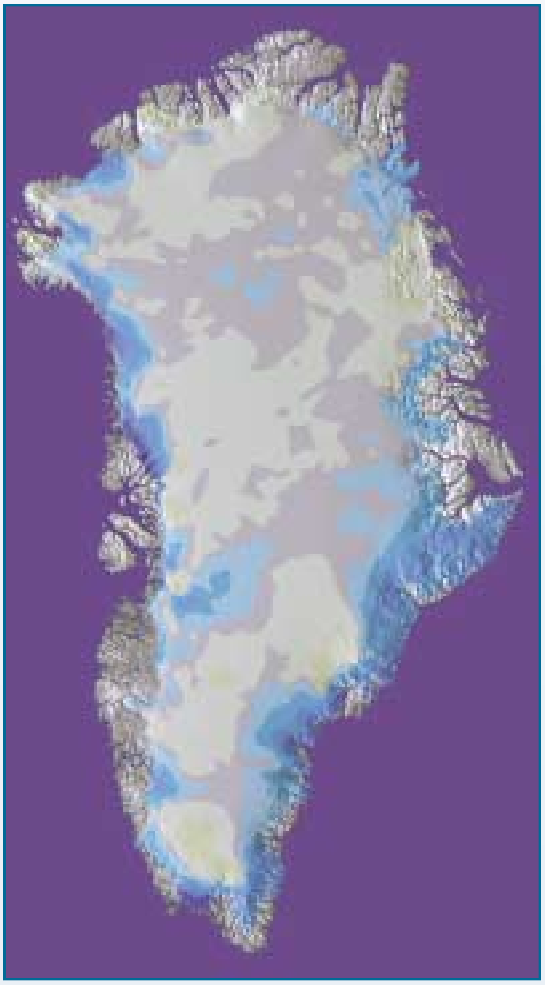
This diagram illustrates the hydrologic cycle and shows how water in solid, liquid and vapor forms, circulates over, under and above the surface of the Earth. Gravity fluctuations correlate with variations in the density of the land surface below. These illustrations can be used to track water movement. In effect, gravity becomes a mechanism to track water movement our eyes cannot see. GRACE data may lead to the identification of new sources of fresh water—which is of particular interest to populations located in arid regions of the Earth.



These figures illustrate the ability of GRACE to recover month-to-month variations in the water stored in individual river basins as compared to more traditional methods. The figure on the left looks at the entire Mississippi River basin while the figure on the right focuses on one sub-basin of the Mississippi. In each figure, the upper panel shows an outline of the river basin, along with a color contour of a mathematical averaging function that GRACE might use to estimate the water variations within that basin. The red line in the lower panel shows monthly variations in the actual water storage signal, in units of cm of water thickness; the blue line shows the values that GRACE would recover. In general, GRACE can recover water storage signals to about 1 cm or better for basins where the effective radius is 250-300 km or larger. The larger the basin, the more data from GRACE will improve the accuracy of these calculations. Hence it will do a better job looking at the entire Mississippi basin than it will do on individual sub-basins. (Image provided by John Wahr, University of Colorado.)

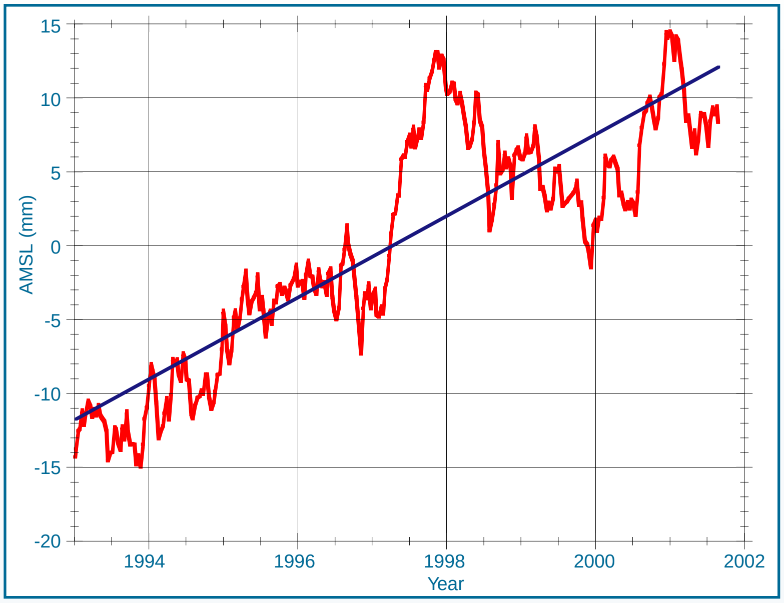
Tracking changes in ice sheets and changes in global sea level

The question of whether ice caps are shrinking or growing is important for climate change studies. As the area covered by ice sheets decreases, the surface area of the Earth's oceans increases, leading to increased heat absorption and rising temperatures. This, in turn, melts more ice and contributes to global sea level rise. Data provided by GRACE will help scientists better understand how ice sheet mass is changing and the impact the changes are having on global sea level. GRACE data, when combined with height variations measured with ground-based, aircraft, and satellite instruments, like the Geoscience Laser Altimeter System (GLAS) on the Ice, Clouds, and Land Elevation Satellite (ICESat), will allow for improved computations of ice sheet mass balance. Also by combining the GRACE gravity field measurements with surface elevation measurements (such as from radar altimeters), scientists will be better equipped to distinguish between the mean ocean level changes due to thermal expansion and those due to actual redistribution of water.



▲ The issue of long-term changes in ice sheet mass is an important one for climate studies, and data from GRACE should help scientists quantify these changes. The diagram illustrates the idea that as the ice sheet melts, the increased surface area of open water absorbs more heat, raising temperatures, melting more ice, and also contributing to sea level rise.

