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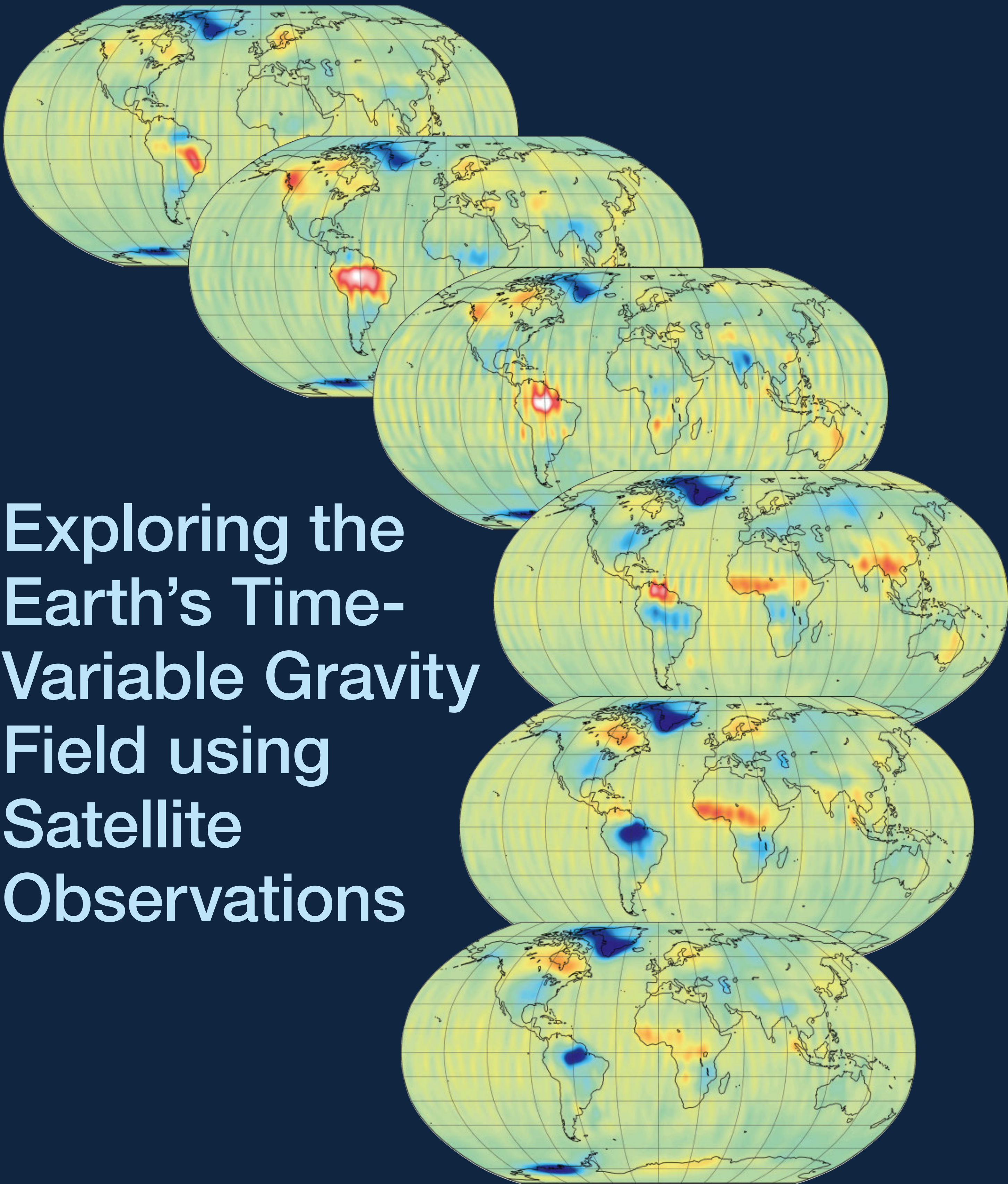

Exploring the Earth's Time-Variable Gravity Field using Satellite Observations

Editorial

In 1958, the two geophysicists and geodesists Veikko Aleksanteri Heiskanen and Felix Andries Vening-Meinesz published the book "The Earth and Its Gravity Field". At that time, this treatise looked like a relict representing out of date terrestrial (ground-based) geodesy. In 1966, NASA published a series of ten booklets summing up recent developments in space science, among them "Scientific Achievements in Satellite Geodesy 1958–1964". The unknown editor of the papers in this booklet wrote in the preface: "The beginning of the era of space geodesy may be set in 1958 with the announcement, based on the analysis of observations of Vanguard I (1958), that the flattening of the Earth's poles is significantly smaller than had been derived from terrestrial geodesy […]. The first definite evidence that the Earth's gravitational field was irregular was derived from observations of several satellites early in 1959. These observations and analyses showed that the Northern Hemisphere of the Earth contains slightly more material than the Southern Hemisphere. Therefore the equipotential surface is farther from the Equator at the North Pole than it is at the South Pole. Since water follows such an equipotential surface, the oceans define a pear-shaped Earth. This result was quickly followed by further analyses of the Earth's gravitational field as it affects the orbits of satellites. Mathematicians find it convenient to describe this field in terms of components which vary with latitude, and components which vary with longitude. The latter are somewhat harder to determine, since they affect satellite orbits in much the same way as atmospheric drag, light pressure, and other disturbing factors. […] Not only can a detailed knowledge of the Earth's gravitational field be derived from the analysis of orbits of satellites but the process can and must be reversed to provide us more accurate predictions for satellite- and space-probe trajectories."

Today, the developments and results achieved in Space Geodesy have not only confirmed, but considerably surpassed all of the editor's visions. It is no longer the goal to determine the Earth's gravity field most accurately by using spaceborne Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR) techniques, but to monitor its time-variability due to mass redistributions caused by climate change effects such as melting of ice sheets and glaciers, floods and droughts, etc.

The content of this issue of *Spatium* is based on a talk delivered by Prof. Dr. Adrian Jäggi (Director of the Astronomical Institute of the University of Bern, Switzerland) on March 24, 2021. As an outstanding expert in the field, he presented the modern approach to explore the Earth's time-variable gravity field using satellite observations of unprecedented precision, allowing it in near real-time to monitor and forecast changes of the gravity field caused by seasonal and climate effects.

PD Dr. Andreas Verdun
Zimmerwald, May 2022

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Monthly Gravity Field Models derived by COST-G.

Exploring the Earth's Time-Variable Gravity Field using Satellite Observations

Prof. Dr. Adrian Jäggi, Astronomical Institute of the University of Bern, Switzerland

Nearly 300 years ago, in 1728, John Conduitt published the book "De mundi systemate liber" based on a manuscript written in 1687 by Humphry Newton according to the dictation of Isaac Newton. It contains the description (and a figure most likely added by Conduitt) of different trajectories of stones thrown horizontally from a mountain in the same direction and with increasing initial velocities **(Figure 1).** The stones fall down to Earth at increasing distances from that mountain. But if the velocity assumes or even exceeds a critical value (the so-called orbital velocity), the stone never returns to ground and thus orbits (or even leaves) the Earth for all times (if the Earth's atmosphere is disregarded). It has become an artificial Earth satellite, and its orbit is exactly circular if the Earth's body is supposed to be of spherical shape and homogeneous density (and if the initial velocity vector is horizontal and has the size of the orbital velocity). In this case, the orbit is fixed with respect to inertial space.

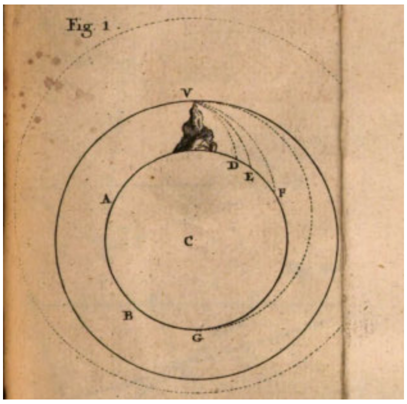


Figure 1: Figure 1 from "De mundi systemate liber" ([Newton], 1728). Credit: Bayerische Staatsbibliothek, München.

