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Editor's Corner

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On May 22, 2018 at 12:47 PM PDT (3:47 PM EDT), the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission launched from Vandenberg Air Force Base in California aboard a SpaceX Falcon 9 launch vehicle—see launch photo below—as a shared ride with five Iridium NEXT communications satellites. The twin GRACE-FO satellites successfully separated from the spacecraft over the Pacific Ocean and are now slowly drifting toward their operational positions.

Like its predecessor, GRACE-FO uses a microwave ranging link—called the Microwave Instrument (MWI)—to determine the precise *separation distance* between two identical satellites orbiting Earth about 220 km (137 mi) apart at an initial altitude of approximately 490 km (305 mi). The MWI, using two frequencies at 24 GHz (K-band) and 32 GHz (K_a-band), is capable of measuring the distance between the two satellites to within one micrometer.

The changes in separation distance, tracked over time, can be used to create maps of Earth's gravity field at least every 30 days, which allows for tracking of changes in Earth's near-surface mass. In addition, each of the satellites will use GPS antennas to supply at least 200 profiles of atmospheric temperature distribution and water vapor content daily—see *Measuring Atmospheric Temperature and Humidity* on page 8 of this issue.

continued on page 2

The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission launched onboard a SpaceX Falcon 9 rocket, Tuesday, May 22, 2018, at 12:47 PM PDT (3:47 PM EDT) from Space Launch Complex 4E at Vandenberg Air Force Base in California. **Photo credit:** NASA/Bill Ingalls

In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive.*

GRACE-FO also tests a new experimental ranging technology that uses lasers instead of microwaves—called the Laser Ranging Interferometer (LRI). While the new technology provides a stepping stone to future missions, it also measures changes in the angle between the two spacecraft and thus enhances conventional microwave-ranging observations. Together, the very precise measurements of location, force, and orbital change translate into an observation of gravity with improved accuracy. Congratulations to the entire GRACE-FO team! Please turn to page 4 of this issue to learn more about the mission.

NASA is preparing to launch two instruments to the International Space Station (ISS) this year: the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and the Global Ecosystem Dynamics Investigation (GEDI, pronounced like "Jedi" of *Star Wars* fame).[1]

ECOSTRESS was delivered to Kennedy Space Center on April 9, 2018, where it is in final preparations for launch to the ISS aboard the SpaceX-15 commercial resupply mission (CRS-15), currently scheduled to launch no earlier than June 28, 2018. ECOSTRESS will be robotically installed on the exterior of the station's Japanese Experiment Module–External Facility (JEM-EF) site 10 as soon as it arrives at the ISS.

ECOSTRESS is expected to provide key insights into how plants respond to heat and water stress by measuring *evapotranspiration* (ET).[2] These measurements allow scientists to understand the way in which plants respond to changing water availability. In addition, scientists hope to determine how changes in ET throughout the day affect plant growth.

In practical terms, the year of data anticipated from ECOSTRESS will also be useful for agricultural water managers. By working with the USDA and other partnering organizations, the ECOSTRESS team will advance our understanding of how key regions are affected by drought conditions and evaluate ways in which water management communities can make more efficient use of water resources for agriculture. The high spatial resolution of ECOSTRESS data will be particularly useful for research on the effects of drought on agriculture at the field-scale. While ECOSTRESS data will initially be used to address key ecosystem questions, they can also be used for a range of other applications such as studying volcanic activity, urban heat stress and heat waves, and surface temperature for ecosystem and resource management.

ECOSTRESS was built at and is managed by JPL, with **Simon Hook** serving as Principal Investigator (PI). To learn more about the current status of the mission as it prepares for launch, please see the News story on page 33 of this issue.[3]

[1] Both ECOSTRESS and GEDI were selected in 2014 as the winning proposals from the Earth Venture Instrument-2 (EVI-2) Announcement of Opportunity. Earth Venture is run by NASA's Earth System Science Pathfinder program, which oversees a portfolio of projects ranging from satellites, instruments on the space station, and suborbital field campaigns on Earth that are designed to be lower-cost and more focused in scope than larger, free-flying satellite missions.

[2] *Evapotranspiration* is the combined effects of *transpiration*, the process plants use to release water in order to regulate heat (similar to the way humans perspire) and *evaporation* of water from the soil.

[3] To learn more about ECOSTRESS, visit *https://ecostress.jpl.nasa.gov*.

Meanwhile, GEDI is also now on an accelerated track for launch, after being moved from the SpaceX CRS-18 mission, which is now delayed to May 2019, to SpaceX CRS-16, which is currently scheduled for a November 2018 launch. The move to an earlier launch window is possible because the GEDI team's plan all along had been to have the GEDI instrument ready to launch by this fall. The lidar instrument is now undergoing final integration and testing at GSFC.

While NASA has flown multiple Earth-observing lidars in space (e.g., ICESat and CALIPSO) GEDI will be the first to provide high-resolution laser ranging of Earth's forests. Like ECOSTRESS, it will be robotically installed on the exterior of the station's JEM-EF site 6. That perch will be the perfect vantage point from which to measure the structure of Earth's tropical and temperate forests in high resolution and in three dimensions. These measurements will help fill in critical gaps in scientists' understanding of how much carbon is stored in the world's forests, the potential for ecosystems to absorb rising concentrations of CO_2 in Earth's atmosphere, and the impact of forest changes on biodiversity.