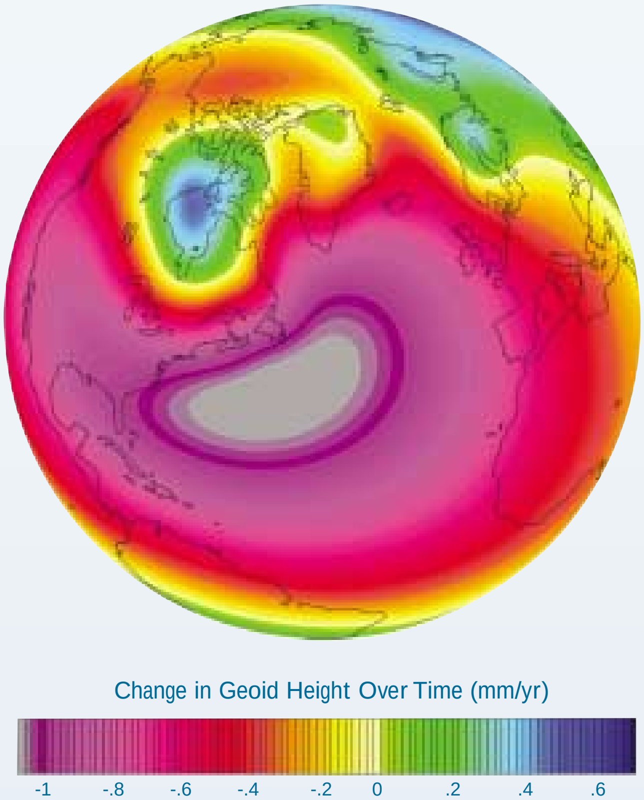
◀ GRACE will be able to precisely measure very small changes in Earth's gravitational field that result from changes in the mass of ice sheets. Shown here is computer generated image of Greenland that shows how the ice mass is changing. Blues indicate areas where the loss of ice is greatest, and yellows indicate regions that are apparently thickening. Gray areas indicate no significant change in ice thickness.



Satellite altimeters such as those on TOPEX/Poseidon and Jason-1 can measure the total mean sea level change, as illustrated here with TOPEX/Poseidon data from 1993 to the middle of 2001. However, the altimeter alone cannot distinguish between what portion of the observed anomaly can be attributed to warming of the ocean and what part is due to water being added from melting ice sheets. Data provided by GRACE, used in conjunction with altimeter measurements like those shown here, should help scientists better distinguish between these two phenomena. (Image courtesy of Don Chambers, University of Texas, and Steve Nerem of the University of Colorado.)

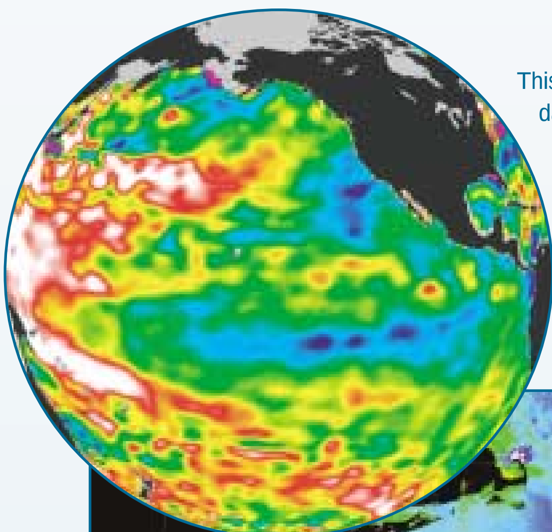
For example, data from GRACE is expected to greatly improve scientists' understanding of how much global sea level is being impacted by a phenomenon known as *postglacial rebound*. Postglacial rebound refers to the slow rebounding of the Earth's crust that is occurring now that the weight of the ice from the last Ice Age is no longer present. The rebounding of the crust can affect relative sea level at the coastline in a manner that varies from place to place. This can confound efforts to determine how much of the overall observed change in sea level is actually caused by thermal expansion of the oceans resulting from global warming.

Postglacial rebound accounts for the vertical movement of land in many parts of the world. These shifts, which have been continuing since the last Ice Age ended, affect relative sea level at the coastline in a manner that varies from place to place. Such movements can confound tide gauge records obtained from coastal sites and thus complicate efforts to track the overall change in global sea level. The data retrieved by GRACE will be combined with the previously mentioned altimeter readings to get a better handle on how much of the perceived change in sea level is attributable to the phenomenon of postglacial rebound and how much might be attributed to global warming. This particular image depicts the predicted time rate of change in geoid height expected to result from postglacial rebound as predicted by the ICE-4G (VM2) Toronto model (Image provided by W.R. Peltier, University of Toronto, Canada.)

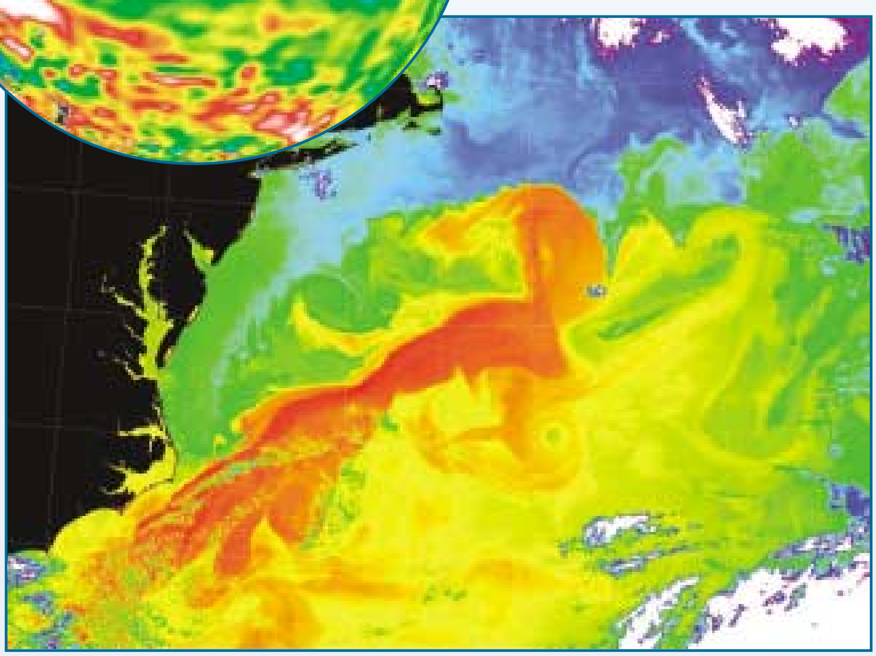


Studying ocean currents both near the surface and far beneath the waves

If the ocean were motionless, the sea surface would still have hills and valleys. This *static topography* of the ocean is caused by the fluctuations in the gravity field caused by variations in density over the surface of the ocean. Because the oceans are always in motion—swept by winds, seething with waves, and circulating in gigantic currents and gyres driven by surface winds and by the rotation of the Earth—the shape of the ocean's topography cannot be determined by static gravity measurements alone. An additional component, known as the *dynamic topography* must be accounted for to precisely measure the shape of the ocean surface at any given time. Although dynamic topography only accounts for about one percent of the total variation of the ocean's topography, it is an extremely important component for it contains important information about the speed and direction of ocean currents. Consequently, scientists would very much like to improve their ability to measure and track changes in dynamic topography.