And if the shooting point is situated at, e.g., the Earth's North Pole, the orbit of the stone is called a polar orbit. Therefore, the Earth will rotate beneath this orbit. As seen from ground, the stone's or satellite's ground tracks gradually cover the Earth's surface with time **(Figure 2).**

However, the Earth is neither spherical nor of homogeneous density, which is why the satellites' acceleration is varying in a complicated way and its orbit is continuously changing. Satellites in low Earth orbits (abbreviated as LEOs) experience these effects much more pronounced than satellites in mean or even in high orbits (as indicated by the outer dotted line representing an elliptical orbit in **Figure 1**). While covering the Earth's surface, Earth orbiting artificial satellites are thus sort of "scanning" the Earth's gravity field and therefore continuously change their orbits accordingly. If precisely observed, these trajectories may be used to determine the Earth's global gravity field, including its time-variability.

Section 1 presents the order of magnitudes and key properties of the Earth's static and time-variable gravity field. Section 2 addresses how the Earth's gravity field can be mathematically represented as spherical harmonic expansion of its potential function and specifically explains how the time-variable

Figure 2a: Ground tracks of GRACE-FO covering 1 day.

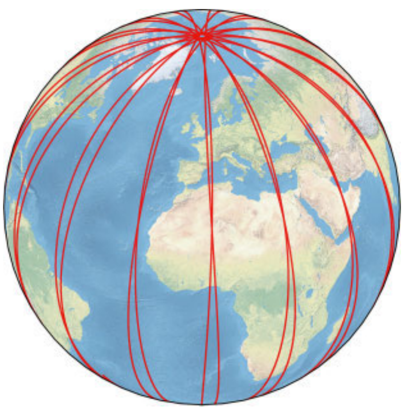


Figure 2b: Ground tracks of GRACE-FO covering 15 days.

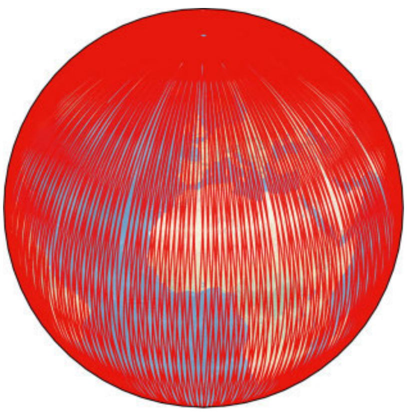
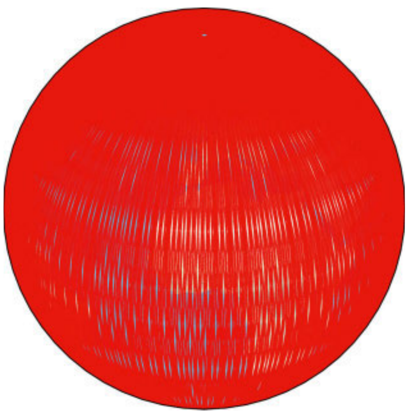


Figure 2c: Ground tracks of GRACE-FO covering 30 days.



part can be recovered from satellite data collected by dedicated gravity missions. Section 3 focuses on some of the most pronounced signals of the Earth's time-variable gravity field such as the global water cycle and ice mass loss in the polar regions. Section 4 summarizes the need to continuously monitor the observed changes and presents the initiatives of the European Gravity Service for Improved Emergency Management (EGSIEM) and the Combination Service for Time-Variable Gravity Fields (COST-G) initiated by the author. Section 5 concludes this *Spatium* and provides a short outlook.

1. The Earth's gravity field

In a first rough approximation the Earth's shape may be considered as spherical **(Figure 3a).** In this case, the gravitational pull at the Earth's surface is at every point about 9.81 m/s². This is what we also call gravitational acceleration or simply "gravity" according to Newton's second law (cf. *Spatium* 31, p. 5–6). Due to the Earth's rotation, centrifugal forces cause the Earth's figure to be flattened, oblate at the poles and oblong at the equator **(Figure 3b).** Because the Earth is not a rigid body but a deformable planet, this flattening amounts to about 1/300. Consequently, gravity varies at such a surface between 9.78 and 9.83 m/s² due to centrifugal forces and the resulting flattening. This ellipsoidal shape may be considered as a second approximation of the true Earth figure.

In reality, the true figure is defined by the mass distribution in the Earth's interior, the topography, as well as the local and global distribution of water (oceans, groundwater, etc.) and ice (ice sheets, glaciers, etc.), which may undergo seasonal and secular variations. This means that the true figure and mass distribution of the Earth changes with time. The mean contribution of all these irregularities to the gravitational pull amounts at maximum only to about ±0.001 m/s² when comparing the acceleration at the geoid, a surface defined as being everywhere horizontal, with the acceleration at the ellipsoid. **Figure 3c** shows a snapshot of the Earth's "true" gravity field for a certain point in time (after having reduced the effects shown in **Figure 3b**). The colored variations are scaled in units of ±100 mGal, where 1 mGal = 0.00001 m/s², and thus correspond to about 0.1‰ of the gravitational pull at the Earth's surface. For comparison: the gravitational pull

Figure 3a: Acceleration at the surface of a spherical, homogeneous Earth.

Figure 3b: Acceleration at the surface of a rotating, oblate Earth.

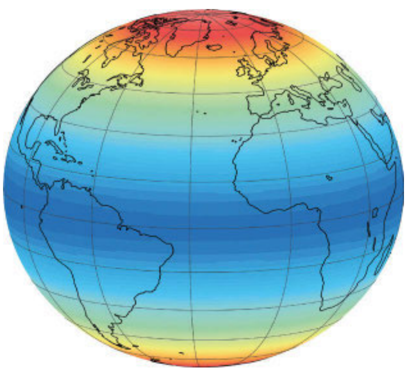
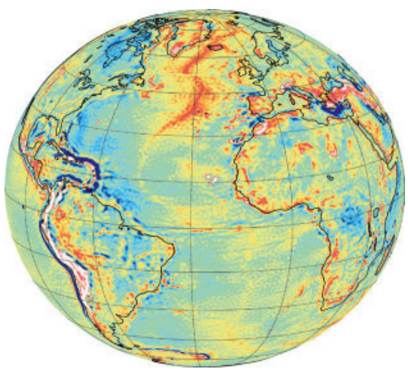


Figure 3c: Acceleration of the "true" gravity field wrt Fig. 3b.



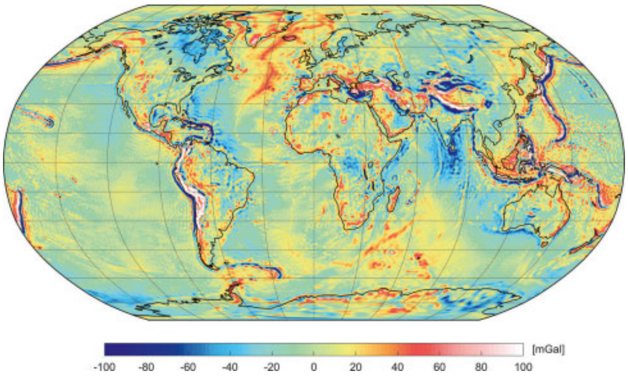


Figure 4a: Earth's gravitational field in March 2021.

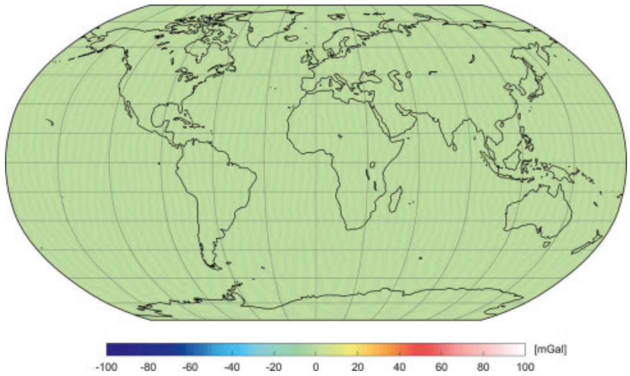


Figure 4b: Difference of the Earth's gravitational field in September and March 2021.

