RICERCHE DI
GEODESIA, TOPOGRAFIA E FOTOGRAMMETRIA

n. 13

Working Group on Measurements and Methods of High Precision Space Geodesy

ASI Research (1998-1999-2000)

Milano, Ottobre 2002

DIIAR - Politecnico di Milano – P.za L. da Vinci, 32 - 20133 MILANO

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ISSN 1720 - 657X
ISBN 88 – 7398 – 004 - X

Edizione a cura di Epitesto
Via Pascoli 70/4 Milano
Riprodotto da Globalprint, Gorgonzola

The contents of this volume also appear on the IGES web site at
http://www.iges.polimi.it/other_publications
ISSN 1721-2537

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Preface

The Working Group on measurements and methods of high precision space geodesy of the Italian Space Agency has been working under various titles since 1989. The period between 1989-1997 has been illustrated by a comprehensive report called “Metodi Fisici e Matematici per la Geodesia Spaziale di Alta Precisione”.
The present book collects and summarizes the works done between 1998 and 2000, included.

The overall picture of the researches developed by the working group is well summarized by the title, since we had to do with measurements of very high precision as applied to various fields of planetology, geodesy and observation of the earth.
The items object of research, according to the annual reports, are:

1) Space Missions
2) Net of permanent stations of geodetic space observations
3) Applications of GPS
4) Radaraltimetry
5) Definition of the altimetric datum
6) Geophysical interpretation
7) SAR applications

We try shortly to see what have been, for each item, the major achievements as seen in their development at the international level:

1) several groups of the W.G. have been engaged in national and international competitions for the definition and realization of geodetic space missions.
   A particular place in this sense has the project of the SAGE mission for the determination of the gravity field with an Italian accelerometer, a spaceborne Italian GPS, launched by an Italian launcher. This mission has been studied as one of the possible ASI small missions and has been very highly evaluated, both on a national and international level. In addition several groups have participated in the researches that have contributed to the final outline of the ESA mission GOCE for the determination of the gravity field of the earth by gradiometry. This mission is now between phase B and C. Finally one of the outcomes of our studies has been the design of the Mercury Orbiter mission on which many tools and softwares studied for SAGE will be applied.
2) The traditional studies of the W.G., some years ago concentrated on fine orbital analysis and Laser Ranging techniques, have more recently turned to the very important problem of building a national network of permanent GPS stations to serve as the backbone of the Italian Permanent Geodetic Reference System. In particular this has obvious implications in building a system capable of monitoring the crustal deformations at a national scale.
   Important studies and experiences have been done in this field including the definition of a practical but essential procedure for the establishment of GPS stations for geodynamic purposes. Also the theoretical item of the real level of accuracy of the deformations as derived from GPS observations has been discussed in depth showing that many so-called “preliminary results” of geodynamical networks were not statistically significant. In particular the need of increasing our capability of modeling the tropospheric contribution to GPS phase measurements, has been object of several studies.

3) GPS applications are in the fields of Geodesy, Geodynamics, Navigation, GIS and Engineering in general.
   For such applications the Working Group has allotted a wealth of energies; we do not believe that the works done in the previous fields have been on the front line at an international level, however the best international level has been rapidly spread in the Italian scientific community, particularly of engineering, by our working group. So this technological transfer operation has been essential.
   Particular contributions have been given on the ground of data analysis and certainly an experiment of controlled deformation measurements has been very important for a precise assessment of accuracies.
4) The analysis of radaraltimetric data for ERS1, ERS2 and TOPEX POSEIDON in the Mediterranean Sea has been conducted by our own software and the corresponding stationary Sea Surface has been determined. The comparison of this with the Mediterranean gravimetric geoid has been performed and the geostrophic flow thereby identified.
5) The altimetric datum problem is the choice and determination of a particular equipotential surface of the gravity field to serve as reference for the orthometric heights. Space geodesy is related in two ways to this problem: a) the connection of the national geoid to other local geoids in the world, b) the computation of gravimetric geoids for the oceans or seas to derive the seas surface topography. Several results have been obtained for Italy in both fields.
6) Geophysical interpretation.
   Geodetic spatial observations allow a number of analyses of the physical behaviour of the solid earth: the polar motion, the LOD, the time variation of the first harmonic coefficients of the gravity field provide information on the global interaction between core and mantle and on the effects of viscosity in such interaction.
   In addition more stringent information can be given when the crust deformation is continuously monitored by such methods like GPS observations.
   The two items have been deeply studied and original results, recognized at an international level, derived.
7) SAR interferometry.
   Here some work has been done complementary to international researches on deformation analysis. In particular some solutions to the problem of separating the time varying signal related to surface deformation from the time varying signal due to changes in meteorological conditions, have been implemented.

Summarizing one could say that the coordination of space geodetic techniques in different application fields has been successfully conducted; scientific communities such as astronomers, interested in celestial mechanics and planetology, pure geodesists, interested in orbit theory, gravity field theory and positioning, geophysicists, interested in dynamics of the earth and in crustal deformation, and engineers, interested in applications to GIS and building control, have been strongly pushed to cooperate to the benefit of each of them and of all of them jointly.