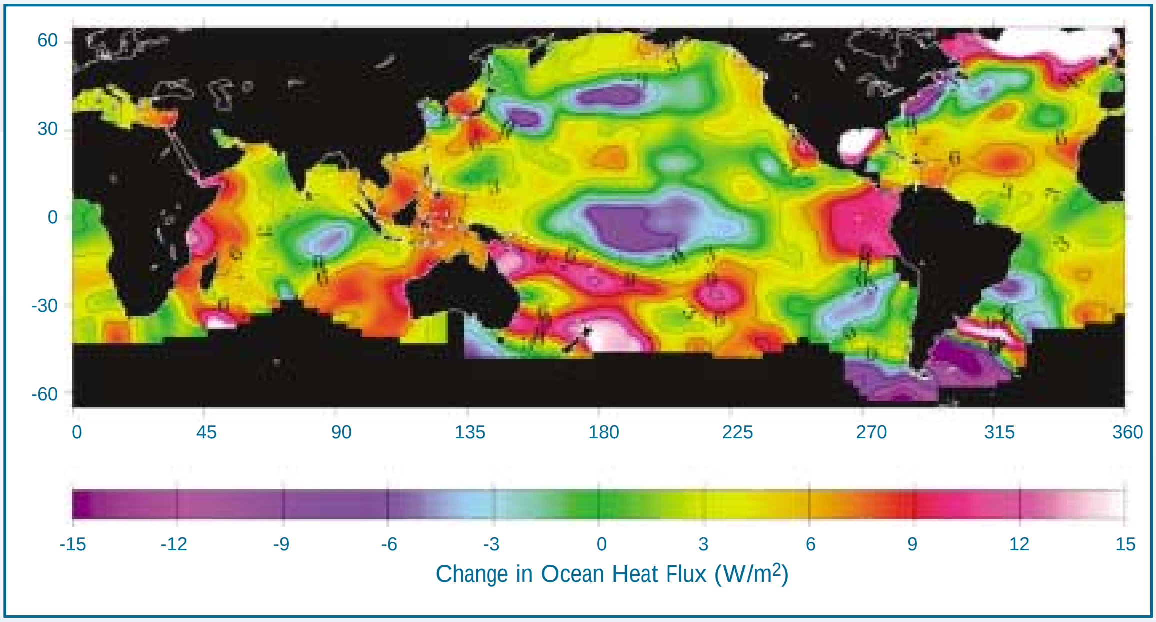
This image shows sea surface topography data from TOPEX/Poseidon. When such data are combined with the precise geoid measurements expected from GRACE, scientists should be able to study currents from satellites using a technique known as dynamic topography. This image was acquired in March 2001 in the aftermath of earlier El Niño/La Niña conditions in the tropical Pacific. Areas toward the blue end of the spectrum represent anomalously low sea surface heights for March and areas toward the red end represent anomalously high values for March.



GRACE data should help scientists understand the role ocean currents play in regulating Earth's climate. This image from the MODIS sensor onboard the Terra satellite shows the Gulf Stream (red), a surface ocean current that plays a critical role in redistributing heat from the tropics to the poles. It has a moderating influence on the climate of Northwest Europe, which would otherwise be much colder—similar to other locations at the same latitude, such as Greenland. This particular image was obtained on May 2, 2001 and was provided by Liam Gumley of the MODIS Atmosphere Team, University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies.

Two pieces of information are needed to make a dynamic topography measurement, sea surface height and a model for the Earth's geoid. Since the impact of dynamic topography on the shape of the ocean surface is quite small compared to the impact of the static gravity field, the measurements must be extremely precise and of high resolution. Satellite altimeter measurements from TOPEX/Poseidon and Jason-1 can provide this level of detail for sea surface height measurements, but to date, there are no geoid measurements with sufficient precision and resolution to allow satellite-derived measurements of dynamic topography. Scientists expect the data returned by GRACE to provide the precise, high resolution geoid measurements required to measure dynamic topography affects. They hope to use these data to better understand the role that ocean currents play in regulating the Earth's climate.

Ocean currents regulate Earth's climate by transporting heat from equatorial regions to the poles. The Earth's oceans essentially serve as huge heat reservoirs and currents both at the ocean surface and far beneath the waves—known as deep ocean currents—act as massive "conveyor belts" that distribute this heat over the surface of the Earth. Consequently, any changes in these equator-to-pole "conveyor belts" could significantly change the weather all around the globe. Scientists are particularly hopeful that GRACE will help them better understand the role that deep ocean currents play in regulating climate. Until now, deep ocean currents have remained shrouded in mystery since they have been very difficult to measure. However, the design of the GRACE satellites makes them ideally suited to examine deep ocean currents and should lead to improved ability to track them and study their impact on global climate.



