GRACE-FO LAUNCH PRESS KIT

National Aeronautics and Space Administration

MAY 2018

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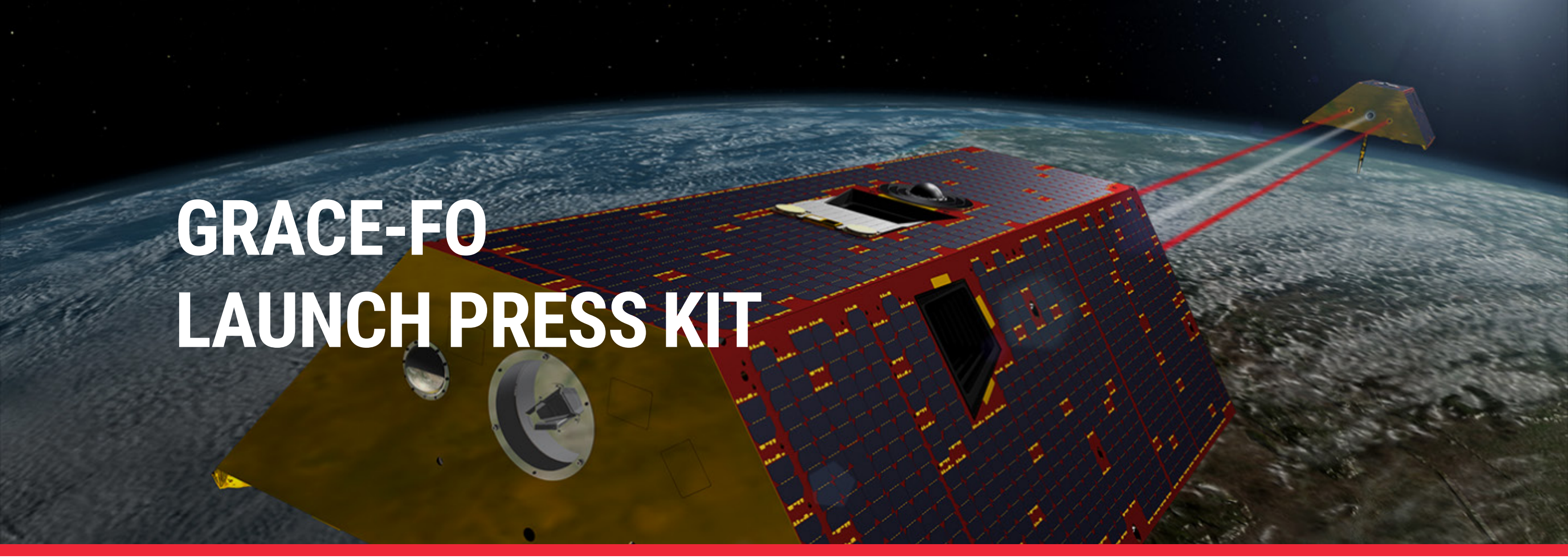
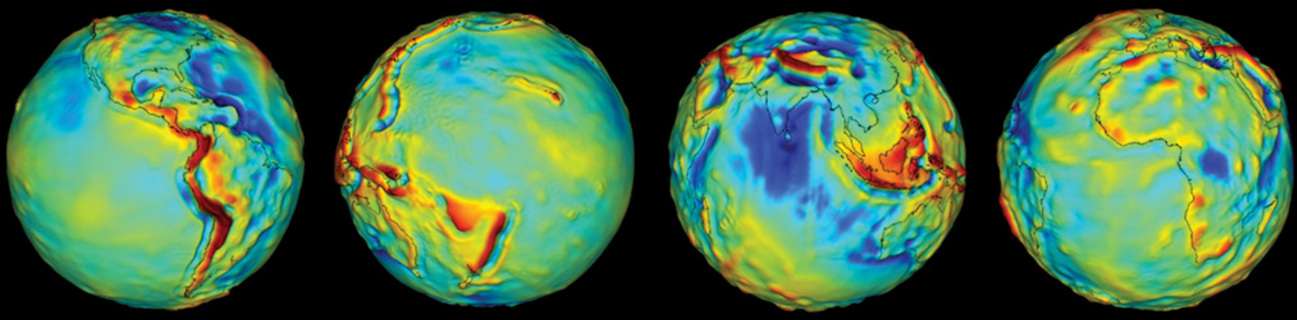


INTRODUCTION

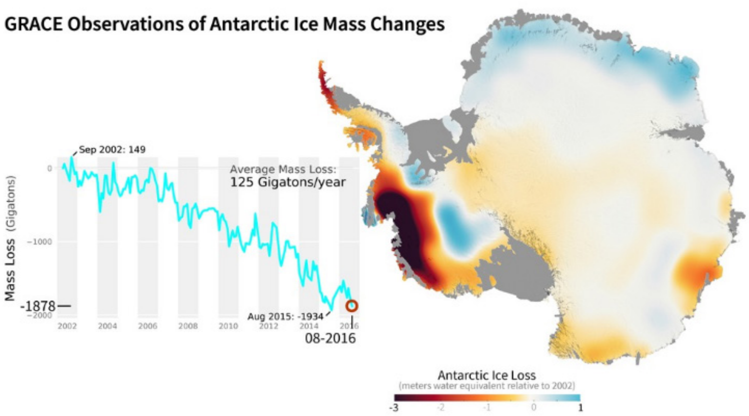
Many of today's most pressing climate science challenges hinge on knowing how and where water is moving on Earth. But keeping track of Earth's evolving water cycle is a formidable task. Water can be in plain sight in a lake or hidden underground. It can evaporate in moments when sunlight warms Earth's surface or be stored for centuries as ice in a glacier. It can be almost anywhere on, above and below Earth's surface, from your kitchen sink to the South Pole.

Regardless of whether water is solid, liquid or vapor, visible or invisible, it has one attribute that does not change: its mass, which exerts a gravitational pull. By tracking the changing pull of gravity very precisely around Earth, the U.S./German Gravity Recovery and Climate Experiment, or GRACE, mission observed the movement of water around our planet from 2002 to 2017 -- from the top of the Himalayas to the depths of the ocean to deep underground. GRACE Follow-On, set to launch in spring of 2018, will continue GRACE's critical mission of tracking the evolution of Earth's water cycle by monitoring changes in the distribution of mass on Earth. It will also continue the successful partnership between NASA and Germany that began on the original GRACE mission, via NASA's GRACE-FO mission partner, the German Research Centre for Geosciences (GeoForschungsZentrum – GFZ).

Maintaining a consistent, continuous climate data record of water and mass transport in the Earth system over decades is essential to understanding short-term climate variability and long-term climate change. Because some climate patterns take several decades to unfold, the only way to determine whether a multi-year trend is representative of a long-term change is to extend the length of the observational record.



GRACE-FO data will improve our understanding of Earth system processes, and the accuracy of environmental monitoring and forecasts, by extending GRACE's legacy of scientific achievements, which includes several thousand scientific publications.

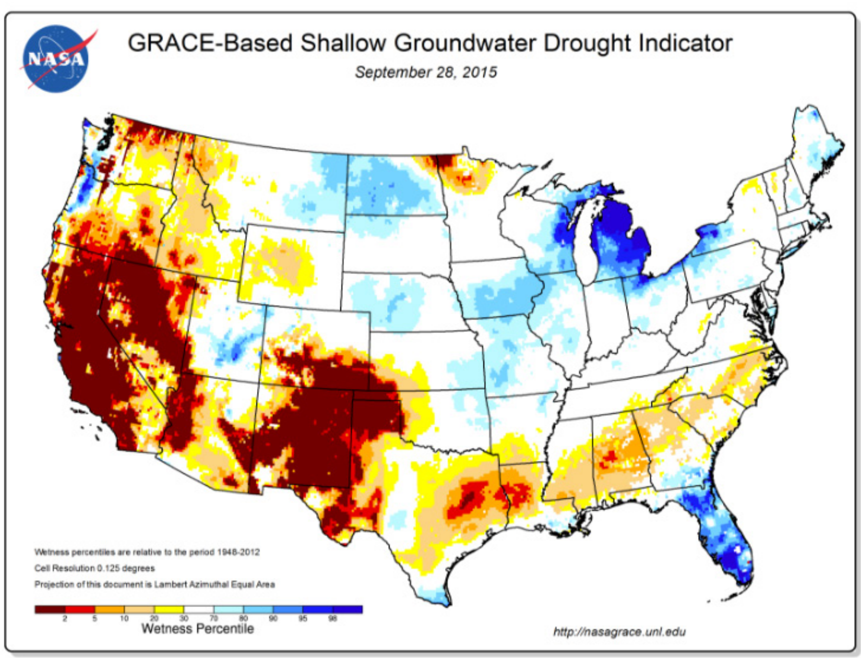


GRACE Observations of Antarctic Ice Mass Change
Image credit: NASA/GSFC/SVS

These include:

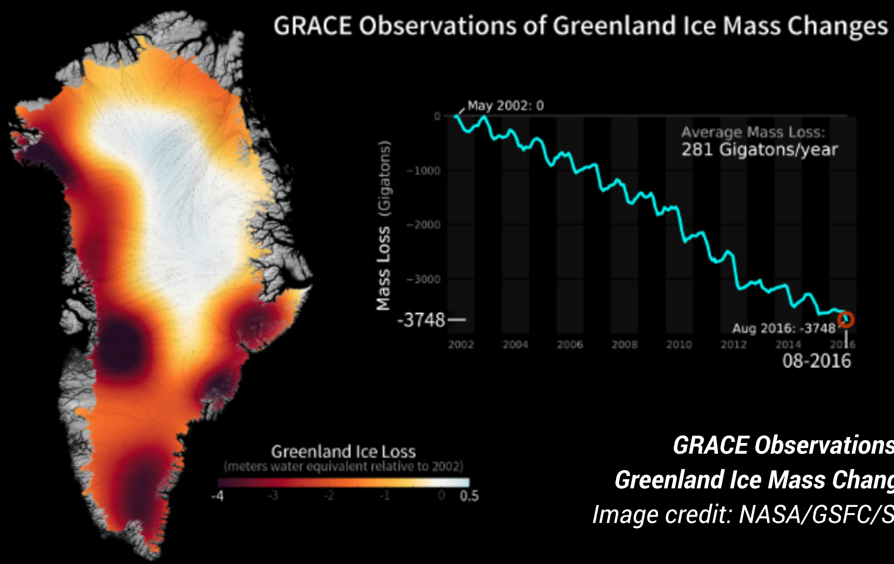
- Tracking mass changes of Earth's polar ice sheets.
- Estimating global groundwater storage changes.
- Measuring mass changes caused by large earthquakes.
- Inferring changes in deep ocean currents, a driving force in climate.

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 and its water and energy cycles, with far-reaching societal benefits.



U.S. map, groundwater drought indicator
Image credit: NDMC

The importance of mass change measurements from space -- first provided by GRACE and now to be continued by GRACE-FO -- to understanding the Earth system was recognized by the National Academy of Sciences in its 2017-2027 Decadal Survey, Thriving on Our Changing Planet, released in December 2017. In this community report, mass change measurements were identified as one of the five highest-priority Earth observation needs that are considered essential to NASA's overall Earth science program, addressing the "most" and "very important" objectives for studies of climate, hydrology and the solid Earth. The measurements were also identified as contributors to the water and energy-cycle Earth System Science themes identified in the report. The survey recommended that mass change measurements be continued on future missions to maintain continuity with the GRACE and GRACE-FO data records.



GRACE Observations of Greenland Ice Mass Changes
Image credit: NASA/GSFC/SVS

While similar in design to GRACE, GRACE-FO incorporates lessons learned from 15 years of GRACE operations. The changes made will improve the new mission's satellite performance and reliability, as well as mission operations. GRACE-FO will also fly a technology demonstration of a new, more precise inter-satellite laser ranging interferometer, developed by a German/U.S. instrument team, for use in future generations of GRACE-like missions.