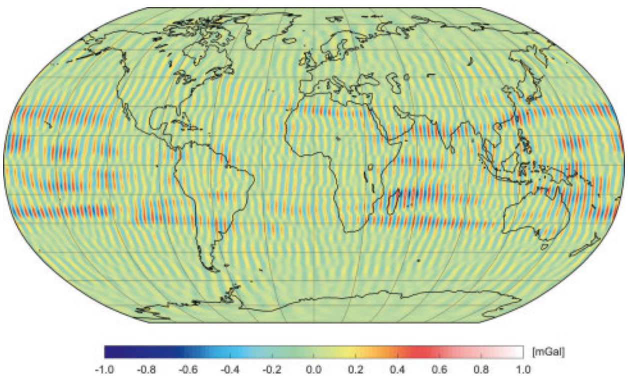


Figure 5a: Reduced scale of Fig. 4b.

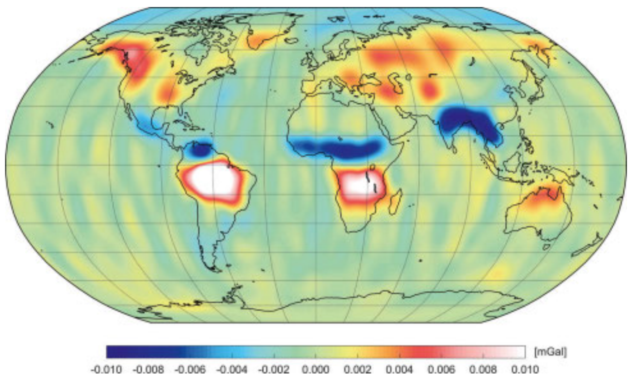


Figure 5b: Post-processed and reduced scale of Fig. 5a.

decreases with increasing altitude by 1000 m by about 0.3‰.

The colored variations in **Figure 3c** are closely related to geophysical phenomena such as subduction zones, ocean ridges, etc. They are characteristic for the static part of the Earth's gravitational field, which has been determined with an unprecedented accuracy of 1 mGal at a spatial half wavelength resolution of 100 km from data of the GOCE mission (see Sect. 2 and *Spatium* 31, p. 9–12).

Figure 4a shows in analogy to **Figure 3c** the Earth's gravitational field in March of the year 2021. Plotting the gravitational field half a year later would not show any obvious differences. **Figure 4b** confirms that the differences are "zero" (or almost zero) on this scale. If the scale is reduced by a factor 100, "noise effects" resulting from insufficient ground track coverage of the satellites, measurement characteristics, and mismodelling appear **(Figure 5a).**

Different post-processing techniques, e.g., filtering, allow it to remove or at least to reduce these "noise effects" to a large extent. We may now considerably reduce the scale, again by a factor 100, i.e., wrt Figure 4b in total by a factor 10 000, so that the remaining Earth's gravity field reveals variations of the order ±0.01 mGal **(Figure 5b).** Only then it is possible to monitor the time-variability of the Earth's gravity field from a time series of monthly snapshots in a meaningful way.

2. Exploiting the Earth's time-variable gravity field

The satellites orbiting the Earth are affected by the Earth's mass distribution. Their orbits have thus "imprinted" signals of these gravity anomalies, implying that their trajectories thus become more complicate. If the Earth was a point mass, bounded satellite orbits would be perfect ellipses. This is, as we have shown in Sect. 1, not the case. Satellite orbits therefore need to be determined regularly, e.g. for daily arcs. An orbit is defined by six so-called orbital elements, which are equivalent to the so-called state vector, composed of the position and the velocity vectors. The goal of orbit determination in its simplest form is to find the state vector for every epoch of an arc from observations of the satellites. These observations may include distance measurements and distance change measurements, e.g., to GPS satellites orbiting the Earth at higher altitudes (cf. *Spatium* 10) or to other LEO satellites.

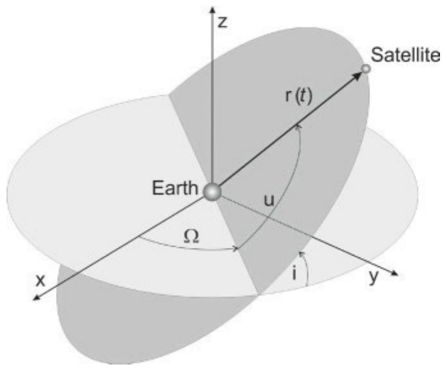


Figure 6: Keplerian orbital elements.

Figure 6 shows the so-called Keplerian orbital elements with respect to the Earth's center of gravity situated at one focus of the satellite's elliptical orbit. In this idealized situation, the orbital elements are defined by:

- *a:* Semi-major axis of the ellipse
- *e:* (numerical) Eccentricity of the ellipse
- *i:* Inclination of the orbital plane wrt the Earth's equator
- Ω: Right ascension of ascending node
- *w:* Argument of perigee
- u_0: Argument of latitude at epoch t_0

In reality, these orbital elements are functions of time, which is why so-called osculating orbital elements are defined as "instantaneous Keplerian orbital elements". The inhomogeneous mass distribution due to, e.g., the flattening of the Earth or mass anomalies, represent perturbations (among others) causing these orbital elements to change with time, e.g., a secular change in right ascension of the ascending node and thus a secular precession of the satellite's orbital plane, as illustrated by **Figures 7a**, **7b** and **7c**, respectively.

Optical observations of the first artificial satellite, Sputnik 1, thus already allowed it to determine the Earth's oblateness based on very short time spans of observed orbital arcs due to the large secular changes of its orbit **(Figure 7c).** This revolutionized the work of decades of terrestrial surveying to determine the figure of the Earth.

The gravitational field is, e.g., described by its potential *V*. This is a function depending on the distance *r* and the direction (given by the latitude ϕ and longitude λ) from the center of gravity to the

Figure 7a: Fixed orbital plane of a satellite for a spherical, homogeneous Earth.

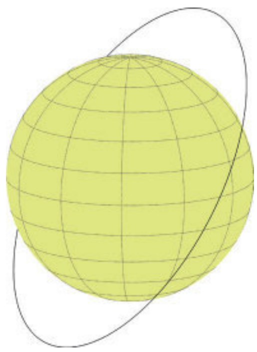


Figure 7b: Precession of the orbital plane of a satellite for an oblate Earth.

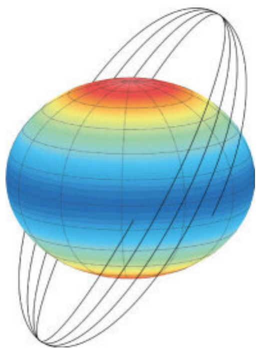
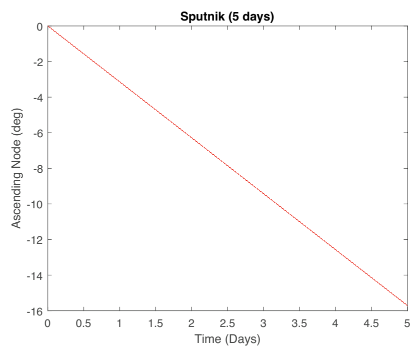


Figure 7c: Secular change of the ascending node Ω of Sputnik's orbit.



