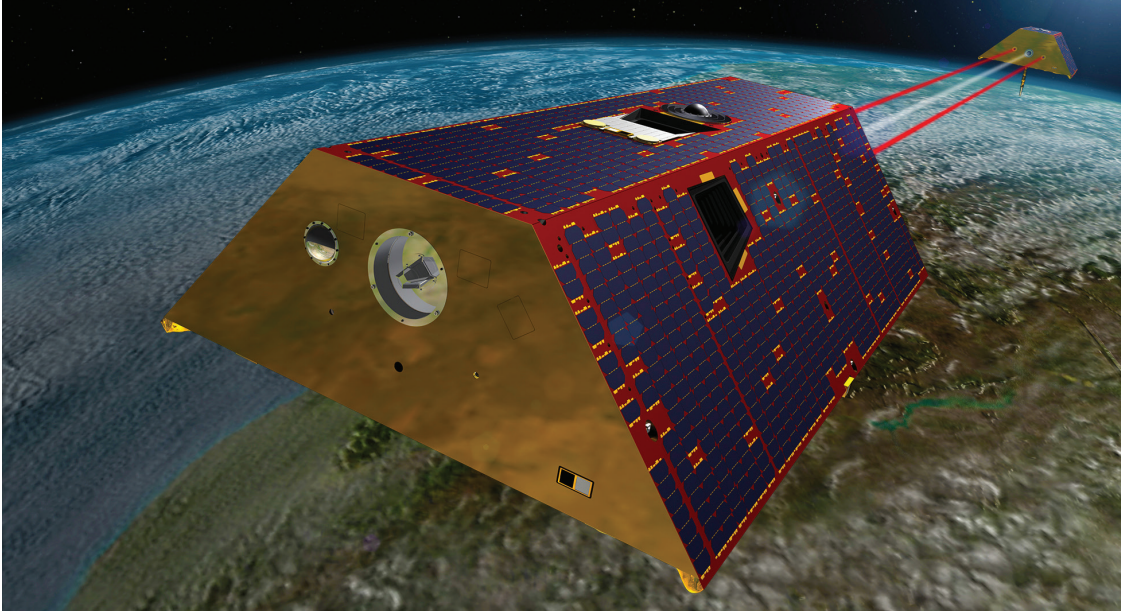


GRACE-FO

Gravity Recovery and Climate Experiment Follow-On



Many of today's most pressing climate science challenges hinge on knowing how water is moving on Earth. But that isn't always easy to measure. Water can be in plain sight in a lake or hidden underground. It can evaporate in moments when sunshine heats Earth's surface or be stored for centuries as ice in a glacier.

Regardless of whether water is solid, liquid or vapor, visible or invisible, one of its traits does not change: its mass. That mass has a gravitational pull. By tracking the changing pull of gravity around Earth very precisely, the U.S./German Gravity Recovery and Climate Experiment, or GRACE, observed the movement of Earth's water masses from the top of the Himalayas to the deepest ocean depths and underground for 15 years, 2002 to 2017.

GRACE Follow-On, scheduled to launch in spring 2018, will continue the critical mission of measuring the movements of mass within and between Earth's atmosphere, oceans, land and ice sheets, as well as below Earth's surface. It will also continue NASA's extremely successful partnership with Germany, which began with the original GRACE mission, through its German mission partner GeoForschungsZentrum.

Mission Overview

If our planet were a perfectly round, uniform sphere, every location would have the same mass. A satellite orbiting this unlikely Earth would undergo the same gravitational pull everywhere. The real Earth has mountains and flat-

lands, ocean trenches and seamounts, iron ore and sand. The mass below an orbiting satellite varies constantly, meaning gravitational pull varies constantly as well.

Most of Earth's mass hardly moves at all from one month to the next, barring natural disasters or human intervention. But water is always moving — flowing, evaporating, falling as rain or snow, and so on. Rapid changes in a region's gravitational pull are mostly the result of moving water.

The concept of using two satellites flying in formation to measure gravity and its changes can be traced back to the late 1960s. But it wasn't until the 1990s that advances in technology, notably GPS, matured enough to enable the development of a viable flight mission, which culminated in the launch of GRACE in 2002.

Throughout the GRACE mission, researchers worldwide developed innovative techniques to use GRACE's data and combine it with other observations and models for new insights into the Earth system. Here are a few of the areas where GRACE has revolutionized scientific understanding:

- In the decades before GRACE, observations of melting ice in Greenland and Antarctica from the ground or by remote sensing were few — not enough even to be sure whether Antarctica's ice sheet was growing or shrinking overall. GRACE measurements unequivocally show that Greenland has been losing about 280 gigatons of ice per year on average — a bit less than twice the weight of Mt. Everest — and Antarctica has

NASAfacts

lost slightly under 120 gigatons a year. With indications that both melt rates might be increasing, it is crucial to continue these observations with GRACE-FO and future GRACE-like missions.