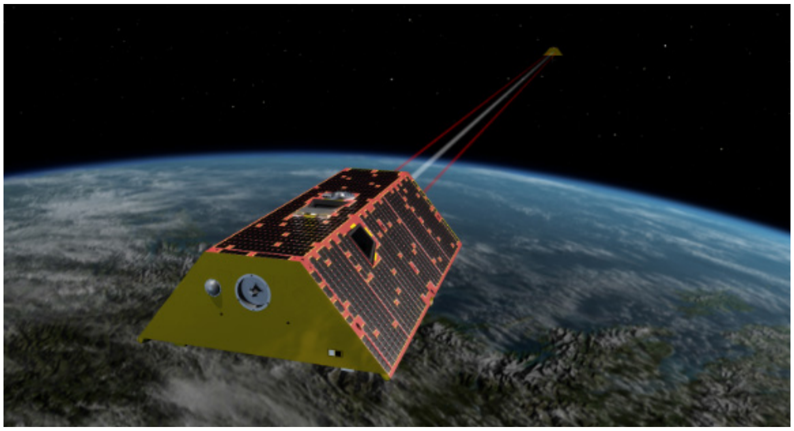
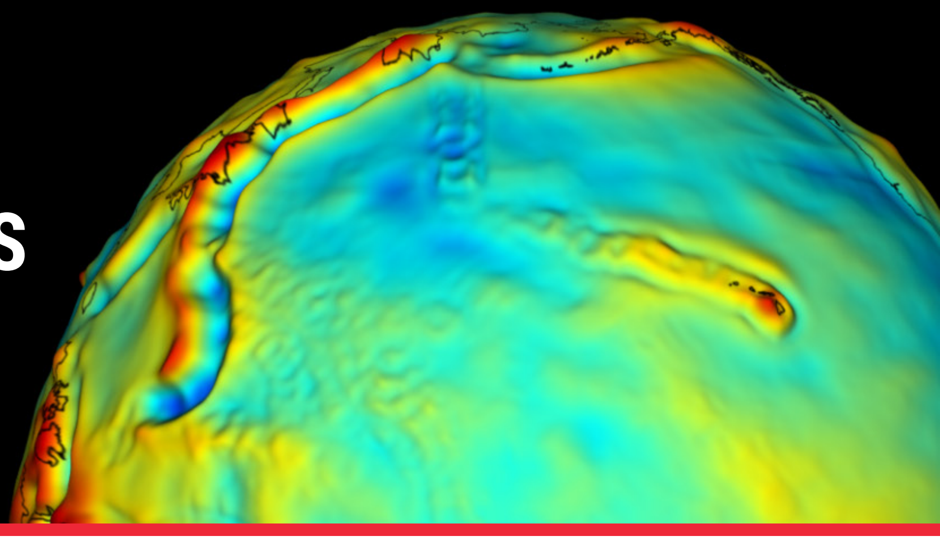


Illustration of GRACE-FO orbiting Earth
Image credit: NASA/JPL-Caltech

Launch services for GRACE-FO are contributed by Germany, which procured a rideshare for the two GRACE-FO satellites from Iridium Communications Inc. The GRACE-FO satellites and five Iridium NEXT communications satellites will be launched into orbit together on a SpaceX Falcon 9 rocket from Vandenberg Air Force Base in California. This unique rideshare launch will first deploy the GRACE-FO spacecraft, then the Falcon 9 second stage will continue onward to the deployment orbit for the Iridium NEXT satellites.

MEDIA SERVICES



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PRODUCTS AND EVENTS

News and Status Reports

NASA and the GRACE-FO team will issue periodic news releases, feature stories, media advisories and status reports on launch and mission activities and make them available online at **https://nasa.gov/gracefo** and **https://gracefo.jpl.nasa.gov/**. Media advisories in advance of the launch will include details on media accreditation, briefings, pre-launch media activities at Vandenberg Air Force Base, California, and NASA TV and Web coverage.

Video and Images

Video and images related to the GRACE-FO mission are available at the following websites: **https://vimeo.com/266146377** and **https://nasa.gov/gracefo**.
(See also: **Appendix – Gallery**).

NASA Television

NASA Television channels are digital C-band signals, carried by QPSK/DVB-S modulation on satellite Galaxy-13, transponder 11, at 127 degrees west longitude, with a downlink frequency of 3920 MHz, vertical polarization, data rate of 38.80 MHz, symbol rate of 28.0681 Mbps, and ¾ FEC. A Digital Video Broadcast (DVB) compliant Integrated Receiver Decoder (IRD) is needed for reception. For NASA TV information and schedules on the Web, visit **https://nasa.gov/ntv**.

Live NASA TV programming on NASA's public channel is available on the web at **https://nasa.gov/live**. The NASA TV media channel is available live at **https://ustream.tv/channel/nasa-media-channel**. Archived NASA TV programming is available soon after it airs at **https://youtube.com/nasatelevision** and at **https://images.nasa.gov/**.

ADDITIONAL LIVE VIDEO STREAMS

Additional live streaming video of the launch minus 30-day ("L minus 30") news conference at NASA Headquarters, launch minus two-day ("L minus 2") prelaunch news conference at Vandenberg Air Force Base and coverage of the launch itself on NASA TV is available at: **https://youtube.com/nasajpl/live** and **https://ustream.tv/nasajpl2**.

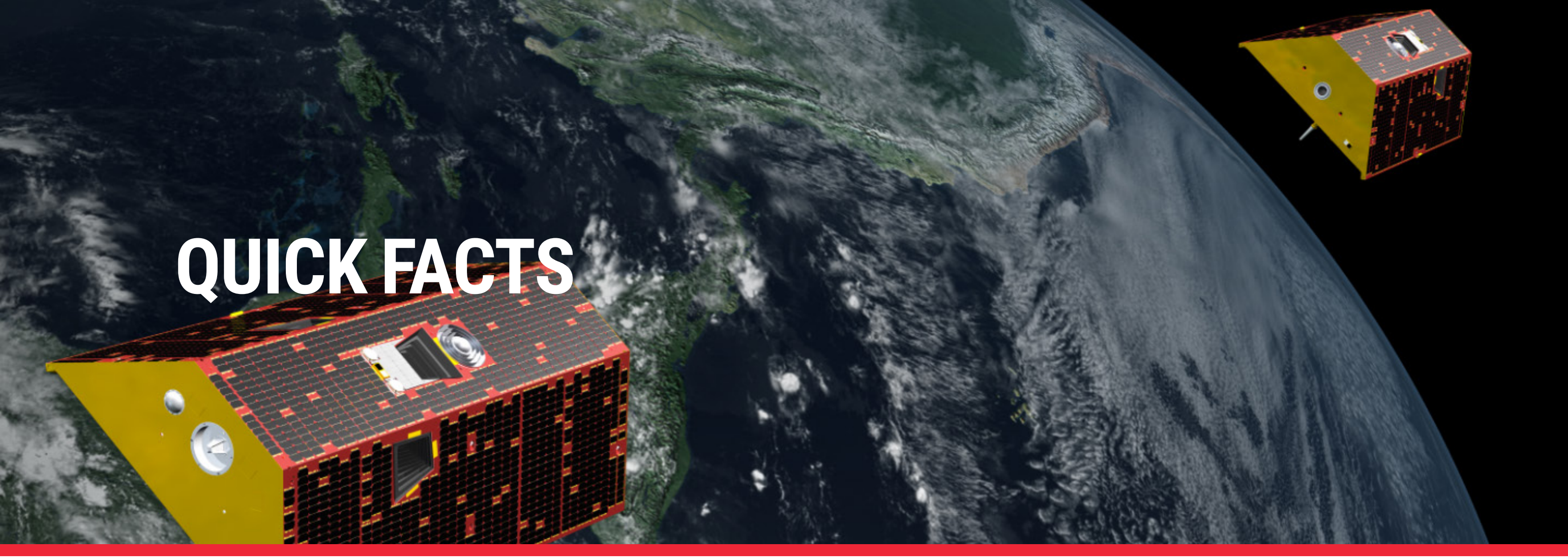
AUDIO

Audio of the L minus 2 pre-launch readiness and science news conference at Vandenberg Air Force Base and NASA TV launch coverage will be available on "**V-circuits**" that may be reached by dialing **321-867-1220, -1240, -1260** or **-7135**.

GRACE-FO on the Web

GRACE-FO information, including this press kit, news releases, fact sheets, mission details and background status reports and images, is available on the web at: **https://nasa.gov/gracefo** and **https://gracefo.jpl.nasa.gov/**.

Mission updates are also available on Twitter (**@NASAEarth**) and Facebook (**https://facebook.com/NASAEarth**).



QUICK FACTS

GRACE Follow-On in a clean room
Image credit: Airbus DS GmbH/A. Ruttloff

SPACECRAFT

Size: 10 feet, 3 inches (3.123 meters) long, 2 feet, 6.7 inches (0.78 meters) high, 6 feet, 4.5 inches (1.943 meters) wide at bottom, 2 feet, 3.3 inches (0.69 meters) wide at top
Mass: 1,323.2 pounds (600.2 kilograms) each, including onboard propellant at launch
Power: Panels of gallium arsenide solar cells mounted on satellite's top and side exterior surfaces
Batteries: 78-ampere-hour battery consisting of lithium-ion cells
Instruments: Microwave instrument, accelerometer, laser ranging interferometer (technology demonstration), laser retro-reflector

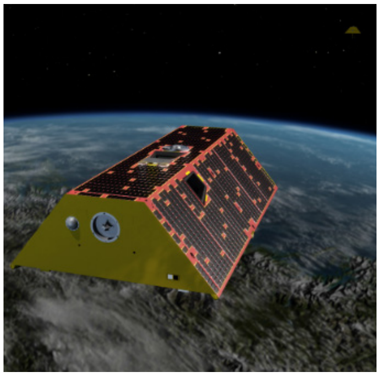


Illustration of GRACE-FO orbiting Earth
Image credit: NASA/JPL-Caltech

MISSION

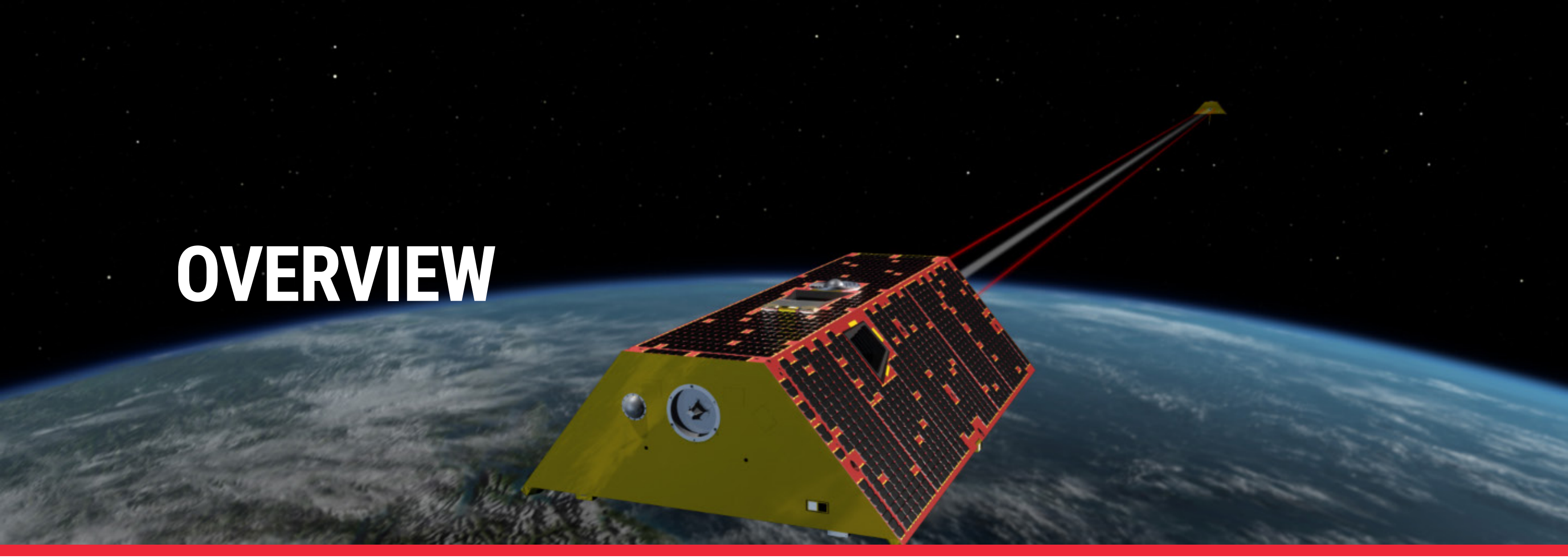
Launch: No earlier than May 19, 2018
Prime mission: Five years
Orbit altitude: Approximately 305 miles (490 kilometers)
Orbit's inclination to Earth's equator: 89 degrees (near-polar)
Orbit duration: Approximately 90 minutes
Orbits per day: Approximately 15
Velocity: Approximately 16,800 mph (7.5 km/s)
Separation between spacecraft: 137 miles (220 kilometers) optimal separation, plus or minus 31 miles (50 kilometers)

LAUNCH

Launch is scheduled for no earlier than May 19, 2018, from Vandenberg Air Force Base, California, aboard a SpaceX Falcon 9 launch vehicle as a rideshare with five Iridium NEXT communications satellites.

