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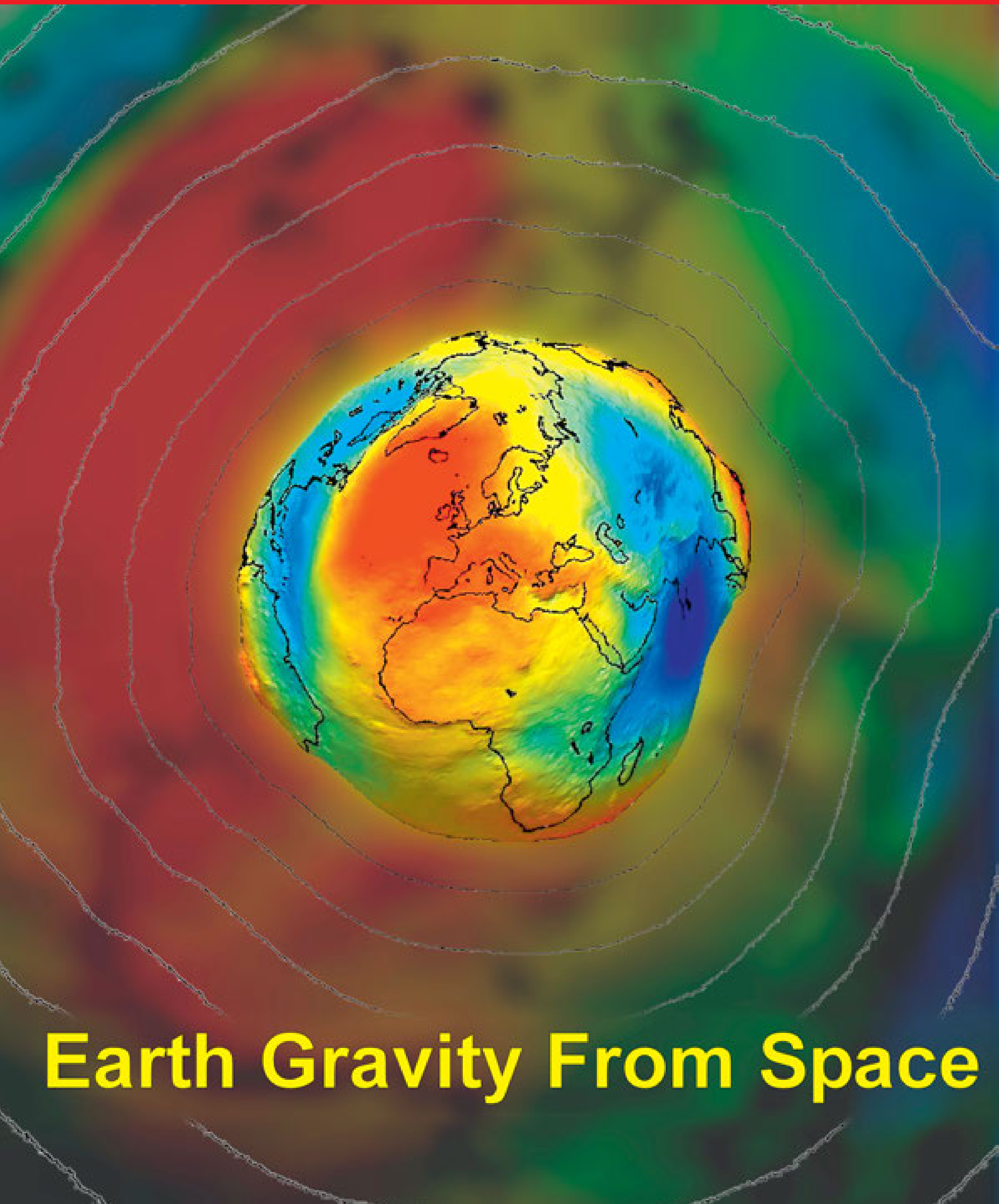

Earth Gravity From Space

Editorial

After all, one might wonder whether scientific discoveries are still feasible with all the effort made by generations of gifted – and no less assiduous – researchers. Did they leave any *terra incognita* for future generations of scientists?

Those of our contemporaries who have to deal with banks (presumably most of us) know pretty well that after continuously withdrawing money from their account, one day or the other, a telling zero appears. Fortunately though, Nature is infinitely more generous than a bank account; rather, she is the contrary: the more you draw the more you get. So, in contrast to us ordinary mortals, scientists stay in a paradise where the stuff on which they live is of unlimited availability.

That might make you desire to be a scientist as well. Nothing is easier than that. Remember: a good scientist is an individual with more questions than answers. So, simply return to your childhood when asking *why, when* and *who* was part of your daily business. Or start reading the present issue of *Spatium* dealing with the great trilogy of mass, gravity and weight, of which the latter might be known to some of our contemporaries only too well. Surprisingly yet, here already you come across one of those exhaustless bonanzas where generations of scientists have been digging without ever reaching the bottom.

Our old planet Earth has a mass that generates gravity which in turn keeps us safely together. Even better: it is such an exhaustless bonanza as well, you just have to look a bit more carefully than you are used to do every day. For instance ask yourself whether Earth's gravity (responsible for your weight anyhow) is constant, and you will be amazed to find out that it depends on such different things as the groundwater below you or the Moon above you. So, if your weight should outbalance your expectations once again: the following pages might tell you why.

It was on 6 November 2012 that the PRO ISSI audience had the pleasure of listening to Prof. Reiner Rummel, Technische Universität München, a foremost expert when it comes to gravity. He is one of the intellectual fathers of ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE), a spacecraft faithfully mapping Earth's gravity field from space with the highest accuracy ever. Since its launch in 2009, it has downloaded a wealth of data providing revolutionary insights in the Earth's surface and subsurface processes that shape its face, or in mechanisms that govern the global climate.

So, entrust yourself to a professional gold digger and enjoy reading the following pages: a shiny gold nugget is yours for sure!

Hansjörg Schlaepfer
Brissago, May 2013

Impressum

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Front Cover
The image shows a graphic interpretation of the Earth geoid, that is the surface of an ideal global ocean in the absence of tides and currents, shaped only by gravity. See page 10 for further details.

Earth Gravity from Space[1]

Prof. Reiner Rummel, Technische Universität München

Introduction

A mundane occurrence such as weight unsurprisingly challenged thinkers of all times. This is true for Aristotle[2] who explains weight as the result of Earth attracting all other bodies in the entire universe. Much later, in the medieval, Indian and Arabic luminaries continue reflecting about the fact of weight and falling objects. In the early 17th century, Galileo Galilei[3] realizes that all objects accelerate equally when freely falling. Then comes Isaac Newton[4] **(Fig. 1)**, who interprets weight as the attractive force between two masses which in turn allows him to formulate the famous universal law of gravitation in 1687[5] (see box). *This law spread the light of mathematics on a science which up to then had remained in the darkness of conjectures and hypotheses*[6]. The universal law of gravitation stipulates that two bodies attract each other with a force proportional to the bodies' masses and the inverse square of their distance and, finally, proportional to the gravitational constant G. The law is called universal, as it is valid throughout the universe. In fact, Newton is able to confirm mathematically the laws of planetary motion found by Johannes Kepler[7] some 80 years earlier intuitively based on data gathered by Tycho Brahe. Yet, even Newton has to admit that his law describes the how, but not the why, meaning that it does not tell anything about the real source of the gravitational force, which, by the way, remains unknown up to this day.

