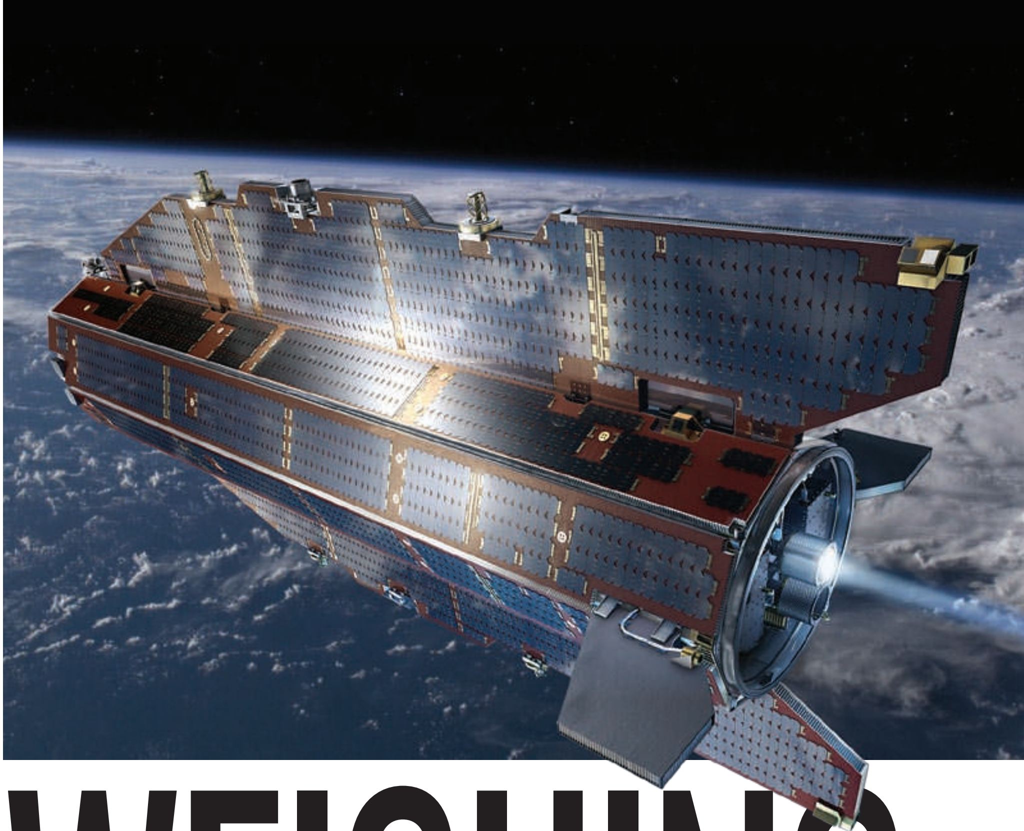
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WEIGHING THE WORLD

After a near-death crisis, the best gravity sensor in space is back to full strength, providing data that will keep scientists on the level. BY QUIRIN SCHIERMEIER

On 18 July, geophysicist Reiner Rummel received a phone call that made his heart sink. The European Space Agency (ESA) had stopped receiving data from a €350-million (US$471-million) satellite that Rummel had spent nearly 20 years designing, building, testing and shepherding into orbit. The craft, burdened with the unwieldy name of the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), had been in space for little more than a year. Now it looked as if it might be lost for good, undone by a glitch in the communications system that sends data back and forth from the satellite to the ground.

Rummel, who works at the Technical University of Munich in Germany and is joint principal investigator of the GOCE project, got little sleep throughout the summer as he and his colleagues tried various strategies to restore the on-board computer system, which had failed once before. Mission scientists developed software to combine the system with a back-up computer so that they could fix the apparent problem, but still the craft failed to respond. Then, in early September, ground controllers tried something new. They sent a signal to raise the temperature of GOCE's computer compartment.

At stake was the most finely tuned gravity sensor ever to fly in space. GOCE was designed to map the subtle gravitational differences that arise across the globe because Earth's mass of roughly six sextillion (10^{21}) tonnes is not distributed evenly. Using data collected by the small satellite, researchers planned to construct a sophisticated gravitational map called the geoid, accurate to the nearest centimetre: a fivefold improvement over previous efforts to map gravity from space. Such data would provide geoscientists with a global reference for precisely measuring the heights of continents, mountain peaks and the ocean surface, which is rising because of global warming.

GOCE data could also reveal the scars from a giant extraterrestrial impact 250 million years ago, keep tabs on the shifting tectonic plates that cause huge earthquakes, and help to measure the strength of ocean currents such as the Gulf Stream — critical information that will improve climate forecasts.