BUDGET

NASA investment: Approximately $430 million



OVERVIEW

All matter in the Earth system has mass and exerts a gravitational pull, including a pull on orbiting Earth satellites. By precisely measuring changes in Earth's gravity field with regional resolution from month to month, the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission continues the GRACE mission's critical task of measuring and monitoring the movements of mass within and between Earth's atmosphere, oceans, land and ice sheets, as well as within Earth itself (such as from large earthquakes and slow changes in Earth's viscous mantle). These data provide unique insights into Earth's changing climate, Earth system processes and even the impacts of some human activities. They also have far-reaching benefits to society, such as improving the accuracy of environmental monitoring and forecasts.

GRACE-FO, a partnership between NASA and the German Research Centre for Geosciences (GeoForschungsZentrum, GFZ), extends the 15-plus-year data record of GRACE, which operated from 2002 to 2017, and will demonstrate new technology to potentially improve upon the precision of GRACE's measurements for future GRACE-like missions. The importance of continuing measurements of mass change was recently highlighted by the National Academy of Sciences in its 2017-2027 Decadal Survey for Earth Science and Applications from Space, released in December 2017. The survey identified measurements of mass change as one of NASA's five highest-priority Earth observation needs for the next decade and as a foundational element to ensure continuity with both GRACE and GRACE-FO.

Having a time series of measurements of sufficient length, consistency and continuity is vital to determining climate variability and change. Whether or not observed multiyear trends represent long-term changes in mass balance can only be determined by extending the length of the observations. By continuing the essential climate data record established by GRACE, GRACE-FO will provide invaluable observations of long-term climate-related mass changes, such as the ongoing loss of mass of the West Antarctic and Greenland ice sheets, and many other land glaciers, as well as changes in the water cycle and land water storage. Longer records allow climate scientists to separate short-term variability from longer-term trends.

Conceptually nearly identical to the GRACE mission, GRACE-FO consists of two identical satellites flying in formation around Earth at an initial altitude of approximately 305 miles (490 kilometers) and a nominal separation distance of 137 miles (220 kilometers). Instruments on board the satellites precisely measure changes in the distance between them due to orbital perturbations caused by variations in Earth's gravity field over space and time. By combining these data with precise knowledge of the satellites' positions as determined by GPS observations, position and orientation of the satellites as measured by star trackers, and non-gravitational forces acting on each satellite as measured by high-precision accelerometers, the distribution of Earth's mass changes near the surface will be calculated every month and tracked over time.

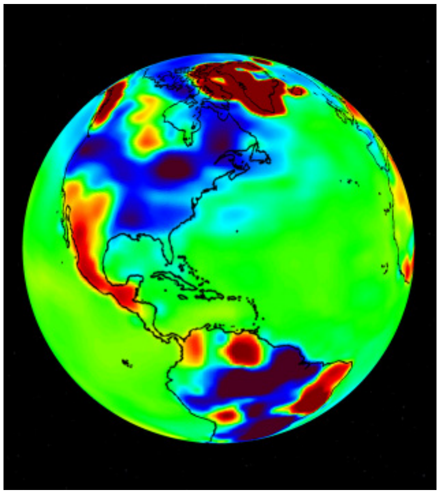
GRACE Follow-On being built
Image credit: Airbus DS GmbH/A. Ruttloff

GRACE-FO will expand GRACE's legacy of scientific achievements. These include tracking mass changes in Earth's polar ice sheets and mountain glaciers (which impact global sea level); estimating total water storage on land (from groundwater changes in deep aquifers to changes in soil moisture and surface water); inferring changes in deep ocean currents, a driving force in climate; and even measuring changes within the solid Earth itself, such as postglacial rebound and the impact of major earthquakes. To date, GRACE observations have been used in more than 4,300 research publications.

GRACE-FO's primary mission 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 twofold: first, GRACE-FO will demonstrate the effectiveness of a novel Laser Ranging Interferometer (LRI) in improving satellite-to-satellite tracking measurement performance, laying the groundwork for improved GRACE-like geodetic missions in the future. The LRI will be the first-ever demonstration of laser interferometry in space between satellites. Second, GRACE-FO will measure the structure of Earth's atmosphere by performing radio occultation measurements of GPS tracking signals, a cost-effective technique to measure vertical atmospheric temperature and humidity profiles by observing how much signals from GPS satellites are distorted as they travel through the atmosphere. The sounding process will provide 200 to 250 vital profiles of atmospheric temperature and water vapor content per satellite each day to aid weather forecasting. GPS Radio Occultation (GPSRO) data from GRACE were provided to U.S. and European weather prediction centers for use in weather forecasting products.

As on GRACE, NASA is partnering with Germany on GRACE-FO to provide continuity with the GRACE measurements. While for continuity the baseline science and performance requirements are the same, the GRACE-FO mission implements improvements based on lessons learned from GRACE. Design changes were limited to those that were required to meet the recommendations of the GRACE Science Study Team, to use the current-generation satellite bus, to resolve hardware obsolescence issues and to accommodate the Laser Ranging Interferometer as a technology demonstration.

WHAT GRACE-FO WILL DO



GRACE gravity map
Image credit: NASA/JPL-Caltech

Over its five-year lifetime, GRACE-FO will:

- Provide monthly maps of how gravity changes are distributed on Earth to precisely track variations in ice mass, total water storage on land (from deep aquifers to soil moisture and surface water), sea level and ocean circulation, as well as some solid Earth processes, including postglacial rebound and major earthquakes.
- Obtain accurate global and high-resolution models for the static (i.e., non-changing) component of Earth's gravity field to support other geodetic missions such as satellite altimetry over the oceans.
- Provide 200 to 250 profiles of atmospheric temperature and water vapor content every day per satellite.

BRIEF PROGRAM HISTORY

The concept for using satellite-to-satellite tracking to determine a planetary gravity field dates back to the late 1960s. In 1997, NASA selected the GRACE mission under its Earth System Science Pathfinder program to use this technique to resolve the time-varying gravity field of Earth.

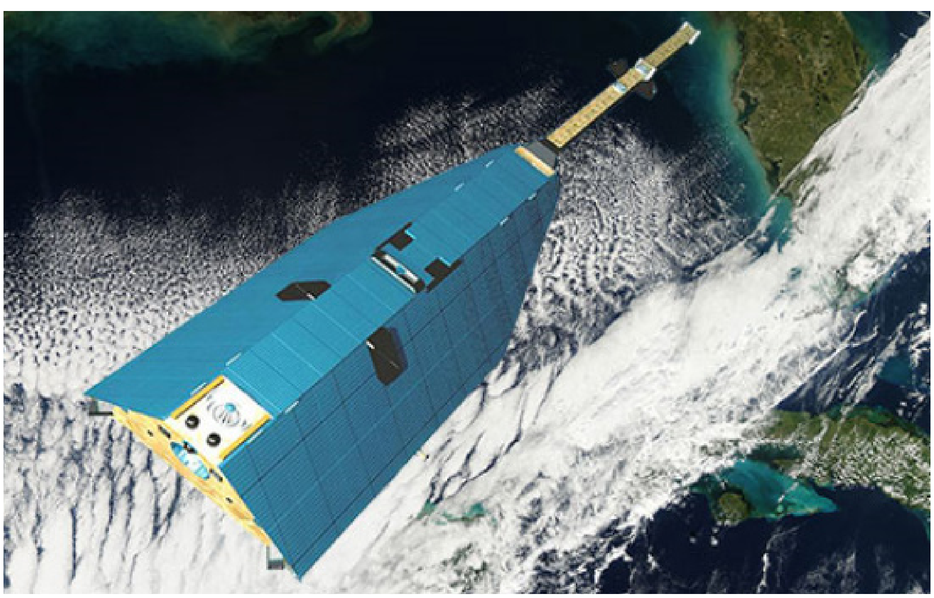
GRACE built on the heritage of a predecessor mission called the Challenging Minisatellite Payload (CHAMP). Built by Dornier Satellitensysteme, managed by the German Research Centre for Geosciences (GFZ) and launched in July 2000, CHAMP's instruments and its orbit allowed it to generate simultaneous, highly precise measurements of Earth's gravitational and magnetic fields. It measured how both fields vary across Earth's surface as well as how they change with time. In addition, CHAMP tested the use of GPS instruments flown in low-Earth orbit to study Earth's atmosphere and ionosphere, with potential applications in weather prediction and weather monitoring from space.

While CHAMP significantly advanced the field of geodesy, scientists had long desired an even more advanced mission based on dual satellites flying in formation to improve CHAMP's relatively low resolution. The unique design of the GRACE mission dramatically improved existing gravity maps and allowed much-improved resolution of the broad- to finer-scale features of Earth's gravitational field over both land and sea. It also showed how much Earth's gravitational field varies over time. Before GRACE, current models of the static geoid were accurate from 20 to 90 centimeters at horizontal scales of 180 miles (300 kilometers). GRACE improved these numbers to the sub-centimeter level.

GRACE, a competitively selected principal investigator mission led by Principal Investigator Byron Tapley of the University of Texas at Austin Center for Space Research (UT-CSR) and Co-Principal Investigator Christoph Reigber (later followed by Frank Flechtner in 2009) of GFZ, was a joint mission between NASA and the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Germany. The original NASA project scientist was Mike Watkins of NASA's Jet Propulsion Laboratory (later followed by JPL's Carmen Boening in 2015). Watkins, a former student of Tapley's, was instrumental in the development of GRACE's proposal to NASA. Tapley was directly responsible to NASA for the success of the mission, including developing the flight mission hardware, accomplishing the scientific objectives, and delivering the data products to the broader Earth science community and general public. Tapley delegated day-to-day project management and implementation authority for the mission to JPL.

GRACE was launched on March 17, 2002, from Plesetsk Cosmodrome, Russia, on a planned five-year mission. Its science mission concluded in October 2017 after more than 15 years of successful operations, with GRACE-B re-entering the atmosphere in December 2017 and GRACE-A in March 2018.

In June 2010, NASA identified development of GRACE-FO as one of the "Climate Continuity Missions" in its NASA Climate Architecture report. Development of GRACE-FO subsequently began in 2012.



The CHAMP Satellite
Image credit: NASA

NASA/GERMAN COLLABORATION

GRACE-FO will continue a highly successful partnership between NASA and Germany. The original GRACE mission was a joint project between NASA and DLR. GRACE ground segment operations were co-funded by GFZ, DLR and the European Space Agency.

GRACE-FO is a partnership between NASA and GFZ, with participation by DLR.

NASA is responsible for overall mission management, with project management assigned to JPL. JPL is responsible for the twin satellites, built by Airbus Defence and Space in Germany under contract to JPL. JPL is also responsible for the accelerometer, built by ONERA in France, the microwave instrument, the electronics portion of the Laser Ranging Interferometer, and U.S. science processing and science distribution.

GFZ is responsible for European science and science processing (jointly with JPL), mission operations, optical components of the Laser Ranging Interferometer, the Laser Retro-Reflectors, and launch services (contracted to Iridium for a rideshare on a SpaceX Falcon 9 rocket), with support from Bundesministerium für Bildung und Forschung (BMBF), Bundesministerium für Wirtschaft und Energie (BMWi), Helmholtz Association of German Research Centres (HGF), Albert Einstein Institute/Max Planck Institute for Gravitational Physics (AEI) and DLR. GFZ has subcontracted mission operations to DLR, which operates the German Space Operations Center, providing the support and infrastructure needed to operate the GRACE-FO satellites.

WHY WE NEED MORE GRACE

With 15 years of monitoring how water and ice are distributed on our planet, the GRACE mission proved its value for monitoring and studying the global water cycle so thoroughly that the recent Earth Science Decadal Survey report released by the National Academy of Sciences in December 2017 listed measurement of mass changes as one of five top priorities in Earth observations for the next decade. The same recognition of GRACE's value led to the recommendation in NASA's 2010 Climate Architecture report to develop GRACE-FO as a directed NASA mission.

WHAT DOES GRAVITY HAVE TO DO WITH WATER?

"Everything flows." These famous words by the ancient Greek philosopher Heraclitus express the truth that our complex world is ever-changing and evolving. Even Earth's gravity is continually changing. The pull of gravity varies naturally from place to place on Earth, depending on the mass at the surface; greater mass exerts a stronger gravitational pull. But this geographically varying gravity itself also changes constantly as mass moves in time. The land and ocean move and change relatively slowly, but water mass on the land -- or above or below it -- changes daily.