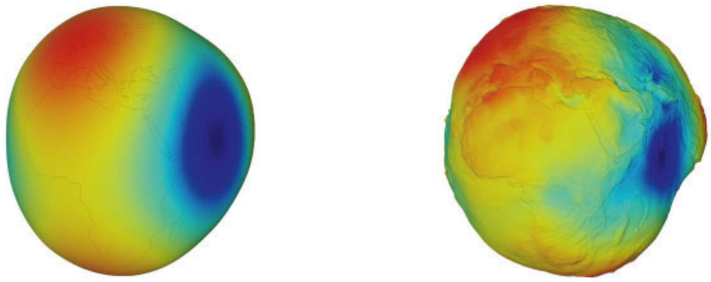


Figure 8: Spherical harmonic development for low and high maximum degrees.

satellite. The first derivative of this function with respect to these coordinates, the so-called gradient, represents the gravitational acceleration the satellite is experiencing. A spherical harmonic expansion up to a certain maximum degree $n_{\max}$ is most commonly used to represent the Earth's global gravitational potential. If the Earth was spherical with radius R and homogeneous density, its potential would be $V(r,\phi,\lambda) = GM/r$, where G is the gravitational constant, M the Earth's total mass, and $0<R<r$.

$$V(r,\phi,\lambda) = \frac{GM}{r} \sum_{n=0}^{n_{max}} \left(\frac{R}{r}\right)^n \sum_{m=0}^{n} P_{nm}(\sin\phi)\ (C_{nm}\ \cos(m\,\lambda) + S_{nm}\ \sin(m\,\lambda))$$

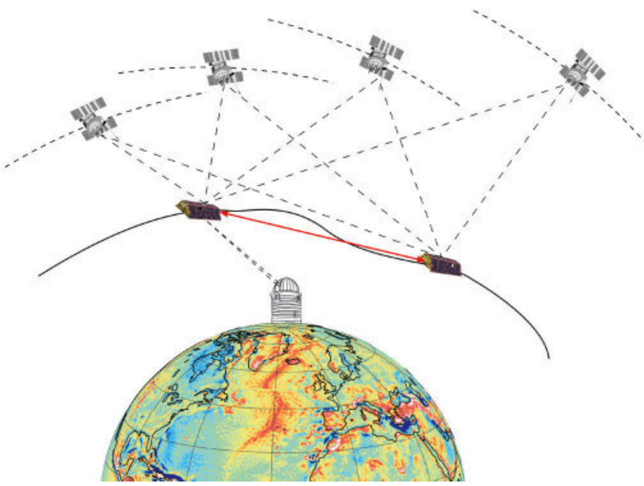
On the one hand, this spherical harmonic expansion contains the so-called associated Legendre functions P_{nm}, which are responsible for the "deviations" from the sphere. On the other hand, the potential V is characterized by the two sets of coefficients C_{nm} and S_{nm}. They define the "amplitude" or the size of these "deviations" from the sphere. The main task is to determine these coefficients from analyzing satellite tracking data. The higher the degree of expansion, the more detailed the potential can be described, as **Figure 8** shows.

An increase of n_{max} implies a considerable increase in the number of coefficients to be determined, but also an increasing spatial resolution of the potential in terms of the spatial half wavelength expressed in km **(Table 1).**

$n_{\max}$	#Coeff.	λ [km]
20	441	1000
100	10 201	200
200	40 401	100
250	63 001	80

The Earth's global potential V defined by the coefficients C_{nm} and S_{nm} may, e.g., be recovered from the satellite trajectories given by the coordinates (r,ϕ,λ) as a function of time. This means that the determination of C_{nm} and S_{nm} of the Earth together with the state vectors of the satellites and other (additional) parameters defines a very complex parameter estimation problem using different observations of different precision **(Figure 9).** Global Navigation Satellite Systems (GNSS) such as the US-American Global Positioning System (GPS) allow it to determine the positions of LEOs with centimeter precision. In addition, the orbits of LEOs can also be determined from ground-based observatories by Satellite Laser Ranging (SLR) with the precision of a few centimeters. Dedicated LEOs orbiting the Earth in formation and being interconnected by microwave or laser beams, such as the GRACE (Tapley et al., 2004) and GRACE-FO (Landerer et al., 2020) dedicated gravity missions

Figure 9: GPS high-low satellite-to-satellite tracking, LEO low-low satellite-to-satellite tracking, and satellite laser ranging.



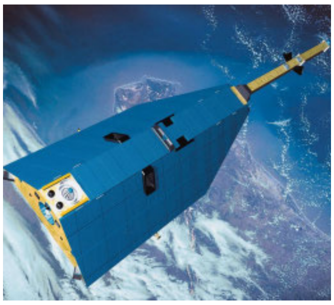


Figure 10a: CHAMP (CHAllenging Minisatellite Payload).
Credit: AIRBUS (Astrium)

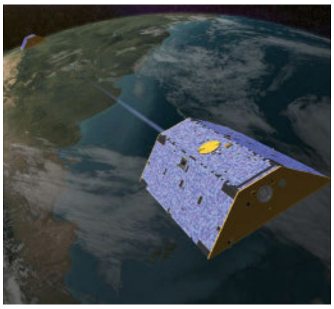


Figure 10b: GRACE (Gravity Recovery And Climate Experiment).
Credit: NASA/JPL

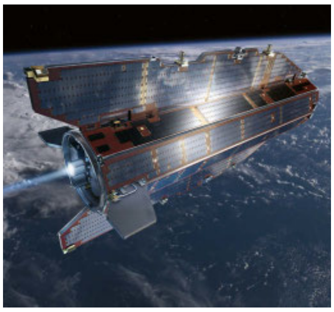


Figure 10c: GOCE (Gravity field and steady-state Ocean Circulation Explorer).
Credit: ESA/AOES Medialab

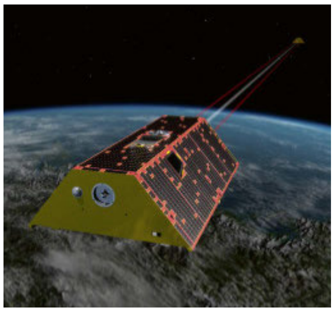


Figure 10d: GRACE-FO (GRACE Follow-On).
Credit: NASA/JPL-Caltech

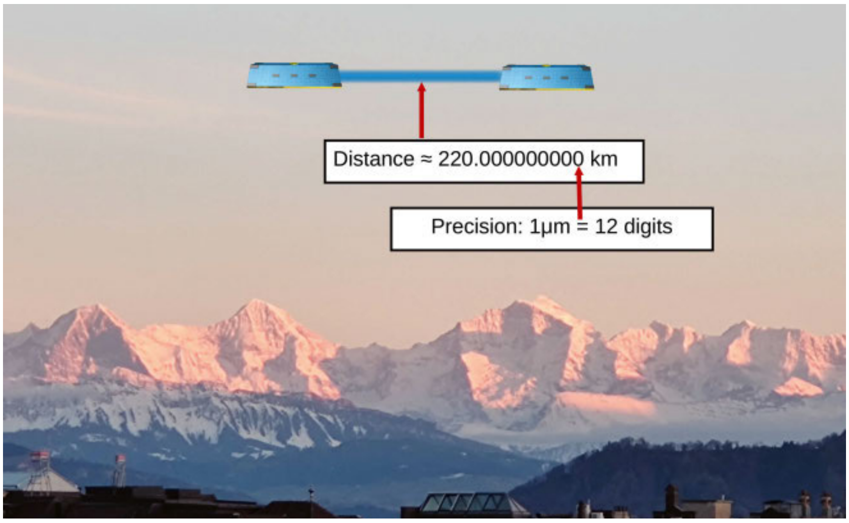
(see below), allow it to measure the distance changes in between them with µm or even nm precision.

