Final Report

Ref:

GUTS Phase 3: GUT Development and Supporting Scientific Studies

Extension to ESRIN/Contract No. 19568/06/I-OL

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Contents:

Executive Summary

The Gravity and Steady State Ocean Circulation Experiment - GOCE satellite mission is a new type of Earth observation satellite that is measuring the Earth gravity and geoid with unprecedented accuracy. By combining GOCE geoid models with satellite altimetric observations of the sea surface height substantial improvements in the modelling of the ocean circulation and transport are foreseen. 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. The scientific community clearly expressed a need for a GOCE User Toolbox (GUT). Within the ESA supported GUT Specifications project (GUTS), the user requirements for GUT associated with geodetic, oceanographic and solid earth applications were consolidated. During the second phase of GUTS the first version of the GUT was developed.

GUT is a compilation of tools for the utilisation and analysis of GOCE Level 2 products. GUT supports applications in Geodesy, Oceanography and Solid Earth Physics. The GUT Tutorial provides information and guidance in how to use the toolbox for a variety of applications. GUT consists of a series of advanced computer routines that carry out the required computations. It may be used on Windows, UNIX/Linux and MacOS systems. The toolbox is supported by The GUT Algorithm Description and User Guide and The GUT Install Guide. A set of a-priori data and models such as a-priori mean dynamic topography models derived from e.g. ocean circulation models are made available as well. Applications of the Variance-covariance Matrix require additional software not included in GUT. The software has been developed by Georges Balmino and made available to the community. Those applications require heavy computational resources. In the current version of GUT documentation and tutorial they are not supported.

During this activity the second version of the GOCE User Toolbox (GUT) was developed to enhance the exploitation of GOCE level 2 data with ERS-ENVISAT altimetry. The developments of GUT focused on the following issues:

- Implementation of remaining functionalities, including those for determination of covariance values (implemented as external variance/covariance tool),
- Evaluation of the GOCE error covariance matrix to describe error covariances associated with geoid, mean dynamic topography and geostrophic currents , ,
- Independent validation of preliminary GOCE Level-2 products.

Furthermore, two supporting scientific studies were carried out; one on Solid Earth applications of GUT and one on the development of error characteristics associated with the Mean Sea Surface.

INTRODUCTION

Scope of the document

This document is the Final Report of the project carried out by a consortium led by DTU, **"GUTS Phase 3: Development and Supporting Scientific Studies"** in response to Statement of Work XGCE-DTEX-EOPS-SW-09-0001.

Objectives of the activity

The objective of this activity was to further develop the first generation of the GOCE User Toolbox (GUT) that is required by the general science community for the exploitation of GOCE level 2 and ERS-ENVISAT altimetry. The purpose of this study was accordingly to:

- Implement remaining functionalities, including those for determination of covariance values,
- Evaluate the GOCE error covariance matrix to describe error covariances associated with geoid, mean dynamic topography and geostrophic currents,
- Plan and carry out independent validation of preliminary GOCE Level-2 products.

Furthermore, two supporting scientific studies are carried out; one on Solid Earth applications of GUT and one on the development of error characteristics associated with the Mean Sea Surface.

Subsequently, the GUT activities aim at maintaining the interaction within a scientific GOCE user consortium covering Geodesy, Oceanography, and Solid Earth Physics,

Applicable documents

AD1 "GOCE High level processing facility – GOCE Level 2 Data Handbook", GO-MA-HPF-GS-0110, iss. 3.0, 22-sep-2006
AD2 "User Requirement Consolidation Document", Deliverable of GUTS WP2000
AD3 "Toolbox Functionality and Algorithms Specification Document" Deliverable of GUTS WP3000
AD4 "System Specification and Architectural Design", Deliverable of GUTS WP4000
AD5 "Summary and Tutorial Document", Deliverable of GUTS WP5000

Reference documents

RD1 "GOCE User Toolbox Specifications (GUTS) Statement of Work", ESA/XGCE-DTEX-EOPS-SW-04-0001
RD2 RFQ/3-12046/07/I-OL, "GUTS Phase 2: GUT Implementation and Supporting Scientific Studies"

Abbreviations

ADT	Absolute Dynamic Topography
AWI	Alfred-Wegener-Institut
CLS	Collecte Localisation Satellites
DNSC	Danish National Space Center
DTU	Technical University of Denmark
EC	European Commission
ECMWF	European Centre for Medium range Weather Forecast
ENVISAT	ESA Earth Observation satellite (see http://envisat.esa.int/)

EO	Earth Observation
ESA	European Space Agency
ESTEC	European Space Research and Technical Centre
EU	European Union
GHRSST	GODAE High Resolution SST Pilot Project
GMES	Global Monitoring and Environment Security
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GOCINA	Geoid and Ocean Circulation In the North Atlantic
GOCINO	GOCE in Ocean Modelling
GODAE	Global Ocean Data Assimilation Experiment
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GUT	GOCE User Toolbox
GUTS	GOCE User Toolbox Specification Study
HPF	High-level Processing Facility
IGOS	Integrated Global Observing System
IODD	Input-Output Definition Document
IP	Integrated Project
ISSI	International Space Science Institute
ITT	Invitation To Tender
KO	Kick-Off
MDT	Mean Dynamic Topography
MSSH	Mean Sea Surface Height
NERSC	Nansen Environmental and Remote Sensing Center
NOCS	National Oceanography Centre, Southampton
PM	Progress Meeting
POL	Proudman Oceanographic Laboratory
PSS	ESA Procedures, Standards and Specifications
SoW	Statement of Work
SST	Sea Surface Temperature
TBC	To Be Confirmed
TUM	Technische University München
UST	University of Stuttgart
UCPH	University of Copenhagen
UH	University of Hamburg
UR	University of Reading
WBS	Work Breakdown Structure
WP	Work package

BACKGROUND

Toolbox rational

Data from the ESA GOCE mission are of fundamental importance to the oceanographic community. It is expected that in conjunction with altimetric observations, gravity data from the ESA GOCE Mission will - for the first time in history - allow access to the absolute ocean dynamic surface topography and to compute the absolute ocean surface geostrophic currents at spatial scales down to about 100 km. At the moment, only the variable part of the sea level, and thus of the geostrophic currents, can be inferred from altimetric heights as errors in the existing geoid models corrupt the mean surface height signal.

Despite their importance for oceanographic studies, the processing and analysis of gravity mission data has proven to be complicated to the point that the lack of proper processing software is hampering progress in the use of those data. Success in the exploitation of GRACE data therefore seems to depend fundamentally on the proper knowledge of several steps of the detailed gravity data processing procedure in terms of spatial harmonics, their implicit consistent normalization factors, filtering and error data, among others. To facilitate the easy use of GOCE products for oceanographers and to support the needs of specific applications, the development of a user toolbox (GOCE user toolbox study = GUTS) was identified as an urgent step at the Second International GOCE User Workshop. Such a toolbox is required to guarantee optimal use of the existing and future gravity data acquired from GRACE and GOCE. In particular it is recognized and accepted that software packages are required that allow the gravity field data, in conjunction and consistent with any other auxiliary data sets, to be pre-processed by users not intimately familiar with gravity field processing procedure, for oceanographic and hydrologic application, regionally and globally.
From previous work, a preliminary idea about the scope of a GOCE toolbox exists already in the community, especially from experience gained through GRACE data processing. Any new effort should build directly on this insight and should expand on user needs in a flexible way. The GOCINA and GOCINO projects are another source of valuable information about needs and solutions that will be consulted while defining GOCE user needs and toolboxes.

The GOCE User Toolbox Specifications study (GUTS)

The objective of the GOCE User Toolbox Specifications 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 and ERS-ENVISAT altimetry. The purpose of the study was accordingly to:

- Consolidate the User Toolbox requirements.
- Carry out a scientific trade off study to select the toolbox processing and viewing functions.
- Produce a Toolbox output specification document.
- Produce an algorithm specification document which details the necessary level for coding.
- Produce a Toolbox architectural design document mapping the required functionality and interfaces such as auxiliary data.

The GOCE User Toolbox Implementation (GUT)

The objective of the GUTS follow up activity called GUTS#2 was to develop the first generation of a GUT that is required by the general science community for the exploitation of GOCE level 2 and ERS-ENVISAT altimetry. The purpose of this project was accordingly to:

- Review toolbox specification and consolidate the technical requirements for a first version of GUT,

- Develop the first generation toolbox,
- Introduce visualisation functions via GUI based on BRAT,
- Develop toolbox tutorial,
- Evaluate and test the toolbox.

Furthermore, two supporting scientific studies were carried out; one on a new Mean Sea Surface and one on error covariance matrix handling.

The first version of GUT is a compilation of tools for the utilisation and analysis of GOCE Level 2 products. GUT supports applications in Geodesy, Oceanography and Solid Earth Physics. The GUT Tutorial provides information and guidance in how to use the toolbox for a variety of applications. GUT consists of a series of advanced computer routines that carry out the required computations. It can be used on Windows, UNIX/Linux, and Mac OS X systems. The toolbox is supported by the GUT Algorithm Description and User Guide and the GUT Install Guide. A set of a-priori data and models are made available as well.

GUT is a command line processor. Its output may be exported and visualised using the ESA Basic Radar Altimetry Toolbox BRAT (http://earth.esa.int/brat). The plotting module of BRAT is included with all binary installers of GUT for convenience.

Applications of the Variance-covariance Matrix require additional software not included in the GUT 1 software packages. The software has been developed by Georges Balmino and made available to the community. Those applications require heavy computational resources. In the current version of GUT documentation and tutorial they are not supported.

Relation to the HPF Effort

As part of the GOCE Ground Segment, ESA is running a GOCE High-level Processing Facility (HPF) which is responsible for the generation of the final Level 2 products, and the generation of Quick-Look and External Calibration products. The final Level 2 products consist of: the precise orbit of GOCE, the gravity field in terms of spherical harmonic coefficients, the corrected, calibrated and geo-located gravity gradients, a map of the gravity anomalies and a map of the geoid. This effort will be an essential element in the entire GOCE data stream. However, no ocean circulation products are planned to be delivered as Level-2 products as part of the HPF project so that a strong need exists for GUTS to deliver oceanographers with additional information and tools that can turn the HFP products into application-dependent fields by further processing the GOCE Level-2 geoid and merging it with Radar Altimetry and other auxiliary data. Among the fields that are important for oceanographers is the geoid error covariance function. This field will be provided by HPF for spherical harmonic coefficients. For many oceanographic applications it is required in geographic coordinates or at specific locations. The toolbox therefore need to perform this and other extra functions that are essential for using the GOCE geoid fields efficiently and for testing it in geoid validation studied. To reach a maximum benefit from GUT, the GUTS effort worked in close collaboration with the HPF project. This is facilitated through joint memberships.

