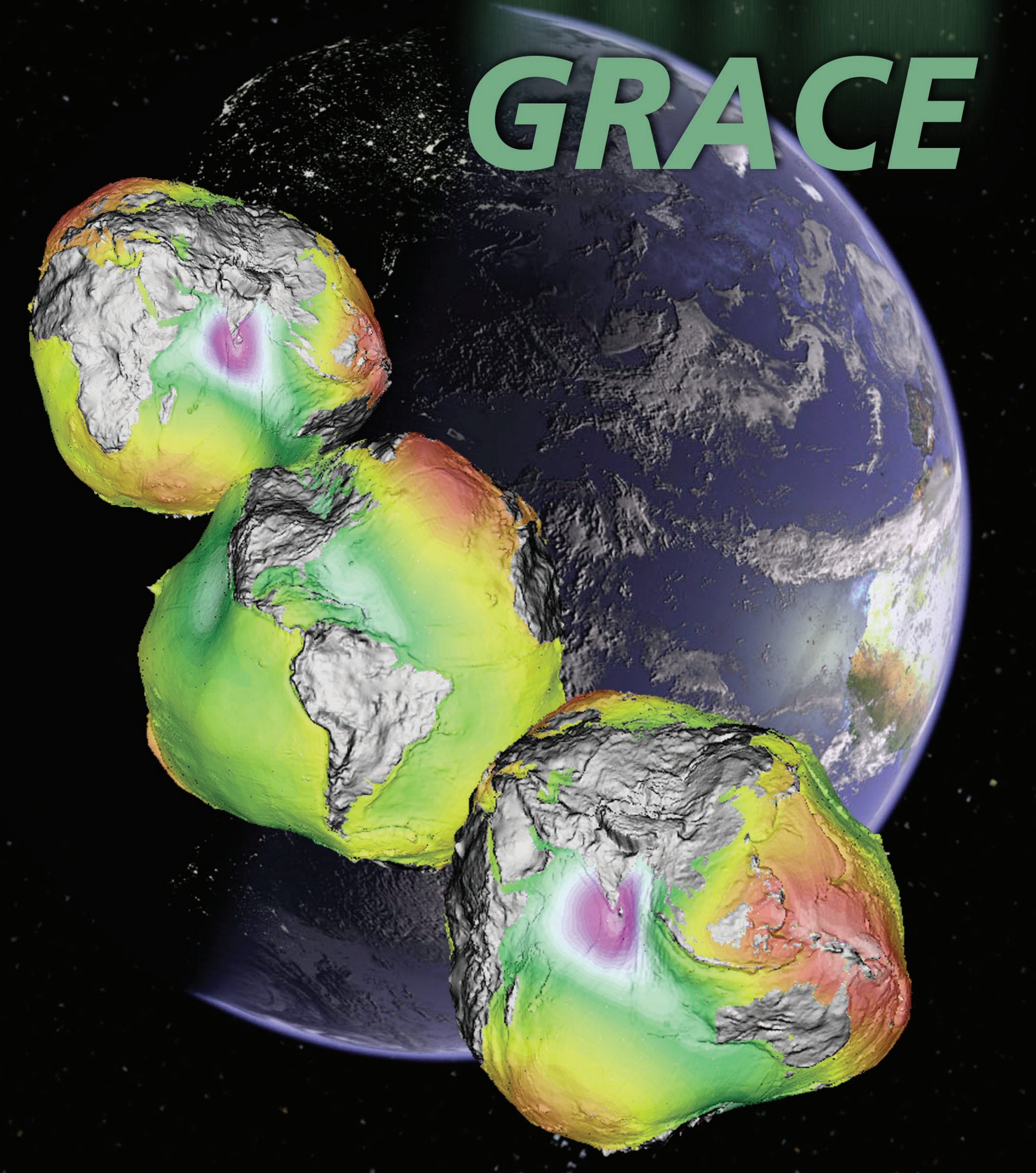
Gravity Recovery and Climate Experiment

GRACE



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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 CHAMP, launched by the German research center GeoForschungs Zentrum (GFZ). CHAMP is the sister mission for GRACE and similar renderings will be accomplished using data from GRACE with an expected improvement in accuracy of several orders of magnitude.

Back Cover:

This is a photograph of the two identical spacecraft in the environmental test facility at IABG in Ottobrunn, 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 about 220 kilometers.

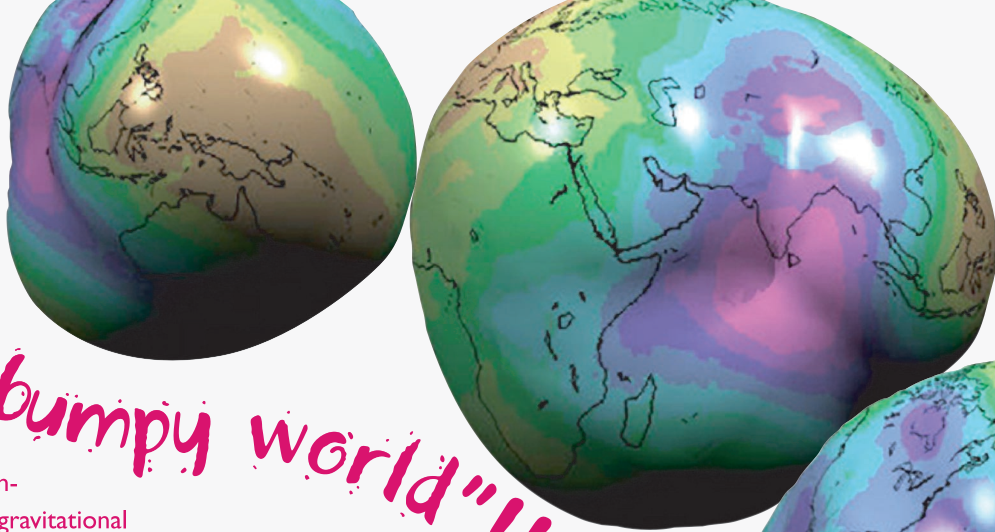
Gravity!