There were several dedicated gravity missions (Flechtner et al., 2021), one of them still going on:

– CHAMP (CHAllenging Minisatellite Payload), operated by the German GFZ from 2000 to 2010, which provided GPS high-low satellite-to-satellite tracking (hl-SST) data and on-board accelerometer data **(Figure 10a)**
– GRACE (Gravity Recovery And Climate Experiment), operated by NASA and the German DLR from 2002 to 2017, which provided K-Band low-low satellite-to-satellite tracking (ll-SST) data in addition to GPS hl-SST data and on-board accelerometer data **(Figure 10b)**
– GOCE (Gravity field and steady-state Ocean Circulation Explorer), operated by ESA from 2009 to 2013 with GPS hl-SST data and satellite gravity gradiometry (SGG) based on the measurements of six on-board accelerometers **(Figure 10c)**, and
– GRACE-FO (GRACE Follow-On), operated by NASA and GFZ since 2018, which provides K-Band and laser ranging interferometer (LRI) ll-SST data, GPS hl-SST data, and accelerometer data **(Figure 10d).**

The two GRACE-FO satellites are flying in the same orbit separated only by about 220 km. Therefore, both satellites are affected by the same gravity anomalies on Earth, but somewhat delayed by about 30 seconds due to their separation and velocity. Consequently, the distances between these satellites, which are continuously measured by a microwave K-Band link and a LRI link, vary according to the slightly different accelerations experienced by the two satellites. These spatial differences are a measure for the gravitational

Figure 11: Precision of GRACE inter-satellite K-Band ranging.



strength of the mass anomalies overflown by these satellites. The distance variations caused by the mass anomalies are very small, but they are measured with a precision in the micrometer range (or even in the nanometer range for GRACE-FO using the laser ranging interferometer) **(Figure 11).** GRACE and GRACE-FO data are used to derive a time series of monthly snapshots of the Earth's gravity field.

The data processing, however, is challenging: it includes the interaction of multiple instruments. The measurements of the different instruments are affected by different noise characteristics, environmental disturbances (ionosphere, gravitational effects due to short-term mass variations in the atmosphere and oceans, etc.). Due to all these challenges, it is not straightforward to derive one "true" gravity field solution.

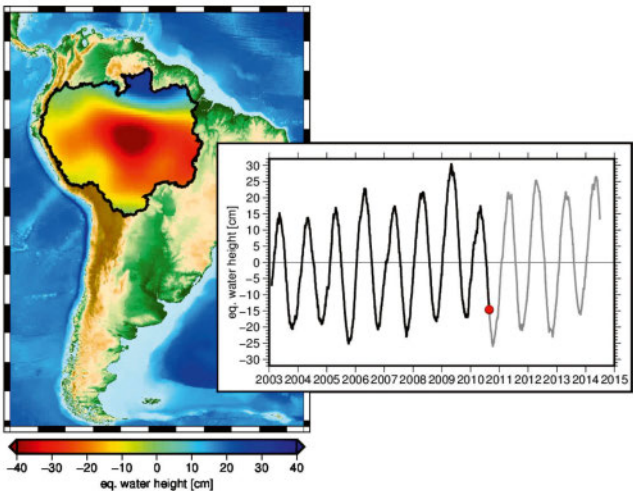
3. Monitoring global and regional climate change effects

For the monitoring of the time-variable Earth's gravity field its potential can be expanded at the moment up to degree and order 60 to 120, corresponding to a spatial (half) wavelength of about 333 to 166 km with a time resolution of about one month. After reduction of non-hydrological mass variations such as in the atmosphere, in the oceans, and by tides, the measured changes may be expressed in so-called equivalent water heights (EWH), given in cm, such that the EWH multiplied by the corresponding area represents the observed remaining effect in the gravity field. Using EWH, areas on Earth's surface can directly be multiplied by the corresponding EWH to get, e.g., the volume of water that corresponds to the observed mass variation.

Subsequently, global and regional seasonal and climate change effects are illustrated. The first example shows the seasonal water cycle of the Amazon basin measured by GRACE for more than a decade **(Figure 12).** The blue areas represent in the chosen color scale large EWH, the red areas low equivalent water heights. A movie of these plots (available at *http://egsiem.eu/42-amazon-video*) impressively shows the seasonal water cycle with slowly varying amplitudes.

GRACE and GRACE-FO were/are able to measure global water cycles with a spatial half wavelength resolution of about 300 km in the sense of a global average. GRACE/GRACE-FO is capable to measure the whole change in total terrestrial water storage (TWS). TWS is composed of different components which, however, cannot be distinguished by GRACE/GRACE-FO. To achieve a separation, further measuring techniques are required, e.g., remote sensing missions like the ones from the Copernicus Earth Observation Program or in-situ measurements. In this way, the Earth's TWS may be decomposed into groundwater, surface water, snow water equivalent, soil moisture, and water run-off. Currently, this challenging separation is being studied in the frame of the H2020 project "Global Gravity-based Groundwater Product" (see Sect. 4). TWS change, which can only be measured by GRACE and

Figure 12: Seasonal water cycle of the Amazon river basin. Credit: EGSIEM



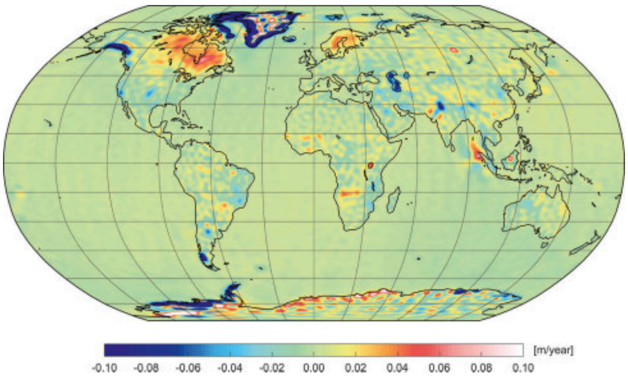


Figure 13: Trends in the Earth's time-variable gravity field extracted from the model GOCO06S (Kvas et al., 2021).

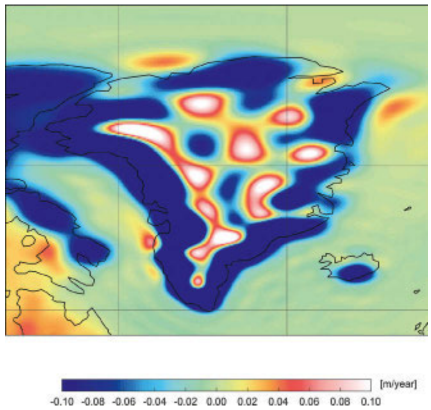
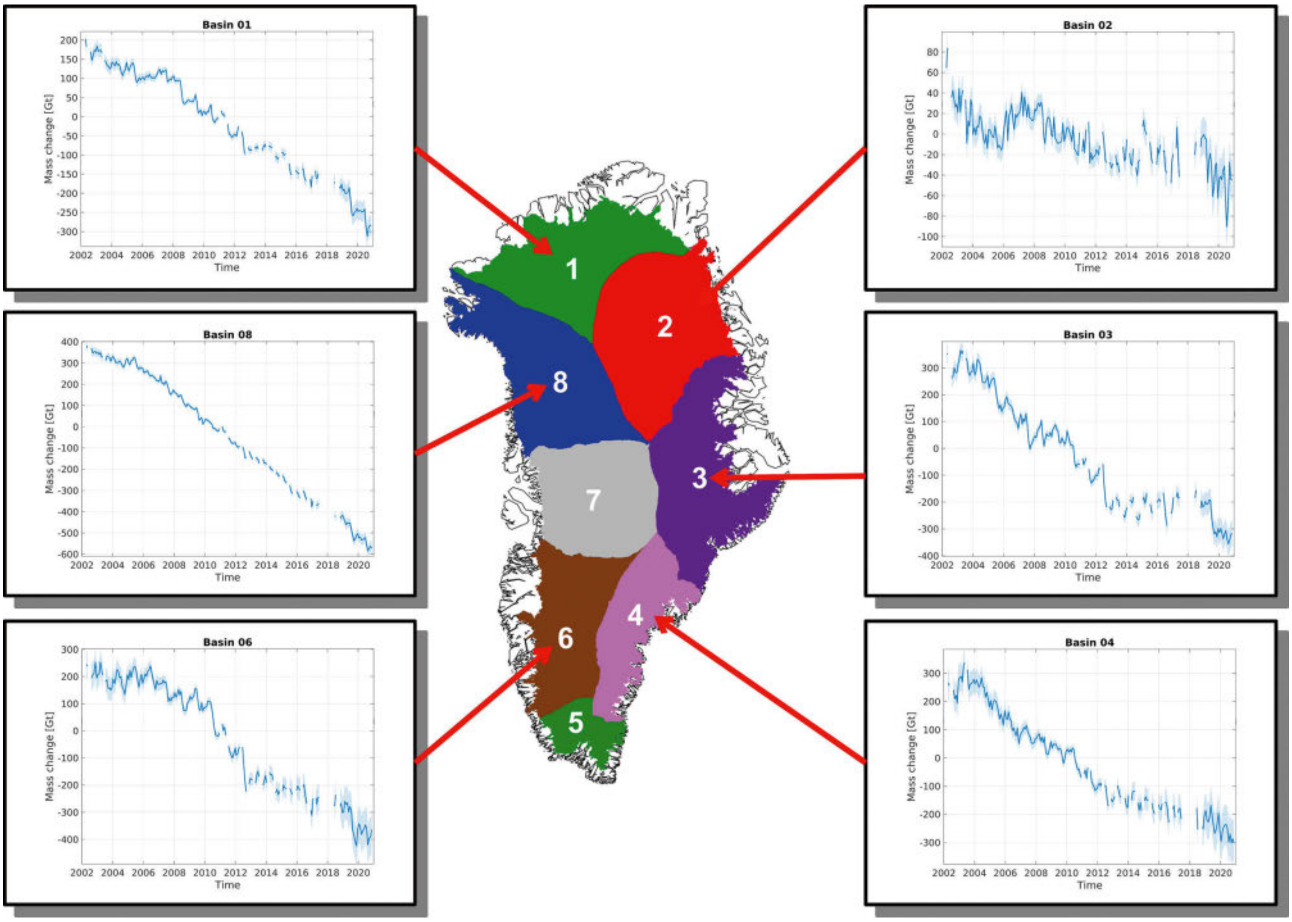