Consortium

The study has been carried out by a consortium led by DTU. The consortium is composed of a core team involved in the day-to-day work. The consortium consists of seven institutes from three European countries (in alphabetical order):

- Collecte Localisation Satellites (CLS), France

- Technical University of Denmark (DTU), Denmark
- National Oceanography Centre, Southampton (NOCS), UK
- Newcastle University (NU), UK
- Science and Technology (S&T), NL
- University of Copenhagen (UCPH), Denmark
- University of Hamburg (UH) Germany
- Institut de Physique du Globe de Paris (IPGP), France

The consortium provides all the required expertise in physical oceanography, geodesy, solid earth physics, altimetry, algorithms and system specifications, software development, and project management. This structure assured that the project was executed by an experienced team with all the relevant qualities (financial, management and administrative).

Work package structure

The activity had six main work packages that correspond to the project management and synthesis, and to the five main tasks described above. The responsibilities and role of partners for the different work packages are defined as follows:

<u>WP1000: Project management</u>
WP leader DTU.

<u>WP2000: Development of GUT version 2</u>
WP leader S&T with participation of CLS and NOCS.
WP2100 Specification and Design
WP2200 Implementation of processing functions
WP2300 Implementation of Graphical Workflow Editor
WP2400 Update of toolbox documentation
WP2500 Validation and Verification of GUT v2

<u>WP3000: Evaluate the synthetic GOCE error covariances</u>
WP leader NU with participation of DTU and UCPH.
WP3100 Describe errors associated with the gravity field
WP3200 Describe errors associated with geostrophic surface currents

<u>WP4000: Independent validation of preliminary GOCE Level-2 products</u>
WP leader CLS with participation of DTU, NU, and UH.
WP4100 Develop plan for independent validation
WP4200 Carry out validation and report

<u>WP5000: Solid Earth applications in GUT</u>
WP leader IPGP with participation of DTU and UCPH.
WP5000: Develop basic set of user requirements
WP5200: Derive workflows using GUT functionality
WP5300: Identify needs for additional GUT functionality

<u>WP6000: Assessment and development of MSS error characteristics</u>
WP leader CLS with participation of DTU and UH.

WP7000: GUT User Support and Maintenance
WP leader S&T.

WP8000: GUT Outreach and Promotion
WP leader DTU.

Results

WP1000: Project management

WP leader DTU (120h).

Proposal Statement

This is a standard project management task that was active throughout the study. It includes: Project administration, contractual negotiation, contract administration, organisation of meetings, participation to meetings, project, financial and resources control, planning and schedule control, configuration identification and management, preparation of meeting minutes and preparation of deliverables. A WWW/ftp site will be maintained to facilitate the exchange of documents between the coordinator, ESA and the partners of the study.

Name of Deliverable	Date	Responsible
WP1000: Final Report	T0+18	DTU
	25-09-2011	

WP2000: Development of GUT version 2

WP leader S&T (770h) with participation of CLS (60h) and NOCS (92h).

Proposal Statement

The objective of this activity is to develop GUT version 2. GUT v2 is an evolution of GUT v1, including the additional functionality as specified in the SoW. Because one task in the Statement of Work, the Graphical Workflow Editor, would have required a considerate amount of effort to implement, this task was offered as an option in the proposal and at the end descoped.

The GUT v2 development task was further divided into the following sub-workpackages:

- WP2100 Specification and Design
- WP2200 Improvements to console application
- WP2300 Graphical Workflow Editor
- WP2400 Update of toolbox documentation
- WP2500 Validation and verification of GUT v2

Outstanding Work-Package Outcomes

WP2100 Specification and Design

Many of the requested v2 toolbox functionalities require more detailed specification of what is requested before implementation can commence. For this reason there a quick requirements consolidation phase was carried out at the start of the project where all open items are clarified. This task was concluded with the delivery of a Technical Specification and Architectural Design document that describes the proposed changes that would be developed within workpackage WP2200.

WP2200 Improvements to console application

This task covered the implementation of all toolbox extensions, except for the Graphical Workflow Editor, which was to covered by WP2300.

The items that were implemented in GUT v2 are associated with the following requirements:

Data Extraction

1.1 GUT shall extract a Spherical Harmonic Potential from a file in the GRACE data format.

1.2 GUT shall extract a Spherical Harmonic Potential from a file in the EIGEN data format.

1.3 GUT shall attempt to extract the Time System information from files for Grid, Track and Spherical Harmonic functions.

1.4 GUT will consider the Time System for all Grid, Track and Spherical Harmonic Functions and attempt to determine the resulting Time System in operations between these types. Warnings will be given when performing calculations with incompatible Time Systems, but the operations will not be prevented.

1.5 GUT shall support extraction of Grid and Track Functions from multi-data netCDF files.

Generation

2.1 GUT shall be able to generate a Grid and Track Function from the addition or subtraction of a constant from another Grid or Track Function respectively.

2.2 GUT shall be able to generate a Grid Function from a windowed bicubic spline interpolation of a Grid Function at positions specified by a Grid.

2.3 GUT shall include a workflow to include height correction terms in geoid height generation

Filtering

3.1 GUT shall be able to generate an Anisotropic Filter Kernel defined by a meridional scale length and an orthogonal scale length (i.e. east-west in the equator)

3.2 GUT shall generate a Filtered Track Function by convolution with a Spatial Filter Kernel. The filter shall only consider contiguous positions when filtering a Track Function.

3.3 GUT shall allow the specification of scale length in kilometers.

Data Save and Restore

4.1 GUT shall store the command line of the current process in the standard netCDF global history attribute.

4.2 GUT shall be able to support exporting multiple Grid and Track Functions to a single file if and only if they are defined on the same grid and positions respectively.

4.3 GUT shall provide a workflow to explicitly set the Time System in Grid, Track, Spherical Harmonic Functions and Spherical Harmonic Potentials stored in netCDF files.

4.4 GUT shall be able to store/read geostrophic velocities as a magnitude/direction pair.

Low-Level Algorithmic

5.1 GUT shall perform statistics on limited regions of a Grid Function specified by longitude/latitude ranges.

5.2 GUT shall report the location of the minimum and maximum quantities in its report of statistics.

WP2300 Graphical Workflow Editor

This task covered the development of a graphical tool that allows construction, modification, and execution of workflows. The tool should co-exist with the current command line tool and the graphical tool should use the same XML format for storing workflow definitions as is used by the command line tool. However, it was decided not to include this task in the project.

WP2400 Update of toolbox documentation

The GUT User Guide and Algorithm Description document (RD4), GUT Installation Guide (RD5), and GUT Tutorial (RD6) were updated to cover the changes made to the software within the scope of this project (except WP2300).

WP2500 Validation and Verification of GUT v2

In this work-package a Test Plan was created, that allows verification of the GUT v2 software deliverable against the Technical Specification from WP 2100.

The testing and validation was carried out in order to evaluate the ability of the toolbox to:

- Reproduce the validated results generated by the v1 release of the software using v2 of the software.
- Validate the results generated by the new options available in the v2 release, as specified in [AD2], in particular:
    - Validate the new functionality to add or subtract a constant from a grid function
    - apply a height correction term to geoid height field
    - generate a Grid Function from a windowed bicubic spline interpolation of a Grid Function at positions specified by a Grid
    - generate an Anisotropic Filter Kernel defined by a meridional scale length and an orthogonal scale length (i.e. east---west in the equator)
    - generate a Filtered Track Function by convolution with a Spatial Filter Kernel
    - store/read geostrophic velocities as a magnitude/direction pair.
    - perform statistics on limited regions of a Grid Function specified by longitude/latitude ranges.

The correctness and completeness of the toolbox documentation was also assessed.

The test plan was specified by S&T and conformance with the test plan ensured that the toolbox release conforms with those aspects of the technical specification and architectural design document [AD2] that were specified as requiring a specific test to be implemented.

The current release of the software has passed all tests on the following platforms:

- MacOS X (10.6) using source distribution
- Linux (Ubuntu) using source and binary distributions
- Linux (SUSE Enterprise Desktop 10) using source distribution
- Windows XP using Windows32 binary distribution
- Linux debian (4.0) using src distribution (development system)

The final testing of GUT v2.0 of the software revealed an error in the implementation of the application of the geoid height correction file. By default, the GUT v2 supplied workflow incorrectly scales the input height correction file by a factor of 1/100. This error was introduced by the inability of v1 to correctly recognise the units of the input file (cm). Instead, the units were provided as 'm', and a scaling factor of .001 applied to convert from cm to m. As GUT v2 correctly assigns the units, the scaling factor creates an error. This has been correctly in the beta v2.1 version of GUT.

No remaining issues were identified by the formal testing.

The validation of the toolbox outputs was carried out in addition to the formal test plan. This validation ensured not only the correct functioning of the toolbox, but also the ability to generate results that are equivalent to those generated using alternative methodologies.

Name of Deliverables in WP2000	Date	Responsible
WP2100: Technical Specification and Architectural Design document	T0+3 25-06-2010	S&T
WP2200: GUT v2 (source + binary packages)	T0+11 25-02-2011	S&T
WP2400: Updated GUT User Guide and Algorithm Description document	T0+11 25-02-2011	S&T
WP2400: Updated GUT Installation Guide	T0+11 25-02-2011	S&T
WP2500: Test Plan	T0+3 25-06-2010	S&T
WP2500: Validation Report	T0+12 25-03-2011	NOCS

WP3000: Evaluate the synthetic GOCE error covariances

WP leader NU with participation of DTU (60h), NU (270h), and UCPH (60h).

Proposal Statement

The objective of this activity is to study the error characteristics of the GOCE gravity field. It is important to understand how the anisotropic and inhomogeneous properties of the error covariance function depend on location (latitude mainly), chosen maximum harmonic degree or interval for both geoid and for deflections of the vertical in order to use a GOCE derived MDT in ocean circulation modelling fully. Based on the results of GUTS2 the software developed by G. Balmino will be used together with a GOCE error covariance matrix based on real data. The comparisons of covariances computed using rigorous and approximate expressions will be continued to find alternative representations for fast computations. Furthermore, models for the geoid omission error as well as errors in the Mean Sea Surface will be included.

The work-package was originally structured in the following sub-workpackages:

WP3100 Describe errors associated with the gravity field
WP3200 Describe errors associated with geostrophic surface currents

However, it was decided to focus the analyses on the geoid errors and to merge the deliverables into one deliverable and to descope the analysis of error with geostrophic surface currents.