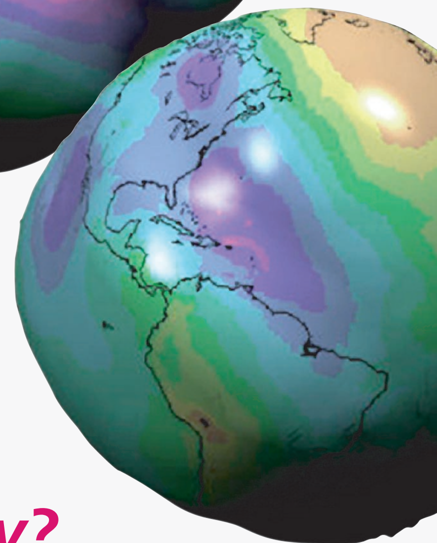
What is it?
You can't see it!
You can't smell it!
You can't touch it!
But it's there. In fact, it's everywhere.

While gravity is the weakest of the known basic forces in nature, such as magnetism and electricity, its effects are the most far-reaching 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 far reaching benefits to 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. These 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 the conduct of research investigations data from these instruments. Subsequent launches are planned over the next few years.





"It's a bumpy world"!!

In reality, our world is quite "bumpy". This three dimensional rendering simulates the gravitational field of the Earth magnified about a thousand times – with the portion due to the Earth's oblateness removed. It highlights smaller scale variations in the gravity field, which GRACE will study with unprecedented precision. The uneven distribution of mass on our planet Earth leads to the observed fluctuations - bumpiness – in the gravitational field. (Graphic courtesy of Jet Propulsion Laboratory.)

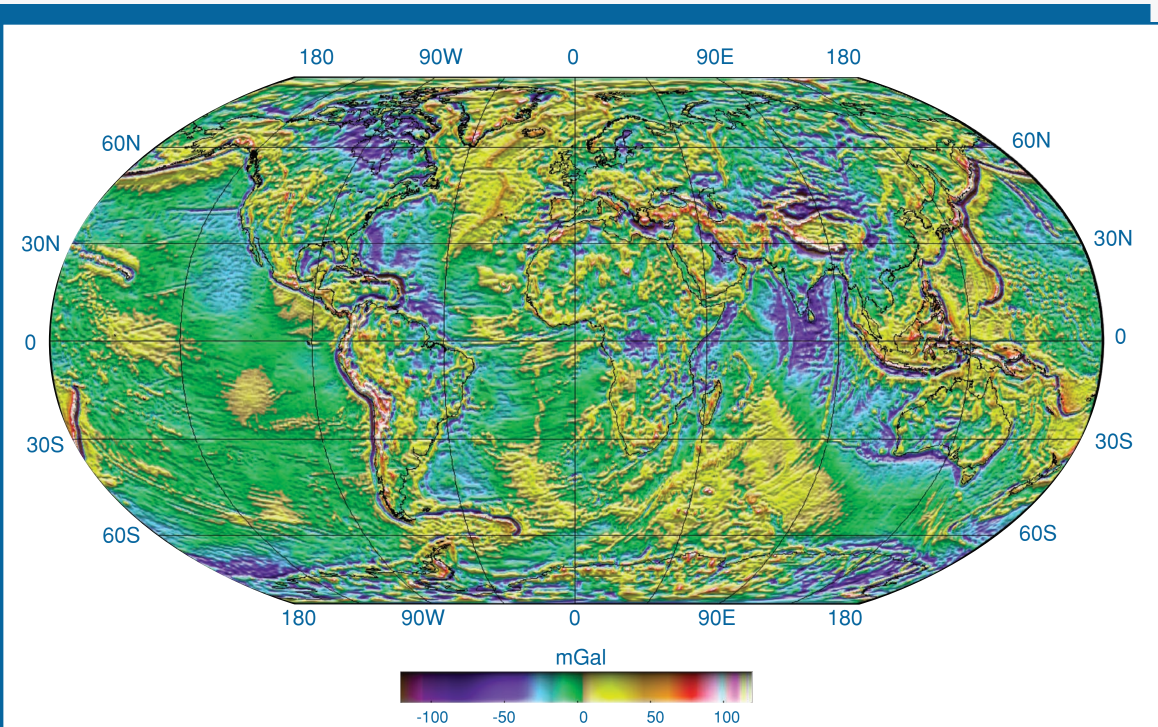
Why A Mission To Study Gravity?

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.

Previous satellite 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 constantly changes with time, mostly due to variations in water content as it cycles between the atmosphere, hydrosphere (oceans), lithosphere (beneath the surface) and cryosphere (polar ice and glaciers). By far the largest "lump" is the flattening observed at the poles, called the Earth's *oblateness*. The above profiles have removed the portion of the response due to oblateness in order to focus in on the other 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 gravity field varies with time.

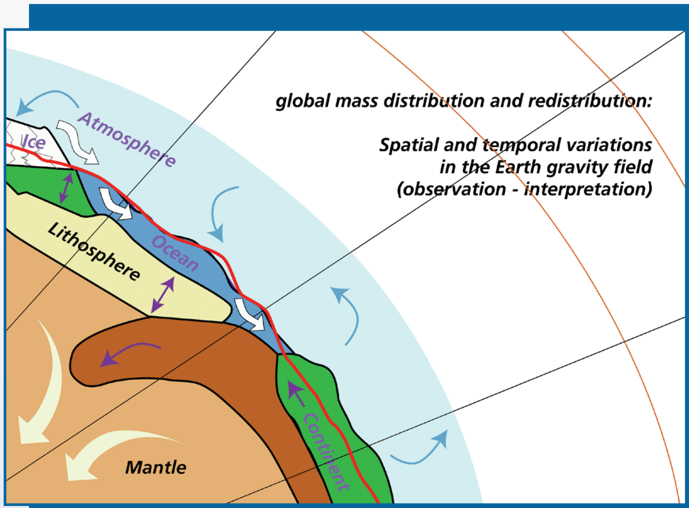
GRACE 2002: A Scientific Geodesy

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 simulating the large-scale features of Earth's gravitational field but cannot resolve finer-scale features or accurately describe the small month-to-month variations in the gravity field 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 Enhanced Gravitational Model (EGM96), one of many models used for gravity studies. This model was developed by the Space Geodesy branch of NASA Goddard Space Flight Center in collaboration with the National Imagery and Mapping Agency (NIMA) and The Ohio State University (OSU). Data from GRACE is expected to allow for a quantum leap of several orders of magnitude in the precision 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 is a way to talk about 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 reflected in variations in the gravity field. As the twin GRACE satellites orbit the Earth together, these gravity field variations cause changes in the distance between the two. These changes will be measured with unprecedented accuracy by the instruments aboard GRACE leading to a more accurate rendering of the gravitational field than has ever been possible to date.

