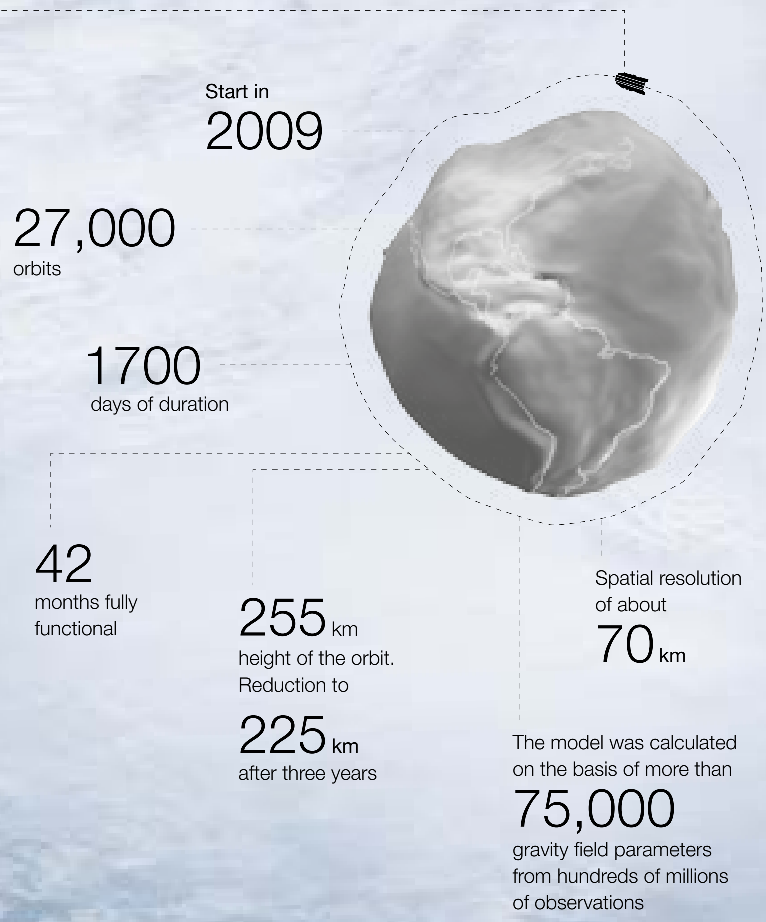


New Views of Earth in the **“Light” of Gravity**

The completion of ESA’s GOCE satellite mission is not so much an ending as a milestone in the ongoing exploration of Earth – as revealed by gravity. By providing the most accurate measurements and models yet of Earth’s gravitational field, GOCE is enabling researchers to sharpen the picture of our dynamic planet, from mantle convection to melting glaciers. TUM Prof. Roland Pail coordinates the international GOCE Gravity Consortium.

Picture credit: ESA - AOES Medialab

Link

www.iapg.bgu.tum.de

Gravitationsmessungen zeigen ein neues Bild der Erde

Im November 2013 verglühte der Satellit GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) bei seinem Wiedereintritt in die Atmosphäre. Die Satelliten-Mission der Europäischen Weltraumbehörde ESA hatte die Vermessung des Schwerefelds der Erde zum Ziel. Die im Juli 2014 vollständig veröffentlichten GOCE-Daten werden die beteiligten Forscher – mit dabei ein Team der TUM – über Jahre hin beschäftigen. Die vorliegenden Daten zeigen das Schwerefeld der Erde in nie dagewesenem Detail. Winzige Variationen in den Konturen des Felds entsprechen der ungleichen Massenverteilung, ob in der Kruste oder im Mantel, in den Ozeanen oder im Eis. Die Schwerkraftmessungen ermöglichen eine neue Sicht auf unseren Planeten – zusätzlich zu den bereits bekannten Beobachtungen, die auf Licht, Magnetismus oder seismischen Wellen basieren.

Prof. Roland Pail vom TUM Institut für Astronomische und Physikalische Geodäsie (IAPG) koordiniert das internationale GOCE Gravity Consortium. Das IAPG entwickelte das Schwerefeldmodell der Erde sowie die dazugehörigen, auf die Anforderungen unterschiedlicher Nutzergruppen zugeschnittenen Datenprodukte.