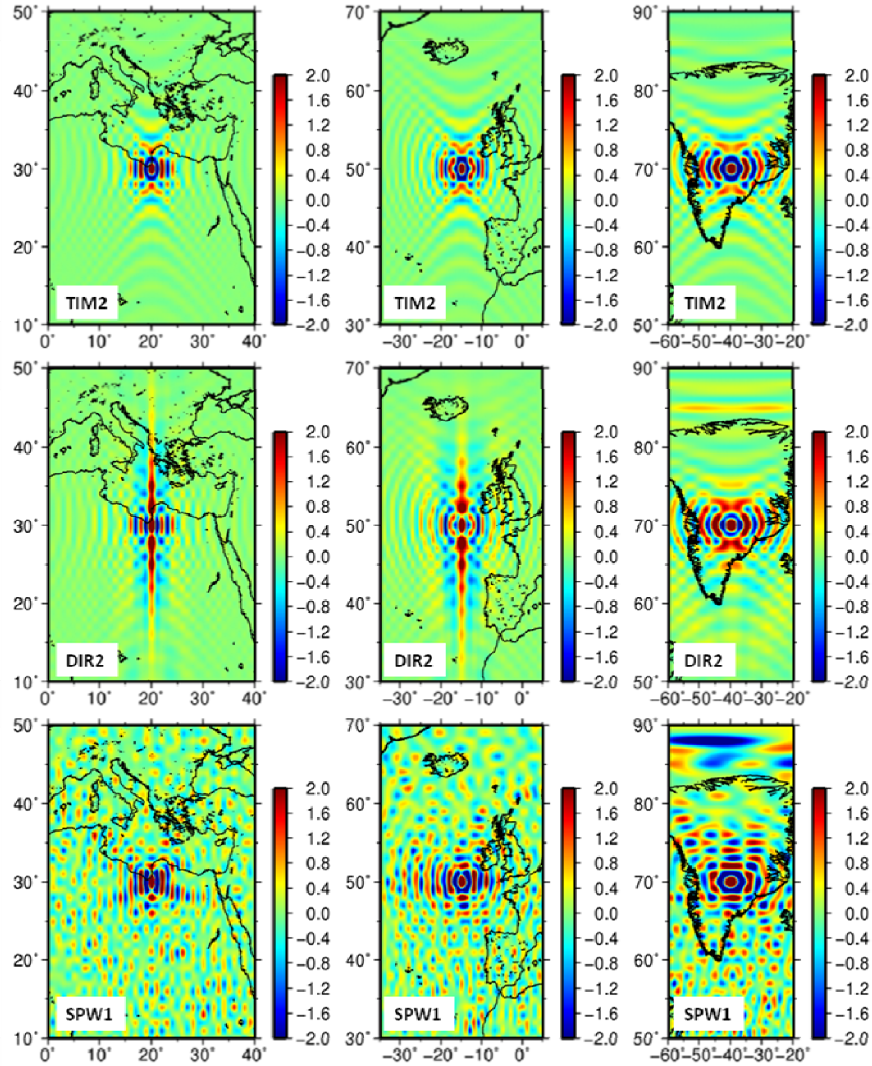
Outstanding Work-Package Outcomes

The error calculations were performed using a set of routines developed by George Balmino. The computational issues associated with using these routines are described. The initial challenge was to convert the ascii form in which the GOCE error variance-covariance information is supplied into a format useable by the Balmino routines. How this was challenge was meet is described in the report. The report then examines then error fields associated with the GOCE geoids.

Maps of the accumulated errors for the geoids were derived from the first and second releases of the direct (DIR) ,timewise (TIM) and spacewise (SPW) GOCE gravity models. Although some zonal variation results from the satellite orbits, the variation in error magnitude is primarily meridional, with errors at their lowest just below the polar gap (approx. 86 degrees) and at their greatest at low latitudes.

The zonal mean errors as a function of maximum spherical harmonic degree and order (L) for the first and second generations of the various GOCE models have been derived as well. Comparing TIM1 and TIM2 for L=224 (the maximum for TIM1), we find that the maximum error in TIM2 has been reduced by 6 cm to just under 16 cm compared with TIM1, while for L=250 (the maximum for TIM2) the maximum errors are 23 cm, similar to those for TIM1. For large L, a hemispheric asymmetry is clear, with maximum errors at about 15°S, and errors a few cm lower at high northerly latitudes than at similar southern hemisphere latitudes. This is related to the elliptical satellite orbit.

DIR1 uses the EIGEN5C GRACE gravity model as a constraint. For L>150, this suppresses the growth of errors seen in the other models (first and second releases), such that for L=240 the maximum errors of DIR1 are nearly half those of TIM2. The DIR2 solution does not use this a priori constraint and consequently the errors are greater than for DIR1, although still lower than those of TIM2. Comparing with the GRACE errors, it is seen that for L<100, the errors from GRACE are lower than those from the GOCE models, but by L=150 the reverse is true. This is what is expected from the two missions.



Normalised error covariances (scaled by a factor of 10) at three latitudes for the second generations of the TIM (top row) and DIR (middle row) models and the first generation of the SPW model (bottom row).

From the error covariance maps shown above it is clear that the primary anisotropy is with respect to the zonal (x) and meridional (y) directions. The panels show error covariances for the unfiltered geoids. Clearly the orbital configuration of the satellite impacts on the error covariance structure. Short wavelength noise tends oscillate between decaying positive and negative correlation in the zonal (across track) direction, but decays more straightforwardly in the meridional (along track) direction.

In addition to error magnitudes, knowledge of error length scales is required for the assimilation of a geodetic MDT into an ocean model. For now we must assume that MDT errors results entirely from the geoid, since error covariance information for the mean sea surface is not available. Due to the anisotropy discussed above, we can expect long wavelength errors in the meridional (along track) direction to have greater length scales than those for the zonal direction. For each location the error covariance function is approximately symmetric about the zonal and meridional axes and has an approximately Gaussian form as shown in the previous panel. This permits the zonal and meridional correlation length scales to be defined as the distance at which the covariance drops to e^{-1} of its value at the origin, so so-called e-folding length scale.

The zonal and meridional correlation length scale maps for the geoid/MDT derived from the TIM2 model, filtered with a 200 km Gaussian filter are shown in the top and bottom left hand panels below. The zonal length scales vary between about 340 to 400 km, and, like the errors themselves, vary mainly in the meridional sense, growing larger towards the poles, and bulging toward the equator. The orbital configuration of the satellite is reflected in the longitudinal variations of the zonal length scale. As noted above, the meridional length scales are much greater than the zonal scales, varying between about 900 and 980 km, because errors in the long wavelength range tend to be related along the satellite orbits. Again the variation in length scale is primarily meridional, but, compared with the zonal length scales, there is a greater degree of zonal variation.

The zonal average scales to be used in the assimilation are shown in the right hand panel. Presently, it is unclear the impact these length scales and the large difference between the meridional and zonal lengths will have on the assimilation.

With regard to the GOCE User toolbox and the initial aims of this work package, the main conclusions of this report are that once the initial challenges of handling the large ECFs are meet, the efficiency of the Balmino routines are such that the error calculations are likely to be feasible for most users. This is fortunate, since it is unlikely the fast approximations to the error covariance functions, as originally suggested, can be easily found. Without substantial recoding effort is would not be possible to fully integrate all of the error calculation functionality of the Balmino routines in the GUT toolbox, and so they will likely remain as standalone tools. However, the small conversions routines developed as part of this work package could, without too much effort be incorporated into the toolbox. Thus providing a convenient entry point for those wishing to explore the error characteristics of the GOCE gravity models. The most useful, and perhaps feasible, next step would be to include the ability to calculate error fields on an arbitrary grid or set of points and to an arbitrary degree and order.

On the basis of the experience gained during the completion of WP3000 the following recommendations are made to the HPF (given in order of decreasing importance):

- Supply error variance-covariance matrix with a standard ordering scheme. Ideally the interleaved scheme required by Balmino routines.
- Supply error variance-covariance matrix with a standard number format, with only the numbers only given to minimum required precision to reduce size of files that the user must download, store and handle.
- Supply users with a stand alone tool to convert supplied ASCII files into unformatted binary as required by the Balmino routines.
- Integrate conversion tool into GUT.
- Extend GUT functionality to allow error variance fields to be calculated.
- Extend GUT functionality to allow error covariance fields to be calculated.

Name of Deliverable in WP3000	Date	Responsible

WP3000: Report describing error correlations in the GOCE gravity field and errors associated with geostrophic currents	T0+10 25-01-2011	NU

WP4000: Independent validation of preliminary GOCE Level-2 products

WP leader CLS with participation of CLS (240h), DTU (60h), NU (60h), and UH (60h).

Proposal Statement

The objective of this activity is to carry out an independent validation of the preliminary GOCE Level-2 products. Hereby, the GUT consortium wishes to contribute actively to the ESA/HPF effort developing the products. The independent validation would be carried out using GUT with the preliminary GOCE Level-2 products for the determination of a MDT which, subsequently will be compared with other MDT estimates derived using other geoid models, ocean circulation model outputs, or in-situ oceanographic data.

The MDT comparisons might be carried out by analysing MDT residuals as well as their associated geostrophic surface currents at different maximum harmonic degrees or intervals. Prior to the effective comparison exercise a validation plan will be prepared, in order to define a number of common diagnostics upon which all comparison to the different MDT will be based. An important point will be to assess the consistency between the residuals obtained and the cumulative contribution of the different variance/covariance error information on the different field entering in the MDTs computations (MSS, geoid, models…) when available. In particular, anisotropic and inhomogeneous characteristics of the residual fields will be derived and compared with the results obtained in WP3000.

The workpackage was structured in the following sub-workpackages:
WP4100 Develop plan for independent validation:
WP4200 Carry out validation and report

Outstanding Work-Package Outcomes

WP4100 Develop plan for independent validation

In this workpackage the validation was developed. Basically, a standard set of actions will be performed each time a new GOCE geoid model is made available. Those are:

1. Compute the ocean Mean Dynamic Topography from GOCE data using the GUT toolbox.
2. Compute the corresponding mean geostrophic circulation using the GUT toolbox.
3. Perform validation of obtained GOCE MDT by comparison to existing MDT
    a. Existing external MDT to be used for GOCE data validation
    b. Definition of a common set of diagnostics
    c. Comparison of GOCE MDT (and external MDTs) to synthetic mean height and velocity estimates (filtered and unfiltered) for different spatial lengths.

In the GUT toolbox, this MDT computation can be done using either the standard point-wise approach, or the spectral approach. The two approaches will be applied and compared. The differences between the two approaches over a range of truncations reveal interesting things about the relative impact of omission and commission errors. By eliminating omission errors the spectral method will allow the point at which commission errors become significant to be identified, and it will show us what they look like. This will allow us to make an informed choice about the suitable width of spatial filter.

The GOCE-based MDT can also be computed using different altimetric Mean Sea Surfaces. We plan to test the impact of two different solutions: the DNSC08 MSS (that is part of the GUT auxiliary data) and the CNES-CLS10 MSS.

This validation was be done comparing the obtained GOCE MDTs to existing MDT solutions as well as to synthetic estimates of the MDT based on the combination of in-situ oceanographic measurements and altimetric anomalies. A bunch of already existing MDTs will be used as 'reference fields' to which GOCE MDT will be compared. Once all external MDT have been homogenized, systematic comparison will be performed to the different GOCE MDTs (using different truncations if computing the MDT in the spectral domain, or different filtering lengths if computing the MDT in the spatial domain).