On Earth, the processes that cause water to move and change are fundamental to today's most pressing climate science challenges. But keeping track of Earth's evolving water cycle is a formidable task. Water constantly changes its shape, form and state as it moves between oceans, atmosphere and land. It can be in plain sight in a lake or hidden in an aquifer underground. It can evaporate from Earth's surface in moments after a rain shower or be stored for hundreds or thousands of years as ice in glaciers and ice sheets.

But regardless of whether water is solid, liquid or vapor, visible or invisible, it has one attribute that does not change: its mass. And since mass has a gravitational pull associated with it, engineers and scientists have come up with a unique twin-satellite observing system that uses the changing forces of gravity to track and follow Earth's water masses from the top of the Himalaya to the deepest ocean depths and deep underground. The record of changing gravity and changing mass, combined with sea surface height observations, is directly linked with the heat trapped on Earth by greenhouse gases and stored in the ocean.

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, enabled the development of a viable flight mission. Researchers and engineers led by Byron Tapley of the University of Texas at Austin and Michael Watkins, now director of NASA's Jet Propulsion Laboratory in Pasadena, California, came together and realized the unique potential for new Earth observations and data that could be gleaned from measuring variations in gravity. They proposed the GRACE mission to NASA and won the competition under NASA's Earth System Science Pathfinder program.

HOW GRACE FOLLOW-ON WORKS

Like its predecessor, the GRACE-FO mission consists of two identical satellites orbiting Earth about 137 miles (220 kilometers) apart, one behind the other, at an initial altitude of approximately 305 miles (490 kilometers). One of the unique aspects of GRACE and GRACE-FO is that the pair of satellites themselves are the "instrument." Unlike other Earth-observing satellites, which are equipped with instruments pointing down at Earth's surface to measure some property of the electromagnetic spectrum such as light or heat, the GRACE-FO satellites instead "look" at each other and measure the varying distance between themselves. Together, they represent a single measurement system.

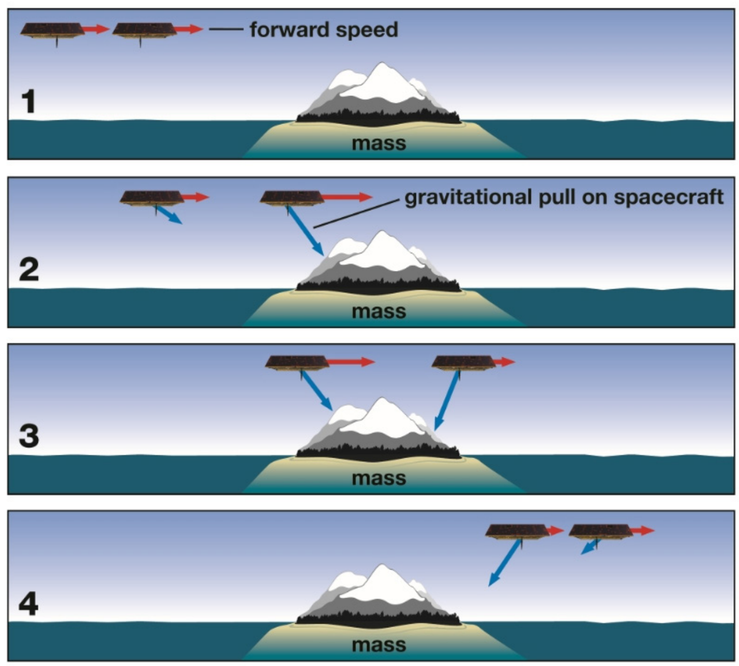


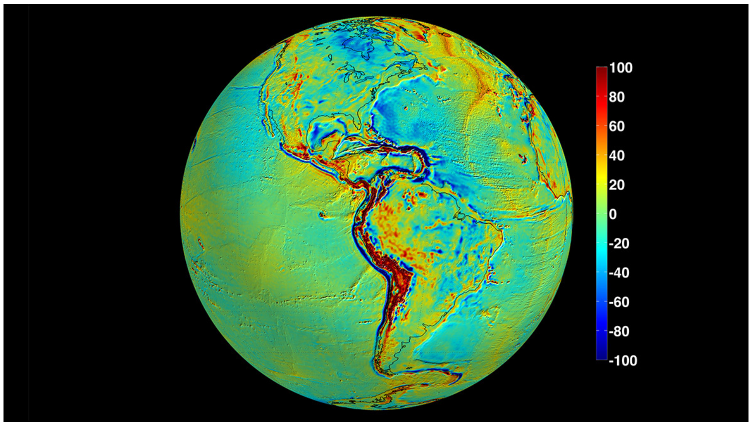
Diagram of changes in satellite separation distance
Image credit: NASA

As one satellite follows the other along the same orbit, both continually send microwave signals to each other and use the incoming signals to accurately measure the distance that separates them, tracking any changes. As the GRACE-FO satellites fly over a massive Earth feature – such as a mountain range or underground aquifer -- the distance between the two satellites will change by a fraction of the thickness of a human hair. By accurately tracking how the satellites' separation distance changes during each orbit and over time, it is possible to detect gravity changes that vary by region with high precision.

A GPS system keeps track of each spacecraft's position relative to Earth's surface, and onboard accelerometers record forces on the spacecraft other than gravity, such as atmospheric drag and solar radiation. These data are then combined to produce monthly maps of the regional variations in global gravity and the corresponding surface mass variations.

THE WEIGHT OF WATER

GRACE's observations are so different from other types of hydrology data that researchers had to develop innovative techniques before they could use the new data set and combine it with other observations and models. Within a year or two of launch, however, the GRACE data record began yielding new insights into how the water cycle is changing, especially in places almost impossible to monitor from the surface. Sixteen years later, researchers continue to develop new techniques to process and analyze the data to obtain information that's not measured by other sensors. There's every reason to expect innovative uses to continue with GRACE-FO.

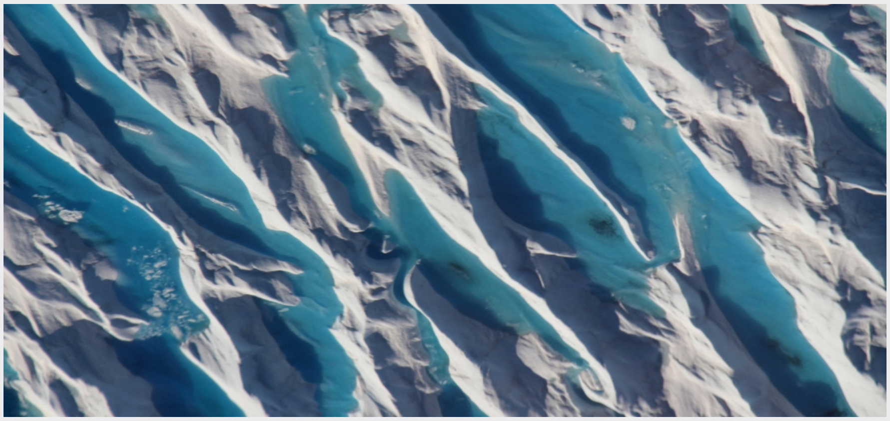


Map of static gravity anomalies
Image credit: NASA/JPL-Caltech

Here are a few areas where GRACE has revolutionized our understanding.

MELTING ICE SHEETS

In the decades before GRACE, only limited observations of melting ice in Greenland and Antarctica from the ground or by remote sensing were available -- not enough even to be sure whether Antarctica's ice sheet was growing or shrinking overall. Within a few years of its launch, several university research groups were able to calculate that ice losses from both ice sheets were dramatically larger than some previous estimates had suggested. Since GRACE launched, its measurements have shown Greenland has been losing about 280 gigatons of ice per year on average, and Antarctica has lost almost 120 gigatons a year, with indications that both melt rates are increasing. One gigaton of water would fill about 400,000 Olympic-sized swimming pools.

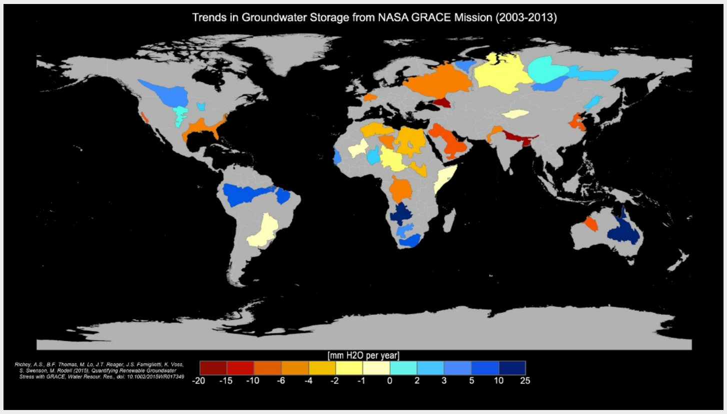


Melt ponds on the Greenland ice sheet
Image credit: NASA / OIB / John Sonntag

Isabella Velicogna of JPL and the University of California, Irvine, and colleagues recently used GRACE data to estimate that ice loss has also accelerated over 2003-2013 by about 25 gigatons per year every year in Greenland and 11 gigatons per year every year in Antarctica. If the acceleration continues, the melting of the two ice sheets will be the dominant contributor to sea level rise in the 21st century.

UNDERGROUND WATER

Water stored in aquifers below Earth's surface is very sparsely measured worldwide. GRACE has given us the first regional and global-scale measurements of this significant freshwater resource. The data measure changes in underground water mass, so it is not possible to know how much water remains underground. Over the last decade, however, hydrologists including Matt Rodell of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and Jay Famiglietti of NASA's Jet Propulsion Laboratory in Pasadena, California, have found more and more locations where humans are pumping out groundwater faster than it is replenished. In 2015, their team published a comprehensive survey showing a third of Earth's largest groundwater basins are being rapidly depleted.



Groundwater storage map
Image credit: UC Irvine/NASA/JPL-Caltech

Dry soil
Image credit: USGS

DRY SOIL AND DROUGHT

Dry soils can add to drought risk or increase the length of a drought. Rodell (NASA GSFC) and his team provide GRACE-derived data on deep soil moisture and groundwater to the National Drought Mitigation Center each week, using a hydrology model to calculate how the moisture is changing throughout the month between one map and the next. The data are used in preparing weekly maps of U.S. drought risk.

SEA LEVEL

Sea level is rising because melting ice from land is flowing into the ocean and because seawater expands as it warms. Very precise, continuous measurements of sea level heights worldwide began in 1992 with the U.S./French Topex/Poseidon mission, and continue through the Jason series of sea level altimetry missions. Altimeter measurements, however, see only the full effect of ocean height changes from all causes – that is, the combined impacts of ocean warming, ice melting and runoff from land. To get an in-depth view of the processes responsible for the changes, it is necessary to know how much of the full effect is due to each one.

Rising seas
Image credit: UN / Milton Grant

GRACE observations enable 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 disruptions in the global water cycle from the large 2011 La Niña event. 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. Australia does not have large river systems leading from the interior to the ocean, so most of the rain that fell there remained there until it evaporated. The finding provided a new view into the dynamics and connections that shape the global water cycle.

OCEAN BOTTOM CURRENTS

Ocean currents distribute heat across the planet, and thus any changes in ocean currents are an important indicator of how our planet is responding and evolving in a warming climate. At the bottom of the atmosphere -- 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 pressure tell us about flowing water, or currents. Felix Landerer and colleagues at JPL developed a way to isolate the signal in GRACE data that indicates tiny pressure variations at the ocean bottom caused by changes in deep ocean currents. The measurements showed a significant, temporary weakening of the Atlantic meridional overturning circulation, a crucial global climate regulator that transports vast amounts of heat from lower to higher latitudes. A network of ocean buoys that spans the Atlantic near 26 degrees north latitude also recorded this drop in the winter of 2009-10, but GRACE enabled the detection of this signal several thousand miles north and south of the buoys' latitude, providing new insights into large-scale ocean current processes. The measurements from GRACE agreed well with estimates from the buoy network, giving the researchers confirmation that the technique can be expanded to provide estimates throughout the Atlantic and beyond.