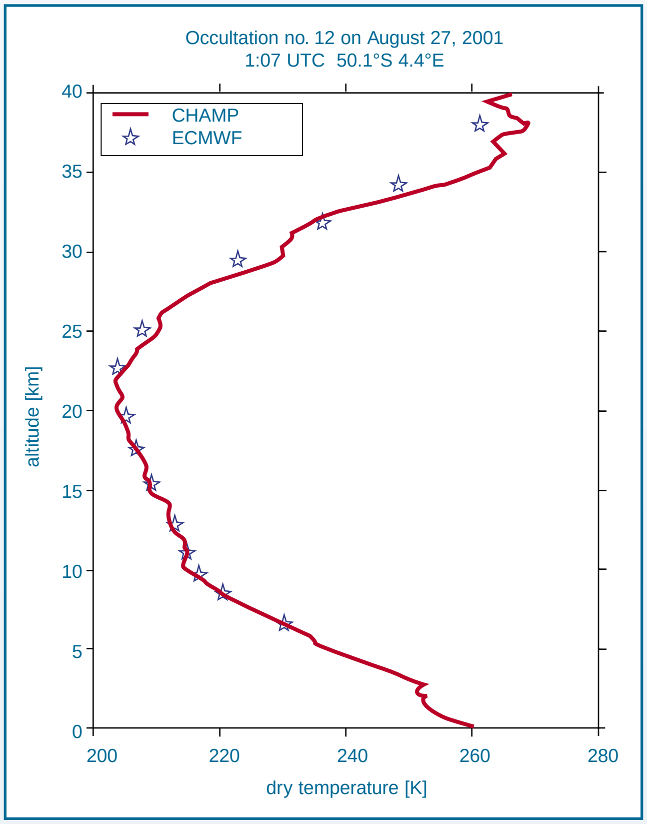
This map illustrates the heat exchange flux over Earth's oceans for a five year period. A negative value indicates an area where the ocean is losing heat while a positive value indicates an area where the ocean is absorbing heat. Ocean heat exchange flux plays a crucial role in regulating the Earth's climate and data from GRACE should help improve the accuracy of these measurements

Tracking changes in the solid Earth

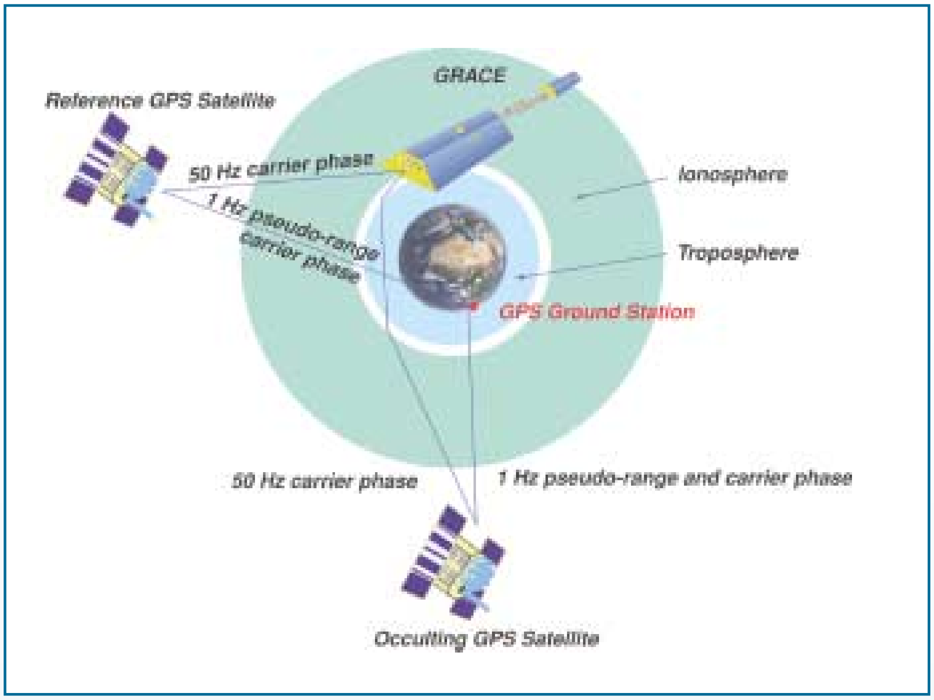
GRACE data will also improve our understanding of Earth's lithosphere—solid Earth. More precise measurements of the Earth's gravity field, such as those provided by GRACE, should lead to an improved understanding of the dynamics of the inner structure of the Earth. The characteristics of the continental lithosphere are the subject of varying opinions. Questions remain regarding its thermal and compositional nature, thickness, and mechanical properties. GRACE can track variations in the density of the lithosphere by looking at its impact on the Earth's gravitational field. Thus, data from GRACE will be used to compare competing models of the lower mantle viscosity and contribute to the improved understanding of mantle convection.

Using GPS Receivers as Atmospheric Limb Sounders

In addition to the gravity measurement, the GRACE mission will also employ an innovative new technique that uses its extremely precise Global Positioning System (GPS) receivers as atmospheric limb sounders. Limb sounding measures the excess delay of radio waves as they pass through and are bent by the Earth's atmosphere. Just as light is refracted or bends as it enters water because of the slower speed of light in the water, GPS signals are refracted as they pass through the atmosphere. The precise degree of bending (and hence the precise excess delay) is highly dependent on atmospheric pressure, temperature, and moisture content. These can all be estimated from precise observations of the changing signal delay as the



The graph shows a dry temperature profile derived by GeoForschungsZentrum Potsdam (GFZ) from CHAMP occultation data observed on August, 27, 2001. The corresponding meteorological analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) is plotted for comparison.



This diagram, originally provided by GFZ, illustrates how the occultation process works. The GRACE satellite tracks a GPS satellite as it "rises" and "sets" through the limb of the atmosphere, while a second GPS serves as a reference point.

GPS Satellite rises or sets. The ionosphere, which is the name applied to the ionized upper atmosphere above 100 km altitude, also affects the speed of radio waves according to the density of electrons in the ionosphere. It turns out that GPS signal distortion caused by the ionosphere varies as the radio frequency of the signal changes but that atmospheric distortions remain constant with changing radio frequency. Thus, this technique not only measures the distortion of the GPS signal but it can also distinguish how much of the observed distortion is caused by the atmosphere and how much is caused by the ionosphere.

As GRACE orbits the Earth, it will use forward and aft looking antennas to measure the signals from the slower orbiting GPS satellites as they appear to rise or set behind the Earth's limb. GRACE will also measure GPS signals from higher elevation GPS satellites that are not affected by the atmosphere (illustrated in the diagram) as a standard of comparison.