The University of Maryland, College Park is leading development of GEDI, with **Ralph Dubayah** serving as Principal Investigator; the instrument is being built at GSFC.[4]

Coincident GEDI and ECOSTRESS measurements provide a unique synergy to address ecosystem dynamics questions that cannot be answered using the instruments independently. The measurements from ECOSTRESS will provide information on the plant's function, evaporation, and its water-use efficiency. GEDI will provide information on the vegetation structure. Together these data can be used to obtain a better understanding of canopy functional traits and the global carbon sink potential. These data will be further complemented with data from two other instruments scheduled for launch to the ISS in 2019: NASA's Orbiting Carbon Observatory-3 (OCO-3) and the Japanese METI's Hyperspectral Imager Suite (HISUI). These instruments will collect information on vegetation functional traits and chemical composition through high-spectral-resolution measurements. Together these datasets will provide an unprecedented opportunity to better understand the Earth's vegetation.[5]

With regard to the status of ongoing missions, in our last issue, we reported that, on February 22, 2018, CloudSat successfully exited the Afternoon "A-Train" constellation via two thruster burns that placed the satellite in an orbit below the altitude of the A-Train and near the *CALIPSO graveyard orbit*—the orbit altitude that will be used by the CALIPSO spacecraft for eventual end-of-life operations.[6] We are delighted to report that CloudSat resumed taking data in Daytime-Only Operations (DO-Op) mode from its new position on May 7, 2018. The satellite is successfully operating with three of four reaction wheels, and has full capability to make both large and small on-orbit maneuvers. The CloudSat and CALIPSO teams are discussing future operational plans, including an option for both CALIPSO and CloudSat to fly at the CALIPSO graveyard orbit and resume formation-flying under the A-Train. A decision has not yet been reached.

Last but not least, as it has done for the past six years, NASA participated in Earth Day activities held April 19-20 at Union Station in Washington, DC. This year's theme was *Amazing Technology.* The event featured 23 hands-on activities that ran the gamut from virtual reality experiences, to classifying coral using a touchscreen interface, to using a handheld spectrometer to test the reflectance of different vegetables. The centerpiece of the outreach, as it is with many NASA exhibits, was the Hyperwall—a nine screen, high definition video wall—where NASA's senior management, scientists, and outreach representatives delivered 40 multimedia stories over the course of the two-day event. Each story lasted about 15 minutes, covering a variety of Earth-science, heliophysics, planetary, and space-science topics. This was an extremely successful outreach event for NASA. Many thanks to all participants and the Science Communications Support Office for organizing this activity each year. Turn to page 13 of this issue to learn more about this year's Earth Day. ■

[4] To read a recent more detailed summary of the status of GEDI, see the "Summary of the Fourth GEDI Science Definition Team Meeting" in the March–April 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 2**, pp. 17-19—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Mar_Apr_2018_color%20508_0.pdf*]. There was also a more recent NASA press release available at *https://www.nasa.gov/feature/goddard/2018/may-the-forest-be-with-you-gedi-to-launch-to-iss*.

[5] To learn more about the potential synergies between GEDI, ECOSTRESS, OCO-3, and HISUI, see the article by Stavros *et al.* in the June 22, 2017 issue of *Nature Ecology & Evolution*—*https://www.nature.com/articles/s41559-017-0194*.

[6] To learn more, see "CloudSat Exits the A-Train" in the March–April 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 2**, p. 4].

Note: List of undefined acronyms from the *Editor's Corner* and the *Table of Contents* can be found on **page 36**.

GRACE-FO: Tracking Earth's Mass in Motion

EDITOR'S NOTE: This feature content is taken from the GRACE-FO pre-launch mission brochure (*https://eospso.gsfc.nasa.gov/sites/default/files/publications/GRACE_FO%20Mission%20Brochure_508.pdf*). While the intent is to reprint it with its original content largely intact, it has been modified slightly to match the style used in *The Earth Observer*, and to fit the layout space allocated for it.

But regardless of whether water is solid, liquid, or vapor, visible or invisible, it has one attribute that does not change: its mass. Because everything that has mass inevitably has a gravitational pull associated with it, a unique twin satellite observing system has been used to measure the changing forces of gravity to track and follow Earth's water masses from the top of the Himalayas to the deepest ocean depths and deep underground.

Mass Transport and Gravity Change On Earth

Panta rhei—"Everything flows." These famous words by the Greek philosopher Heraclitus express the truth that our complex world is ever changing and evolving. Even Earth's gravity field is continually changing. The pull of gravity varies naturally from place to place on Earth, depending on the mass distribution; greater mass exerts a stronger gravitational pull. But gravity also changes constantly as mass moves. While the masses of Earth's land features, such as mountains and valleys, change relatively slowly, the amount of water above, on, or below a particular location can vary seasonally, monthly, weekly, and even daily as water cycles between the subsystems (e.g., atmosphere, land, ocean, glaciers, polar ice caps, and underground).