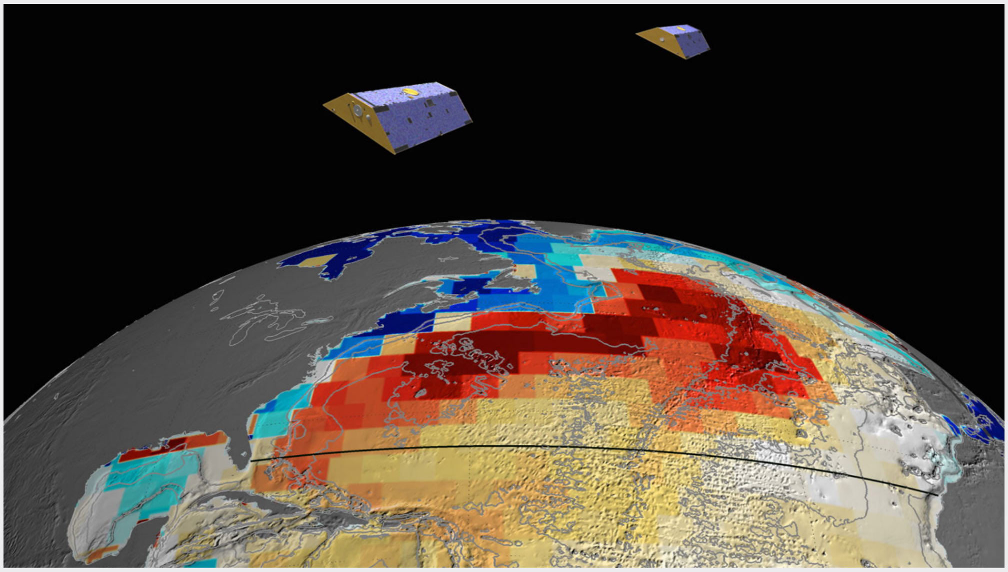


Illustration of ocean bottom pressure
Image credit: NASA/JPL-Caltech

EARTH, FIRE AND AIR

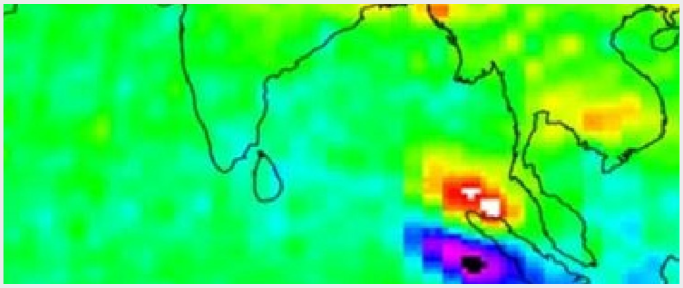
Although most of GRACE's discoveries have involved water and ice, its data are useful in other areas of Earth science. A recent research project suggested that eventually GRACE soil moisture data might help in forecasting regional wildfire risks. Thus, the satellites' data have now been applied to all four elements of the ancient cosmos -- earth, water, fire and air -- an appropriate indicator of how their use is expanding.

SOLID EARTH

The viscous mantle under Earth's crust is also moving ever so slightly in response to mass changes from water near the surface. NASA scientists 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.

In the early GRACE mission stages, it was not clear if the mission's measurement could be used to detect the changes in mass associated with large earthquakes, because only certain large earthquakes move enough mass for GRACE to detect. But during its 15 years in orbit, GRACE was able to measure the instantaneous mass shifts from several large earthquakes. For the first time, Jeanne Sauber-Rosenberg (NASA GSFC) and collaborators could identify in the GRACE data gravity changes associated with the large but slow tectonic mass adjustments that go on for months or 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 the 2011 Tohuku (Japan) quake, both of which caused devastating tsunamis.

Large mass shifts on the surface (e.g., from ice melt) can even affect Earth's rotation. Any change in the distribution of mass will cause Earth's axis to shift, wobble, and readjust like a spinning top. GRACE helps pinpoint those rotation changes and understand their causes.



Earthquake data from GRACE
Image credit: NASA/JPL/University of Texas-CSR

Clouds at dusk
Image credit: UCAR / Caryle Calvin

THE ATMOSPHERE

Each satellite, using its GPS receivers and special antennas, makes at least 200 radio occultation observations a day for determining atmospheric temperature and humidity profiles. This is done by measuring how much signals from GPS satellites are distorted by the atmosphere. Forward- and aft-pointing antennas on each satellite measure signals from GPS satellites as they appear to rise or set behind Earth, "looking" horizontally through a thick layer of atmosphere. Water vapor in the atmosphere bends and refracts the GPS signals. By comparing these distorted GPS signals with signals from higher-elevation GPS satellites, which do not pass through so much atmosphere, profiles of temperature and humidity down to an altitude of about 60 miles (100 kilometers) are calculated.

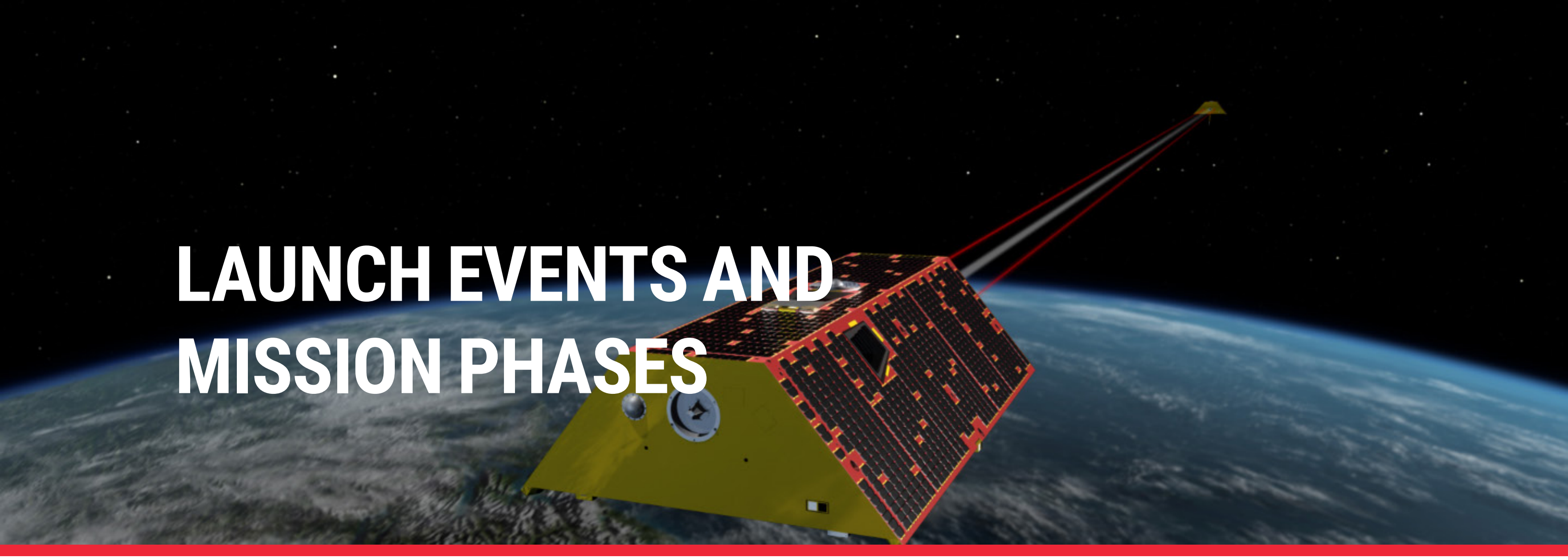
CONTINUITY IS CRITICAL

Rising sea levels, changing aquifers, floods, droughts and melting ice sheets: it's obvious why researchers want GRACE-FO to continue monitoring these high-impact changes in the Earth system that GRACE first allowed them to quantify.

Continuing mass change measurements will open up new science territory. Rainfall, ocean currents and other processes vary naturally. Many of the processes that GRACE measured, like the melting polar ice sheets, were not quantified before this mission. While 15 years of high-quality, global and nearly uninterrupted data have already produced a plethora of discoveries, the longer data record from GRACE-FO is essential to tease out the signal of long-term climate evolution from the effects of recurring climate patterns. This will allow a better understanding of how climate change, natural climate cycles and natural variability interact.

SCIENCE TEAM

NASA has been funding a competitively selected science team for the GRACE mission, and since 2016, for both the GRACE and GRACE-FO missions. The annual team meetings include scientists from more than 10 countries and were sponsored by the U.S. and GFZ co-principal investigator institutions, alternating the meeting location between Austin, Texas and Potsdam, Germany.



LAUNCH EVENTS AND MISSION PHASES

LAUNCH SITE AND VEHICLE

The twin GRACE-FO satellites will be launched together aboard a SpaceX Falcon 9 rocket from Space Launch Complex 4E (SLC-4E) at Vandenberg Air Force Base in central California. They will share the launch to Earth orbit with five Iridium NEXT communications satellites as part of a commercial rideshare mission procured by GFZ from Iridium Communications Inc.

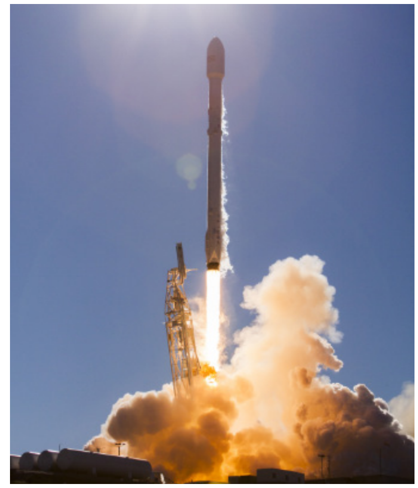
GRACE-FO will share a ride to space with Iridium NEXT communications satellites on a SpaceX Falcon 9 rocket. The photo shows an earlier rocket and Iridium payload from the same series of launches.
Image credit: SpaceX

LAUNCH TIMING

The GRACE-FO spacecraft will be launched into a near-circular polar orbit with an inclination of 89 degrees and an orbital period of approximately 90 minutes.

The time of launch is determined by the launch requirements of Iridium.

The launch date is based on the readiness of the payloads, the Falcon 9 launch vehicle and the Western Test Range at Vandenberg Air Force Base. Launch is currently scheduled for no earlier than May 19, 2018, at 1:04:24 p.m. PDT (4:04:24 p.m. EDT). The launch window on subsequent days falls earlier by approximately 5 minutes, 35 seconds each day.

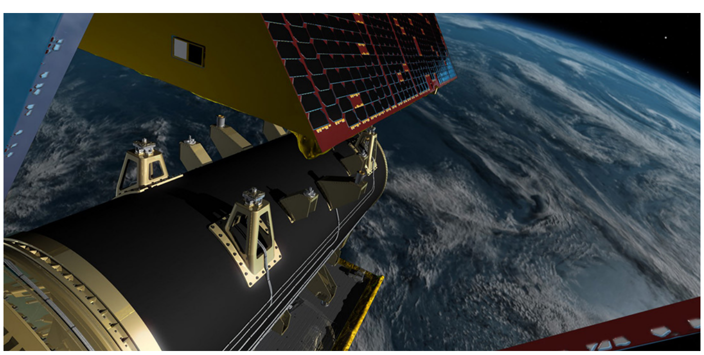


A SpaceX Falcon 9 launching with an Iridium payload
Image credit: SpaceX

LAUNCH SEQUENCE

The Falcon 9 will launch GRACE-FO from SLC-4E down an initial flight azimuth of 180.1 degrees from true north (south-southwest). The boost-phase trajectory is designed to place the Falcon 9 upper stage, along with the GRACE-FO and Iridium satellites, directly into an approximately 305 mile (490-kilometer) circular orbit by the time of the first cutoff of the Falcon 9 Second-Stage engine (SECO-1). The nominal altitude of the injection orbit for GRACE-FO was chosen to match that of GRACE.

The Falcon 9's Merlin first-stage engine start sequence begins approximately three seconds prior to liftoff. After liftoff, the launch vehicle will travel through maximum dynamic pressure (max Q). The nine first-stage engines burn for approximately two minutes and 45 seconds before being commanded to shut down at Main Engine Cutoff (MECO). Separation of the Falcon 9's first and second stages occurs seconds later, followed by ignition of the second-stage engine for second-engine start 1 (SES1), which burns until reaching the injection orbit. During the second-stage burn, the payload fairing, or launch vehicle nose cone, will separate into two halves, like a clamshell, and fall away.



Artist's concept of GRACE-FO seperating from the launch vehicle
Image credit: NASA/JPL-Caltech

After separating from the first stage and completing its ascent with the orbit insertion burn, the second stage pitches down 30 degrees to its separation attitude for GRACE-FO and rolls so that one of the GRACE-FO satellites is on the Earth-facing side of the launch stack and the other on the opposite side is facing space.

Approximately 11.5 minutes after liftoff, a separation system on the re-ignitable second stage will deploy the twin GRACE-FO satellites in nearly the same nominal orbit. The separation impulses are within 20 milliseconds of each other and push the two spacecraft in opposite directions, with the only differences being that the separation mechanisms will have pushed the two satellites crossways in opposite directions by 0.8 feet (0.25 meters) to 1 foot (0.30 meters) per second each, resulting in slight relative velocity differences and magnitudes. Thus one of the GRACE-FO satellites will be pushed up into a larger, higher orbit that is slower on average, and the other will be pushed down into a smaller, lower orbit that is faster on average.

