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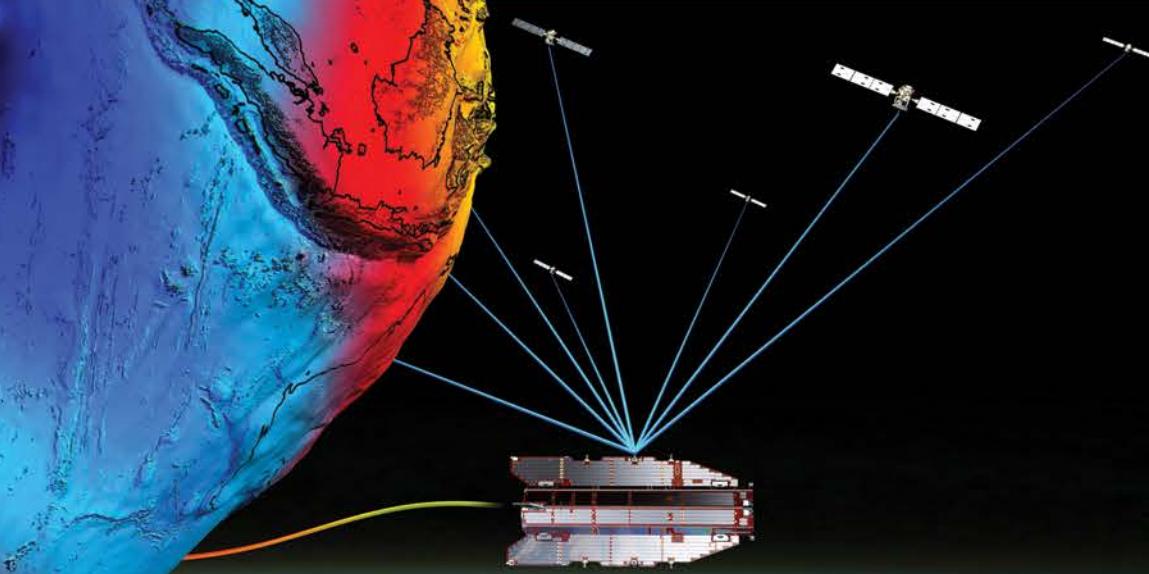
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→ GOCE USER TOOLBOX



earth.esa.int/gut



→ GRAVITY FIELD AND STEADY-STATE OCEAN CIRCULATION EXPLORER (GOCE)

Launched on 17 March 2009, ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission was the first Earth Explorer mission in orbit. This novel mission delivered a wealth of data to bring about a whole new level of understanding of one of Earth's most fundamental forces of nature – the gravity field.

This sleek, high-tech gravity satellite embodied many firsts in its design and use of new technology in space to map Earth's gravity field in unprecedented detail. As the most advanced gravity space mission to date, GOCE data are realising a broad range of fascinating new possibilities for oceanography, solid Earth physics, geodesy and sea-level research, and significantly contributing to furthering our understanding of climate change.

Although invisible, gravity is a complex force of nature that has an immeasurable impact on our everyday lives. It is often assumed that the force of gravity on the surface of Earth has a constant value, but in fact the value of 'g' varies subtly from place to place.

These variations are due to a number of factors such as the rotation of Earth, the position of mountains and ocean trenches and variations in density of Earth's interior. GOCE mapped these variations in the gravity field with extreme detail and accuracy. This resulted in a unique model of the 'geoid', which is the surface of equal gravitational potential defined by the gravity field – crucial for deriving accurate measurements of ocean circulation and sea-level change, both of which are affected by climate change.

GOCE-derived data are also being used to understand more about processes occurring inside Earth and for use in practical applications such as surveying and levelling. In addition, the measurements are being used to improve estimates of polar ice-sheet thickness and their movement.

On 21 October 2013, the mission came to a natural end when it ran out of fuel. Three weeks later, on 11 November, the satellite disintegrated in the lower atmosphere. Although its flight is over, the wealth of data from GOCE continues to be exploited to improve our understanding of ocean circulation, sea level, ice dynamics and Earth's interior.

