Deliverable: WP5000:

"Summary and Tutorial Document"

27 March 2007

Version 2.0

GOCE User Toolbox Specifications (GUTS)

DEVELOPMENT OF ALGORITHMS FOR THE GENERATION OF A GOCE USER TOOLBOX AND AN ABSOLUTE DYNAMIC TOPOGRAPHY PRODUCT

Ref:

ESA/XGCE-DTEX-EOPS-SW-04-0001 “GOCE User Toolbox Specifications (GUTS)”

Coordinator: Per Knudsen (DNSC)

Deliverable: WP5000: “Summary and Tutorial Document”

Responsible partner: DNSC

Prepared by: Marie-Hélène Rio

DOCUMENT CHANGE LOG				
Rev.	Date	Sections modified	Comments	Changed by
0	January 2007	All	Draft	M.-H. Rio
1	9 February 2007	All	Final version	M.-H. Rio
2	27 March 2007	All	Revised Final version	M.-H. Rio

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GLOSSARY

ADT	Absolute Dynamic Topography
API	Application Programming Interface
AVISO	Archivage, Validation et Interprétation des données des Satellites Océanographiques
BRAT	Basic Radar Altimetry Toolbox
CSR	Center for Space Research
ECCO	Estimating the Circulation and Climate of the Ocean
GFZ	GeoForschungZentrum
GOCINA	Geoid and Ocean Circulation in the North Atlantic
GUI	Graphical User Interface
HPF	High Processing Facility
MDT	Mean Dynamic Topography
MDTC	Combined Mean Dynamic Topography
MDTS	Satellite-only Mean Dynamic Topography
MSSH	Mean Sea Surface Height
SLA	Sea Level Anomaly
SH	Spherical Harmonics
TP	Topex Poseidon

1. Introduction - Executive summary of the GOCE User Toolbox Study

Following the recommendations explicitly expressed in several conferences and workshops such as the GOCINA final workshop (Proceedings of the GOCINA workshop, 2006) and the 2nd International GOCE User Workshop (Proceedings of the GOCE workshop, 2004) ESA reacted positively and set out to develop a GOCE User Toolbox. Indeed, no ocean circulation products are planned to be delivered as level-2 products as part of the GOCE project so that a strong need exists, for oceanographers, to further process the GOCE level-2 geoid and merge it with Radar Altimetry as well as basic tools to support all GOCE mission products user including the Solid Earth scientists. As the specifications for such a Toolbox were far from being known, ESA decided to develop the Toolbox in two phases: 1) a user requirement consolidation and trade-off study of the toolbox functionalities leading to a toolbox specification and 2) the actual implementation of the consensus toolbox specifications. GUTS, the GOCE User Toolbox Specification study is phase 1. Phase 2 is called GUT, the GOCE User Toolbox implementation and is the subject of the follow-on contract. The GUTS Team was founded by co-optation of the principal European geodesy and oceanography specialists in an open group structured around a core team and a group of observers taking part of the brainstorming progress meetings and reviewing the produced documentation.

The objective of the GOCE User Toolbox Study was to develop – in close collaboration with ESA's HPF effort – algorithms and input and output specification for the subsequent generation of a user toolbox that is required by the general science community for the exploitation of GOCE level 2 products and altimetric data.

In order to achieve this goal, the study was divided into different work packages including the Review of user requirements (WP2000), the Toolbox Functionality and Algorithm Specification (WP3000) and the Toolbox System Specification and Architectural Design (WP4000). The main results and recommendations from these three work packages are synthesized hereafter.

- The goal of the "Review of user requirements" work package was to produce a user requirements and an input/output specification document, which will be a reference to identify the main users together with Products and Functionalities they require from a toolbox.

In a first step, a review of all functionalities that optimally would be included in the toolbox, mostly in a qualitative way, was done, covering three main aspects, related to their use in geodetic, oceanographic and the solid Earth applications.

In a second step, all functionalities that could possibly be incorporated in the toolbox were described quantitatively. A detailed input/output definition document and an Algorithm Specification document were compiled, providing a general overview of the input data, ancillary data and output data.

At this stage, the decision was made to use the full expressions for the wanted quantities instead of the spherical approximations used in the products obtained from the HPF since using the non-approximated algorithms will give a higher accuracy.

- The objective of WP3000 was to define and describe the “Toolbox Functionality and Algorithm Specification” This work package entailed different tasks described hereafter including a scientific trade-off study whose aim was to select the best (in terms of accuracy and computational demands) algorithms to compute the variables listed in the user requirement document.

First, the User requirements from WP2000 were reviewed and sorted by priority order. It was recommended that the first release of the GOCE User Toolbox should prioritise those products and functions, identified in the User Requirement Document, that relate to the oceanographic community. This should bring immediate benefit to a community currently unfamiliar with the use of gravity and geodetic products whilst providing basic functionality in support of all science areas. In particular, it was recommended that the toolbox should focus on the generation of dynamic topography fields, through merging satellite altimeter and GOCE gravity model data, the estimation of the absolute dynamic topography and therefore the absolute geostrophic currents from altimetry being a key objective of the GOCE mission.

Also, seven different classes were defined: “basic” “essential”, “highly desirable”, “desirable but low priority”, “Functionality requiring extensive computing resources or not yet at consensus”, “nice added features”, ”Functionality Desirable at Future Date”.

The main element that was included in the category: “Functionality requiring extensive computing resources” concerns the handling of the full error variance-covariance matrix of the spherical harmonic coefficients. Although it was recognized that this is an important step in the use of GOCE data, it was not recommend that propagation of the full errors, from the spherical harmonic error covariances, should be carried out within the toolbox. This is primarily due to the high computational and storage space demands this would place on the toolbox. Further investigation were recommended into the possibility of allowing such calculations to be carried out using remote, possibly GRID, computing facilities, using parameters determined from the toolbox.

Part of the “Functionalities not yet at consensus” is the optimal filtering functionality. At the moment, all filters considered in GUTS are suboptimal and further investigations into the subject of filtering a geoid and sea surface height or the resulting dynamic topography are sorely required before we can consider including such functionality into the toolbox.

Then, the functionalities going into the first three categories (and some of the fourth category) were organized into 7 workflows. One workflow, the main workflow, includes the core functionality of the toolbox in a default processing mode and default input data designed for fast access of the main output fields and use in tutorials. It is recommended that the input data used in the main workflow should be included in the toolbox distribution; so that the main workflow is the ready-to-use playground for novices.

The convenient use of the toolbox including the application of the user’s own data and applications deviating from the main workflow is supported by the remaining 6 sub-workflows organized in the following six modules:

1. Geoid and gravity field computation

The goal of this workflow is to provide computation of: geoid heights, gravity anomalies and deflections of the vertical.

2. Sea surface height and a-priori dynamic topography selection

The objective of this workflow is, first, to read data from the archive and to calculate the mean for a specified period (averaging routine) and, second, to compute the output field on a grid or at specific points as convenient for the subsequent computations in the toolbox (adaptation routine).

3. Satellite dynamic topography computation

The objective of this workflow is to compute a Satellite-only MDT (MDTS) by subtracting a geoid model from an altimetric mean sea surface and further filtering the obtained field. Computation in both geographical and spectral space is possible.

4. Combined dynamic topography (MDTC) computation

The objective of this workflow is to compute a combined MDT where the short scales are provided by an a-priori (GUT default or user-supplied) MDT through a remove-restore technique (further details in section 3.2). Two variants of a remove-restore combined technique are included in GUT to be used for different purposes.

5. Dynamic topography-derived quantities

The objective of this workflow is to compute geostrophic velocities from dynamic topography on a grid or list of locations (mean or time-dependent).

6. Pre-viewing function

Visualisation functions and graphical user interface were initially identified as important features of the GOCE User toolbox. However, in a second stage, it was decided that the GUT project should concentrate on the toolbox “core”, e.g. the different functionalities and workflows. It was therefore decided to rely on the existing BRAT toolbox for further visualisation (potentially via the BRAT GUI) of the GUT outputs. Furthermore, the BRAT toolbox provides additional functionalities that have been recognized as significant for the completeness of the GOCE User Toolbox (more sophisticated altimeter data access and manipulation facilities: such as generation of mean sea surfaces or generation of time series of absolute dynamic topography by merging mean dynamic topography and sea level anomaly). It is recommended that GUT be able to input altimeter products generated within BRAT, and provide output that be used within BRAT to provided these extended facilities.

The basic elements in the previously described six workflows are the GUT functions as well as input and output fields. The GUT functions are the lowest processing level that can be accessed by the user when running the toolbox. The computations within a function might contain more than one algorithm as specified in the User Requirement Document. An overview of the functionality in GUT was therefore also given in WP3000, providing the input and output definition of the functions and the link to the algorithm specification in the User Requirement Document.

As part of WP3000, a trade-off study was realized for which it was decided to concentrate on investigating the efficiency and accuracy of filtering techniques as this is an essential part of the generation of dynamic topography fields due to the differences in resolved spatial scales between the altimetric and geodetic data. This study concluded that filtering data in spectral space, particularly in conjunction with a remove-restore technique, provided the best option for a current toolbox implementation.

Finally, a number of fields were identified (MSSH, MDTS, a-priori MDT, geoid model) for which it is recommended that a default file is included within the toolbox package and provide the default for appropriate workflows. For instance, two candidates were identified as potential default MSSH file, the KMS04 solution (Andersen et al, 2005) and the CLS01 solution (Hernandez and Schaeffer, 2001). As new fields may (will) be available by the time the GOCE User Toolbox is constructed and delivered, this list of potential candidates may be modified later.

In addition to these default fields, a strong requirement is that users can easily ingest their own data into the toolbox: Consequently, it is recommended that as a minimum requirement, the toolbox documentation must provide the format specifications of the included input data files in order that the user can supply their own data in the same format. In addition, the toolbox should supply the ability for users to write their own input modules for expansion of the toolbox to cover the widest possible range on input data formats.

- The objective of WP4000 (system specification and architectural design) was to provide a logical description of the toolbox architecture and data flow. The aim was not to include any software design details but rather to provide a link between scientists in the GUTS team and the software engineers who will implement the toolbox.

A system specification and architectural design document was produced that contains the definition of all system external interfaces and formats, the description of a logical model of system functions as well as a complete specification of output content: data products, metadata, reports and logs.

The proposed design is based on C and Fortran core scientific codes managed using the Python programming language, which would also provide the main user interface to GUT.

Python is not the only way to implement GUT, and it is possible that the important features of the design specified in the WP4000 report could be implemented in another way. However, if alternative solutions are evaluated during the implementation phase, the following elements need to be considered as basic requirements:

- Capability to re-use existing Fortran programs
- Capability to be easily extensible by adding new C and Fortran based functionality. This is to allow the flexible use and development of the toolbox by the science community
- Multi-platform capability, including Windows
- Good command interface with scripting ability
- API for advanced customisation
- Protective User Environment
- Facilitates good science and traceability of results

All through the study, a number of existing sets of software routines and packages were collected – mainly Fortran routines- for making a first GUT prototype and for input to the subsequent GUT construction. This includes the Harmonic_synth package of Simon A. Holmes and Nikolaos K. Pavlis as well as the GRAVSOFT package (Tscherning et al, 1992, 1994).

In conclusion, this first phase, the GOCE User Toolbox Specification study, has successfully set up the basis for the further implementation of phase 2, the GOCE User Toolbox construction. In addition, it was strongly recommended that two activities should be led in parallel to the toolbox construction as part of the phase 2 project. First, further research is needed into exploiting the full error variance-covariance matrix. Second, it is highly recommended that the GOCE User Toolbox is made available to the users with an updated set of auxiliary data. More particularly, a specific study should be done in order to provide a new altimetric Mean Sea Surface taking advantage of all improved processing of altimetric data, mainly in coastal areas. This new Mean Sea Surface should be provided with an error estimate.

2. Objectives of the GUTS tutorials

The work realized during the one-year GUT Study has led to the writing and delivery of several reports that have been compiled into the GUTS final report and whose executive summary has been given in the previous introductory section. GUTS deliverables also include a collection of existing software that could, potentially, be used for the GUT construction and that can already act as a first GUT prototype, although they don't cover all GUTS identified functionalities.

The next section is dedicated to the description of the GUTS tutorial whose objective is NOT to give a description of this existing software but rather, in continuity and complement of the WP2000, 3000 and 4000 reports, to provide an overall vision of what the GOCE User Toolbox should look like, that can help later software engineers to construct the toolbox in a user friendly manner.

To achieve this goal, the tutorials have been divided into two main components:

The first part aims at providing general information on the scientific aspects covered by the toolbox, mainly the computation of an ocean mean dynamic topography. This part should help a novice user to better understand why all the toolbox functionalities are needed and why the default workflows have been recommended.

In the second part of the tutorials, concrete use cases have been associated with each function and each workflow identified in WP3000.

For clarity sake, and similarly to what has been done for WP4000 report, the tutorials are written as though GUT already exists.

Although they aim to be an important and useful input for the further construction of GUT, they should not be considered as a restrictive canvas for the writing of the future GUT tutorials.

3. Tutorials

3.1. Reminder of the GUT objectives

The objectives of the GOCE User Toolbox are mainly twofold:

- The first objective is directed towards a wide group of users from different communities (solid earth, oceanography…). The aim is to facilitate the handling of the GOCE Level-2 products that will be made available from the GOCE HPF (High Processing Facility). This means translating the HPF GOCE Level-2 products, mainly the set of spherical harmonics coefficients and the variance-covariance error matrix, into spatial representations of geophysical quantities (geoid height, gravity anomalies, deflection from the vertical) and their errors.
- The second objective is directed towards the oceanographic community through the computation of ocean mean dynamic topography, which, added to altimetric sea level anomalies, gives access to the ocean absolute dynamic topography and the corresponding ocean geostrophic circulation.

3.2. Altimetry and the Mean Dynamic Topography issue

Since the beginning of altimetric missions more than 15 years ago, the lack of an accurate geoid has been hampering the full exploitation of altimetric data for oceanographic studies. Only the variable part of the ocean dynamic topography can be extracted with sufficient accuracy (few centimetres) for oceanographic applications. The estimation of an accurate Mean Dynamic Topography is mandatory for the correct interpretation of all past, present and future altimetric data and their use for oceanographic analyses. It has also proved to bring significant improvement for their assimilation into operational forecasting systems (Le Provost et al, 1999, Le Traon et al, 2002, results from the EU GOCINA project).

3.3. How to compute the ocean mean dynamic topography

The objective of this section is to give a brief outline of the main issues a user has to keep in mind when using GOCE data for oceanographic purposes. Further details on these issues can be found in (Hughes et al, 2006).

The ocean mean dynamic topography (MDT) for a chosen period is the difference between an altimetric mean sea surface (MSSH, computed for the chosen period) and a geoid model N:

$$MDT=MSS-N \qquad \text{Eq.1}$$

This apparently very simple equation is actually quite intricate because:

- Altimetric mean sea surfaces and geoid models don't have the same spectral content. Typically, mean sea surfaces are known with a centimetric accuracy at spatial scales down to a few kilometres. On the other hand, the same accuracy on the geoid will be achieved using GOCE data at scales down to around 100 km (GO-ID-HPF-GS-0041). At the present time, this centimetric accuracy is achieved using GRACE data only at scales above around 400 km (Tapley et al, 2003). If a simple difference of the two fields is calculated, the resultant dynamic topography will contain high spatial resolution geoid information, from the altimetric MSSH, that is not included in the geodetic data, giving spurious circulation features. Hence, before subtracting a geoid from a MSSH, the two fields have to be filtered in order to achieve from both of them a similar spectral content. The filtering can be done either in geographical space or in spectral (spherical harmonic) space. In the latter case, the MSSH, which, by construction, is defined only over the oceans, needs to be completed over the continents in order to obtain a global field.

Both altimetric mean sea surface heights and geoid heights are given relative to a reference ellipsoid, which corresponds to a theoretical shape of the Earth. The characteristics of different, currently used, reference ellipsoids are given

- Table 1. Before subtracting a geoid from a MSSH, both fields have to be expressed relative to the same reference ellipsoid. If not, the impact on the resulting MDT is large: Figure 1 shows the height differences between the GRIM and Topex ellipsoids on a global grid.