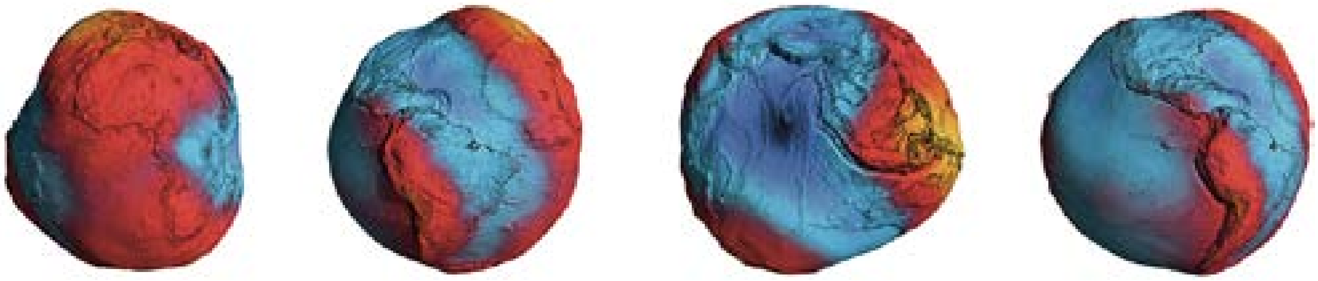
Die ersten Ergebnisse lassen auf neue Erkenntnisse in verschiedensten Bereichen hoffen – von Geophysik und Geologie bis hin zu Ozeanographie und Klimaforschung. GOCE-Datenprodukte werden genutzt, um Meeresströmungen, den Anstieg des Meeresspiegels sowie das Abschmelzen von Eisfeldern zu kartieren und zu beobachten. Die Messungen decken auch verborgene geologische Muster auf. Sie können künftig für die Erschließung natürlicher Ressourcen und zur Bewertung von Risiken von Interesse sein. Geophysiker erkennen aus den Satelliten-Schwerefeldmessungen Dichteunterschiede tief im Erdinneren und gewinnen daraus neue Erkenntnisse über die dynamischen Prozesse, die unsere Kontinente formen und für Erdbeben, Tsunamis oder Vulkanausbrüche verantwortlich sind. Mittlerweile nutzen Forscher aus dem Bauwesen das GOCE-Geoid, um ihr Projekt zur Vereinheitlichung nationaler Höhensysteme voranzubringen, denn die aus den Schwerefeldmessungen berechneten Höhen der Erdoberfläche bieten erstmals eine global einheitliche Bezugsgröße. *Patrick Regan (TUM)*

An artist's impression of GOCE in orbit: One key application of data from the GOCE satellite mission is to monitor signs of global warming in changing sea level, ocean circulation and ice cover.

Picture credit: ESA - AOES Medialab


BREEZE

Picture credit: ESA - AOES Medialab



Earth in the "light" of gravity: These four views show the height of the geoid — which corresponds to the mean ocean surface at rest — above or below a reference model for Earth's shape that is based not on gravity, but on the planet's rotation. Deviations above (red) or below (blue) the reference surface are caused by mass anomalies in Earth's mantle.

In November 2013, a satellite that had been flirting for years with Earth's gravity at the very edge of the atmosphere took its final, fiery plunge. The only known record of its last moments is a snapshot taken from the deck of a ship, by a passenger on a penguin-watching cruise. Any parts of the spacecraft that didn't burn up on re-entry splashed unseen and unheard into the South Atlantic.

The scientific impact, however, was evident long before the satellite known as GOCE fell from the sky. A series of four data releases had already begun enabling new views of our planet's deep interior and vast inaccessible areas of continental crust, as well as ocean currents and ice sheets. One result, the most accurate representation yet of the geoid – a gravity-derived figure of Earth's surface that serves as a global reference for sea level – is helping to advance the project of unifying height systems worldwide. While media headlines heralded the geoid's resemblance to a potato, researchers in a diverse range of fields celebrated the bonanza of new data.

A mission of the European Space Agency (ESA), the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) set out to measure Earth's gravitational field ▷

It is extremely rare to capture any record of a satellite's re-entry. This is the only known photo of the GOCE satellite burning up in the atmosphere, taken by a tourist on a cruise in the Falkland Islands.