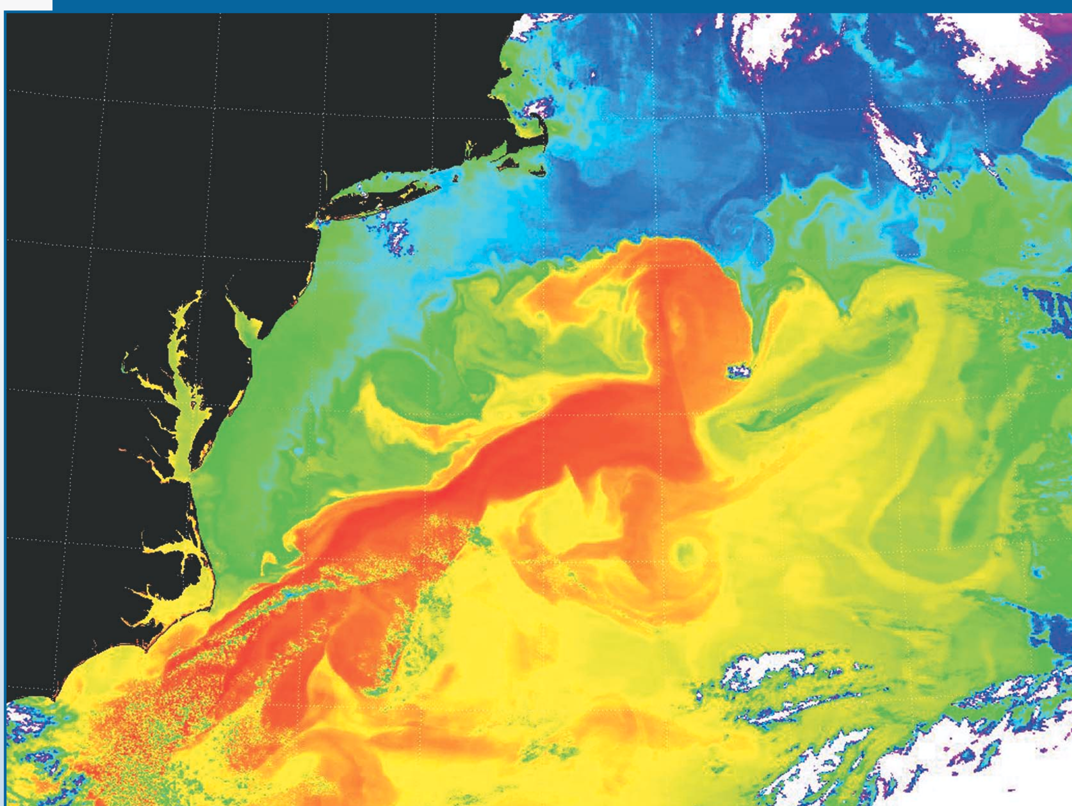


This schematic diagram from GFZ illustrates the different forces that work to redistribute the mass of the Earth. Since mass changes and gravity changes are correlated. GRACE data will provide insight on how mass is being redistributed over the surface of the Earth.

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 – hence the "ACE" in our acronym. Improvements to the accuracy of satellite altimetry, synthetic aperture radar interferometry, and digital terrain models covering large land and ice areas – used in remote sensing applications and cartography - are expected to 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. Among the expected applications:

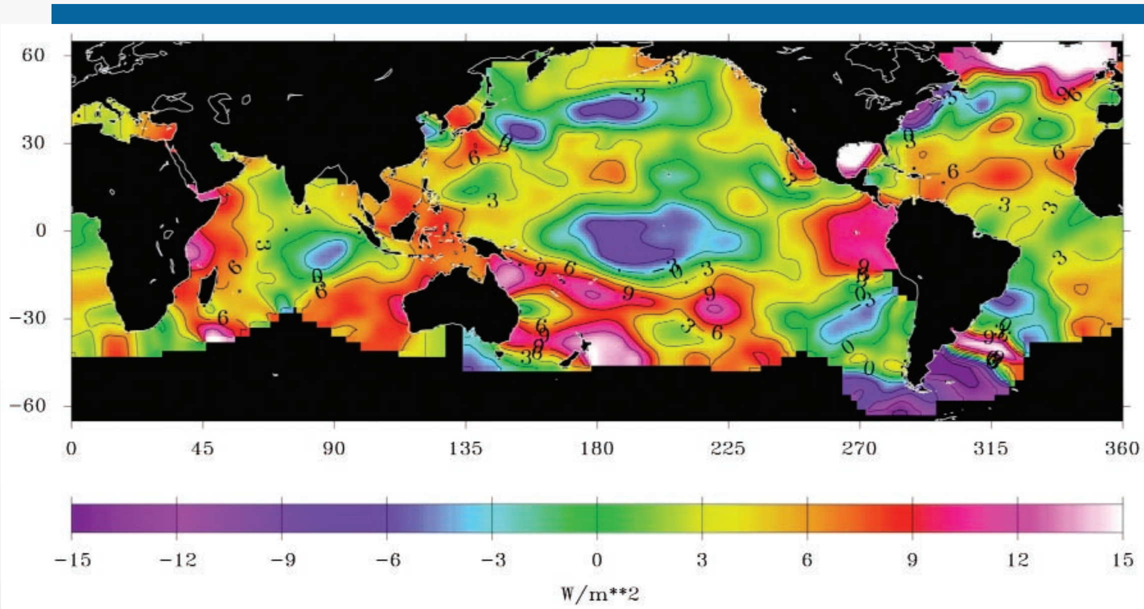
Studying ocean currents both near the surface and far beneath the waves

By examining the slope of the ocean's dynamic topography, which is the deviation of the ocean surface from a level surface, scientists can estimate the speed and direction of ocean surface currents. Two measurements are needed to determine the ocean dynamic topography: sea surface height data from satellite altimeters and a model for the Earth's geoid. In order to study ocean currents using dynamic topography measurements, the measurement must be very precise. Very precise sea height measurements are available from satellite altimeters such as TOPEX/POSEIDON and JASON but, at the moment, the geoid is not known precisely enough. Current measurements of the geoid simply lack the needed precision to be used to study ocean currents. GRACE promises to improve the resolution of the geoid measurement by several orders of magnitude over the current best estimate of the geoid and should therefore allow for advances in the study of ocean currents using dynamic topography.