Gravity vs. Gravitation
In the parlance of geodesy, gravitation is the attractive force between two masses according to Newton's law of gravitation. Gravity on the other hand is the sum of gravitation and the effect of centrifugal acceleration due to the rotation of Earth.

Albert Einstein follows a radically innovative approach in the early 20th century by giving gravity a new form replacing it by the curved space hypothesis underlying his general theory of relativity. This enables him not only to cover the cases where Newton's law is applicable, but also processes at very high speeds or in strong gravitational fields such as in the vicinity of massive stars. Even though the old universal law of gravitation is now superseded by Einstein's ideas, most modern non-relativistic gravitational calculations still use it as it is much easier to work with and sufficiently accurate for most applications.

Fig. 1: Sir Isaac Newton, on a painting by Godfrey Kneller, 1689.

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1 The present issue of *Spatium* is based on a lecture by Prof. Rummel for the PRO ISSI audience on 6 November 2012. The notes were taken by Dr. Hansjörg Schlaepfer and revised by Prof. Rummel.
2 Aristotle, 384–322 B.C., one of mankind's most influential thinkers, originator of a variety of scientific branches such as logics, biology, physics, ethics and others.
3 Galileo Galilei, 1564, Pisa, Italy – 1642, Arcetri, Florence, Italian philosopher, mathematician, physicist and astronomer.
4 Sir Isaac Newton 1642, Woolsthorpe-by-Colsterworth in Lincolnshire, Great Britain – 1726, Kensington, GB, British scientist and administrative clerk.
5 Published in the famous Philosophiæ Naturalis Principia Mathematica, 1687.
6 Citation of the French mathematical physicist Alexis Clairaut, in 1747.
7 Johannes Kepler, 1571, Weil der Stadt, today Germany – 1630, Regensburg, German philosopher, mathematician, astronomer, astrologist and theologian.

What Is Gravity?

Newton interpreted the force acting between two bodies as the effect of their masses. For instance, one body might be his famous apple[8] while the other is the Earth. The apple is attracted by the Earth's mass prompting it to fall upon release from its branch, and, to exactly the same extent, the apple's mass attracts the Earth as well. While the first is easy to grasp, the second is less so, yet it is a consequence of Newton's universal law of gravitation **(Fig. 2)**.

The gravitational constant G in **Fig. 2** belongs to Nature's most fundamental constants, yet, intriguingly, also to the least known. We know it to only 4 decimal places, while others are known to say 12 decimals. The deeper reason behind this is that we still lack an exact understanding of what gravitation and mass basically are.

Now, if one shifts the apple's mass m_{app} to the left in the equation in **Fig. 2**, one gets the Earth's acceleration, that is the rate at which a body, the apple, is accelerated when falling. Its value amounts to the famous 9.81 m/s^2. Now, at a first glance one would expect the Earth's acceleration to be a constant. Yet, not unlike other so-called constants, it turns out to depend on a variety of parameters as outlined below. Careful measurements with sophisticated equipment (see **Fig. 3**) have shown that the Earth's acceleration varies with time and space on a variety of scales:

– One part in 10^3 stems from the Earth flattening at the poles and from the centrifugal force caused by the Earth's rotation
– One part in 10^4 comes from surface features of Earth (hills, valleys, etc.)
– One part in 10^5 originates from the density variations of the Earth's crust and mantle
– One part in 10^6 comes from inhomogeneities of the continents (salt domes, sedimentary basins, etc.)

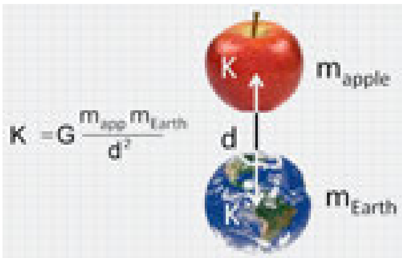

Fig. 2: The thought experiment underlying Newton's universal law of gravitation. The Earth's mass attracts the apple's mass with a force K. The value of K depends on the two masses involved, their distance and the gravitational constant G.

While these contributions to the variability of the Earth acceleration remain (more or less) constant over time the following elements vary both in time and space:

– One part in 10^7 stems from the tides of the oceans and the tidal deformation of the solid Earth by the gravity fields of the Sun and the Moon
– One part in 10^8 comes from the variations of the underground water flow and the varying pressure of the Earth's atmosphere on the surface
– One part in 10^9 finally is accounted for variations of the oceanic topography and the movements of the poles.

It is seemingly a striking contradiction that on the one hand one is capable of determining the acceleration so precisely, while we have only a fuzzy picture of the gravitational constant G. The core problem lies with the mass, as we cannot determine a body's mass with the required precision. The practical reason is that we ought to measure precisely the weak gravitational force acting between two masses in the laboratory[9]. Even with today's most advanced measuring devices one gets a precision of say only one part in 10^4. Mass continues to be a great alien[10].

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[8] A legend tells that Sir Isaac Newton was inspired by a falling apple to draft his universal law of gravitation. What for everybody else would have been a trivial instance, became for Newton's mastermind the great eureka for an epoch making concept!
[9] It is fair to note here that the British scientist Henry Cavendish, thanks to a very brilliant experimental set up, succeeded in determining the gravitational constant with overwhelming accuracy. That was in 1798…
[10] Quite naturally, such an odd situation tends to challenge scientists. New and promising approaches are currently pursued with the goal of linking the mass unit to other well known physical constants, such as the Avogadro number or the Planck constant.