Picture credit left above: IAPG/TUM, left below: Bill Chater, right: ESA - A. Le Floc'h

in unprecedented detail. Tiny variations in contours of the field correspond to uneven distributions of mass, whether in the crust or the mantle, ocean or ice. Thus, gravity offers a way to observe our planet that is complementary to approaches relying on light, magnetism, or seismic waves. Precise measurement and high-resolution modeling of the gravity field can yield insights into processes ranging from plate tectonics to climate change, and into hidden features that could guide resource exploration.

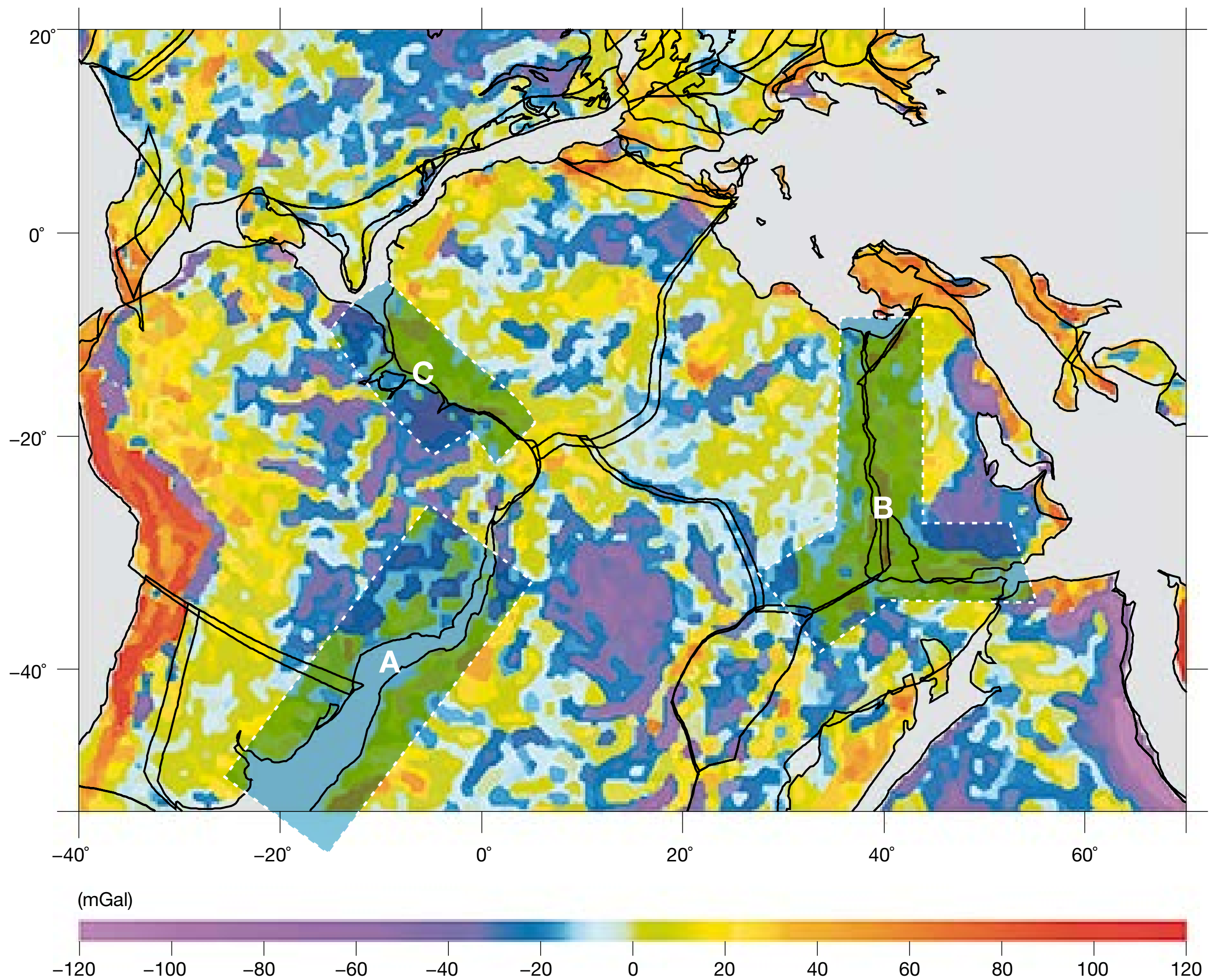
Mission complete – the work goes on

Every element of satellite and mission design, from GOCE's innovative gravitational gradiometers to its sleek aerodynamics and low orbit altitude, pushed the boundaries of engineering and operations. And it all worked beyond expectations. Launched in March 2009, the satellite orbited Earth 27,000 times during 1700 days in orbit, roughly three times longer than its nominal mission period, and was fully operational for 42 months. With the original mission goals being largely achieved after the first three years, a decision was made to further lower the orbit altitude from 255 to 225 kilometers. Flying 30 kilometers closer to the Earth would yield even more sensitive measurements, revealing detailed structures of the gravity field.

As coordinator of the international GOCE Gravity Consortium, the TUM Institute of Astronomical and Physical Geodesy (IAPG) has been responsible for developing the gravity model, as well as associated data products tailored to the needs of various user groups. The model, composed of more than 75,000 parameters describing the global gravity field with a spatial resolution of rough-

Prof. Roland Pail succeeded Prof. Reiner Rummel, a founding father of ESA's GOCE mission, as Director of the TUM Institute for Astronomical and Physical Geodesy and coordinator of the GOCE Gravity Consortium. He also serves as Dean of Civil, Geo and Environmental Engineering.