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THE SCIENTIFIC OBJECTIVES OF THE RESEARCH LINE “GRAD”

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Introduction

The main effort related to the recovery of the gravity field, in which the Politecnico di Milano group was engaged during the year 1998, was SAGE.
SAGE was studied as a project for a satellite accelerometric mission aimed at determining with high precision the low-medium coefficients of the earth gravity field and their time variations.
In the international panorama, SAGE would have been a prosecution of CHAMP, both in time and in space (SAGE would fly polar, filling in the polar gaps).
During a longer time-span, covering the years from 1998 to 2001, the study of Slepian functions as a basis of localized functions in the space spanned by spherical harmonics up to a fixed degree, was carried on. Slepian functions provide a useful tool to deal with local problems in geodesy, as geodetic operators and harmonic extensions outside the earth's surface can be easily applied.

GOCE will be the first satellite gradiometry mission for the exploration of the earth gravity field and has been specifically designed to determine the stationary part of the field (geoid and gravity anomalies) with high spatial resolution and to very high accuracy.
The PoliMi group was involved during the years 1999 – 2000 in a research which was intended as a preparatory work for further studies along the line of the data reduction strategy based on the space-wise approach. The whole concept of the approach is to use the spatial correlation of the field of the measurements, inherited from the correlation of the anomalous potential, to assemble spatially contiguous observations with the purpose of cross-checking one another and forming spatial (block) averages to be used as observations and having a much lower noise.

In the following, the three subjects (SAGE, the use of a Slepian solution for local geodetic problems and GOCE) will be presented.

The SAGE project and its relation to the other gravity field missions

SAGE went through a Phase A study commissioned by the Italian Space Agency (ASI), which lasted from December 1997 to October 1998, putting together Italian groups coming from several research areas.
In fact, SAGE (AA.VV., 1998) was studied as a fully Italian project aiming at determining the gravity field of the Earth by exploiting the concept of high-low satellite-to-satellite tracking (SST). This means that the satellite orbit is determined by GPS, while the non-gravitational perturbations are determined by a three-axes accelerometer which, integrated back two times, gives the “virtual” orbit followed under gravitational effects only.
The main instruments designed to constitute the payload of SAGE were made after Italian technology. The ISA accelerometer was developed at the IFSI Institute (Istituto di Fisica dello

Spazio Interplanetario) of the CNR (National Research Council). This accelerometer was designed to be the fundamental element of a space-borne, room temperature, gravity gradiometer having a sensitivity of 10^{-2} EU/$\sqrt{Hz}$. In this case the accelerometers must have a sensitivity of 5 10^{-13} g/$\sqrt{Hz}$.

The Lagrange instrument was at that time under development at Laben S.p.A. . It was designed as a GPS/GLONASS receiver to be used not only for navigation purposes but also for scientific objectives like Precise Orbit Determination (POD). The error of Lagrange is less than 1 mm at a sampling rate of 10 Hz.

It is interesting to remark that SAGE would be logically and temporarily interwoven with CHAMP, as the two missions were based on the same scientific principle (ESA 1998).

Specifically, SAGE would aim at:

- improving the CHAMP goals aiming at the useful determination of coefficients up to degree 70;
- extending in time the CHAMP mission allowing for a high-low SST sampling of the gravity field at an altitude of 400 km with an overall time span of 7 to 8 years, which could give more reliable information on time variations of the field;
- cross-checking the two missions one with respect to the other, because they would fly together more or less at the same altitude for at least two years, allowing for a reciprocal (indirect) calibration of the two instruments, which are based on different technologies.

As mentioned before, several Italian research institutions and industries participated to the SAGE Phase A study, including research centers (ASI/CGS Matera, IFSI/CNR Roma, Politecnico di Milano – IGeS, Università di Padova, Università di Pisa – CNUCE, Università di Trento) and industrial partners (Carlo Gavazzi Space S.p.A., Laben S.p.A., Telespazio S.p.A.).

The Politecnico di Milano unit was deeply involved in the SAGE mission study. It acted as the reference group, being in charge of the organization and management of the whole project. Besides, regarding the scientific part of the work, it studied the application of the space-wise approach to SAGE data treatment for the retrieval of the gravity field from high-low satellite-to-satellite tracking.

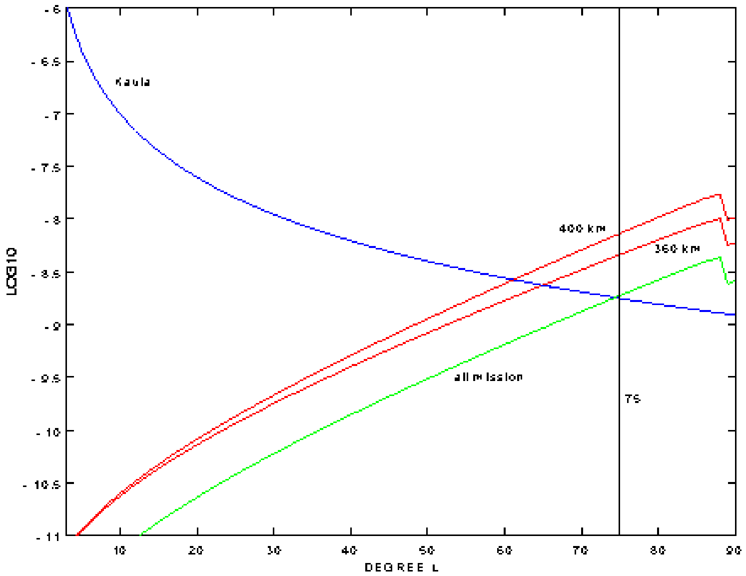

Figure 1 - The performance expected over the entire SAGE mission, assuming 5 years at an average altitude of 400 km plus one year at an average altitude of 360 km. The lower line is the extrapolated performance for such a data set, the upper lines are the formal standard deviation for 180 days of data at 400 and 360 km respectively.

