Toolbox for GRACE-NGGM-MAGIC

Per Knudsen[1]; Ilias Daras[2]; Américo Ambrózio[3]; and Marco Restano[3] , and Jérôme Benveniste.
[1)] DTU Space, DENMARK ; [2)] ESA-ESTEC, Noordwijk, NL; [3)] ESA-ESRIN, Frascati, ITALY.

Abstract
The MAGIC missions are envisaged to advance the applications of satellite based gravity field information for tracking changes in the mass distribution and transport in ground water storages, ice sheets and oceans. The GOCE User Toolbox GUT was originally developed for the utilisation and analysis of GOCE products to support applications in Geodesy, Oceanography and Solid Earth Physics. GUT consists of a series of advanced computer routines that carry out the required computations without requiring expert knowledge of geodesy. Hence, with its advanced computer routines for handling the gravity field information rigorously, GUT may support the future gravity missions such as GRACE-C, NGGM, and MAGIC in developing Level-2 and Level-3 products.

Focusing on MAGIC mission goals on unprecedented recovery of ocean bottom pressures, a more flexible processing of the gravity field information may become essential. Furthermore, an integration of ocean bottom pressure changes with changes in the geostrophic surface currents may advance the analyses further. GUT facilitates such a flexible processing and, in addition, contains tools for the assessment of static gravity field models and for the computation of the dynamic ocean topography models and the associated geostrophic surface currents.

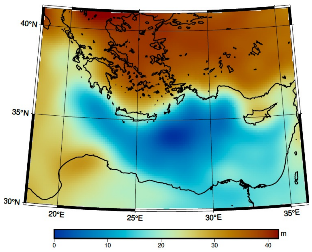

Figure 1: Geoid heights computed using the TIM-R6 up to degree and order 240.

Geoid and gravity anomalies

The examples demonstrating the value of GUT functionality in computing gravity fields quantities are:

- Computation of geoid heights from the EGMs at any specific grid to any max degree and order (Figure 1),
  Also GUT may compute height anomalies. Conversion between reference ellipsoids and tidal systems are facilitated as well.
- Computation of free-air gravity anomalies may be computed to any degree and order, also applying filtering (Figure 2).
  In addition, by combining with DEM or models of gravity from the terrain and its isostatic compensation, Bouguer and isostatic anomalies may be computed as well.

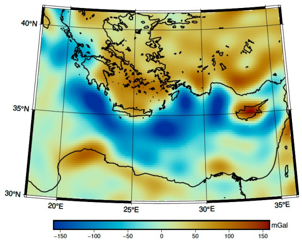

Figure 2: Free-air gravity anomalies from GGM05G to degree and order 240.

- Computation of deflections of the vertical may be computed to any degree and order (Figure 3).
  Also, second order derivatives may be computed.

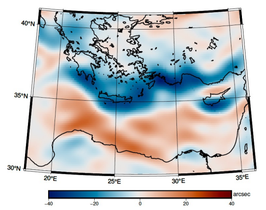

Figure 3: North-south component of the deflections of the vertical from GOGO2025s.

1. MAGIC objectives

The main objective of MAGIC is to extend the mass transport time series of previous gravity missions such as GRACE and GRACE-FO with significantly enhanced accuracy, spatial and temporal resolutions and to demonstrate the operational capabilities of MAGIC with the goal of answering global user community needs to the greatest possible extent.

The future satellite missions will continue providing Essential Geodetic Variable products:

- Gravity field quantities:
  - Regional geoid models
  - Free-air gravity anomalies
  - Gravity disturbances
  - Deflections of the vertical
- Mean dynamic topography
- Mean geostrophic currents.

In most applications, the analyses will be based on processing of EGMs which require expert knowledge in the field of geodesy. Hence, with its advanced computer routines for handling the gravity field information rigorously, GUT may support the MAGIC mission in reaching its goals.

2. Examples

The examples included in this poster demonstrate the value of GUT functionality in computing essential geodetic variables based on Earth gravity field models.

The computation of gravity field quantities is flexible wrt selection of maximum degree and order, reference ellipsoid and tide system. Furthermore, tools for combining with DEM and MSS, filtering, and for deriving statistical parameters may be applied when assessing the results.