→ GOCE USER TOOLBOX (GUT)

The GOCE User Toolbox (GUT) is a compilation of tools for the use and analysis of GOCE gravity field models. It facilitates the use, viewing and post-processing of GOCE Level 2 mission data and allows the gravity field data, in conjunction and consistent with any other auxiliary data sets, to be pre-processed by laymen on gravity field processing, for oceanographic and hydrologic as well as solid earth applications, both regionally and globally. Hence, GUT is an important tool for facilitating a wide use of the existing and future gravity data acquired from GRACE and GOCE.

GUT may be used on Windows PCs, UNIX/Linux workstations and Mac and comes as fully open source software under GNU GPL licence. GUT generates all output files in netCDF format in compliance with the CF-Conventions, and gridded results may be visualised using the BratDisplay tool from ESA's Broadview Radar Altimetry Toolbox (BRAT).

Advanced users can easily extend the toolbox in accordance with the workflow based processing design principles, and contribute these enhancements to the GUT user community.

The current version of GUT is 3.1. This version has been enhanced with a newly developed graphical user interface. This interface is built on top of the command-line interface, providing a more user-friendly alternative to it.

GUT abilities

With GUT a user can:

- Read the GOCE level 2 products and ancillary datasets, including a priori surfaces, calibrated gravity gradients and geoid height errors
- Read global and local gravity models in ICGEM format
- Compute geoid heights at a chosen maximum degree and order over a grid or transect
- Compute gravity and height anomalies, and vertical deflections on the surface of the terrain for a range of maximum degree and order expansions over a grid or transect
- Compute the spherical harmonic synthesis and calculate the 6 potential gradients
- Compute the ocean's mean dynamic topography and associated geostrophic velocities, kinetic energy and the vertical component of relative vorticity

- Smooth gridded fields with a wide range of spatial and spectral filters, including diffusive filtering
- Transform data between different reference ellipsoid and tide-systems
- Compute gravity disturbances, Bouguer and free-air anomalies at different heights
- Produce final output products in netCDF format
- Develop high-level processing routines.

A primary objective of the GOCE mission was to map the ocean's time mean circulation globally in unprecedented detail. Figure 3 shows the ocean's mean dynamic topography (MDT) obtained by subtracting the final GOCE geoid, based on 42 months of gravity observations, from the DTU13 altimetric mean sea surface. This MDT is used to determine a global map of the ocean's time-mean geostrophic surface circulation as shown in Figure 4. The MDT and associated currents were calculated using GUT, taking advantage of the diffusive filter to remove residual noise while preserving the gradients associated with oceanographic structures. Large-scale currents such as the North Atlantic's Gulf Stream, the North Pacific's Kuroshio Current and the Southern Ocean's Antarctic Circumpolar Current, as well as finer-scale structures such as the Brazil-Malvinas Confluence and the Agulhas Retroflection, are revealed in remarkable clarity. This demonstrates the success of the GOCE mission and serves as the basis for on-going efforts to understand the ocean and its central and complex role in Earth's changing climate.

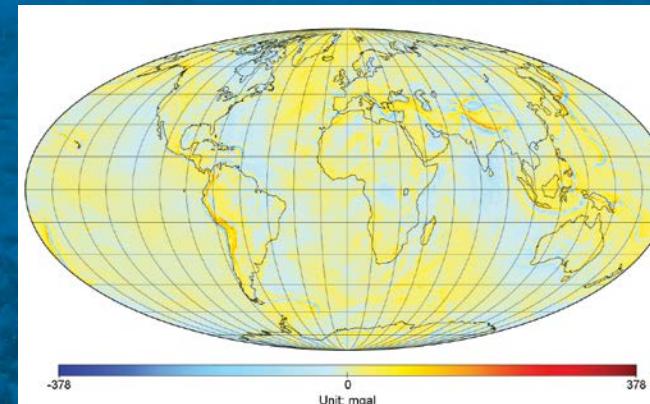


Figure 1: Free air gravity anomaly, computed from the time-wise solution (2009-2013). The free air gravity anomaly is very similar to the gravity anomaly in GUT2, but here the potential W is evaluated at geoid height and the potential U at zero (ellipsoid) height. (Credits S&T)