By observing how the GPS path delays through the atmosphere change, GRACE will create profiles of pressure, temperature, and humidity for the atmosphere and measure the variability of the ionosphere down to 100 km altitude. It is anticipated that the limb sounding technology aboard GRACE will extend and complement other spaceborne atmospheric sensors. GRACE will provide about 500 limb sounding measurements per day, unaffected by weather conditions (such as clouds and storms) that hinder or block other satellite sensors. The GRACE limb sounding measurements will be used to determine the effectiveness of limb sounding in improving numerical weather prediction in a cost effective manner.

GPS sounding of the continuously changing ionosphere aims to advance our understanding of the Sun's influence upon the Earth's environment, including its effects on climate, weather, radar and radio communications. Limb sounding will also be studied as a means of detecting rapid vertical changes of the Earth's surface such as volcanic explosions, earthquakes, tsunamis and other such phenomena, which are thought to cause disturbances in the ionosphere.

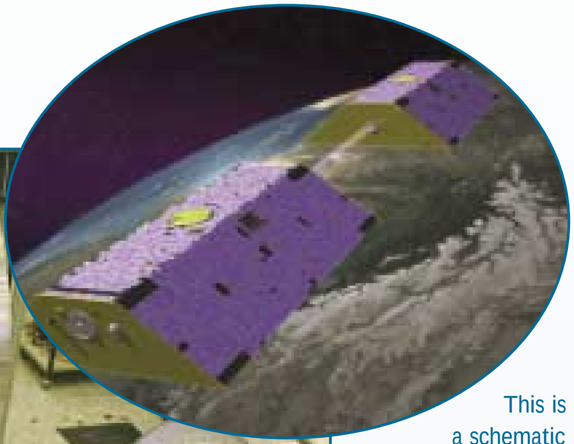
DATA
Processing and Archiving

System development, data processing and archiving are performed in a shared Science Data System (SDS) between the Jet Propulsion Laboratory (JPL), the University of Texas Center for Space Research (UTCSR), and the GeoForschungsZentrum Potsdam (GFZ). Telemetry data are received by the GRACE Raw Data Center (RDC) at Deutsches Zentrum für Luft und Raumfahrt (DLR) in Neustrelitz, Germany—illustrated in the Instrumentation section.

The first level of data processing is performed at JPL, where sensor calibration factors are applied, the data are correctly time-tagged, quality control flags are added, and the data sample rate is reduced from the high rate data of previous levels. Data are then sent to UTCSR and GFZ, where the mean and time variable gravity field is derived from the calibrated and validated data. Data are archived for distribution at JPL's Physical Oceanography Distributed Active Archive Center (PO.DAAC) and at GFZ's Information System and Data Center (ISDC).15 GRACE data include 30-day estimates of gravity fields, as well as profiles of air mass, density, pressure, temperature, water vapor, and ionospheric electron content.

INSTRUMENTATION
and Measurements

A sneak peak at the innards of a spacecraft! For the GRACE mission, the spacecraft itself is the main instrument. This picture shows the GRACE spacecraft with the solar panels removed and gives a clear view of the various components. A diagram of the interior components of the space craft appears on the inside back cover.

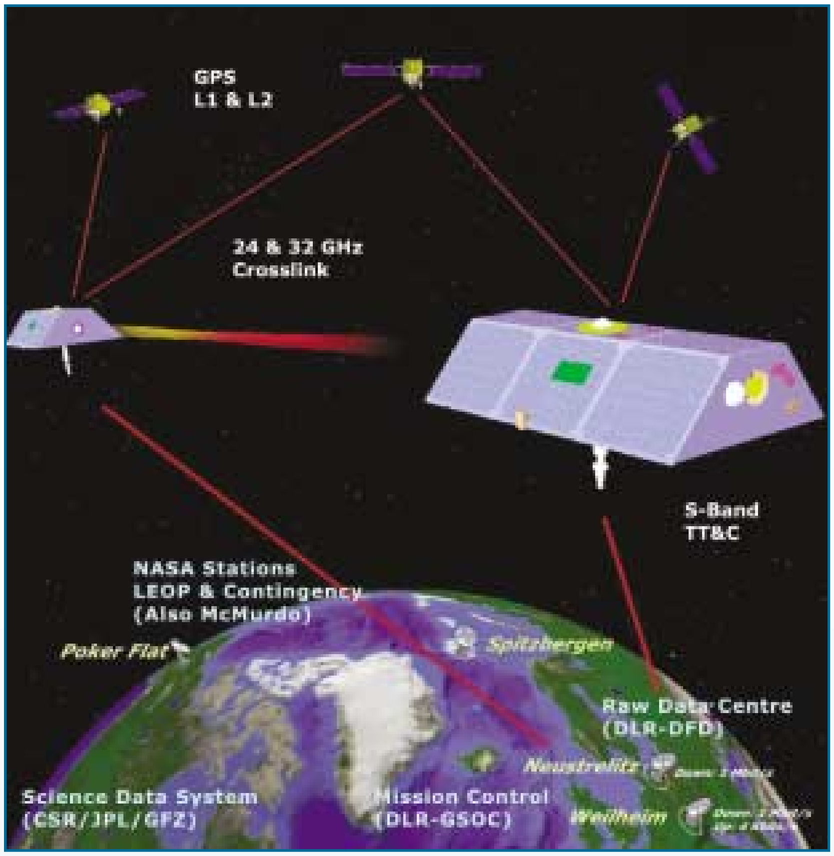


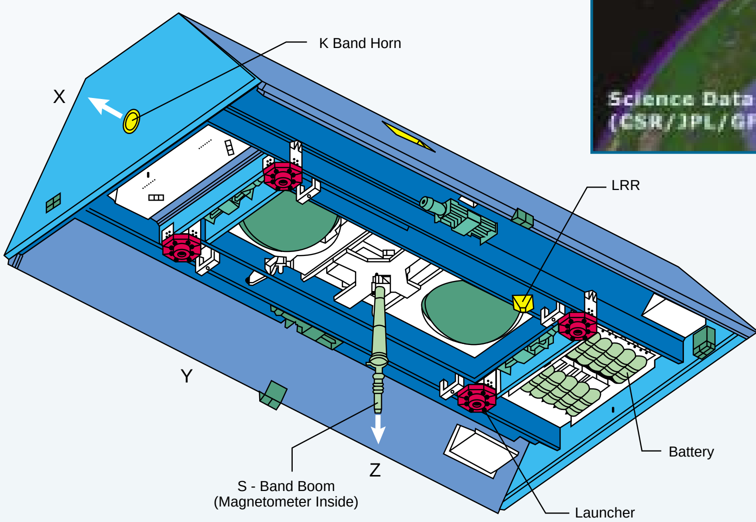
This is a schematic diagram of the two GRACE satellites in orbit with the K-band microwave beam connecting them and precisely tracking fluctuations in the distance between the two satellites. The fluctuations are used to infer changes in the gravitational field on the surface of the Earth below.