Picture credit left: Eckert, right: Prof. C. Braitenberg, Univ. of Trieste

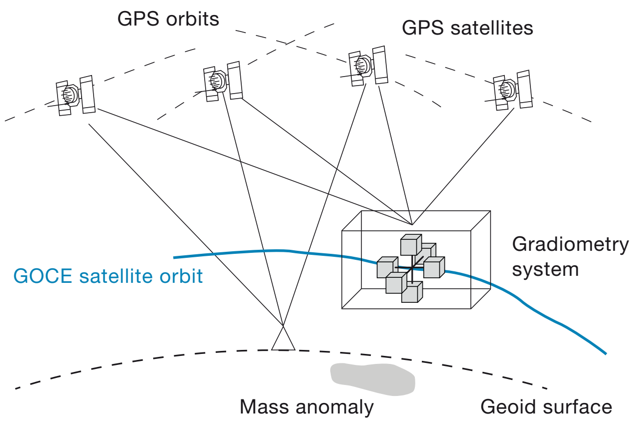


New light on geology and paleogeography: This figure highlights newly revealed features of the former supercontinent Gondwana (black lines), which began to break up around 184 million years ago. With the new high-resolution gravity data, reflecting mass anomalies in Earth's interior, researchers can directly measure continental structures and identify geological lines in greater detail than ever before. Symmetrical "gravity highs" due to magmatism can be clearly seen across the plate margins where the Atlantic Ocean (A) and the Red Sea (B) formed. The lack of symmetry in the margin between Brazil and West Africa (C) may contribute to solving open geological questions. Such insights can also be used to guide resource exploration.

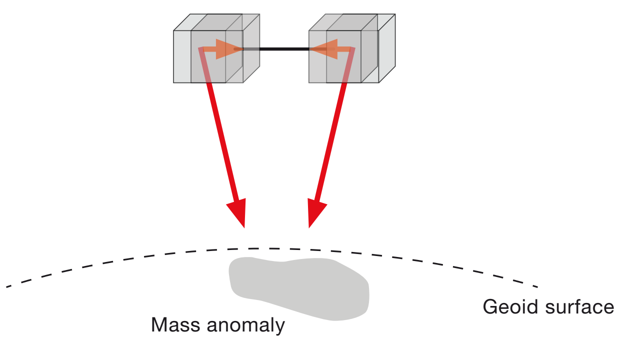
ly 70 kilometers, was computed from hundreds of millions of observations. This exercise in high-performance computing applied sophisticated processing algorithms to the rigorous solution of a very large equation system. Each time more data could be incorporated, the model improved.

The satellite's re-entry yielded an unexpected bonus. Much of the way down, the global positioning system (GPS) receiver continued reporting the satellite's position to an accuracy of two to three centimeters. Several of the main instruments kept on taking measurements even longer, failing only after the temperature on board rose above 90 degrees C. The final phase, from the time the satellite fell below 130 kilometers to the time it started burning, lasted roughly 90 minutes, or one full orbit. Now the record of GOCE's last day is being pored over by a separate community of scientists interested in atmospheric sciences, aerospace engineering and even space debris.