The Gulf Stream is an example of an ocean current that plays a critical role in regulating the Earth's climate by distributing heat from the tropics to the poles. It has a moderating influence on the climate of Northwest Europe, which would otherwise be much colder and harsh – akin to other locations at the same latitude such as Greenland. The improved rendering of the geoid using GRACE data should allow for improved understanding of ocean currents such as the Gulf Stream. This particular image was produced by the MODIS sensor onboard Terra on 2 May 2001. The image was provided by Liam Gumley of the MODIS Atmosphere Team, University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies.

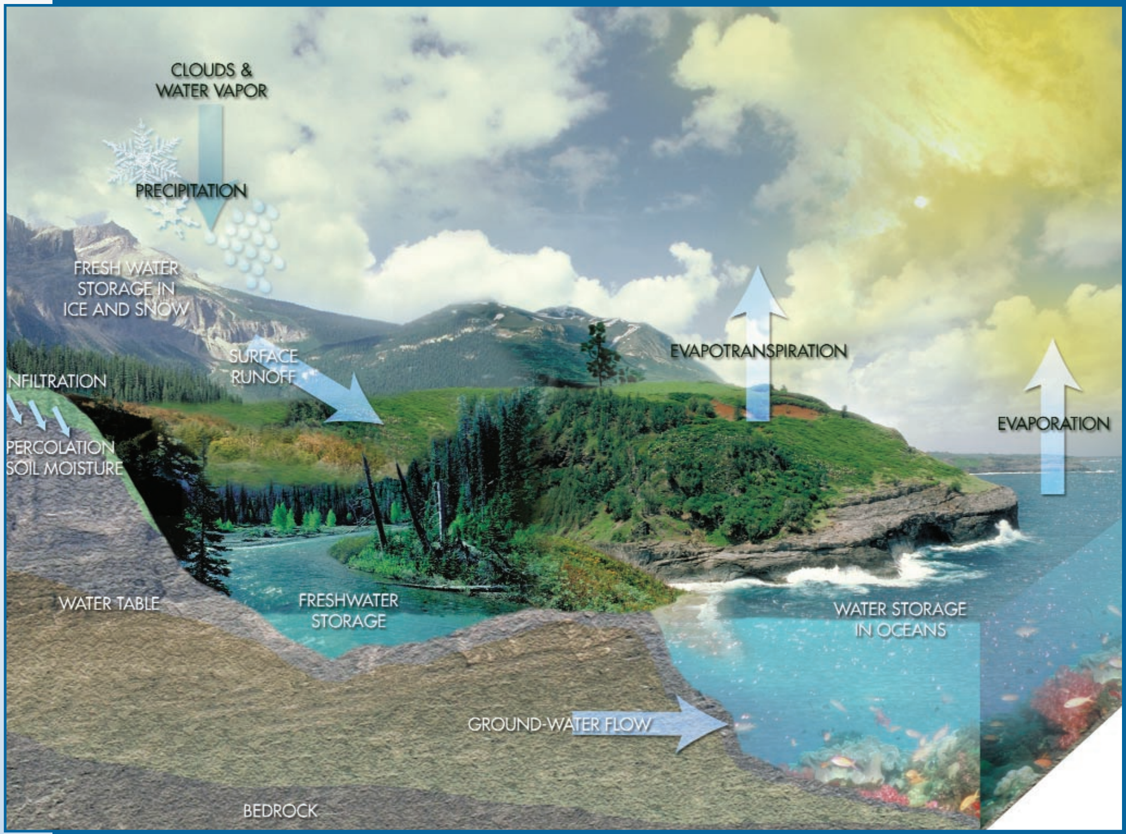
Understanding the ocean currents is important because the Earth's oceans are huge heat reservoirs, and ocean currents transport that heat from the equatorial regions to the poles and play a key role in regulating the Earth's climate. Changes in the nature of these currents can have a profound impact on weather all around the world. In addition, deep ocean currents are a subject of particular interest to oceanographers and their impact on climate has not yet been fully determined. GRACE measurements of ocean mass changes are expected to shed considerable light on the magnitude and effect of deep ocean currents.



This is a map that illustrates the heat exchange flux over the Earth's oceans. A negative value indicates an area where heat is being lost by the ocean and a positive value represents heat being absorbed by the ocean. The heat exchange flux plays a critical role in regulating the Earth's climate and data from GRACE should help to improve the accuracy of these measurements.

Tracking water movement on and beneath Earth's surface

The primary cause of fluctuations in 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 or water cycle (see diagram) and at a rapid rate relative to other slower moving processes such as erosion. Therefore, the gravitational variations observed by GRACE are primarily attributable to the movement of water throughout the water cycle. This means that by combining measurements from GRACE with measurements taken on the ground, scientists should be able to improve their models of the balance of water movement between the ocean and the land surface – 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 shows what is known as the water cycle. It illustrates how water, in solid liquid and vapor forms, circulates over, under and above the surface of the Earth. GRACE will have unprecedented capability to detect variations in gravity; gravity fluctuations correlate with variations in the density of the land surface below and can be exploited to track water movement. In effect, gravity becomes a tracer to track water movement our eyes cannot see. GRACE data may lead to the identification of new sources of fresh water – which is particularly of interest for populations located in arid regions of the Earth.

