

# ITALIAN GEODETIC RESEARCH ACTIVITIES IN THE PERIOD 2007-2011



## IAG REPORT

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ITALIAN DELEGATE TO IAG

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In 2003 after the IUGG General Assembly in Sapporo, IAG has been reorganized following a modern vision of Geodesy in the international scientific forum, according to the following components structure:

Commissions  
Services  
Inter Commission Committees  
Communication and Outreach Branch  
Projects

Shortly, the Commissions, which embody the main activity of scientific research, are

Commission 1	Reference Frames
Commission 2	Gravity Field
Commission 3	Earth Rotation and geodynamics
Commission 4	Positioning and Applications

The services could be clustered into so called geometric services, mainly related to space techniques, and gravity field services, federated into a unique IGFS (International Gravity Field Service) structure. They are naturally related to one or other commission and, in the last four years period, they have found a larger coordinating component into the IAG project called GGOS (Global Geodetic Observing System).

In the period 2007-2011 the Italian geodetic community has been working in the frame work of all the IAG structures. What follows is a short report on this activity organized in accordance to the Commissions structure. The bibliographic list has been strongly restricted to relevant contributions.

A short report on the activities in the framework of ICCT (Intercommission Committee on Theory) follows.

From the organizing point of view four main activities have to be mentioned:

- the Italian Space Agency, through its staff at the Centro di Geodesia Spaziale in Matera, head by Dr. Giuseppe Bianco, has taken over the job of the secretariat of GGOS,
- the OGS (Istituto Nazionale di Oceanografia e Geofisica Sperimentale) has offered to IAG the support for the Bureau of IGFS, under the chair of prof. Iginio Marson,
- the University of Roma “La Sapienza” has hosted the VII Hotine Marussi Symposium in Rome, with the support of the Local Organizing Committee, chaired by prof. Mattia Crespi,
- an international school on the Computation and Use of the Geoid has been held in 2008 in Como.

The report has received contributions from:

Commission 1: L.Biagi, A.Borghini, A.Caporali, P.Sarti, V.Tornatore, L.Vittuari, G.Bianco, V.Luceri, R.Pacione, F.Vespe, S.Gandolfi, M.Barbarella, R.Maseroli

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## Commission 1 : Reference Frames

*Reference systems and frames are of primary importance for many Earth science researches and applications, satellite navigation as well as for practical applications in geo-information.*

*Commission 1 activities and objectives are to deal with theoretical aspects of reference systems and the practical applications for their realizations as well as applied researches.*

### **(Dr. L.Biagi)**

In the framework of IAG Commission I, studies and activities have been conducted by several researchers in different institutions. Synthetically, the list of the topics is the following.

1. time series analysis,
2. deformation analysis,
3. co-location,
4. NEQ stacking,
5. VLBI observations of Global Navigation Satellite Systems
6. EUREF activities,
7. National Dynamic Network,

The detailed description of the researches is provided.

### **Time series**

A new methodology has been studied in defining the stochastic model of the GPS coordinates time series. When the residual data, after linear and periodic trend reduction, behave as a stationary and ergodic stochastic process, the noise characteristics of the GPS signal can be analyzed through the empirical auto-covariance Function (ACF). If the stationary condition is satisfied, the empirical ACF can be estimated without any assumption about the spectrum of the data (i.e. PLNP), and the proper stochastic proprieties of the time series can be derived interpolating the empirical ACF, in a rigorous and fast method, using proper model covariance function.

By considering observed GPS time series, it can be proved that the stationary behaviour of the GPS residuals is satisfied in most of the cases, especially when the data are properly reduced for periodic components by means of the analysis of the periodogram. Furthermore, the time series residuals show very short time correlation, typically 10-14 days, whereas the ARIMA(0,d,0) process with positive d are more appropriate for slowly decaying sample autocorrelation function.

### **Deformation analysis**

A new approach has been developed to estimate the invariant deformation parameters from the time series of coordinates provided by GNSS permanent networks. In the proposed approach the regional deformation is modelled as a process which is linear-deterministic in time and stochastic with respect to space. The time series of 2D coordinates are interpolated to estimate the sites displacements; the spatial field of displacements and deformations is then predicted through a minimum mean square error principle. Prior trend removal is based on the transformation to a new reference system satisfying a discrete Tisserand principle. In the time interpolation, special emphasis is given to the empirical estimation of the displacements covariances; in the spatial interpolation, a new approach to model the covariance structure of the displacements and the rigorous estimation of the accuracies of the predicted deformation parameters have been studied. The implementation of all the proposed algorithms has been completed: a test on a one year period of data stemming from the national Japanese permanent network has provided the first results on real data.

### **Co-location**

Tie vectors (TVs) between co-located space geodetic instruments are essential for combining terrestrial reference frames (TRFs) realised using different techniques. They provide relative positioning between instrumental reference points (RPs) which are part of a global geodetic network such as the international terrestrial reference frame (ITRF). The VLBI of Medicina and Noto (Italy) are a 32-m twin antennae that were surveyed several times, adopting an indirect method, for the purpose of estimating the eccentricity vector between the co-located VLBI and Global Positioning System instruments. In order to fulfill this task, targets were located in different parts of the telescope's structure. High accurate topographical measurements on the targets, and laser scanner measurements of the dish at different elevations of the antenna, highlight a consistent amount of deformation that biases the estimate of the instrument's reference point height up to 1 cm, depending on the targets' locations. Therefore, whenever the estimation of accurate local ties is needed, it is critical to take into consideration the action of gravity and thermal deformations on the structures. Furthermore, deformations induced on VLBI telescopes may modify the length of the path travelled by the incoming radio signal to a non-negligible extent. As a consequence, differently from what it is usually assumed, the relative distance of the feed horn's phase centre with respect to the elevation axis may vary, depending on the telescope's pointing elevation. This demonstrates the need to precisely measure gravitational deformations of other VLBI telescopes and to apply them in routine geodetic data analysis.

### **NEQ stacking**

The daily processing of big networks requires a distributed adjustment. To apply it, usually the network is split into overlapping subnetworks in such a way that each station belongs to several subnetworks. On a daily basis, each subnetwork is daily processed by one Processing Facility (PF): all the daily subnetworks solutions are transmitted to a coordination center and are combined by NEQ stacking to produce a network solution. The final solution can be obtained either by a daily or by a weekly stacking. This approach introduces duplicated observations because the same daily files are processed by more PF's. In particular, it builds false independent repeated baselines and closed polygons among different subnetworks. An alternative approach has been proposed, that allows the rigorous combination of overlapping networks by stacking solutions that are really independent. Each day the network is split into simply connected subnetworks and the daily configuration of the split varies in a cycle over more days. In different days, each station is included in different subnetworks, in such a way that the subnetworks overlap at the end of the cycle. At the end of the cycle, the daily solutions of all the subnetworks are combined in a final solution. On a daily basis, this approach is comparable to the batch adjustment of the whole network: in particular no false repeated baselines and closed polygons are built. At the end of the cycle it allows the rigorous combination and the cross check of subnetworks that overlap and have been independently estimated. The different splitting techniques have been compared by analyzing their respective advantages and disadvantages on realistic case studies.

### **VLBI observations of Global Navigation Satellite Systems**

The VLBI technique (geodetic mode), was used to observe signals emitted by some GLONASS (GLOBAL NAVIGATION Satellite System) satellites. The baseline, observing simultaneously, one by one, each satellite had at its ends Medicina (32 m) and Onsala85 (25 m) radio telescopes. The goals of such tests were to develop and check the scheduling, signal acquisition and processing routines to verify the full tracking pipeline, foreseeing the cross-correlation of the recorded data at least on a single baseline. Software tools, primarily developed for spacecraft tracking, proved to be very important to be used to analyze also signal emitted by GLONASS satellites. A narrow band approach using the high-resolution spectrometer software SWSpec and SCTracker developed at Metsähovi Radio Observatory and JIVE (Joint Institute for VLBI in Europe) was applied to extract the narrow band carrier. Differential frequency on the baseline Medicina-Onsala was also evaluated to compute differential phase which was then adopted to determine satellite coordinate corrections with respect to ITRF values, such corrections were found to be of the order of 10 cm. Broad band correlation was also performed both on calibrator and satellite data using the SFXC software developed at JIVE. Correlation fringes were found, but some problems are still present in the results, a bias of several nanoseconds was found in the residual delays. Currently we are busy with fine tuning of our delay model for near field objects. Then an EVN (European VLBI Network) proposal has also been recently submitted to extend the network of observing stations to achieve baseline redundancy required for better estimates of geodetic parameters and to observe satellite of other GNSS constellations.

### **EUREF activities within EUREF TWG**

An Italian scientist (A. Caporali) is a member of EUREF TWG, in which he has worked on the following topics

1. Local Analysis Center UPA for the EPN (European Permanent Network) of EUREF
2. GNSS Station PADO contributes to the IGS, EPN and CEGRN
3. Participation to the Technical Working Group of EUREF
4. Participation to the Thematic Working Group 'Reference Frames' and 'Geographic Grids' for the EU Directive INSPIRE
5. Support to the computation of the Rete Dinamica Nazionale, which realizes ETRS89 in Italy as a ETRF2000 frame
6. Weekly computation of a network of 150 GNSS permanent stations in Italy and surrounding areas for reference frame maintenance, and publication of a Bulletin on the WEB
7. Maintenance and management of a regional network of 25 permanent GNSS stations for reference frame densification, on behalf of the Regional Authority for Geodesy and Cartography

### **Institution and monitoring of the new zero order Italian network: Dynamic National Network (RDN)**

A first research was conducted to verify the feasibility of a permanent zero order network in Italy. In 2008 the new Italian zero order network, called Dynamic National Network (RDN) has been established by Istituto Geografico Militare (IGM, the official cartographic Italian agency); RDN is composed of 100 permanent stations that, at the present, are not permanently monitored. Five campaigns, six months spaced, each one of four weeks have been acquired and processed by three independent analysis centres, with particular attention to the transformation of the results from IGS05 to ETRF2000. Procedures are being developed to automate a continuous monitoring of RDN.

### **(Dr. G.Bianco)**

#### **Italian Space Agency/Space Geodesy Center "G. Colombo" (ASI/CGS)**

The ASI Space Geodesy Center "G. Colombo" (CGS) has contributed to the IERS Technique Centers (ILRS, IVS, IGS/EUREF) since the beginning of the Service activities both in its role of fundamental station and analysis center. The SLR data analysis activities at the ASI/CGS started in the 80's, the VLBI and GPS data analysis activities in the '90s and, since then, have been focused primarily on global, extended solutions in support of the reference frame maintenance. Due to the multi-technique nature of the CGS mission, geodetic technique combination methods and applications are a top priority objective of the data analysis activities performed at the center.

The ILRS Governing Board recognized ASI/CGS's continuous and rigorous contribution and appointed it as one of the official ILRS Analysis Centers (ACs) when the ILRS AC structure was finalized (2004). In June 2004 the Center was selected by the International Laser Ranging Service (ILRS) as its primary Official Combination Center (CC) for station coordinates and Earth Orientation Parameters.