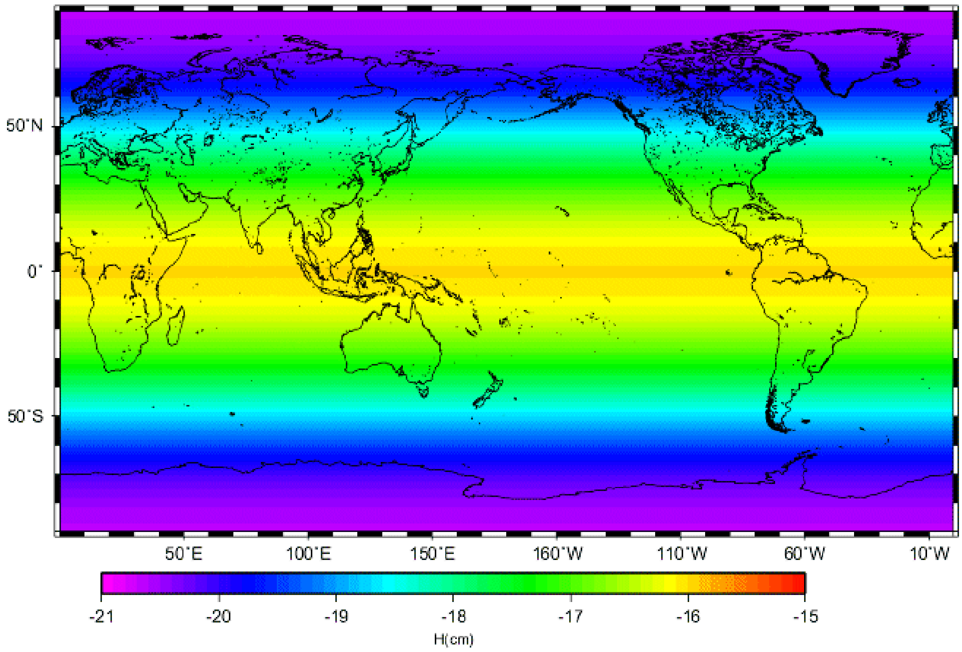

Figure 1: Height difference between the TOPEX and the GRIM ellipsoids.

Ellipsoid name	a (km)	1/f
“GRIM”	6378.13646	298.25765
“TOPEX”	6378.1363	298.257
“GRS80”	6378.137	298.257222101
“WGS84”	6378.137	298.257223563

Table 1: The different reference ellipsoids and their characteristics

- Geoid heights (and mean sea surface heights) also differ depending on what tidal system is implemented to deal with the permanent tide effects. In the MEAN TIDE system, the effects of the permanent tides are included in the definition of the geoid. In the ZERO TIDE system, the effects of the permanent tides are removed from the gravity field definition. In the TIDE FREE or NON-TIDAL system, not only the effects of the permanent tides are removed but the response of the Earth to that absence is also taken into account. Altimetric mean sea surfaces are usually expressed in the MEAN TIDE system. The GRACE GGM02 geoids from the CSR are defined relative to the ZERO TIDE system. The GRACE EIGEN geoids from the GFZ are defined relative to the TIDE FREE system. When computing an ocean mean dynamic topography, the MSSH and the geoid first have to be computed in the same system. If not, the impact on the resulting MDT is large: for instance, Figure 2 shows the difference between the TIDE FREE and the MEAN TIDE reference systems.

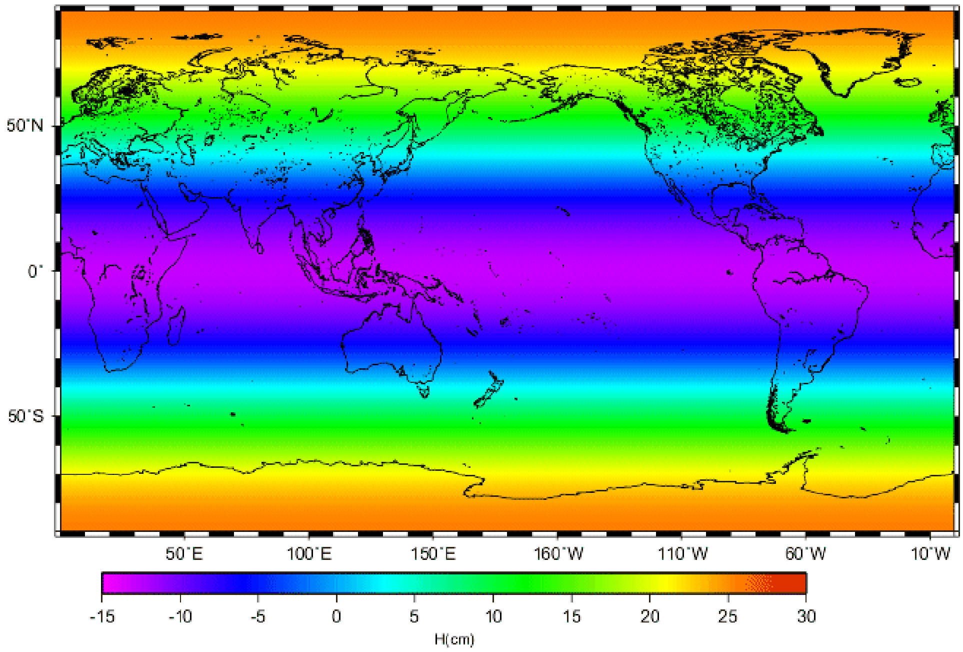

Figure 2: Height difference between the TIDE FREE and the MEAN TIDE reference systems

Once these three points have been taken into account and both the MSSH and the geoid have been adequately processed, the mean dynamic topography can be computed. This MDT product will hereafter been referred to as a "Satellite-only" MDT or MDTS.

By construction, the spectral content of the MDTS is limited by the spectral content of the geoid model. In the case of GOCE, the corresponding MDTS will thus have a centimetric accuracy at a 100 km resolution. In some areas of the world ocean, notably coastal areas, straits, semi-enclosed seas such as the Mediterranean Sea and close to steep bottom topography, the MDT is expected to contain signals at shorter spatial scales.

The GOCE User Toolbox hence provides the user with more sophisticated MDT computation techniques allowing to integrate short-scale information from other MDT sources. These techniques will be further referenced to as Remove-Restore techniques.

Two variants of a remove-restore "combined" technique are included in GUT. The first (method A) utilizes a high-resolution a-priori MDT, eg from hydrodynamic modelling or observations, to restore the small-scale structure in the 'satellite' MDTS. The filtered satellite solution here will be the output of the previous MDTS calculation and the filtering can be spatial or spectral – but the filtering of the a-priori MDT must be carried out in the same way.

The second variant (method B) takes the a-priori MDT as the basis and restores the large-scale structure by comparing the spectral equivalents of an a-priori geoid (based on the filtered difference of MSSH and a-priori MDT) and the GOCE geoid. This requires that we use the *unfiltered* version of MDTS (η_G, *i.e.* direct difference of MSSH – Geoid).

These two variants can be used for different purposes. Method A puts higher priority on the MDTS fields and assumes the high resolution features of the a-priori MDT are consistent with MDTS. The second method puts higher priority on the a-priori MDT and would be appropriate (*e.g.*) when using an ocean model for the a-priori to provide an improved model surface suitable for data assimilation fields, that was consistent with the ocean model dynamics and the GOCE geoid.

For both remove-restore variants, as well as for the MDTS calculation, the filtering required can be carried out spatially or spectrally. For better consistency, it is recommended that user remains within the same filtering space.

3.4. Using the toolbox

As recommended in the previous work packages, the GOCE User Toolbox should be designed so that it can be used at different levels, depending on the expertise and the needs of the user. The first level is the use of "workflows" allowing the computation of geoid/gravity field/MDT in one single step, with few inputs required. The toolbox is made of 6 workflows which are described in section 3.5

Example1:

User need:

Get a grid of GOCE geoid heights developed at degree/order 120 of

Workflow 1a of the GOCE User Toolbox

Example 2:

User need:

Compute a MDT on a ¼° regular grid, at 100 km resolution (SH200) filtering the GUT default geoid and MSSH data in the spectral

Workflow 3b of the GOCE User Toolbox

Each workflow is a succession of processes that can also be called independently by the user.

Example 3:

User need:

Interpolate a grid of GOCE geoid

Use the Grid Interpolation routine

This is the "single step" approach for which the different available functions are described in section 3.6.

Furthermore, many single functions may be called successively, providing an even more complex and flexible processing tool. For instance, when the grid of GOCE geoid heights at 100 km resolution will be available, a GUT user may want to compare it to the latest GRACE geoid model available. He/She will be able to do it through the succession of four GUT functions.

Example 4:

User need:

Compare the default grid of GOCE geoid heights with a user provided grid of GRACE

Four steps:

1- Compute the GOCE geoid relative to the same reference ellipsoid as the user provided geoid

2- Compute the GOCE geoid relative to the same tide system as the user provided geoid

3- Compute the GOCE geoid on the same grid as the user provided geoid

4- Compute the difference between the two geoids

This is the "step by step" approach, described in section 3.7

In the following sections (3.5 to 3.7), concrete examples or "use cases" will be given for each of the three approaches. In order to make an explicit link to WP3000, where the workflows and the GUT functionalities have been defined as well as the different input/output, we associate to each use case a "command line" like phrase containing the algorithm/workflow nomenclature followed by a list of options (in red), a list of input files (in yellow) and a list of output files (in green). For the algorithms, the nomenclature defined in WP3000 (GUT_FAXX) is used. Consistently, a GUT_WFXX nomenclature is used for the workflows.

The detailed description of all input and output formats can be found in the WP2000 report (User Toolbox Requirements Document), section "Required functionality, input and output parameters" as well as in the WP3000 report (Toolbox functionality and algorithm specification document), section " Input Output Definition".

The detailed description of all options relative to the different functionalities can be found in the WP3000 report (Toolbox functionality and algorithm specification document), section " Algorithm Specification".

3.5. The workflow approach

The main workflow associated with the GOCE User Toolbox is shown Figure 3.

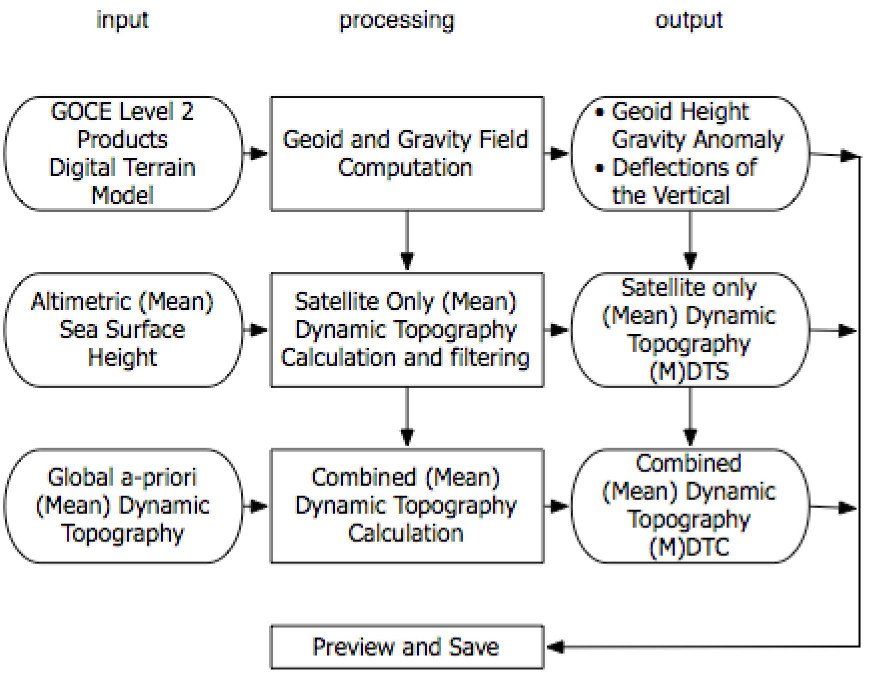

Figure 3: GUT main workflow

Through the use of this workflow, the user has access to the three main outputs of the toolbox, namely geodetic fields (geoid height, gravity anomaly, deflections of the vertical), a satellite-only mean dynamic topography and a combined mean dynamic topography. All products are computed using the default procedures and parameters recommended by the GUTS expert team. For instance, the MDTS is computed in spectral space using a Jekeli filter with a default filter width (that will depend on the GOCE data and is therefore not defined yet – around 100 km). All outputs are gridded fields (1/2° resolution, regular).

When used with the default input fields (MSSH and a-priori MDT) provided with the toolbox, the default MDTS and MDTC are obtained.

This main workflow can be split into 6 sub-workflows that can be called directly by the user for increased flexibility.

3.5.1. Workflow 1

Workflow 1 concerns the computation of different geodetic fields (workflow 1a - Figure 4) and their errors (workflow 1b - Figure 6).

A number of parameters can be defined by the user depending on the desired resolution of the output field (maximum degree and order of spherical harmonic expansion), the reference system he/she would like the output field to be expressed in (reference ellipsoid, tide system), the representation type (area average, single points), the output type (on grid or at user defined points)…

Workflow 1a: The geoid and gravity field computation

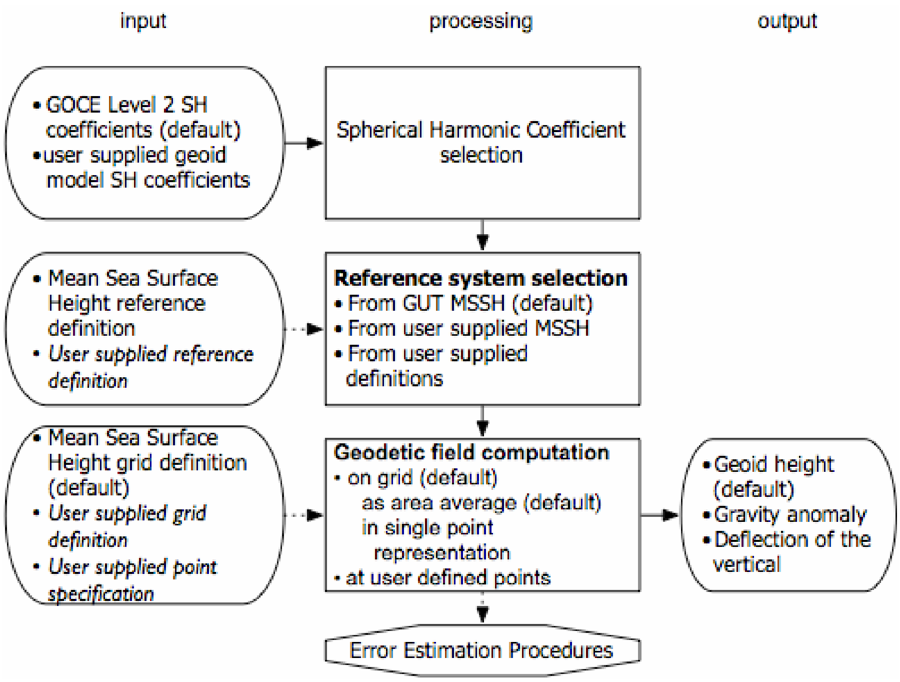

Figure 4: Workflow 1a: The geoid and gravity field computation

Workflow 1a should be used with the following parameters:

Options:
-Fg: geoid height computation (default)
-Fa: gravity anomaly computation
-Fd: geoid deflections from the vertical
-R *e/w/n/s*: Region of interest in the order western, eastern, northern and southern limits in degrees north of the equator and east of the prime meridian (default:79.75/-79.75/0.25/359.75). Only used for regular (latitude-longitude) grid.
-I *dx/dy*: grid increment for regular (latitude-longitude) grid in degrees (default:0.25/0.25)
-Gg *grid_definition_file_x/grid_definition_file_y*: An irregular grid is used. The files contain matrices with latitude/ longitude definitions of the grid. The -I and -Roptions are ignored
-Gu *specific_points_definition_file*: Specific points are defined by a list given in the file. Two columns are expected containing the longitude in the first and the latitude in the second column. The -I and -R options are ignored.
-H *digital_terrain_model*: The geodetic field is computed on the terrain as defined in *digital_terrain_model*. By default the reference ellipsoid is taken. A default terrain model is part of the GUT distribution and is used if no filename is given. -H is ignored if -Fg is selected.
-Ma: The area average for the grid cell is computed. By default the geodetic field is computed on the specified grid points. -Ma is ignored when using -Gu.