WP4200 Carry out validation and report

The two releases based on the direct approach (EGM_DIR_R1 and EGM_DIR_R2) are developed to order and degree 240 of spherical harmonics (83 km resolution). EGM_DIR_R1 results from 2 months of GOCE data constrained toward Eigen_51C that combines surface and GRACE data [Bruinsma et al, 2010] while EGM_DIR_R2 results from 6 months of GOCE data constrained toward ITG_Grace2010s that is a GRACE (Gravity Recovery And Climate Experiment) only solution. The first release based on the time-wise approach (EGM_TIM_R1) is developed to order and degree 224 of spherical harmonics (89 km resolution) while the second release (EGM_TIM_R2) is developed to order and degree 250 (80 km resolution). EGM_SPW is based on the space-wise approach and is developed to order and degree 210 of spherical harmonics (95 km resolution).

In order to evaluate the accuracy of the different GOCE geoid models described above for oceanographic use, they were used to determine the ocean MDT (Mean Dynamic Topography). The ocean Mean Dynamic Topography is the simple difference between an altimetric Mean Sea Surface (MSS – Mean sea level above a reference ellipsoid) and a geoid model (relative to the same reference ellipsoid). A MSS resolves spatial scales as short as 10-20 km while the geoid models are developed up to degree and order 210-250 (i.e. 95-80 km resolution). Further filtering is hence needed.
The various MDT obtained were subsequently compared with other MDT estimates derived using other geoid models (based on GRACE data), or computed from the use of in-situ oceanographic data or ocean general circulation models. The MDT comparisons were carried out by analysing MDT residuals as well as their associated geostrophic surface currents at different maximum harmonic. Both the impact of the different methodologies used to compute the gravity field as well as the contribution of the four months of supplementary data have been checked. Finally, both global assessments have been performed.

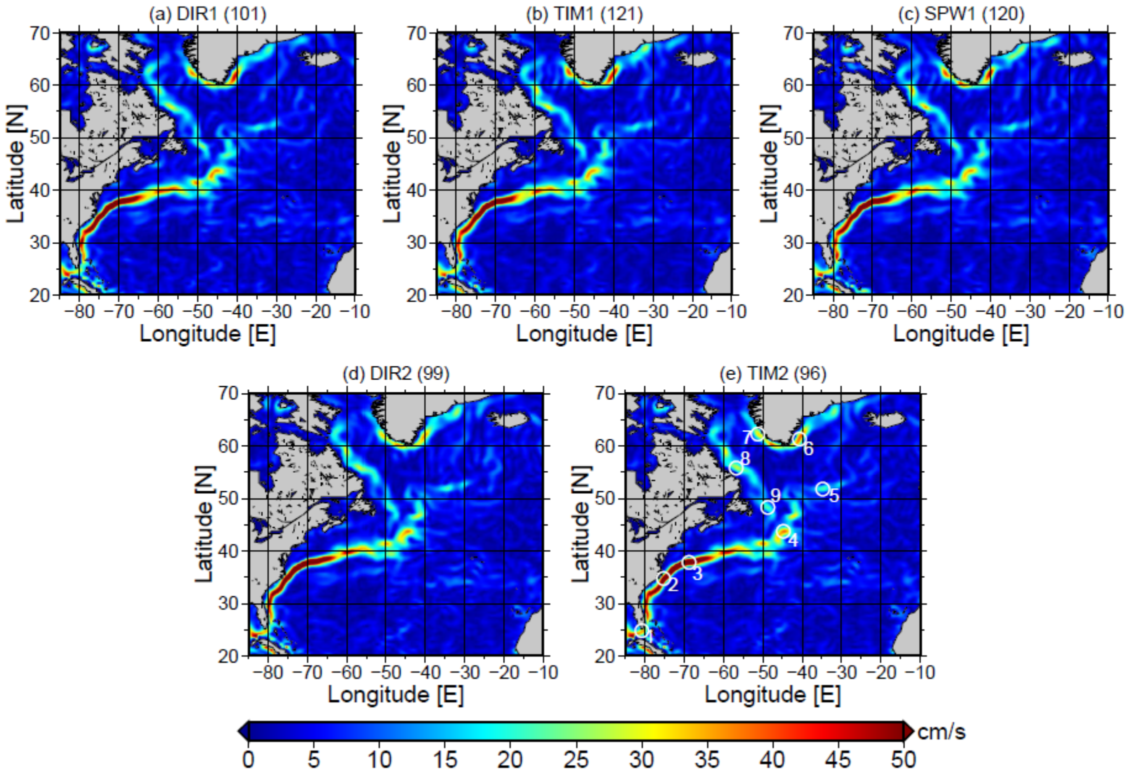


Figure showing geostrophic current speeds obtained from the GOCE MDTs once the MDTs have been diffusively filtered as described in the text. The number of iterations required to minimise the RMS difference with the Niiler MDT are shown above each panel.

This work has allowed to highlight:
- The superiority of using only two months of GOCE data compared to GRACE data when computing satellite-only solutions
- The strong impact of using 3 more times more GOCE data in the second HPF release compared to the first HPF release
- The positive impact at scales ranging between 120 and 200 km of using GOCE data to improve combined geoid models (where short scales are resolved using information derived from altimetric MSS)
- The efficiency of the validation methods used to inter-compare the different geoid solutions and assess their quality and defaults.

On the other hand, this study has allowed highlighting the following limits:
- of the current preliminary geoid models: The difficulty to use GOCE data to estimate the ocean MDT in the Mediterranean Sea. This region may be used as a challenging objective for testing the future geoid models.
- of the current filtering techniques: in the future, some more sophisticated filtering should be tested, using the information from the GOCE covariance error matrix.

Name of Deliverables in WP4000	Date	Responsible

WP4100: Plan for independent validation	T0+3 25-06-2010	CLS
WP4200: Report on validation of preliminary GOCE products.	T0+10 25-01-2011	CLS

WP5000: Solid Earth applications in GUT

WP leader IPGP with participation of DTU (40h), UCPH (40h), and IPGP (140h).

Proposal Statement

The objective of this science study is to focus on the use of gravity data in Solid Earth Physics in order to enhance the use of GOCE Level-2 data and GUT for such applications. Functionalities for the solid Earth applications will be developed for GOCE combined with DEM using preferably already implemented components in GUTv1, such as filtering and spherical harmonic analysis components. This will be done for the computations of e.g. Bouguer anomalies and Isostatic anomalies.

The Solid Earth applications will be reviewed through the development of a set of basic user requirements. Subsequently, workflows will be derived using GUT functionalities. A few missing elements in the GUT functionalities, such as upward continuation and response function from MOHO, may be identified. Additional functionalities as well as documentation may be implemented in GUT version 2 tutorials.

The workpackage was structured in the following sub-workpackages:
WP5100: Selection of basic set of user requirements
WP5200: Derive workflows using GUT functionality
WP5300: Identify needs for additional GUT functionality

Outstanding Work-Package Outcomes

WP5100: Selection of basic set of user requirements

The following functionalities were selected as basic user requirements:

- EXTRACTION OF THE GOCE POST-PROCESSED GRADIENTS (STEP 4)
- EXTRACTION OF THE HEIGHTS (STEP 1, 3)
- DERIVATION OF FREE AIR GRAVITY ANOMALIES(STEP 1)
- DERIVATION OF FAYES ANOMALIES (STEP 2, 6)
- TERRAIN CORRECTIONS (STEP 2, 3, 5, 6)
- BOUGUER ANOMALIES (STEP 2 , 6)
- GRAVITY GRADIENTS (STEP 3)
- TO COMPUTE THE EFFECT OF THE TOPOGRAPHY ON THE GOCE GRADIENTS (STEP 5)
- TO PLOT EACH OF THE ABOVE DESCRIBED EXTRACTED OR CALCULATED QUANTITIES (STEP 1, 2, 3, 4, 5, 6)
- SIMPLE BOUGUER ANOMALY/DISTURBANCE MAPS

WP5200: Derive workflows using GUT functionality

To realise the requirements, some functionalities should be added to the GOCE User toolbox. Those are:

Functionnality	DESCRIPTION	Workflow proposed
Temporal selection of EGG_TRF_2	This functionnality allow user to select EGG_TRF_2 files based on file date selection Input: Gravity gradients Output: Temporal selection gradients	tempselectionEGG_TRF_2
Adaptation of EGG_TRF_2	This functionnality allow user to create interpolated or subsampled grid with EGG_TRF_2 files Input: Gravity gradients Output: Interpolated or subsampled grid	adapt_TRF
Importation of EGG_TRF_2	This functionnality allow user to use package EGG_TRF_2 with GUT loads the gradients inside an area (list of points)	import_TRF
Exportation in ascii format	This functionnality allow user to export GUT results in ascii format Input: netcdf file format Output: ascii file format	export_ascii_gf
exportation in netcdf format	This functionnality transform a file in ascii format in GUT internal file format (netcdf) Input: ascii file format of area/list of points Output: GUT internal file format (netcdf) of area/list of points	export_netcdf_area export_netcdf_list
Call to the Gravsoft function "Select" in GUT	This functionnality allow user to call the Gravsoft function Select	CallgravsoftSelect_gf
Call to the Gravsoft function "Tcgrid" in GUT	This functionnality allow user to call the Gravsoft function Tcgrid	CallgravsoftTcgrid_gf
Call to the Gravsoft function "Tc" in GUT	This functionnality allow user to call the Gravsoft function Tc	CallgravsoftTc_gf
Call to the Gravsoft function "GEOCOL" in GUT	This functionnality allow user to call the Gravsoft function GEOCOL	CallgravsoftGEOCOL_gf
Rotation matrix inversion	This functionnality inverse the rotation matrix to allow user to put data in CTRS Input: Gravity gradients or list of points/area in LNOF Output: Gravity gradients or list of points/area in CTRS	Rotmatrixinversion_gf
slabBouguerCorr	This functionnality compute slab bouguer correction Input: Grid data or list of point in ASCII format Output: Slab bouguer correction for the grid data or list of point	slabBouguerCorr

N.B: GEOCOL must be able to manage LNOF and CTRS coordinate systems

The GUT functionalities already implemented that can be recycled for the calculation of the Bouguer Anomalies are:

- adapt_gf: Adaptation of a Grid Function to a specific Grid.
- exportgravsoft_gf: Export a Grid Function in GRAVSOFT grid format.
- filter_gf: Filter a Grid Function by convolution with a filter kernel.
- gravityanomaly_gf: Extract a set of spherical harmonic potential coefficients (and GM, R, tide system) from file and calculate the gravity anomaly (free air anomaly or gravity disturbancce) on a chosen Grid with a specified expansion of the geopotential.
- import_gf: Extract a specific Grid Function from a file, and export in GUT internal netCDF format.
- import_shf: Extract a Spherical Harmonic Function from a file, and export it in GUT internal netCDF format.
- import_shp: Extract a Spherical Harmonic Potential from a file, and export it in GUT internal netCDF format. The degree and order of the output can be set explicitly, zero-padding or truncating the spherical harmonic series as appropriate.