ASI-CGS is an official IVS Station, Data Center and Analysis Center since the beginning of the service (1999).

ASI-CGS is EUREF LAC since 1996, producing since then the requested solutions for the European reference frame densification and tropospheric applications, including all the GPS sites from the ASI Italian GPS Fiducial Network since their establishment (12 sites at present). In the recent times (2009), ASI-CGS became also an EUREF NTRIP Broadcaster for Real Time data and solutions from the EPN.

ASI-CGS has been participating since 1999 to many GPS Meteorological projects (COST 716, MAGIC, TOUGH, E-GVAP) and is presently participating to E-GVAP II (2009-2013, contribution to the operational meteorology) as Analysis Center and Combination Center.

Information on the CGS and some of the analysis results are available at the CGS WWW server GeoDAF (Geodetic Data Archiving Facility, <http://geodaf.mt.asi.it>).

## **SLR Data Analysis at Matera ASI-CGS**

### **ILRS Activities**

In the year 2007-2010, the ASI/CGS has been deeply involved in the ILRS activities, mainly in support of the reference frame maintenance and under the coordination of the Analysis Working Group.

The center's main contributions as ILRS Analysis Center were:

### **Pos+EOP products**

- weekly submission of loose coordinate/EOP solutions estimated using LAGEOS and ETALON data and following the project requirements. The product is the ASI/CGS input to the official ILRS combined SSC/EOP product.
- daily submission of loose coordinate/EOP solutions estimated using LAGEOS and ETALON data and following the AWG requirements. The product is the ASI/CGS input to the official ILRS combined EOP product that is still in a pre-operative phase.

### **Weekly orbits**

satellite ephemerides for Lageos and Etalon, using the solutions of the ILRS ACs, will be one of the future AWG products. The ASI/CGS estimated state vectors of the 4 satellites are distributed weekly, as requested by the AWG, in the same loose reference frame of the SSC/EOPs as input to the combination.

### **Contribution to ITRF2008**

the time series of weekly loose solutions, from 1983.0 to 2009.0, with estimated site coordinates and EOPs and obtained using LAGEOS and ETALON data, has been submitted as ASI/CGS input to the ILRS combination for the generation of ITRF2008. Each weekly solution has followed the AWG guidelines, bias included.

### **Station qualification**

ASI/CGS is one of the ACs designated by the AWG to validate the data from new or upgraded sites or after an earthquake.

### **CRD validation**

ASI/CGS is one of the ACs designated by the AWG to validate the data submitted by the station in the new CRD format.

### **Bias monitoring**

a routine activity is carried out to compute data corrections whenever the biases are not reported by the station, in close contact with the station engineers.

The center's main contributions as ILRS Combination Center were:

### **Contribution to ITRF2008**

The official ILRS solution, ILRSA (2009) covers a long period, more than 25 year and has been obtained by a direct combination of the loose constrained solutions provided, as final version, in the late Spring 2009 by seven official ILRS ACs (ASI, DGFI, GA, GFZ, GRGS, JCET, NSGF), each one following strict standards agreed upon within the ILRS Analysis Working Group. The remarkable coherence of the contributing ILRS AC series makes the final combined estimates very accurate and the main components (linear trend and small amplitude annual periodic term) of the derived origin and scale time series very neat. During 2010, ITRF2008 validation and assessment activities took place and the results discussed inside and outside the ILRS context.

### **Pos+EOP products**

- weekly submission of the ILRS official solution (ILRSA) derived from the combination of individual contributing SLR solutions based on the observations to Lageos 1-2 and Etalon 1-2 satellites. The ILRSA solutions contain weekly coordinates of the worldwide SLR tracking network and daily EOPs (xpole, ypole, LOD), ITRF-framed for IERS Bulletin B and EOPC04
- daily submission of the combined coordinate/EOP solutions computed using the individual AC contribution. The final product will contain daily EOPs, ITRF-framed with a constant, minimum latency of two days and is still in a pre-operative phase.

Periodic evaluation of the submitted solutions as well as of the final official products were presented at the ILRS AWG meeting to support ACs data analysis activities.

### **Non-ILRS Activities**

The ASI/CGS analysis activities extend beyond the accomplishment of its role within ILRS and were addressed in the following main application fields.

#### **International Terrestrial Reference System (ITRS) maintenance**

- production of IERS oriented products (global SSC/SSV and EOP time series) regularly performed as ASI/CGS operational EOP series: 1-day estimated EOP, from LAGEOS and ETALON data, are available at the IERS website <ftp://hpiers.obspm.fr/iers/series/operational/>;
- generation of the multi-year solution ASI10L01, from Lageos I and II data (1983-2010). Global network SSC/SSV and 3-day EOP (x, y, LOD) are the main parameters estimated in this solution and available under request.

### **VLBI Data Analysis at Matera ASI-CGS**

#### **IVS Activities**

In the year 2007-2010, the ASI/CGS has been deeply involved in the IVS activities.

#### **Global VLBI Solutions**

Every year, global VLBI solutions are produced, including all the observation sessions since 1979 onwards (at present, about 4000 sessions); the most recent solutions are cgs2007a, cgs2008a, cgs2009a, available at the IVS products ftp sites and realized using the CALC/SOLVE software (developed at NASA/GSFC). The estimated parameters of the global solution are:

- Celestial Frame: right ascension and declination as global parameters for 637 sources
- Terrestrial Frame: Coordinates and velocities for 92 stations as global parameters
- Earth Orientation: Unconstrained X pole, Y pole, UT1, Xp rate, Yp rate, UT1 rate, dps, and deps.

#### **IVS Tropospheric Products**

Regular submission of tropospheric parameters (wet and total zenith path delays, east and north horizontal gradients) for all VLBI stations observing in the IVS R1 and R4 sessions has been performed in 2007-2010 period. The analysed sessions cover the period from 2002 onwards; the results are available on the IVS products ftp sites.

#### **IVS Pilot Project “Time Series of Baseline Lengths”**

Regular submission of station coordinate estimates, in SINEX files, has been performed in 2007-2010 period for the IVS pilot project “Time Series of Baseline Lengths”. The series is composed of about 4000 sessions, from 1979 onwards.

#### **CGS Contribution to IERS EOP Operational Series**

Since 2008, ASI-CGS has been delivering IERS R1 and R4 session EOP estimates as a regular contribution to the IERS EOP operational series. The cgs2007a solution, available when the contribution started, has been delivered to IERS as a reference series updated by the periodic EOP solution submission.

## **GPS Data Analysis at Matera ASI-CGS**

### **EUREF/IGS Activities**

#### **EPN Final weekly product**

ASI-CGS provides “Final” weekly products (Coordinates and ZTD) since September 1996, using IGS Final products, now covering a European subnetwork (41 sites) including all the ASI Italian GPS permanent stations; solutions have been realized using the VMSI Microcosm SW up to 2010 and the JPL GIPSY/OASIS SW since 2011.

#### **EPN Rapid daily product**

ASI-CGS provides “Rapid” daily products (Coordinates and ZTD) since March 2007, using IGS Rapid products, covering the same subnetwork (41 sites) including all the ASI Italian GPS permanent stations; solutions have been realized using the VMSI Microcosm SW up to 2010 and the JPL GIPSY/OASIS SW since 2011.

#### **EPN NRT hourly product**

ASI-CGS provides “NRT” hourly products (Coordinates) since September 2007, using IGS Ultra-Rapid products, covering the same subnetwork (41 sites) including all the ASI Italian GPS permanent stations; solutions have been realized using the JPL GIPSY/OASIS SW since the beginning.

#### **EUREF NTRIP Broadcaster**

ASI-CGS acts as EUREF NTRIP Broadcaster since 2009, supporting the distribution of RT data/solutions in the European region; it contribute directly to the data stream with 3 RT GPS stations.

### **GPS Meteorology Activities**

ASI/CGS has been processing GPS data for meteo applications since 1999, participating to several European projects:

- MAGIC (1999-2001), one of the first projects being set up to develop and test the capacity for meteo organizations to benefit from GPS as new data source
- COST-716 (2001-2003), a NRT demonstration campaign;
- TOUGH (2003-2006) Targeting Optimal Use of GPS Humidity Measurements in Meteorology
- E-GVAP (2005-2009), towards operational use and establishing a GPS delay observing system

Since 2009, ASI-CGS takes part to E-GVAP II phase (2009-2013), the EUMETNET GNSS water vapour programme, set up to provide its EUMETNET partners with European GPS delay and water vapour measurements in Near-Real-Time for operational meteorology.

ASI-CGS provides:

#### **NRT ZTD estimates**

Every hour, 15' ZTD estimates with a 1h45' latency for a European network of almost 100 sites are produced; values are obtained by an analysis strategy combining PPP and Network analysis realized with the JPL GIPSY/OASIS SW.

#### **NRT ZTD combined estimates**

Every hour, the 15' ZTD estimates from the contributing Analysis Centers are combined and made available to the projects, using a combination SW developed at ASI-CGS.

## **Multi-technique Data Analysis at Matera ASI-CGS**

### **EOP excitation functions**

Production of the geodetic excitation functions from the ASI/CGS estimated EOP values for IERS to make them available on the ASI geodetic web site (<http://geodaf.mt.asi.it>): operational daily geodetic excitation functions are produced every Tuesday along with the operational weekly SLR solution, staked and compared whenever possible with the atmospheric excitation functions from the IERS SBAAM, under the IB and non-IB assumption, including the “wind” term. In 2010 also GPS and VLBI EOP solutions have been used to perform the computation; results are still under evaluation.

### **Geodetic solution combination**

Realization, implementation and testing of combination algorithms for the optimal merging of global inter- and intra-technique solutions and of regional (e.g. Mediterranean) solutions to densify tectonic information in crucial areas.

- Once a year, ASI-CGS produces a combined velocity solution for the Mediterranean area using its original single-technique velocity solutions (SLR, VLBI and GPS) that cover the whole data span acquired by the three co-located systems from the beginning of acquisitions in Matera. The ASIMed solution ([http://geodaf.mt.asi.it/html\\_old/ASImed/ASImed\\_06.html](http://geodaf.mt.asi.it/html_old/ASImed/ASImed_06.html)) gives a detailed picture of the residual velocity field in the area, profiting of the dense permanent GPS coverage. The semiannual updating profits of the improvements in the velocity field information as geodetic sites become stable in terms of their data acquisition history.

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## Commission 2 : Gravity Field

*Accurate determination of the gravity field and its temporal variations is a prime target of modern geodesy: It is closely related to geophysics, geodynamics, navigation, metrology and other related disciplines including the Earth's environmental issues as well.*

*Commission 2 has been established for promoting, supporting, and stimulating the advancement of knowledge, technology, and international cooperation in the geodetic domain associated with Earth's gravity field..*

**(Prof. F.Migliaccio)**

### Gravity model computation from GOCE data

The activities which are carried on at Politecnico di Milano regarding the ESA satellite mission GOCE are set within the European Consortium EGG-C (established in 2001) to process GOCE data within the GOCE HPF (High-level Processing Facility). GOCE is an ESA mission, the first one based on gravity gradiometry, having the goal of estimating the Earth gravitational field in terms of a spherical harmonic expansion up to degree 200-250, with a commission error of 1-2 cm in terms of geoid. The mission was launched on March 17, 2009 from Plesetsk and is fully operative since October 31, 2009.