Tracking the movement and changing mass of ice sheets

GRACE can tell us about the movement of solid water as well – in the form of icecaps and glaciers. As ice depth increases, so too does the mass of the ice. GRACE data, when combined with height variations measured through ground-based aircraft and satellite measurements (like the GLAS instrument on ICESat) will allow for improved computations of ice sheet mass balance. An important question in climate change studies is whether icecaps and glaciers are shrinking, and if the melting water is entering the ocean and contributing to sea level rise. By combining GRACE and ICESat measurements, one can measure and remove the contribution due to postglacial rebound, which is the response of the Earth to the ice load during the last Ice Age. The combination of data can also help separate changes in ice density from changes in ice mass.

Improving information on sea-level heights and sea-level rise

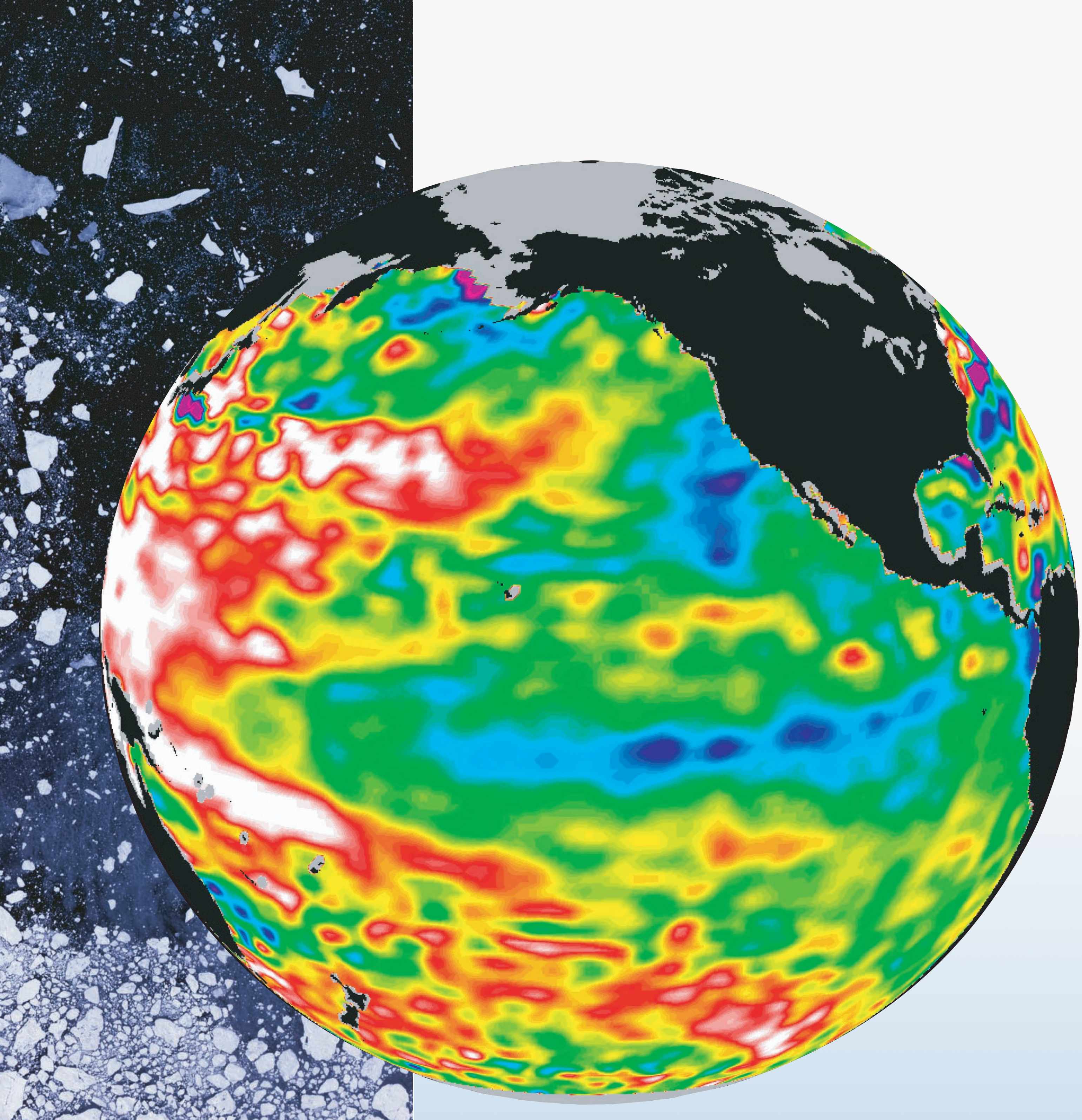
By combining the GRACE gravity field measurement with surface elevation measurements (such as from radar altimeters) scientists will be better equipped to distinguish between the mean ocean level changes due to thermal expansion and those due to actual redistribution of water – again by looking at gravity changes which correlate to mass changes. Both long-term ice sheet changes and thermal expansion of the oceans contribute to sea-level rise. Improved ability to distinguish between these two phenomena should lead to more accurate assessments of the extent of sea-level rise expected to result from global warming.

Tracking changes in the 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. For example, the characteristics of the continental lithosphere are a subject of varying opinions. Questions remain regarding its thermal and compositional nature, thickness, and mechanical properties. GRACE can track variations in the lithosphere by looking at the impact on the Earth's gravitational field. For example, GRACE will easily measure 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. Thus, GRACE should be able to distinguish between competing models of the lower mantle viscosity and contribute to the understanding of mantle convection.

Place holder for Post -Glacial Rebound or Mantle Convection with caption

This true-color image of the Larsen Ice Shelf and nearby icebergs that have split off from the shelf was obtained by Landsat-7 in February of 2001. Data from GRACE in conjunction with visible imagery and altimeter data should help to track changes in the mass of the ice sheets as never before possible.