The Phase A studies and simulations of the mission showed that SAGE could meet its targets.
Though SAGE was not developing a new scientific concept, its scientific targets were new: this mission would extend the gravity sampling of CHAMP for three more years and improve the spatial resolution of high low SST; in case SAGE would fly polar, polar caps would be surveyed and filled with data; moreover, the accuracy of the measurements and the data analysis in SAGE would allow for the determination of a much higher degree than CHAMP.

SAGE simulations were performed both applying the time-wise and the space-wise approach for the data reduction.
The largest simulation with the space-wise approach was performed with one year of data. The results of the space-wise treatment were, as expected, similar to the ones of the time-wise approach, if the noise was assumed to be white. However, there was no time during the project to compute a complete solution with an accurate enough algorithm. The influence of coloured noise could further degrade the results by a factor of about 2 in accuracy. The small differences between these results and the ones obtained with the time-wise approach are certainly worth a deeper theoretical and numerical investigation; nevertheless, they are not large enough to result in different evaluation of the scientific merit of the mission.
The possibility to obtain a solution up to a comparatively high degree with only six months of data implied the possibility of detecting time variations. The geopotential coefficients were not expected to change by 100 % of their value, however, and the significant result was the possibility to detect changes of 1 % with periods of one year and longer, up to and even beyond degree 25. This should be compared with the present knowledge of secular trends for the coefficients of degree 2 and 3 only.

Using Slepian functions for local geodetic computations

Slepian functions have been introduced in geodesy to deal with polar gaps occurring in satellite data. They are an orthonormal basis for band-limited functions on the unit sphere, obtained in the space spanned by spherical harmonics up to a given maximum degree by choosing a suitable sequence of orthonormalized functions with decreasing square integral on the belt resulting by subtracting polar caps from the whole sphere. The name of Slepian functions comes from D. Slepian, who introduced them on the real line, in order to deal with some problems in communication theory; most of their properties can be easily generalized on the unit sphere. The main advantage is in that a number of basis functions with suitably small square integral on the belt can be disregarded when representing functions whose values are known only on the belt itself. It turns out that, for fixed maximum degree, the number of functions whose square integral on the belt is smaller than a fixed level is roughly proportional to the cap amplitude.

In principle, one can conjecture that the same procedure can be applied to any subdomain of the sphere and that, if the domain is small with respect to the whole sphere, functions known only on it can be well approximated in terms of a relatively small number of Slepian functions, even starting from spherical harmonics up to a very high maximum degree. Thus a method could be envisaged to build up local representations of functions, taking profit of the localizing properties of a suitable basis at a sufficiently high resolution level.

A numerical test was carried out, with $A_n = n-1$, reproducing the spectral behaviour of the gravity anomaly operator. In a first simulation the input function was randomly generated, with the degree range from 30 to 90, and the Slepian procedure was applied with max degree 180; the comparison area was obtained cutting off a frame 3° wide from the 30° x 30° test area. The results were not very satisfactory, showing a contribution of long-wave terms to the recovered function $\hat{f}$. A significant improvement was obtained by removing the lowest degrees up to n=6 (i.e., roughly speaking, the waves whose half-length exceeds the area width). A much more relevant improvement has been achieved introducing as input the coefficients of the EGM96 global model. In this case for the ratio r the value 0.023 has been obtained; a qualitative comparison of the simulated and the recovered function can be seen in fig.2.

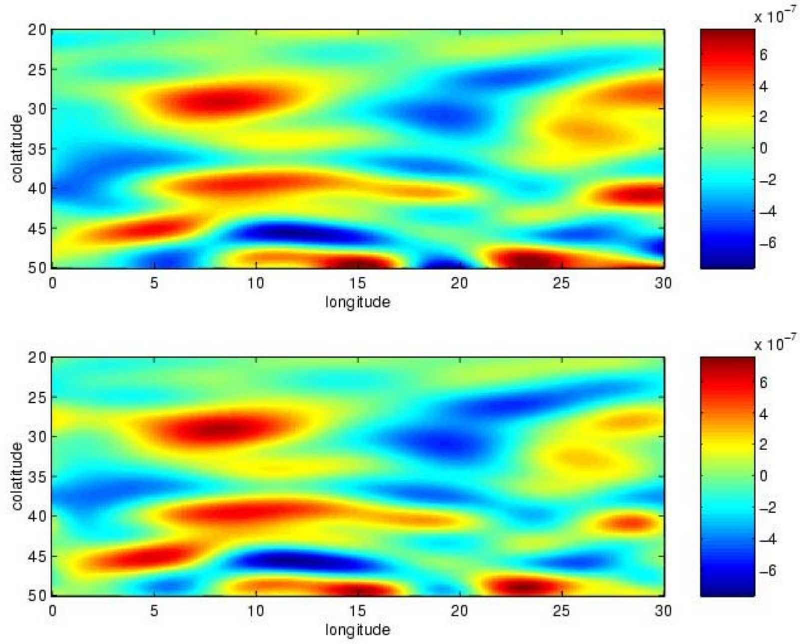

Figure 2 - The simulated function f (upper picture) and the recovered function $\hat{f}$ (lower picture)

The result was substantially confirmed with max degree 360.
The results show that satisfactory approximations are actually attainable on a rectangular region using a small number of Slepian basis functions at a given maximum degree; the ratio between this number and the total number of spherical harmonics up to the same maximum degree is comparable with the ratio between the area of the region and the total area of the sphere.
Slepian functions can be introduced at different resolution and localization levels and used for different applications in local geodetic problems, more or less as spherical wavelets. They do not share with wavelets many important properties, as scaling and shifting, and are not generated from a single mother function. Yet, it is possible to define procedures for the transition from a larger to a smaller support area and from a lower to a higher resolution level. Therefore it can be expected that, with further refinements in the implementation of numerical algorithms, the adoption of Slepian functions will provide a useful tool for geodetic applications.