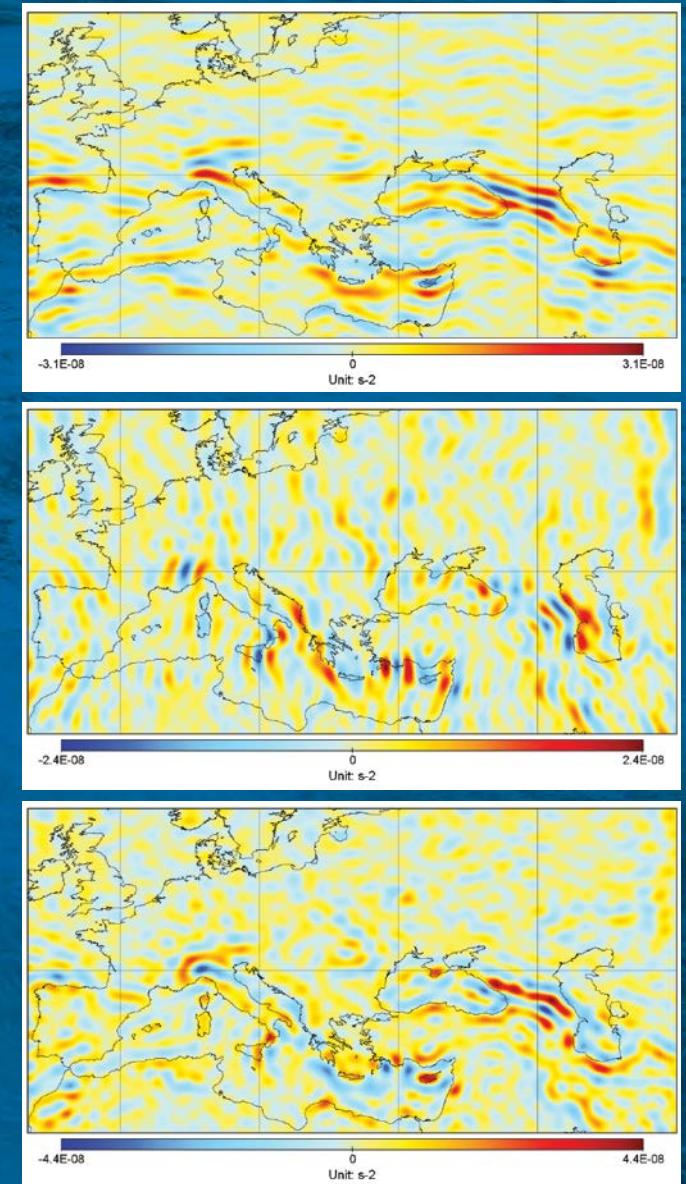


Figure 2: GUT now has the ability to compute the gravity potential gradients from a gravity model. The implementation is based on the derivations from M.S. Petrovskaya, 2008. Shown here are T_{xx} , T_{yy} , T_{zz} over Europe, computed from the direct solution of GOCE data from 2009 to 2013. (Credits S&T)

For more advanced users, the GUT package also includes additional tools for fully exploiting the error variance-covariance matrix of each GOCE gravity model. They allow both the magnitude and correlation structure of the formal errors for the geoid, or other derived quantities, to be rigorously determined from the error variance-covariance matrices on a standard desktop PC.

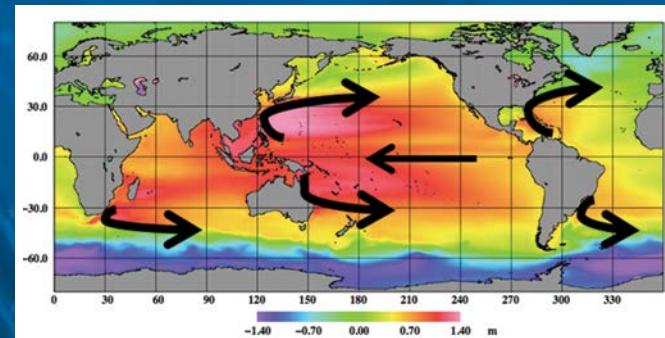


Figure 3: The DTU13MDT model ranging from -1 to 1 meter with a rough sketch of the currents following the gradient in the MDT. GUT can be used to derive the detailed magnitude of these currents. (Credits DTU Space)