The main activity of the group of Politecnico di Milano (supported by colleagues from UCPH Copenhagen) during the period 2007 – 2009 has been to design and implement the processing chain of GOCE data based on the originally developed space-wise approach. Afterwards, from the launch of the satellite on, the group has worked on the real GOCE data processing.

Basically, two types of data are used in the space-wise approach: satellite-to-satellite tracking data (SST data) which allow to estimate the gravitational potential by the energy conservation method (for low-degree estimation) and satellite gravity gradiometry data (SGG data) to retrieve the second derivatives of the gravitational potential, e.g.  $T_{rr}$ , (for medium-high degree modelling).

### The space-wise approach

The main idea behind the space-wise approach is to estimate the spherical harmonic coefficients of the geopotential model by exploiting the spatial correlation of the Earth gravitational field. However, a unique collocation solution is computationally unfeasible due to the huge amount of data downloaded from the GOCE satellite. That is why a two-step collocation solution is implemented, namely a gridding of second derivatives of the potential on a sphere at mean satellite altitude, and a spherical harmonic analysis to finally retrieve the potential coefficients. In particular, in order to implement the local gridding a prior model is used to reduce the spatial correlation of the signal and a Wiener orbital filter is used to reduce the highly time correlated noise of the gradiometer. The procedure is then iterated in order to recover the signal frequencies cancelled by the Wiener orbital filter and to improve the rotation from gradiometer to local orbital reference frame. In the process of computing the space-wise model coefficients, intermediate results are obtained that can be used for local applications. They are: filtered data (potential and gravity gradients) along the orbit and grid values at mean satellite altitude.

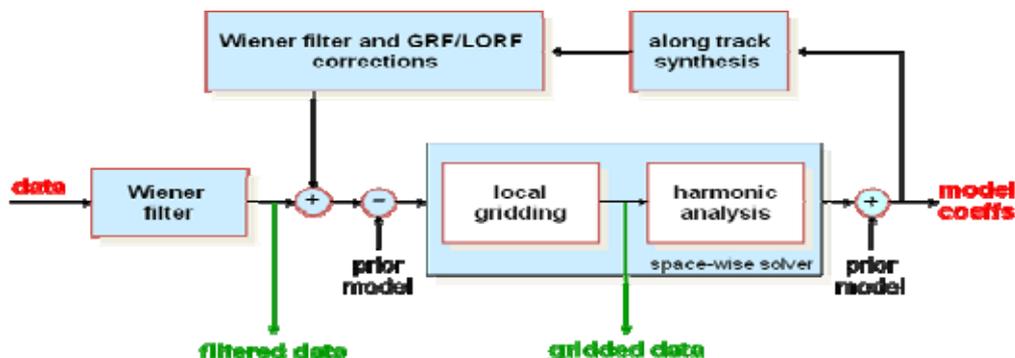


Figure 1. Scheme of the processing chain of the space-wise approach for the estimate of a GOCE-only gravity field model

## The GOCE-only space-wise model

So far, two gravity models have been computed by the space-wise approach. The first one was released at the Bergen 2010 ESA Living Planet Symposium. It was based on GOCE data from 30 October 2009 to 11 January 2010, corresponding to about 73 days of data. The statistics of this GOCE space-wise model up to degree 200 and for  $|\varphi| < 83^\circ$  are: predicted geoid error = 10.86 cm; predicted gravity anomaly error = 3.03 mgal.

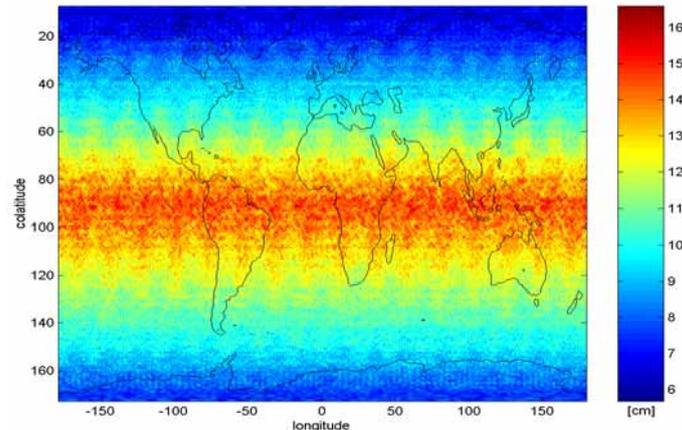


Figure 2. Predicted geoid error up to degree 200, for the first GOCE space-wise model

The second GOCE space-wise solution was derived from about eight months of data, in particular the covered time period goes from 31 October 2009 to 6 July 2010. This space-wise GOCE-only model improves the accuracy of the estimation by exploiting three times the amount of data available for the first release. This can be seen, for example, from the plots of the error degree medians with respect to EGM08 (Figure 3).

The estimated accuracy of the new space wise model up to degree and order 200 is about 8.5 cm in terms of geoid undulations, and about 2.5 mgal in terms of gravity anomalies.

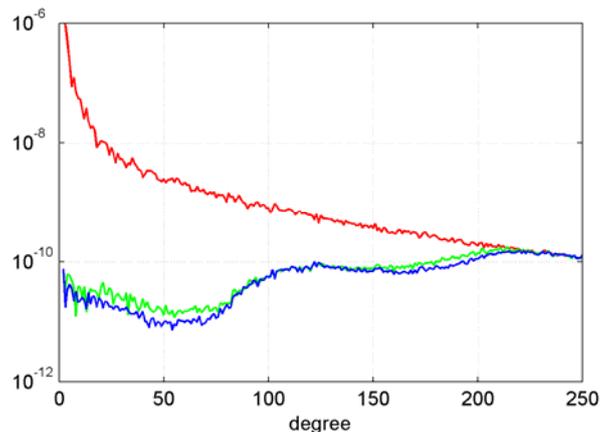


Figure 3. Error degree medians of the second GOCE space-wise solution (in blue), as compared with the first SPW solution (in green). The reference model is EGM08

## Grids of GOCE observables and of filtered data along orbit for scientific applications

In the course of the space-wise processing chain, grids of GOCE observables (potential  $T$  and second radial derivatives  $T_{rr}$ ) are computed at satellite altitude with a resolution of  $0.5^\circ \times 0.5^\circ$  and their error covariances are used for merging intermediate solutions. Such grids could be made available to the scientific users of GOCE data and could be exploited for geophysical applications.

Other data that can be made available to scientific users are filtered observations along the orbit.

## **Local geophysical interpretation in the Italian area**

At the Italian national level, the GOCE-Italy Consortium has been established in 2007 with the aim of exploiting GOCE data for geophysical, geological, oceanographic applications, in particular in the Italian area. GOCE-Italy activities are going on. First experiments on geophysical analysis have been carried on based on GOCE space-wise internal products such as grids of potential and second derivatives at satellite altitude with their error covariance matrix. The Politecnico di Milano group has performed studies on the Moho estimation, producing first preliminary results.

## **Future gravity field missions**

Activities carried on at Politecnico di Milano include also studies on future gravity field missions based on satellite-to-satellite tracking and laser interferometry. Applications of this concept to geophysical data interpretation have been studied together with geophysics experts.

Polimi also participated in the proposal for the Earth Explorer Opportunity Mission EE-8 of ESA “e.motion”. Studies on a possible lunar gravity mission “MAGIA”, funded by the Italian Space Agency (ASI).

First investigations (Thales Alenia Space contract “Laser Doppler Interferometry Mission for the Determination of the Earth’s Gravity Field”) that had been carried on regarding SST missions based on laser interferometry have been refined in the framework of a Ph.D. study.

## **(Prof. Iginio Marson)**

- a) Related to local geoid.

An improved geoid, called ADBVE2006 (Autorita di Bacino di Venezia 2006), has been calculated for the north-east of Italy using new land and marine gravity data together with new high resolution multibeam bathymetric data. A standard processing procedure has been applied to gravity data in order to compute the Free Air and the Bouguer anomalies. The gravity reference datum is IGSN71. The long wavelength part of the gravity field has been modeled by EGM96. The computation has been carried out by the remove-restore spectral technique (Stokes approach) using the software GRAVSOFIT. The goal of the calculated model was to improve the geoid estimation in the coastal areas, where the calculated geoids usually suffer from the lack of gravimetric data as well as a good bathymetry.

- b) Related to acquisition of gravity data

OGS owns a research vessel (OGS Explora) equipped, among others, with a marine gravimeter KSS31 Bodenseewerk. In recent years several marine surveys have allowed the acquisition of new gravity data which have upgraded the marine gravity data bank of OGS: Ionian sea about 6000 km; Antarctica: Ross Sea, 4630 km; Antarctica: Oates land 1026 km; Aegean Sea: 2800 km. Total amount of gravity lines < 14456.

- c) Related to Gravity Field Service

Starting from January 2011 OGS has been charged with the duty of hosting and running the Central Bureau of the International Gravity Field Service (IGFS). The kick-off meeting has been held on the 29<sup>th</sup> of march 2011.

**(Prof. R. Barzaghi)**

During the four years period 2007-2011, the activities in gravity field estimation were mainly focused on:

- Italian geoid estimation refinements based on gravity and GPS/levelling data integration;
- Geodetic activities in the context of IGeS

i) The Italian geoid estimation based on gravity and GPS/levelling undulations.

Coupled observations of GPS and levelling data are nowadays commonly available. In Italy, IGM has surveyed more than 1000 levelling points with GPS. As it is well-known, on these GPS/levelling points geoid undulations can be estimated by simply subtracting the orthometric height from the ellipsoidal height. These undulations can be used to check for the precision of the gravimetric geoid estimate. Also, theoretical and numerical method can be applied to merge this data set and gravity observations to get an integrated geoid estimate. In this way, gravity and observed undulation are both used to compute a joint estimate of the undulation. Based on collocation, two distinct approaches were devised to compute the final estimate (A. Albertella et al., 2008). They differ only in the way collocation is used to solve the problem. The first method (method A) applies collocation to interpolate the residuals between the gravimetric quasi-geoid estimate and the GPS/levelling undulations. The interpolated residuals are then added to the gravimetric estimate to get refined values. The second method (method B) applies collocation in the classical geodetic framework. Gravity data and GPS/levelling undulations are the input data which are used to compute the undulation  $N(P)$ . As it is well known, this is possible using collocation which allows the combination of any linear (or linearized) functional of the anomalous potential  $T(P)$  to get the estimate of any other functional of  $T(P)$ . GPS/levelling derived undulation data were split into two sets. The largest one (consisting of 700 data points) has been used in the estimation procedures together with gravity data. The second set (300 control points) has been used for checking purposes, i.e. to assess the precision of the computed undulation. The two procedures used to merge gravity and undulation data based on collocation proved to be effective. The mean and the standard deviation of the residuals on the 300 control points are sharply better than those obtained with the last gravimetric quasi-geoid estimate ITALGEO05 (Barzaghi et al., 2007). The statistics of the residuals on these control points are listed in the following table for method A and B respectively.