Separation occurs over the Pacific Ocean at about 17.5 degrees North latitude, 122.6 degrees West longitude. VAFB will confirm a successful separation using downlinked telemetry data from the upper stage. The first data from the spacecraft are expected to be received through the first pass over NASA's tracking station at McMurdo, Antarctica. The satellites will be in range of the McMurdo station about 23 minutes after separation and within range of the Alaska Satellite Facility tracking station about 45 minutes later, providing a good chance of acquiring early telemetry data for mission operations.

After separation of the GRACE-FO satellites, the Falcon 9 second stage will coast before re-igniting its engine (SES2) to take the Iridium NEXT satellites to a higher orbit, where they will be deployed, one by one.

MISSION PHASES

LAUNCH AND EARLY OPERATIONS PHASE

The purpose of the Launch and Early Operations Phase (LEOP) is to gain control over the two GRACE-FO satellites and establish nominal formation. The LEOP starts at the time of launch and ends when the following conditions have been met:

- Both satellites are in safe, stable orbits, approximately 137 miles (220 kilometers) apart, with no danger of collision with each other, with the launch vehicle or with co-passenger satellites.
- Both satellites have attained nominal attitude control, including successful star camera acquisition.
- Nominal uplink and downlink communications are achieved with ground stations.
- No anomalies exist that pose a near-term threat to the mission.

In the absence of major unexpected events, LEOP will be completed within the first five days after launch. This phase provides frequent opportunities for monitoring the satellites' status so that controllers can intervene from the ground if required.

Throughout the mission lifetime, telemetry and telecommanding activities will be carried out by DLR/German Space Operations Center (GSOC) at its mission control center in Oberpfaffenhofen, communicating with the satellites via ground stations in Weilheim and Neustrelitz, Germany, and, during the first days of the mission, at the NASA Near Earth Network ground stations at McMurdo, Antarctica; Poker Flat, Alaska; Svalbard, Norway; and Wallops Island, Virginia for uplink. The GFZ Satellite Receiving Station at Ny-Ålesund on Spitsbergen will be the primary downlink station, with backup provided by the uplink stations.

After the satellites are simultaneously released from the Falcon 9's second stage, the leading satellite will move away from the trailing satellite at a relative speed of about 1.6 feet (0.5 meters) per second. Separation from the launch vehicle causes systems on board the satellites to activate. Less than a minute later, a boom that holds each satellite's radio frequency S-band antenna is deployed, and the low-rate radio transmitter is activated. The S-band transmitters will continue to transmit until turned off by ground command. During LEOP, the satellites must be capable of survival and attitude recovery with little or no real-time ground interaction.

The separation from the launch vehicle will leave the two satellites in somewhat different orbits. The goal of the maneuvers in LEOP will be to establish the operational formation with the two satellites separated by 137 miles (220 kilometers) sometime between two and a half and four days after separation.

During LEOP, between two and three days after separation from the launch vehicle, the leading spacecraft (which is in the lower orbit) will perform a maneuver to increase the size of its orbit to match that of the other spacecraft and stop the spacecraft from drifting apart. The stability of the separation orbit will be verified six days after launch.

Following their first pass over McMurdo, Antarctica, where separation will be verified, the two satellites will come within radio range of Svalbard, Norway, and then Poker Flat, Alaska. These two ground stations will be used to receive telemetry and to relay commands issued by the German Space Operations Center. On later orbits, the performance of both satellites will be verified, and commands will be issued as needed.

The orbits of the two satellites will evolve naturally for the remainder of the mission. Due to differences in drag forces, the separation between the satellites will vary between 106 and 193 miles (170 and 270 kilometers). Station-keeping maneuvers will be carried out as necessary, approximately every five months, to keep the two satellites at their desired separation.

To insure uniform exposure and aging of the K-band microwave antennas on each satellite, once or twice during the mission, the leading and trailing satellites may exchange positions. The altitudes of the two satellites will decay (gradually get lower) in tandem, from approximately 305 miles (490 kilometers) at the beginning of the mission to 186 miles (300 kilometers) toward the end of the mission; however, the exact altitude decay over time will depend on solar activity and corresponding radiation pressure. At various intervals in the mission, it will also be necessary to carry out certain science instrument calibration maneuvers.

Up to 3.7 gigabytes of instrument, ancillary and spacecraft data will be downlinked to Earth via the S-band antenna from each satellite every day. The DLR German Remote Sensing Data Center will serve as the Raw Data Center at Neustrelitz.

IN-ORBIT CHECK OUT PHASE

After the orbit and basic satellite operations are well established during LEOP, there will be an In-orbit Checkout (IOC) phase of approximately 85 days, during which the science instruments are powered up and the instruments and satellite systems are evaluated, and calibrations and alignments are carried out. The mission transitions from LEOP to the IOC phase when the LEOP conditions are fulfilled and confirmed by the project.

Some of the activities that occur during this phase include:

- Full power-on and checkout of all systems
- Instrument calibrations/characterizations.
- Achieve thermal stabilization of the two satellites in the operational mode.
- Software patches and parameter updates (as required).
- Flight system characterization: science parameter updates.
- Science analysis (e.g., 1st Quick Look gravity fields etc.).
- Science Data System inter-comparisons/validations/updates.

A Post-launch Assessment Review will take place near the end of this phase to verify that the operations system is ready to proceed into the validation and operational part of the Science Phase.

SCIENCE PHASE

Following the In-Orbit Checkout phase, the mission will enter its Science phase, in which science data will be routinely gathered and processed. This phase will continue until the end of the mission and will include brief interruptions for orbit maneuvers and instrument re-calibrations. The science phase begins with a 120-day gravity model validation sub-phase focused on providing an end-to-end characterization of the science instrument and data systems before making the first science delivery. During this time, measurements for three monthly gravity science products will be acquired.

The following activities will be performed during this phase:

- Continuous records of science data are downlinked from the satellites, and data flow problems are resolved.
- The microwave instrument K-band ranging system boresight alignment is calibrated and verified.
- Precise orbit solutions are obtained and verified using ground-based laser tracking data.
- Initial solutions for the gravity field are calculated.
- Preliminary gravity field solutions are verified through a combination of internal consistency checks and comparisons with complementary data gathered on the ground.

The orbits and ground tracks of the GRACE-FO satellites are not actively controlled during the In-Orbit Checkout and Science phases. The orbits are freely evolving, except when interrupted by station-keeping maneuvers or a satellite exchange maneuver. To maintain the separation between the GRACE-FO satellites to 137 miles (220 kilometers) plus or minus 31 miles (50 kilometers), station-keeping maneuvers will be carried out.

During the Science phase, the science and satellite housekeeping data are routinely collected by GRACE-FO's Mission Operations System and analyzed by the Science Data System team. DLR ground stations at Weilheim and Neustrelitz will be used for tracking, telemetry and telecommand activities for the duration of the Science phase. The GFZ ground station at Ny-Ålesund will be used as the primary downlink station. Each satellite transmitter is powered for a maximum of 19 minutes every orbit to support data transmission.

DECOMMISSIONING PHASE

Orbital debris are a hazard to all low-Earth orbiting satellites. Even non-operating spacecraft are a concern, as they are passive targets for debris strikes that could spawn more debris to threaten active missions. To limit debris strikes, satellite missions decommission their spacecraft in orbits that are predicted to decay within a specified time. At the end of the Science phase (including any extensions to the mission), the GRACE-FO mission will enter its Decommissioning phase.

Nominally, the orbit at the end of the mission will already be low enough to ensure compliance, so no orbit change will be needed, and the propellant depletion maneuvers that begin the passivation of the satellites will be designed to further reduce the risk of collision during decay of their orbits. The spacecraft with the most remaining propellant will use it to lower its orbit as much as possible. The other spacecraft will perform its depletion maneuver in a manner that separates the orbit planes of the two spacecraft as much as possible.

After propellant depletion, the battery on each spacecraft will be disconnected from the solar array; it will continue to power the spacecraft until discharged by that power draw. Then, fault protection on the spacecraft will be deactivated. Finally, the transmitter of each spacecraft will be turned off, terminating all orbital operations for GRACE-FO.

Final data and science processing will be completed, and data products will be archived.

Per NASA procedural requirements, GRACE-FO's end-of-mission orbits will assure that the twin spacecraft reenter the atmosphere within 25 years of decommissioning or 30 years of launch, whichever is earliest.

GROUND SYSTEM AND DATA PRODUCTS

The GRACE-FO mission ground system includes all the assets needed to command and operate the twin satellites in orbit, as well as manage, process and distribute their data.

To communicate with the satellites, the operations center in Oberpfaffenhofen, Germany, sends commands through ground stations in Weilheim or Neustrelitz directly to the GRACE-FO satellites. Once data have been recorded onboard the spacecraft, they are transmitted to the two German stations or to the GFZ station in Ny-Ålesund, Norway. From there, all received telemetry is sent to the Raw Data Center in Neustrelitz, Germany, and to the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at JPL in Pasadena, California, the Information System and Data Center (ISDC) at GFZ in Potsdam and to UT-CSR for monitoring and further analysis. Real-time data analysis takes place at the German Space Operations Center (GSOC), which will respond with new software commands as necessary for optimal operations.

JPL and GFZ will carry out the first level of processing, generating calibrated and processed metric observables. JPL, GFZ and UT-CSR will generate gravity field products from these intermediate products. The validated data products will be distributed to the science community through archives at JPL's PO.DAAC and GFZ's ISDC.

Data from the GRACE-FO satellites are returned approximately every 90 minutes. During most of the mission, the ground tracks of the GRACE-FO satellites will trace sufficiently dense patterns over Earth to enable a global gravity field to be generated every 30 days.

Data products will include 30-day estimates of gravity fields as well as daily profiles of air mass, density, pressure, temperature, water vapor and ionospheric electron content.

Once GRACE-FO is fully operational, high-resolution, monthly global models of Earth's gravity field will be freely available at: **https://grace.jpl.nasa.gov/data**.

SPACECRAFT AND INSTRUMENTS

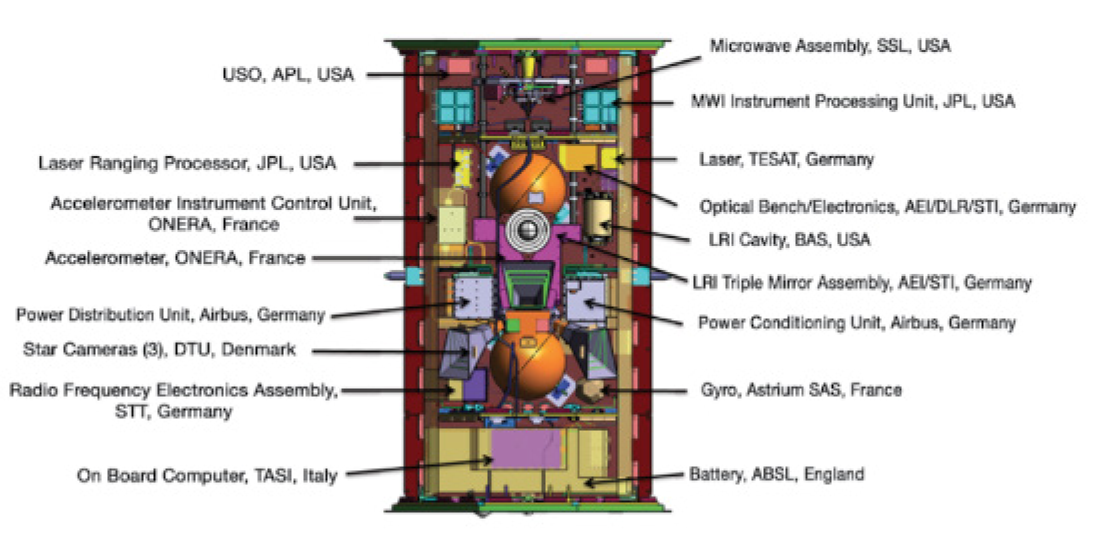


Diagram of a GRACE Follow-On satellite
Image credit: Airbus-DS, GmbH

GRACE-FO is different from most Earth-observing satellite missions. Except for its atmospheric limb sounder GPS measurements, which will provide data to aid weather forecasting, it does not carry a suite of independent science instruments that point down at Earth's surface to observe some part of the electromagnetic spectrum. Instead, the twin satellites act in unison as the main instrument, pointing their microwave and laser ranging instruments at each other to obtain data on distance changes between the two spacecraft that are used to generate monthly models of Earth's gravity field.