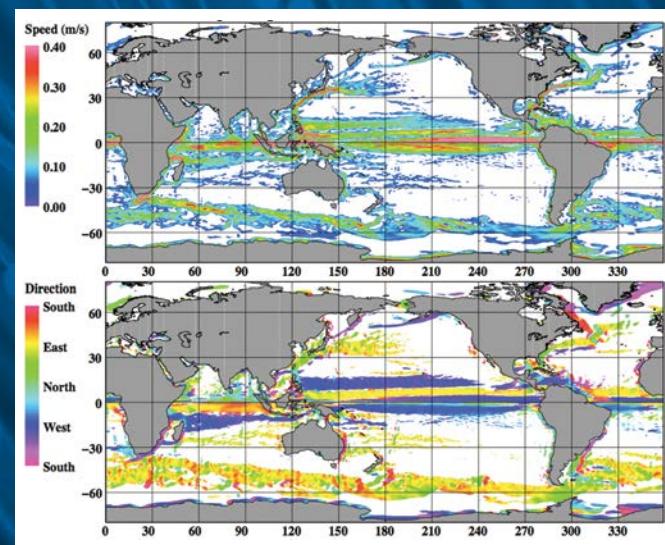


Figure 4: The ocean current derived from the DTU13MDT (model which resulted from the difference between the DTU13MSS and the EIGEN6-c4 models). The upper panel shows the magnitude of the current in m/s, with currents less than 5 cm/s masked out. The lower panel shows the direction of the currents. (Credits DTU Space)

For example, Figure 5 shows a global map of the formal geoid error magnitudes calculated using the error tools for one of the GOCE gravity models (TIM5) expanded to degree and order 280 – the maximum degree and order to which the model is defined. Meanwhile, Figure 6 shows how the geoid error at one location (0E, 60N) is correlated to the error at surrounding points. Such information is essential for optimal filtering, data assimilation and for rigorously combining the GOCE gravity observations with other data types.

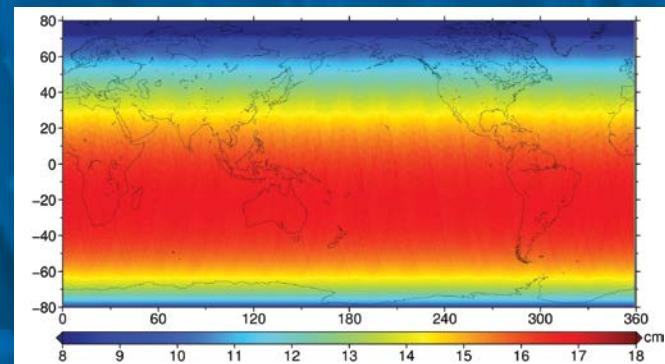


Figure 5: The formal geoid error for one of the GOCE gravity models (TIM5) expanded to degree and order 280 – the maximum degree and order to which the model is defined. (Credits UB)

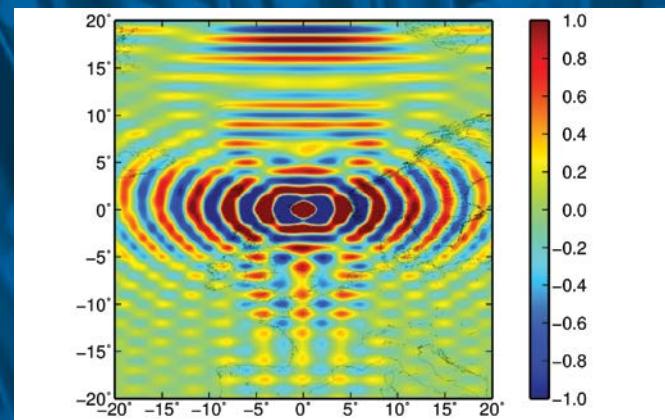


Figure 6: The correlation between the TIM5 geoid error at one location (0E, 60N) and the error at surrounding points. (Credits UB)

→ GUT GRAPHICAL USER INTERFACE (GUT GUI)

A graphical user interface (GUI) is included with GUT 3.1 for increased usability. A user can drag and drop workflows from a workflow library to a project canvas, on which multiple workflows can be easily chained together, given inputs and executed.

After execution, the output of the processing chain can be visualised by any netCDF viewer, right from the GUI. GUT is packaged with BratDisplay, which is used as the default visualiser.