Input:
- Data set with spherical harmonic coefficients (GUT default data: EGM_GCF_2)
-**SH**: Maximum degree & order of the expansion used in the geodetic field computation
-**EllipsOut**: Reference system selection
-**TideOut**: tide system selection

Output:
For grids:
- Depending on output parameter:
-Fg: 2D matrix (grid) of geoid (m)
-Fa: 2D matrix (grid) of gravity anomaly (mgals)
-Fd: 2D matrix (grid) of the E-W deflections from the vertical and 2D matrix (grid) of the N-S deflections from the vertical (arcsecs).
- Locations of grid nodes as 2 vector arrays of latitudes and longitudes (latitudelongitude
grid) or as two matrices (irregular grid) in degrees.
- Flag reflecting whether point-wise or area averaged values (-Ma option) have been calculated
For User Specified Points (-Gu):
- Depending on output parameter:
-Fg: Vector of geoid at each data point (m)
-Fa: Vector of gravity anomaly at each data point (mgals)
-Fd: Vector of the E-W deflections from the vertical and vector of the N-S deflections from the vertical at each data point (arcsecs).
- Locations of data points as 2 vector arrays of latitudes and longitudes (degrees).
For All Cases:
- Maximum degree and order and approximate associated spatial scale (in spatial dimensions, ie km or degrees lat) of the calculation.
- Reference ellipsoid definition of the calculated field
-For gravity anomaly or deflections from the vertical the actual height above the reference ellipsoid for the calculation.

Example 1a:

An example of how to use workflow 1a is given below. The spherical harmonics coefficients of the EIGEN-GL04S1 GRACE model computed by the GFZ (http://www.gfz-potsdam.de/pb1/op/grace/results/) are used to compute a ½° resolution grid of geoid heights above the TOPEX reference ellipsoid and in the mean tide system at a 500 km resolution (SH expansion= degree and order 40).

```
GUT_WF1a
        –Fg –R 89.75/-89.75/0.25/359.75 –I 0.5/0.5
        –EllipsOut=TP –TideOut=MEAN –SH=40
        EIGENGL4S_SH150_coef.fic
        EIGENGL4S_SH40_Etp_MT_grid.fic
```

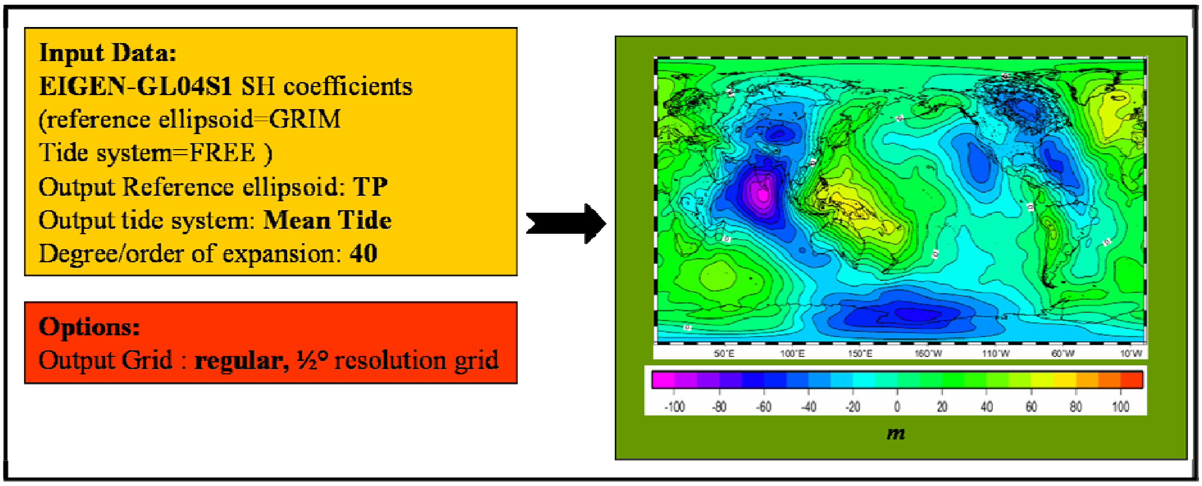

Figure 5: Example 1a

Workflow 1b: Error computation for geoid and gravity field

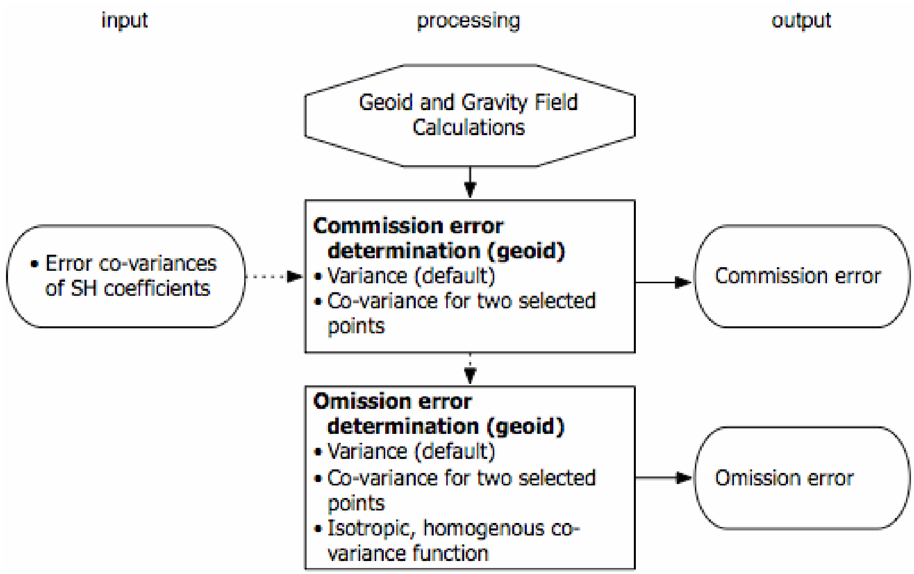

Figure 6: Workflow 1b

Following the recommendations from the previous work packages, this workflow is limited in the first GUT version to functionalities not requiring the storage and handling of the SH coefficients variance/covariance matrix. This means that concerning the commission error, only the gridded commission error variance as provided by HPF as Level-2 product and further interpolated to the required grid or data points, will be available for display. As for the omission error, it is estimated using a model of the expected power spectrum for all spherical harmonics higher than the maximum degree and order included in the spherical harmonic synthesis.

However, the full description of the workflow is detailed below.

Workflow 1b should be used with the following parameters:

Options:
-Om : Omission error computation
-Com : Commission error computation
-Fg: geoid height error computation (default)
-Fa: gravity anomaly error computation
-Fd: geoid deflections from the vertical error computation
-R e/w/n/s: Region of interest in the order western, eastern, northern and southern limits in degrees north of the equator and east of the prime meridian (default:79.75/-79.75/0.25/359.75). Only used for regular (latitude-longitude) grid.
-I dx/dy: grid increment for regular (latitude-longitude) grid in degrees (default: 0.25/0.25).
-Gg grid_definition_file_x/grid_definition_file_y: An irregular grid is used. The files contain matrices with latitude/ longitude definitions of the grid. The -I and -R options are ignored.
-Gu specific_points_definition_file: Specific points are defined by a list given in the file. Two columns are expected containing the longitude in the first and the latitude in the second column. The -I and -R options are ignored.
-H digital_terrain_model: The error field is computed on the terrain as defined in digital_terrain_model. By default the reference ellipsoid is taken. A default terrain model is part of the GUT distribution and is used if no filename is given. -H is ignored if -Fg is selected.
-Ma: The area average for the grid cell is computed. By default the geodetic field is computed on the specified grid points. -Ma is ignored when using -Gu.
-C lon1/lat1/lon2/lat2: The error co-variance is computed for the two points defined by lon1/lat1 and lon2/lat2 (longitude/ latitude in degrees). By default only the variances are computed (see options -R, -I, -Gg, -Gu).
-F d1/d2/dx: Applicable only if the -Om option has been put.
The omission error is provided as an isotropic, homogenous function of distance. The function is evaluated in the intervall [d1,d2] using dx as increment. By default only the variances are computed (see options -R, -I, -Gg, - Gu).

Input:
- Data set with error-covariance for spherical harmonic coefficients used in geodetic field computation (GUT default data: EGM_GVC_2)
-**SH**: Maximum degree & order of the expansion used in the geodetic field computation
-**EllipsOut**: Reference system selection
-**TideOut**: tide system selection

Outputs
For grids:
- Depending on geodetic parameter:
  -Fg: 2D matrix (grid) of geoid error variance (m2)
  -Fa: 2D matrix (grid) of gravity anomaly error variance (mgal2)
  -Fd: 2D matrix (grid) of the error variance in the E-W deflections from the vertical and 2D matric (grid) of the error variance in the N-S deflections from the vertical (arcsec2).
- Locations of grid nodes as 2 vector arrays of latitudes and longitudes (latitude-longitude grid) or as two matrices (irregular grid) in degrees.
- Flag reflecting whether point-wise or area averaged values (-Ma option) have been calculated

For User Specified Points (-Gu):
- Depending on output parameter:
  -Fg: Vector of geoid error variance at each data point (m2)
  -Fa: Vector of gravity anomaly error variance at each data point (mgal2)
  -Fd: Vector of the error variance in the E-W deflections from the vertical and vector of the error variance in the N-S deflections from the vertical at each data point (arcsec2).
- Locations of data points as 2 vector arrays of latitudes and longitudes (degrees).

If co-variances are computed (-C):
- 2x2-matrix containing variances and co-variance of the two specified points
- Locations of the two data points.

If an isotropic homogenous co-variance function is provided for the omission error computation (-Om -F):
- Vector of error co-variances
- Vector of distances corresponding to the error co-variances.

For All Cases:
- Maximum degree and order and approximate associated spatial scale (in spatial dimensions, ie km or degrees lat) of the calculation.
- Reference ellipsoid definition of the calculated field
- For gravity anomaly or deflections from the vertical - the actual height above the reference ellipsoid for the calculation.

Example 1b:

In this example, the cumulative error variance of the EIGEN-GL04S1 geoid is computed for degree 50 of spherical harmonic expansion. The obtained error field ranges between zero (in blue on the colour scale) to three millimetres (in pink on the colour scale).

GUT_WF1b

–Fg –R 89.75/-89.75/0.25/359.75 –I 0.5/0.5
–EllipsOut=TP –TideOut=MEAN –SH=40
EIGENGL4S_SH150_cov_mat.fic
EIGENGL4S_SH50_Etp_MT_com_error_grid.fic

Input Data:
EIGEN-GL04S1 error covariance matrix of SH coefficients
(reference ellipsoid=GRIM
Tide system=FREE)
Output Reference ellipsoid: **TP**
Output tide system: **Mean Tide**
Degree/order of expansion: **50**

Options:
Output Grid : **regular, ½° resolution grid**

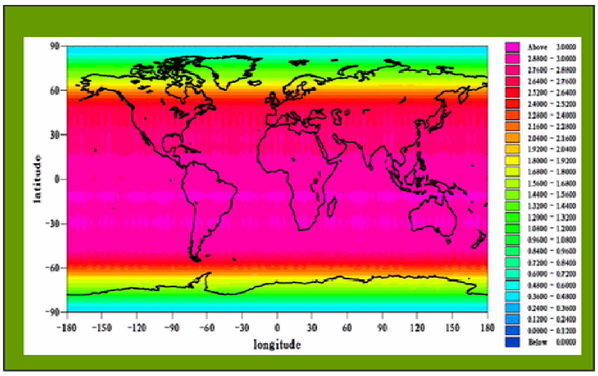

Figure 7: Example 1b

3.5.2. Workflow 2: Sea surface height and a-priori MDT selection

Workflow 2 concerns the selection of the sea surface heights and the a-priori MDT (Figure 8). It is composed of an averaging routine, (in order to compute a mean dynamic topography from a series of time varying dynamic topography fields or to compute a MSSH from a series of time varying sea surface heights) and an adaptation routine in order to interpolate the mean field onto a user specified grid or list of points. It is worth noticing that this functionality could be devolved to BRAT as long as the implemented version of GUT can input the BRAT output data

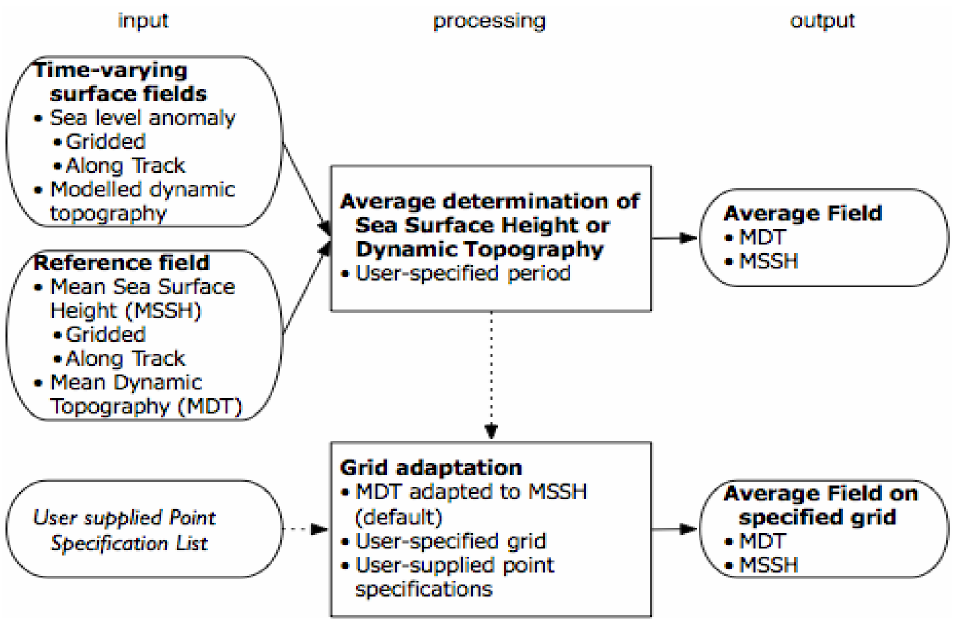

Figure 8: Workflow 2

This workflow should be used with the following parameters:

Options:
-R ***e/w/n/s***: Region of interest in the order western, eastern, northern and southern limits in degrees north of the equator and east of the prime meridian (default: 79.75/-79.75/0.25/359.75). Only used for regular (latitude-longitude) grid.
-I ***dx/dy***: grid increment for regular (latitude-longitude) grid in degrees (default: 0.25/0.25)
-Gg ***grid_definition_file_x/grid_definition_file_y***: An irregular grid is used. The files contain matrices with latitude/ longitude definitions of the grid. The -I and -R options are ignored
-Gu ***specific_points_definition_file***: Specific points are defined by a list given in the file. Two columns are expected containing the longitude in the first and the latitude in the second column. The -I and -R options are ignored.
-Tbeg: First day to consider for the averaging time period
-Tend: Last day to consider for the averaging time period

Input :
Time series of 2D matrices or vectors of parameters to be calculated

Output:
Returned mean value for the specified period at each location specified in option by the user. Default: the averaged field is given at the same locations than the input fields and the average is done on the entire input serie.

Example 2:

In the example below (Figure 9), a mean dynamic topography of the Mediterranean Sea is computed from 7 years (1993-1999) of dynamic topography outputs from the MFSTEP model.