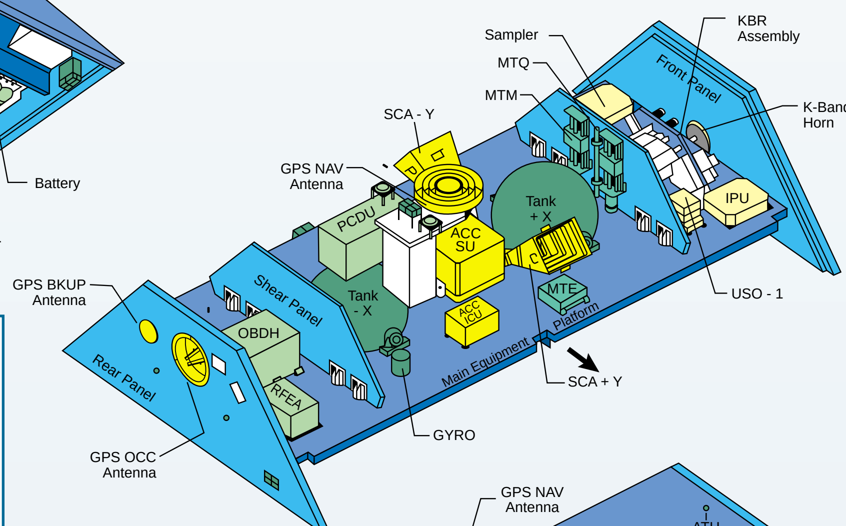
GRACE is different from most Earth observing satellite missions—Terra and Aqua for example—because it will not carry a suite of independent scientific instruments on board. The two GRACE satellites themselves act in unison as the primary instrument. Instantaneous changes in the distance between the twin satellites are used to make an extremely precise gravitational field measurement.

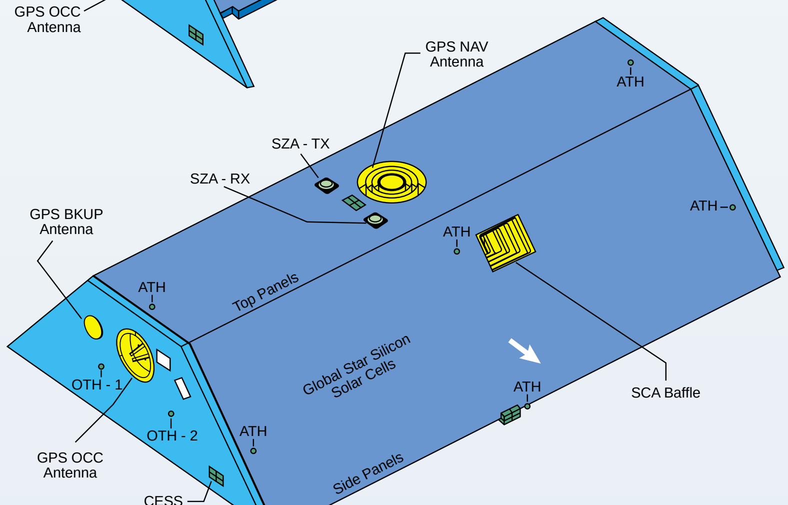
To measure gravity from space, the two identical GRACE satellites fly in the same orbit—one 220 km (137 miles) ahead of the other. As the pair circles the Earth, areas of slightly stronger gravity will affect the lead satellite first, pulling it away from the trailing satellite. The uniquely designed Superstar Accelerometer is used to distinguish gravity influences from those of air drag. The K-band ranging instrument is capable of measuring the distance between the satellites with a precision better than the width of a human hair. By monitoring this distance, GRACE will be able to detect fluctuations in the gravitational field and, therefore, differences in the density of the Earth's surface beneath the satellites. The data will be combined with GPS data to produce a map of the gravity field approximately once a month.

This diagram illustrates the flight configuration and ground support for the GRACE mission. Fluctuations in density of the Earth's surface result in very small changes in the distance between the two satellites, which are measured with very high precision by the K-band ranging system. The S-band relay (shown protruding from the bottom of each satellite) allows for communication with surface tracking stations. The GPS satellites are used as references to determine the precise location of the two satellites in orbit and allow for the creation of gravity maps—approximately once a month.









Abbreviations Used in GRACE Satellite Diagrams

ACC ICU	Superstar Accelerometer Interface Control Unit
ACC SU	Superstar Accelerometer Sensor Unit
ATH	Attitude Control Thrusters
CESS	Coarse Earth and Sun Sensor
GPS BKUP Antenna	GPS Backup Antenna
GPS NAV Antenna	GPS Navigational Antenna
GPS OCC Antenna	GPS Occultation Antenna
IPU	Instrument Processing Unit
KBR Assembly	K-Band Ranging System Assembly
LRR	Laser Retro Reflective Assembly
MTE	Center of Mass Trim Assembly Electronics
MTM	Center of Mass Trim Assembly Mechanism
MTQ	Magnetorquers
OBDH	On Board Data Handling
OTH-1, OTH-2	Orbit Control Thrusters
PCDU	Power Control and Distribution Unit
RFEA	Radio Frequency Electronics Assembly
SCA Baffle	Star Camera Assembly Baffle
SCA +Y, SCA -Y	Star Camera Assembly
SZA – RX	S-Band Zenith Antenna, Receive
SZA – TX	S-Band Zenith Antenna, Transmit
Tank -X, Tank +X	Cold Gas Tanks
USO-1	Ultra Stable Oscillator