For details on the functionalities see "GUT User Guide and Algorithm Description".

<u>WP5300: Identify needs for additional GUT functionality</u>

In this workpackage a series of complementary items are identified that could be implemented in the future in GUT in order to enhance the use of GOCE data for the Solid Earth community. The mandatory items for the purpose have been listed in WP5100-5200 report. These items can be summarized in the following short list:

- Computation of gravity at specific heights
- Computation of gradients from GOCE EGMs
- Bouguer / Isostatic anomalies (land-ocean)
- Terrain corrections / reductions (TC,TC-GRID)
- Upward continuation
- Band-pass filtering
- Horizontal and vertical derivatives
- Merge with terrestrial gravity data
- Power spectrum
- Display functionality

Furthermore, additional functionalities are proposed that could be implemented in a future version of GUT. These new functionalities could boost the usage of GOCE products among the solid Earth community and also provide benefits for teaching purposes. The functionalities perform some of the classical operations done by geophysicists to build, analyse and interpret the gravity maps over their area of investigation in terms of Earth's structure. Those are:

1. Local high resolution gravity maps and error maps
   The local error characteristics of the GOCE-derived gravity anomaly maps should be provided to the users, because a global mean error may not be necessarily representative of the local distribution of error. Knowing the level of precision of the local gravity anomaly maps is also essential to combine them with other kinds of data (ground gravity but also other geophysical/geological data as seismological ones for instance).

2. Elementary analysis tools for geodynamic interpretation

After the local high-resolution gravity anomaly map has been derived, it is necessary to apply various analysis tools in order to interpret it for geodynamic studies at crustal and lithospheric scales. Additional functionalities in GUT would thus be very useful to perform elementary analysis and interpretation steps, not only for research studies but also for teaching purposes. Graphic views of the analysed gravity maps in BRAT should be proposed, in addition to ASCII files of results of the analyses.

3. Standard transformations

It is a common process to compute maps of derivatives (both vertical and horizontal) in order to analyse the gravity anomaly maps. Derivatives will act as high-pass filters and emphasize the smaller scale features. They are used to enhance geological boundaries. In practice, vertical derivatives are used to uncoalesce gravity anomalies, while the horizontal ones allow identifying contacts between geological objects with density contrast. Upward and downward continuations are also very practical tools. They can be used to compare data sets acquired at different altitudes, for example ground and satellite data. In addition, upward continuation is equivalent to a low-pass filter and downward continuation corresponds to a high-pass one. The wavelength of gravity anomalies are a function of the position and size of sources, so continuations can provide insight on the depth and size of sources anomalies.

4. Local energy spectrum of the gravity anomaly map.

The identification of linear segments with constant slopes in a log-log plot of the energy spectrum of a gravity map can be related to the depth of the sources of anomaly in local studies of Earth's structure. In addition, wavelengths associated with slope discontinuities can be used as cut-off wavelength in filtering operation in order to isolate the different kind of sources of anomalies.

5. Isostatic anomalies.

Computation of the isostatic residual gravity anomalies can be performed for better investigating possible strain and stress disequilibrium in the upper part of the lithosphere and for removing a gravity effect of the crust (under some assumption) that can mask interesting signals. For this, one removes the gravity effect of the crust with its lower interface, the Moho, having a shape such that the forces due to topographic loads are mechanically balanced. The isostatic hypothesis corresponds to a perfect equilibrium in a given waveband of masses from the topography down to a so called compensation level. Among the various models of isostasy, the simplest one, that is known to be always valid at long wavelengths, is the Airy Model wherein the crust is divided into prisms of different heights but equal densities. Practically, in this simple Airy model the shape of the Moho inversely mimics the topography being magnified with a coefficient depending upon crustal and mantle densities.

6. Elementary inversions for density anomaly sources.

Elementary inversions for density anomaly sources can be provided. One may consider providing tools to perform Euler deconvolution. This system is based on Euler’s homogeneity equation, which relates the field and its gradient components to the depth of the source, with the degree of homogeneity N, called a "structural index", related to the geometry of the sources. This index is an exponential factor corresponding to the rate at which the field falls off with distance, for a source of a given geometry.

Name of Deliverables in WP5000	Date	Responsible
WP5100: Basic set of requirements Solid Earth studies	T0+8 25-11-2010	IPGP
WP5200: Workflows using GUT functionalities	T0+10 25-01-2011	IPGP
WP5300: Additional functionalities	T0+11 25-02-2011	IPGP

WP6000: Assessment and development of MSS error characteristics

WP leader CLS with participation of CLS (150), DTU (120h), and UH (40).

Proposal Statement

The objective of this supporting science study is to continue the effort in the previous project phase (GUTS#2) to characterise the errors in the mean sea surface models. Building on the results of GUTS2 the error sources are analysed and assessed individually with respect to magnitude and scale. Subsequent, error covariance functions for each error component affecting the accuracy of the Mean Sea Surfaces should be constructed.

Outstanding Work-Package Outcomes

The analysis considered the following error sources:

	Corrections
Dry Troposphere	ECMWF (Model) NCEP (Model)
Wet Troposphere	Radiometer (on board) ECMWF (Model)
Ionosphere	Smoothed Dual Frequency Radiometer IRI 2007 (model)
Dynamic Atmosphere Correction	IB (Model, Local pressure) MOG 2D_IB Model
Tides	FES 2004 (Model) GOT 4.7 (Model)
Sea State Bias	BM4 (model) CLS NPARAM-GDRC (model)

In addition the temporal and spatial characteristics of the sea surface height variability were analysed in order to quantify the influence of long term variations on the calculation of a MSS using data from a limited time interval.

Gridded MSS estimates are derived from along-track mean profiles or from the original datasets used to build the MPs. Thus any error on the repeat track analysis is also contained in the gridded MSS proxy. Conversely, the gridding process and the use of geodetic data in the MSS creation can add new terms of error.

			Error if not corrected	Current status in DUACS Profiles
Mean Profile Error	A	Uncorrected mesoscale variability error	6mo-1year : 5 to 7cm min (WL: 20-50km) 3-5years: <3.5cm 7-15years: <1cm (WL: 100-200km)	Non-existent. Instantaneous ocean varibility is removed before the time average, average computed over 10+ years on all tracks).
	B	Interannual variability error	<5cm (WL: >5000km) <5-8cm in wb currents (WL: 200-500km)	Non-existent as re-referenced on a common period and cross-calibrated on the reference mission (both SSH and <SSH>)
	C	Geophysical corrections errors	>3.8cm (2001, all WL) 3.5cm (2001 standards, WL>50km) >1 to 3cm (GDR-B)	GDR-C or equivalent used for all missions. Remaining error not well-defined.
	D	Cross-track geoid gradient	>2.5 cm if cross-track geoid gradient correction is not used	CTGG applied <1cm between CTGG methods

			MSS computed before 2008	Recent MSS (CLS/CNES, DNSC, DTU)
MSS Error	E	Correlated error averaging (discrepancy between missions → mix of errors)	**Difference between cross-calibrated MPs and MSS actually using them :** 1 cm (WL < 100km) 1-3 cm (WL > 100km)	
	F	Map smoothing (scales which cannot be resolved away from known tracks, degrading along-track content)	**Local difference between EGM08 and recent MSS, high-pass filter, located on bathymetry gradients** 3 to 5 cm (WL : 10 to 30km + noise) 2 to 5 cm (WL : mesoscale)	
	G	Omission error	**Small scales(difference between MSS computed with and w/o specific TP or GFO tracks):** 1.6 to 2.5cm (WL: <100km)	
	H		**Larger scales (SSHA increase during on new track if tandem data are not used, difference between CLS01 and CLS10 in ERS diamonds)** 3 to 7 cm (WL: all) 1.5 cm (WL: 50 to 500km)	**Best case (SSHA increase during T/P drift using DNSC or CLS/CNES)** 1 cm (WL: 100 to 500km) **Worst case (different behaviour of CLS and DNSC when compared to a common EGM08):** <3 to 5 cm (WL < 75km)
	I	Mesoscale variability from geodetic data not properly removed before absorption in MSS		

Table showing overview of Sea Level Anomaly Errors associated with the temporal reference. Error terms A to D are present on all <SSH> temporal references (repeat track analysis or gridded MSS), and terms E to I are specific to gridded mean sea surfaces (geodetic altimetry or uncharted repetitive track).

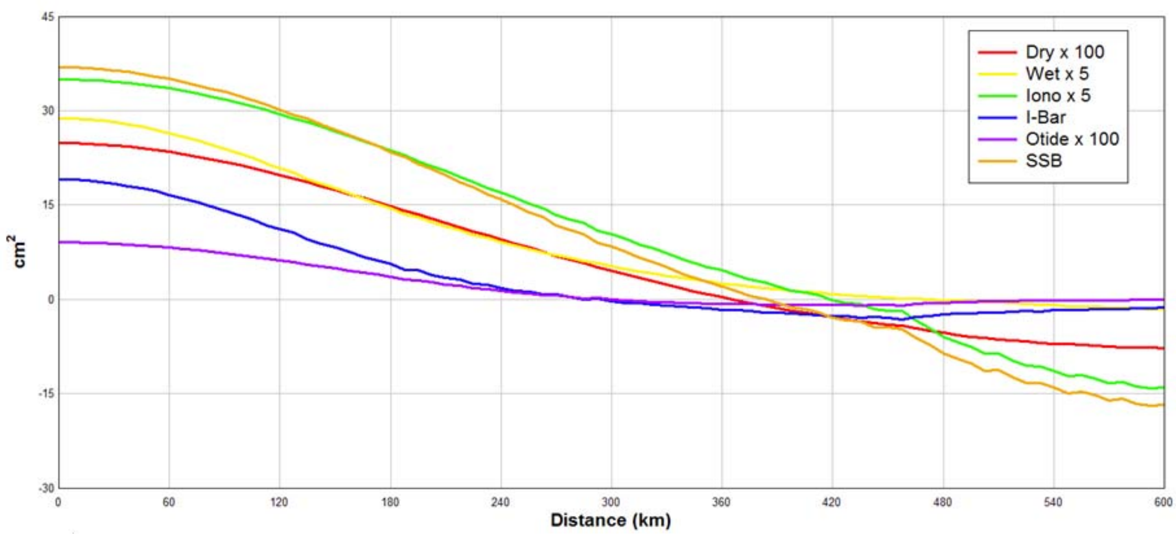
To summarize, internal coherency tests and relative estimates point to an error level from 1 cm rms (100 to 500km) to 3 cm rms (shorter scales) if only the omission error is considered, and 2cm or more if sensor-specific residuals are taken into account. This optimistic estimate is obtained if we make the (wrong) assumption that the CLS/CNES data and processing are error-free and that the CLS/CNES2010 MSS is perfect. Conversely, if we (rightly) assume that all recent MSS have an error of the same order of magnitude, then error estimates from internal tests of this section provide only very optimistic error bars.