On Earth, the processes that couple and transport water and energy are fundamental to today's most pressing climate science challenges. However, keeping track of Earth's evolving water system is a formidable task. Water constantly changes its shape, form, and state as it cycles between the ocean, atmosphere, and land—see **Figure 1**. It is in plain sight in lakes, rivers, and seas. It infiltrates the soil and groundwater. It accumulates on the ground as snow and can be stored as ice in glaciers and ice sheets, sometimes for hundreds and thousands of years. This makes it challenging to comprehensively observe and measure how much water cycles between Earth's subsystems. But regardless of whether water is solid, liquid, or vapor, visible or invisible, it has one attribute that does not change: its mass. Because everything that has mass inevitably has a gravitational pull associated with it, a unique twin satellite observing system has been used to measure the changing forces of gravity to track and follow Earth's water masses from the top of the Himalayas to the deepest ocean depths and deep underground. The measurements contribute to the assessment and monitoring of the Earth's heat and sea level budgets.

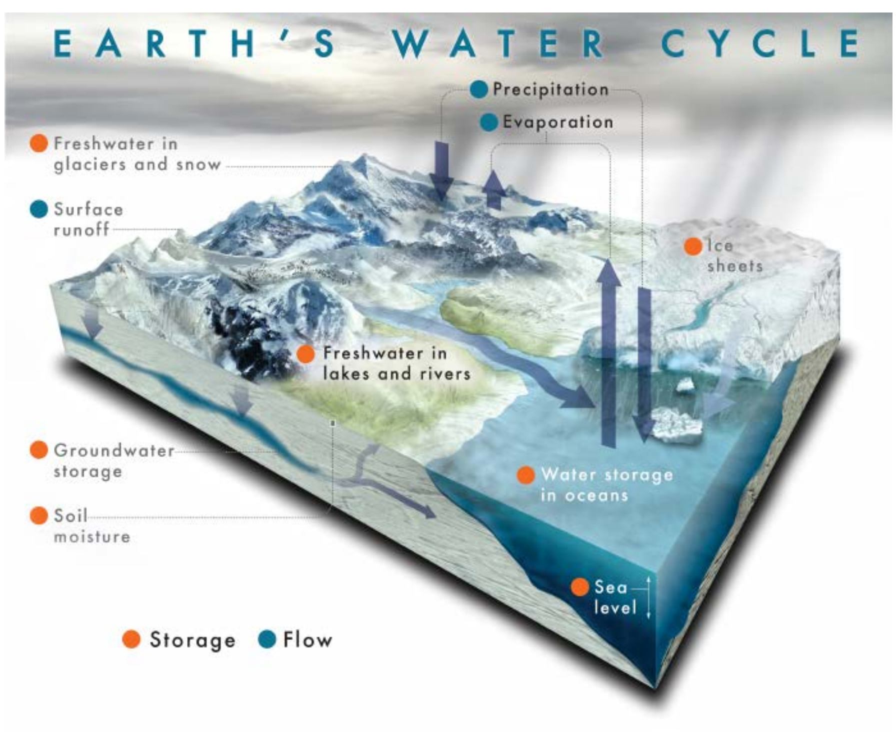
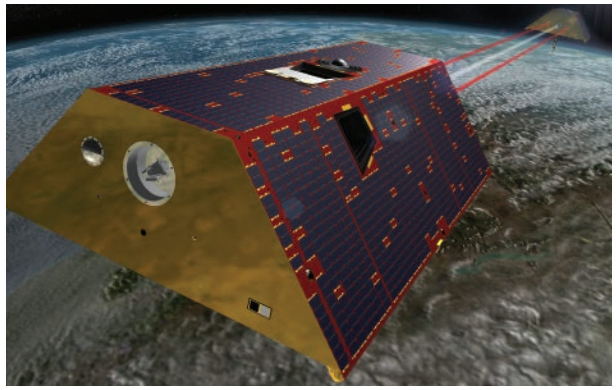


Figure 1. Changes in Earth's gravity field are due primarily to variations in water content as it moves through the water cycle—one of Earth's most powerful systems. Earth's gravity field is continually changing, mostly (but not solely) due to seasonal and climatic changes in water storage and flow. **Image credit:** NASA/JPL-Caltech

Given that the force of gravity is an ever-present driving force in the Earth system, it should come as no surprise that people have sought to describe and quantify its static component since ancient times. These efforts led to the development of the field of *geodesy*, the science branch that accurately measures the size and shape of Earth, defined by Earth's geometry and gravity field, and Earth's position and orientation in space. The field of geodesy took a major leap forward in 2002, when NASA and the German Aerospace Center (DLR) launched the Gravity Recovery and Climate Experiment (GRACE) satellite mission to map Earth's static gravitational field *and* how it changes from month to month. Circling the planet every 90 minutes for over 15 years at an altitude of 350-500 km (about 217-310 mi), the twin GRACE spacecraft closely tracked how their relative positions in space are affected by Earth's gravity.