$N_{GPS/lev} - \hat{N}$		
	Method A	Method B
E (m)	0.00	0.00
$\sigma$ (m)	0.03	0.04
Min (m)	-0.11	-0.18
Max (m)	0.12	0.15

*Statistics of the differences between GPS/levelling derived and estimated undulations on control points.*

ii) Geodetic activities in the context of IGeS

The International Geoid Service (IGeS) participated to several international projects on geoid computation. The main activities were related to the validation test on EGM2008 and to a comparison among different geoid estimation methods.

The global geopotential model EGM2008 has been checked in the Central Mediterranean area using gravity and GPS/leveling data available in this area. This was done both with respect to previous existing

geopotential models (EGM96, GPM98CR and EIGEN-GL04C) and the last estimate of the Italian geoid, ITALGEO2005. The test area has boundaries  $35^{\circ} \leq \text{lat.} \leq 48^{\circ}$ ,  $5^{\circ} \leq \text{lon.} \leq 20^{\circ}$ . In this area, 310.660 point gravity values and 977 GPS/leveling data are available. These comparisons show that the EGM2008 is as accurate as the last Italian gravimetric geoid. This can be clearly seen in statistics of the residuals with respect to GPS/derived undulations which are listed in the following

	NEGM2008 - NGPS/lev	NGPM98CR - NGPS/lev	Nitalgeo05 - NGPS/lev
E (m)	0.00	0.00	0.00
$\sigma$ (m)	0.10	0.35	0.12
Min (m)	-0.33	-1.30	-0.50
Max (m)	0.34	0.64	0.32

*Statistics of the GPS/leveling residuals after geoid model reduction*

This comparison was a regional test which was a part of a global comparison documented in a special issue of the Newton's Bulletin (Barzaghi and Carrion, 2009).

The test on different geoid computation methods has been performed in the framework of the so called the Auvergne test. Data were provided by H. Duquenne (IGN) in the Auvergne area and were distributed by IGeS. IGeS and EGGP co-operated in defining the testing procedures and the general framework of this test. Six research groups participated to the test estimating the geoid undulation over the same area, checking the undulation precision following a common methodology.

Furthermore, IGeS international activities were developed in order to support foreign institutions in the field of geodetic sciences. The National Geophysical Research Institute of Hyderabad (India) contacted IGeS in order to get support in computing a gravimetric geoid in South India. A co-operation was also established with the Survey of Bangladesh. A researcher of the Survey of Bangladesh was hosted at IGeS in Milano, in February, 2009. During this period, a refinement of EGM2008 over Bangladesh was computed, based on GPS/leveling points which were collected by the Survey of Bangladesh. This refinement proved to be effective and led to a significant improvement of the global EGM2008 model. Finally, in June 2011, three researchers coming from the Center of Geodesy and Geodynamics of Nigeria (National Space Resource and Development Agency) attended a dedicated fifteen day training course on geoid computation procedures.

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### Commission 3 : Geodynamics and Earth Rotation

*Geodynamics in the broader and most traditional sense addresses the forces that act on the earth, whether they derive from outside or inside of our planet, and the way in which the earth moves and deforms in response to these forces.*

*Commission 3 studies the entire range of physical processes associated with the motion and the deformation of the solid earth. The purpose of Commission 3 is to promote, disseminate, and, where appropriate, to help coordinate research in this broad arena.*

#### **(Prof. Susanna Zerbini)**

#### **GPS Height**

During the period 2007-2011 the group, lead by Professor Susanna Zerbini at the Department of Physics of the University of Bologna, has carried out scientific activity mostly concerning studies of regional and local deformation of the Earth's crust by means of space and terrestrial techniques, namely GPS and gravimetry. The group is also working on the combination of different space and terrestrial techniques and on GPS-based estimates of tropospheric delays to enhance the coherence and to allow the application of InSAR in a wider range of applications. Studies concerning hydrological signals in height and gravity by using principal components analysis have also been developed. Professor Zerbini, member of the Executive Committee of the Global Geodetic Observing System (GGOS) of the IAG, has also participated in a number of studies contributing to the global reference frame and to earth science requirements for geodesy (Plag et al., 2007; Plag and Zerbini, 2008; Plag et al., 2009; Rummel et al., 2009; Blewitt et al., 2010).

Starting in July 1996, the group has initiated a program to install a network of permanent GPS stations in the southeastern Po Plain (Italy), with the aim of monitoring and studying land subsidence in the region. The stations considered for this study are Medicina, Marina di Ravenna, Bologna, and Loiano (see Figure 1). The first two GPS receivers were installed in July 1996 at Medicina, close to Bologna, and Marina di Ravenna on the Adriatic coast. Both stations have been operational since the installation. The GPS stations at Medicina (MSEL) and Bologna (BOLG) have become sites of the European Permanent Network (EPN) of EUREF. The Marina di Ravenna and Trieste stations are installed in close proximity of the tide gauges operational in the respective harbours.



Figure 1. Location of the permanent GPS stations of the Department of Physics of the University of Bologna.

Although the historical deformation of these regions is well constrained from geological evidence, a measurement of the present-day vertical motions is discontinuous both in space and in time. Natural subsidence affects the entire Po Plain and decreases from the south, where it exceeds 1 mm/yr, to north. During the second half of the last century, exploitation of subterranean fluids, primarily water and gas, has

significantly increased the natural long-term behavior, in particular in the southeastern part of the plain and along the northern Adriatic coast. At local scales, anthropogenically driven subsidence rates of 10 to 20 mm/yr have superimposed onto the regional tectonic component. There is then a particular need for the study of vertical crustal movements, which are also less known and quantified than are the horizontal ones. At the CGPS stations several environmental parameters are also collected with the aim to provide significant information on the potential effects induced on height variations by phenomena of climatic origin.

Among the terrestrial observation techniques used for estimating vertical land movements, gravimetry is a completely independent method with respect to space geodetic techniques. Over the last five decades, gravimetry has made impressive progress. The precision of both absolute and relative measurements has improved by almost three orders of magnitude to presently  $10^{-9}$ . The instrumental accuracy of the absolute gravimeter FG5 is about 1–2 microGal at good stations for a 24-hour observation period. In collaboration with the Bundesamt fuer Kartographie und Geodaesie (BKG, Frankfurt, Germany), at the Medicina station, since October 1996, the variations of the gravity field are monitored continuously by means of a superconducting gravimeter (SG), a technology which allows to measure the temporal variations of the gravity field continuously at a given site. The SGs are relative instruments but very stable in time. Absolute gravimeter observations taken at the location of a SG allows the identification of outliers and the correction for long period, mostly environmental, signals. Continuous monitoring of height and gravity changes allows the separation of the gravity potential signal due to mass redistribution from the geometric signal due to height changes and the sound interpretation of crustal deformation processes.

At Medicina, the SG is controlled twice a year by means of absolute gravity measurements performed by the Italian Space Agency (ASI) and the BKG teams. Absolute gravity measurements are also performed biannually at the CGPS stations of Bologna and Loiano.

The data of the four CGPS stations have been analyzed to produce daily coordinate time series and estimates of the relevant long-period linear trends. The height series of the stations and the linear trends are shown in the left panel of Figure 2. For the Trieste site two different plots are presented because the station location had to be changed (on the upper level of the same building) due to restoration work. The stations in south eastern Po Plain are characterized by negative linear trends of different magnitude. Loiano, on the Apennines, shows a moderate uplift rate, while as regards Trieste it is difficult from the two separate series to accurately estimate a unique trend. However, by considering the two time series, also Trieste shows a slope inversion. Bologna (BOLG) and Marina di Ravenna exhibit larger subsidence rates which are mainly of anthropogenic nature because of ground fluids exploitation during the second half of last century before the adoption of groundwater control policies in the 80's. Medicina and Trieste show linear trends of a few mm/yr. The residual series (linear trends removed, Figure 2 right panel) are characterized by significant long-period as well as seasonal oscillations. Seasonal oscillations have been modelled by accounting for atmospheric, non-tidal oceanic and hydrologic effects (Zerbini et al., 2007). The residual plots suggest the presence of a change in slope around 2004. This behaviour has been investigated in a subsequent study which will be described in the following.

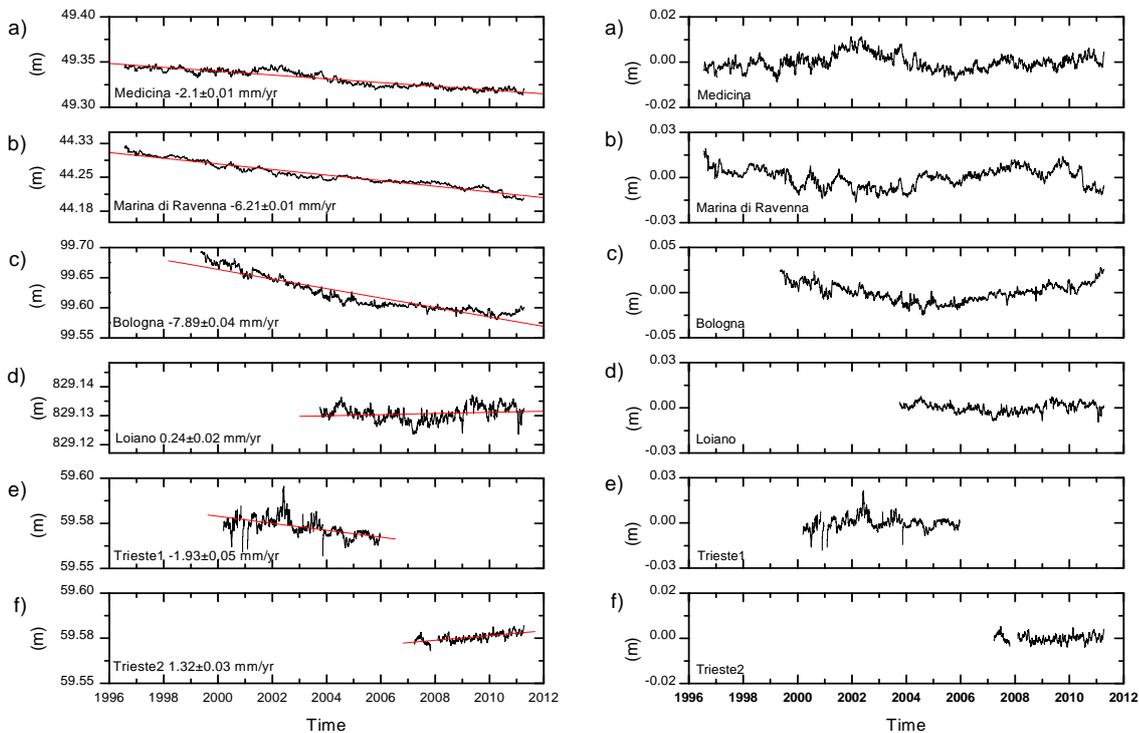


Figure 2. Time series of GPS daily solutions smoothed by a 15-day window averaging and linear trends (left panel); residual series (linear trend removed, right panel).

