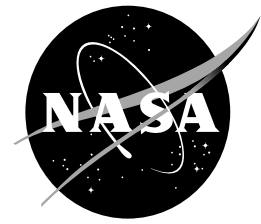


# NASA Facts

National Aeronautics and  
Space Administration



**Goddard Space Flight Center**  
Greenbelt, Maryland 20771  
<http://www.gsfc.nasa.gov>

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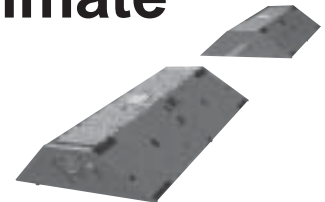
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## The Earth System Science Pathfinder Series

*These articles discuss the missions and science priorities of the ESSP Program.*

The ESSP Program: <http://essp.gsfc.nasa.gov>  
The GRACE Mission: <http://www.csr.utexas.edu/grace>  
NASA's Earth Observatory: <http://earthobservatory.nasa.gov>

# Studying the Earth's Gravity from Space: The Gravity Recovery and Climate Experiment (GRACE)

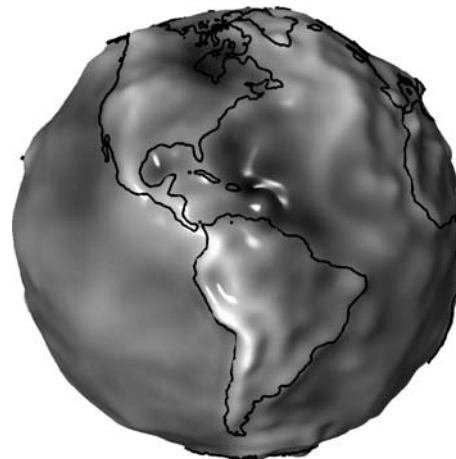


### Introduction

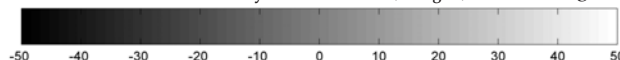
Gravity! What is it? You can't see it! You can't smell it! You can't touch it! But, it's there. In fact it's everywhere. We are familiar with gravity because we live with its effects every day. We know that when we drop an

object, it falls to the floor, and we know gravity is the reason. While the force of gravity is weak compared with other forces in nature, such as electricity and magnetism, its effects are the most far-reaching and

*The first 111 days of preliminary data from GRACE were used to produce a map of the Earth's gravity anomalies. A gravity anomaly map shows us how much the actual Earth's gravity field departs from "normal" as defined by a simplified mathematical gravity model that assumes the Earth is perfectly smooth and featureless. In this grayscale representation, brighter areas represent positive gravity anomalies (note the Andes mountain range in South America), while darker areas represent negative gravity anomalies (note the Puerto*



Earth's Gravity Field Anomalies (milligals)



*Rico trench and the area around Hudson Bay in Canada.) The gravity anomalies (measured in milligals—a unit of gravity acceleration named after Galileo) are only about one-millionth as strong as the actual gravity field, yet GRACE is sensitive enough to produce a detailed map of the variations like this one. Even more accurate maps will follow as the GRACE mission progresses. It is expected that GRACE will eventually be able to detect anomalies approaching one-billionth the strength of the Earth's average gravity field.*

dramatic. Gravity controls everything from the motion of the ocean tides to the expansion of the entire universe.