The comparison of different surfaces based on different data and processing yields a much larger error estimate if we assume that each surface contains independent error sources. Even after inter-annual discrepancies are removed, mean sea surfaces exhibit discrepancies ranging from 3 to 5 cm for large mesoscale wavelength, and locally more than 5 cm for shorter scales, with rare outliers larger than 10cm. Furthermore the distribution of the error is neither random, nor gaussian, and global RMS values largely underestimate the extent and the spatial coherency of the largest MSS errors, let alone rare local outliers.

In order to further investigate the error covariance functions associated with the range and geophysical corrections four typical regions where selected. Naturally more regions could be investigated, but in the sake of limiting the number of pages and choosing the most typical regions these four regions were selected. The regions are thought to represent regions of typical ocean features and dynamics and regions at different latitudes and proximity to the coast.
The four regions are:

- North Atlantic Region (center of the North Atlantic Ocean)
- Tropical Pacific Region (Equator)
- South East Asia Region (close proximity to the coast)
- Antarctic Region (very high latitude)

Some of the results obtained in the North Atlantic region are shown below.



Covariance functions associated with the approximate errors in the range and geophysical corrections for 6 year mean difference based on Jason sampling is shown in the figure above. Different scaling has been applied to the different covariance functions in order to plot these on the same figure. In this region the SSB dominates followed by the Dynamic Atmosphere, ionosphere and wet troposphere. The two dimensional covariance function for the six range and geophysical corrections are shown in the figure above. Only the wet troposphere is close to being isotropic.

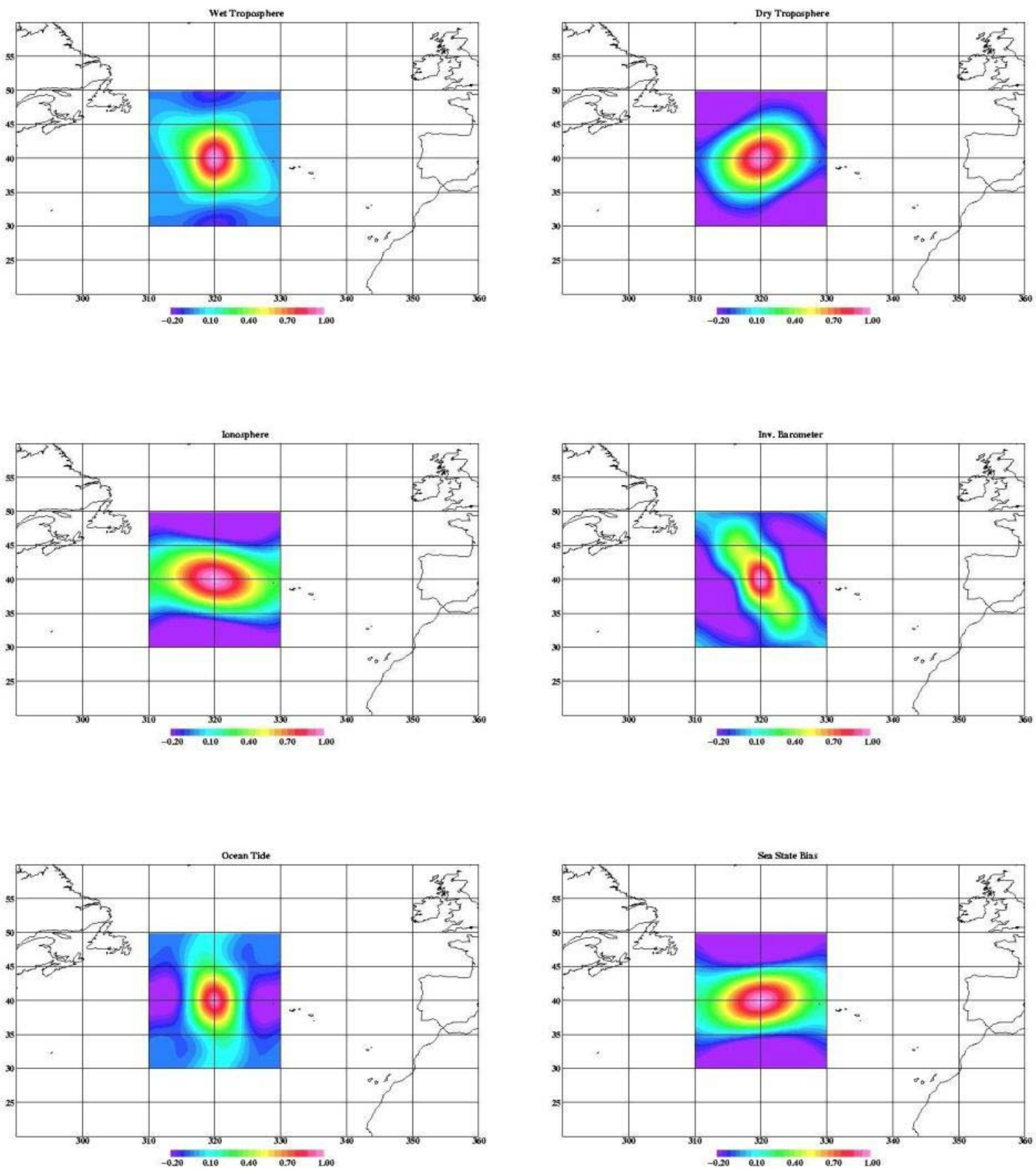


Figure showing the two dimensional covariance function for the centre of the North Atlantic region for each of the range and geophysical errors for 6 year mean Jason profiles

The full set of results are shown and described in the WP6000 deliverable.

Name of Deliverable in WP6000	**Date**	**Responsible**

WP6000: Report on MSS error characteristics	T0+11 25-02-2011	CLS

WP7000: GUT User Support and Maintenance

WP leader S&T.

Proposal Statement

The workpackage include software maintenance and user support for the current version of the toolbox for the entire duration of the project (14 months)as well as for the version 2 for 4 months after the project has ended. The maintenance was intended for minor evolutions, outside the normal guarantee to fix bugs, for quick responses to user request.

The tasks required to the contractor in this workpackage are:

- Provide helpdesk support (quick response)
- Track SPRs (Software Problem Reports)
- Resolve SPRs (including to provide users with temporary workaround solutions)
- Update toolbox documentation eventually and verify consistency between all toolbox components
- Provide new releases (in binary and source) with resolved SPRs

Outstanding Work-Package Outcomes

S&T has monitored and recorded the SPRs during the initial period of 12 months and included them in a report deliverable. 13 issues were reported. 9 corrections to the toolbox software were made.

Name of Deliverable in WP7000	Date	Responsible
WP7000: Report on Software problems	T0+18 25-09-2011	S&T

WP8000: GUT Outreach and Promotion

WP leader DTU.

Proposal Statement

The purpose of this task is to prepare material to be used for outreach. This material shall have as scope the promotion of the GUTv2 toolbox and be intended for didactic purpose. That is to prepare presentation material and a didactic demo of the toolbox's purpose and functionalities, to be used for special events like training workshop events. Furthermore, a toolbox training kit shall be produced which latter will be used for toolbox training sessions. This material will be used to populate the ESA GUT web site, the purpose of which is to promote the output of this research and development activity. This web site will be released under the responsibility of ESA, whereas the contractor is required to produce the promotion content.

An important task is to produce one or more scientific publications to be submitted in a peer-reviewed journal with the findings and novelties of this project. GUT will be presented at conferences and workshops such as the GOCE User Workshop, the EGU meeting, and the ESA Living Planet Symposium.

Deliverables will be the toolbox demonstration package (promo presentation and didactic demo, training kit) and the peer-reviewed papers.

Outstanding Work-Package Outcomes

WP8000: Toolbox promo package

The GUT promotion and demo materials have been prepared in collaboration with ESA. DTU has prepared poster presentations and presented GUT at scientific conferences: EGU in Vienna 2010, ESA LP in Bergen 2010, AGU in San Francisco 2010, GOCE WS in Munich 2011, and EGU in Vienna 2011. IPGP will present GUT at IUGG in Melbourne 2011.

Based partly on the poster presentation and the GUT Tutorials ESA prepared the promotion material and carried out demonstrations of GUT at the ESA LP in Bergen 2010 and at the GOCE WS in Munich 2011.
DTU prepared the presentation of GUT at the 4th GOCE Workshop as well as the manuscripts for the proceedings. In addition DTU participated in the press conferences at EGU in Vienna 6 April 2011. Those three presentations are enclosed in the Appendix

Presentations by GUT project participants at the 4th GOCE Workshop in Munich:

1. GOCE User Toolbox and Tutorial by P. Knudsen,
2. Impact of New, Accurate Geoid Information on Ocean State Estimation by F. Siegismund,
3. GOCE MDT combined with drifter info for improving ocean currents? M.-H. Rio,
4. An initial estimate of the North Atlantic steady-state geostrophic circulation from GOCE by R. Bingham ,
5. Gravity Anomaly and Gradient Recovery from GOCE Gradient Data using LSC and Comparisons with Known Ground Data. by C.C. Tscherning,
6. A global Mean Dynamic Topography and Ocean Circulation Estimation using a Preliminary GOCE Gravity Model by P Knudsen,
7. An oceanographic assessment of the preliminary GOCE geoid models accuracy. By S. Mulet,
8. On the accuracy of current Mean Sea Surface Models for the use with GOCE data by O Andersen,
9. Regional gravity modelling from a combination of GOCE and ground data by I. Panet,

WP8000: Scientific paper
During this phase of the GUT project two scientific papers on GUT were written and accepted for publication in peer-reviewed journals. Those are:

1. Bingham, R., P. Knudsen, O. Andersen, and R. Pail, An initial estimate of the North Atlantic steady-state geostrophic circulation from GOCE, Geophys. Res. Lett., VOL. 38, L01606, 5 PP., 2011, doi:10.1029/2010GL045633.

2. Knudsen, P., R. Bingham, O. Andersen, M.-H. Rio, Enhanced Mean Dynamic Topography and Ocean Circulation Estimation using GOCE Preliminary Models, J. of Geodesy, 2011, DOI 10.1007/s00190-011-0485-8.

In addition the GUT project participants individually contributed to the Proceedings of the GOCE Workshop held in April 2011 in Munich.