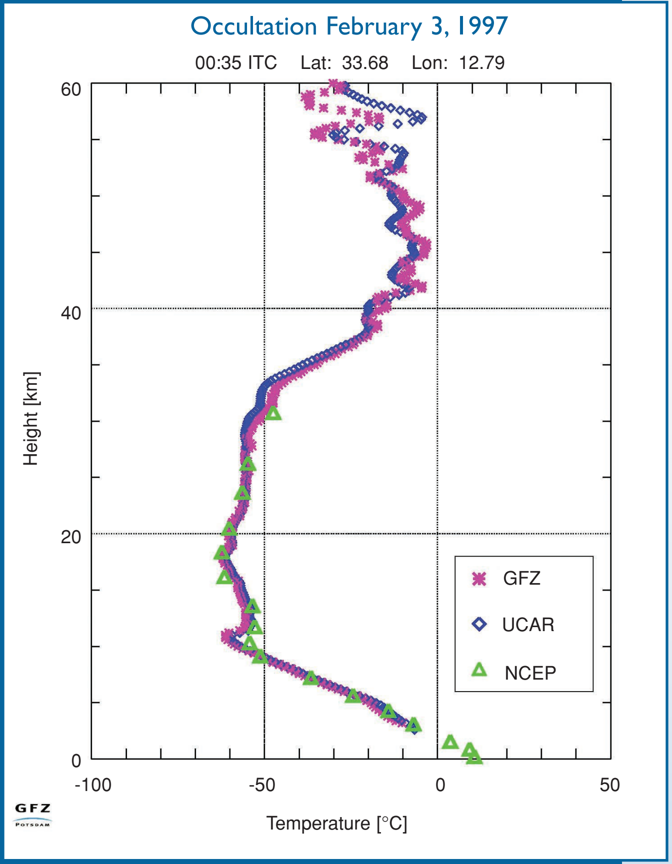


The image above was obtained in March of 2001 by TOPEX/Poseidon and shows sea-suface heights in the Pacific Ocean after the recent El Nino/La Nina. In the image above, sea level height is being compared to its average value based on climatology. Areas toward the blue end of the spectrum represent anomalously low heights for March and areas toward the red end represent anomalously high heights for March. Data from GRACE is expected to improve our ability to predict fluctuations in sea level height (which correlates to temperature) and to distinguish how much of the height change is due to thermal expansion. This should help to more accurately assess the possible impact of sea level rise expected from global warming.

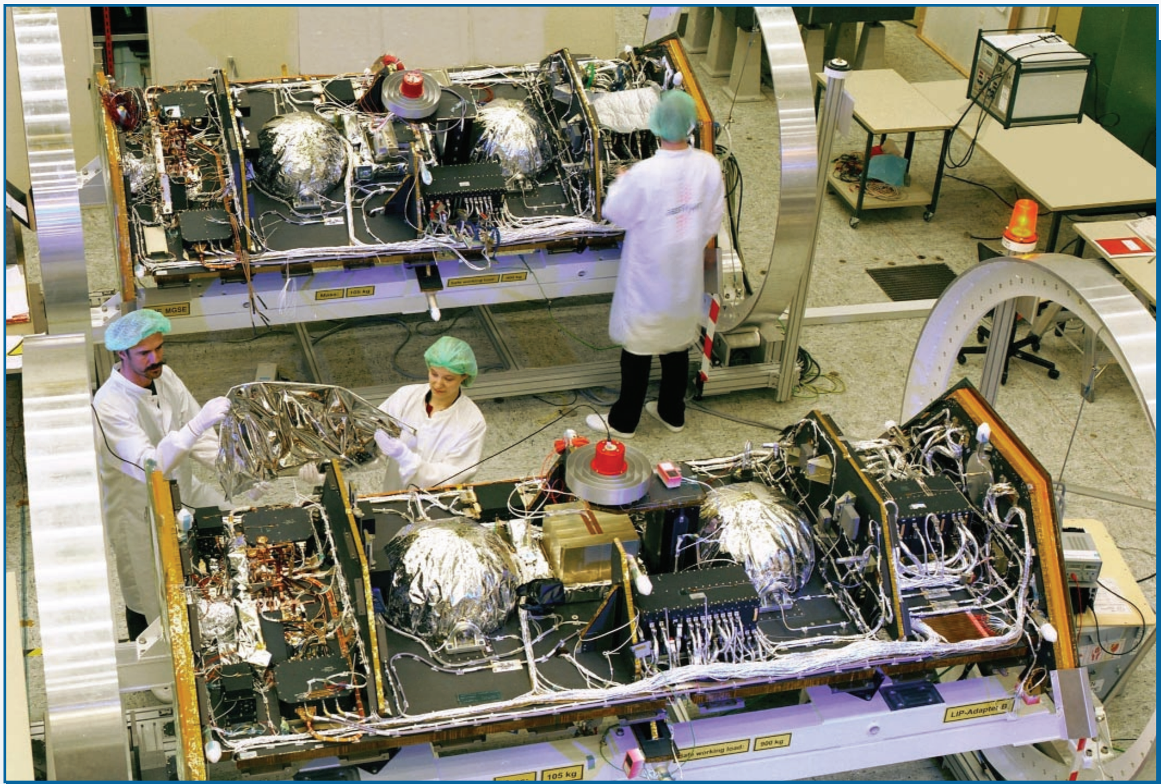
Improving the accuracy of GPS measurements and products derived from them

Today's Numerical Weather Prediction models have reached a state where major improvements of meteorological products will depend on more timely, precisely, densely and evenly distributed key parameters such as pressure, temperature, and humidity. A limb sounder on board GRACE will measure the amount by which the Global Positioning Satellite signal is distorted by the atmosphere. Scientists will use this data to develop key atmospheric datasets to improve the understanding and modeling of the short-term weather.

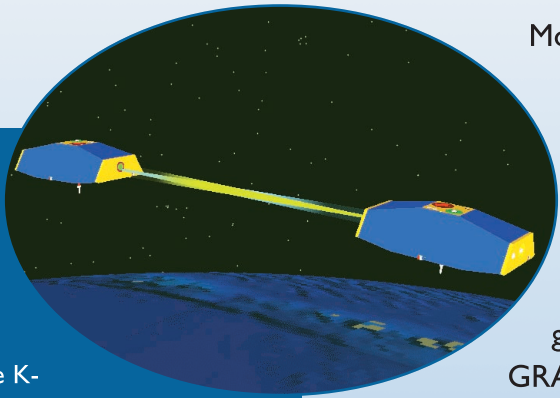
The graphic illustrates the output from a typical sounding measurement. This is a temperature profile from 3 February 1997. Data from three different sources is shown: GeoForschungZentrum (GFZ); National Center for Environmental Prediction (NCEP); and University Corporation for Atmospheric Research (UCAR). The limb sounder on board GRACE is expected to improve the accuracy of GPS measurements used for these retrievals, which should improve the accuracy of the profiles and contribute to improved ability to predict the short-term weather.