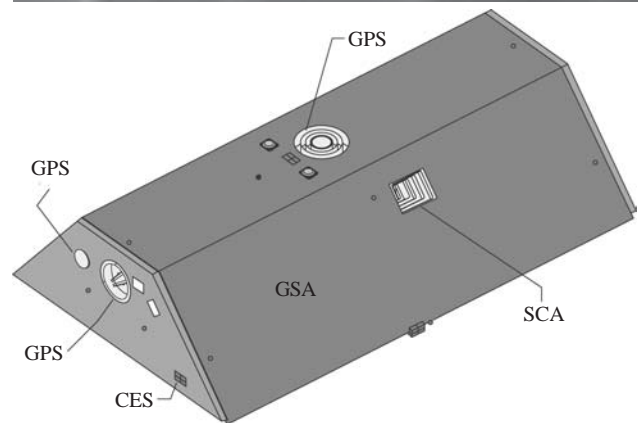
One of the NASA Earth Science Enterprise's main focus areas is Earth Surface and Interior studies, which includes studying the gravity field. The Gravity Recovery and Climate Experiment (GRACE), launched by NASA on March 17, 2002, is revealing more detail about the gravity field than has ever been available before. Data provided by GRACE are substantially improving our knowledge of Earth's gravity and of a number of very important aspects of global change.

How does GRACE really work? How is it possible for a satellite in space to make such a precise measurement of gravity from so far away? It seems like something only an expert in gravity studies could understand, and we might tend to think the details beyond our comprehension. Perhaps, however, if we take another look at how this familiar force really works, we can begin to better understand how GRACE measures gravity from space.

### Gravity 101

We can think of gravity as the invisible force that pulls two masses together. When we speak of mass, we're talking about the amount of matter in a substance. Density is a measure of how much mass is concentrated in a given space. Sir Isaac Newton discovered that as an object's mass increases, the gravitational attraction of that object increases. For example, a container filled with a more dense material like granite rock, has more mass and thus more gravitational attraction, than that same container filled with water. The Earth's Moon has considerably less mass than the Earth itself. Not only is the Moon smaller than the Earth, but it is only about 60 percent as dense as Earth. Thus, the gravitational attraction on the Moon is much less than it is here on Earth, and one weighs less on the Moon. This is why we have the famous images of the Apollo astronauts taking "one giant leap for mankind" on the Moon's surface.

On planet Earth, we tend to think of the gravitational effect as being the same no matter where we are on the planet. We certainly don't see variations anywhere near as dramatic as those between the Earth and the Moon. But the truth is, the Earth's topography is highly variable with mountains, valleys, plains, and deep



*The above picture shows the two identical GRACE satellites. The diagram immediately below the photo helps to identify the important parts—labels defined on pages 4 and 5.*

ocean trenches. As a consequence of this variable topography, density varies depending on one's exact position on the Earth's surface. These fluctuations in density cause slight variations in the gravity field, which, remarkably, GRACE can detect from space.

### A Closer Look at the Gravity Field

Although the Earth's surface is not uniform, for the most part, the variations are constant over very long time intervals. In other words, if a mountain was at a given location last month, it's probably going to be at

that same location this month as well, and for all intents and purposes the mass of the mountain is unchanged. This means that the gravity influence of these larger features is pretty much the same over a very long time and is known as the mean (or long term average) gravity field.

There are other mass variations, however, that occur on much smaller time scales. These are mostly due to variations in water content as it cycles between the atmosphere, oceans, continents, glaciers, and polar ice caps. These shorter-term mass fluctuations contribute to what is known as the time variable gravity field.

The mean gravity field is of considerable value in understanding the structure of the solid Earth and helping to reveal aspects of ocean circulation, while variations in the time variable gravity field are used for other applications such as studying changes in water storage over the continents, sea ice studies, sea level rise, deep ocean currents, ocean bottom pressure, and ocean heat flux. GRACE data have been used to create new mean gravity field maps and are also used to create very high-resolution maps of the monthly average gravity field that are especially useful for tracking changes in time-variable gravity effects.

### **Gravity Anomaly Maps and The Geoid**

The Earth's gravity field is depicted in two principal ways: *gravity anomaly maps* and maps of the Earth's *geoid*.