The high-accuracy estimate of vertical rates at tide gauge stations allows the separation of the true sea-level variations from the vertical crustal motions in the tide gauge records, thus providing key information for climate-related sea-level rise studies (Wöppelmann et al., 2006).

### GPS height and gravity

The Medicina SG gravity data have been analyzed and interpreted. Figure 3 describes an example of such analysis and a comparison between the SG data, a series of absolute gravity measurements and the height time series obtained from the data of the two GPS receivers operative at Medicina, namely MSEL and MEDI. The gravity data are the daily averages of the SG recordings, smoothed by a 15-day window averaging together with 21 absolute gravity measurements performed since the beginning of the SG observations. The time series of the GPS heights are in the ITRF2005. Gravity has been multiplied by a factor  $(-1)$  in order to facilitate the visual comparison with the height data. The two GPS series and those of gravity are comparable. They all show from about 2005 a different long-term behavior, a reduction of subsidence, with a tendency to uplift starting around 2004-2005. The GPS height and a series of 19 absolute gravity measurements performed at the BOLG station show a similar long-term behavior (Fig.4)

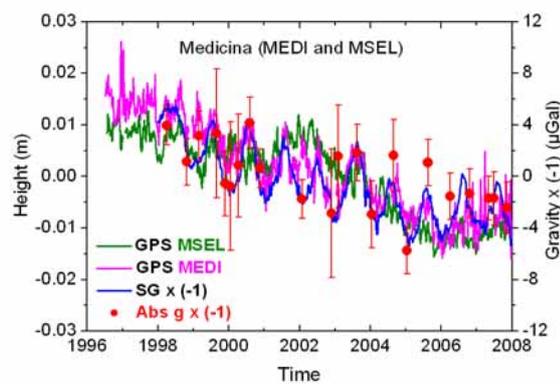


Figure 3. Daily averages of SG data (blue line, multiplied by -1), absolute gravity measurements (red dots multiplied by -1) and GPS heights (MSEL green line; MEDI magenta line).

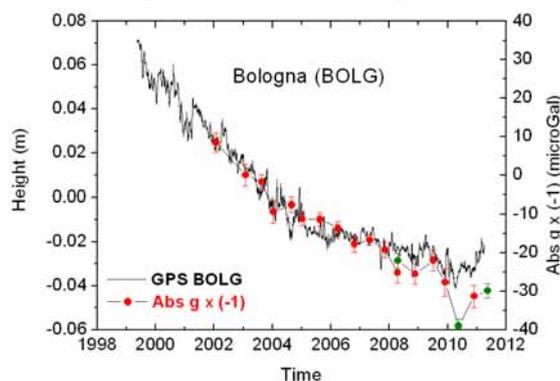


Figure 4. GPS height series (black line) of the BOLG station and a series of absolute gravity measurements (multiplied by -1). Red dots indicate measurements performed by BKG, green dots represents measurements carried out by ASI.

### Principal Components Analysis

A study of GPS heights, gravity and hydrological time series collected by stations located in northeastern Italy (Fig. 5) has been carried out. During the last 12 years, changes in the long-term behaviors of the GPS heights and gravity time series are observed. In particular, starting in 2004–2005, a height increase is observed over the whole area. The temporal and spatial variability of these parameters has been studied as well as those of key hydrological variables, namely precipitation, hydrological balance and water table by using the Empirical Orthogonal Functions (EOF) analysis. The coupled variability between the GPS heights

and the hydrological balance and precipitation data has been investigated by means of the Singular Value Decomposition (SVD) approach (Zerbini et al., 2009).

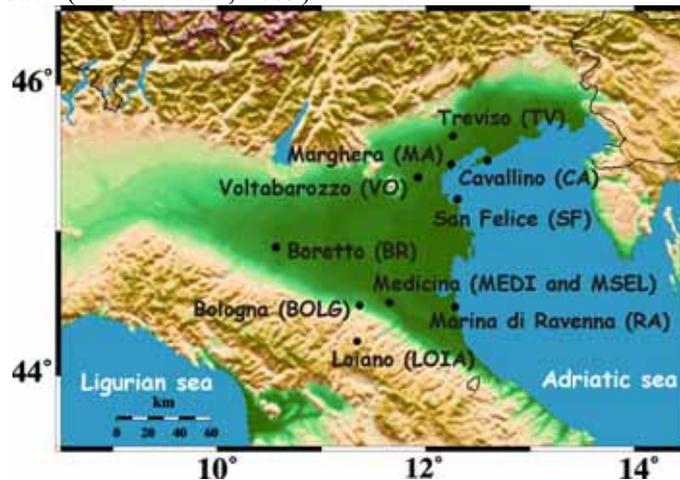


Figure 5. Map of station locations in northeastern Italy. Bologna, Loiano, Marina di Ravenna, Medicina (MSEL) are stations of the GPS network run by the University of Bologna; Boretto belongs to Telespazio; Cavallino, Marghera, San Felice, Treviso and Voltabarozzo are stations of the GPS network run by Consorzio Venezia Nuova for the Magistrato alle Acque of Venice; the MEDI station belongs to the Italian Space Agency.

Significant common patterns in the spatial and temporal variability of these parameters have been recognized. In particular, hydrology-induced variations are clearly observable starting in 2002–2003 in the southern part of the Po Plain for the longest time series, and from 2004–2005 over the whole area. These findings, obtained by means of purely mathematical approaches, are supported by sound physical interpretation suggesting that the climate-related fluctuations in the regional/local hydrological regime are one of the main contributors to the observed variations. A regional scale signal has been identified in the GPS station heights; it is characterized by the opposite behavior of the southern and northern stations in response to the hydrological forcing. At Medicina, in the southern Po Plain, the EOF analysis has shown a marked common signal between the GPS heights and the Superconducting Gravimeter (SG) data both over the long and the short period.

The principal components analysis was also applied to a 20-stations GPS network encompassing the whole Europe and Mediterranean area (Zerbini et al., 2010). In this study the time series of both the horizontal and vertical components of the GPS station positions were analyzed. Environmental parameters, among which surface atmospheric pressure and water storage, as well as GRACE surface-mass anomalies were also investigated to contribute to a better understanding of the observed position variability. A paper describing these latest results is in preparation.

### Horizontal motions

Station horizontal motions have also been studied. The observed velocities were compared to the estimates provided by the NUVEL1A NNR plate motion model (Fig. 6a). The results indicate that these sites are moving faster than predicted by the model and with azimuths slightly more northward oriented. The GPS-derived velocities with respect to stable Europe (Fig. 6b) of the stations in the Veneto and Friuli Venezia-Giulia regions indicate a N-S shortening in the order of 2-to-3 mm/yr. The data also suggest NE-SW shortening of a few mm/yr between Trieste, located at the leading edge of the Dinarides orogen and the Emilia-Romagna Marina di Ravenna, Medicina and Bologna sites positioned above the Apennines accretionary prism. This can be interpreted either as active thrusting of the Dinarides or/and active thrusting in the Apennines accretionary prism. Seismic reflection profiles and seismicity indicate that both orogens are active, but the Dinarides appear to have slower convergence rates.

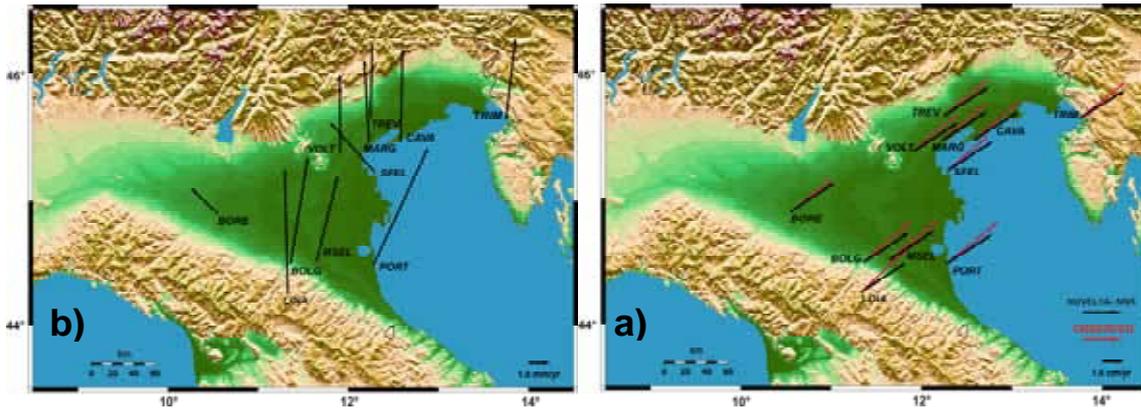


Figure 6. a) The observed motion vectors (cm/yr) in red and, in black, for comparison purposes, the NUVEL1A -NNR model vectors; b) the residual motion vectors (mm/yr) after the NUVEL1A-NNR model has been subtracted.

### Combination of techniques

A study has been carried out presenting a multidisciplinary approach that combines observations derived from continuous Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), and terrestrial gravimetry in combination with times series of local environmental parameters to estimate subsidence in the southeastern Po Plain. By using the Permanent Scatterers (PS) technique of InSAR it was possible to extend the knowledge of the velocity field in space (Zerbini et al., 2007). The combination takes advantage of the techniques' complementary aspects, proving to be a powerful means to observe and study vertical deformation with reliable spatial and temporal continuity. The long-term linear trends estimated by using the data of the different techniques show a very good agreement. By combining GPS, InSAR, and gravity, subsidence in the southeastern Po Plain has been mapped, revealing a noticeable spatial variability. Large vertical rates, mostly of anthropogenic nature, in the order of 20 mm/yr have been observed in and around the city of Bologna. The transition between a subsiding region and the uplift of the adjacent Apennines occurs over a narrow zone as evidenced by the analysis of the InSAR PS results. These results identify clearly the separation line between the different geodynamic characters of the two zones: the subsiding foredeep, where the sediments allow ground-fluids withdrawal to significantly enhance the natural tendency, and the uprising Apennines belt.

### GPS, InSAR and the tropospheric delay

In the framework of the COSMO-SkyMed (CSK) call for proposals issued by the Italian Space Agency (ASI), the project entitled "Comparison of ground deformation measurements and atmospheric artifacts carried out with GPS and Permanent Scatterers techniques" has been funded. P.I. of the project is Prof. Claudio Prati from the Dipartimento di Elettronica ed Informazione of the Politecnico of Milan and Co.I. is Prof. Susanna Zerbini from the Dipartimento di Fisica of the University of Bologna.

The main goal of this project is to apply the Permanent Scatterers (PS) Technique to a number of repeated CSK high resolution strip-map SAR images acquired over a 40x40 km<sup>2</sup> area, including the towns of Bologna and Medicina and Loiano (Apennines) (see, for example, Fig. 5), to evaluate:

1. the density of Permanent Scatterers that can be identified in urban and non-urban areas compared with that achievable in C band with a longer revisiting time and a lower resolution;
2. the accuracy of elevation and motion measurements achievable in X band by comparing and integrating radar and GPS measurements carried out simultaneously;
3. the accuracy of the tropospheric delay estimates by comparing and integrating radar- and GPS-derived information.

