EXPLOITATION OF GOCE DATA FOR A LOCAL ESTIMATE OF GRAVITY FIELD AND GEOID IN THE PIEMONTE AREA (NORTHERN ITALY)

R. Barzaghi(2), R. Conte(1), G. Falletti(3), A. Maggi(2), M. Martino(3), F. Migliaccio(2), M. Reguzzoni(2), F. Sansò(2), F. Solitro(3), N. Tselfes(2)

(1) Protezione Civile Regione Piemonte, Corso Marche, 79, 10146, Italy
(2) Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133, Italy
(3) ALTEC S.p.A., Corso Marche, 79, 10146, Italy

ABSTRACT

This paper describes the activities carried out by a working group that comprises the Civil Protection Department of Regione Piemonte, Altec S.p.A. (Advanced Logistic Technology Engineering Center) and Politecnico di Milano, regarding the exploitation of GOCE data for a local estimate of gravity field and geoid in the Piemonte area.

The idea of the project was conceived in July 2004; the different groups operate as follows: Altec is prime contractor of the project and responsible for the coordination of the work, development of the demonstrative and/or operative products, analysis of the user requirements; Politecnico di Milano is responsible for the technical and scientific analysis and the development of specific algorithms needed for the modelling of the local gravity field and the geoid; Civil Protection of Regione Piemonte is interested in gravimetric and seismic applications (new gravity field map of the Piemonte area and evaluation of solid earth processes – geodynamics).

The “GOCE Data for Civil Protection” Project started in February 2005. The main activities of the project are the following: analysis of the requirements of Civil Protection of Regione Piemonte; collection of gravimetric data at ground level and data validation; definition of technical procedures to estimate the gravity field and to evaluate the actual impact of GOCE data in the local geoid estimation procedure; integration of GOCE simulated data for the Piemonte area with gravimetric data at ground level; development of a “tool box” for the applications of the project, based on the exploitation of data collected over the area of interest and on software specifically developed with the aim of data updating, of evaluating project products, and possibly of identifying new potential applications (training, education, product promotion, etc).

Most of the scheduled activities have been already carried out successfully. In particular, the scientific approach has proved the positive impact of the GOCE information on the local geoid estimation using simulated data. Besides, a specific “tool box” is well under construction and can now be used to estimate the gravitational field and the geoid in the Piemonte area, and to compute point-wise values. When the project will be completed, in the frame of a specific GIS, it will be possible to integrate a new gravimetric map of the Piemonte area with other data and also to compare the Piemonte geological map with gravimetric data.

1. INTRODUCTION

The primary objective of the GOCE mission is to provide global and regional models of the Earth gravity field and the geoid, with high spatial resolution and accuracy. A precise model of the Earth’s geoid is crucial for deriving accurate measurements of ocean circulation, sea-level changes and terrestrial ice dynamics. The geoid is also used as a reference surface for mapping applications. Besides, an improved knowledge of gravity anomalies will contribute to a better understanding of the Earth’s interior, such as the physics and dynamics associated with volcanism and earthquakes.

The integration of data from the GOCE mission with geodetic data from on ground measurements can prove fundamental to obtain a more complete and deeper knowledge of the terrestrial gravity field in a specific region.

The “GOCE Data for Civil Protection” Project, whose results and products are described in this paper, was started up with the concept that a gravimetric map and a digital terrain model of Piemonte (in north-western Italy), defined with a good accuracy, would allow to develop a geophysical model for the improvement of tectonics study, bedding fault knowledge and seismic zone control.

The main objective of the project is to define and evaluate, before the launch of the GOCE mission, a methodology for the integration of ground gravimetry and GOCE data for a local estimate of gravity field and geoid in the Piemonte area.
The principal results of the project are:
- a gravimetric map and a geoid estimate for the Piemonte area, based on a validated database containing all the data at ground level (local gravimetric data, DTM, levelling data, etc.);
- a methodology for merging GOCE and ground level data which has been tested with proper simulations;
- an operative “tool-box” to manage the developed products.

Regarding the last point, it refers to a product operative instrument, which has been developed based on the exploitation of data collected during the project and software procedures. It is intended as a multimedia tool for the execution of operative evaluation of project products, for data updating and for the identification of new potential applications (training, education, product promotion, etc).