GUT_WF2 (GUT_FA07)
ADT_MFSTEP_time_serie_1993_1999.list
MDT_MFSTEP_1993_1999.fic

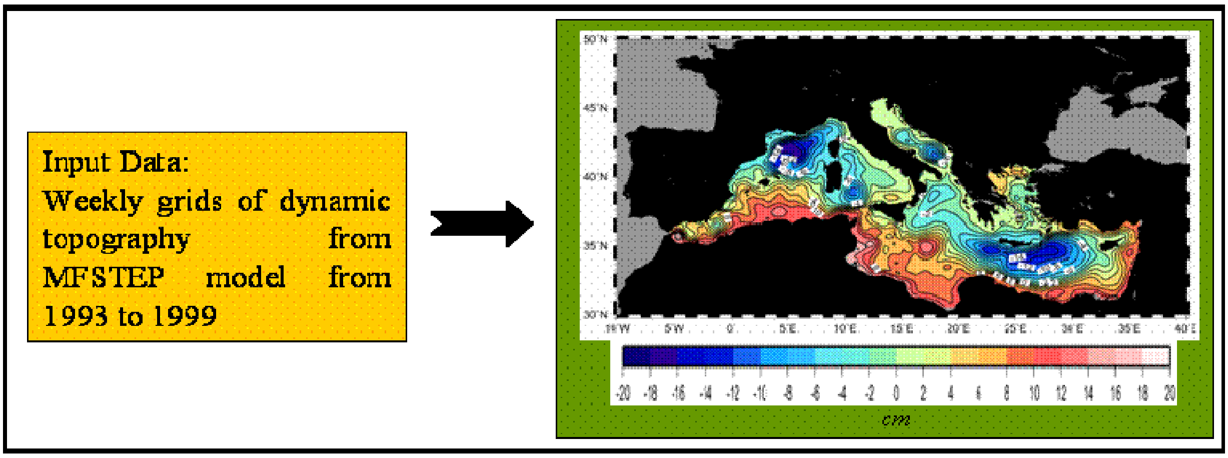

Figure 9: Example 2

3.5.3. Workflow 3: Satellite Dynamic Topography Computation

Workflow 3 is dedicated to the computation of satellite-only mean dynamic topographies either in the space domain (Workflow 3a - Figure 10) or in the spectral domain (Workflow 3b - Figure 12). A number of parameters can be defined by the user, depending on the selection of filter type and filter width. The different filter types available are described in WP3000 report. The computation can be done with user supplied geoid heights and MSSH heights or using the GUT default files. The consistency between the reference frames of the two surfaces (reference ellipsoid and tide system) is checked automatically inside the workflow and the reference frames are homogenized if necessary.

Following the conclusions of the trade-off study realized in WP3000, the use of the gaussian filter is recommended for filtering in the space domain. Also, although two workflows are available, it is highly recommended to use Workflow 3b (filtering in the spectral domain) when computing MDTS for global grids (See also Bingham et al, 2007).

Workflow 3.a: MDTS computation in the space domain

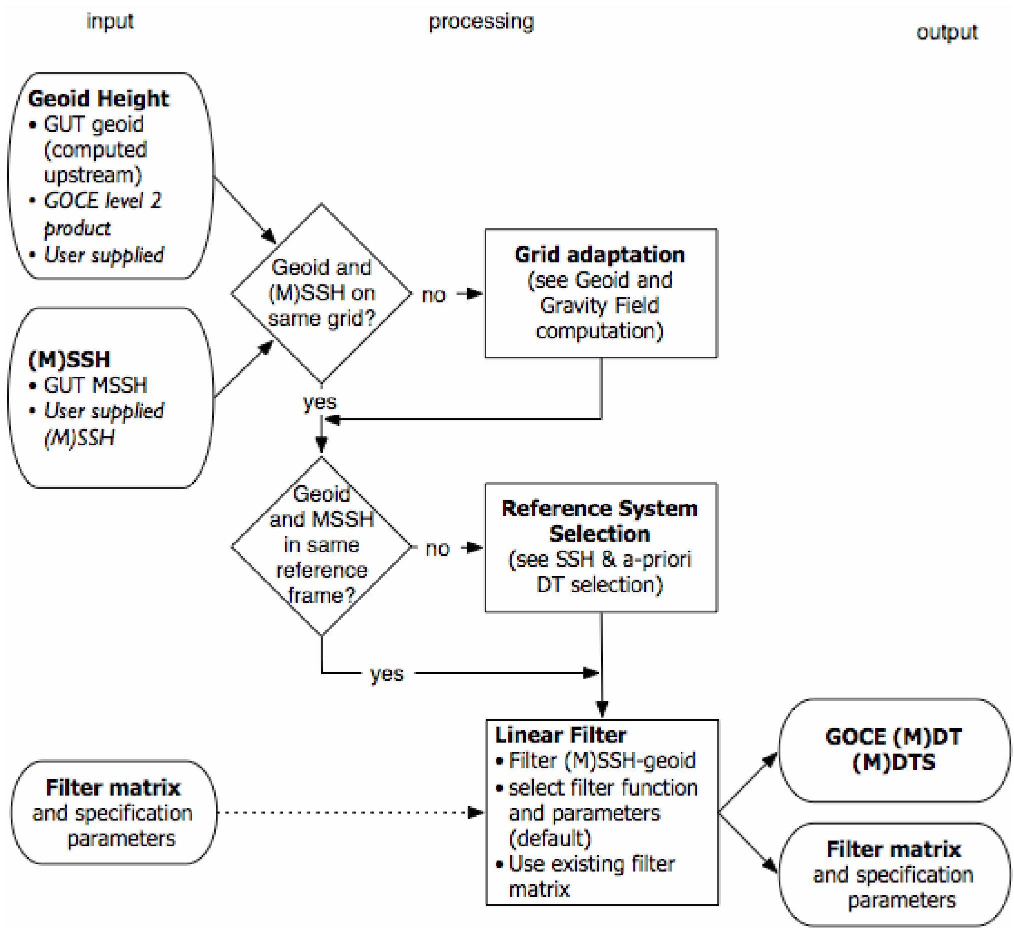

Figure 10: Workflow 3a

Workflow 3a should be used with the following parameters:

Options:
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (*default option*)
-Fg scale: Gaussian filter with full filter width scale
-Fc scale: Spherical cap with diameter scale
-Fhm scale: Hamming window of width scale
-Fhn scale: Hanning window of width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-O filter_matrix_file: The filter matrix is stored in filter_matrix_file. There is a limitation for large grids depending on available resources. The limit grid size is defined in .GUTdefaults.

Input :
- Grid of geoid height (GOCE level-2 product or user provided)
- Grid of Mean Sea Surface Height (GUT MSSH or user provided)

Output:
- GOCE MDTS
- Filter matrix

Example 3a:

In the example below, the MSSH CLS01 and the EIGEN-GL04S1 geoid model are used as input to workflow 3a to compute the satellite-only mean dynamic topography at a 400 km resolution using a Gaussian filter in geographical space. This filter is quite satisfying in the open ocean, where a quite realistic 400 km resolution MDT is obtained. Along the continental coasts however, strong, unrealistic gradients are created (Indonesian through flow, Western coasts of South America…).

A file name for storing the filter matrix is specified (option –O) so that this filter may be used afterwards for other similar computations.

GUT_WF3a
–Fg400 –O my_filter_matrix.fic
MSSCLS01_grid.fic EIGENGL04S_SH150_grid.fic
MSSCLS01_EIGENGL4S_fg400_grid.fic

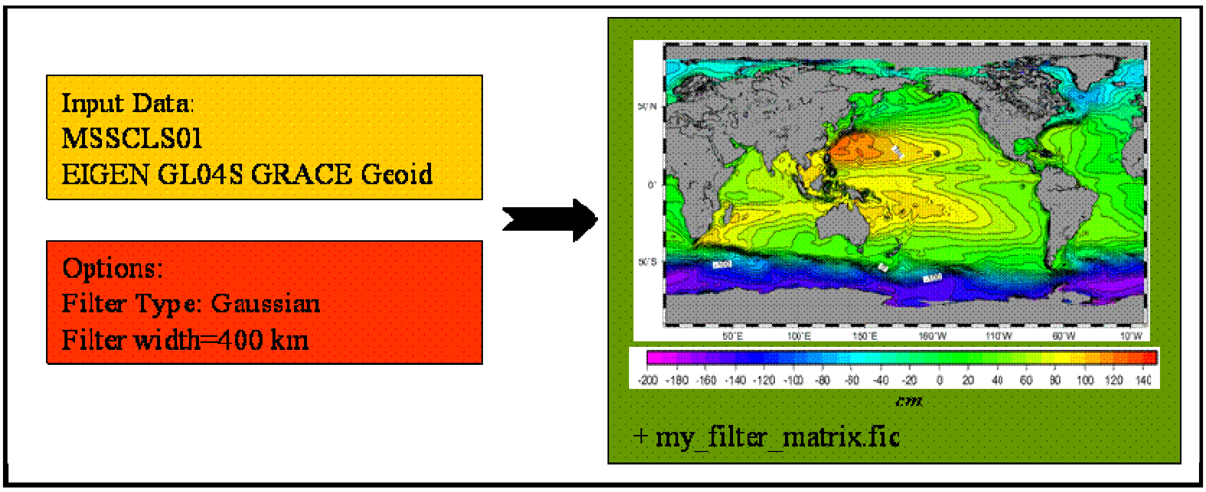

Figure 11: Example 3a

Workflow 3b: MDTS computation in the spectral domain

Using this workflow allows computation of the MDTS in spectral space. This means that the (default or GUT user supplied) MSSH is first completed over the continental gaps, using a geoid field, before being further expanded into spherical harmonics coefficients. The difference between the MSSH and the geoid is then done in the spectral domain (the coefficients are subtracted and MDT SH coefficients are obtained). Then, the user can choose to go back into geographical space for further filtering or to directly filter the MDT SH coefficients (recommended).

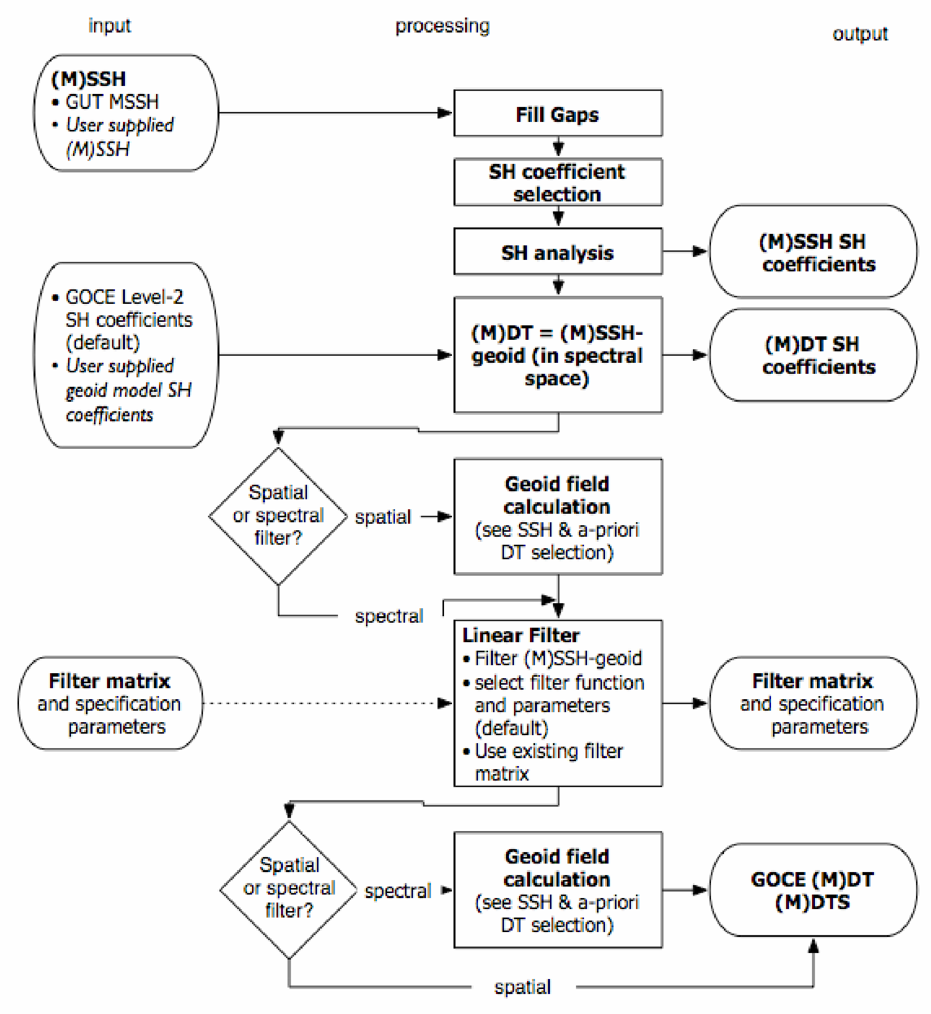

Figure 12: Workflow 3b

Workflow 3b should be used with the following parameters:

Options:
-Spatial: Filtering is done in physical space
-Spectral: Filtering is done in spectral space
If the -Spatial option is chosen:
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (*default option*)
-Fg scale: Gaussian filter with full filter width scale
-Fc scale: Spherical cap with diameter scale
-Fhm scale: Hamming window of width scale
-Fhn scale: Hanning window of width scale
If the -Spectral option is chosen:
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (*default option*)
-Fc scale: Pellinen filter with full width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-**O filter_matrix_file:** The filter matrix is stored in filter_matrix_file. There is a limitation for large grids depending on available resources. The limit grid size is defined in .GUTdefaults.

Input:
- MSSH Grid (GUT or user supplied MSSH)
- GOCE Level-2 or user supplied spherical harmonic coefficients

Output:
-MSSH SH coefficients
-MDT SH coefficients
-Filter matrix
-GOCE MDTS

Example 3b:

In the example below, the MSSH CLS01 and the GGM02S geoid from CSR (Tapley et al, 2005) are used to compute the mean dynamic topography at a 400 km resolution using a Jekeli filter in spectral space. Compared to the MDTS obtained using workflow 3a (Figure 11) the unrealistic gradients near the coasts have been significantly reduced.

GUT_WF3b

–Spectral -Fj400 –O my_filter_matrix.fic

MSSCLS01_filled_with_GGM02S.fic GGM02S_SH160_coef.fic

MSSCLS01_EIGENGL4S_fj400_grid.fic MSSCLS01_coef.fic

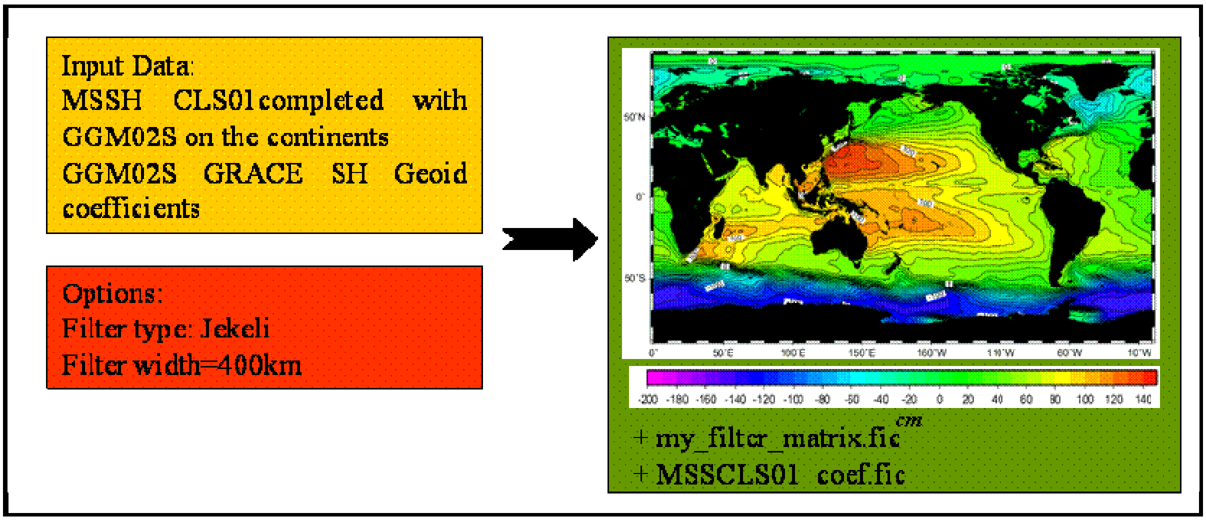

Figure 13: Example3b

3.5.4. Workflow 4 Remove-restore combined technique A

Workflow 4 is dedicated to the computation of combined mean dynamic topographies using the remove-restore technique A as described in section 3.3. The computation can be done in geographical space (Workflow 4a - Figure 14) or in spectral space (Workflow 4b - Figure 16). Computation in spectral space is recommended.