Figure 14: Zoom of Fig. 13 on Greenland.

Figure 15: Ice mass loss of Greenland's ice sheet. Credit: COST-G

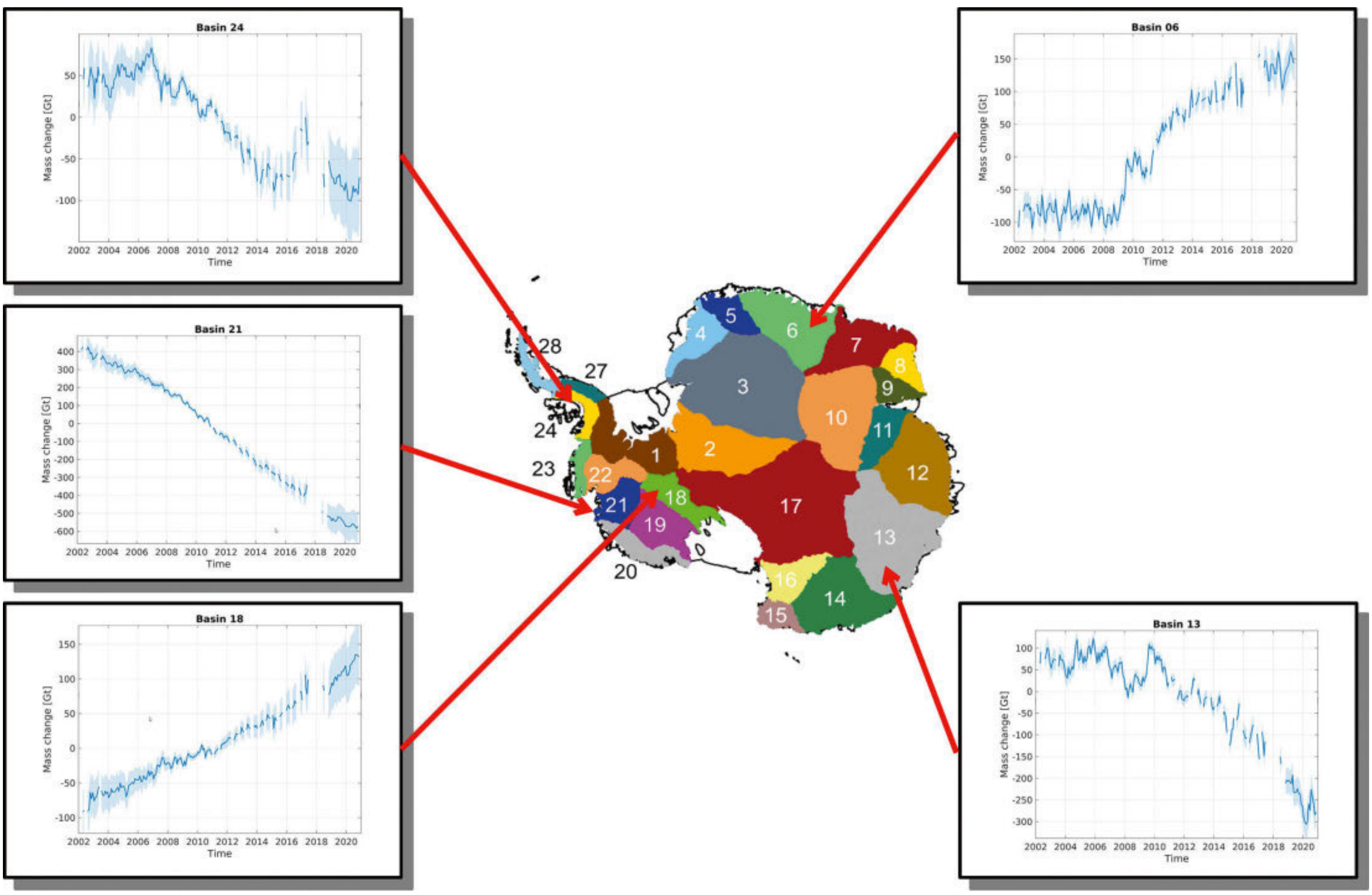


GRACE-FO, is the essential input to isolate individual compartments such as groundwater by a subtraction process. Only TWS change provides, e.g., the full picture of hydrological changes on the continents.

The most prominent signals in the Earth's time-variable gravity are caused by climate change on Greenland and Antarctica. As opposed to other gravity variations on the Earth's surface, e.g., in the Amazon basin in South America, the Congo basin in Central Africa, or the Ganges-Brahmaputra delta in Bangladesh (see again **Figure 5b**), they do not only consist of seasonal variations but also of secular changes **(Figure 13).** Even on a global map, but in particular in a zoom plot, the mass changes on Greenland measured by GRACE and GRACE-FO show different long-term trends at different regions of the West, East, North and South coast of this island **(Figure 14).**

Considering and reducing other effects contributing to the overall signal, which GRACE and GRACE-FO cannot distinguish, e.g., land up-lift due to Global Isostatic Adjustment (GIA) in Canada and Fennoscandia, these satellites are able to monitor trends or even accelerations in the ice sheet mass loss for different regions of Greenland, as illustrated by **Figure 15** from the COST-G solutions (see Sect. 4). The trend in total mass loss of Greenland's ice sheet derived from

Figure 16: Ice mass loss in Antarctica. Credit: COST-G



these results amounts to about 280 Gt/year, corresponding to a loss of about 10 000 m^3 ice every second.

GRACE and GRACE-FO revealed a quite similar picture of the Antarctic as already seen in Greenland **(Figure 16).** A dramatic ice mass loss is observed as well for different regions of the Antarctic, in particular on the West coast of Antarctica. This mass loss contributes significantly to the sea level rise. The sea level equivalent for the entire Greenland ice sheet would be about 7 m, for Antarctica it would be about 60 m. The GRACE/GRACE-FO missions are the ideal tool to weigh these ice sheets and to identify losses and gains on a regional level.