Instrumentation



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. It was taken the Astrium test facility in Friedrichshafen, Germany.



This is a schematic diagram of the two GRACE satellites in orbit with the K-Band microwave beam connecting them and tracking fluctuations in the distance between the two bodies. These fluctuations are used to measure changes in the gravitational field of the underlying surface.

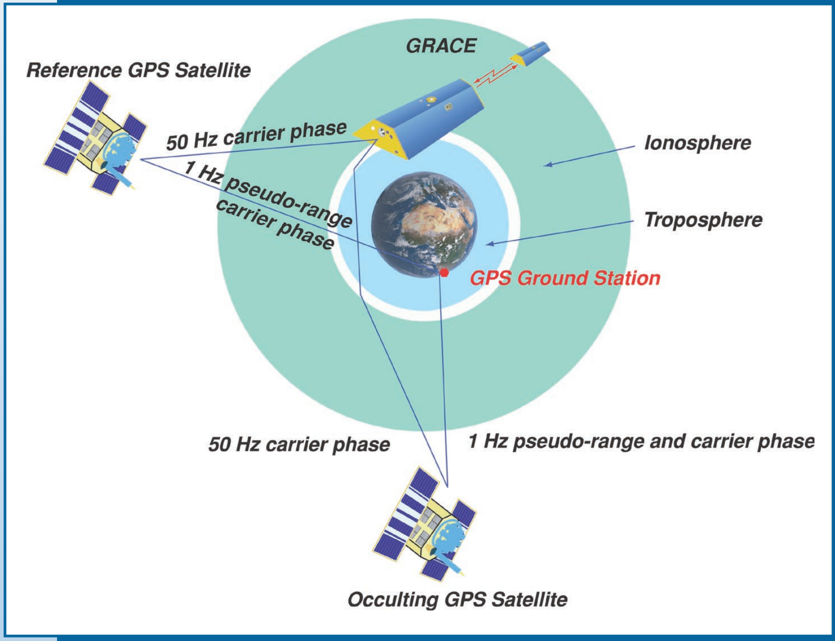
Most satellite missions — like Terra and Aqua — carry a suite of scientific instruments on board. GRACE is different because fluctuations in the distance between the twin satellites are used to derive the primary gravity measurement. So, for GRACE, the satellites are the primary instrument. GRACE will also carry one additional instrument, a GPS limb sounder intended to correct for atmospheric and ionospheric distortions to GPS measurements.

The gravity measurement

The primary gravity measurement is made by recording changes in the speed and distance between the two GRACE satellites. The two satellites fly in formation over the Earth and the precise speed of each satellite and the distance between them is constantly communicated via a microwave K-band ranging instrument. As the gravitational field changes beneath the satellites - correlating to changes in mass of the surface beneath - the orbital motion of each satellite is changed. This change in orbital motion causes the distance between the satellites to expand or contract and can be measured using the K-band instrument. From this, the fluctuations in the Earth's gravitational field can be determined.

The limb-sounding technique for atmospheric correction of GPS measurements

Each day the GRACE mission will provide several hundred measurements of how the signals from Global Positioning Satellites (GPS) are affected as they travel through the atmosphere. Just as light is refracted or bends as it enters water, the GPS signals are refracted as they pass through the atmosphere. By observing the signals in the atmosphere, profiles of the pressure, temperature, and humidity can be derived. These clues help the scientist predict the weather around the Earth. The GPS receivers on the GRACE satellite track refracted signals from the GPS satellites as they rise or set through the Earth's atmosphere (demonstrated in the diagram). The scientific term for this measurement is known as occultation and such measurements will be made throughout the mission life to assist us in predicting global weather.



This diagram 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 satellite is used as a reference.

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 DLR in Neustrelitz.

The next level of data processing is performed primarily 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 sent to UTCSR and GFZ, where the mean gravity field is derived from the calibrated and validated data. Data are archived for distribution at JPL's Physical Oceanography Distributed Active Data Center (PODAAC) and at GFZ 's Integrated System Data Center (ISDC). GRACE data include 30-day mean gravity fields, as well as profiles of air mass, density, pressure, temperature, water vapor, and ionospheric electron content.