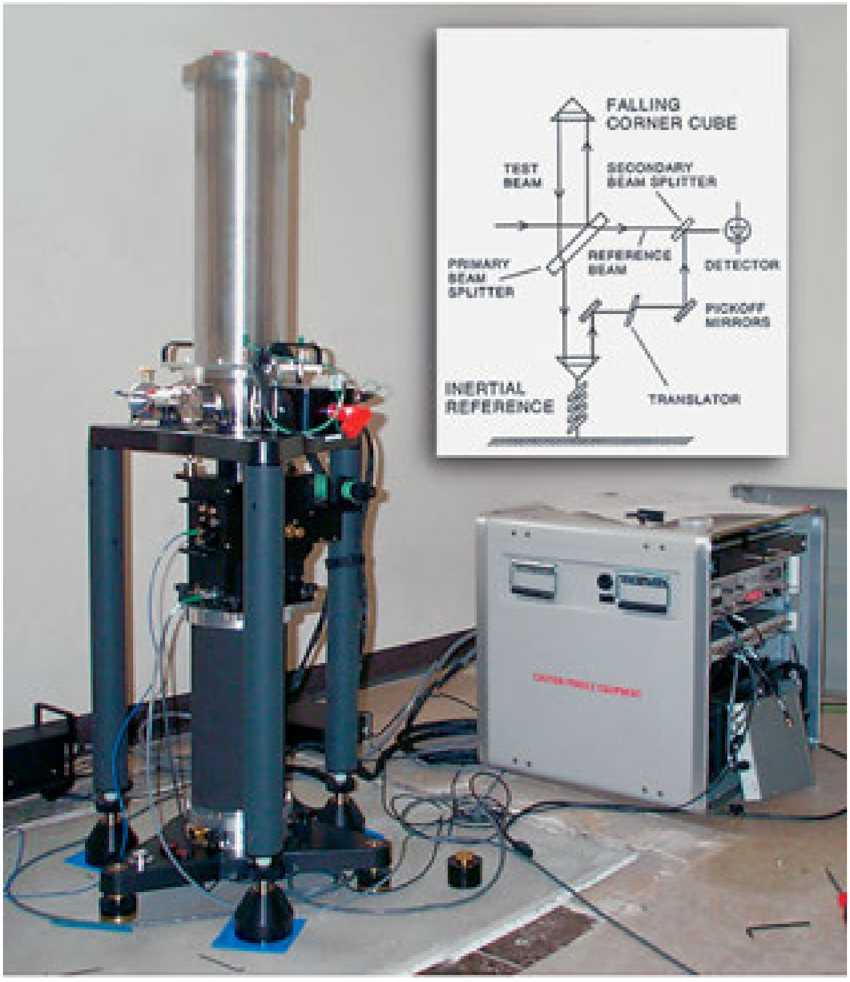


Fig. 3: Determining the Earth's acceleration with a laboratory set up installed in the Technical University of Hannover. It consists of a laser that injects a test beam (from the left on the graph) to a primary beam splitter. This optical device creates two beams: one part passes the mirror towards the detector while the other is bent orthogonally. The latter is sent up towards the falling corner cube in a tube holding a vacuum. This corner cube reflects the beam back down to the inertial reference on the bottom of the graph. Here, a second corner cube reflects the test ray which, after passing through some further optical elements, reaches the secondary beam splitter that combines both light rays. The two waves are superposed on the detector. One of them is constant, as its light path length is constant, while the second's path length varies when the corner cube is falling. This leads to interference fringes on the detector, which are counted. From this count, the falling corner cube's instantaneous position and speed can be determined with very high precision. Safely shielded from any external vibration and measuring the time by means of an atomic clock, the set up is able to determine Earth's acceleration to an accuracy of 9 decimal places.

What Is Mass?

Galileo Galilei, around 1637, wondered about the interrelation between the two seemingly unrelated ways mass manifests itself. He measured the period of pendulums of different mass but identical length, but found no difference. He concluded that the pendulum's mass plays a twofold role that both are equivalent: on the one hand, it exerts a force against any change of its velocity. This is called the *inertial mass.* On the other hand, the pendulum's mass is attracted by Earth as a consequence of its *gravitational mass.* Obviously, the two appearances of mass are equal counterparts. His equivalence principle states that the gravitational mass and the inertial mass are equivalent in the sense that irrespective of their other properties like chemical composition, size, form, etc. two masses fall exactly the same way (in a vacuum). More precisely: with the same initial position and the same initial velocity all bodies travel on the same fall path[11]. Today, we know that the two displays of mass are identical with a precision of 12 decimal places, yet we still do not know why.

[11] This is called the weak equivalence principle. In contrast, the strong equivalence principle stipulates that in a free falling reference system no gravitational fields can be determined on small time – and space scales.

This equivalence between gravitational and inertial mass is not the only miracle in the realm of gravity. In 1915, Albert Einstein predicted the existence of gravitational waves, an outstandingly weird consequence of his general theory of relativity. Produced by fast moving very large masses such as binary stars, they are supposed to rush through space with the speed of light. Yet, to this day no one has been able to prove their existence conclusively. And, last but not least, it was Albert Einstein, too, who showed the equivalence between mass and energy as per his splendid formula $E=mc^2$. In contrast to gravitational waves, though, this law has been confirmed firmly in the mean time. All these equivalences may be seen as suggesting a deep harmony in Nature.

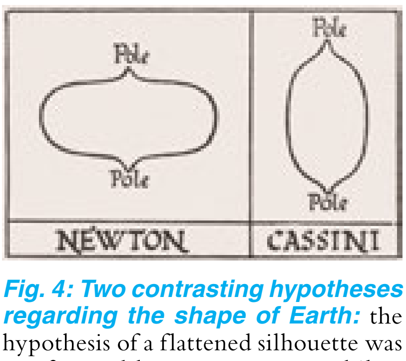


Fig. 4: Two contrasting hypotheses regarding the shape of Earth: the hypothesis of a flattened silhouette was put forward by Isaac Newton while a stretched version was favoured by Giovanni Cassini. (Origin: see Fig. 5)

Gravity on Earth

In Newton's days, the shape of the Earth was one of the foremost scientific issues. The two then leading scientific parties in Europe, the British Royal Society on the one hand and the Académie Française on the other were in a fierce dispute on the topic. The British party, not surprisingly led by Newton, pledged for a slightly flattened shape at the poles as a consequence of the centrifugal forces that tend to increase the Earth's diameter near the equator[12], **see Fig. 4.** Newton advocated this concept based on a simple but telling thought experiment **(Fig. 5)**: he imagined a channel filled with water conducting from the North pole right to the Earth's centre and from there out to the equator. When taking into account not only gravitation but the centrifugal forces caused by the Earth's rotation as well, then it must have a larger radius at the equator than at its poles. The two water columns of the channel – the one along the polar axis and the one in the equator plane must be in balance. The former is under the influence of gravitation only, while the latter is affected by gravitation and the centrifugal force. (Needless to say that Nature favours Newton's view.) In contrast, the French party tended to assume a stretched shape towards the poles. This comes as a surprise since the very Giovanni Domenico Cassini[13], one of the leading members of the Académie Française at that time, had been able to demonstrate the flattened shape of Jupiter a few years earlier. The reason for their faulty conclusion is that the French had laid a meridian of their coordinate system through Paris, which, unfortunately, was so imprecise that Earth needed to be squeezed into such a strange shape.

Ironically, Newton based the flattened Earth hypothesis on measurements conducted by his antagonist Cassini. In order to quantify the distance to Mars, the latter defined two sites on Earth, one at La Rochelle, the other at Cayenne near the equator, from where he intended to evaluate the angle of Mars. To this end, he ordered an extremely precise pendulum clock with one of his colleagues, Jean Richer. Now, as the period of the

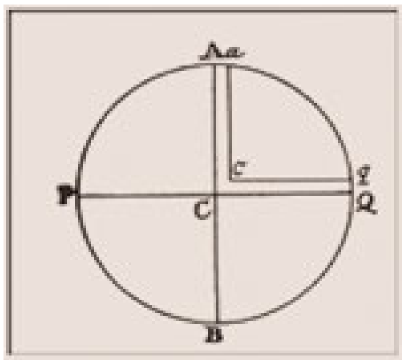


Fig. 5: Newton's basic idea for advocating the flattened Earth hypothesis. (From Isaac Newton: Philosophiæ Naturalis Principia Mathematica, vol. 3, 1687)

12 The increase of the Earth's diameter at the equator with respect to the poles amounts to 42.8 km which compares to the entire polar diameter of 12,713.5 km.

13 Giovanni Domenico Cassini, 1625, Perinaldo, Italy – 1712, Paris, Italian/French astronomer and mathematician.

pendulum depends on gravity, and as gravity is somewhat smaller near the equator than in La Rochelle, Richer had to shorten the clock's pendulum by 2.6 mm at Cayenne in order to obtain the same period without, however, being able to explain why. Still, for Newton that case was clear: the outcome of Richer's experiment convincingly proved his hypothesis.