Plots were produced using pygmt and color-blind friendly palettes by Fabio Crameri

Among its functionality, GUT allows a user to:

- 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 and workflows.

For this work the model package was updated with the following EGMs GGM05G, DIR-R6, TIM-R6, GOCO06s, and XGM2019e from ICGEM in *.gfc format; mean sea surfaces from DTU 2021, CNES-CLS 2022, and the SIO-CLS-DTU Hybrid 2023 model.

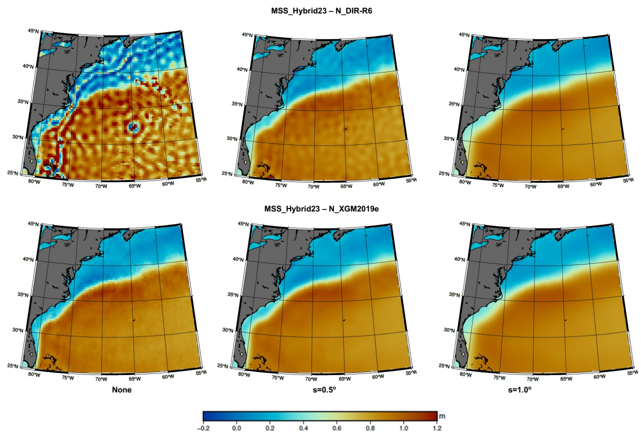

Figure 5: An example where MDTs have been computed as differences between the Hybrid23 mean sea surface and two geoid models, the satellite only model DIR-Rel.6 to d/o 300 (upper panels) and the combination model XGM2019e to d/o 2190 (lower panels). The differences are shown without filtering (left) and after applying Gaussian filters having half-width lengths of 0.5 and 1.0 degrees, respectively.

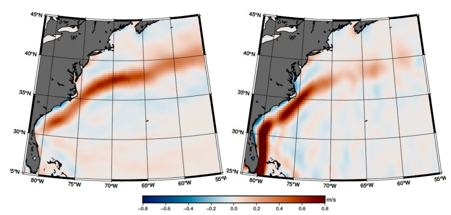

Figure 6: Geostrophic surface currents, E-W (left panel) and N-S (right panel), associated with the MDT shown in Fig. 5 middle panel in the bottom row..

MDT and geostrophic surface currents

The examples demonstrating the value of GUT functionality in modelling the mean dynamic topography are:

- Computation of dynamic ocean topography by combining a mean sea surface with a geoid model ensuring consistency in reference ellipsoids, tidal systems, grid specs. Both simple and more advanced filters are available (Figure 4),
- Computation of geostrophic surface currents from a MDT model in both Northern and Eastern directions (Figure 5).

The GUT package
The GOCE User Toolbox (GUT) can compute and process a range of higher level products at global and regional scales.
GUT comes as fully open source software package under GNU GPL licence.

The GUT package includes:

- The source package for building on UNIX/Linux/Mac
- Binary packages for Linux and Windows
- Algorithm description and user guide
- Tutorial and install guide and
- A set of a-priori data and models.

GUT generates all output files in netCDF. Gridded results may be visualised using generic tools such as GMT and QGIS.

In addition, software developed by Georges Balmino for rigorous analyses of error variance-covarince matrices is available.

The GUT Team:
GUT specifications and tutorials have been developed with contributions from:

- J. Benveniste, M. Restano, A. Ambrozio, R. Floberghagen, A. Horvath (ESA),
- P. Knudsen, O. Andersen (DTU),
- M.-H. Rio, S. Mulet, G. Larnicol (CLS),
- J. Johannessen, L.Bertino (NERSC),
- H. Snaith, P. Challenor (NOC),
- K. Haines, D. Bretherton (NCEO),
- C. Hughes (POL),
- R.J. Bingham (U Bristol),
- G. Balmino,
- S. Niemeijer, C. Aas, I. Price, L. Cornejo (S&T),
- M. Diament, I Panet (IPGP),
- C.C. Tscherning, M. Herceg (UCPH),
- D. Stammer, F. Siegismund (UH),
- C. Braitenberg (U Trieste)
- T. Gruber (TUM),