The study of the GOCE mission data

GOCE will be the first satellite gradiometry mission for the exploration of the earth gravity field and has been specifically designed to determine the stationary part of the field (geoid and gravity anomalies) with high spatial resolution and to very high accuracy. Such an advance in the knowledge of the Earth gravity field and its geoid will help to develop a much deeper understanding of how the Earth interior system works. New and fundamental insight is therefore expected into a wide range of research and application areas, including Solid Earth Physics, Oceanography and Geodesy. To reach the measurement goal and meet the scientific objectives, the payload consists of an electrostatic gradiometer and a combined GPS/GLONASS precise positioning system.

The PoliMi group was involved during the years 1999 – 2000 in a research which was intended as a preparatory work for further studies along the line of the data reduction strategy based on the space-wise approach. The whole concept of the approach is to use the spatial correlation of the field of the measurements, inherited from the correlation of the anomalous potential, to assemble spatially contiguous observations with the purpose of cross-checking one another and forming spatial (block) averages to be used as observations and having a much lower noise. The advantage of this approach is to allow comparisons of measurements distant in time but close in space, with a superior capability of controlling biases and to permit the application of anti-aliasing techniques. The method is considered as complementary to the frequency-domain approach, having possibly certain advantages when employed to cross-validate the scientific results.

In the framework of the GOCE studies, the PoliMi group worked in the above mentioned period on two specific problems, namely the check of the operational state of the gradiometer (which is part of the procedures for quality assessment) and the analysis of the GOCE data series for outliers detection.

Check of the operational state of the GOCE gradiometer on-the-fly ("self-calibration")

Observables of the same kind coming from the same mission can be compared by predicting the value of one point starting from the value observed at a different point. The aim is to check the operational state of the gradiometer, in order to identify the presence of gross errors. It is possible to perform checks on-the-fly for observations taken at cross-over points, loop points and on repeated tracks. The possibility to check data are different, depending on the different conditions given.
In general, the checks consist in verifying that the two estimated values lie in an interval of given significance; if one of the observed tensor components used in performing the estimates is affected by a gross error, the test will fail and the data set in use should be re-examined.

- CROSS – OVER: it happens when observations are collected on two different orbital arcs (at different altitudes), but at positions with the same (ground) geographic coordinates;
  For altitude differences within 1 km the available check is
  $$T_{ZZ}(C) = T_{ZZ}(C_0)$$
  C, C_0 = cross-over points (see also loop-checking procedure, same reasoning).
  For altitude differences of 3 km, on the contrary, the noise propagation shows that the proposed checking procedure cannot be performed.
  In this case, another check would be possible, namely
  $$Q^+(K) = Q^-(K)$$
  where Q is a suitable functional of T_{XX}, T_{XY}, T_{ZY}, computed at point K, which is the average altitude point between C and C_0, respectively starting from the upper orbit (Q^+) and from the lower orbit (Q^-).

- LOOP: it happens when the cross-over is produced after only one cycle (the height difference is then proved to be less than 100 m, which produces negligible variations in the tensor components); the available check is:
  $$T_{ZZ}(C) = T_{ZZ}(C_0)$$
  C, C_0 = loop points.
  As the measures are not directly performed in C, C_0, but must be interpolated starting from other points, systematic errors and noise propagation of the procedure must be assessed.

- OVERLAPPING TRACKS (REPEATED TRACKS): they occur when two orbits exactly repeat the same ground track; if the altitude difference of the two orbits is within 1 km, then pieces of arcs can be considered as coinciding; if the altitude difference is much larger, a check on a 2nd order along track derivative can still be established.

For tracks with an altitude difference of less than 1 km, the available checks are:

$$T_{XX}(P') = T_{XX}(P'')$$
$$T_{YY}(P') = T_{YY}(P'')$$
$$T_{ZZ}(P') = T_{ZZ}(P'')$$

where P' and P'' are corresponding points (same geographic coordinates) on the upper and lower orbital arc: of course, the points along one orbital arc are observation points, while the observations along the other orbital arc must be interpolated.

For tracks with an altitude difference of more than 1 km, the available test is on the T_{XX} component:

$$T_{XX}(P') \cong T_{XX}(P'') + T_{XXZ}(P'') \cdot H$$

where H is the orbital height difference.

Analysis of the GOCE data series for outliers detection

It consists of a procedure for outliers detection and rejection based on a hypothesis test which uses a statistics with student t distribution on regular series of GOCE gradiometer measurements along the orbit. The structure of the test is summarized as follows:

- predict the signal $\hat{F}$ (t_k) from neighbouring data;
- compute the prediction error $e_k = F(t_k) - \hat{F}(t_k)$;
- based on e_k, construct a sample variable of known distribution, suitable to test a deviation from the zero-mean hypothesis (i.e. presence of outliers);
- the sample variable to test the hypothesis H_0 : E{e_k} = 0 (zero-mean prediction error) is:

$$\frac{e_k}{\sqrt{C\,(1-\underline{r}_0^T\,R^{-1}\underline{r}_0)}} = t_{2\Delta-1}$$

where:

e_k = prediction error

Δ = width of the window of data entering the testing procedure (the distance at which the correlation function drops to zero)

C = variance of the data series

$\underline{r}_0$ = correlation between the point to be tested and the other data of the series

R = correlation matrix of the data series

The interesting thing is that the concept of this test is suitable for automatic implementation. The output consists in positions in the time series of the data corresponding to the detected outliers.