*Gravity anomaly maps* (see globe on front page) show how much the Earth's actual gravity field differs from the gravity field of a uniform, featureless Earth surface. The anomalies highlight variations in the strength of the gravitational force over the surface of the Earth. Gravity anomalies are often due to anomalous concentrations of mass in a region. For example, the presence of mountain ranges will usually cause the gravitational force to be more than it would be on a featureless planet—a positive gravity anomaly. Conversely, the presence of ocean trenches or even the depression of the landmass that was caused by the presence of glaciers millennia ago can cause negative gravity anomalies.

The *geoid* is a hypothetical surface that corresponds to mean sea level in the absence of winds, currents, and most tides. The geoid is important because it

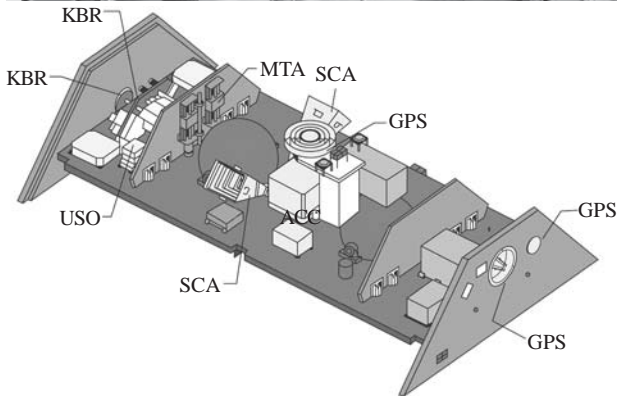
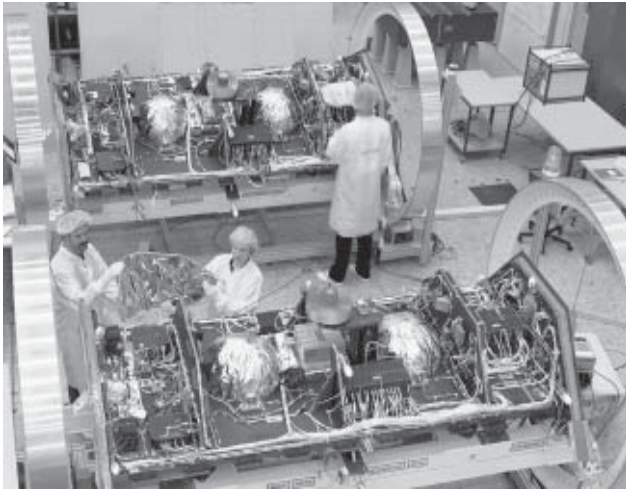
serves as a useful reference surface. It defines the horizontal everywhere and gravity acts perpendicular to it. A carpenter's level aligns itself along the geoid and a carpenter's plumb bob points down the vertical or perpendicular to the geoid. Water will not flow in aqueducts if the pipes are perfectly aligned along the geoid. Surveyors use knowledge of the geoid and the horizontal when they lay out highways and boundaries.

Producing a precise model of the geoid has proven to be a challenge. Until recently, there was no single source for producing a geoid map. Data from several dozen satellites, along with surface measurements over land and from ships at sea, had to be combined to produce a model of the gravitational field. Traditionally, the models have done a fairly good job reproducing large-scale features of the gravity field, but have fallen short when it comes to reproducing finer-scale features or accurately describing time-variable gravity effects like those associated with the hydrologic cycle.

GRACE changes that, as for the first time, we get global coverage every 30 days from a single source. GRACE is also able to measure the gravity field with a level of precision that is several orders of magnitude better than any existing measurement. The finer details of the geoid that have evaded scientists for so long are on the verge of being revealed. GRACE also gives us our best opportunity to date to study time-variable gravity effects. As the mission progresses and more data are added to the model, the resolution of the geoid will improve even further.