- Water stored within soil or farther below ground in aquifers is very sparsely measured from the ground. By measuring changing mass on what appears to be dry land, GRACE has found that in a third of Earth's largest aquifers, humans are pumping out groundwater faster than it is being replenished.
- Rising sea levels have been monitored very precisely by satellite altimetry missions for about 25 years. These measurements, however, give only the grand total. To understand the pace of future sea level rise, scientists need to know how much of this total comes from each of two main causes: melting ice flowing into the ocean from land, and the expansion of seawater as it warms. By combining GRACE and altimetry data, scientists are able to partition these two causes.
- The viscous mantle under Earth's crust moves ever so slightly in response to changes in water mass near the surface. GRACE has a community of users who calculate these shifts for their research. Scientists at NASA's Jet Propulsion Laboratory in Pasadena, California, used GRACE data to calculate how ice sheet loss and groundwater depletion have literally changed the rotation of Earth as the system adjusts to these movements of mass.

These are only a few of the findings that the precise measurement of Earth's changing gravity has allowed. Scientists continue to develop new techniques to extract new information from the GRACE data set.

Extending these measurements for an additional five years with GRACE-FO will not only allow tracking of these critical changes in the Earth system to continue, but it will improve understanding of the underlying processes causing these changes. Many processes that GRACE measured were poorly quantified, or not quantified at all, before the mission. With 15 years of data, scientists have been able to make the discoveries mentioned here. But, since many natural climate patterns can take several decades to unfold, 15 years is not always enough time to tell whether a particular phenomenon is just a natural variation or the result of a warming climate. Extending the data set with GRACE-FO will provide the necessary record to recognize the signal of climate change from the background noise of natural variability and should improve forecasts of sea level rise and other significant threats to society.

Instrument Overview

Unlike other Earth-observing satellites, which carry instruments that observe some part of the electromagnetic spectrum — for example, visible light or infrared energy — the two GRACE-FO satellites themselves act as the observational system.

GRACE-FO uses the same method to map gravitational fields that GRACE and the lunar Gravity Recovery and Interior Laboratory (GRAIL) mission used. The satellites travel along the same orbit, one about 137 miles (220 kilometers) behind the other. As the lead satellite approaches a region with high mass, such as a mountain range, the higher gravita-

tional pull tugs the satellite a little farther ahead of the following satellite. Moments later, the following satellite is pulled forward in its turn, shortening the distance between them. When the lead satellite moves past the mountains, their high mass drags at it from behind, again narrowing the gap between the two satellites.

Both satellites constantly send microwave signals to each other, precisely measuring the changes in distance between them. "Precisely" is the key word: the measurement is accurate to within a few microns, about the thickness of a blood cell. A highly accurate accelerometer, located at each satellite's center of mass, measures accelerations caused by anything other than gravity, such as atmospheric drag. Satellite GPS receivers determine the exact position of the satellites in orbit around the Earth.

All this information is sent to the ground and forwarded to data processing centers, where the observations are combined to construct monthly maps of the Earth's average gravity field. The maps offer details of how mass, in most cases water, is moving around the planet and changing from month to month and year to year.

The two GRACE-FO satellites will also test an experimental instrument that uses laser light instead of microwaves to measure the separation distance between satellites. For future GRACE-like missions, a laser instrument could improve the accuracy of the measurement by tenfold or more and lead to higher-resolution gravity missions. The instrument is jointly managed by JPL and the Max Planck Institute for Gravitational Physics (Albert-Einstein Institut) in Hannover, Germany.

Launch and Orbit

GRACE-FO will be launched as part of a commercial rideshare mission, sharing a SpaceX flight-proven Falcon-9 rocket with five Iridium Communications, Inc., satellites. The rocket will launch from Vandenberg Air Force Base, California, no earlier than late April.

The GRACE-FO satellites will deploy into a nearly circular polar orbit at an altitude of almost 300 miles (490 kilometers). Each orbit will take about 90 minutes to complete.

The two satellites, GRACE-FO-A and GRACE-FO-B, will deploy at the same time about 10 minutes after launch. GRACE-FO-A will then move ahead of GRACE-FO-B at about 0.3 meters per second until the spacecraft reach their optimal separation distance of 137 miles (220 kilometers) about three days after launch. The operations team will then do drift stop maneuvers to stop the satellites from moving farther apart.

Mission Duration

GRACE-FO is designed to operate for at least five years.

Partners

GRACE-FO is a partnership between NASA and the German Research Center for Geosciences (GeoForschungsZentrum, or GFZ). JPL manages the mission for NASA's Science Mission Directorate, with participation from the Earth Systematic Missions Program Office at NASA's Goddard Space Flight Center in Greenbelt, Maryland.