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GEOID DETERMINATION IN THE ITALIAN REGION

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Abstract
Geoid estimate is nowadays one of the most relevant topic in Physical Geodesy.
Precise geoid estimates (few centimetre precision) are required on the oceans and on land areas. Having a reliable geoid estimate on the oceans allows SST computation which can give valuable information on currents dynamic that are related to climate changes.
Precise geoid estimates are also required over land to be used in connection with GPS observations to compute orthometric heights, thus replacing spirit leveling (although with lower precision).
In this paper, an overview on geoid determination in the Italian area, land and surrounding seas, is given and comparison with GPS/leveling is discussed to define the estimate precision.

Geoid computation in Italy

The altimetry research line has been developed significantly up to the 1999. Here achievements have been reached in

- methodology: the clarification of the split between time-varying and areawise signals along tracks by collocation and time-spectral analysis has been a major breakthrough which has not, to the date, been overwhelmed;
- the analysis of the rank deficiency problem in cross over adjustment for bounded areas (e.g. the Mediterranean) has been fully accomplished
- software has been produced to perform signal splitting (timewise – areawise) and the subsequent cross over adjustment.
  The software has been made operational and results have been numerically achieved, yet it has never reached a standard operability and as such it cannot be considered as finished;
- numerical results on Mediterranean SST have been derived which are still, to our knowledge, one of the two only internationally known acknowledged solutions.

Overall we can say that these researches had to be stopped due to lack of manpower; however the results obtained are still better than the international average level and in future the research could start again.
On the other side, the researches on geoid estimation and the comparison with GPS/leveling data have been carried out intensively in the 1998-2000 period. A new geoid estimate has been computed over the whole Italian area using the remove-restore procedure and fast-collocation. As it is well known, the geoid, i.e. the equipotential surface of the Earth gravity field which is close to the mean ocean surface, can be used, for instance, in combination with radar-altimetric data to get ocean currents. Furthermore, GPS observations together with geoid estimates can give orthometric heights. This is of particular relevance, since this can be done in a faster and cheaper way than using spirit leveling, although with lower precision (which is however sufficient in many practical applications). Hence, the estimate of a subdecimetric precision geoid over the whole Italian region is a primary task for the national geodetic community.

Many improvements have been introduced with respect to the previous Italian geoid estimate ITALGEO95 (Barzaghi et al., 1995). The Italian gravity data set has been enlarged introducing 4624 new gravity data in the area $45.3 \le \varphi \le 46.8$; $13.4 \le \lambda \le 16.8$, corresponding to Slovenia. In this way, the gravity data gap in this area, which is very close to the Italian boundaries, was filled so avoiding possible mismodelling in the quasi-geoid estimate in the Friuli Venezia Giulia area. Furthermore, the 7.5" x 10" Italian DTM (Carrozzo et al., 1982) has been carefully checked for outliers using the values extracted from an independent 100 m resolution DTM, supplied by I.G.M. (Istituto Geografico Militare). In this way, 327 outliers, distributed randomly in the whole Italian area, have been found and corrected.
New geopotential models have been also considered in computing the new geoid estimate. Since the ITALGEO95 computation, two new geopotential models have been made available: EGM96, complete up to degree 360, (Lemoine et al, 1998; IGeS Bulletin, 1997) and the high resolution model GPM98CR by Wenzel, complete up to degree 720, (Wenzel, 1998). These models were adopted to account for the long wavelength component of the geopotential field.
Based on the two global geopotential models EGM96 and GPM98CR, two quasi-geoid estimates have been computed in the Italian area.
In both cases, the classical "remove-restore" (Barzaghi et al.,1996) procedure has been used and the residual quasi-geoid components have been evaluated using the Fast Collocation approach (Bottoni and Barzaghi, 1993).

The computation of the quasi-geoid named ITG99_EGM96, based on the EGM96 global model, has been carried out on a regular 3' x 3' grid in the area $36°\le\varphi\le47°$, $6°\le\lambda\le19°$.
RTC has been computed up to 70 km from each computation point both in the gravity component and quasi-geoid effect.
Statistics of the "remove" step are listed in tab. 1. Point gravity values have been then gridded on a regular 3' x 3' geographical grid. GEOGRID program of the GRAVSOFT package (Tscherning et al., 1994) was used for such a step: statistics of the residual gridded gravity values Δg_r^G are shown in tab. 1. The empirical covariance of these values and the best fit model are represented in fig. 1.
As one can see, a very good fit is reached between the empirical values and the best fit model covariance which, in terms of anomalous potential T(P), is given by

$$COV_{TT}(P,Q) = \sum_{i=2}^{\infty} \sigma_i^2 \left(\frac{R^2}{rr'} \right)^{i+1} P_i(\cos\psi) \qquad (1)$$

where: $$\sigma_i^2 = \begin{cases} \varepsilon_i \text{ error degree variances} \\ \text{degree variances, e.g. } \dfrac{A}{(i-1)(i-2)(i-B)} \left(\dfrac{R_B}{R} \right) \end{cases}$$

R is the Earth radius
r, r' are respectively the radial distances of points in space P, Q
P_i the Legendre Polynomial of degree i
ψ the spherical distance between P and Q