As we have seen above, Earth's gravity not only depends on latitude but on a range of further parameters. So, it may well be that measuring and analyzing those variations might provide new answers to old scientific questions. In fact, for some 60 years numerous measurements all over the globe were made in the hope for getting more information about the Earth's interior. Yet, the remarkable effort did not lead to more than a patchy insight since large areas of the surface had to remain uncovered which prevented a clearer picture. The space age has solved this problem: spacecraft can cover all regions on Earth quickly and regularly. Yet, measuring acceleration from space precisely enough is an art that had first to be developed.

Probing Earth's Gravity From Space

No wonder that the art of measuring Earth's gravity from space starts with Isaac Newton, too. In an ingenious thought experiment he concluded that the trajectory of the falling apple obeys the very same law as such different things as a bullet on its flight path or the orbit of a planet **(Fig. 6)**. He capitalized on earlier findings by Galileo Galilei, who made the relevant experimental research, and Johannes Kepler, who found the laws of planetary orbits.

Newton understood a satellite orbiting Earth as a falling object in the gravity field, yet possessing sufficient horizontal speed to escape hitting Earth in such a way as to stay safely in its orbit. According to Kepler, a satellite's orbit is generally elliptical in shape. Yet, reality is somehow more complex: firstly, since Earth is flattened, the orbit plane precesses slowly in space and at the same time the orbit ellipse precesses in the orbit plane. This is called precession. Secondly, overlaying to this movement is a signal stemming from local variations of the gravitational acceleration. The spacecraft's orbit will therefore not be exactly elliptical but rather reflect the variability of gravity caused by the different surface and subsurface features of Earth. This now is exactly what one is set out for: identifying the variations of Earth's gravity over time and space to get insight into their origins on the Earth's surface and its interior.

If now one starts estimating the orbital variations to be expected one finds that the resulting signals are very weak which in turn translates into a fantastic technical challenge. Yet, progress in space technology has made this a manageable task since about the year 2000[14]. Take for instance a low orbiting spacecraft, say on a

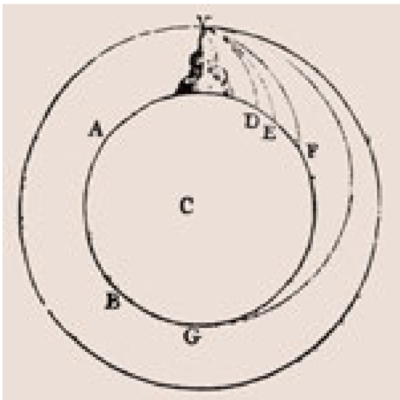


Fig. 6: Isaac Newton's thought experiment shows that the flight path of a bullet shot from a high mountain (D, E, F) is ruled by the very same law as a satellite orbiting Earth. The only difference between the various trajectories is the initial horizontal velocity. (Philosophiæ Naturalis Principia Mathematica, vol. 3, 1715, by Isaac Newton)

[14] To be somewhat more precise it has to be recalled that already with Sputnik and the satellites that followed Sputnik gravity field recovery was done. Yet, the outcome was essentially a coarse patchwork. It was only in 2000 that the first satellite was started for which an uninterrupted and three-dimensional series of measurements could be carried out from the GPS satellites.

200 km altitude equipped with a GPS[15] receiver. This would allow us to reconstruct the spacecraft's orbit with a precision of some 1 cm. At the high altitude of the GPS satellites (20,000 km) the variations in gravity are very small due to the inverse square law of the distance. This facilitates reconstruction of the GPS satellites' orbit very precisely and therefore that of our low orbiting spacecraft as well.

So, evaluating carefully the orbit of a spacecraft helps determine Earth's gravity field very precisely. Yet, space scientists and engineers tend to be demanding and even more innovative. They came up with a further step of sophistication consisting not of just one spacecraft with one single test mass for probing gravity, but resorting to a differential measuring scheme with several masses as outlined in **Fig. 7.** In such an arrangement, the relative position of the test masses will reflect not the absolute value of gravity but rather the local *changes* of gravity.

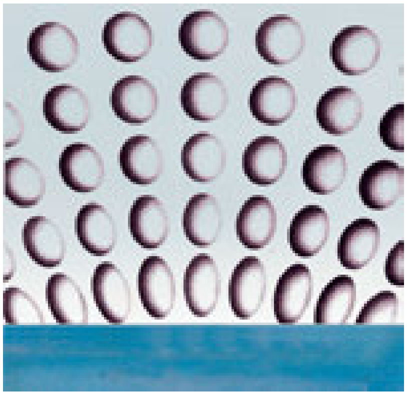


Fig. 7: Tidal forces acting on a set of probe masses. Tidal forces take their name from the fact that they are responsible for the tides in the Earth's oceans. These arise because the gravitational force of the Moon (and the Sun) is not constant across the Earth's diameter as a consequence of Newton's inverse square law of gravitation. Rather, the side towards the Moon gets somewhat more attracted than the far side. This difference causes the tides of the oceans on Earth. Similarly, as outlined in this graph, the initially circular shape of the test masses becomes slightly elliptical (Credit: H. C. Ohanian & R. Ruffini, 1976).

Our spacecraft is now assumed to possess four test masses symmetrically around the craft's centre, **Fig. 8.** A fifth test mass added at the craft's centre would remain still in the satellite as it would see the very same forces of gravity as the host spacecraft, and there would be no relative acceleration and hence no relative movement. This is in contrast to the four red test masses that would be subject to a slightly different acceleration than the host structure. Those differences would lead to slight movements relative to the craft's frame. If now, one could measure the relative motion between the four test masses very accurately, one would have a very sensitive set-up for determining the fine structure of gravity. The challenge, however, resides in the required precision to measure the acceleration differences between the test masses, which must be in the order of one part in 10^{12} of the Earth's acceleration. Progress in space technology made this possible, and the first satellite capitalizing on this principle is the **G**ravity and Steady State **O**cean **C**irculation **E**xplorer (GOCE) launched by the European Space Agency ESA in 2009.

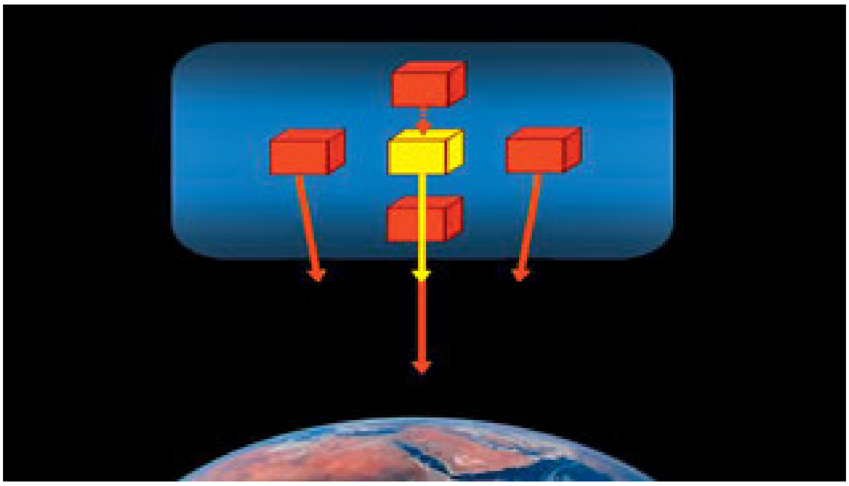


Fig. 8: The principle of gravitation gradiometry. A spacecraft (shaded in blue) contains 5 test masses of which one (the yellow) is located exactly at the craft's centre, while the others are slight off-centre. The various test masses will experience somewhat different gravitational forces, which translates into an effective system for probing the variations (or gradients) of Earth's gravity field.