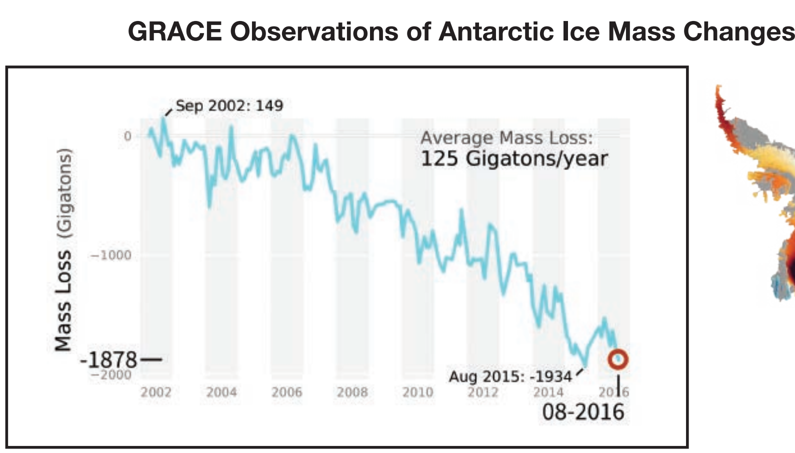
Artist's conception of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellites in orbit around the Earth. **Image credit:** NASA

GRACE's monthly maps of regional gravity variations provided new insights into how the Earth system functions and responds to change. Among its innovations, GRACE for the first time measured the loss of ice mass from Greenland and Antarctica—see **Figure 2**; improved our understanding of the processes responsible for sea level rise and ocean circulation; provided insights into where global groundwater resources may be shrinking or growing, where dry soils are contributing to drought and even forest fires; and monitored changes in the solid Earth (e.g., from earthquakes).[1] After more than 15 productive years in orbit—lasting three times longer than originally planned—the satellite mission ended science operations in late 2017. During its operation, GRACE provided truly global gravity measurements 100 times more accurate, and at spatial and temporal resolution higher, than had ever been achieved before from space, providing the much-needed measurements for characterizing how water is transported and cycled through the Earth system.

During its operation, GRACE provided truly global gravity measurements 100 times more accurate, and at spatial and temporal resolution higher, than had ever been achieved before from space, providing the much-needed measurements for characterizing how water is transported and cycled through the Earth system.

The GRACE Follow-On (GRACE-FO) mission will continue GRACE's legacy. Monitoring changes in ice sheets and glaciers, underground water storage, the amount of water in large lakes and rivers, and changes in sea level, provides a unique view of Earth's evolving climate as well as its water and energy cycles, with far-reaching benefits for its people. Measuring the redistribution and transport of mass around Earth is an essential observation for understanding current and future changes of the Earth's hydrosphere and its subcomponents.

[1]To learn more, read "GRACE Mission: 15 Years of Watching Water on Earth" online at *https://gracefo.jpl.nasa.gov/news/117/grace-mission-15-years-of-watching-water-on-earth*.



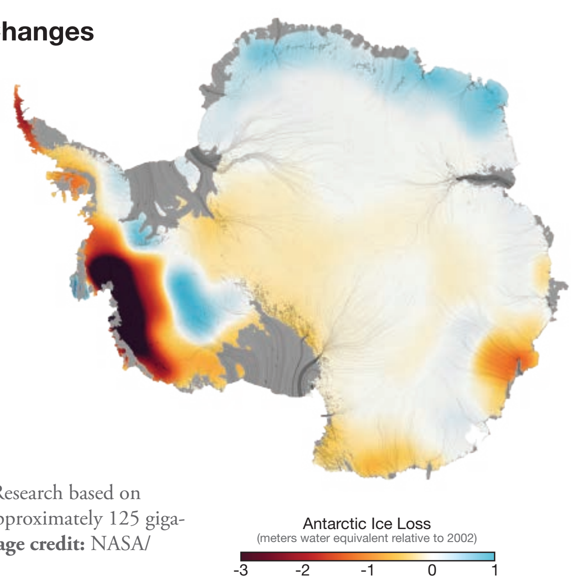


Figure 2. The mass of the Antarctic ice sheet has changed over the last several years. Research based on observations from GRACE indicates that between 2002 and 2016, Antarctica shed approximately 125 gigatons of ice per year, causing global sea level to rise by 0.35 mm (0.01 in) per year. **Image credit:** NASA/JPL-Caltech/University of California, Irvine

The twin GRACE satellites, launched on March 17, 2002, have transformed scientists' view of how water moves and cycles between the ocean, land and atmosphere, and how water storage and availability are affected by droughts, floods, and human intervention.

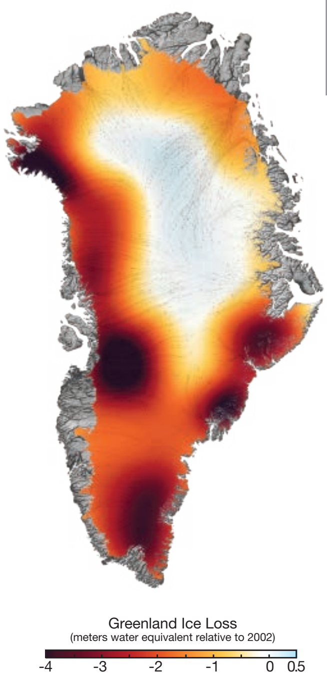
The First GRACE Mission: A Legacy of Discoveries

"Revolutionary" is a word you hear often when people talk about the first GRACE mission. The twin GRACE satellites, launched on March 17, 2002, have transformed scientists' view of how water moves and cycles between the ocean, land, and atmosphere, and how water storage and availability are affected by droughts, floods, and human intervention.