All this explains why researchers were mightily relieved when, as the GOCE computer warmed up, it sputtered back to life.

A MASSIVE MISSION

GOCE races across the skies at 30,000 kilometres per hour, skimming the edge of Earth's atmosphere at an altitude of about 250 kilometres. The craft has to maintain such a low orbit to make its measurements because gravity falls off rapidly with distance. But flying through the atmosphere creates drag on the satellite, so project engineers have given it an unusually aerodynamic design and an ion engine to counteract the air friction. From its low orbit, GOCE's main on-board instrument, a gravity gradiometer, is sensitive enough to measure the gravitational tug of giant reservoirs on Earth's surface.

The heart of the sensor consists of three pairs of cubes, arranged perpendicular to each other to form a three-dimensional cross. As the satellite passes overhead, the cubes each feel a different pull from the mountains and other masses on and below the planet's surface. An electrostatic control system measures those differences with such precision that GOCE can detect changes on the order of one-millionth of the average strength of Earth's gravity at the surface (see 'The pull of the planet').

Because the gradiometer is so sensitive, engineers could not truly test it before launch. They simulated zero gravity by dropping the sensor within a tall tower, but this was not an ideal test. "We're basically flying a prototype in orbit," says Rummel.

After GOCE was launched in March 2009, it took several months to fix problems such as difficulties in orienting the satellite with the required accuracy. But the team eventually achieved the planned sensitivity for the gravity measurements, and released its first big batch of data at an ESA symposium in Norway in June. If no further glitches occur, GOCE will complete its planned mission in April 2011.

"It's a tremendous achievement," says Philip Woodworth, a sea-level expert at the National Oceanography Centre in Liverpool, UK. "GOCE-derived gravity data will be usable for decades."

Researchers are already turning the initial harvest of data into a highly accurate geoid, a mathematically derived surface resembling a hypothetical mean global sea level. Real sea levels respond to winds, currents and other dynamic features of the planet. The geoid, by contrast, reflects what the ocean surface would look like if the world were covered by a static skin of water whose height is influenced only by gravity. It is a bulbous affair, with bumps and dips matching mountains, ocean trenches and density variations deep within the planet. At every point, the force of gravity operates perpendicular to the surface of the geoid.

The geoid was first conceived of in 1828 by German mathematician Carl Friedrich Gauss, who recognized that surveyors would need such a reference surface to determine the precise elevation above sea level for any point on Earth. To this day, uncertainties in the height of the geoid make it difficult to compare altitude measurements for different parts of Earth's surface.

GOCE will finally remedy this. The global geoid derived from the gravity measurements taken since April shows, among other things, a pronounced 'depression' in the Indian Ocean and 'plateaus' in the North Atlantic and western Pacific — mirroring convective activity and density anomalies in Earth's mantle. More of these delicate features will be added to the map in the coming months.

CURRENT EVENTS

Geodesists — scientists who study Earth's shape — have for the past few years been using a different space mission to map the planet's gravity field. The Gravity Recovery and Climate Experiment (GRACE), a joint mission of NASA and the German space agency, was launched in 2002 and uses a pair of satellites to measure relatively large-scale gravity variations, such as the loss of mass from melting sections of the Greenland ice cap. GOCE adds detail to the picture, with gravity measurements five times more precise than those of GRACE and with almost three times higher spatial resolution. Armed with its data, researchers will be able to distinguish between the ocean topography shaped by gravity and that of the 'hills' and 'valleys' of water created by wind, pressure gradients and Earth's rotation.

That will help scientists to measure ocean circulation, because large currents are slightly higher than the surrounding ocean, with the topographic height of the current directly related to its strength. "You can think of the Gulf Stream as a gentle hill that you'd need to climb if you could walk from Boston to the Bermudas," explains Woodworth. "If you're able to accurately measure the shape of the hill you can calculate the mean strength of the flow."

GOCE-derived data should therefore allow researchers for the first time to calculate the mean strength of the Gulf Stream, which carries warm water north from the Gulf of Mexico towards the Arctic. Such data on this and other currents are essential for improving computer models of the ocean and the atmosphere.

Geoid information should also help to determine the mean sea level to within a few millimetres, something not possible before. Local sea-level changes, such as those from one year to the next, can be measured by radar altimetry and tide gauges. But geodesists need an accurate global reference to compare measurements on different continents.