15 Global Positioning System. The NAVSTAR GPS system is a global satellite system for positioning and time measurement operated by the US Department of Defense.

GOCE

The GOCE spacecraft **(Fig. 9)** features a mass of 1,100 kg, a body size of 5.3 m in length and 1 m in diameter. It orbits Earth on a circular polar orbit at a mere 260 km altitude, the lowest orbit ever used by a scientific spacecraft. At such a low altitude the residual atmosphere gives rise to an air drag that eventually will cause a spacecraft to dive into denser zones and thereupon to burn up. Hence, the drag has to be compensated appropriately. This is done in the GOCE spacecraft by two ion thrusters[16]. The spacecraft has a GPS receiver onboard for the purpose of reconstructing the spacecraft's exact orbit. In order to avoid any eventual gravitation noise from the satellite and its instruments, GOCE has no moving parts whatsoever, and in order to eliminate any change in the geometrical arrangement that could impact the gravity signal, the spacecraft capitalizes on extremely stiff materials based on carbon sandwich structures, developed by the Swiss space company RUAG Space, Zurich.

Fig. 9: The GOCE spacecraft undergoing final tests in the clean room at the Plesetsk Cosmodrome in Russia. (Credit: ESA).

The satellite's main payload is the Electrostatic Gravity Gradiometer (see box) that consists of a suite of six individual test masses in order to facilitate derivation of the gravitational signals in the three space directions. Each of the test masses consists of a cube of an alloy of platinum and rhodium with a weight of 320 gr and a size of 4×4×2 cm, **see Fig. 10.** Each cube is held floating within its case by means of electrostatic forces in such a way that it never touches the walls of the case even though the space between is a mere 20 μm wide. To keep the cube floating, a feedback scheme is used. The feedback signal actuates the electrostatic field appropriately to keep the test mass in place, and at the same time serves as the measure of variability of Earth's local gravitational field.

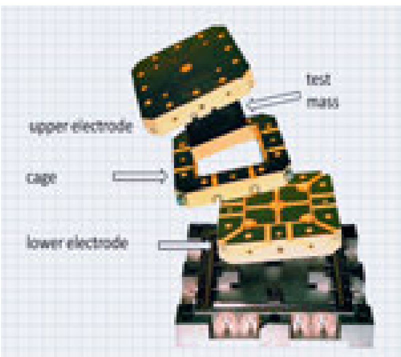


Fig. 10: Exploded view of one of the six acceleration sensors of GOCE. (Credit: Onera, the French Aerospace Laboratory)

Gravity Gradiometer

A gradiometer measures the gradient, that is the numerical rate of change, of a physical quantity, such as gravity. A gravity gradiometer hence measures the rate of change of Earth's gravity.

[16] An ion thruster is a form of electric propulsion creating thrust by accelerating ions.

Results of the GOCE Mission

Probing Earth's gravity from space by gradiometry is a fundamentally new approach to a well established field of science. This is why the scientific implications are wide-ranging confining us to presenting just a few examples below.

Few science results made such an appearance not only in scientific circles but in general news media as well **(Fig. 11).** The headlines were something like: Earth is not a sphere but rather a potato! The potato is a highly exaggerated presentation of the local differences between a hypothetical best fitting ellipsoid and the actual geoid (see box).

Geoid
The geoid is a physical model of Earth defined by the virtual surface of a global ocean at rest, that is in the absence of wind, tides and currents.

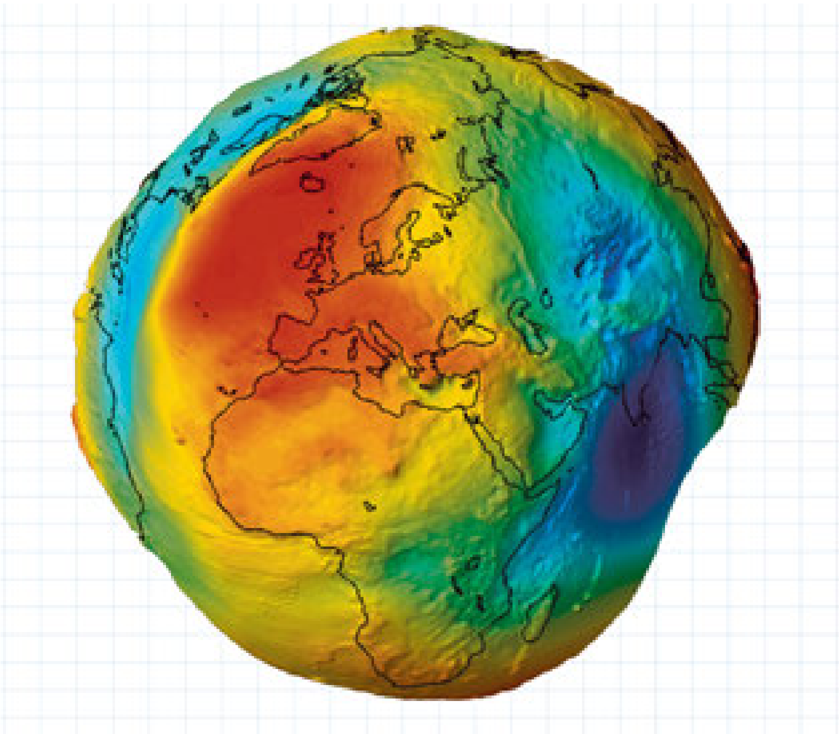


Fig. 11: The Earth potato: Based on GOCE data, this image shows the local differences between an ellipsoidal equilibrium figure and the actual geoid. Their maximum values amount to some 100 metres which is small as compared to the Earth's diameter of some 12,800 km, yet impressive on a local scale. In order to make them readily visible, the deviations have been firstly largely exaggerated in this sketch and secondly colour-coded: red hues indicate a geoid surface higher than the ellipsoid, while regions lower than the ellipsoid are shaded in blue. (Credit: ESA)

For a more detailed analysis, **Fig. 12** shows the global large scale gravity undulations. In contrast to what one would expect, this image hardly shows any correlation with the continents. The reason is that the continents are not simply put on a rigid globe, but rather swim on the ductile crust in a buoyancy equilibrium which tends to balance the geoid signal. Continuing this line of thought one comes to the conclusion that the image rather shows the *deviations* from the buoyancy equilibrium which is of course much more telling as it provides insight into the dynamics of the Earth's interior. The large blue