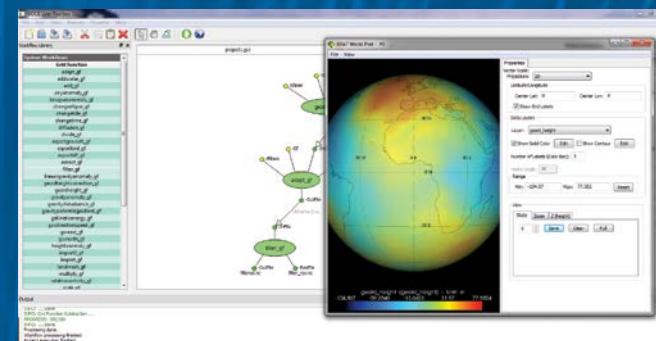


Figure 7: A user can easily build processing chains of multiple workflows using the GUT3 GUI, visualising the output using the BratDisplay tool from ESA's BRAT. (Credits S&T)

Individual workflows can be edited by manipulating automatically generated graphs, depicting structure and relations of processing units. Advanced users can create new workflows for their unique needs.

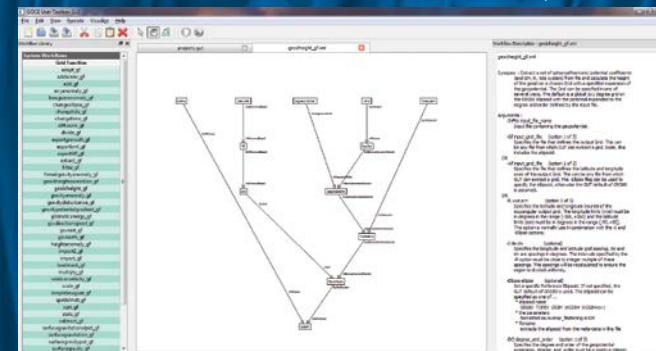


Figure 8: Users can create their own custom workflows by connecting multiple processing units of choice and linking the dependencies as the user sees fit. (Credits S&T)

→ GUT TUTORIAL

Besides the toolbox, a tutorial is available. It provides some recommendations and use cases (geodesy, solid earth and oceanography). For instance, you can learn how to compute a Mean Dynamic Topography with GUT from one of the GUT a priori geopotentials (GO_CONS_EGM_GOC_2_20091101T000000_2010_0630T235959_0001.DBL) and one of the Mean Sea Surface Height files (MSS.nc), using a Hanning filter with a window of length of 3° in longitude and 2° in latitude. You can then visualise it with BratDisplay (Figure 9):

```
gut spatialmdt_gf -InShpFile GO_CONS_EGM_GOC_2_20091101T000000_00_20100630T235959_0001.DBL -InShpFile MSS.nc -InLsmFile GUT_LSM.nc -Fhan 2,3 -Ellipse TOPEX -R 0.5:359.5,-89.5:89.5 -I 1:1 -OutFile SpatialMdt_fhan32.nc
```

BratDisplay SpatialMdt_fhan32.nc

The two commands above produced the following plot:

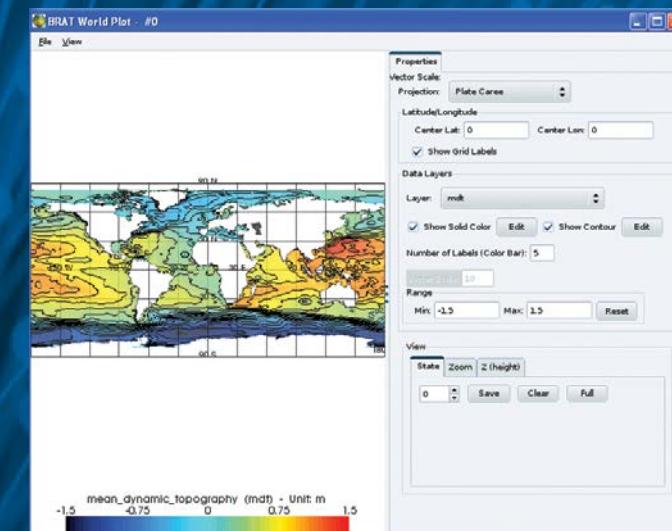


Figure 9: Map of satellite-only MDT obtained using the spatialmdt_gf workflow. The projection and the colour range were set using BratDisplay. (Credits CLS)

→ SCIENTIFIC RESULTS

Drifters comparison

Since the geoid is the missing quantity to reference the altimetric measurements and thus compute the Absolute Dynamic Topography and the associated geostrophic surface current, GOCE mission provides crucial information to oceanographers.