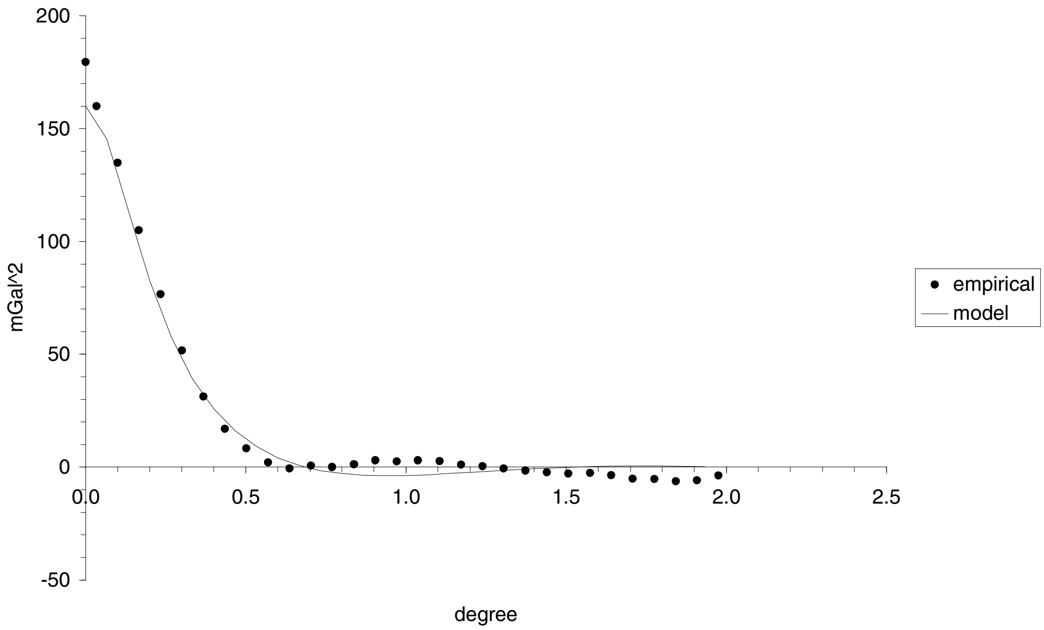


Figure 1 - Empirical and model covariance function of the gridded gravity residuals obtained with the global geopotential model EGM96

	Δg_0 [mGal]	Δg_0 - Δg_M [mGal]	Δg_r [mGal]	Δg_r^G [mGal]
n	109927	109927	109927	57681
E	11.92	-6.71	-2.37	-0.33
σ	61.71	30.75	15.57	12.97
min	-162.36	-253.33	-188.32	-116.13
max	269.71	187.95	109.38	102.86

Table 1 - Statistics of the "remove" step using the EGM96 geopotential model.

Δg_0: observed gravity values (free air) Δg_M: gravity geopotential model component
A_{rtc} :gravity terrain correction component $\Delta g_r = \Delta g_0 - \Delta g_M - A_{rtc}$ gravity residuals
Δg_r^G: gridded gravity residuals

The Fast Collocation solution giving ζ_r has been computed on the same 3'x3' grid used for Δg_r^G. The "restore" step was then accomplished: the ζ_{rtc} and the ζ_M component have been added to ζ_r, thus getting the final quasi-geoid estimate ITG99_EGM96. In tab. 2 and fig. 2, the statistics of the "restore" step and the contour lines of the quasi-geoid are shown.

	ζ_r [m]	$\zeta=\zeta_r+\zeta_M$ [m]	$\zeta=\zeta_r+\zeta_M+\zeta_{RTC}$ [m]
n	56781	56781	56781
E	-0.09	44.26	44.35
σ	0.52	4.96	5.09
min	-1.55	25.73	25.23
max	1.58	54.09	55.28

Table 2 - Statistics of the "restore" step using the EGM96 geopotential model

ζ_r: residual quasi-geoid
ζ_{rtc} :quasi-geoid terrain correction component
ζ_M: quasi-geoid geopotential model component
ζ: quasi-geoid