The limits of the conventional differential InSAR technique becomes critical passing from C to X band radar systems. It is well known that there is almost no penetration of X band through the vegetation. Thus, apart from urban and dry desert areas, only isolated coherent reflectors are expected. This implies that only the PS technique can be exploited for monitoring ground displacement in non-urban areas with CSK. For the first time there is the possibility to validate what has been foreseen by the theory. A higher number of PS with

respect to that obtained with the available C band missions (ERS, ENVISAT, RADARSAT) is expected since the higher reflectors stability requested by the shorter wavelength of CSK should be more than compensated by its higher resolution and shorter revising time.

GPS is, at present, the only time-continuous geodetic observation, although spatially limited to station location, providing precise absolute coordinates with respect to a global well-defined geocentric reference system. The comparison between radar and GPS ground motions will help demonstrating the CSK capability to detect ground deformations with the expected millimeter accuracy. This would be a primary contribution to the first CSK mission civil objective: to provide the Civil Protection Agencies with a powerful tool for hazard monitoring such as, for example, landslides, volcanoes, active faults, earthquakes, single building monitoring and subsidence.

Another aspect of the GPS/InSAR integration regards the fact that today's application of interferometric SAR techniques is limited by the knowledge of the wet tropospheric path delay in microwave observations. GPS-based estimates of tropospheric delays may help in obtaining better corrections which will enhance the coherence and will allow the application of InSAR in a wider range of applications.

In the following preliminary results of this study regarding a comparison between CSK- and GPS-derived vertical motions at Bologna and Medicina as well as estimated tropospheric corrections are presented (Zerbini et al., 2011).

### ***- Comparison between GPS and PS-InSAR tropospheric delays***

A comparison of differential tropospheric delays between MSEL and BOLG has been carried out. Both GPS solutions derived from the 7-hour session with 5 sec. data acquisition rate and the 24-hour session with 30 sec. sampling rate have been considered. The InSAR results are relevant to two PS located at a distance of about 500 m and 28 m from the MSEL and BOLG stations respectively. These are representative of the majority of PSs identified around the two stations (see Figs. 3 and 4). Figure 7 shows that a similar behavior is present in the results achieved by both GPS and PS-InSAR techniques, despite of expected differences due to the almost instantaneous nature of the PS-InSAR estimates compared to the GPS 5-min averaged results. The correlation coefficients computed between the GPS and PS-InSAR differential tropospheric delays (MSEL-BOLG) at the time of the CSK passes turn out to be 0.41, significant at 91% confidence level (24-hour session, 30 sec. rate data) and 0.57, significant 99% confidence level (7-hour session, 5 sec. rate data). They are representative of the good agreement found between the two techniques.

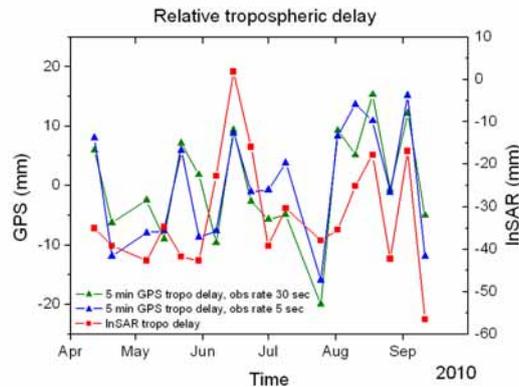


Figure 7. Relative tropospheric delays (mm) between BOLG and MSEL estimated along the CSK line of sight. In red, are shown the tropospheric delays obtained by the PS-InSAR approach, while in blue and green those obtained by GPS using different acquisition rates (5 and 30 seconds) and session length (7 and 24 hours).

### - Comparison between GPS and PS-InSAR height differences

A comparison of differential height between BOLG and MSEL has also been carried out. Both the GPS 7 and 24-session solutions have been considered. They show the high sensitivity of the height solution to the length of the observation interval. As shown in Fig. 8, the vertical dispersion achieved by GPS is higher than that achieved by PS InSAR, as expected, however, a similar linear trend appears in the results of both techniques.

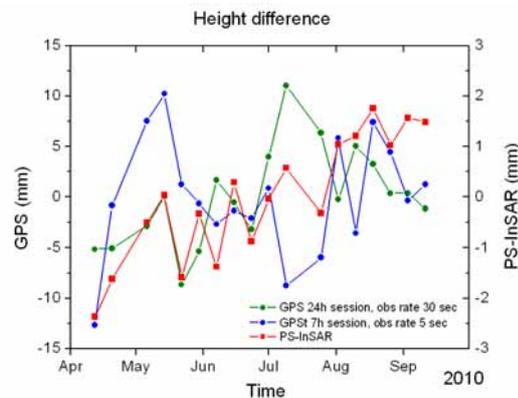


Figure 8. Relative height (mm) between BOLG and MSEL (MSEL-BOLG). In red, is shown the relative height obtained by the PS InSAR approach (using just one acquisition geometry), while in black and green those obtained by GPS using different acquisition rates and session length (7 and 24 hours).

### **(Prof. R.Sabadini)**

#### **Earth Rotation**

Issues related to long timescale instability in the Earth's rotation, named True Polar Wander (TPW), have continuously been debated, after the pioneering works of the sixties.

The UNIMI team has been working on ice age TPW on the basis of a newly developed compressible model (G. Cambiotti and R. Sabadini, 2010), based on the numerical integration in the radial variable of the momentum and Poisson equations and on the contour integration in the Laplace domain which allows us to deal with the non-modal contribution from continuous radial rheological variations.

The long term behaviour of the Earth's rotation has been fully exploited and the effects of the compressible rheology quantified, compared to the widely used incompressible models. The effects of the non-hydrostatic bulge from mantle convection have been evaluated, in order to obtain realistic ice age TPW rates in the lower mantle viscosity range [1021, 1022] Pa s (G. Cambiotti, Y. Ricard and R. Sabadini, 2010).

This analysis represents the attempt to couple the effects on TPW from mantle convection and glacial forcing, by including the non-hydrostatic bulge due to mantle convection but not the her time-dependent driving terms. This partial coupling freezes in space the non-hydrostatic contribution due to mantle convection, thus damping the present-day ice age TPW and forcing the axis of instantaneous rotation to come back to its initial position when ice ages started.

The implication of self-consistent convection calculations of the non-hydrostatic contribution and their impact on the long term Earth's rotation stability during ice ages have also been estimated. The ice age TPW cannot account for more than 70 per cent of the observed one, at least for lower mantle viscosities lower than 1022 Pa s: mantle convection must therefore contribute to the observed TPW.

#### **Time dependent gravity field**

The UNIMI achievements in this field opened up new perspectives on the physics of the Earth's interior for graduate students and researchers working in geophysics and geodesy. Our modelling looks at the Earth in an integrated fashion, and links the physics of its interior with the newly acquired gravity and deformation data from space missions, such as GRACE (Gravity recovery and Climatological Experiments), GOCE (Gravity and steady state Ocean Circulation Explorer), GPS (Global

Positioning System) nowadays recording, over a broad spectrum of spatial wavelengths and time scales, the ongoing changes of our planet, in terms of its gravity changes and displacements of selected points over the

surface of the globe. Taken collectively, our geophysical modelling, jointly with geodetic data, allows to discover the physics of the geodynamical processes occurring within and at the surface of our planet. In fact, any phenomenon is responsible for mass redistribution and this can be appropriately modelled by means of our fully analytical relaxation normal mode theory and sampled by means of the new generation of satellite data. (V.R. Barletta, A. Bordononi, A. Aoudia and R. Sabadini, 2011; G. Cambiotti, A. Bordononi, R. Sabadini, I and L. Colli, 2011; G. Cambiotti, Y. Ricard and R. Sabadini, 2010; G. Cambiotti and R. Sabadini, 2010; Cambiotti, G, V. R. Barletta, A. Bordononi, R. Sabadini, 2009; F. Migliaccio, M. Reguzzoni, F. Sansò, G. Dalla Via and R. Sabadini, 2008; Barletta VR., R. Sabadini and A. Bordononi, 2007)

The UNIMI mathematical Earth's models show that the motion of the Earth's rotation axis over long time scales of million years, as revealed by paleomagnetic data, is the results of mantle density anomalies, and not that of continental drift, as generally thought before our achievements. These approaches and mathematical results are nowadays particularly important in the field of global and climate changes, since they allow to link the geophysical phenomena occurring within the Solid

Earth with those affecting the cryosphere and the hydrosphere, for example, in order to estimate the mass balance in the glaciated regions of the Earth and to predict the sea-level changes along the coastlines of countries facing the seas. Ice mass imbalance in Antarctica and Greenland is considered a major climate signal and the scientific community and society are thus interested to quantify, as accurately as possible, within the available methodology and instrumentation, the amount of present-day melting in the polar regions of the Earth: such estimates have of course a huge social impact, since they establish the ongoing changes of the planet where humanity is living.

The UNIMI approach allows to make a step ahead, not only in terms of monitoring the actual changes of the Earth, but even to predict the evolution of our planet in the near future, by means of our accurate forward modelling. The group of Solid Earth Geophysics at the University of Milan contributed to open this route, based on the concept that any geophysical phenomena occurring within or over the Earth's surface mass changes the gravity field, to measure the ice mass balance in the polar regions and to constrain the physical properties of the interior, by making use of the first generation of space gravity data, such as the SLR (Satellite Laser Ranging) ones. This concept evolved into GRACE and GOCE data usage. Thanks to our modelling, the UNIMI team was the first in the international literature to predict that the large Sumatra (2004) earthquake would have been the first event visible from space, as it actually occurred after GRACE data exploitation.

(Dr. Roberto Devoti)

### Geodynamics of the Italian District

Geodynamic deformation analysis at the scale of the whole Italian peninsula has been performed at INGV through the elaboration of a dense network of permanent GNSS stations (RING) deployed by the Institute itself.

This net has more than 150 stations and it is continuously working since 2006 year. The estimated velocities are shown in Figure 1 proving the great detail that can be reached in performing a strain analysis.

In turn, as shown in Figure 2, this allows a quite significant interpretation in terms of seismic hazard.

In the Figure coloured bands show the main seismogenetic faults of Italy and the color illustrates their velocities.