Throughout the GOCE mission, the GOCE geoid models have improved and are in good agreement with independent estimates at scales higher than 100 km of resolution (for instance, Figure 10 shows the decrease of standard deviation of the difference with drifters from the release 4 to release 5).

Thanks to the impressive performance of this mission, when using GOCE geoid models the oceanic signal is better resolved between 100 and 200 km of resolution than when using the state of the art combined geoid model EGM2008 (that do not include GOCE data but previous satellite gravimetric data, in-situ gravimetric data and altimetry). Therefore, the use of GOCE data is strongly recommended.

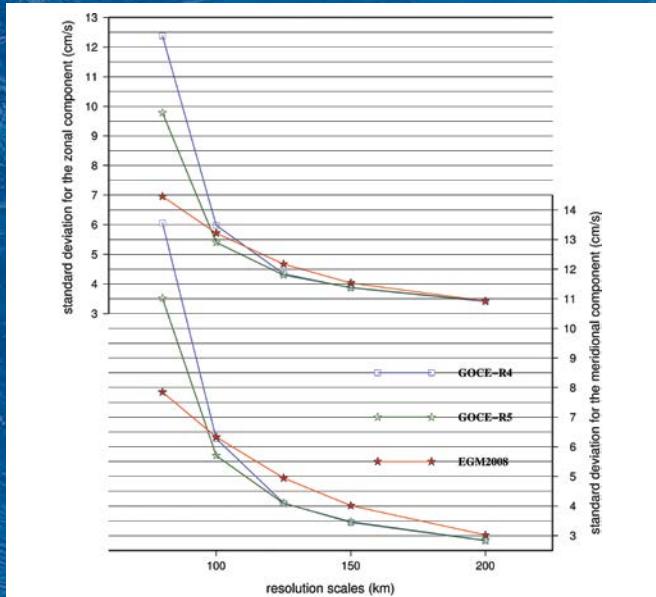


Figure 10: Global standard deviation of the difference between filtered geostrophic current computed from different geoid models and filtered geostrophic current estimated from surface drifters for zonal (top) and meridional (bottom) component (cm/s). (Credits CLS)

Use of GOCE L2 Gravity Gradients for full resolution geoid

The objective is to use GOCE gradiometer data to additionally enhance GOCE spherical harmonic coefficient model above the degree 240. Hence, the use of gradients may lead to improved resolution of e.g. the marine geoid, which in turn will improve the estimation of the ocean circulation. This work is under progress.

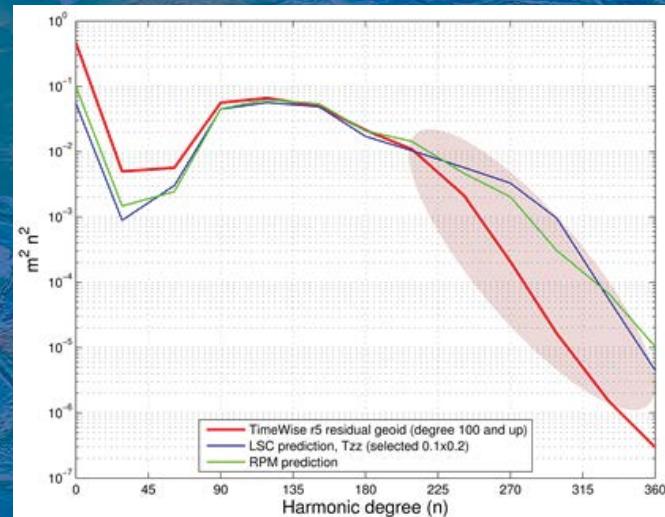


Figure 11: Power spectrum of the enhanced TIM5 based geoid using GOCE Tzz gradients on top of GOCE TIM5 EGM in the GOCINA region (prediction was done using Least Squares Collocation and Reduced Point Masses). The ellipse demarks the spectrum band where additional signal is present when GOCE gravity gradients are introduced. (Credits UCPH)

Solid Earth

GUT 3.1 has many tools that are useful in solid Earth studies, such as the calculation of the global Bouguer gravity field. This is accomplished through the spherical harmonic synthesis of the Earth gravity potential and of the global gravity effect from global topography and bathymetry. The outcome of the Bouguer values are a bit different than the ones calculated with the classical Hayford radius, due to the fact that the gravity effect of topography is calculated globally. In Figure 12 the Bouguer field for the Tibetan Plateau and surrounding orogens is shown, which is used for estimating the crustal thickness variations. The extremely low Bouguer values of $-500 \times 10^{-8} \text{ m/s}^2$ correspond to a crustal thickness of 70 km, against the normal crust of 35 km thickness.