As the geoid map becomes more detailed, the accuracy of satellite altimetry, synthetic aperture radar interferometry, and digital terrain models covering large land and ice areas—all used in remote sensing applications and cartography—will improve. These techniques provide critical input to many scientific models used in oceanography, hydrology, geology, and related disciplines, and will be used for a variety of applications including:

- measuring shallow and deep ocean currents;
- measuring the changing mass of polar ice caps;
- measuring changes in water resources on land;
- understanding sea level change resulting from ocean temperature and water mass changes;
- understanding atmosphere-ocean mass exchange;



The above picture shows the two GRACE satellites with the solar panels removed and reveals many of the key spacecraft components. The diagram immediately below the photo helps to identify many of the important parts—labels defined on pages 4 and 5.

- understanding the forces that generate Earth's geomagnetic field; and
- understanding internal Earth forces that move tectonic plates and result in earthquakes and volcanic eruptions.

This enhanced knowledge should lead to a better understanding of the forces that drive El Niño, more accurate seasonal forecasts of Earth's weather patterns, an ability to track the changing distribution of water resources in critically important land aquifers, and improved forecasting of natural hazards.

### The Workings of GRACE

GRACE is different from most Earth observing satellite

missions—Terra and Aqua for example—because it doesn't carry a suite of independent scientific instruments on board. It does not make measurements of the electromagnetic energy reflected back to it from the Earth's surface. Instead, the two GRACE satellites themselves act in unison as the primary instrument. Changes in the distance between the twin satellites are used to make gravitational field measurements.

The two identical satellites orbit one behind the other in the same orbital plane at an approximate distance of 220 km (137 miles). As the pair circles the Earth, areas of slightly stronger gravity (greater mass concentration) will affect the lead satellite first, pulling it away from the trailing satellite, then as the satellites continue along their orbital path, the trailing satellite is pulled toward the lead satellite as it passes over the gravity anomaly. The change in distance would certainly be imperceptible to our eyes, but an extremely precise microwave ranging system on GRACE is able to detect these minuscule changes in the distance between the satellites. A highly accurate measuring device known as an accelerometer, located at each satellite mass center, will be used to measure the non-gravitational accelerations (such as those due to atmospheric drag) so that only accelerations caused by gravity are considered. Satellite Global Positioning System (GPS) receivers will be used to determine the exact position of the satellite over the Earth to within a centimeter or less. Members of the GRACE science team can download all this information from the satellites, and use it to construct monthly maps of the Earth's average gravity field during the planned five-year mission.

### Key Spacecraft Components

Now that we have an idea how GRACE works, let's peer "under the hood" of this high-tech wonder and understand some of the component parts of GRACE. These components can be seen in the photos on pages 2 and 4; the letters following the name of each component in parentheses correspond to the labels on the diagrams below each photo.

**K-band Ranging System (KBR).** Provides precise (within 10  $\mu\text{m}$ ) measurements of the distance change between the two satellites needed to measure fluctuations in gravity.

**Ultra Stable Oscillator (USO).** Provides frequency generation for the K-band ranging system.

**SuperSTAR Accelerometers (ACC).** Precisely measures the non-gravitational accelerations acting on the satellite.

**Star Camera Assembly (SCA).** Precisely determines the two satellites' orientation by tracking them relative to the position of the stars.

**Coarse Earth and Sun Sensor (CES).** Provides omnidirectional, reliable, and robust, but fairly coarse, Earth and Sun tracking. Used during initial acquisition and whenever GRACE operates in safe mode.

**Center of Mass Trim Assembly (MTA).** Precisely measures the offset between the satellite's center of mass and the "acceleration-proof" mass and adjusts center of mass as needed during the flight.

**Black-Jack GPS Receiver and Instrument Processing Unit (GPS).** Provides digital signal processing; measures the distance change relative to the GPS satellite constellation.