While similar in most respects to their predecessor GRACE satellites, GRACE-FO incorporates design upgrades gleaned from 15 years of GRACE operations that will improve satellite performance, reliability and mission operations.

SATELLITE BUS

Built by Airbus Defence and Space in Friedrichshafen, Germany, under subcontract to JPL, the twin GRACE-FO satellites – known respectively as GRACE-FO-A and GRACE-FO-B -- are identical in all respects except for transmit and receive frequencies. Each is 10 feet, 3 inches (3.123 meters) long, 2 feet, 6.7 inches (0.78 meters) high, 6 feet, 4.5 inches (1.943 meters) wide at bottom, 2 feet, 3.3 inches (0.69 meters) wide at top, and weighs 1,323.2 pounds (600.2 kilograms), including onboard propellant.

POWER SYSTEM

An electrical power subsystem generates, converts, conditions, regulates, distributes and stores primary electrical power in accordance with instrument and satellite bus user needs. Electrical energy is generated using gallium arsenide solar cell array panels that cover the top and sides of each satellite. Excess energy on each satellite is stored in a lithium-ion battery with a capacity of 78 amp hours. The system provides an average of 355 watts of electrical power on orbit and is manufactured by Airbus.

THERMAL CONTROL

A thermal control subsystem keeps all spacecraft and science instrument temperatures within allowable limits. It does this using a combination of active and passive control elements. It consists of 64 independent thermistor-controlled heater circuits for in-flight temperature housekeeping, monitoring and heater control, as well as for on-ground verification testing. The thermal control subsystem is manufactured by Airbus.

TELECOMMUNICATIONS

The Radio Frequency Electronics Assembly allows the satellites to communicate with Earth via radio in the microwave S-band spectrum. It receives telecommands and transmits onboard telemetry and science data from the instruments to the ground. It consists of two redundant transceivers coupled to a transmit/receive helix antenna mounted on the end of a boom that is deployed from the bottom of the satellites after separation. Additional redundant transmit and receive patch antennas are mounted to the top of the satellites. Each satellite uses a separate set of S-band frequencies for transmission and reception.

ON-BOARD DATA HANDLING

The onboard data handling system provides the central processor and mass memory software resources for the spacecraft and management of the science and housekeeping data. It provides necessary input and output capabilities for the attitude and orbit control system, and power and thermal systems operations. In addition, it performs spacecraft health functions, including fault detection, isolation and recovery operations.

MASS TRIM MECHANISM

For the accelerometer to measure only non-gravitational forces, it is important that the spacecraft center of gravity be placed at the center of the proof-mass of the accelerometer. The mass-trim mechanism and associated mass-trim electronics serve this function. The six mass-trim mechanisms each consist of a mass moving on a spindle, with each pair providing center-of-gravity trim along one axis.

The mass trim mechanism will be completely operated from the ground. The mechanism is a rebuild from GRACE with slightly increased mass and trim ranges.

ATTITUDE AND ORBIT CONTROL SYSTEM

The satellite's "attitude," or orientation and orbit control, are controlled by a system consisting of sensors, actuators and software. The Attitude and Orbit Control System provides three-axis stabilized Earth-pointing attitude control during all mission modes and measures spacecraft rates and orbital position. It features numerous improvements from the GRACE design. The system consists of a GPS receiver, Star Tracker Assembly, coarse Earth and sun sensor, fluxgate magnetometer, inertial measurement unit, magnetic torquers and a cold gas propulsion system.

The GPS receivers are used as references to determine the precise location of the two satellites in orbit. The receivers continuously receive location information from the constellation of GPS satellites circling Earth. Each spacecraft has three GPS antennas. One antenna is used to collect navigation data, one collects the mission's atmospheric occultation data, and the other is used for backup navigation. The GPS receivers were manufactured by JPL.

The Star Tracker Assembly enables fine attitude and orbit control of the satellites and precise transformation of science data into inertial references. It precisely determines each satellite's orientation by tracking their relative position in reference to the stars. It consists of three star tracker camera heads and control electronics. The GRACE mission used two star tracker camera heads. The GRACE-FO design increases attitude data availability during Sun/Moon blinding and improves accuracy about all spacecraft axes.

The coarse Earth/Sun sensor provides coarse attitude determination during all mission phases.

The magnetometer provides coarse attitude based on the satellite's position as determined by onboard GPS position and a model of Earth's magnetic field.

An inertial measurement unit provides three-axis rate information. The satellites are "three-axis stabilized," meaning that their orientation is fixed in relation to their momentary flight path, and they do not spin for stability.

Fine corrections of orientation can be adjusted using six 30-Amp-m2 magnetorquers, which help to minimize satellite fuel consumption over the mission lifetime.

The redundant cold gas propulsion subsystem uses small cold gas thrusters to position the twin spacecraft into their operational orbit and establish the satellite constellation. Once inserted into their operational orbit, very little acceleration is required to maintain the constellation. GRACE-FO will use 69 pounds (31.3 kilograms) of gaseous nitrogen as propellant. The subsystem features a set of twelve 10 millinewton thrusters mounted two on each of the six sides of the satellite, and two 40 millinewton orbit-control thrusters mounted on the rear-panel of the satellite.

MAIN EQUIPMENT PLATFORM

All science instruments, fuel tanks and batteries and other satellite subsystems are mounted on a carbon-fiber reinforced plastic platform. This material, which has a very low coefficient of thermal expansion, provides the dimensional stability necessary for precise range change measurements between the two spacecraft.

MICROWAVE INSTRUMENT

As with GRACE, the key science instrument for GRACE-FO is the microwave tracking system, known on GRACE-FO as the Microwave Instrument (MWI). The MWI provides precise (1 micron, about the diameter of a blood cell or a small fraction of the width of a human hair) measurements of the distance changes between the two satellites -- and, in turn, fluctuations in Earth's gravity -- by measuring microwave signals sent between the two satellites. Each satellite transmits signals to the other at two frequencies – 24 gigahertz (K-band) and 32 gigahertz -- (Ka-band), allowing for ionospheric corrections.

The MWI on each satellite consists of a redundant pair of **ultra-stable oscillators**, a **K/Ka-band ranging assembly** and an **instrument processing unit**.

ULTRA-STABLE OSCILLATORS

The ultra-stable oscillators serve as the frequency and clock reference for the GRACE-FO satellites. They are built by the Johns Hopkins University Applied Physics Laboratory in Baltimore, Maryland, and are based on the ultra-stable oscillators flown on NASA's GRACE and Gravity Recovery and Interior Laboratory (GRAIL) missions.

K/KA-BAND RANGING ASSEMBLY

The K/Ka-Band Ranging Assembly is the radio frequency front-end of the GRACE-FO microwave measurement system. It is comprised of a dual-band, dual-linearly polarized horn antenna, waveguide feeds and redundant Microwave Assembly K/Ka-Band transmitter/receivers. The ranging horn transmits and receives K-band (24 gigahertz) and Ka-band (32 gigahertz) carrier signals to and from the other GRACE-FO satellite. The antennas are nearly identical to those flown on GRACE, with a few modifications to the aperture cover and feed components. The MWAs up-convert the ultra-stable oscillator signal to K and Ka-Band for transmission, and down-convert the received K and Ka-Band signals to baseband frequencies of 670 kilohertz and 500 kilohertz. They are based on the original GRACE design, with minor improvements from the design used on GRAIL.

INSTRUMENT PROCESSING UNIT

The Instrument Processing Unit (IPU) is the nerve center for the science instruments for the spacecraft. It provides the digital signal processing functions for the K and Ka band signals, as well as for the GPS signals. It also provides various timing references for the satellite. The IPU includes a Trig Navigation Processor, Trig GPS sampler front end, and GRAIL Radio/Frequency Unit. The GPS component provides navigation information, time tagging/correlation of data products and ancillary Earth limb occultation measurements. The IPU subsystem includes the primary, redundant and occultation GPS antennas. The IPU was manufactured by JPL.

ACCELEROMETERS

The GRACE-FO satellites may speed up or slow down for reasons other than changes in Earth's gravity field. These other forces acting on the satellites are measured using a science instrument called an accelerometer, mounted at the center of gravity of each satellite. This instrument allows scientists to distinguish between satellite motions due to gravity influences and those caused by other influences such as air drag in the atmosphere or thruster firings. The three-axis electrostatic accelerometers are similar to the SuperSTAR accelerometers flown on GRACE and were developed by ONERA, a French national research laboratory.

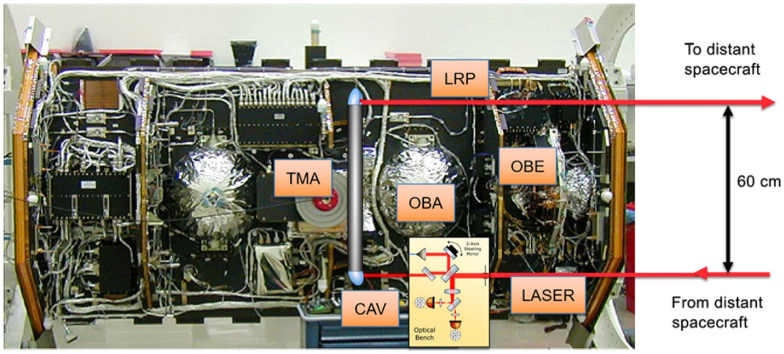
LASER RETRO-REFLECTORS

Each of the GRACE-FO satellites is equipped with a laser retro-reflector consisting of four corner cubes mounted in a small pyramid, which is located at the underside of the satellites. The laser retro-reflectors were contributed by GFZ and provide a means of tracking the GRACE-FO satellites from the ground for backup and orbit verification purposes. They will be tracked by the Satellite Laser Ranging (SLR) global ground station network of the International Laser Ranging Service (ILRS). Ground controllers can verify the satellite's orbits by firing lasers upward toward the satellites, where the laser beam bounces back off of the reflector. The data will be valuable in evaluating and strengthening orbit and gravity field solutions.

LASER RANGING INTERFEROMETER

The experimental Laser Ranging Interferometer (LRI) is a technology demonstration that uses laser interferometry instead of microwaves to measure fluctuations in the separation distance between the two GRACE-FO spacecraft. This is the same measurement made by the MWI, but the LRI offers the potential to improve the precision of range fluctuation measurements by a factor of at least 10, largely due to the laser wavelength being 10,000 times shorter than the microwave wavelength. These improvements will enable the satellites to detect gravitational differences at smaller scales. The LRI will demonstrate precision inter-spacecraft laser interferometry for future GRACE-like geodetic missions. GRACE-FO LRI data are for technology demonstration purposes only and will not be the mission's data of record for use by the science community.

The LRI was developed jointly by the United States and Germany. JPL managed the development of the laser, laser frequency stabilization reference cavity, and interferometer readout and control electronics, and supported spacecraft integration. Germany provided the optical components of the LRI (optical bench assembly and electronics, triple mirror assembly and baffles) and supported spacecraft integration. The German contribution was managed by the Max Planck Institute for Gravitational Physics Albert Einstein Institute (AEI) in Hannover, with implementation by SpaceTech (STI) in Immenstaad.



The LRI instrument

Image credit: Albert Einstein Institute, Hannover, Germany

The components of the LRI include:

- An Optical Bench Assembly, which routes, detects and points the laser optical beams. The Optical Bench Assembly was developed by STI. The steering mirror was developed by Airbus. The photoreceivers were developed by the German Aerospace Center (DLR) in Adlershof.
- Optical Bench Electronics, which provide power to the steering mirror and photoreceiver and signal conditioning between the photoreceiver and laser ranging processor. The Optical Bench Electronics were developed by Apcon Aerospace and Defence in Neubiberg/Munich.
- A Triple Mirror Assembly, which routes the beam around the MWI. The Triple Mirror Assembly was developed by STI and Hensoldt Optronics in Oberkochen, Germany.
- Optical Baffles, which prevent obstruction of the laser beams and control scattered light effects in the interferometer. The baffles were developed by STI.
- A Light Path Closure, which protects the LRI during spacecraft integration and covers the triple mirror assembly mirrors to avoid contamination from the spacecraft. The Light Path Closure was developed by STI.
- A Laser Ranging Processor, which measures the phase of the laser interferometer signal from the photoreceiver as representative of fluctuations in the separation between the two orbiters, provides control of the laser frequency, and commands the steering mirror angle and implements the search to establish the optical link. The Laser Ranging Processor was developed by JPL.
- The laser, which provides the light used for laser interferometry and emits approximately 25 milliwatts of light at 1064 nanometers. The laser is based on a commercial spaceflight unit developed by Tesat Corporation for inter-satellite laser telecommunications, and successfully flown on several projects, including the USAF Near Field Infrared Experiment (NFIRE) and German TerraSAR-X projects.
- The LRI's laser frequency stabilization and laser ranging processor are based on prototypes developed under NASA's Instrument Incubator Program by Ball Aerospace and JPL.
- An Optical Cavity, which stabilizes the laser light wavelength. The Optical Cavity was built by Ball Aerospace in Boulder, Colorado. The phase-modulator for the cavity was produced by Photline, part of iXblue in Saint-Germain-en-Laye, France.
- The LRI's laser frequency stabilization and laser ranging processor are based on prototypes developed under NASA's Instrument Incubator Program by Ball Aerospace and JPL.
- Optical fibers for the LRI were produced by Diamond USA Inc. and Diamond SA in Losone, Switzerland.
- Optical ground support equipment for the LRI was developed by the German Aerospace Center (DLR) Institute of Space Systems in Bremen, the Albert Einstein Institute (AEI) and JPL.