In March 2017, GRACE celebrated the fifteenth anniversary of its launch. The discoveries achieved using GRACE data reflect the work of researchers worldwide, who have developed innovative techniques to use the data and combine them with other observations and models for new insights into complex Earth system processes, as well as for applications.

Melting Ice Sheets

Antarctica is one of the world's toughest places to collect data, and Greenland isn't far behind. Measuring how fast these ice sheets are melting is crucial to better understand rates and variations of sea level rise around the world. In the mid-2000s, GRACE data were used to clearly show that ice losses from Greenland and Antarctica were significantly larger than previous estimates from more indirect observations had suggested. Since GRACE launched, its measurements show Greenland has been losing about 280 gigatons of ice per year on average—see **Figure 3**—and Antarctica has lost approximately 125 gigatons a year with indications that both melt rates are increasing. To give perspective on how much water this is, a single gigaton of water would fill about 400,000 Olympic-sized swimming pools!



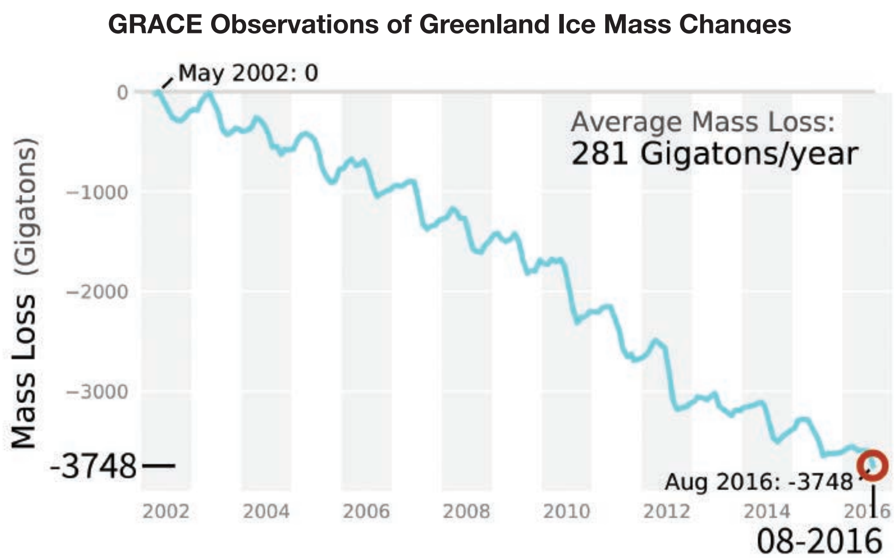


Figure 3. Research based on observations from the GRACE satellites indicates that between 2002 and 2016, Greenland shed approximately 280 gigatons of ice per year, causing global sea level to rise by 0.8 mm (0.03 in) per year. This image, created from GRACE data, shows changes in Greenland ice mass from 2002 to 2016. Darkest shades indicate areas that lost ice mass. The largest mass decreases of up to 30 cm (11.8 in) (equivalent-water-height) per year occurred along the West Greenland coast. **Image credit:** NASA

Underground Water

Water stored in soil and aquifers below Earth's surface is sparsely measured worldwide. Before GRACE, hydrologists were skeptical if they would be able to use the data to reveal unknown groundwater depletion. However, over the last decade, by measuring mass changes with GRACE, scientists from NASA and around the world have found more and more locations where humans are pumping out groundwater faster than it is replenished. For example, in 2015, a team of researchers published a comprehensive survey showing a third of Earth's largest groundwater basins are being rapidly depleted—see **Figure 4** on page 7. Adding the GRACE data to other existing sources of hydrological data has led to the development of a more efficient and sustainable approach to water management.