2. THE PIEMONTE GRAVITY FIELD AND GEOID: AN ESTIMATION BASED ON GROUND GRAVITY DATA

A large number of gravity data (free-air gravity anomalies), available in an area 6° × 6° centered on Piemonte (42° ≤ ϕ ≤ 48°, 5° ≤ λ ≤ 11°), was collected from different sources: ENI (Ente Nazionale Idrocarburi) and NIMA (National Imagery and Mapping Agency). These data have a high density, with a mean density of 1’, but there are some areas in the Alps still characterized by poor coverage. This database is shown in figure 1.

The gravimetric data may contain some incorrect values due to instrumental errors or different reference systems, so a procedure for the detection of outliers was developed and applied. This procedure is essentially based upon statistical tests applied to the residual gravity anomalies that rule out values having a large difference with respect to the nearest values. The residual gravity anomalies were obtained by subtracting the effect of the GPM98 global model [12] and the residual terrain correction, calculated from an accurate digital terrain model from the satellite mission SRTM [8], with spacing of 100 m. The correct database finally contains about 84,000 values.

Then the residual gravity anomalies were interpolated on a regular grid, with spacing of 1’ and with boundaries 43° ≤ ϕ ≤ 47°, 6° ≤ λ ≤ 10°, using the well-known collocation technique [6]. The aim of the interpolation was to get a dense and regular gravity field over the whole selected area. Collocation was tested together with kriging [11] and simple weighted mean, however collocation proved to be the most accurate interpolation technique, with an error variance less than 2% of the signal variance.

From this interpolated grid it was then possible to estimate the geoid undulation applying the fast-collocation technique [1]. Moreover a free-air gravity anomaly grid and a Bouguer anomaly grid from the residual gravity anomaly grid were obtained. The estimated geoid undulation was checked by calculating it on a set of control points with geoid undulations obtained from leveling and GPS measurements [10]. The undulation differences for about 300 points have a standard deviation of the order of 10 cm, indicating a good accuracy of the geoid. In figure 2 the geoid undulation is shown.

![Figure 1: The gravimetric database in the North-West area of Italy](image1)

![Figure 2: The geoid undulation (m) in the North-West area of Italy](image2)
A further improvement of the estimate was obtained by combining gravity and GPS/leveling derived undulations. The method used to combine the two data sets was collocation, which allows data combination via the propagation of covariance. The final result is a geoid estimate having a higher precision which is around 4 cm (r.m.s. error).

### 3. IMPACT OF THE GOCE INFORMATION ON THE LOCAL GEOID ESTIMATION

The satellite mission GOCE (Gravity field and steady-state Ocean Circulation Explorer), designed by ESA (European Space Agency), will be launched in 2007. It is dedicated to measuring the Earth’s gravity field and modelling the geoid with extremely high accuracy and spatial resolution [2]. The main instrument on board the satellite is the “gradiometer” that is composed by six accelerometers and measures the second derivatives of the gravitational potential (the so-called gravity gradients) along the satellite orbit. More information on the gravity field will be derived from the tracking of the satellite orbit by means of a GPS receiver. The effects of non-gravitational accelerations on the orbit have to be accounted for in order to derive the best possible gravity field model.

Tests have been performed for evaluating the effect of using GOCE data to improve the knowledge of the local geoid undulation. The improvement can be obtained in two different ways: a new global gravity field model, calculated from the GOCE data, and the availability of new data, e.g. the second radial derivative data ($T_{rr}$). The study was carried out using “realistic” simulated data representing a possible scenario, that means data with similar characteristics of noise, spatial resolution and frequency as those which will be expected from the satellite mission. In particular 6 months of data were simulated with a sample rate of 1 Hz and the orbit was calculated from the model EGM96 up to degree 50 [3]. The second radial derivative was simulated from GPM98, up to degree and order 720; it has a coloured noise with standard deviations of 5 mE.