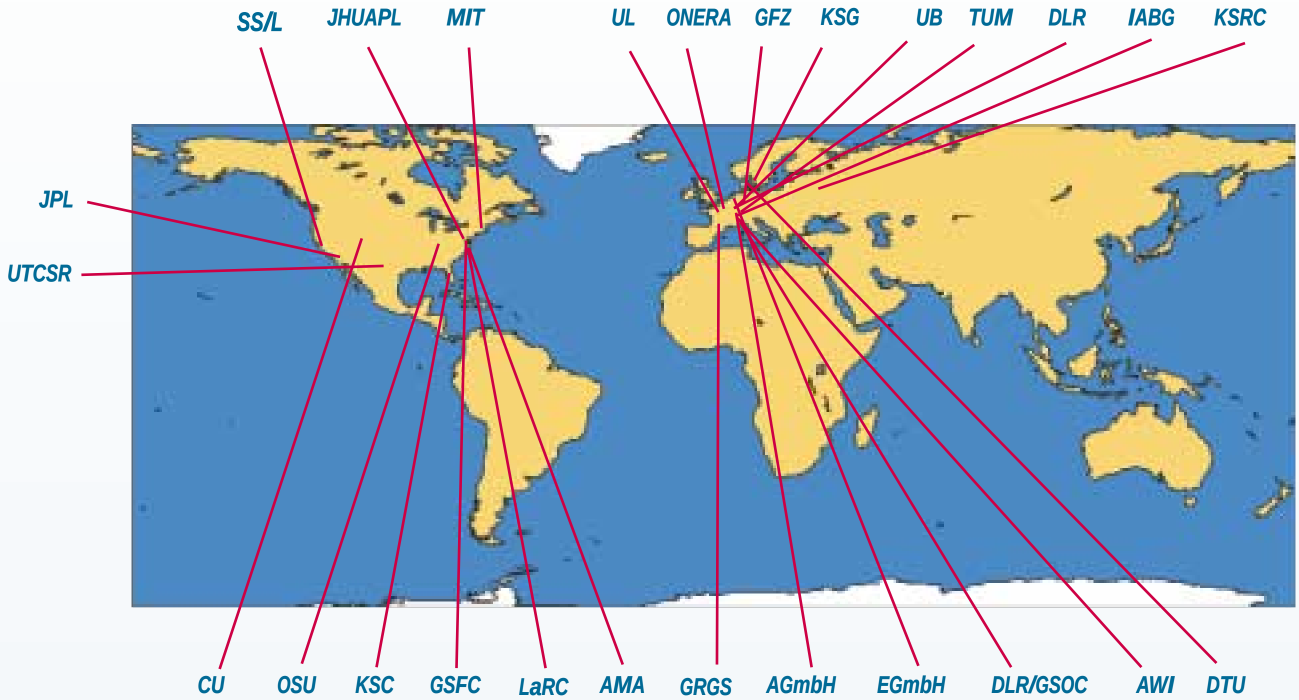
EDUCATION
and Public Outreach

The GRACE mission benefits from and will build upon the interest in oceanography that has been growing in recent years with the recognition of the El Niño/La Niña phenomenon. GRACE provides a strong basis to draw public and student interest since new, extremely accurate models of the Earth's gravity field will be generated.

The Texas Space Grant Consortium (TSGC) works in partnership with the mission team to develop and implement GRACE education and outreach. GRACE master teachers were selected from across the nation through an application and review process. These master teachers have created interdisciplinary K-12 educational materials that meet the National Educational Standards to support the GRACE mission in the areas of Satellites, Gravity, Weather/Climate/Atmosphere, Oceans, and GRACE general mission facts and objectives. These master teachers have trained hundreds of teachers about the GRACE mission impacting tens of thousands of students, and the activities have been tested in classrooms across the nation. When GRACE launches, the activities will be available to all educators on the TSGC web site, http://www.csr.utexas.edu/grace/education/. In addition to classroom activities, an on-line GRACE activity guide, coloring book, and on-line quiz will be available for all interested.

Animations, photos and interviews with mission personnel will be available to all traditional media outlets—television, print, and radio. Computer animation, showing the spacecraft deployments, orbit ground tracks, data collection, and real world applications of the data, is available. The GRACE web site will also document, publicize, and expand the mission's science data including computer animations, downloadable educational materials, a frequently asked questions (FAQ) archive, and evaluation/ suggestion forms for feedback. This information will be updated regularly.

GRACE will revolutionize the way we look at Earth, providing new benefits for six billion people living on this beautiful, blue planet. Through youth development and education we will enhance our understanding of this dynamic and living world we call home.



Participating Institutions

United States

AMA	Analytical Mechanics Association, Inc.	Hampton, VA
CU	The University of Colorado	Boulder, CO
GSFC	Goddard Space Flight Center (NASA)	Greenbelt, MD
JPL	Jet Propulsion Laboratory (NASA)	Pasadena, CA
JHUAPL	Johns Hopkins University Applied Physics Lab.	Laurel, MD
KSC	Kennedy Space Center (NASA)	Cocoa Beach, VA
LaRC	Langley Research Center (NASA)	Hampton, VA
MIT	Massachusetts Institute of Technology	Cambridge, MA
OSU	The Ohio State University	Columbus, OH
SS/L	Space Systems/Loral	Palo Alto, CA
UTCSR	University of Texas Center for Space Research	Austin, TX

European

AGmbH	Astrium GmbH	Friedrichshafen, Germany
AWI	Alfred Wegener Institute for Polar and Marine Research	Bremerhaven Germany
DLR	Deutsches Zentrum für Luft und Raumfahrt	Bonn, Germany
DLR/GSOC	DLR German Space Operations Center	Oberpfaffenhofen, Germany
DTU	The Technical University of Denmark	Copenhagen, Denmark
EGmbH	Eurockot GmbH	Bremen, Germany
GFZ	GeoForschungsZentrum Potsdam	Potsdam, Germany
GRGS	Groupe de Recherches de Géodésie Spatiale	Toulouse, France
IABG	Industrieanlagen-Betriebsgesellschaft GmbH	Ottobrunn, Germany
KSG	Kort & Matrikelstyrelsen	Copenhagen, Denmark
KSRC	Khrunichev State Research and Production Space Center	Moscow, Russia
ONERA	Office National d'Etudes et de Recherches Aerospatiale	Paris, France
TUM	Technical University of Munich	Munich, Germany
UB	University of Bonn	Bonn, Germany
UL	University of Lyon	Lyon, France