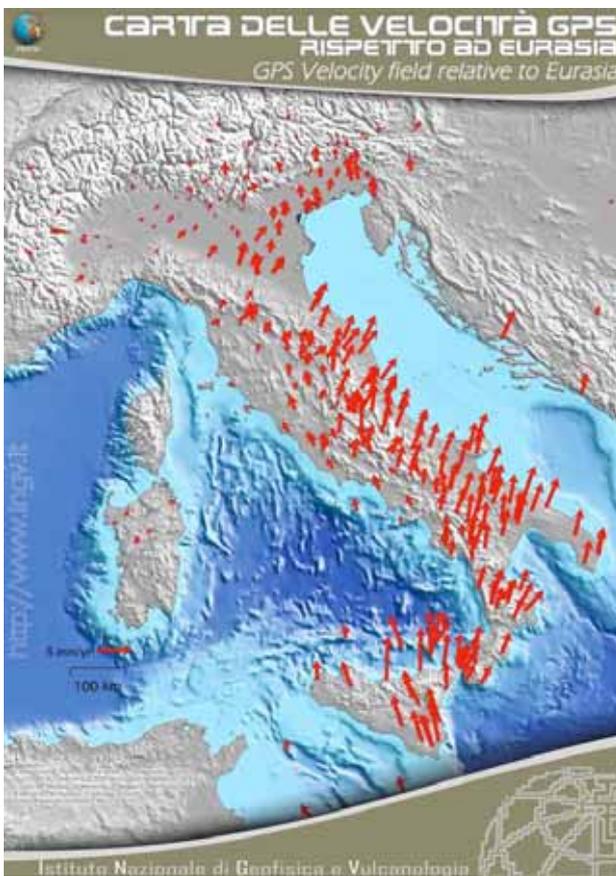


Figure 1

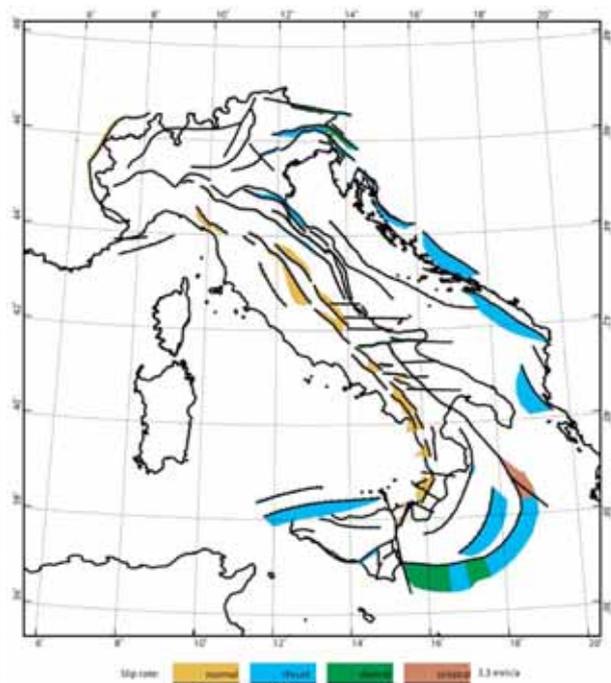


Figure 2

(Prof. A. Capra)

Geodetic observations for geodynamics studies in northern Victoria Land - Antarctica

PNRA ( Italian National Program on Antarctic Research) project

A semi-permanent global positioning system (GPS) network of 30 vertices known as the Victoria Land Network for Deformation Control (VLNDEF) was set-up in the Austral summer of 1998 in Northern Victoria Land (NVL), including Terra Nova Bay (TNB), Antarctica. The locations were selected according to the known Cenozoic fault framework that is characterized by a system of NW-SE regional faults with right-lateral, strike-slip kinematics. The TNB1 permanent GPS station is within the VLNDEF, and following its installation on a bedrock monument in October 1998 it has been recording almost continuously. The GPS network has been surveyed routinely every two summers, using high-quality, dual-frequency GPS receivers ( see at fig.1).

An improved reference frame definition was implemented, including a new Euler pole, to compute the Antarctic intra-plate residual velocities. The projection of the residual velocities on the main faults in NVL show present-day activities for some faults, including the Tucker, Leap Year, Lanterman, Aviator, and David faults, with rightlateral strike-slip kinematics and local extensional/ compressional components. This active fault pattern divides NVL into eight rigid blocks, each characterized by their relative movements and rigid rotations. These show velocities of up to several mm/yr, which are comparable to those predicted by plate tectonic theory at active plate margins.

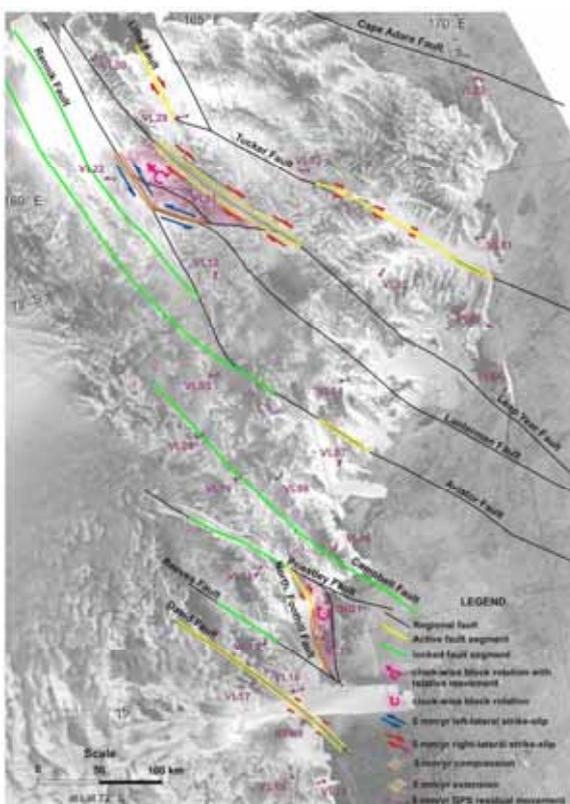


Fig. 1 Horizontal residual velocities projected along the main Cenozoic faults in NVL assuming block tectonic kinematics.

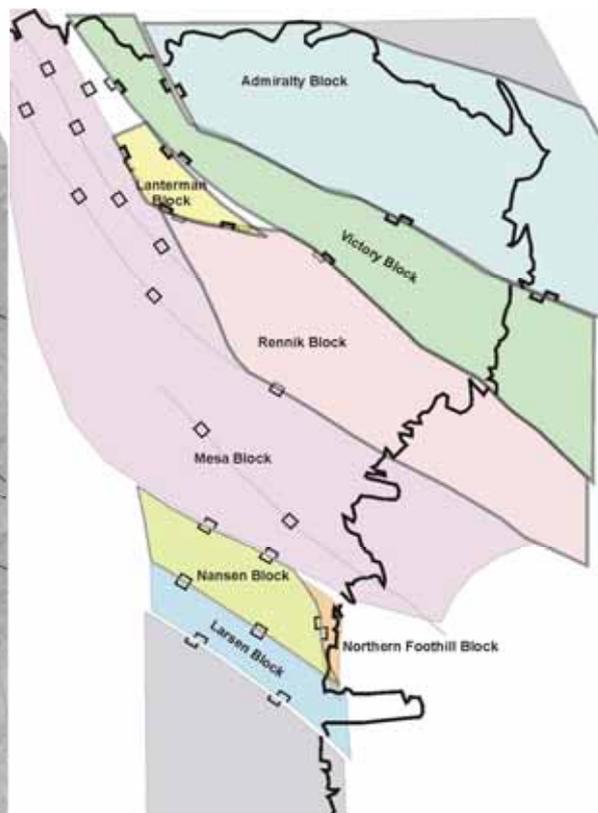


Fig. 2 Sketch map showing the eight rigid crustal blocks dissected out by the active fault network in NVL during the recording time

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## Commission 4 – Positioning and Applications

*To promote research into the development of a number of geodetic tools that have practical applications to engineering and mapping.*

*The Commission will carry out its work in close cooperation with the IAG Services and other IAG Entities, as well as via linkages with relevant Entities within Scientific and professional Sister Organizations:*

*Recognising the central role that Global Navigation Satellite Systems (GNSS) plays in many of these applications, the Commission's work will focus on several Global Positioning System (GPS)-based techniques, also taking into account the expansion of GNSS with Glonass, Galileo and Beidou.*

### **(Prof. M. Crespi)**

#### **Main research topics**

Navigation: goGPS

GPS Seismology: VADASE

GPS Meteorology

GNSS Permanent Network for Positioning Services

High resolution optical and SAR satellite imagery orientation and Digital Surface Model generation

#### **Navigation: goGPS**

goGPS is a software package designed to enhance the accuracy of single frequency low-cost GPS devices by employing double differenced code and phase observations in an extended Kalman filter, specifically tailored for addressing the issues related to low-cost GPS receivers. Double differences can be applied either in post-processing or in real-time by connecting to an NTRIP caster providing data in RTCM format from a network of GPS permanent stations. Innovative approaches to GPS positioning have been studied and tested, by merging in one Kalman filter solution not only GPS observations, but also other sources of information like surface constraints (e.g. digital elevation models) or line constraints (e.g. a polyline representing a railway if the receiver is mounted on a train). goGPS is being developed as open source software both in MATLAB and Java. A collaborative environment for fostering research and business has been set up by means of a web site (<http://www.gogps-project.org>), a mailing list and code repositories for carrying out joint development.

#### **GPS Seismology: VADASE**

GPS seismology has been proven an effective tool, but requires either high quality products (orbits, clocks, EOPs) to obtain an a-posteriori highest accuracy estimation of coseismic displacements in a global reference frame, or a complex and continuously linked infrastructure (GPS permanent network) in order to obtain in real-time high accurate (at 1 cm level), but only relative, coseismic displacements.

A new approach to estimate coseismic displacements in a global reference frame in real-time is based on a single GPS station technique, able to overcome some of the difficulties displayed by the two aforementioned presently adopted approaches for GPS Seismology. This approach (named VADASE – Variometric Approach for Displacements Analysis Stand-alone Engine) is based upon a so called “variometric” solution; it just requires the standard GPS broadcast products (orbits and clocks). Since VADASE does not require either additional technological complexity or a centralized data analysis, in principle it can be embedded into the GPS receiver firmware, thereby providing a significant contribution to tsunami warning systems. The effectiveness of VADASE was tested on several earthquakes, including the last extremely strong one occurred in Japan on March 11, 2011 (Figure 1).