According to ESA contract No. 18308/04/NL/NM (GOCE High-level Processing Facility), the global gravity field model will be estimated by three different approaches [11]. Politecnico di Milano and University of Copenhagen have developed the so-called “space-wise” approach [5]. In this approach a spherical harmonic model of the gravitational potential is computed by integration of GOCE data (potential and gradiometric observations) interpolated on a spherical grid. The simulations have shown that this global model should have a lower error degree variance (obtained from the differences between true coefficients and estimated coefficients) in the long wavelengths ($\ell < 200$) with respect to the currently used global models like EGM96, as we can see in figure 3.

![Figure 3: Error degree variances](image)

This improvement causes as a consequence a decrease in the error of geoid undulation in the long wavelengths. The effect on a local geoid was calculated in the area $42^\circ \leq \varphi \leq 48^\circ$, $4^\circ \leq \lambda \leq 12^\circ$, and results in an improvement of accuracy of one order of magnitude, with the standard deviation decreasing from about 10÷15 cm to 2÷3 cm. In fact, this will be the main contribution of GOCE to local gravity field modelling, since long wavelength errors cannot be corrected by local gravity data [4]. The results can be seen in figure 4.

Another aspect that was considered in this work deals with directly exploiting the effect of the second radial derivative data in the estimate of the local geoid undulation.

In this case gravity anomalies and second radial derivatives were used as inputs in collocation and geoid undulation was the output. Gravity anomalies and geoid undulations were simulated on the real grid at ground level as seen in the previous chapter, the gravity anomalies had a white noise with standard deviations of 6 mGal, and the geoid undulations were considered “true” values without noise. The residuals of all functionals were calculated by subtracting a long wavelength model different from the model used for the simulation: in this case the EIGEN_CG03C model up to degree and order 360 was used as reference model [6]. Collocation was applied using about 2,000 values of $T_{rr}$ (undersampled) and 2,400 values of $\Delta g$: 441 undulations values were predicted and compared with the simulated values.
Three cases were considered: prediction using only $\Delta g$, using only $T_{rr}$, and finally using both functionals. The results are summarized in Table 1.

What can be seen is that the use of $T_{rr}$ only produces a worse result than the case of $\Delta g$ as only input, but the use of both functionals causes the empirical r.m.s. to decrease from decimetres to centimetres level. This effect is probably produced by the long wavelength information contained in $T_{rr}$ that partly corrects the error of the reference model. Figure 5 shows the spatial distribution of the empirical errors.

<table>
<thead>
<tr>
<th>Input</th>
<th>r.m.s. (empirical)</th>
<th>s.t.d. (empirical)</th>
<th>r.m.s. (predicted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta g$ only</td>
<td>16.3 cm</td>
<td>5.2 cm</td>
<td>10.0 cm</td>
</tr>
<tr>
<td>$T_{rr}$ only</td>
<td>17.1 cm</td>
<td>16.8 cm</td>
<td>17.5 cm</td>
</tr>
<tr>
<td>$\Delta g$ and $T_{rr}$</td>
<td>3.9 cm</td>
<td>2.6 cm</td>
<td>3.3 cm</td>
</tr>
</tbody>
</table>

In the end, the results of this realistic simulation are promising, because they show that the use of GOCE data can improve the accuracy of local geoid undulation of one order of magnitude, both subtracting a new reference model calculated from GOCE data and integrating $\Delta g$ and $T_{rr}$ in the collocation technique.

4. DEMONSTRATIVE TOOL-BOX

A tool-box for the specific applications of the project has been conceived, with the aim of facilitating the “easy use” of the developed/to be developed operative products. It is composed of data collected over the area of
interest (local gravimetric data, DTM, levelling data, etc.) and on specifically developed software. The architecture of the tool-box will allow any user to substitute and integrate data and software routines to extend the exploitation for individual applications.

The principal operative objectives of the tool-box are:
- evaluating project products
- updating data
- identifying new potential applications
- training, education
- product promotion.

4.1 Requirements

The functionalities of the demonstrative tool-box have been selected on the basis of the following user requirements:
- production and visualization of a new regional gravimetric map (static visualization of data with respect to regional maps)
- point-wise estimate of the geoid
- gravity profile estimate along a path defined by the user
- visualization/comparison of the Piemonte area geological maps with geodetic maps generated by databases
- visualization of regional DTMs
- visualization of "Gravity Map of Italy. CNR Progetto Finalizzato Geodinamica a scala 1: 500.000, anno 1991"
- evaluation of advantages that can be obtained by introducing data from a regional network of GPS permanent stations
- updating the databases, on the basis of new data availability, and validation
- updating maps on the basis of new data availability
- tools based on methodology for seism-genetics analysis.