Key Participants

B. Tapley	UTCSR, Principal Investigator (PI)
C. Reigber	GFZ, Co-PI
A. Davis	JPL, Project Manager
M. Imhoff	GSFC, ESSP Project Scientist
E. Koenemann	DLR, GRACE Manager
R. Fitzgerald	GSFC, GRACE Mission Manager
M.M. Watkins	JPL, Project Scientist

U.S. Science Team

B. Tapley	UTCSR, Lead
S. Bettadpur	UTCSR
R. Gasparovic	JHUAPL
R.S. Gross	JPL
W.G. Melbourne	JPL
D. Porter	JHUAPL
C.K. Shum	OSU
J. Wahr	CU
M.M. Watkins	JPL
C. Wunsch	MIT

European Science Team

C. Reigber	GFZ, Lead
G. Balmino	GRGS
F. Flechtner	GFZ
K.H. Ilk	UB
N. Jakowski	DLR
P. Knudsen	KSG
Y. Ricard	UL
R. Rummel	TUM
J. Schroeter	AWI
P. Schwintzer	GFZ

Technical Specifications

General Spacecraft Information (Twin Satellites)

- **Width:** 1942 mm
- **Length:** 3123 mm
- **Height:** 720 mm
- **Mass:** 487 kg per satellite
- **Design Life:** 5 years

Orbit Characteristics

- Two satellites, co-orbiting at near polar inclinations at 300-500 km altitude.
- Separated along track by 220 km.

Key Components

- **K-band Ranging System.** Provides precise (within 10 µm) measurements of the distance change between the two satellites and hence measures the fluctuations in gravity.
- **S-band Boom.** Used to send data from the satellites back to Earth for processing.
- **SuperSTAR Accelorometers.** Precisely measures the non-gravitational accelerations acting on the satellite.
- **Star Camera Assembly.** Precisely determines satellite orientation by tracking them relative to the position of the stars.
- **Ultra Stable Oscillator.** Provides frequency generation for the K-band Ranging system.
- **Coarse Earth and Sun Sensor.** Provides omni-directional, reliable and robust, but fairly coarse Earth and Sun tracking. To be used during initial acquisition and when GRACE is operating in “safe mode.”
- **Center of Mass Trim Assembly.** Precisely measures offset between the satellite’s center of mass and the “acceleration-proof” mass, and adjusts center of mass as needed during flight.
- **Black-Jack GPS Receiver and Instrument Processing Unit.** Provides digital signal processing; measures the distance change relative to the GPS satellite constellation; and provides secondary atmospheric occulation experiments.
- **Laser Retro-Reflective Assembly.** Provides measurements of the GRACE satellite orbits relative to terrestrial tracking networks.
- **Globalstar Silicon Solar Cell Arrays.** Covers the outer shell of the spacecraft and generates power.
- **Three-axis Stabilized Attitude Control System:** Uses star camera and gyro sensors and a cold-gas nitrogen thruster system, with magnetorquers for fine corrections of spacecraft position.
- **1750-A Microprocessor for Flight Computer.** Performs calculations for attitude adjustment and telemetry processing.

* See photos and diagrams on page 14 and 15 for detailed layout of spacecraft.

Science
Measurement Objectives

The following table presents a concise summary of exactly what measurements GRACE will obtain and the instruments that are used to obtain them, as well as how many spacecraft are involved in each measurement.

Science Application	Measurement	Instrument	# of spacecraft needed for measurements
Earth Gravity Field	Inter-Satellite Range Change Link	K-Band Microwave	2
Earth Gravity Field Accelerations	Non-Gravitational	Accelerometer	2
Earth Gravity Field	Satellite Orbits	Black Jack GPS Receiver	2
Atmospheric Occultation	GPS-to-GRACE Phase Change	Black Jack GPS Receiver	1

This science data in conjunction with ancillary data, will then be used to gain estimates of spherical harmonic coefficients of the Earth's gravitational potential. These coefficients are necessary to construct the 30-day maps of gravitational potential that will be the end-product from the primary GRACE measurements.

Gravity Measurement Error

Inter-satellite Range Measurement:	< 4 µm @ twice/rev < 10 µm total @ 0.1 to 0.0001 Hz
Non-Gravitational Acceleration Measurement:	< 10 -10 m/s^2 noise (+1/f) < 4 x 10 -12 m/s^2 tones.
Precision Orbit Measurement:	5 cm absolute < 0.2 mm, relative in plane

SCIENCE
Applications Summary

The estimates of the Earth gravity field from GRACE, in conjunction with other space-based measurements, *in situ* data and geophysical models will be used to determine the time varying changes in the mass of the Earth's dynamical system due to different geophysical processes as described in detail in this brochure.

Static Gravity Field Measurements

APPLICATION	RESOLUTION
Oceanic Heat Flux	>1000 km
Ocean Currents	>1000 km
Solid Earth Sciences	>300 km

Time Variable Gravity Field Measurements

APPLICATION	RESOLUTION	TIME SCALE	COMMENTS
Oceanic Heat Flux	>1000 km	Seasonal	30 day estimate
Ocean Bottom Pressure	>500 km	Seasonal	30 day estimate
Deep Ocean Currents	>500 km	Seasonal	30 day estimate
Sea Level Rise	>700 km	Secular	5 year estimate
Evapo-Transpiration	>300 km	Seasonal	30 day estimate
Greenland/Antarctic Ice		Secular Seasonal	5 year estimate 1 year estimate


astrium
EUROCKOT
Launch Service Provider
DLR
NASA Langley
Research Center
G R A C E
Gravity Recovery And Climate Experiment
JPL
ONERA
The University of Texas at Austin
C S R
Center for Space Research
Space Systems
LORAL
GFZ
POTSDAM
IABG