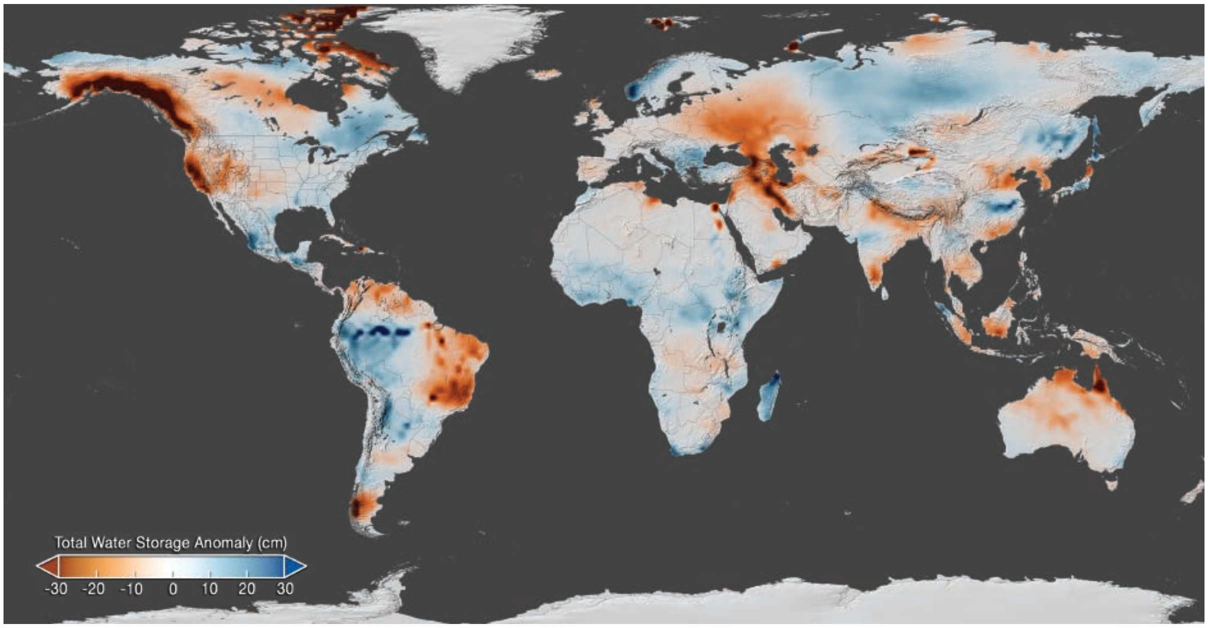


Figure 4. The gravity variations measured by GRACE can be used to determine water storage on land. By comparing current data to an average over time, scientists can generate an *anomaly map* to see where terrestrial water storage has decreased or increased. This map, created using GRACE data, shows the global terrestrial water storage anomaly in April 2015, relative to the 2002-2015 mean. Rust colored areas show where water has decreased, and areas in blue are where water levels have increased. The significant decreases in water storage across most of California are related to groundwater, while decreases along the Alaska coastline are due to glacier melt. **Image credit:** NASA's Scientific Visualization Studio

Dry soils can add to drought risk or increase the length of a drought. To help monitor these changes, NASA provided data on deep soil moisture and groundwater from GRACE to the National Drought Mitigation Center each week, using a hydrology model to calculate how the moisture was changing throughout the month between one map and the next. These data were used to prepare weekly maps of U.S. drought risk.

Sea Level

Sea level is rising because melting ice from land is flowing into the ocean and seawater is expanding as it warms. Since 1992, very precise, continuous measurements of sea level heights worldwide have been made by the NASA-Centre National d'Études Spatiales (CNES) Topography Experiment (TOPEX)/Poseidon mission and the successor Jason series of sea level altimetry missions. Altimeter measurements show how much sea level has risen, but not what causes it to rise—i.e., how much of the observed rise is from thermal expansion of seawater and how much is from increased volume due to ice melting and land runoff.

GRACE measured the monthly mass change of the ocean, and these data have enabled us to distinguish between changes in water mass and changes in ocean temperatures. An example of the value of this ability was a study that documented a sizable—if temporary—drop in sea level and linked it to changes in the global water cycle that was disrupted by the large La Niña event in 2011. The study showed that the water that evaporated from the warm ocean, causing the drop in sea level, was mostly rained out over Australia, South America, and Asia. The finding provided a new view into the dynamics and connections that shape the global water cycle.

Ocean Currents

When combined with measurements from sea-surface-height-measuring satellite altimeters, GRACE observations have greatly improved the precision of ocean current estimates. Beyond this classic application for ocean currents, GRACE observations have also directly been used to assess changes of large-scale current systems. At the bottom of the atmosphere—i.e., on Earth's surface—changes in air pressure (a measure of air's mass) tell us about flowing air, or wind. At the bottom of the ocean, changes in water pressure tell us about flowing water, or currents. A team of scientists at NASA developed a way to isolate the signal found in GRACE data indicating tiny pressure differences at the ocean bottom that are caused by changes in deep ocean currents. The measurements showed that a significant weakening in the overturning circulation, which a network of ocean buoys recorded in the winter of 2009-10, extended several thousand miles north

GRACE-FO Mission Objectives

The primary objective is to continue the high-resolution monthly global maps of Earth's gravity field and surface mass changes of the original GRACE mission over a period of five years.

The secondary objectives are to demonstrate the effectiveness of a novel Laser Ranging Interferometer (LRI) in improving the Satellite-to-Satellite Tracking (SST) measurement performance, laying the groundwork for improved future space-gravimetry missions. GRACE-FO will also continue measurements of radio occultations for operational provision of vertical atmospheric temperature and humidity profiles to weather services.

and south of the buoys' latitude near 26° N. The new measurements from GRACE agreed well with estimates from the buoy network, confirming that the technique can be expanded to provide estimates throughout the Atlantic and beyond. Because ocean currents distribute heat across the planet, any changes in ocean currents are important indicators of how our planet is responding and evolving in a warming climate.

Solid Earth Changes

The viscous mantle under Earth's crust is also moving ever so slightly in response to mass changes from water near the surface. GRACE has a community of users that seek to quantify these shifts. Scientists at NASA used GRACE data to calculate how ice sheet loss and groundwater depletion have actually changed the rotation of Earth as the system adjusts to these movements of mass. Like a spinning top, any change in the distribution of mass will cause Earth's axis to shift, wobble, and readjust. GRACE helps to pinpoint those rotation changes and understand their causes.

In addition, some large earthquakes move enough mass for GRACE to detect. During 15 years in orbit, GRACE was able to measure the instantaneous mass shifts from several large earthquakes and monitor the large but slow tectonic mass adjustments that go on for months and even years after an earthquake. These measurements provide unprecedented insights into what is happening far below Earth's surface during and after big quakes, such as the 2004 Sumatra event and 2011 Tohuku (Japan) quake, both of which caused devastating tsunamis.