<u>Workflow 4a spatial filtering</u>

If spatial filtering is chosen, the a-priori MDT is processed in order to extract its short spatial scales, that are then added to the GUT MDTS as a corrective field. It is essential, for consistency sake, that the filter applied on the a-prior MDT for the short scales extraction is the same as the filter used for computing the MDTS (through workflow 3a or 3b). This can be simply done by providing, as input, the filter matrix produced during the MDTS computation (output from workflow 3a or 3b).

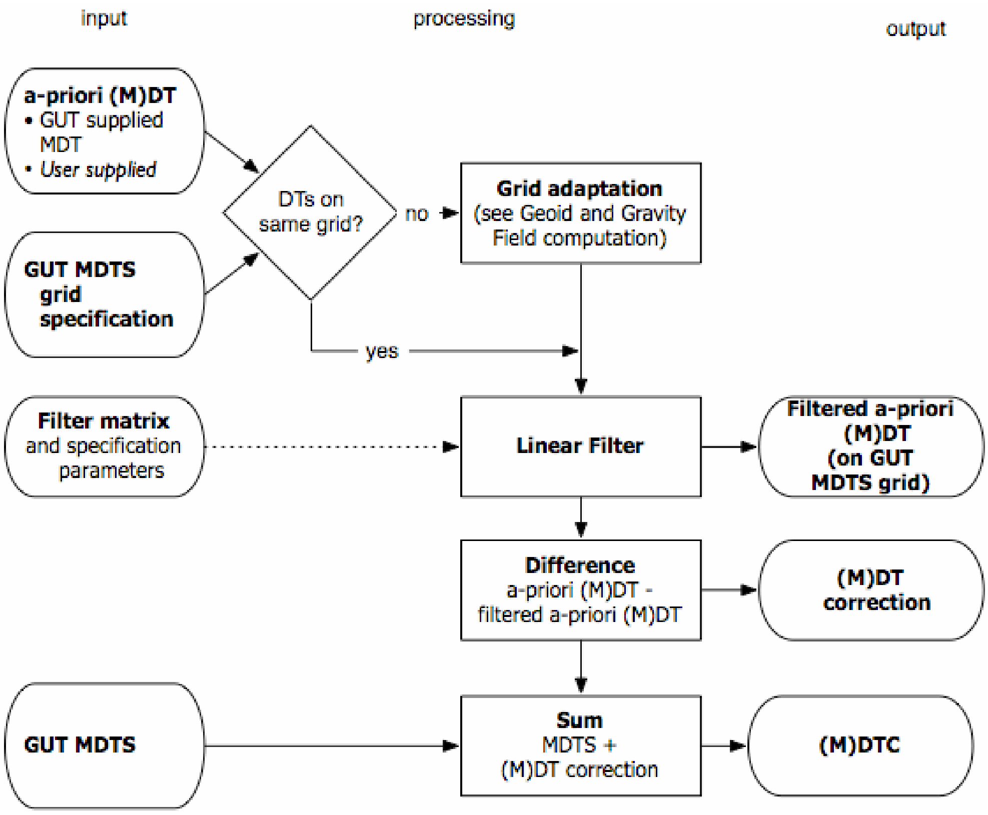

Figure 14: Workflow 4a

Workflow 4a should be used with the following parameters:

```
Options:
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (default option)
-Fg scale: Gaussian filter with full filter width scale
-Fc scale: Spherical cap with diameter scale
-Fhm scale: Hamming window of width scale
-Fhn scale: Hanning window of width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-O filter_matrix_file: The filter matrix is stored in filter_matrix_file. There is a limitation for large grids depending on available resources. The limit grid size is defined in .GUTdefaults.
```

```
Input:
- A-priori MDT (GUT or user-supplied)
- GUT MDTS
- Grid specification of GUT MDTS:
        -R e/w/n/s: Region of interest in the order western, eastern, northern and southern limits in degrees north of the equator and east of the prime meridian.
        -I dx/dy: grid increment for regular (latitude-longitude) grid in degrees
```

```
Output:
- Filtered A-priori MDT
- MDT correction
- MDTC
```

Example 4a:

In the example below, a combined MDT is computed using as a-priori MDT the (Niiler et al, 2003) field provided on a regional grid (Gulf Stream area) and the MDTS computed in workflow 3a. In the obtained field, the large scale structures come from the MDTS, while the shorter scales (signature of the mean of Gulf Stream eddies north and south of the main jet, signature of the Mann eddy) come from the (Niiler et al, 2003) a-priori field.

GUT_WF4a

Niiler_MDT.fic MSSCLS01_EIGENGL04S_fg400_grid.fic Grid.fic
MDTC_niiler_grid.fic

Input Data:
(Niiler et al, 2003) MDT
EIGEN GL04S MDTS (filtered at 400 km)
MDTS Grid characteristics (Grid.fic):
½° resolution
LonMin=-80°E, LonMax -30°E
LatMin=30°N, LatMax=50°N

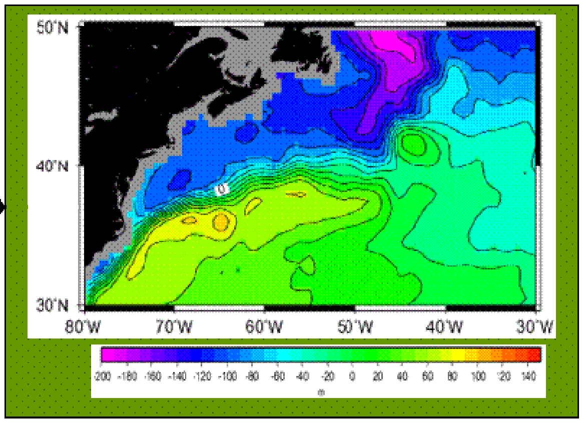

Figure 15: Example 4a

Workflow 4 b spectral filtering

If spectral filtering is chosen, the a-priori MDT is first expanded into Spherical Harmonic coefficients (after the continental gaps have been filled) and the extraction of the a-priori MDT short scales in done in the SH domain. Here again, the filter used must be consistent with the provided MDTS. The filter matrix obtained as output of Workflow 3b in the computation of the MDTS should therefore be used here as input information. After the computation is done in spectral space, the MDTC is further transformed in geographical space and the user can choose the grid specification of the output field.

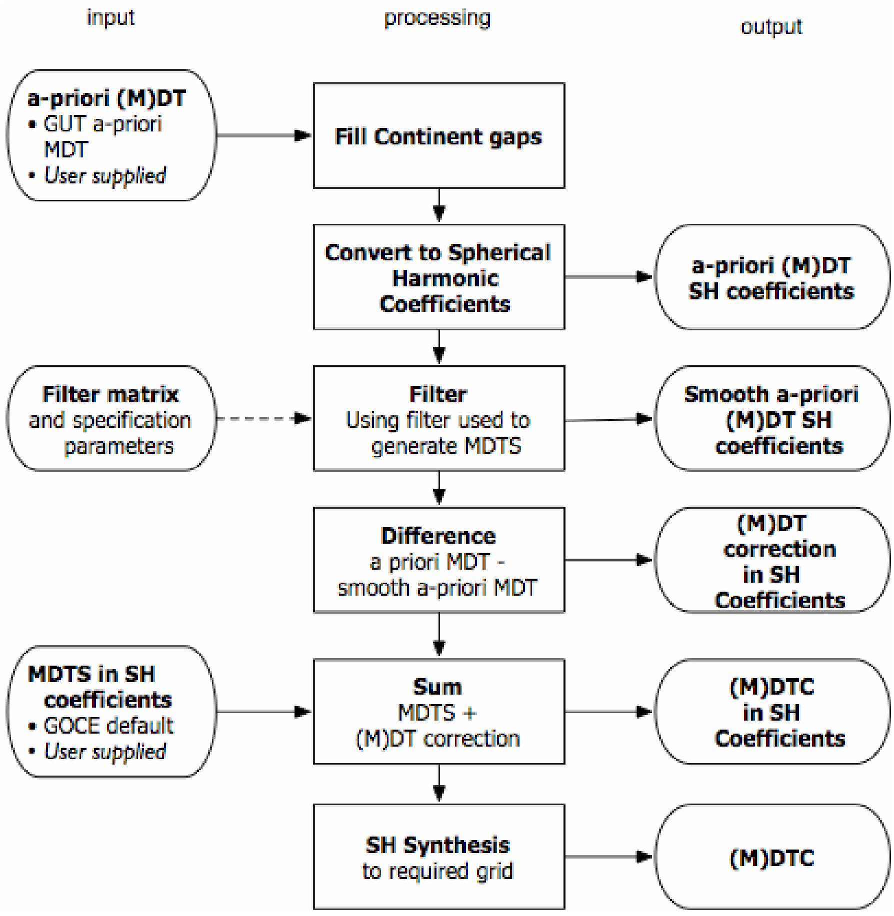

Figure 16: Workflow 4b

Workflow 4b should be used with the following parameters:

Options:
-R *e/w/n/s*: Region of interest in the order western, eastern, northern and southern limits in degrees north of the equator and east of the prime meridian (default: 79.75/-79.75/0.25/359.75). Only used for regular (latitude-longitude) grid.
-I *dx/dy*: grid increment for regular (latitude-longitude) grid in degrees (default: 0.25/0.25)
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (*default*)
-Fc scale: Pellinen filter with full filter width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-O filter_matrix_file: The filter matrix is stored in filter_matrix_file. There is a limitation for large grids depending on available resources. The limit grid size is defined in .GUTdefaults.

Input:
- SH coefficients of GOCE or user-supplied geoid
- GUT or user-supplied (M)SSH
- A-priori MDT

Output:
- A-priori MDT SH coefficients
- Smooth a-priori MDT SH coefficients
- SH coefficients of MDT correction
- SH coefficients of MDTC
- MDTC on user specified grid

3.5.5. Workflow 5 Remove-restore combined technique B

Workflow 5 is dedicated to the computation of combined mean dynamic topographies using the remove-restore technique B as described in section 3.3. The computation can be done in geographical space (Workflow 5a -Figure 17) or in spectral space (Workflow 5b -Figure 19). Here again, computation in spectral space is recommended.

Workflow 5a: spatial filtering

Compared to workflow 4a, the inputs to this workflow are independent of any previously computed MDTS and any type of filter and filter characteristics can be chosen.

Three grids are needed as input, a MSSH, a geoid and an a-priori MDT that are automatically adapted to a consistent grid (the MSSH grid is used as the default). The MDTC output grid characteristics are therefore, by default, identical to the MSSH input grid characteristics.

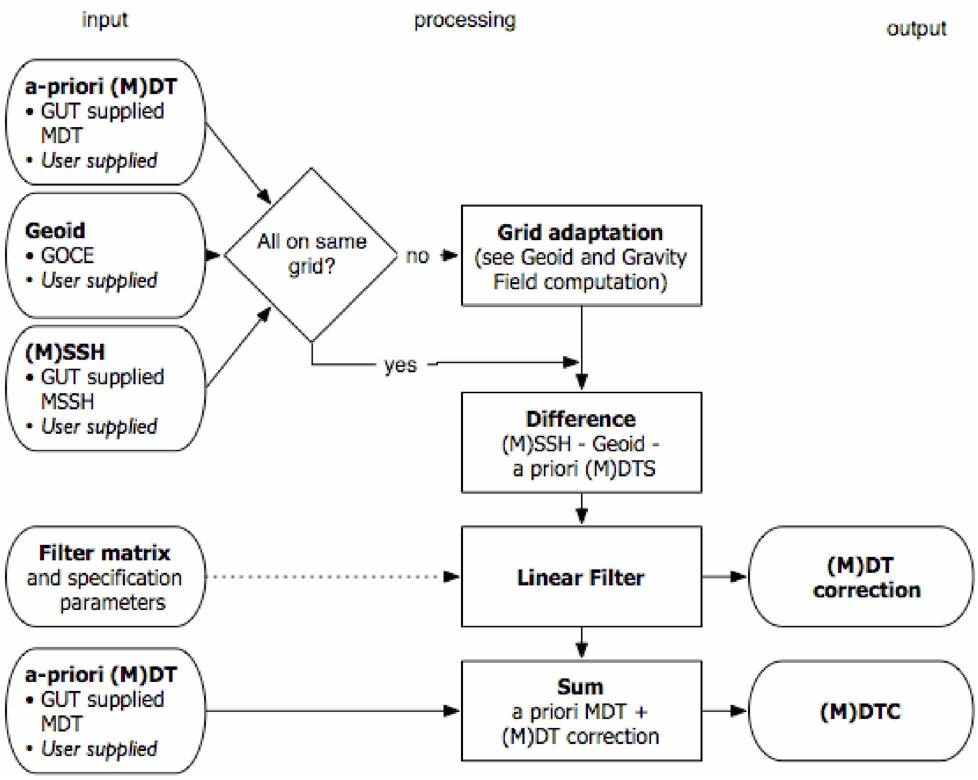

Figure 17: Workflow 5a

Workflow 5a should be used with the following parameters:

Options:
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (*default option*)
-Fg scale: Gaussian filter with full filter width scale
-Fc scale: Spherical cap with diameter scale
-Fhm scale: Hamming window of width scale
-Fhn scale: Hanning window of width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-O filter_matrix_file: The filter matrix is stored in filter_matrix_file. There is a limitation for large grids depending on available resources. The limit grid size is defined in .GUTdefaults.

Input:
- GOCE or user-supplied geoid
- GUT or user-supplied (M)SSH
- A-priori MDT

Output:
- MDT correction
- MDTC

Example 5a:

In the example below, the RIO05 MDT (Rio et al, 2005), provided on a regular grid of the North Atlantic, is used as a first guess for the computation of a remove-restore MDTC using Workflow 5a. The EIGEN-GL04S1 geoid model is provided as input as well as the CLS01 MSS. The filter chosen for the processing is Gaussian type with a 400 km width. A correction is computed (right plot on Figure 18) that, added to the a-priori MDT, provides the output MDTC (left plot on Figure 18).

```
GUT_WF5a
            –Fg400
            RIO05_MDT.fic MSSCLS01_grid.fic EIGENGL04S_grid.fic
            MDTC_rio_natl_grid.fic MDTC_rio_natl_correction_grid.fic
```

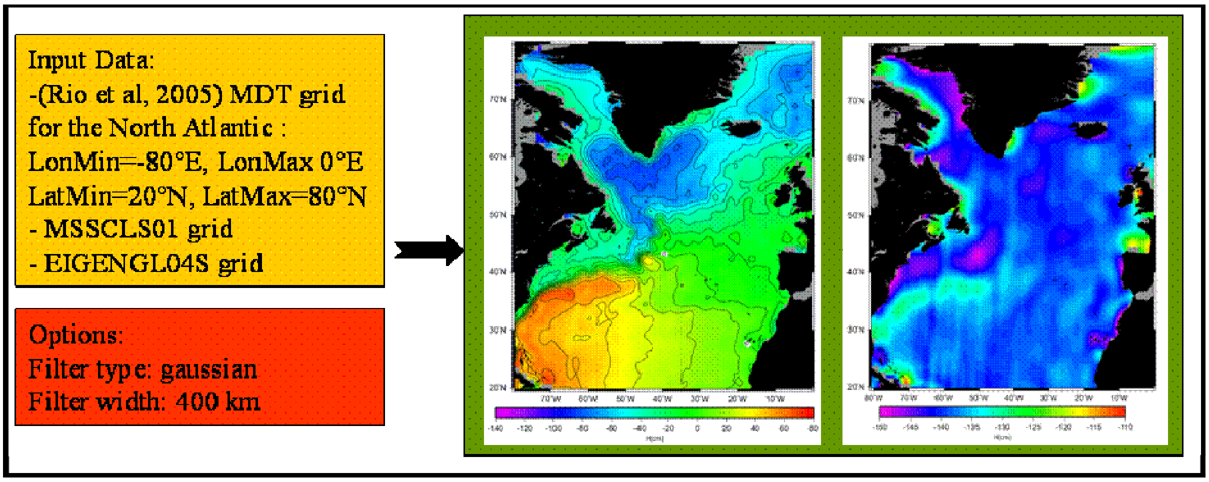

Figure 18: Example 5a

Workflow 5b spectral filtering

In Workflow 5b, the same approach as that of workflow 5a is applied but in spectral space. The user can provide grid specifications for the output grid since the MDTC is first produced in SH coefficients and then developed back to geographical space on the user-required grid.