4. Situational awareness and sustainability

Climate change asks for a situational awareness of emerging water distribution and availability. These climate change effects concern not only the sea level rise and the groundwater levels (cf. *Spatium* 46), but – as a consequence of both effects – floods and droughts, as well (cf. *Spatium* 25). An often quoted example for the latter issue is the ongoing groundwater depletion and drought in California lasting since more than one decade with a possible or partial direct human impact (Rodell et al., 2018). While droughts are typically long-term effects, floods occur on a very short time scale. Although the global situation as illustrated by **Figure 17** for March 2006 seems not to be so dramatic at a first glance, a closer look reveals, e.g., increased water storage in the Danube basin in Europe that led to a large-scale flood event in the Danube basin in the April 2006 time period (see the highest peak values in the monthly time series shown in **Figure 18**).

Such short term effects can only be detected on that specific spatial resolution by close ground track coverage of the Earth's surface by the satellites. This is a real problem, because a sufficient coverage required for a high spatial resolution is only achieved after many revolutions of the satellites, which needs, e.g., in the case of the GRACE-FO satellites, typically one month (see again **Figure 2**). Here is the conflict: floods usually happen on much shorter time scales. This problem can only be solved by aiding the gravity field recovery by modeling the natural variability of Earth's time-variable gravity based on longer time series, such that even a few passes of one day can be exploited to detect significant signals of possibly emerging events. One initiative dealing with this problem was the European Gravity Service for Improved Emergency Management (EG-

Figure 17: Snapshot of the Earth's time-variable gravity field in March 2006.

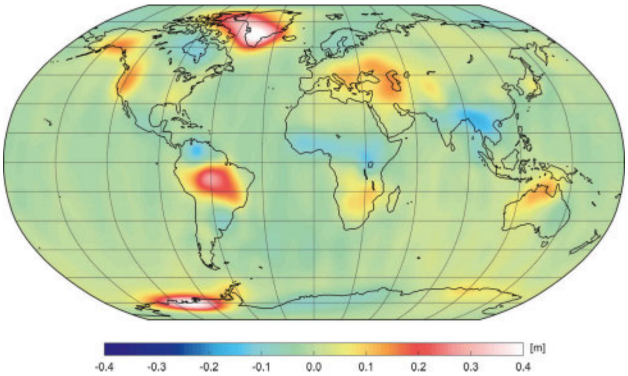
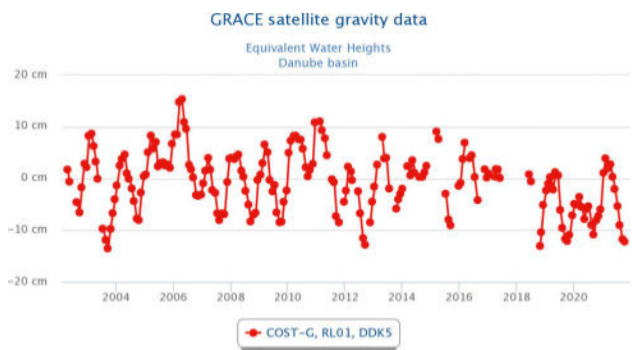


Figure 18: Total Terrestrial Water Storage Variations in the Danube basin plotted with the publicly available COST-G plotter at http://plot.cost-g.org/.



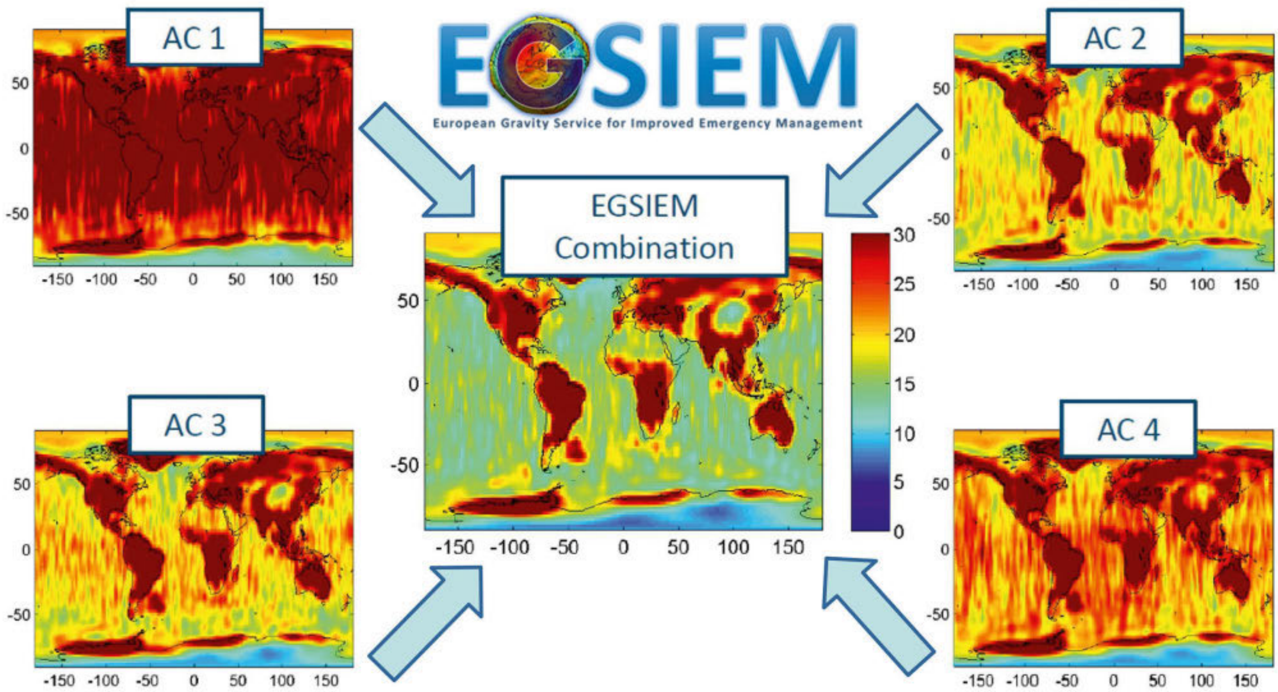


Figure 19: Principle of the combination process developed by the EGSIEM initiative. Credit: EGSIEM

SIEM), which received funding from the Horizon 2020 Framework Program for Research and Innovation (Jäggi et al., 2019). On one hand, it brought together several Analysis Centers (AC) producing consolidated combined monthly solutions of the Earth's time-variable gravity field using GRACE and today GRACE-FO data **(Figure 19)**, and on the other hand it explored new applications based on gravity field solutions derived on much shorter (daily) time scales.

Could daily gravity field solutions be helpful for early warning? Potentially yes! In the case of floods, saturated soils may be one factor for the development of floods. Therefore, it is worthwhile to check whether unusual developments in TWS may serve in future as an additional indicator for the potential development of floods. However, this information, e.g., a TWS-derived flood or wetness index, can currently only be derived with a delay of a few months, and only with a time resolution of one month. In order to be useful, it will be necessary to have this information available in near real-time and with a significantly improved (daily) time resolution. The build-up of basin-wide water storage of several weeks duration prior to the larger flood events is particularly important when dealing with early flood warning. An operational test run of near real-time gravity field solutions has already been successfully performed in the final months of the GRACE mission. In the future, earlier alarms, e.g., of flood events, may become feasible thanks to gravity-augmented indicators.