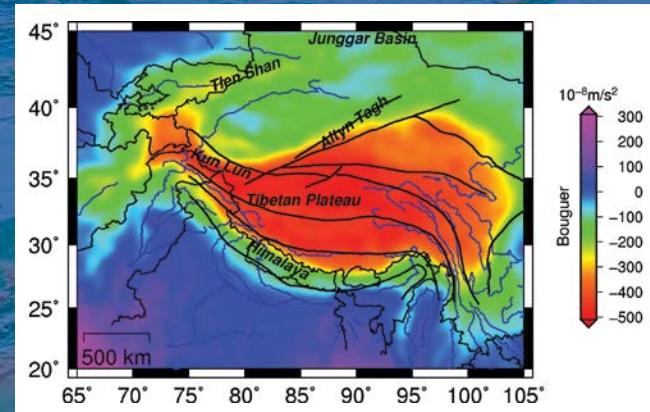


Figure 12: Bouguer gravity field at 8 km height calculated with the GUT software tool. Rivers in blue, national boundaries in black, principal faults and main sutures in black. (Credits UNITS)

The gravity anomaly differs from the Bouguer field by the gravity effect of topography and bathymetry. The Free Air gravity is shown in Figure 13, where it can be seen that in the Tibetan plateau the free air gravity has much smaller values than the Bouguer field. This is due to the gravity effect of the high topography cancelling the gravity effect of the doubled crustal thickness.

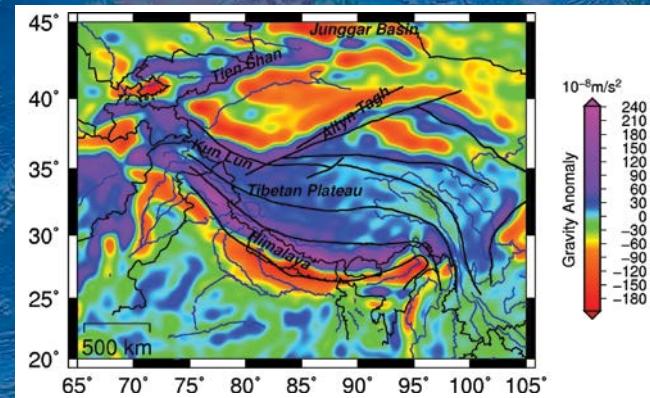


Figure 13: Gravity anomaly at 8 km height calculated with the GUT software tool. Rivers in blue, national boundaries in black, principal faults and main sutures in black. (Credits UNITS)

Another useful tool is the calculation of the gravity gradients. The example shown in Figure 14 shows again the Tibetan plateau. The gradient follows the faults much more markedly than the Bouguer field shown in Figure 12, and this is due to the fact that the gradient senses the crustal density variations more and is insensitive to tabular mass anomalies, as is the relatively flat Tibetan plateau. In Figure 14, the margins of the plateau, rather than the high plateau itself, give rise to elevated variations in the gradient.

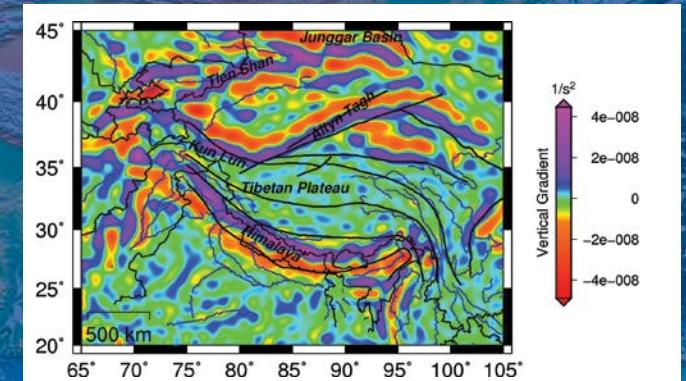


Figure 14: Vertical gravity gradient calculated at 8 km height for Tibetan Plateau and surrounding orogens. Rivers in blue, national boundaries in black, principal faults and main sutures in black. (Credits UNITS)