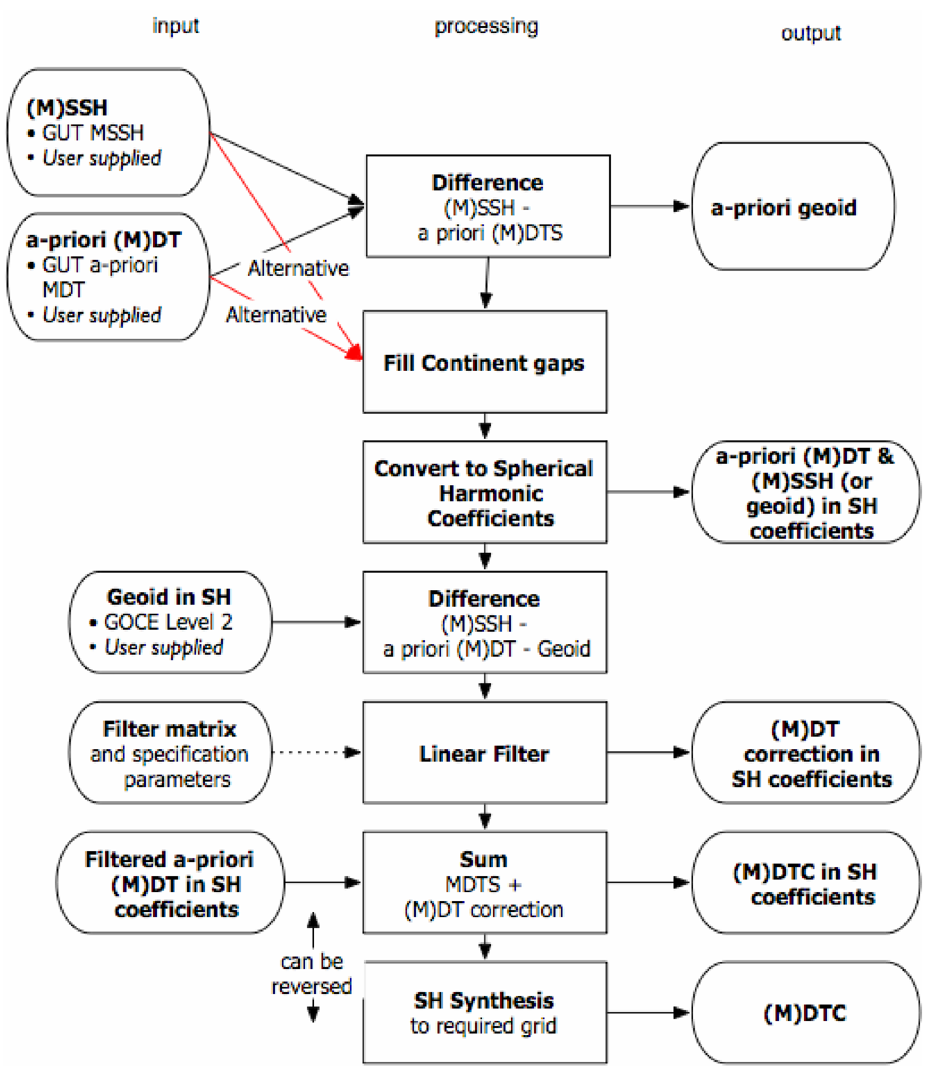

Figure 19: Workflow 5b

This workflow may be used with the following parameters:

Options:
-R *e/w/n/s*: Region of interest in the order western, eastern, northern and southern limits in degrees north of the equator and east of the prime meridian (default: 79.75/-79.75/0.25/359.75). Only used for regular (latitude-longitude) grid.
-I *dx/dy*: grid increment for regular (latitude-longitude) grid in degrees (default: 0.25/0.25)
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (*default*)
-Fc scale: Pellinen filter with full filter width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-O filter_matrix_file: The filter matrix is stored in filter_matrix_file. There is a limitation for large grids depending on available resources. The limit grid size is defined in .GUTdefaults.

Input:
- SH coefficients of GOCE or user-supplied geoid
- GUT or user-supplied (M)SSH
- A-priori MDT

Output:
- A-priori geoid
- SH coefficients of a-priori MDT
- SH coefficients of MSSH
- SH coefficients of MDT correction
- SH coefficients of MDTC
- MDTC grid

3.5.6. Workflow 6: dynamic topography derived quantities

Workflow 6 (Figure 20) is dedicated to the computation of surface geostrophic currents, from a list of dynamic topographies (mean or time-dependent) distributed on a grid or along transects.

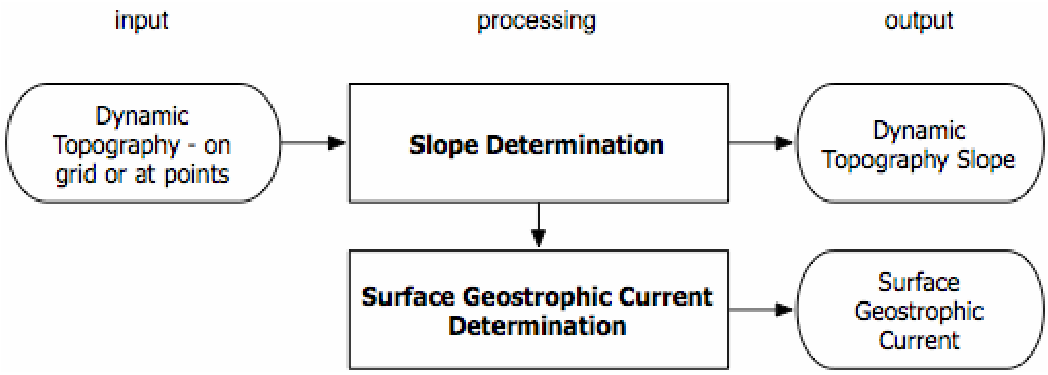

Figure 20: Workflow 6

This workflow may be used with the following parameters:

Options:
-T: Dynamic Topography is provided on a transect (default: topography on 2D grid)
-G: Currents are required on the same grid as the input topography. This involves interpolation on larger scales than the default four point calculation (see algorithm description below)

Input:
For 2D Dynamic Topography:
- 2D matrix of gridded Dynamic Topography (m)
- Locations of grid nodes as 2 vector arrays of latitudes and longitudes (latitude-longitude grid) or as two matrices (irregular grid) in degrees.

For transects:
- Vector containing (mean) dynamic topography (m) at points values
- 2 vectors containing the latitude and longitude coordinates of the points

Output:
For 2D Dynamic Topography:
- 2 2D matrices of East and North velocities respectively
- Locations of grid nodes at which the velocity was calculated, given as 2 vector arrays of latitudes and longitudes (latitude-longitude grid) or as two matrices (irregular grid) in degrees.

For transects:
- 2 vectors containing East and North components respectively of velocity across the transect
- 2 vectors containing the latitude and longitude coordinates of the points at which the velocity was calculated.

By default, for gridded data, the velocity values will be calculated for a grid offset by $\delta\varphi/2$ in latitude and $\delta\lambda/2$ in longitude for the dynamic topography grid (*i.e.* for a grid offset by ½ grid cell dimension from the input grid. For global grid, the longitude will be wrapped.

By default, for transect data, the velocities will be calculated at the midpoints between each location

Example 6:

In the example below (Figure 21), the absolute geostrophic circulation is computed in the Gulf Stream area on June 7^{th}, 2006 from a grid of absolute dynamic topographies (ADT). The ADT map was computed by adding the SLA map to the MDTC computed using workflow 4a.

```
GUT_WF6 (GUT_FA13)
        -G
        ADT_June_7th_2006.fic
        AbsGeosVel_June_7th_2006.fic
```

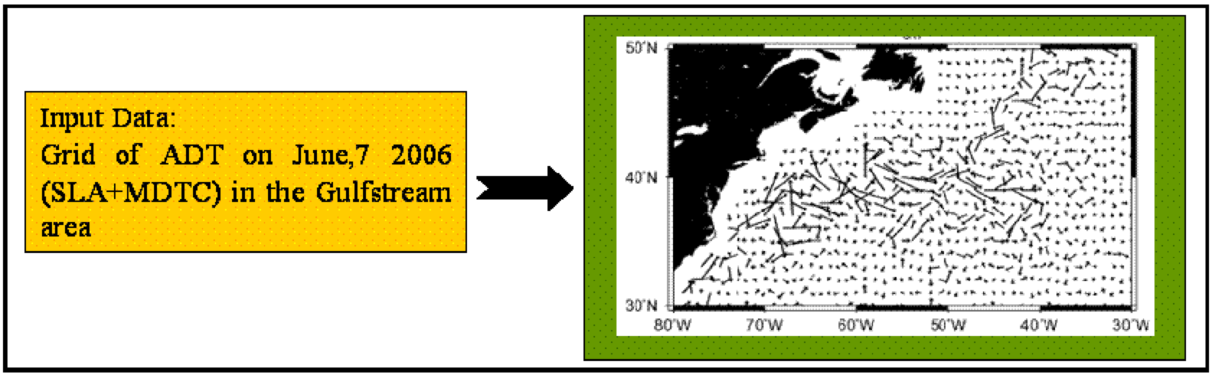

Figure 21: Example 6

3.6. The "single step" approach

The different workflows described in the previous section are composed of a number of functionalities that have been defined and described in the GUTS WP2000 and WP3000. Each of these functions can be called independently by the user for specific applications.

3.6.1. GUT_FA08: Grid adaptation

The GUT_FA08 function provides the user with the possibility of interpolating a given grid to another user specified grid or to a list of points.

This function should be used with the following input/output specifications:

```
Input:
- Required new regular grid specification for output fields (default is GUT MSS grid)
- Regular grid specification of existing input field
- Input data field
```

```
Output:
- Input data field interpolated to grid locations of the required new grid
- Latitude and Longitude values of new grid nodes
```

Example

In the example below (Figure 22), the MDTS computed through workflow 3a (Figure 11) is interpolated along a transect through the Drake Passage. This transect could, for example, correspond to an altimeter satellite track along which temperature and salinity CTD profiles have been measured during a dedicated sea campaign. The altimetric SLA, added to the interpolated MDTS, gives the absolute values of the ocean dynamic topography along the altimeter track, which can be compared to the steric dynamic heights deduced from the in-situ T/S measurements. The difference between the two data types gives an estimate of the barotropic component of the flow in this area (since it is contained in the altimetric data but not in the in-situ dynamic heights data).

```
GUT_FA08
        MSSCLS01_EIGENGL4S_fg400.fic Grid.fic Points.fic
        MSSCLS01_EIGENGL4S_fg400_points.fic
```

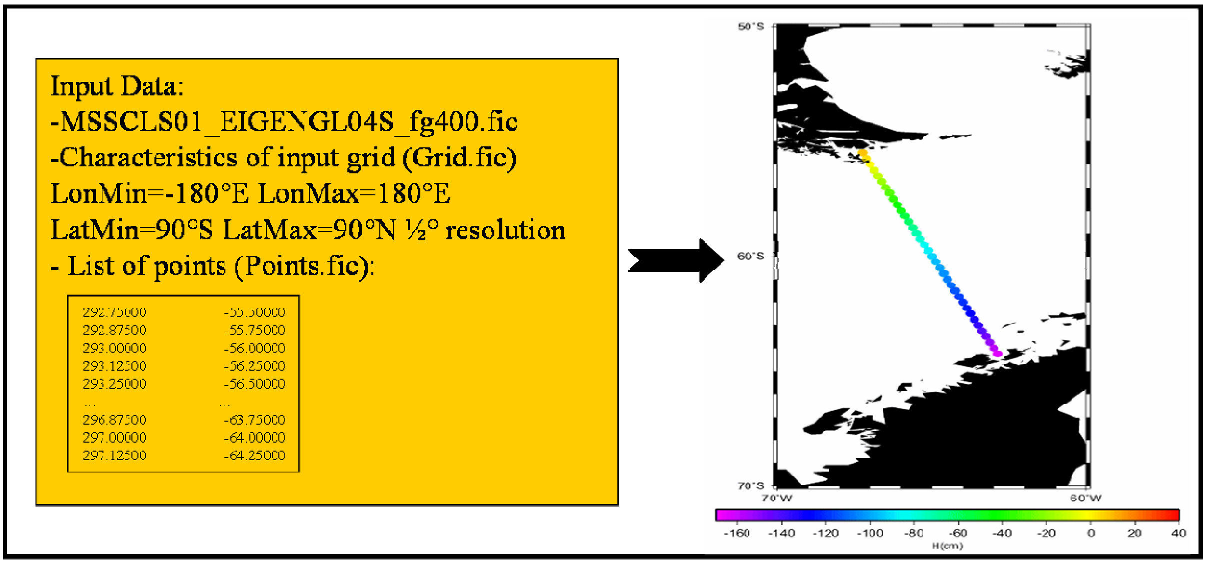

Figure 22: Grid adaptation

3.6.2. GUT_FA09: Filtering in geographical space

The GUT_FA09 function allows the user to filter a gridded data field in geographical space. The user can choose between different types of filters (Quasi-gaussian, Gaussian, Spherical cap, Hamming window, Hanning window) or can provide a filter matrix that was created, for instance, during a previous use of this function.

This function should be called using the following parameters:

```
Options:
-Fj scale: Quasi gaussian (Jekeli) filter with full filter width scale (default option)
-Fg scale: Gaussian filter with full filter width scale
-Fc scale: Spherical cap with diameter scale
-Fhm scale: Hamming window of width scale
-Fhn scale: Hanning window of width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-O filter_matrix_file: The filter matrix is stored in filter_matrix_file. There is a
limitation for large grids depending on available resources. The limit grid size is
defined in .GUTdefaults.
```

```
Input:
- Grid specification (default is the default GUT MSS grid specification)
- Input field
```

```
Output:
- Filtered version of input field
```

Example:

In the example below (Figure 23), the difference field (obtained using the later described GUT_FA14 function) between the MSSH CLS01 and the EIGENGL04C geoid model (http://www.gfz-potsdam.de/pb1/op/grace/index_GRACE.html) is filtered using a Gaussian filter of 200 km width. The obtained MDTS contains numerous erroneous short scale, structures due to the poor accuracy of the geoid model at that resolution.

```
GUT_FA09
        –Fg200 –O my_filter_matrix.fic
        MSSCLS01_EIGENGL4C.fic Grid.fic
        MSSCLS01_EIGENGL4C_fg200.fic
```

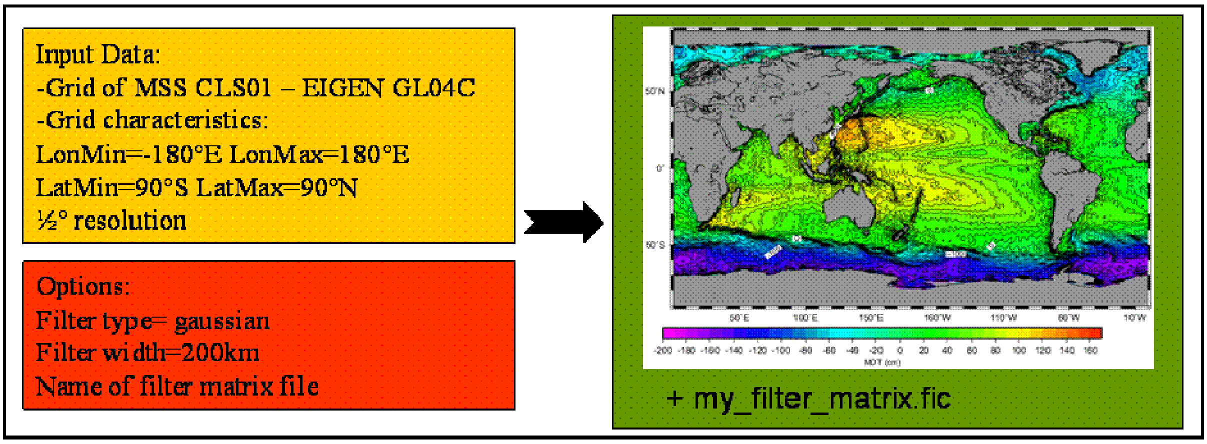

Figure 23:Filtering in geographical space

3.6.3. GUT_FA10: Linear filter (spherical harmonics)

The GUT_FA10 function allows the user to filter a field (defined by a set of spherical harmonic coefficients) in spherical harmonic space.