Name of Deliverables in WP8000	Date	Responsible
WP8000: Toolbox promo package	T0+14 25-05-2011	DTU
WP8000: Scientific paper	T0+14 25-05-2011	DTU

List of all deliverables

The following table presents the list of the study deliverables:

Name of Deliverable	Date	Responsible
WP1000: Final Report	T0+18 25-09-2011	DTU
WP2100: Technical Specification and Architectural Design document	T0+3 25-06-2010	S&T
WP2200: GUT v2 (source + binary packages)	T0+11 25-02-2011	S&T
WP2400: Updated GUT User Guide and Algorithm Description document	T0+11 25-02-2011	S&T
WP2400: Updated GUT Installation Guide	T0+11 25-02-2011	S&T
WP2500: Test Plan	T0+3 25-06-2010	S&T
WP2500: Test Report	T0+12 25-03-2011	NOCS
WP3000: Report describing error correlations in the GOCE gravity field and errors associated with geostrophic currents	T0+10 25-01-2011	NU
WP4100: Plan for independent validation	T0+3 25-06-2010	CLS
WP4200: Report on validation of preliminary GOCE products.	T0+10 25-01-2011	CLS
WP5100: Basic set of requirements Solid Earth studies	T0+8 25-11-2010	IPGP
WP5200: Workflows using GUT functionalities	T0+10 25-01-2011	IPGP
WP5300: Additional functionalities	T0+11	IPGP

	25-02-2011	
WP6000: Report on MSS error characteristics	T0+11	CLS
	25-02-2011	
WP7000: Report on Software problems	T0+18	S&T
	25-09-2011	
WP8000: Toolbox promo package	T0+14	DTU
	25-05-2011	
WP8000: Scientific paper	T0+14	DTU
	25-05-2011	

GUT Website statistics

Main website page

The following charts are relative to the period from 30th of March to 13th of November. The end of March coincides with the release of GUT 2.0, right before the GOCE Workshop (Munich). The second software release of GUT, v 2.1, as made publicly available on the 12th of July.

The above chart shows the visitor trend on the main page of the GUT website (http://earth.esa.int/gut). Each segment of the plot is a week.

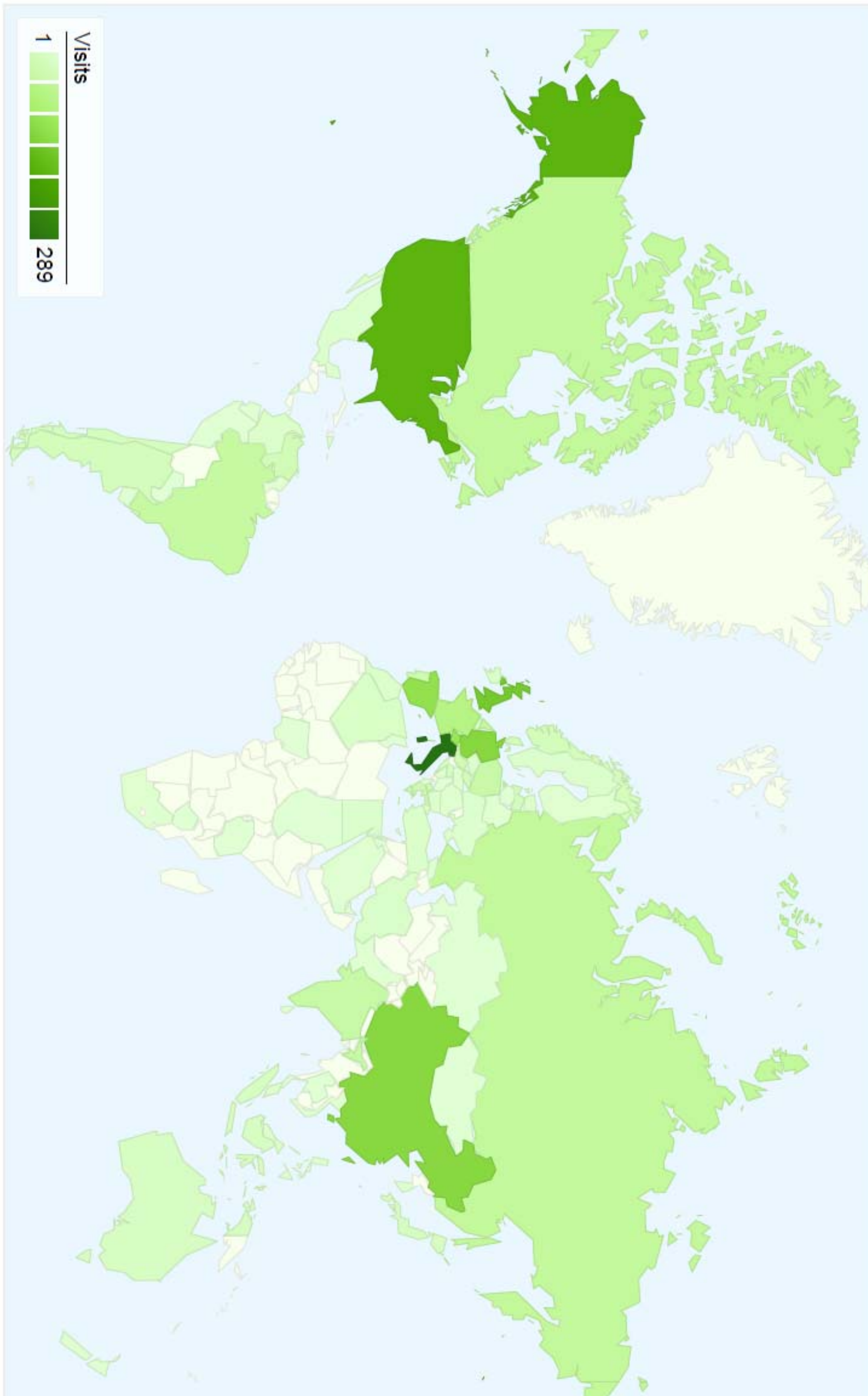
Unique Visitors: 2041

Page Views: 2962

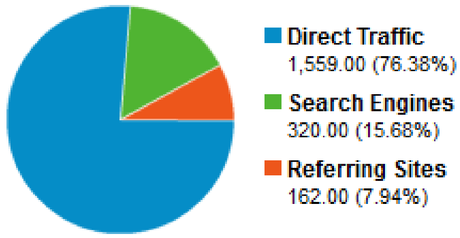
Since the tracking of the visitors started the website received over 2000 unique visitors and almost 3000 page visualizations, with about 9 unique visitors per day.

The data below shows the origin of the visitors to the GUT webpage:

Country/Territory	Visits	Visits
Italy	289	14.16%
United States	180	8.82%
United Kingdom	150	7.35%
Germany	131	6.42%
China	130	6.37%
Spain	117	5.73%
Switzerland	110	5.39%
France	69	3.38%
Canada	48	2.35%
Russia	48	2.35%



The sources to traffic to the website main page can be summarized in the following pie chart.



The search engine traffic arrived to the website by search the following keywords:

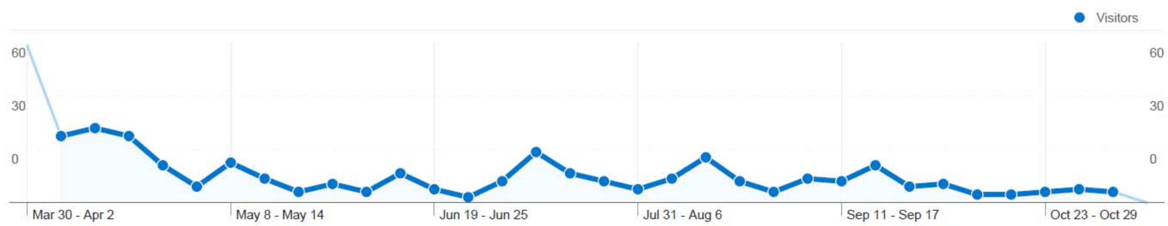
Keyword	Visits	Visits
gut esa	69	21.56%
esa gut	60	18.75%
goce user toolbox	30	9.38%
goce gut	25	7.81%
gut goce	24	7.50%
goce toolbox	11	3.44%
goce poster	7	2.19%
gut + goce	5	1.56%
selenium move mouse screen	5	1.56%
esa goce gut	4	1.25%

The top referring sites to GUT can be seen in the next image. Beside the ESA websites (#1, #3, #4), International Gravimetric Bureau (#2), Mail Servers (#5, #10), GUT Consortium websites (#6, #9), Webteam (#7) and NASA's Global Change Master Directory Search (#8).

Source	Visits	Visits
eopi.esa.int	36	22.22%
bgi.omp.obs-mip.fr	19	11.73%
envisat.esa.int	19	11.73%
earth.eo.esa.int	7	4.32%
36ohk6dgmcd1n.yom.mail.yahoo.net	5	3.09%
ganymede.ipgp.jussieu.fr	5	3.09%
eodisp-stag.netcetera.ch	4	2.47%
gcmd.nasa.gov	4	2.47%
stcorp.nl	4	2.47%
eg1a154.mail.163.com	3	1.85%

Download Page Statistics

While these numbers are different from the ones shown in the submission form, this happens because direct access hits to the download page are not counted in the .csv file, although most links are disable if the submission form is bypassed.



Unique Visitors: 582
Page Views: 1 027

Country/Territory	Visits	Visits
Italy	83	14.26%
China	60	10.31%
United Kingdom	50	8.59%
United States	47	8.08%
Poland	28	4.81%
India	25	4.30%
Germany	24	4.12%
Chile	19	3.26%
Portugal	15	2.58%
Greece	15	2.58%
Switzerland	14	2.41%
Egypt	13	2.23%
Algeria	12	2.06%
Venezuela	12	2.06%
Indonesia	10	1.72%
Morocco	10	1.72%
Russia	10	1.72%
Spain	10	1.72%
Norway	8	1.37%
Argentina	8	1.37%
France	8	1.37%
Malaysia	6	1.03%
Estonia	6	1.03%
Taiwan	6	1.03%
Denmark	6	1.03%

Download List

On the period of 30th of March to 13th of November 2011 there were **440 download** requests, 252 of which came from unique emails. That is an average of 2 effective download per day (1,92 per day, 13,75 per week.

Recommendations

Without any doubt the studies carried out in the GUTS projects and the development of the GOCE user toolbox have played a major role in paving the way to successful use of the GOCE data for oceanography. The results of the preliminary analysis carried out in this phase of the GUTS project have already demonstrated a significant advance in the ability to determine the ocean's general circulation. The improved gravity models provided by the GOCE mission have enhanced the resolution and sharpened the boundaries of those features compared with earlier satellite only solutions. Calculation of the geostrophic surface currents from the MDT reveals improvements for all of the ocean's major current systems.

Recommendations from the 4th GOCE user workshop

The 4th international GOCE user workshop held in Munich in spring 2011 was very successful in bringing GOCE data users together to exchange experiences and results from their analyses of the GOCE data and gravity models. The results and discussion following the oceanographic session spawn suggestions for a number of following up activities for securing the success of GOCE. Two activities were suggested to facilitate the use of GOCE data in oceanography: 1) workshops with participation of ocean modellers together with experts in processing altimetry and GOCE EGM data, 2) promote GOCE to students in universities; both at general level and at more advanced level. Besides, it was mentioned that in addition to the strong western boundary currents, the impact of the GOCE data for oceanography should be better investigated in lower variability areas. Also studies should be carried out in order to make best use of GOCE data in seasonally ice-covered areas, where altimetric Mean Sea Surfaces are less accurate / seasonally biased.