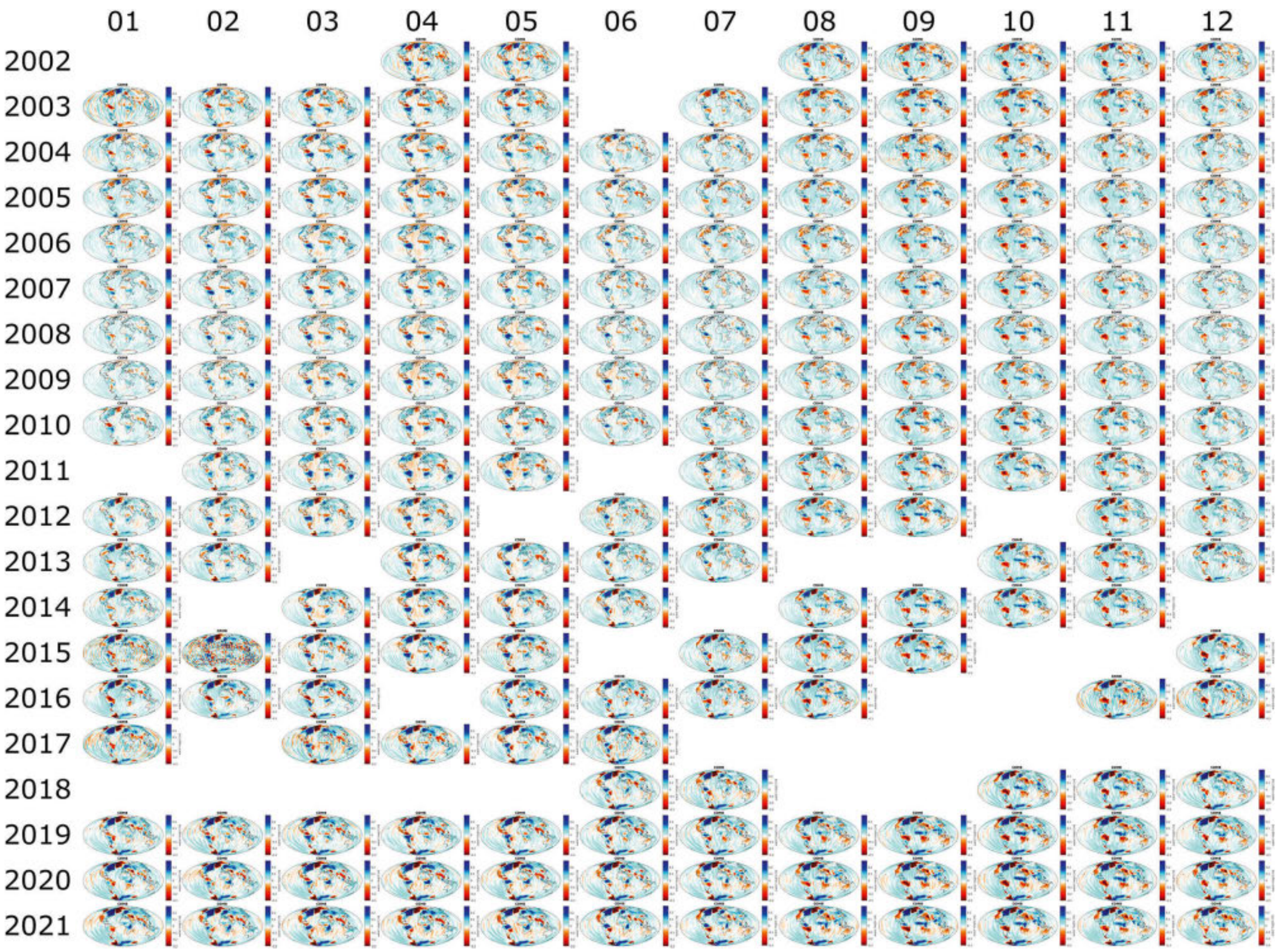
Parts of EGSIEM are continued as a new product center of the International Association of Geodesy (IAG) called COST-G (Jäggi et al., 2020), coordinated by the Astronomical Institute of the University of Bern (AIUB) and producing monthly combined gravity field solutions now even on an operational basis **(Figure 20)**. The monthly gravity field solutions missing in the figure are related to the gap between the GRACE and the GRACE-FO mission in 2017-18, or due to instrument data which are missing for different reasons. Only low resolution solutions can be derived by GPS hl-SST or SLR for these months.

The University of Bern also suggested to strive for a follow-up project of EGSIEM with the same gravity core-group as in EGSIEM, which resulted in the Global Gravity-based Groundwater Product (G3P) initiative, a Horizon 2020 project coordinated by the Helmholtz Centre Potsdam, German Research Centre for Geosciences (2020-2022). G3P aims at developing a product of groundwater storage variations with global coverage and monthly resolution by a cross-cutting combination of GRACE and GRACE-FO satellite gravity data with water storage data that are based on the existing portfolio of the Copernicus services. This global gravity-based groundwater product is developed for later operational implementation as Essential Climate Variable (ECV) Groundwater into the Copernicus Climate Change Service.

5. Conclusion and outlook

The Astronomical Institute of the University of Bern (AIUB) is hosting one of the GRACE/GRACE-FO Analysis Centers and is coordinating the generation of combined GRACE/GRACE-FO monthly gravity field solutions in the frame of COST-G under the umbrella of the International

Figure 20: Combined monthly gravity field solutions operationally generated by COST-G. Credit: COST-G



Association of Geodesy (IAG). COST-G was emerging from the Horizon 2020 project EGSIEM and was brought to an operational level by an international team receiving support from the International Space Science Institute (ISSI) in Bern, Switzerland. A further extension of COST-G with GRACE/GRACE-FO Analysis Centers located in China has been initiated by a further international team receiving support from the ISSI in Beijing, China.

TWS consists of the sum of all the water storage on the Earth's continental areas in frozen and liquid state. Because satellite gravimetry with GRACE (2002–2017) and GRACE-FO (2018–) is the only technique to observe TWS variations, it opens the door for numerous exciting initiatives, e.g., the development of a global product of groundwater storage variations derived by a combination of GRACE and GRACE-FO satellite gravity data with water storage data based on the existing portfolio of the Copernicus services. Europe's Earth Observation Program Copernicus contains already today a wealth of activities such as atmosphere monitoring, marine environment monitoring, emergency management, land monitoring, climate change, and security. But "gravity" is one of the missing links in the Copernicus Earth Observation Program, although gravity contributes to a large number of Essential Climate Variables (ECVs). ECVs are variables defined by the Global Climate Observing System (GCOS), which are critical for characterizing the climate system and its changes. ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to assess risks, to guide adaptation measures, and to underpin climate services. The importance of TWS has recently been recognized by GCOS by including it in the GCOS implementation plan that is currently (at the time of writing in 2022) being formulated.

The cornerstones of these activities are the satellite missions. Dedicated gravity missions such as GRACE and GRACE-FO brought spectacular results, leading to insights into the global water cycle, polar and mountain ice mass loss, sea level rise, etc. Once the GRACE-FO mission will be finished, there will be an urgent need for sustained observations of mass transport in the system Earth. Our efforts need therefore be directed to continue and further improve these observations with next generation gravity missions in order to extend all the time series which are of such great societal relevance.

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Web resources

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http://cost-g.org Website of the COST-G product center, visited May 2022.

The Author

Adrian Jäggi studied Astronomy, Physics, and Mathematics at the University of Bern, Switzerland, from 1996 to 2001 and finished these studies with a Diploma in Astronomy. In addition, he received a High-School Teaching Certificate for Physics and Mathematics in 2002. Between 2002 and 2006, he was engaged in his Ph.D. studies at the Astronomical Institute of the University of Bern (AIUB), where he received his PhD degree in 2006 with a thesis entitled "Pseudo-Stochastic Orbit Modeling of Low Earth Satellites Using the Global Positioning System". From 2007 to 2009, he was awarded a Carl von Linde Junior Fellowship to perform research on global gravity field recovery at the Institute for Advanced Study (IAS) at the Technical University of Munich, Germany. In 2009, he returned to AIUB as a Senior Research Scientist and was appointed as Professor and Director of the AIUB in 2012. In 2019, he was Visiting Scientist at the University Corporation for Atmospheric Research in Boulder, Colorado.

Adrian Jäggi is member of numerous commissions, working groups, and societies related to Space Geodesy. In particular, he is a Fellow of the International Association for Geodesy (IAG) since 2015, and since 2019 president of IAG's Commission 2 (Gravity Field), member of the Executive Committees of the IAG and of the Global Geodetic Observing System (GGOS), and Chair of the COST-G Directing Board. He has initiated several international scientific projects, among them projects funded by the Horizon 2020 Framework Program for Research and Innovation and the European Research Council (ERC).