4.2 System design

Figure 6 describes the global architecture of the tool-box prototype under development.

It is constituted by two major processing modules, covering two different data processing phases:
- Pre-processing module
- User module.

The Pre-processing module contains the algorithms and the different processing pipelines that lead to the final validated Gravity Database for the Piemonte area.

Figure 6: Architecture of the demonstrative tool-box

The Pre-processing prototype includes two different processing pipelines:
- The first process works only on gravity data measured on ground and obtained from different sources and with different methods. The pipeline processes perform the computations as described in chapter 2, namely data selection, outlier analysis, bad data exclusion, interpolation and finally computation of the gravity databases (free-air and Bouguer gravity anomalies, geoid estimation). This pipeline is based on a sequence of Fortran programs that generate proper output to be used for the verification and validation of the produced data.
- The second process takes the validated gravity anomalies obtained from ground measurements as input and integrates this data set with GOCE data for the same geographic region, as described in chapter 3. The result is a new database (free-air and Bouguer gravity anomalies, geoid estimation). This pipeline includes a set of algorithms developed using Matlab software.

The first pipeline of the pre-processing module has been used for obtaining a validated database for the gravity anomalies based on ground measurement only, which can be immediately used by the final user for any specific analysis.
The second pipeline, at the present stage, has been used based only on simulated data from GOCE, and thus only for providing an initial assessment of the improvement coming from the usage of both satellite and ground data.

The pre-processing module is expected to be run each time new gravity data will be available from a new measurement campaign, thus providing updating of the validated database. This applies also when GOCE data will be available, converting the data product from a “simulated” to a real one.

The User Module provides the set of software tools that allows the end user to access the Gravity Database and perform the required analysis. It also allows the access to all available user specific data, like DTM, maps, etc. and their utilization for subsequent analysis.

This module includes three major components:

- The user interface module, providing an easy way to the user for selecting the data necessary for the analysis and automatically starting the proper visualization (dedicated scripts are used for interfacing with the other two modules)
- The visualization and analysis tools, a set of COTS (Commercial Off-The-Shelf) software, like e.g. Surfer, or open source tools that support advanced visualization and data analysis
- The computation module, providing the software routines for the correct data analysis of the gravity database content, namely:
  - Single point gravity analysis
  - Path gravity analysis

To-date the selection of the software tools for the user module has been based on limiting as much as possible new software development and on using tools already available and well known to the end user, in order to simplify the immediate utilization of the prototype. This is true mainly for the visualization and analysis tools, for which a COTS software like Surfer has been used, but the architecture has been designed in order to allow an easy replacement (for example using open source software running also on non-Windows platform). The user interface has been developed in JAVA, while the software routines for the computation modules have been developed in Fortran.
5. CONCLUSIONS

The project presented in this paper for the Piemonte area proves to be able to reach the proposed objectives, in particular:

- the developed products can be directly and easily utilized by means of the demonstrative tool-box;
- the products based on ground measurements already represent an improvement in the knowledge of gravimetric features of Piemonte area, in terms of data updating, better gravimetric coverage, and better accuracy of geoid undulation;
- a demonstration has been obtained of the possible improvement given by the integration and processing of data at ground level with GOCE simulated data. The effect on a local geoid was calculated in the area $42^\circ \leq \varphi \leq 48^\circ$, $4^\circ \leq \lambda \leq 12^\circ$, and resulted in an accuracy improvement of one order of magnitude, with the standard deviation decreasing from about $10\pm 15$ cm to $2\pm 3$ cm.

The project results are extremely encouraging and we have great expectations with regard to the use, in the next future, of the real data from GOCE mission.

Acknowledgments. We acknowledge ENI Company for the permission to use gravity data from their database (updated to 2004) and Dr. S. Rao, Settore Cartografico Regionale Piemonte, for providing the regional DTM and levelling/GPS data.

References