This function may be called using the following parameters:

Options:
-Fj scale: Quasi-gaussian (Jekeli) filter with full filter width scale (*default*)
-Fc scale: Pellinen filter with full filter width scale
-F filter_matrix_file: The filter matrix is read in from a file.
-O filter_matrix_file: The filter matrix is stored in filter_matrix_file. There is a limitation for large grids depending on available resources. The limit grid size is defined in .GUTdefaults.
-A: The parameter is given on a regular grid and a transformation to spherical harmonic coefficients is needed (default). -A- indicates that the parameter is given in spectral space and no analysis is necessary.
-S: Transformation into physical space is invoked after filtering (default). -S- indicates that the output is required in spectral space.
-D: The parameter filtered is a dynamic topography. No reference surface (as specified in .GUTdefaults) is substracted when transforming to physical space (-S option). Default: Subtraction of reference.

Input:
If parameter provided on regular grid (-A option):
- Grid specification (default is the default GUT MSS grid specification)
- Input field
If parameter is provided in spectral space (-A- option):
- Data set with spherical harmonic coefficients

Output:
- Filtered field on grid (-A option) or as spherical harmonic coefficients (-A- option).

Example:

This function can be used to filter the difference field between the MSSH CLS01 and the GGM02S geoid (expressed in spherical harmonic coefficients) using a Jekeli filter with a 400 km width.

GUT_FA10

MSSCLS01_GGM02S_SH360_coef.fic Grid.fic

MSSCLS01_GGM02S_fj400_grid.fic

In this case the output field is identical to the one displayed on Figure 13 (Output example of workflow 3b).

3.6.4. GUT_FA11: Filling gaps

The GUT_FA11 function allows the user to replace the default value of a grid by values from another grid. In oceanography, this is needed to complete an oceanic field (for example an altimetric mean sea surface or a mean dynamic topography) on the continents in order to obtain a globally defined grid. Globally defined grids are needed so that expansion into spherical harmonic coefficients can be performed.

This function can be called with the following input/output specifications:

```
Input:
- geodetic field
- global field to fill gaps in geodetic field (default GUT gridded geoid)
```

```
Output:
- patched geodetic field
```

Example:

In the example below (Figure 24), the Mean Sea Surface CLS01 is completed over the continents using the geoid heights from the GGM02S model. This field can now be used as input to the next function: GUT_FA12.

GUT_FA11

MSSCLS01.fic GGM02S.fic

MSSCLS01_filled_with_GGM02S.fic

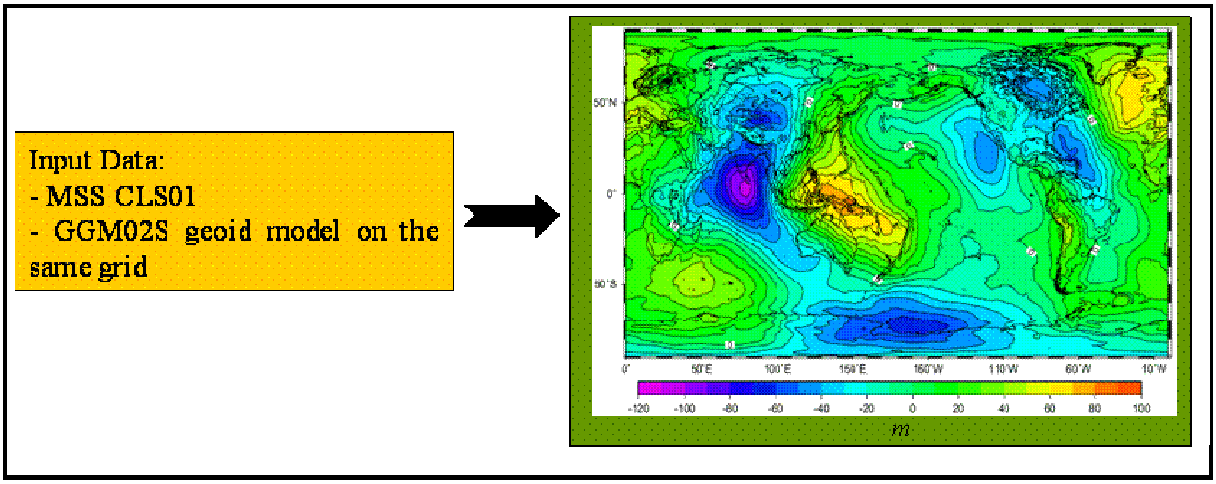

Figure 24: Filling gaps

3.6.5. GUT_FA12: SH analysis

The GUT_FA12 function allows the user to expand a gridded field, defined globally, into spherical harmonic coefficients.

This function may be used with the following input/output specifications:

```
Input:
- Global gridded field
- Regular grid specification of input field
- Maximum degree and order of spherical harmonic expansion to calculate (read from
.GUTdefaults)
```

```
Output:
- Spherical Harmonic expansion of coefficents of global field
- Maximum degree and order included in expansion
```

3.6.6. GUT_FA14: Difference/Sum in geographical space

The GUT_FA14 function allows calculation of the sum or difference of two fields defined on the same grid.

This function may be used with the following parameters:

```
Options:
-Diff: compute the difference
-Sum: compute the sum
```

```
Input:
- Input field 1
- Input field 2
```

```
Output:
- Difference or Sum of the two grids
```

Example:

Difference

The example below (Figure 25) computes the differences between two MSSH solutions computed in the North Atlantic area during the GOCINA project. The first one was computed by CLS while the second one was computed by DNSC. computed in the GOCINA area by CLS and the EIGEN-GL4C geoid model. Prior to subtract the two solutions, the user must be careful that both fields have been previously computed relative to the same reference ellipsoid and tide system. This can be done using the further described GUT_FA15 and GUT_FA16 functions. In this particular example, the DNSC MSSH field has been first computed relative to the TP reference ellipsoid and in the mean tide system to be consistent with the CLS MSSH reference frame.

GUT_FA14

-Diff

MSS_CLS_grid_Etp_MT.fic MSS_DNSC_grid_Etp_MT.fic

Diff_MSS_CLS_DNSC_Gocina.fic

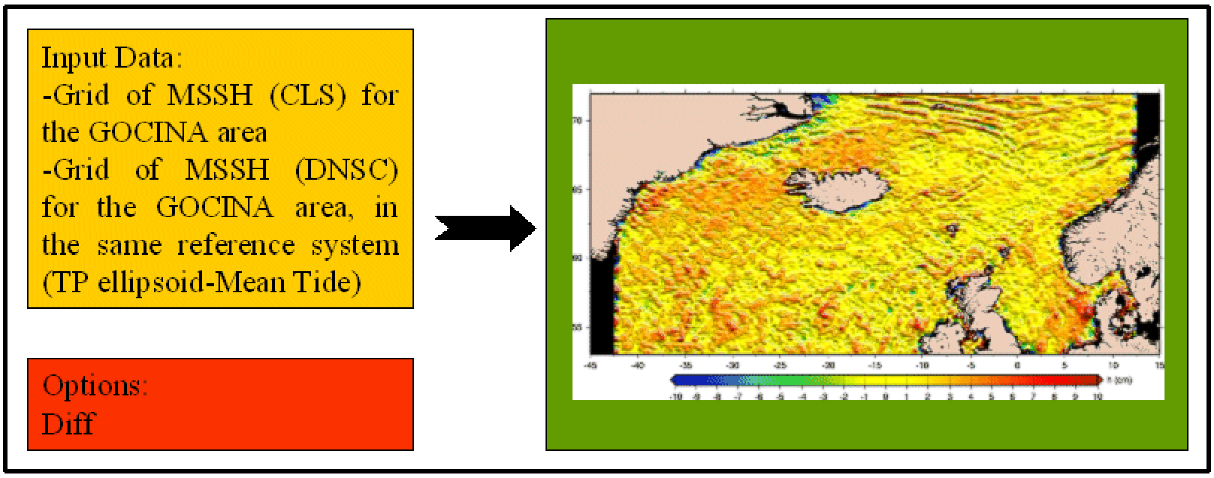

Figure 25: Grid difference

Sum:

The example below (Figure 26) computes the sum of the MDTC obtained using the Workflow 4a (Figure 15) and the sea level anomalies measured on June, 7th 2006 in the Gulf Stream area. The resulting field is the absolute dynamic topography, from which geostrophic velocities may be derived using the GUT_FA13 function (see section 3.5.6).

GUT_FA14

-Sum
MDTC_Niiler_GL4S_fg400_RRA.fic SLA_June_7th_2006.fic
ADT_June_7th_2006.fic

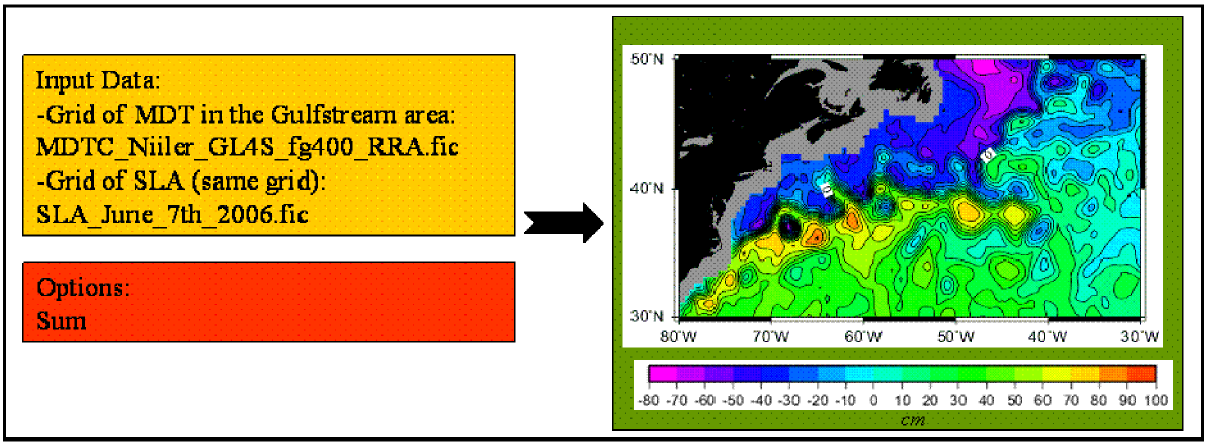

Figure 26: Grid Sum

3.6.7. GUT_FA15: Change tide system

The GUT_FA15 function allows the user to convert a height field from a given tide system to another.

This function may be called using the following parameters:

```
Options:
-TideIn: Tide system of the input field
-TideOut: Tide system required for the output field
```

```
Input:
- Gridded input field
```

```
Output:
- Input field relative to the new tide system
```

Example:

In the example below (Figure 27), the EIGEN-GL4C geoid heights are converted from the TIDE FREE system into the MEAN TIDE system.

```
GUT_FA15
        EIGENGL4C_SH360_grid_Etp.fic –TideIn=FREE –TideOut=MEAN
        EIGENGL4C_SH360_grid_Etp_MT.fic
```

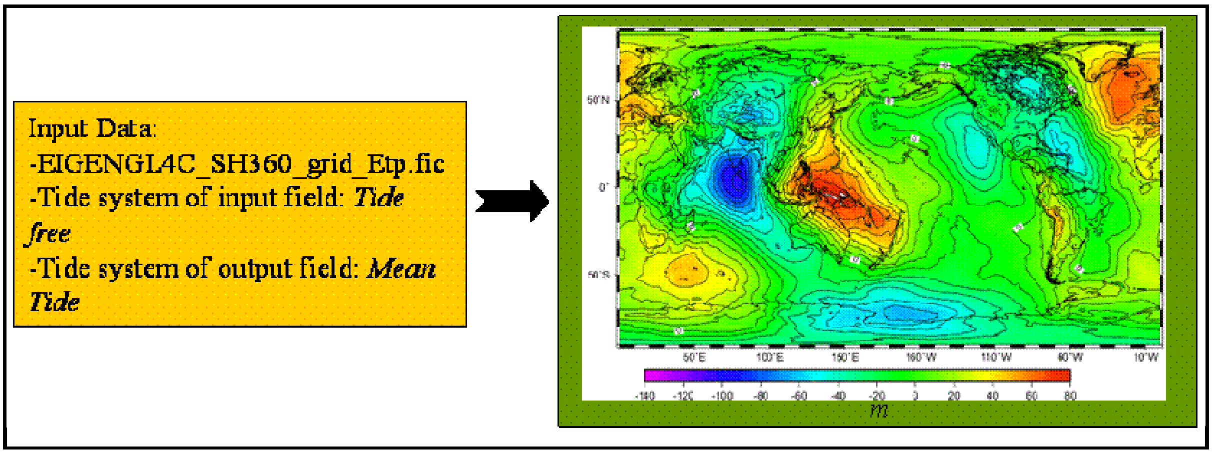

Figure 27: change the tide system

3.6.8. GUT_FA16: Change reference ellipsoid

The GUT_FA16 function allows the user to convert a height field from a given reference ellipsoid to another.

This function may be called using the following parameters:

```
Options:
-EllipsIn: Reference ellipsoid of the input field
-EllipsOut: Reference ellipsoid required for the output field
```

```
Input:
- Gridded input field
```

```
Output:
- Input field relative to the new ellipsoid
```

Example:

In the example below, the EIGEN-GL4C geoid heights are converted from the GRIM reference ellipsoid to the TOPEX reference ellipsoid.

GUT_FA16
EIGENGL4C_SH360_grid.fic –EllipsIn=GRIM –EllipsOut=TP
EIGENGL4C_SH360_grid_Etp.fic

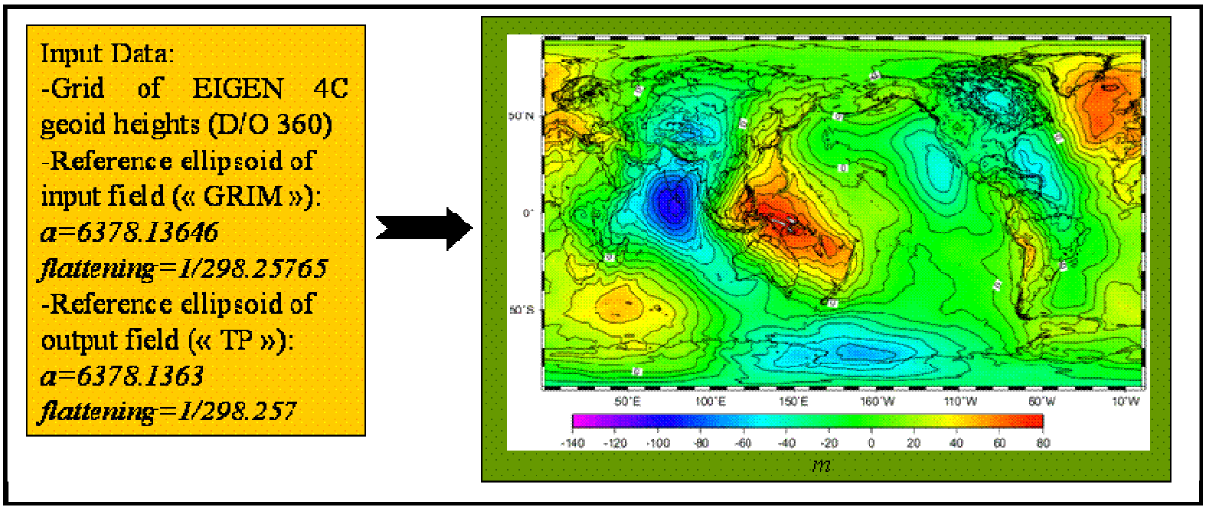

Figure 28: Change the reference ellipsoid

3.6.9. GUT_FA18: SH synthesis

The GUT_FA18 function allows to develop a set of spherical harmonic coefficients into a gridded height field.