GRACE Follow-On: Mission Overview

The GRACE Follow-On joint mission by NASA and the German Research Centre for Geosciences (GFZ) will continue the successful GRACE data record. The GRACE-FO mission builds on and extends the capabilities of its predecessor, and also includes an experimental instrument that promises to be more accurate and allows for the detection of even smaller gravitational signals—see *GRACE-FO Mission Objectives*. In orbit, the twin satellites will provide accurate measurements of changes in Earth's gravitational field at least every 30 days, and allow for the tracking of changes and redistribution in Earth's near-surface mass. In addition, each of the satellites will use global positioning system (GPS) antennas to supply at least 200 profiles of atmospheric temperature distribution and water vapor content daily—see *Measuring Atmospheric Temperature and Humidity*.

Like its predecessor, the GRACE-FO mission consists of two identical satellites orbiting Earth at about 220 km (137 mi) apart at an initial altitude of approximately 490 km (305 mi). One of the unique aspects of GRACE and GRACE-FO is that the satellites themselves are effectively the "instruments." Unlike other Earth-observing satellites equipped with instruments pointing down at Earth's surface, the GRACE-FO satellites instead "look" at each other. Together, they represent a single measurement system.

Measuring Atmospheric Temperature and Humidity

While the main global positioning system (GPS) receivers on the first GRACE mission were used for precise orbit determination, a set of secondary GPS antennas measured the bending of the signals between GRACE and GPS satellites that were low over the horizon. This way, the GPS signals graze and pass through Earth's atmosphere—known as *occultation*. The GPS radio waves are altered slightly as they pass through the atmosphere due to refractive effects, and these changes can be analyzed to create atmospheric profiles including refractivity, temperature, pressure, and humidity. Radio occultation measurements complement and continue a long series of similar data obtained by sensors on other satellites and are very useful for weather forecasting and climate studies.

GRACE-FO will provide at least 200 daily near-real-time occultation observations from each satellite—data that are used operationally worldwide by leading weather centers to improve global weather forecasts. Over longer time scales, the GPS radio-occultation data are contributing to climate variability studies.

One satellite will follow the other along the same polar orbit, with both continually sending ranging signals to each other and carefully tracking any changes in the distance between the two satellites. When the GRACE-FO satellites encounter a change in the distribution of Earth's mass—such as a mountain range or reduced mass of underground water—the distance between the two satellites will change—see **Figure 5**. By precisely and continuously tracking this change to within a fraction of the thickness of a human hair during each orbit every month, regionally and temporally varying gravity changes can be measured with high precision.

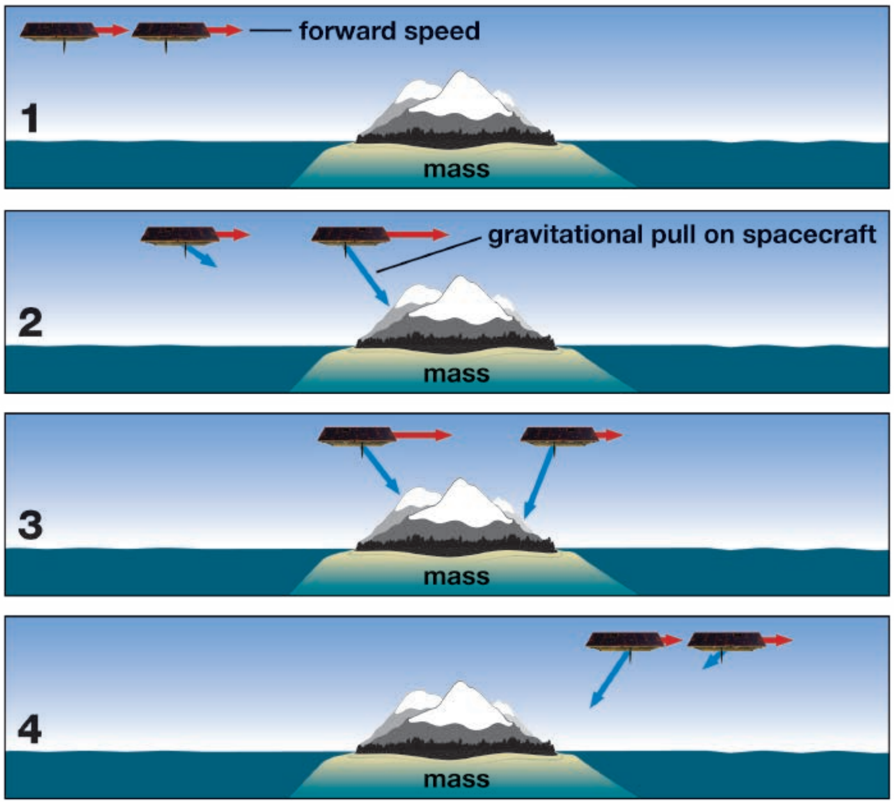


Figure 5. How GRACE-FO Works. This simplified example illustrates the movements of the satellites as they pass southward from the Caribbean Sea across Colombia and Peru (i.e., a denser landmass) to the Pacific Ocean. The two satellites begin over the ocean (*Panel 1*), but when the leading spacecraft encounters land, the land's higher gravity pulls it away from the trailing spacecraft, which is still over water (*Panel 2*). Once the second satellite encounters the land, it too is pulled toward the mass and consequently toward the leading spacecraft (*Panel 3*). When the lead spacecraft moves back over water, it is pulled back slightly by the land, while the trailing spacecraft continues over the land. Once both spacecraft are back over water, the trailing spacecraft is slowed by the land (*Panel 4*) before returning to its original distance behind the leading spacecraft. **Image credit:** NASA