There seems not to exist a "best filter" for oceanography. There was agreement in the audience that the improvements in the filtering should be carried out by considering proper reliable signal/error covariance information. This would require an improved knowledge about those covariances associated with both the geoid, the MSS and the MDT. The importance of proper error estimate of the MDT for assimilating altimetry into ocean models was highlighted. Alternatively, it would be interesting to investigate if/how along-track altimetric Sea Surface Heights (above the ellipsoid) can be jointly used with the geoid height for computing Absolute Dynamic Topography and for assimilating such data directly into the models (getting rid of the intermediate MDT information).

High resolution geoid information for improved ocean modelling is needed in the coastal zones (such as shelf-slope areas). On average, the use of GOCE gravity gradients may not improve the resolution compared to the GOCE EGMs. However, in areas with a rough gravity field the gradients are expected to improve the resolution. It was mentioned that a direct use of gradients jointly with MSS information may improve the error estimates of the resulting MDT. Also, an integration of terrestrial and airborne gravity data will improve the geoid resolution locally. Alternatively, the MDT resolution may be improved by integrating the information from oceanographic data (such as drifters, ARGO floats) into GOCE derived Mean Dynamic Topography.

When using altimetric derived gravity anomalies to compute high resolution, combined geoid models, the use of a-priori MDT to correct the altimetric MSS before computing gravity anomalies may have an impact on the derived MDT. Further study is needed to characterize this impact.

In Oceanography synergy between GOCE and the altimetric mission is already very well known. Synergies with SST and SSS missions may exist. However, an integration of such information should be done in an ocean circulation model to have the physical relationship modelled. Also, synergy exists with oceanographic in-situ data (drifters, ARGO floats) for validating/enhancing the resolution of GOCE-based MDT. Synergies might be expected with scatterometer data to improve the estimation of the wind driven surface circulation to improve the comparison with drifter data. Also the promising results based on SAR to estimate total surface flow may be important to consider.

Summary of recommendations

Promotion of the use of GOCE in ocean modelling.
Recommendations:

- Demonstrate GOCE in less dynamic areas
- Promote the use of GOCE to university students
- Promote the use of GOCE to ocean modellers – workshop.

Filtering is still an important issue.
Recommendations:

- Info on signal/error covariances of geoid, MSS and MDT are needed to improve filtering
- This info is also needed to improve the estimation of the errors .
- Investigate how to use sea surface heights relative to the geoid + error estimates (and avoid the MDT)

Enhancement of the resolution of GOCE derived MDT.
Recommendations:

- Improvements are important in coastal zones and in the polar regions – and trench areas,
- Investigate improvements obtained using GOCE gradients.
- Investigate improvements using other data such as gravity data and drifters/floats.

On the use of combination models:
Recommendations:

- Investigate impact of processing issues related to e.g. altimetric gravity and the use of reference MDT models,

Synergies with other instruments/data sources:
Recommendations:

- SST and SSS through models
- Wind scat.s

- SAR

GUT 2 users feed-backs

The practical validation and testing of GUT version 2 by external users leaded to a series of recommendations for improvements of the toolbox. The user feed-backs may be grouped in the following topics:

- GUT graphical user interface (GUI),
- New workflows for Geodesy and Oceanography applications
- New workflows for more sophisticated statistics, data manipulation and data handling
- Improvement of GUT Viewer (BRAT Display)
- An accurate, efficient and fast Tool for Variance/Covariance Error Analysis
- Enhancement of Solid Earth applications and functionalities
- Documentation Improvement (tutorial, user guides, etc.)
- Alternative file formats (i.e. GOCE Gradients),
- Speed up calculation

The request for a graphical user interface to GUT was the request most important to the users.
A user feedback summary is presented in Annex A.

Way Forward for GUT version 3

During the final meeting of the GUTS phase 3 project, the recommendations coming out of the 4th GOCE user workshop, the user testing of GUT v.2 as well as the project itself were compiled into a set of recommendations for a follow up activity:

1. Software Development of GUT v.3:
   a. GUI (Priority Level -->Essential)
      A graphical user interface will make GUT much more user friendly. This may be important when GUT is introduced to a wider range of users including students that are not advanced users.
   b. New Workflows for Oceanography and Geodesy (Priority Level --> Essential)
      Thanks to the operated user feedbacks surveys, many needing functionalities have been identified and requested as workflows by GUT user community and GUT validation team for ocean and geodetic studies. This list includes workflows to handle the GOCE gradients, to speed up calculation for high DO, to compute the geoid on the Earth surface, to compute geoid on a fixed spectral bandwidth, to compute geoid slopes, gravity disturbances, downward continuation, to calculate ocean kinetic energy and vorticity potential, to change reference time period for a given MSS, to implement a diffusive/gradient filtering for ocean current enhancement, to implement new statistics methods (zonal/meridional/spectral/single point statistics), ,etc. etc.
   c. Include SE-functionality (Priority Level --> Essential)
      A series of functionalities have been identified to enhance the use of GUT for Solid Earth studies. Those functionalities, or a sub-set of those, may be implemented into GUT.
   d. Software Optimization of the “Balmino&Bingham Tool” (Priority Level --> Essential)

Rigorously the computation of error covariances should be carried out using the full error covariance matrix and the error covariances might not be modelled easily using approximate models. However, the "Balmino software" (included as separate tool in the GUT package since release v2) provides a fast and accurate way to calculate these error covariances. For GUT 3 it is requested that it be optimized in term of software quality and usability (the handling of the large data files should be addressed as well)

e. Improvement of GUT Display in handling large files (Priority Level --> Only Desirable)
   The GUT Display (derived from BRAT) suffers from memory allocation issues and slowdowns when large file are imported. If the GUT GUI is going to be implemented, this needs to be addressed and fixed to avoid system crashes.

2. Evaluation/Validation of GOCE Data Products (Priority Level --> Essential)
   a. Validation of new GOCE EGM models
      It is important to continue the validation of new GOCE EGMs from oceanographic point of view and to demonstrate and document the value of the GOCE data and models.
   b. Validation of new GOCE VCM models
      The Balmino&Bingham Tool needs to be applied to the Variance-Covariance Matrices of the new GOCE models in order to calculate their error variances and the error covariance functions. The results need to be interpreted and mean dynamic topography and geostrophic currents, Hunting details about the major current systems and smaller currents
      The impact of the GOCE data for oceanography should be better investigated in lower variability areas as well

3. Supporting scientific studies
   a. Use of gradients(Priority Level --> Highly Desirable)
      In specific regions the GOCE gradients may contain more information than the EGMs and improve the determination of e.g. the marine geoid which in turn will improve the estimation of the ocean circulation
   b. Optimal filtering, wavelets (Priority Level --> Only Desirable)
      Both spatial and spectral filtering have problems in the coastal areas and provide no formal error estimated of the filtered quantities. The use of more advanced methods for filtering, such as optimal filtering and wavelets, should be investigated.
   c. MDT Error Characterization/Integration of error covariances (Priority Level --> Essential)
      After the calculation of the error covariance function for the Geoid and the MSS performed in the frame of GUT v2, a proper/rigorous description and characterization of the MDT errors, through integration of Geoid error covariances associated with commission and omission error and the MSS error covariances, is needed.

4. Maintenance and user support (Priority Level --> Essential)
   This service is still needed.

5. Outreach (Priority Level --> Essential)
   a. HPF interaction
      The interaction between HPF and the GUT community is of mutual importance for the evolution of the GOCE products and their use. The results of the evaluation of the models are important in this interaction. It is requested that members of GUT Consortium attend constantly the HPH meeting and viceversa.

b. Workshops eg. on ocean modelling, use of sea surface heights (w/o MDT)
It is important to initiate a closer collaboration with the oceanographic modelling community to demonstrate the value of GOCE and to interact on how the GOCE models may be used in ocean modelling. The work carried out by the GOCINO project should be utilized in this process.
c. Participation to 20 Years of ERS Altimetry Workshop
d. Papers and Publications, Demonstrations and Training Kit Preparations.

ANNEX 1: Results from User Survey

How did you learn about GUT toolbox?

ESA's Living Planet	2	13%
GOCE User Workshop	6	40%
ESA/GOCE Website	4	27%
Internet (Google, etc.)	2	13%
Friend/Colleague	0	0%
Other	1	7%

Are you a regular user of the toolbox?

I have never used GUT	6	40%
I have used GUT only once	3	20%
I use it once in a while	5	33%
I am a frequent user	0	0%

Did you succeed in using GUT?

Yes	5	33%
No	3	20%
Not applicable (Never used GUT)	6	40%

Did the result meet your expectations?

Yes	6 40%
No	2 13%
Not applicable (Never used GUT)	6 40%

How easy did you find to: - Obtaining the Software

Easy	6 40%
Normal	2 13%
Hard	1 7%
Not applicable	5 33%

How easy did you find to: - Installing the Software

Easy	2 13%
Normal	6 40%
Hard	1 7%
Not applicable	5 33%

How easy did you find to: - Using pre-installed workflows

Easy	1 7%
Normal	4 27%
Hard	1 7%
Not applicable	8 53%

How easy did you find to: - Creating a workflow

Easy	0	0%
Normal	4	27%
Hard	1	7%
Not applicable	9	60%

How easy did you find to: - Understating errors (if they happen)

Easy	0	0%
Normal	1	7%
Hard	3	20%
Not applicable	10	67%

How easy did you find to: - Visualizing the output data with BratDisplay

Easy	1	7%
Normal	3	20%
Hard	2	13%
Not applicable	8	53%

How easy did you find to: - Handling output data

Easy	1	7%
Normal	3	20%
Hard	1	7%
Not applicable	9	60%

How easy did you find to: - GUT usage in general

Easy	2	13%
Normal	3	20%
Hard	1	7%
Not applicable	8	53%

What improvements would you like to see in the upcoming releases of GUT?

Ability to read other Data (if checked specify below which one)	3	21%
Ability to write output in other Data format (if checked specify below which one)	2	14%
Graphical User Interface	4	29%
Easier access to GOCE data	5	36%
More Information in the user manual/website	2	14%
Implementation of new algorithms/workflows (if checked specify below which one)	2	14%
Addition of new data in the a priori data package	0	0%
Improvement of the BratDisplay	1	7%
None, GUT is perfect	0	0%
Other (if checked specify below which one)	6	43%

People may select more than one checkbox, so percentages may add up to more than 100%.

What is the Operating System where you use GUT?

Linux	9	64%
Mac	4	29%
Windows	11	79%
Other Unix System	2	14%

People may select more than one checkbox, so percentages may add up to more than 100%.

Did you download the Source Code or the Binary Installers?

Source Code	2	20%
Binary Installation	9	90%

People may select more than one checkbox, so percentages may add up to more than 100%.

Fields of Interest

Geodesy and Geophysics	9 75%
Solid Earth	1 8%
Oceanography and Current Circulation	5 42%
Climate and Sea Level Change	1 8%
Atmosphere, winds and waves	0 0%
Cryosphere	0 0%
Industry	1 8%
Education	0 0%
Other	0 0%

People may select more than one checkbox, so percentages may add up to more than 100%.