This function may be called with the following input/output specifications:

Input:
- Spherical Harmonic expansion of coefficents of global field
- Regular grid specification of output field
- Maximum degree and order of spherical harmonic expansion to calculate

Output:
- Global gridded field

Example:

In the example below (Figure 29), the Spherical Harmonic coefficients of the EIGENGL4C geoid model are developed up to degree 360 on a 1/2° regular grid.

GUT_FA18

EIGENGL4C_SH360_coef.fic -SH360 Grid.fic

EIGENGL4C_SH360_grid.fic

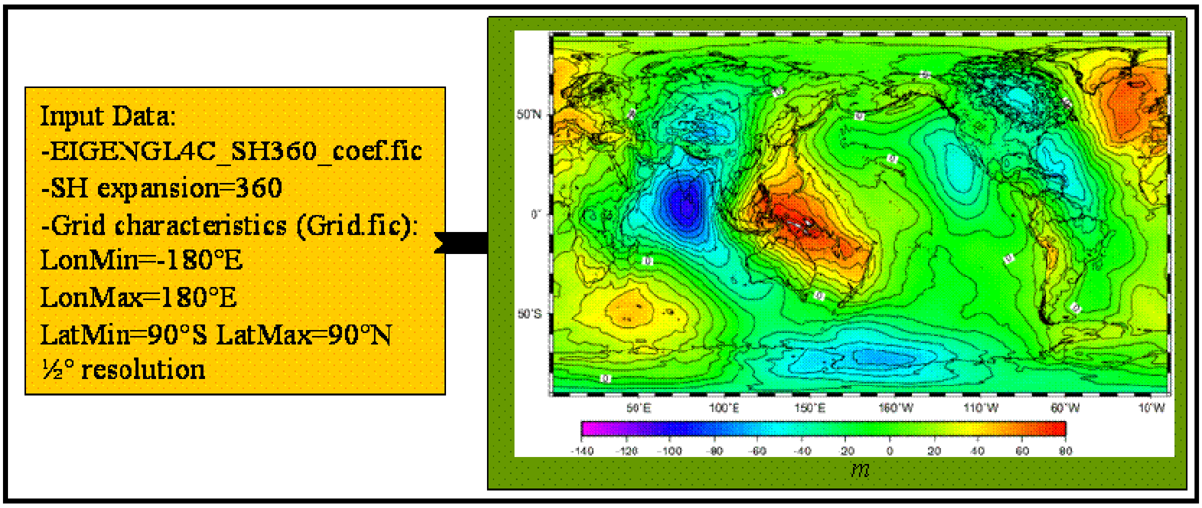

Figure 29: SH synthesis

3.7. The step by step approach

The "single step" functions described above can be used individually and successively. This provides the user with the possibility to build his/her own workflows for specific research purposes.

We give below some examples of what can be done combining the different "single step" functions:

3.7.1. Example1: Compare two geoid models

In this example (Figure 30), two different geoid models based on 110 days of GRACE data are compared: the GGM02S model from CSR (Tapley at al, 2005), and the EIGEN-GRACE2S model from GFZ (Reigber et al, 2005). Both models have first been developed at their maximum SH degree (160 for GGM02S and 150 for EIGEN-GRACE2S).

The GGM02S model is provided by CSR relative to the ellipsoid and in the zero tide system while the EIGEN-GRACE02S model is provided by GFZ relative to the GRIM ellipsoid and in the tide free system.

Both models are therefore first processed in order to be expressed relative to the same reference ellipsoid (the TP ellipsoid is chosen) and the same tide system (the mean tide system is chosen) and are then subtracted.

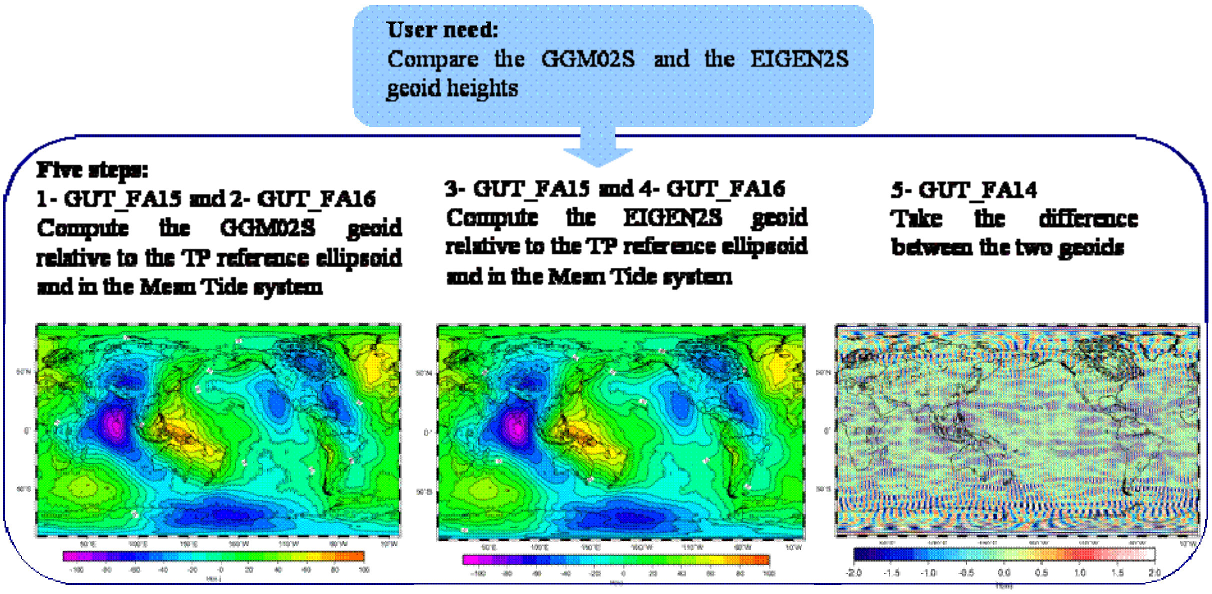

Figure 30: Example1

3.7.2. Example 2: Change the average period of a Mean Dynamic Topography field to another.

In this example (Figure 31), the Mean Dynamic Topography from the ECCO model, corresponding to the 1992-2002 time period, is computed relative to the 1993-1999 time period. This processing is often needed in oceanography when combining SLA and MDT to compute absolute values of the dynamic topography: SLAs are obtained subtracting from the altimetric Sea Surface Heights an altimetric mean profile (computed for a given period). In order to compute absolute values of the dynamic topography, the SLA needs to be added to an estimate of the MDT corresponding to the same time-averaging period. For instance, the SLA distributed by the AVISO center are computed relative to the 1993-1999 period. If the user wants to use the ECCO MDT to compute absolute dynamic topographies from these SLA, he/she first needs to express the ECCO MDT relative to the same 1993-1999 time period. This is done through the following equation:

$$MDT_{1993-1999} = MDT_{1992-2002} - < SLA_{1993-1999} >_{1992-2002}$$

Explanation:

$$\begin{pmatrix} MDT_{1992-2002} = \langle h \rangle_{1992-2002} = \langle MDT_{1993-1999} + SLA_{1993-1999} \rangle_{1992-2002} \\ = MDT_{1993-1999} + \langle SLA_{1993-1999} \rangle_{1992-2002} \\ \\ \Leftrightarrow MDT_{1993-1999} = MDT_{1992-2002} - < SLA_{1993-1999} >_{1992-2002} \end{pmatrix}$$

where h stands for dynamic topography and $SLA_{1993-1999}$ refer to altimetric Sea Level Anomalies computed relative to a 1993-1999 mean profile

Maps of SLA are therefore first averaged over the 1992-2002 time period and the mean is then subtracted from the ECCO MDT.

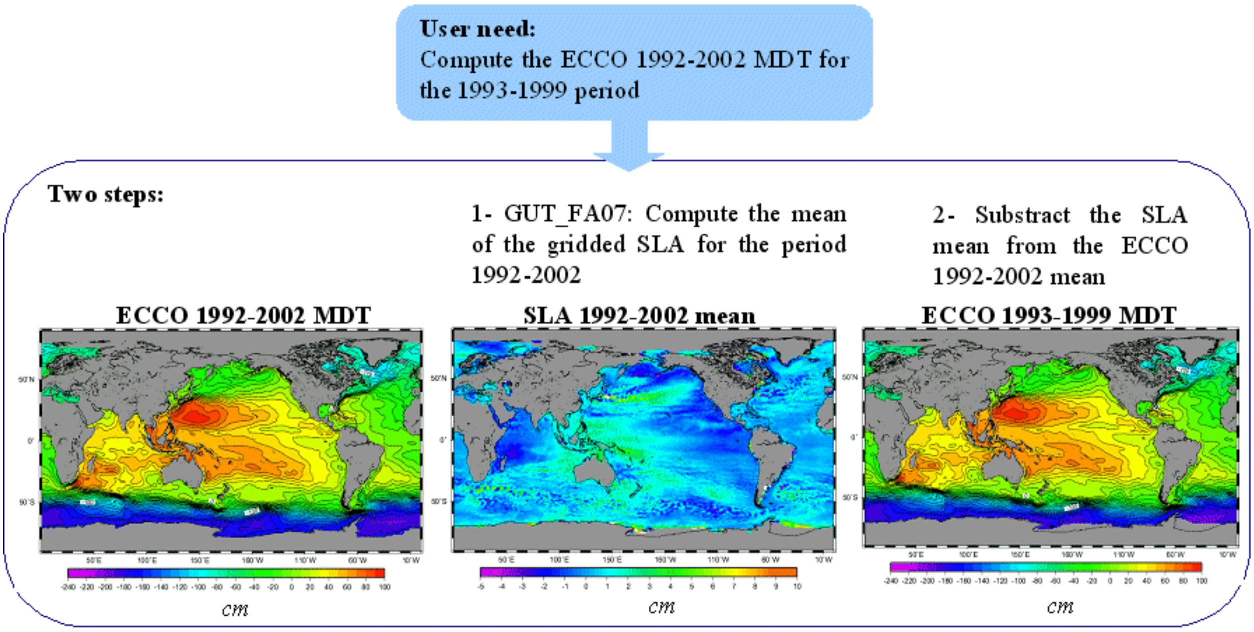

Figure 31: Example 2

3.7.3. Example 3: Compute the MDTC as with workflow 4a, using the step by step approach

The objective of this example (Figure 32) is to decompose the example from Workflow 4a given in the previous section and show the outputs from each single processing step needed when computing a MDTC.

A MDTC can therefore be obtained either using directly Workflow 4a, or using a step by step approach which allow visualizing, modifying, saving, and analyzing each step of the computation.

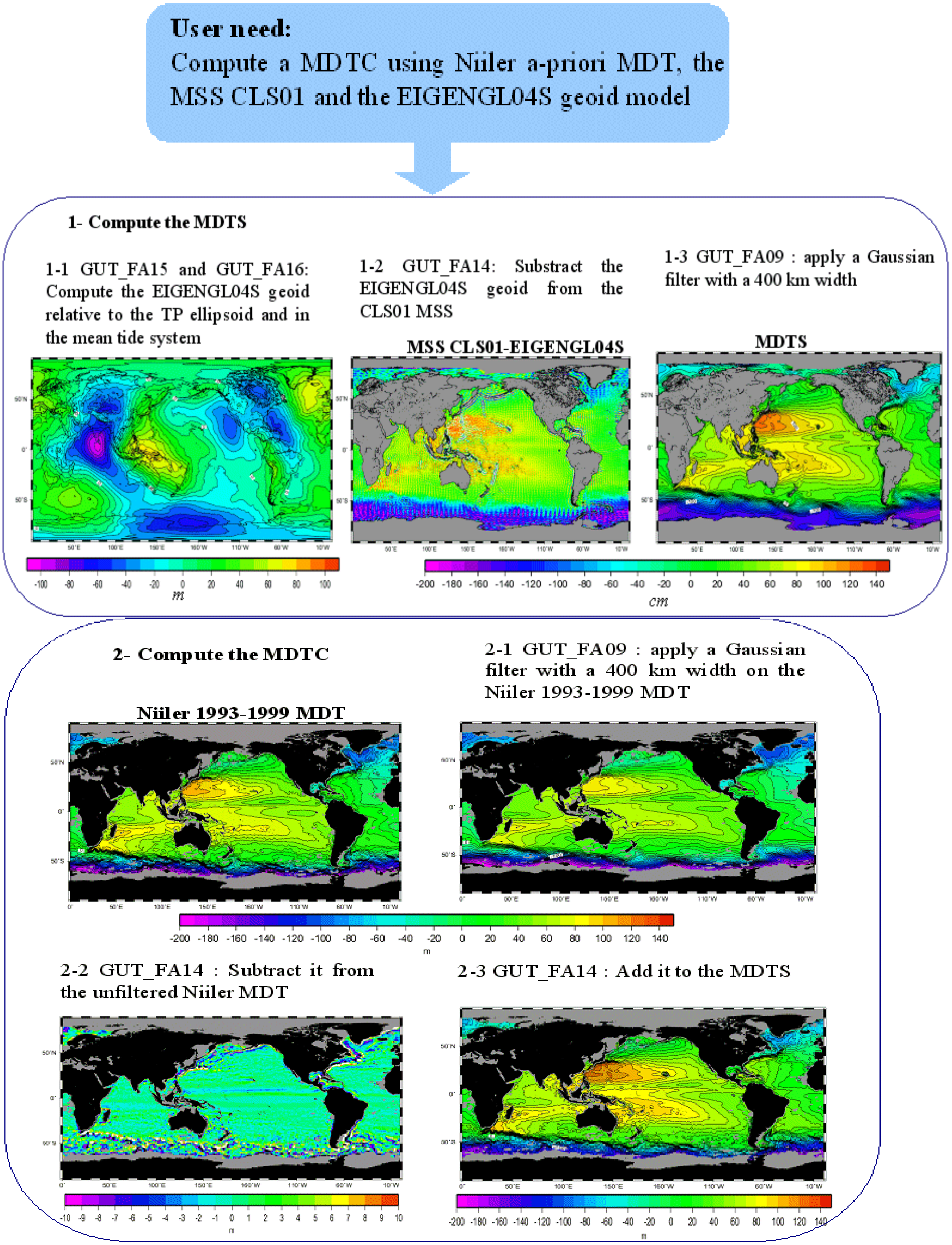

Figure 32: Example 3

4. Recommendation for future GUT tutorials

The objectives of the GUTS tutorial were to complete the previous work packages of the GUTS project in order to provide the software engineers who will be involved in the subsequent toolbox building with a clear view of what the GOCE User Toolbox should look like.

Although they may serve as a basis for their writing, they differ in content and objective from the future GUT tutorials. It is highly recommended that these should include:

- A detailed and didactic course on the use of geoid data for oceanographic applications (mainly) and their combination with altimetry.
- A “default cases” section explaining and describing the different inputs and outputs that will come out from the toolbox when using the default parameters.
- A number of reproducible use cases: the toolbox should be delivered with a number of input and output fields so that the user, when running the toolbox with the input fields and the parameters described in the tutorial, is able to obtain the provided output fields.

5. References

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