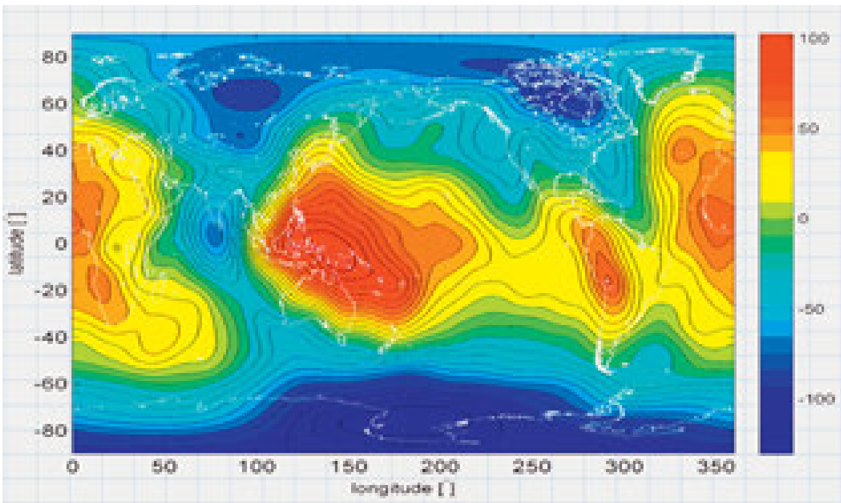


Fig. 12: The large-scale variations of Earth's gravity as seen by GOCE. Zones shaded in blue show areas of lower than the ellipsoidal equlibrium figure while the red zones indicate higher regions. (Credit: IAPG – Institut für Astronomische und Physikalische Geodäsie)

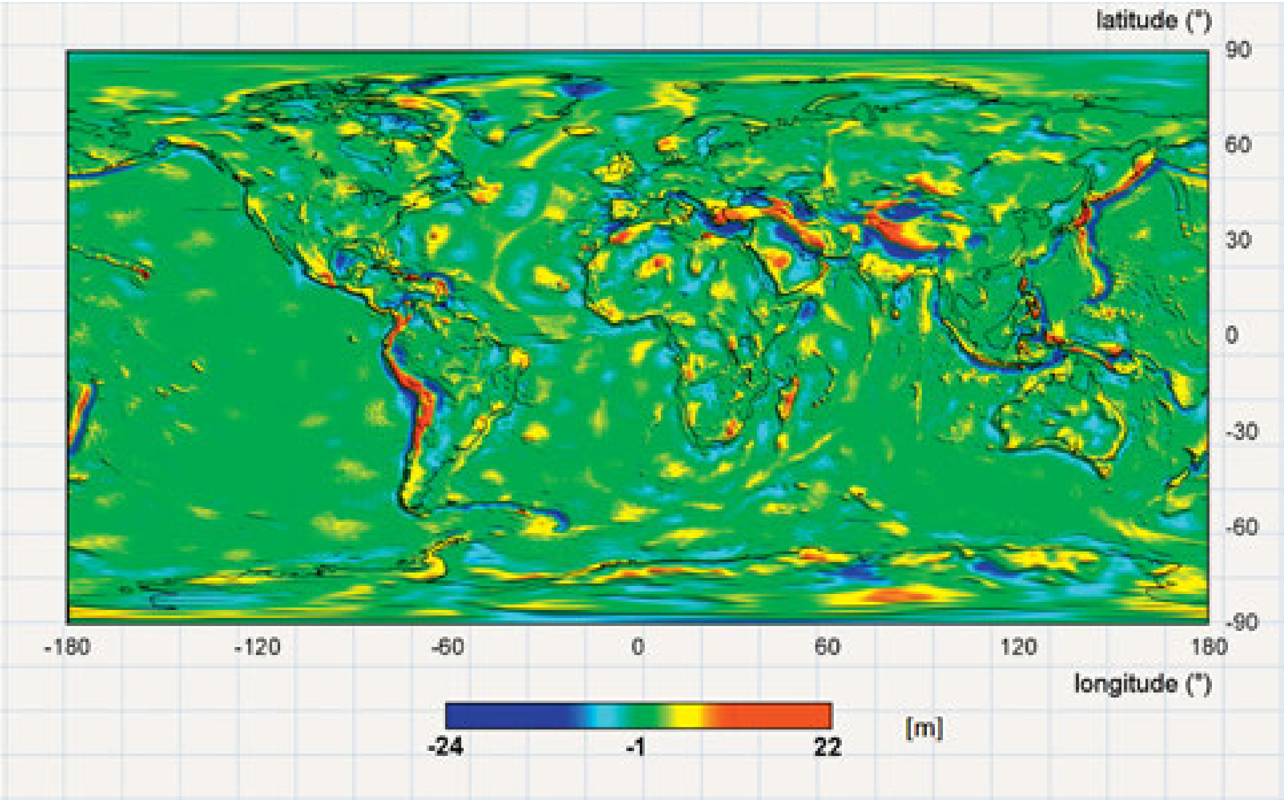


Fig. 13: The small scale variations of the Earth's gravity as seen by GOCE. This sketch reveals a wealth of features important for understanding Earth. Dominant elements are the great subduction zones, for instance along the South American west coast, where the Pacific Ocean's crust is plunging beneath the continental shelf thereby raising the Andes. This zone belongs to the clearly visible ring of fire surrounding the Pacific Ocean where volcanism and earthquakes are frequent. Another salient feature is the Himalayan range, where the Indian plate collides with the Eurasian plate which is up-lifted thereby piling up the highest mountain peaks on Earth. (Credit: Bingham R.J., P. Knudsen, O. Andersen, R. Pail [2011]: An initial estimate of the North Atlantic steady-state geostrophic circulation from GOCE, Geophysical Research Letters: 38, L01606)

areas in the northern hemisphere indicate zones where, during the last ice age, huge ice shields covered the surface, which, to reach buoyancy equilibrium, sank to some extent. Meanwhile, the glaciers have melted away and thus the area is rising again, a process, which, however, is not yet fully accomplished. The remaining depression gives rise to the blue hues.

GOCE also allows us to study the global fine structure of the geoid signals as outlined in **Fig. 13.**

Oceanography is another major field of application of GOCE data. In **Fig. 14,** we see the geoid indicated schematically with a red line, showing the hypothetical ocean surface without winds, tides and circulation. The difference between this theoretical geoid and the actual mean ocean surface as derived from data gathered with high precision satellite-based altimetry is called dynamic ocean topography. Typically, such differences are in the order of +/– 1 to 2 m.