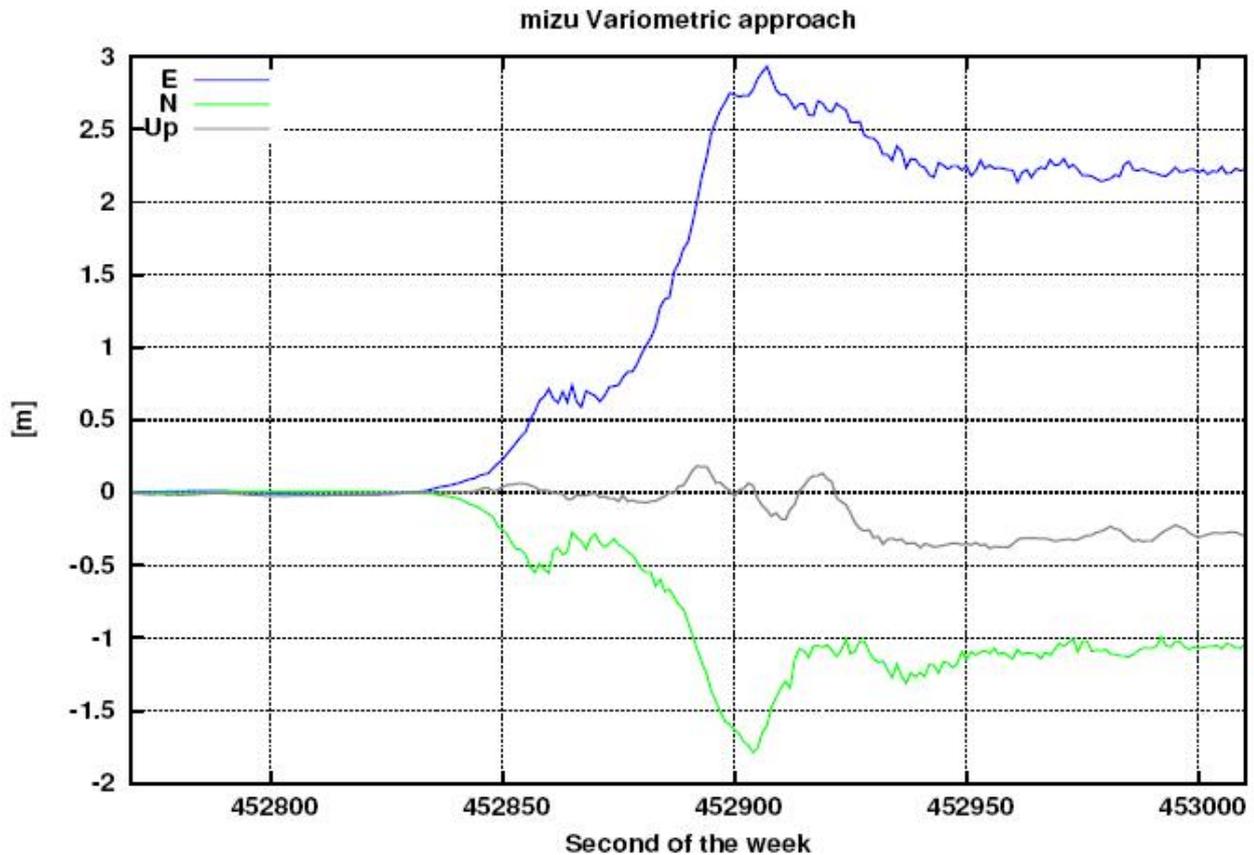


Figure 1: MIZU – variometric solution over the 240 seconds interval 05:46:10–05:50:10, March 11, 2011 (DOY 070) GPS time. Data used: observations data (mizu070f45.11o), broadcast ephemeris (brdc0700.11n).

Awards

G. Colosimo, M. Crespi, A. Mazzoni, 2010. DLR Special Topic Prize at the European Satellite Navigation Competition 2010 ([http://www.galileo-masters.eu/index.php?anzeige=special10\\_dlr.html](http://www.galileo-masters.eu/index.php?anzeige=special10_dlr.html)).

G. Colosimo, M. Crespi, A. Mazzoni, 2010. First Audience Award at the European Satellite Navigation Competition 2010 (<http://galileo-masters.eu/index.php?anzeige=top3.php>)

Italian and International Patent Pending

G. Colosimo, M. Crespi, A. Mazzoni, 2010-2011. Sistema di misura di movimenti cosismici o di vibrazioni di strutture basato su Global Navigation Satellite Systems-GNSS

**GPS Meteorology**

Water vapor (WP) estimation can be performed in several different ways: ground base water vapour radiometer can provide a three dimensional estimation, but only locally and at a very high price; satellite altimeters are provided with radiometers that can cover, at different days and time, the entire sea surface of the Earth; a more widespread option is to use ground-based GNSS networks to estimate WP, what is possible since GNSS measurement suffers a delay from tropospheric refraction as the signal traverse the neutral atmosphere; also numerical weather prediction (NWP) models that ingest data from many different sources can provide WP estimation.

An investigation related to WP estimation has been carried out within the MIST experiment.

This has been set up by a dedicated permanent network of 9 GPS stations measuring in continuous for 6 months, to study the predictability of the refractivity field at different scales. In fact the sides of the network were ranging from 100 m to 20 km, while data from other 3 permanent stations at a mean distance of 30 km have been used too.

A second investigation to perform a two-years comparison of three WP estimation strategies is presently active as a cooperation funded by the Italian Foreign Ministry and the Argentinean Science and Technology Ministry: SIRGAS is regularly producing tropospheric correction based on GNSS in order to maintain the

best possible geodetic frame in South America, the National Institute for Space Research of Brasil (INPE) produces a weather nowcast model that include WP estimations, and TOPEX/Poseidon or Jason-1 missions also give a water vapor estimation. The comparison includes a discussion on how each technique perform in different latitudes, time of the day and season of the year.

### **GNSS Permanent Network for Positioning Services**

#### Reference frame realization

Positioning services based on GNSS Permanent Networks (PNs) disseminate the reference frame to users; hence the networks must be adjusted by constraining the ITRF coordinates of some permanent stations (PS), with the satellite orbits and clocks constrained to the values published by the International GNSS Service (IGS). Furthermore, the positioning service provider must use analysis methods, conventions and practices fully consistent with IGS standards. In this framework some problems arise and some solutions may be proposed.

#### Ionosphere modeling for enhanced pseudorange point-positioning

It has been investigated the possibility to use a local network of permanent GNSS stations to generate and transmit real-time products devoted to ionospheric delay modeling that could remarkably improve positioning accuracy for C/A receiver users. In order to improve the accuracy, ionospheric corrections were estimated using the La Plata Ionospheric Model, based on the dual-frequency observations from the permanent GNSS stations and CODE Differential CODE Bias products. It was demonstrated that horizontal and vertical accuracies at 0.5 and 1 m level (LE95) are achievable. This methodological approach shows the possibility to remarkably improve the real time positioning based on pseudorange measurements only using ionospheric corrections estimations and real-time available products.

#### Low-Cost Mobile Mapping Systems

It has been analyzed the quality and the performance achievable using GIS and mass-market GPS receivers, both in static and kinematic positioning, and the accuracy of these receivers into a GNSS CORS network, and it has been studied the integration between GPS and low-cost IMU. In recent years, these researches have led to realize some prototypes of low-cost systems for land (MMSs) and air (UAVs and hexarotors) surveys. Besides the usual applications of surveying and photogrammetry, these systems are also designed for early-impact surveys during environmental emergencies.

#### Official Reports, Experiments and Data Analysis

Several experiments, also supporting practical applications in environmental and civil engineering, geology and environmental sciences, were carried out using the available GNSS permanent networks for positioning services already operational all over Italy for some years.

Further, dedicated experiments were carried out to investigate the data quality, accuracy and reliability of these networks, following methodologies already established and documented in official reports for the Italian Geomatic Community.

Finally, WebGIS for GNSS permanent networks management were developed in Open Source environment.

### **High resolution optical and SAR satellite imagery orientation and digital terrain modeling**

The availability of new high resolution radar spaceborne sensors offers new interesting potentialities for the acquisition of data useful for the generation of Digital Surface Models (DSMs).

At first a rigorous model to orientate optical and SAR imagery coming from different sensors was implemented in the original software SISAR. In addition, a tool for Rational Polynomial Coefficients generation, based on the rigorous model itself, was also included.

Further, it was implemented an original radargrammetric model related to COSMOSkyMed and TerraSAR-X SpotLight imagery (up to 1 m GSD), considering that two different approaches may be used to generate DSMs from Synthetic Aperture Radar (SAR) (interferometry and radargrammetry) and that, at present, the importance of the radargrammetric approach is rapidly growing due to the new high resolution imagery. First tests demonstrated the possibility to reach an overall average accuracy of 3.5 meters in the height (Figure 2).

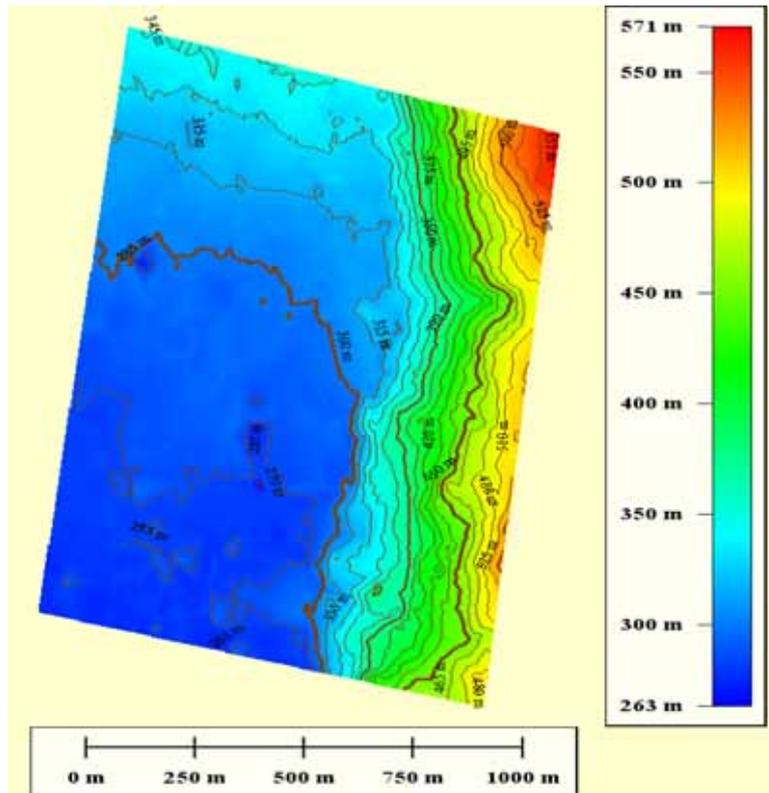


Figure 2 – Radargrammetric DSM from COSMO-SkyMed SpotLight stereopair over Merano (Northern Italy)

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## The Inter-Commission Committee on Theory (ICCT)

*The ICCT strongly encourage frontier mathematical and physical research, directly motivated by geodetic need/practise, as a contribution to science/engineering in general and the foundations of geodesy in particular.*

**(Prof. F.Sansò)**

In the framework of ICCT research activities on the following items have been performed:

- discontinuities in time series
- discontinuities in 2D fields (images)
- potential theory and Boundary Value Problems
- the inverse gravimetric problem

Time series discontinuities analysis is always an important item in geodesy and their detection and repairing is important in a number of applications to geodynamics as well as to GPS data processing (cycle slips). In particular the use of a Bayesian approach to the problem seems to produce incredibly powerful results,

the analysis of discontinuities in a 2D field finds its main use in image analysis, although the solution of the phase unwrapping of SAR data can be an important field of application too. The problem can be treated by suitable variational deterministic approaches or by a stochastic, Bayesian theory. Results have been analyzed and compared,

the analysis of classical BVPS for the anomalous potential usually assume that data are at least square integrable on the boundary (telluroid). In past geodetic literature no reasonable geometric bound was known, allowing the existence of a solution in suitable Sobolev Space. Such bounds have now been found in a realistic range if the first harmonic coefficients of T are assumed to be known,

the inverse gravimetric problem is to determine the full family of mass-densities internal to a body that generate a given external harmonic potential. For  $L^2$  families of mass-densities the problem has been completely understood and solutions characterized. Yet it is interesting to analyze and prove the uniqueness of such a solutions when particular geological constraints are imposed. The interplay of the general solution with isostatic restrictions of various kinds has been studied and clarified.

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