Even regional comparisons are difficult without an accurate geoid. For example, the UK National Tide Gauge Network suggests that the sea level off the north coast of Scotland is 30–40 centimetres lower than that off the coast of Cornwall, a difference that is almost certainly an artefact caused by levelling errors, says Woodworth.

The high-resolution gravity data from GOCE will also help to measure ice loss from Antarctica and Greenland, and can aid geologists in assessing the potential for large earthquakes. The biggest shocks, such as the magnitude-8.8 quake that struck Chile in February, rearrange Earth's tectonic plates, causing a change in the gravity field that can be sensed from space. GOCE data will give researchers new clues as to how masses of different densities readjust before and after large seismic events — and whether it is possible to measure gravity effects before the ground ruptures, says Roberto Sabadini, a geophysicist at the University of Milan in Italy, and a participant in GOCE.

The gravity data may even help to shed light on a planetary disaster: the 'Great Dying' that wiped out a large fraction of existing species 250 million years ago, at the end of the Permian period. Ralph von Frese, a geophysicist at Ohio State University in Columbus, belongs to a school of scientists who suspect that this mass extinction was triggered by the impact of a giant meteorite, more than twice the size of the one thought to have killed the dinosaurs 65 million years ago. Their search for the crater left by this enormous impact focuses on eastern Antarctica, where GRACE data and airborne-radar imagery indicate there might be a depression, 500 kilometres in diameter, under the 2–3-kilometre-thick ice in Wilkes Land (R. R. B. von Frese *et al. Geochem. Geophys. Geosyst.* **10,** Q02014; 2009).

THE GRAVITY DATA MAY EVEN HELP TO SHED LIGHT ON A PLANETARY DISASTER

The impact would probably have lifted high-density mantle material into Earth's crust, causing a lasting gravity anomaly. But because the GRACE signal is blurry, von Frese is eagerly awaiting GOCE data that could back his theory.

He and others are crossing their fingers that the fragile satellite will stay healthy for the next six months and complete its mission without any more drama. ■

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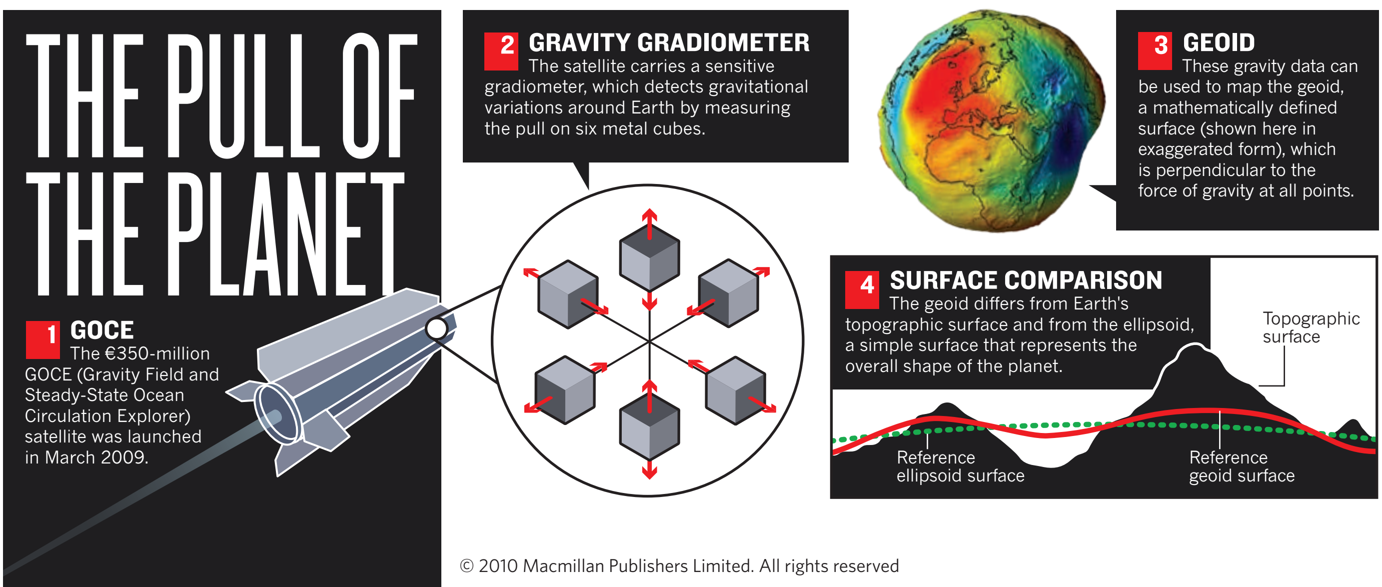

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