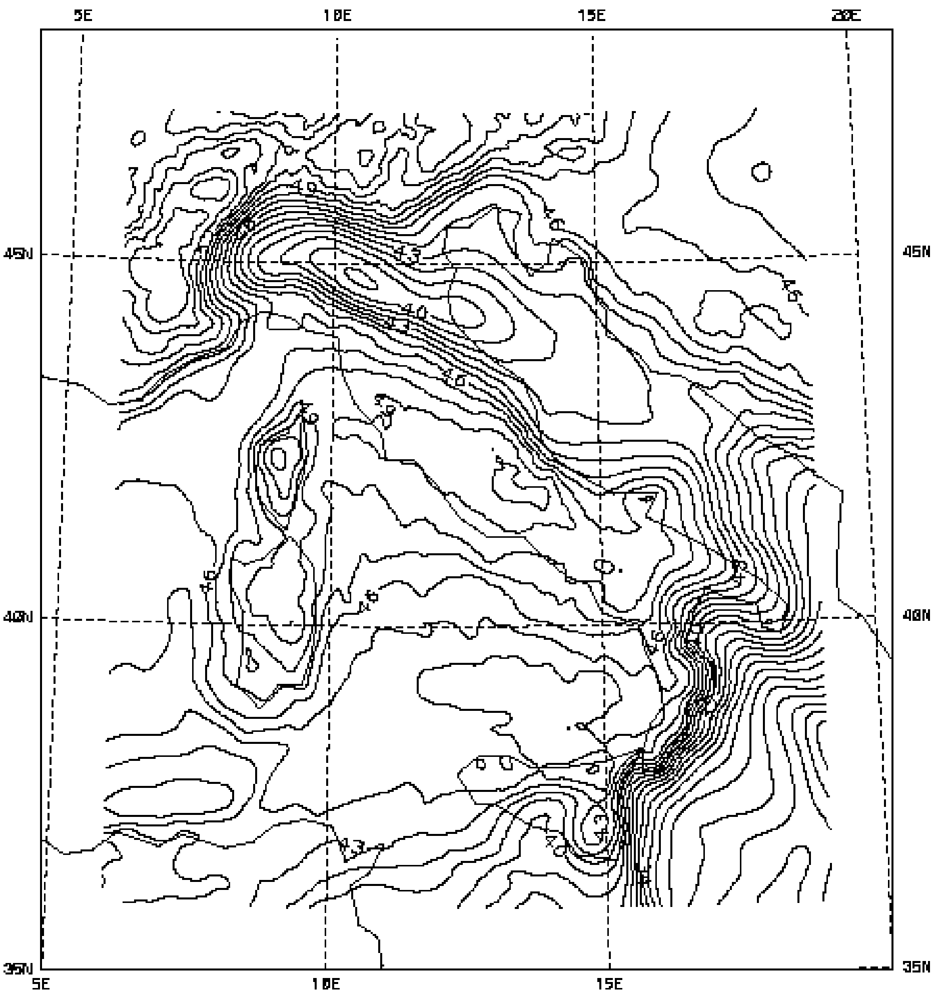


Figure 2 - The Italian quasi-geoid ITG99_EGM96 (equidistance = 1m)

Similarly, the high resolution geopotential model GPM98CR by Wenzel has been used up to degree 720 to get the ITG99_GPM98CR estimate.
Also in this case, the steps described in the ITG99_EGM96 computation have been performed.
Statistics of this "remove" step are given in tab. 3. Residual gravity values have been gridded on a 2'×2' regular geographical grid covering the same area used in the EGM96 based computation (their statistics are listed in tab. 3). The empirical covariance and the best fit model are shown in fig. 3.

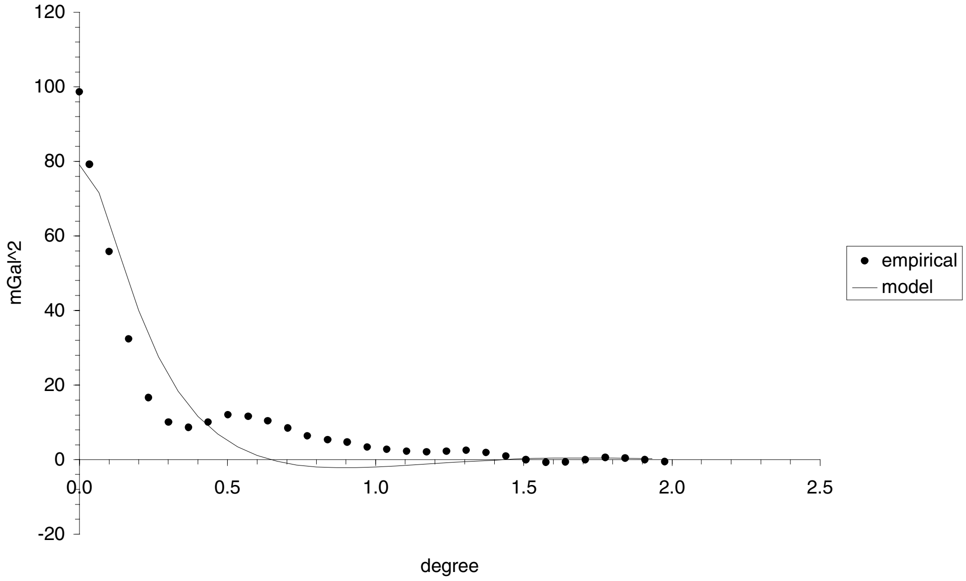


Figure 3 - Empirical and model covariance function of the gridded gravity residuals obtained with the global geopotential model GPM98CR

The empirical covariance is quite irregular but its amplitude is remarkably smaller that the one obtained in the EGM96 empirical covariance. This means that the GPM98CR model and the related RTC reduction can give a better representation of the local gravity data than EGM96 (this can be seen also in the statistics of the gravity residuals in tab. 3)

	Δg_0 [mGal]	$\Delta g_0 - \Delta g_M$ [mGal]	Δg_r [mGal]	Δg_r^G [mGal]
N	109927	109927	109927	129421
E	11.92	-6.07	-0.95	0.22
σ	61.71	25.20	11.15	9.66
Min	-162.36	-200.55	-191.81	-135.32
Max	269.71	164.85	92.37	89.32

Table 3 - Statistics of the "remove" step using the GPM98CR geopotential model.

Δg_0: observed gravity values (free air)
Δg_M: gravity geopotential model component
A_{rtc} :gravity terrain correction component
$\Delta g_r = \Delta g_0 - \Delta g_M - A_{rtc}$ gravity residuals
Δg_r^G: gridded gravity residuals

As in the previous estimates, Fast collocation was applied for computing ζ_r on the 2'x2' regular grid used for Δg_r^G evaluation. The statistics of the "restore" step related to the ITG99_ GPM98CR quasi-geoid are presented in tab. 4, while the plot of the estimate is shown in fig. 4.