The fifth and final version of the GOCE gravity model – based on 800 million measurements and associated data from the entire mission period – was released to the scientific community in July 2014. "Once the final model and data products were placed on the public server, the GOCE mission could be considered complete, but this is by no means the end of satellite gravimetry," says Roland Pail, director of the IAPG. "At the same time users are applying the final GOCE data release to questions in geophysics, geology, oceanography, climate studies and civil engineering, follow-on satellite missions are in the works." ▷



The uneven distribution of mass in the Earth (represented here by a mass anomaly shown in gray) causes satellite orbits to be irregular. The GOCE satellite used GPS to track its own orbit precisely, and deviations from an ideal orbit revealed variations in Earth's gravitational field. The satellite's gravitational gradiometry system provided even more sensitive measurements of subtle contours in the field. At the heart of the system were six test masses (shown as gray cubes) mounted in pairs on perpendicular axes.



Since the gravitational field varies from point to point in space, it would exert a different force on each of the test masses, moving them slightly in different directions. Sensors recorded the acceleration of each test mass, allowing changes in force along each of the three axes to be measured. These gradiometric measurements provided the basis for computing the field.

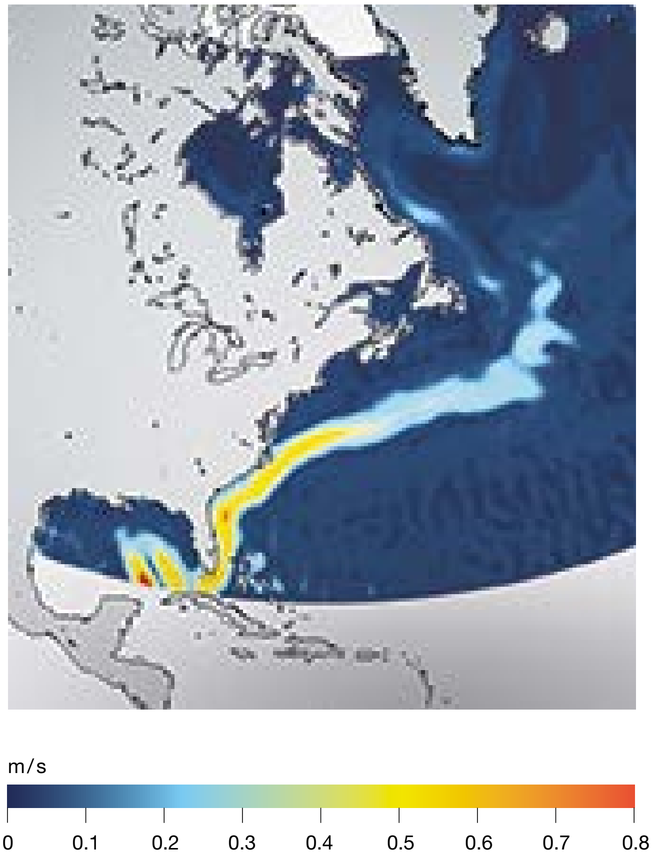
Results to date promise discoveries to come

Some of the earliest results based on GOCE data confirmed scientists' suspicions that previous models were marred by large inaccuracies. In regions such as the Himalayas, the Andes, and parts of Africa, for example, it had been difficult if not impossible to obtain gravity measurements by conventional means. Already by 2010, researchers were able to show that the GOCE satellite could provide adequate coverage and accuracy to correctly model continental areas where data had been lacking.

Similarly, by 2011, the world's oceans were coming into sharper focus. Scientists could now map ocean currents via gravitational variations in masses of water. For the first time, ocean circulation could be observed globally, from space. This is considered crucial for understanding heat transport and the dynamics of Earth's changing climate. Today, large-scale features including the Gulf Stream and the Antarctic Circumpolar Current can be clearly seen in gravity-derived maps; furthermore, even the current velocities can be determined. Also, with the GOCE geoid as a consistent reference, sea level rise due to global warming – caused both by thermal expansion and by melting of ice in the polar regions – can be more accurately measured and monitored.