**Globalstar Silicon Solar Cell Arrays (GSA).** Covers the outer shell of the spacecraft and generates power.

### The Future

GRACE builds on the heritage of GFZ's Challenging Minisatellite Payload (CHAMP) mission in the area of Earth gravity field measurements. The revolutionary new configuration for GRACE—using two satellites following one another on the same orbital track—is expected to improve the accuracy of gravity field measurements dramatically. The European Space Agency plans to launch the Gravity Field and Steady-State Ocean Circulation (GOCE) mission in 2006 as part of its Living Planet Programme, whose measurements of the gravity field will complement those made by GRACE. The science community believes that even more accurate gravity measurements may be possible in the future as new technologies are developed. One possibility involves replacing the microwave ranging system on GRACE with a laser ranging system. This would allow for even more precise distance measurements than GRACE can obtain and thereby increase the accuracy of the resulting gravity field measurements.

### The ESSP Program

A component of NASA's Earth Science Enterprise (ESE), 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 developing and operating remote sensing instruments and conducting research investigations using data obtained from these instruments. Subsequent launches are planned over the next few years. A Program Manager located at Goddard Space Flight Center is responsible for overall management of the ESSP Program. Each individual mission is led by a Principal Investigator (PI) who oversees all aspects of the mission, from ensuring the science accuracy to making sure the mission stays on budget and on time.

### GRACE Management

GRACE was the first ESSP mission to launch, and is a joint partnership between the National Aeronautics and Space Administration (NASA) in the United States and the Deutsches Zentrum für Luft und Raumfahrt (DLR) in Germany. The Principal Investigator is from the University of Texas Center for Space Research (UTCSR) and the Co-Principal Investigator is from the GeoForschungsZentrum (GFZ). NASA's Jet Propulsion Laboratory (JPL) has responsibility for the Project Management of GRACE, and NASA's Goddard Space Flight Center maintains responsibility for Mission Management.

Management of the GRACE Project is further delegated among the following five systems:

**Satellite System (SAT).** JPL led the development of the Satellite System in partnership with Space Systems/Loral (SS/L) and Astrium GmbH (AGmbH). Engineers at JPL developed the GPS receiver and the laser retroreflective assembly. AGmbH provided major elements of two flight satellites based on an existing small satellite designed for the CHAMP mission. SS/L provided the attitude control system, microwave instrument electronics, and system and environmental testing.

**Science Instrument System (SIS).** The SIS is managed by JPL and includes all elements of the inter-satellite ranging system, the GPS receivers, and associated sensors such as the star cameras and accelerometers. This system also coordinates the integration activities of all sensors, assuring their compatibility with each other and the satellite.

**Launch Vehicle System (LVS).** The LVS was managed by the Launch Vehicle System Manager at DLR and supported by JPL and its contractors. The LVS included the three-stage ROCKOT launch vehicle used for launch, multi-satellite dispenser, and the personnel, test equipment, and facilities for preparation, integration, and launch of the satellites.

**Science Data System (SDS).** The SDS functions include science data processing, distribution, archiving, and product verification. The SDS is a distributed entity and managed by UTCSR in cooperation with JPL in the U.S. and GFZ in Germany. The cooperative approach includes sharing of processing tasks, harmonization of product archives, and validation/comparison of products. Data and products to be processed and archived by the SDS include corrected

inter-satellite range and accelerometer measurements, GPS orbit and occultation data, and gravity field and GPS occultation products. The SDS also receives, processes, and archives ancillary data (e.g., meteorological fields) necessary for data processing and verification.

**Mission Operations System (MOS).** The MOS consists of facilities and resources of the German Space Operations Center (GSOC), tracking antennas at Weilheim and Neustrelitz, and other stations and facilities needed for supporting launch and early orbit procedures and contingency operations. These facilities are used to monitor and control the satellite, perform initial processing of the telemetry data, and deliver all data to the SDS for further processing and generating science products. In addition to real-time operations, the MOS function provides the Central Checkout System for ground testing using command and data interfaces. The operations team also monitors satellite performance and health throughout the duration of the mission. Mission operations are conducted at the GSOC control center in Oberpfaffenhofen, Germany.

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To find out more about the GRACE mission and the ESSP program please visit the following websites:

<http://www.csr.utexas.edu/grace>  
<http://essp.gsfc.nasa.gov>