GRACE-FO will be able to make accurate measurements, thanks in part to the innovative use of two technologies: a *microwave ranging system* based on GPS technology, and a very sensitive *accelerometer*—an instrument that measures the forces on the satellites besides gravity (e.g., atmospheric drag or solar pressure). GRACE-FO will use the same two-way microwave-ranging link as GRACE, called the Microwave Instrument (MWI). The MWI operates using two frequencies—at 24 GHz (K-band) and 32 GHz (K_a-band)—and is capable of measuring the distance between the two satellites to within one micron—about the diameter of a blood cell, or a small fraction of the width of a human hair. This allowed the GRACE satellites to detect gravitational differences on the planet's surface with a precision equivalent to a change of 1 cm (0.4 in) in water height across areas of about 340 km (approximately 211 mi) in diameter.

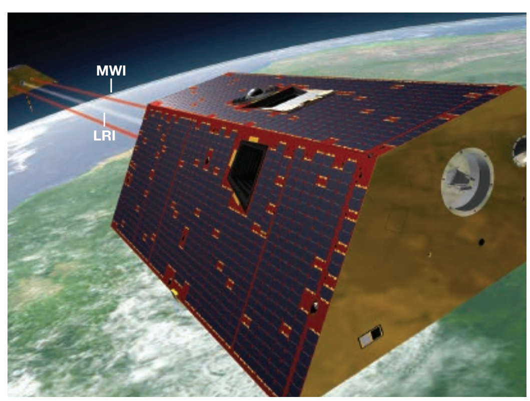


Figure 6. The experimental Laser Ranging Interferometer (LRI) is expected to provide better ranging precision than GRACE's MWI system. LRI is being tested on GRACE-FO as an enabling technology for the next generation of mass-change missions. **Image credit**: NASA

With the same kind of microwave ranging system, GRACE-FO satellites can expect to achieve a similar level of inter-satellite ranging precision. But they will also test and demonstrate an experimental instrument using lasers instead of microwaves, which promises to improve the precision of the separation distance measurements on future generations of GRACE satellites by a factor of about 20, thanks to the laser's higher frequencies. The instrument, developed jointly between NASA's Jet Propulsion Laboratory, the Max Planck Institut für Gravitationsphysik (Germany), and GFZ, is called the Laser Ranging Interferometer (LRI)—see **Figure 6**. The LRI is a stepping

GRACE-FO at a Glance

Size (of each satellite)	1.94 m wide, 3.12 m long, 0.72 m high
Mass	600 kg
Power	Solar cells
Altitude	490 ± 10 km
Velocity	~7.5 km/sec
Inclination	89°
Orbit	Polar orbit
Orbit Duration	90 minutes
Orbits Per Day	~15
Design Life	5 years
Fuel Life	>5 years

stone for future missions to enhance gravity measurements. It will also measure changes in the angle between the two spacecraft and thus support the conventional microwave-ranging observations. Together, the very precise measurements of location, force, and orbital change translate into an observation of gravity with improved accuracy.

Spacecraft Design and Launch

The GRACE-FO satellites follow the successful design of the original GRACE spacecraft. Each identical satellite is 1.94 m (6.36 ft) wide, 3.12 m (10.25 ft) long, and 0.72 m (2.36 ft) high, with a mass of 600 kg (1,323 lbs). Both spacecraft are covered in solar panel arrays that power the satellites.

The GRACE-FO satellites will be launched together from Vandenberg Air Force Base in California into Earth orbit on a SpaceX Falcon 9 launch vehicle as a shared ride with five communications satellites. The GRACE-FO satellites will be deployed first from the launch vehicle into a low-Earth, near-polar orbit, after which the launch vehicle will continue on to a higher orbital altitude before releasing the communications satellites.

The GRACE-FO twin satellites, after release at an altitude of about 490 km (305 mi), will be maneuvered to a separation distance of about 220 km (137 mi) apart. As the satellites circle Earth, the ranging technology will measure separation between the satellites at the micrometer level, and the GPS sensor will provide the location of the satellites in their orbits. These observations will then be combined and processed using supercomputers to estimate month-to-month gravity and surface mass variations.

GRACE-FO launched aboard a SpaceX Falcon 9 from Vandenberg Air Force Base in California on May 22, 2018. Pictured here on the Vandenberg launch pad is a Falcon 9 rocket with the Jason-3 satellite onboard. **Photo credit:** NASA/Shiflett

The GRACE-FO satellites were assembled by Airbus Defence and Space in Germany with major components from a number of countries including Denmark, England, France, Germany, Italy, Sweden, and the U.S. This photo shows the satellites inside the IABG testing facility in Munich, Germany. **Photo credit:** Airbus DS Industrieanlagen-Betriebsgesellschaft GmbH-A.Ruttloff