More recent studies also show tremendous promise for expanding our knowledge of continental geology and deepening our understanding of the processes at work far below the surface. Researchers have found that GOCE data can be used to trace otherwise elusive borders between welded-together fragments of continental crust. Such areas are of interest for two reasons: they tend to be rich in mineral resources, and they can be the locus for earthquakes and other hazards. Previously, the patchy coverage and low resolution of gravity measurements made this impossible. With GOCE data, scientists can now, for example, clearly identify seemingly unconnected geologic units in Africa as being associated not only with each other, but also with formations in South America – recalling the time when the now separate continents were one. In time, this capability will provide new tools for both resource exploration and risk assessment. Satellite gravity measurements are also being used to map density variations in Earth's deep interior, which stem from variations in temperature and chemical composition. Scientists are developing three-dimensional images of mass distribution in the mantle. These static snapshots can in turn reveal more about dynamic processes, including the convection that drives plate tectonics ▷

Satellite assembly and testing: Pre-launch preparations were carried out at ESA's European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands.



This improved view of the Gulf Stream from space, based on the final release of the GOCE gravity model, charts current velocities in meters per second.

and intrudes into human life in the form of earthquakes, tsunamis and volcanic eruptions. Researchers have now identified large-scale gravity variations that follow former tectonic plate boundaries on both sides of the Pacific Ocean, as well as signals thought to correspond to so-called mantle plumes more than 2000 kilometers below the crust. Such findings suggest that deep views based on satellite gravimetry can be combined with independent insights from global seismic tomography, mantle flow models and reconstructions of tectonic plate history to address many unanswered questions.

A new initiative, under the auspices of the TUM Institute for Advanced Study (TUM-IAS), aims to further refine the GOCE gravity maps. As a TUM-IAS Fellow hosted by Pail, Dr. Christian Hirt of Curtin University in Australia is working toward a hundred-fold improvement in resolution, with implications for applications from climate studies to surveying. Hirt is creating a composite model incorporating the latest satellite and terrestrial gravity data, high-resolution topography, and mass-density models. Where data permits, he expects to achieve 100-meter spatial resolution, bringing out details on the scale of mountains and valleys. This is the first-ever effort to create local-resolution gravity maps with global coverage.

Prospects for future gravity missions

The trajectory of a space mission doesn't begin on the launching pad, but with the earliest formation of the constellation of ideas that will define and motivate it. In the case of the new approach embodied in GOCE, that goes back at least as far as the 1970s, when Pail's predecessor, TUM Emeritus Prof. Reiner Rummel, was a postdoctoral researcher at Ohio State University. “Already at that time this idea floated around in NASA documents,” Rummel recalls, “and it stayed with me.” It is not uncommon for a satellite or probe to take decades to get off the ground. By the 1980s, technology had advanced to the point where GOCE started looking practical; the first proposals encountered fierce competition before the project was approved by the European Space Agency in 1999. “And then,” Rummel notes, “it took another ten years to build, because it is a very complicated satellite.”

During this past decade, GOCE was not alone, but accompanied by two complementary gravity missions: the German project CHAMP (Challenging Minisatellite Payload) and the German-American collaboration GRACE (Gravity Recovery and Climate Experiment). To build on their successes, scientists worldwide are preparing for future missions, and TUM researchers are on board. Their main focus is on a prospective joint ESA-NASA mission in the time frame of 2025 to 2030, although they also are taking a close interest in the follow-on GRACE mission set to launch in 2017.

“From the users' point of view,” Pail explains, “the most important thing is that we provide for continuity and extension of the observations and time series. They give this a higher priority than better accuracy.” The upcoming GRACE follow-on mission addresses this concern, but it also incorporates modifications based on lessons learned during the first. In addition, it will carry an experimental instrument to test a new approach to ranging, with the potential for a fifty-fold improvement in accuracy. If the experiment proves successful, such instruments would likely be incorporated into new proposals.

Current ideas for the future ESA-NASA mission include technically ambitious requirements such as coordinating a constellation of satellites – not one pair, as in GRACE, but two pairs. In general, teams developing proposals are keeping the process open and the details more or less confidential, because competition will be tough: out of perhaps 30 to 40 proposals submitted, only one will be selected. Many members of the GOCE collaboration have already joined the race, forming a new team to hammer out a winning proposal. *Patrick Regan (TUM)*

Picture credit: IAPG/TUM