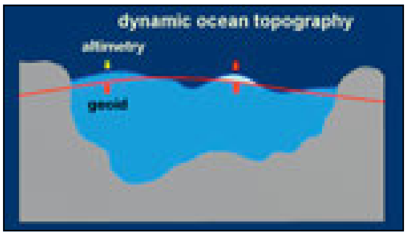


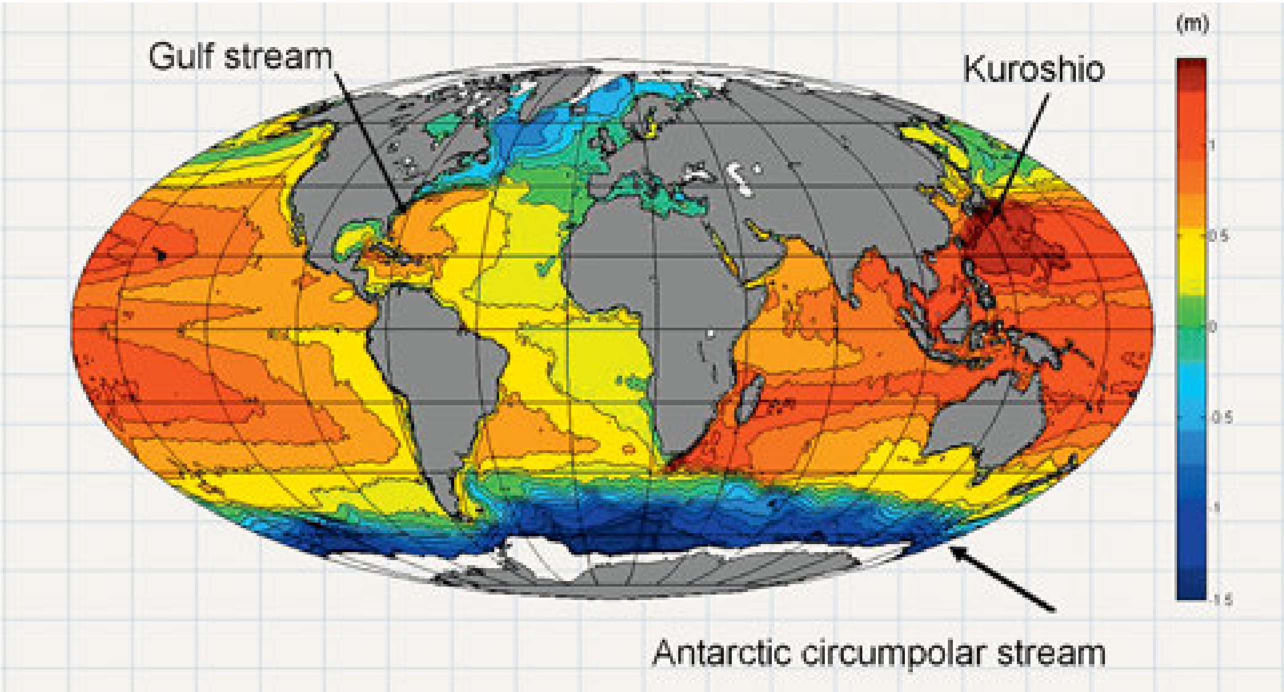
Fig. 14: The Earth geoid and the dynamic ocean topography. If there were no dynamics in the oceans, their surface would reach the geoid as indicated by the red line. Winds, tides and the ocean circulation cause the surface to deviate from the geoid. This is called the dynamic topography that provides insight into the driving forces of ocean currents (Credit: IAPG)

Figures **Fig. 15** and **16** show the local differences between the geoid and the effective mean ocean surface. These differences reflect the variations of pressure of the ocean water that drive the global sea currents. For instance, we see the North Sea in a dark blue shade, where the Gulf Stream arrives from the Caribbean Gulf. The ocean water, driven by pressure differences and balanced by the Coriolis force moves along the contour lines of isobars (lines of the same pressure). On the Northern hemisphere the streams rotate clockwise, while on the Southern hemisphere they rotate counterclock wise. Where the isobars are widely spaced, the water speed is low, and in contrast speed is high where the isobars are located close together. It is worthwhile to note here that this procedures facilitates reconstruction of the speed of the ocean streams from space without resorting to any data from waterborne platforms.

GRACE

While GOCE is an ESA endeavour, the **G**ravity **R**ecovery **A**nd **C**limate **E**xperiment GRACE **(Fig. 17)**, is a joint U.S.-German mission launched in 2002. GRACE is complementary to GOCE: while the latter is based on a single spacecraft embracing six accelerometers (see box), GRACE is a pair of spacecraft with one accelerometer each. The GRACE spacecraft are located in the same 450 km orbit over Earth with a distance of 220 km in between. This distance is measured with the extremely high accuracy of some tens microns (10^{-6} m). The advantage of this concept is that the gravity coarse structure can be measured with far higher precision than with just one satellite alone, at the expense, however, of accuracy in the high frequency part of the gravity undulations.

Fig. 15: Dynamic ocean topography. This graphs shows the oceans' mean actual surface levels as compared to the ideal geoid highlighting the Earth's global ocean currents. Blue shades indicate mean ocean surfaces lower than the geoid, while red hues point to higher than the geoid levels. In the North Atlantic, we see the Gulf Stream, which has a strong influence on the European climate as it brings warm water from the Caribbean to the North Atlantic and the European continent. East of Japan, we can identify the Black Stream at Kuroshio, which plays a similar role there to the Gulf Stream in Europe. Around Antarctica the circumpolar Antarctic stream is indicated in a dark blue hue. (Credit: IAPG/TUM).



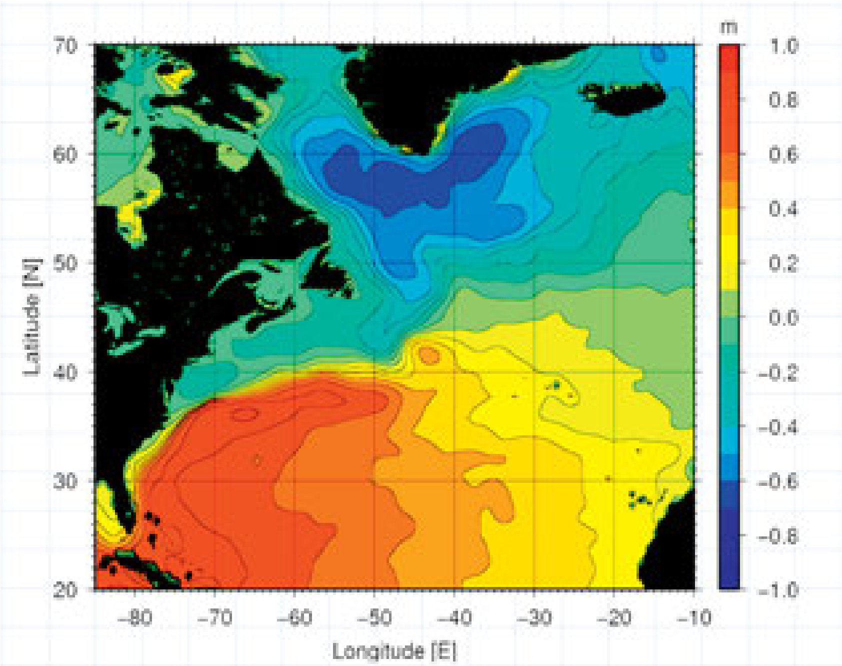


Fig. 16: Details of the dynamic ocean topography in the North Atlantic. Some extra water pressure (indicated in red) in the Caribbean Gulf drives the Gulf Stream north/eastward along the US east coast. In the South of Greenland and Iceland it is bent eastward and then southward to eventually close the cycle. (Credit: Bingham R.J. et al. (2011): An initial estimate of the North Atlantic steady-state geostrophic circulation from GOCE, Geophysical Research Letters: 38, L01606)

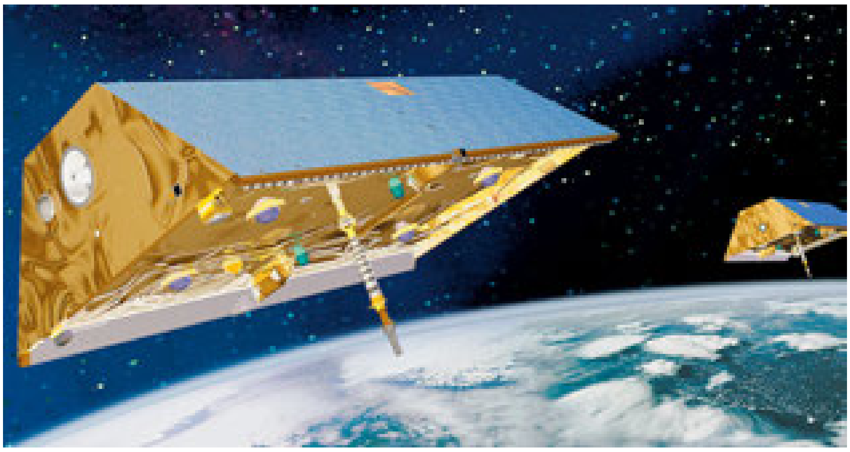


Fig. 17: The twin Gravity Field and Climate (GRACE) Experiment spacecraft shown in an artist's view. The two satellites circle the Earth on the same orbit some 220 km apart. A microwave ranging instrument monitors the distance between the two very precisely. It is the variation of this distance which yields an indication to the variability of the Earth's gravity field. (Credit: NASA).