PROGRAM/PROJECT MANAGEMENT

The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission is a partnership between NASA and the German Research Centre for Geosciences (GeoForschungsZentrum, GFZ) in Potsdam, Germany. NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, manages the mission for NASA's Science Mission Directorate (SMD) at NASA Headquarters in Washington, under the direction of the Earth Systematic Missions Program Office at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

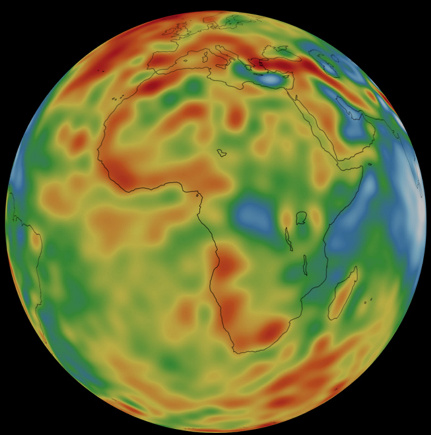
At JPL, **Phil Morton** is the project manager. **Frank Webb** is the project scientist, and **Felix Landerer** is the deputy project scientist. **Mike Watkins** is the Science lead and also the director of JPL.

At NASA Headquarters, **Thomas Zurbuchen** is the associate administrator for SMD, and **Dennis Andrucyk** is deputy associate administrator. **Sandra Connelly** is the deputy associate administrator for programs. **Michael Freilich** is the director of the Earth Science Division within SMD. **Eric Lanson** is associate director for flight programs, **Jack Kaye** is associate director for research, and **Lawrence Friedl** is associate director for applications within the Earth Science Division. **David Jarrett** is the GRACE-FO program executive and **Lucia Tsaoussi** is the GRACE-FO program scientist.

At GFZ, **Frank Flechtner** is the GRACE-FO project manager. **Franz-Heinrich Massmann** is the mission operation system manager. **Christoph Dahle** is the science data system manager.

GFZ has subcontracted mission operations to the Zentrum für Luft- und Raumfahrt (DLR), which operates the German Space Operations Center in Oberpfaffenhofen, Germany. At DLR, **Sebastian Löw** is the GRACE-FO mission operation system manager.

APPENDIX: MISSION OBJECTIVES



The goal of GRACE-FO is to continue and extend the 15-year record of monthly mass change measurements from GRACE, a foundational observation for understanding Earth's evolving climate system. It will do this by accomplishing the following two science measurement objectives:

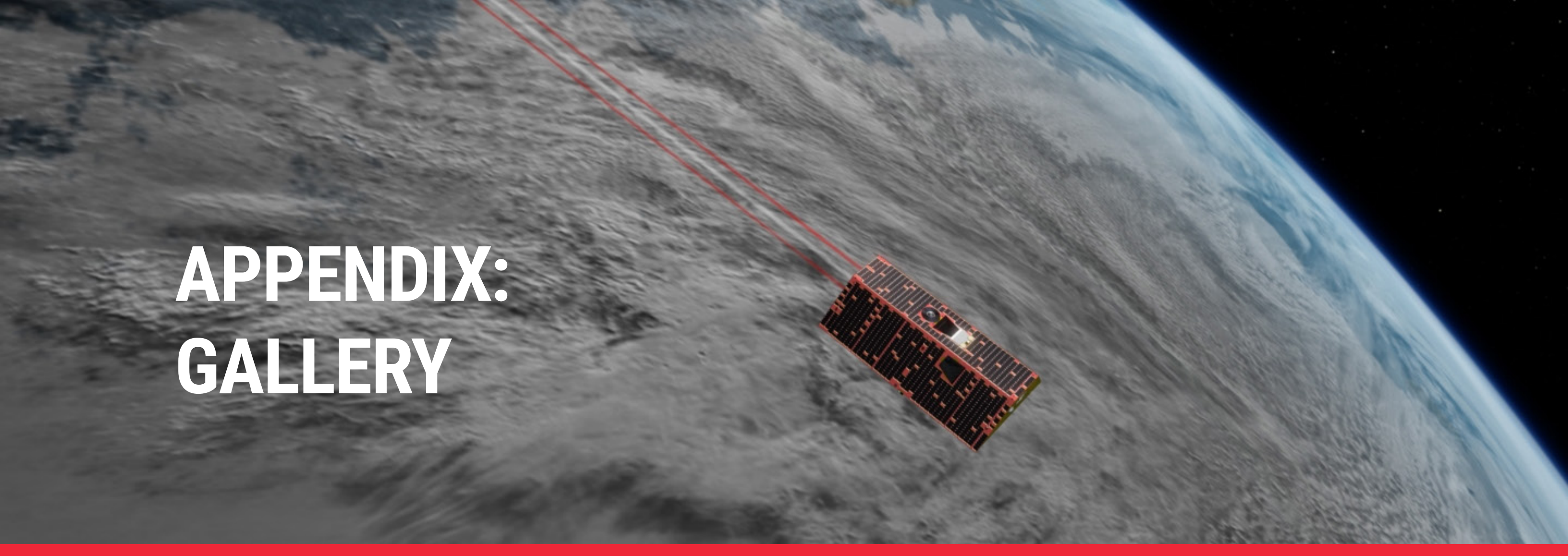
PRIMARY SCIENCE MEASUREMENT OBJECTIVE:

Provide estimates of the global high-resolution models of Earth's gravity field for up to five years at a precision and temporal sampling equivalent to that achieved with GRACE. As with the GRACE mission, the temporal sequence of gravity field estimates will yield the mean Earth gravity field, as well as a time history of its month-to-month variability to globally track surface mass changes.

SECONDARYSCIENCE MEASUREMENT OBJECTIVE:

Provide several hundred globally distributed profiles each day of the excess delay, or bending angle due to the refraction of Global Navigation Satellite System (GNSS) signals by the ionosphere and the atmosphere, using GPS limb-sounding. These signals are routinely used to improve weather, climate and ionospheric predictions by the operational weather services and by the scientific community.

Clouds at dusk
Image credit: UCAR / Caryle Calvin



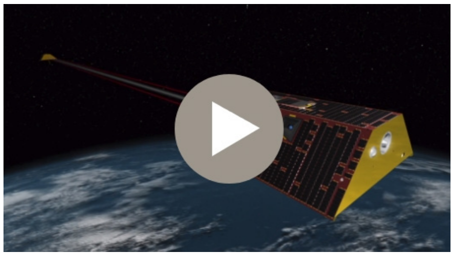
APPENDIX: GALLERY

IMAGES

Illustrations and photographs that appear within this press kit. Click on each below for full resolution and details.

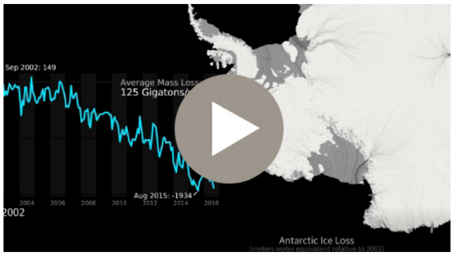
GRACE-FO Images and Illustrations
https://go.usa.gov/xQKuX

VIDEOS



Media Reel
https://vimeo.com/266146377

Airbus Tests GRACE-FO Antenna Boom
https://go.usa.gov/xQKu5



Antarctic Ice Loss 2002-2016
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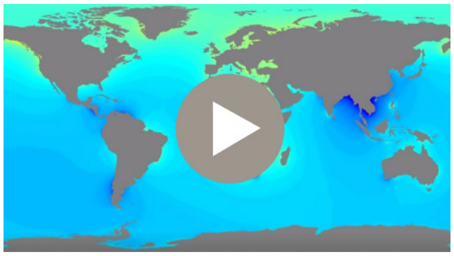
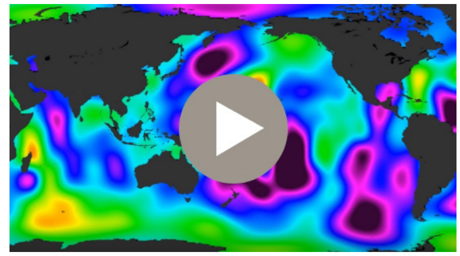


Cumulative Sea Level Change 2002-2015
https://go.usa.gov/xQKuR

15 Years of GRACE Earth Observations
https://go.usa.gov/xQKun



Ocean Bottom Pressure 2002-2012
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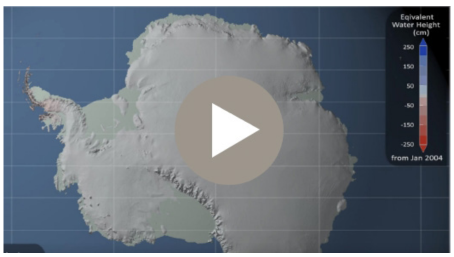

Antarctic Mass Change from GRACE – January 2004 - June 2014
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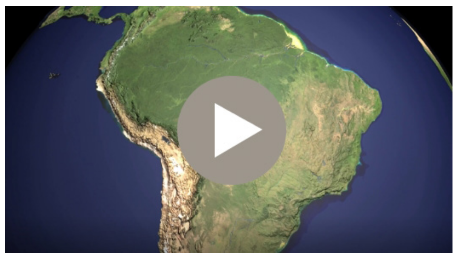
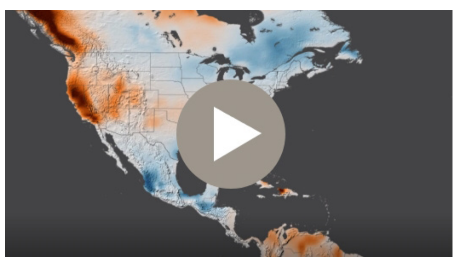


Amazon Basin Monthly GRACE Data
https://go.usa.gov/xQKuP

West Antarctic Collapse
https://go.usa.gov/xQKuE

Scale in the Sky
https://youtu.be/ecBgUrGlKps



Global Terrestrial Water Storage Anomaly
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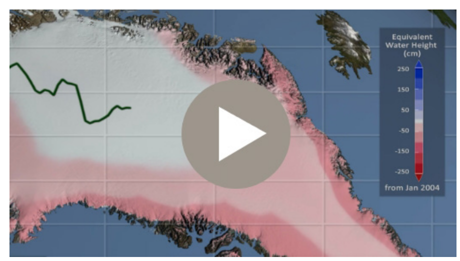

GRACE Mission Measures Global Ice Mass Changes
https://go.usa.gov/xQKuy

GRACE Sees Groundwater Losses Around the World
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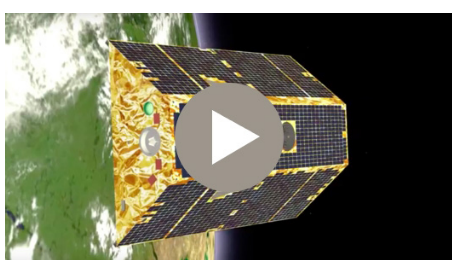
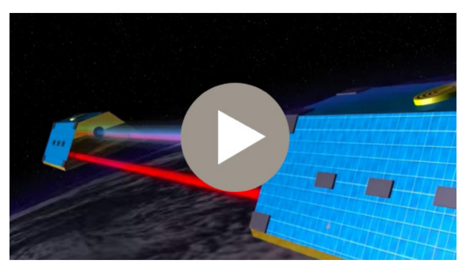


Build Commences on GRACE-FO Satellites
https://youtu.be/ZlQvxBreLng



Laser Ranging Interferometer
https://youtu.be/AC4AJgZ3QWM