Education and Public Outreach

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

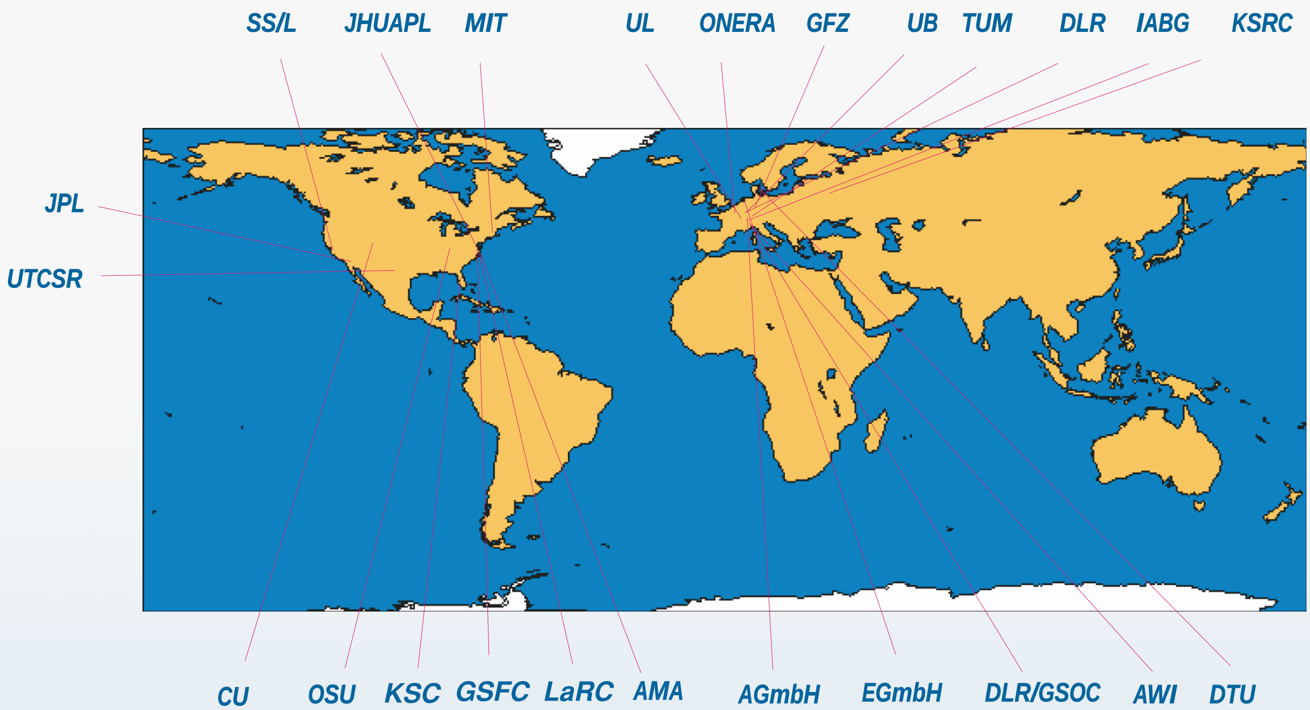
The Texas Space Grant Consortium (TSGC) partners with the mission team to develop and implement GRACE education and outreach. GRACE master teachers were selected from across the nation through an application and review process. These master teachers have created interdisciplinary K-12 educational materials 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. These 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 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 6-billion people living on this beautiful, blue planet. Through youth development and education we will enhance our understanding of this dynamic world.

Science Teams/Key Participants

The map below illustrates the locations of all the participants in the GRACE project. Clearly, the GRACE mission is truly an multi-national effort. It is a joint venture between NASA and the German Space Agency. Both a US and European Science Team have been established. Furthermore, institutions from five different countries are providing input, including government agencies, academia and private industry.



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 fur Luft und Rumfahrt	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	GeoForschungs Zentrum	Potsdam, Germany
IABG	IABG GmbH	Ottobrunn, Germany
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
E. Konemann	DLR, GRACE Manager
R. Fitzgerald	GSFC, GRACE Mission Manager
M.M. Watkins	JPL, Project Scientist

US 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

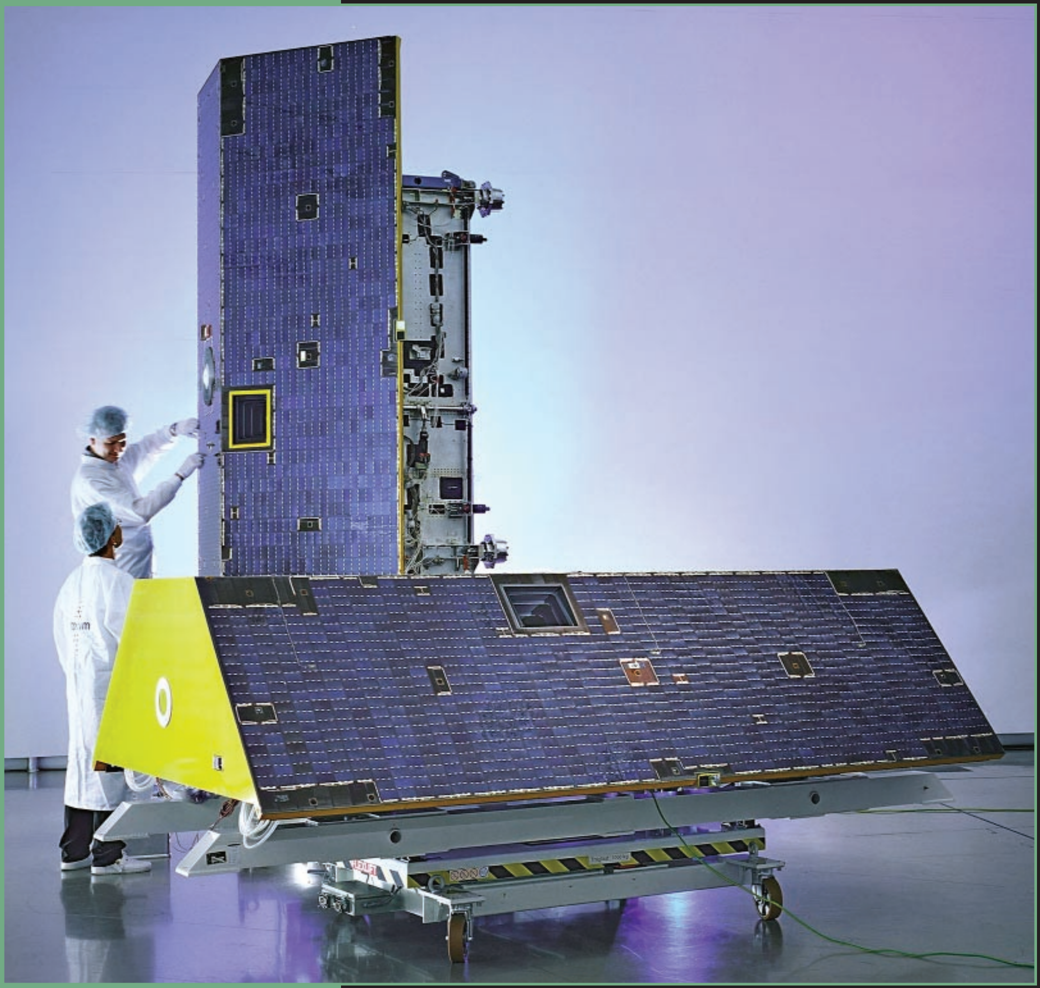
European Science Team

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

Technical Specifications

GRACE MISSION

Twins in orbit fly linked
by microwaves reveal
Earth Mass in motion



EUROCKOT
Launch Service Provider