Accelerometer
An accelerometer is a device that measures proper acceleration that is the acceleration associated with the phenomenon of weight experienced by a test mass in the reference frame of the accelerometer device.

Results of the GRACE Mission

The double spacecraft concept of GRACE makes it possible to probe the geoid's variations in time with an accuracy in the order of 1 mm/year providing valuable information for climatologists. For instance, **Fig. 18** shows the mean volume of the global oceans which is changing as a consequence of melting ice on the continents. It is measured directly by GRACE as change in gravity (red) and compared with an indirect recovery from the total volume change, as measured by satellite altimetry with Jason 1 and 2, minus the thermal expansion contribution derived from the Argo floats[17] (blue). The linear regression suggests an increase of the mean sea level in the order of 1.8 mm/year.

Of course, one would like to know where this increase of the mean sea level comes from. One obvious candidate is the expansion of the ocean water as a consequence of global warming. A second candidate is the water input from the melting glaciers on the continents

[17] Argo is a global observation system for the Earth's oceans providing real-time data on water temperature and salinity. It consists of a large collection of small, drifting oceanic robotic probes deployed worldwide.

with smaller contributions from the melting ice shields on Greenland and on Antarctica. Only now can we separate these two mechanisms by first probing the mean ocean water temperature using Argo floats. Secondly, GRACE analyzes the various mass contributions and, finally, satellite radar altimetry provides information on the total sea level change. This is a striking example of what a combination of the results of different programmes can do.

In that context, the question of whether or not the Antarctic suffers a mass loss by the melting ice shield is currently a hot topic. Of course, the melting ice looses mass to the ocean, but it seems that this loss is at least partially compensated for by precipitation[18]. Such a study has to deal with several uncertainties, of which the behaviour of the bed rock below the Antarctic ice sheet is an important issue. One ought to know whether there is an eventual postglacial up-lift process there just as in the case of Scandinavia or Canada. While in the latter areas, solid Earth is easily accessible and hence lends itself to exact measurements, this is not the case in Antarctica where the rock floor is accessible to GPS measurements only in a few rare places. Space borne gravity sensors hold great promise for solving this problem which again is an important issue for understanding the relevant processes in climatology.

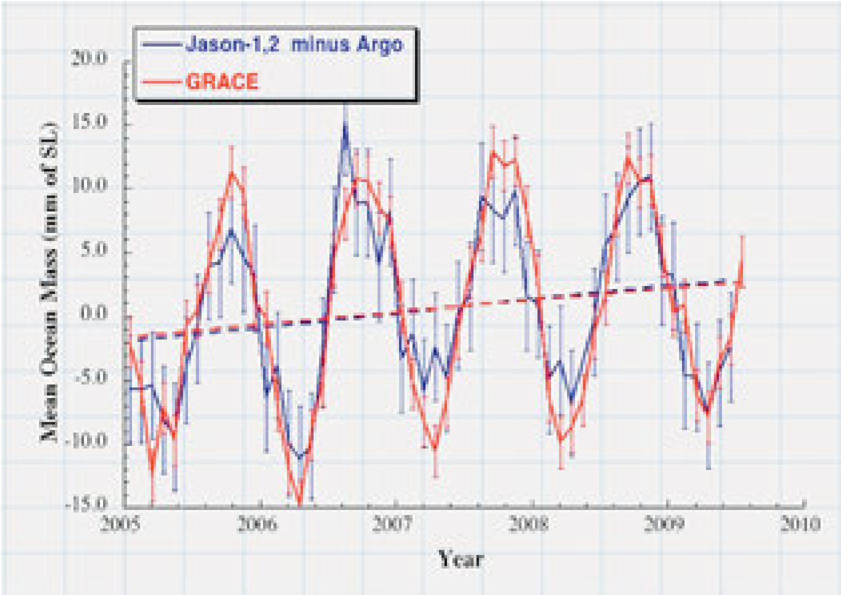


Fig. 18: The evolution of the mean sea level between 2005 and 2009, probed by the US GRACE spacecraft. The data show that during the Northern spring the level is lowest, while in late summer it reaches its maximum as a consequence of more run-off from glaciers on the Northern hemisphere. In addition, there is a slight positive trend showing an increase in the mean global sea level. (After: Chambers D. P., J. Schröter [2011]: Measuring ocean mass variability from satellite gravimetry, Journal of Geodynamics)

18 There is a recent article in *Science* by Shepard et al. Their conclusion is that there is a significant ice loss in West Antarctica (65Gt/y) and the Arctic Peninsula and a mass gain of only 14 Gt/y in East Antarctica coming from precipitation.

Outlook

With the turn of the millennium space borne gradiometry and gravity gradiometry became reality. Now that the sensor technologies are basically at hand, systems are further developed to help other fields of science solve their problems. For instance, it will soon become feasible to address experimentally Einstein's enigmatic gravity waves and the principle of equivalence. With regard to climate research it is desirable to continue the new measuring campaigns with refined sensor systems as the climate processes are very slow as compared to the time span we have disposed of the required technologies. Planetology, the branch of science engaged in the study of planets, is another field where the new concepts are eagerly awaited. It would be very interesting to characterize other planets and moons in the solar system with the new technical means that surely would help understand better our own planet's behaviour.

To conclude our journey through the realm of falling masses we stop now at a masterpiece by Salvador Dalì who painted his wife Gala in a way astonishingly resembling a set of falling masses …

Fig. 19: Galatea of the Spheres, by Salvador Dalí[19], 1952. Dalí was strongly fascinated by the concept of the atomic structure of matter. Becoming aware that those atoms do not touch each other even when constituting solids, he sought to replicate the idea with items suspended and not interacting while constituting a fantastic portrait of his wife Gala.

[19] Salvador Felipe Jacinto Dalí i Domènech, 1904, Figueres, Spain – 1989, Figueres, one of the most prominent painters of the 20th century, a dominant representative of surrealism.

SPATIUM

The Author

Reiner Rummel studied geodetic engineering at Technische Universität München. In 1974 he received his doctoral degree at Technical University Darmstadt. After a period as a post doc at the Ohio State University in Columbus/Ohio and at the Bavarian Academy of Sciences and Humanities in Munich, he was appointed full professor of physical geodesy at Delft University of Technology in the Netherlands in 1980. In 1993 he became professor of physical and astronomical geodesy at Technische Universität München. Currently he is senior fellow at the Institute for Advanced Study there.

His field of research is physical geodesy with a focus on the determination and interpretation of the Earth's gravitational field. He is one of the initiators of the ESA satellite mission GOCE and currently coordinating the mission's level-2 processing. He has served on a number of national and international advisory bodies and is a member of several science academies. In recognition of his research achievements he has received several international and national awards.