	ζ_r [m]	$\zeta=\zeta_r+\zeta_M$ [m]	$\zeta=\zeta_r+\zeta_M+\zeta_{RTC}$ [m]
n	129421	129421	129421
E	0.05	44.40	44.43
σ	-1.63	44.44	5.06
min	0.49	5.06	25.45
max	1.65	25.45	55.27

Table 4 - Statistics of the "restore" step using the GPM98CR geopotential model

ζ_r: residual quasi-geoid
ζ_M: quasi-geoid geopotential model component
ζ_{rtc} :quasi-geoid terrain correction component
ζ: quasi-geoid

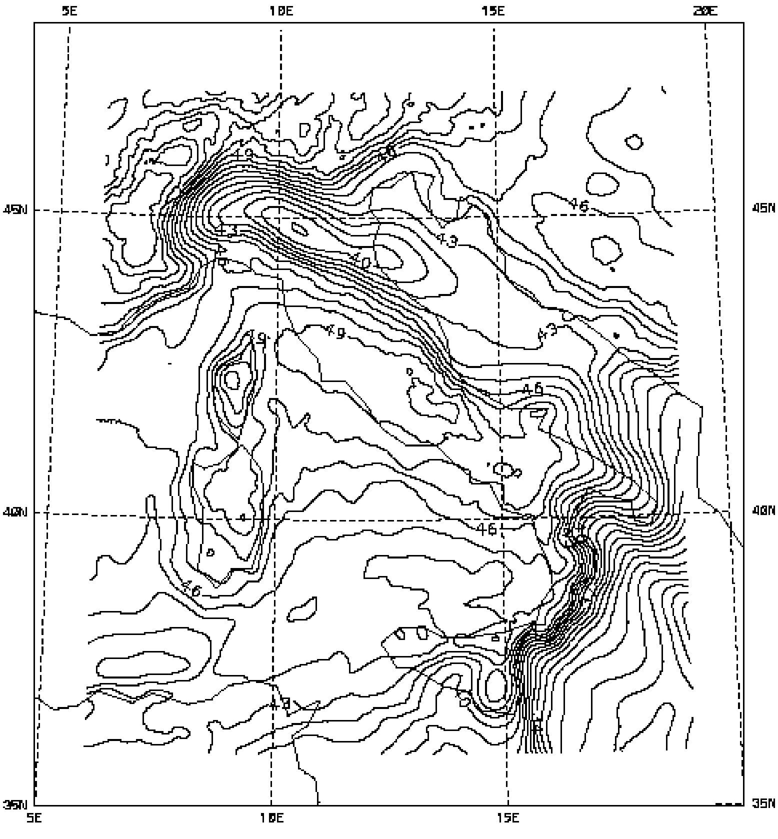


Figure 4 - Italian quasi-geoid ITG99_GPM98CR (equidistance = 1m)

The two gravimetric quasi-geoid estimates have been then compared on 583 points with GPS derived undulations.
In these 583 points, both h (ellipsoidal height) and H (orthometric height) are known so that $N_{GPS/lev} = h - H$ can be computed. The h values refer to the IGM95 GPS campaign whereas the H

values are obtained via spirit leveling (these double points belong to the so called GEOTRAV network and were supplied by IGM). To properly perform the comparison, a datum shift between the gravimetric quasi-geoid estimates and the $N_{GPS/lev}$ must be computed to reduce the data to the same reference system. While $N_{GPS/lev}$ is in the GPS reference system, ζ computed with the "remove-restore" method is in the reference system implied by the global geopotential model.
To this aim, the following formula, which accounts for a translation based datum shift in terms of geoid undulation, has been considered (Heiskanen and Moritz, 1990):

$$
\begin{aligned}
N_{grav} &= N_{GPS/lev} + \Delta N(\theta,\lambda) = \\
&= N_{GPS/lev} + dx \sin\theta\cos\lambda + dy \sin\theta\sin\lambda + dz\cos\theta
\end{aligned}
$$

(dx,dy,dz) = translation between GPS and geoid reference systems
$\theta = 90 - \varphi$

(we remark that only translation is considered in this relationship between the two reference systems).
We also assume that $N_{grav} \sim \zeta$, being ζ the quantity which is effectively estimated: this can induce distorsions and perturbations specially in high mountain areas
The quantities (dx,dy,dz) were estimated by least squares; outliers rejection, in the hypothesis of normal distributed residuals and with significance level α = 1%, was also performed.
The datum shift estimate was done separately for the peninsular part of Italy, for Sicily and Sardinia.
This subdivision reflects the geographical difference of these three areas and also the possible discrepancies among their orthometric height systems (reference tide gauge problems). Hence, comparisons after datum shift computation were carried out separately on the above mentioned zones for the two quasi-geoid estimates.
The results are summarized in the following in tab. 5 and 6 and in fig. 5 and fig. 6.

	ITG99_EGM96: $\zeta - N_{GPS/lev}$ [m]		
	Continental Italy	Sicily Island	Sardinia Island
#	495	36	46
E	0.00	0.00	0.00
σ	0.17	0.08	0.09
Min	-0.44	-0.16	-0.17
Max	0.42	0.13	0.19

Table 5 - Statistics of the residuals between ζ_{ITG99_EGM96} and $N_{GPS/lev}$ after datum shift estimate

	ITG99_GPM98CR: $\zeta - N_{GPS/lev}$ [m]		
	Peninsular Italy	Sicily Island	Sardinia Island
#	496	36	45
E	0.00	0.00	0.00
σ	0.15	0.04	0.06
Min	-0.38	-0.08	-0.13
Max	0.38	0.06	0.15

Table 6 - Statistics of the residuals between $\zeta_{ITG99\_GPM98CR}$ and $N_{GPS/lev}$ after datum shift estimate

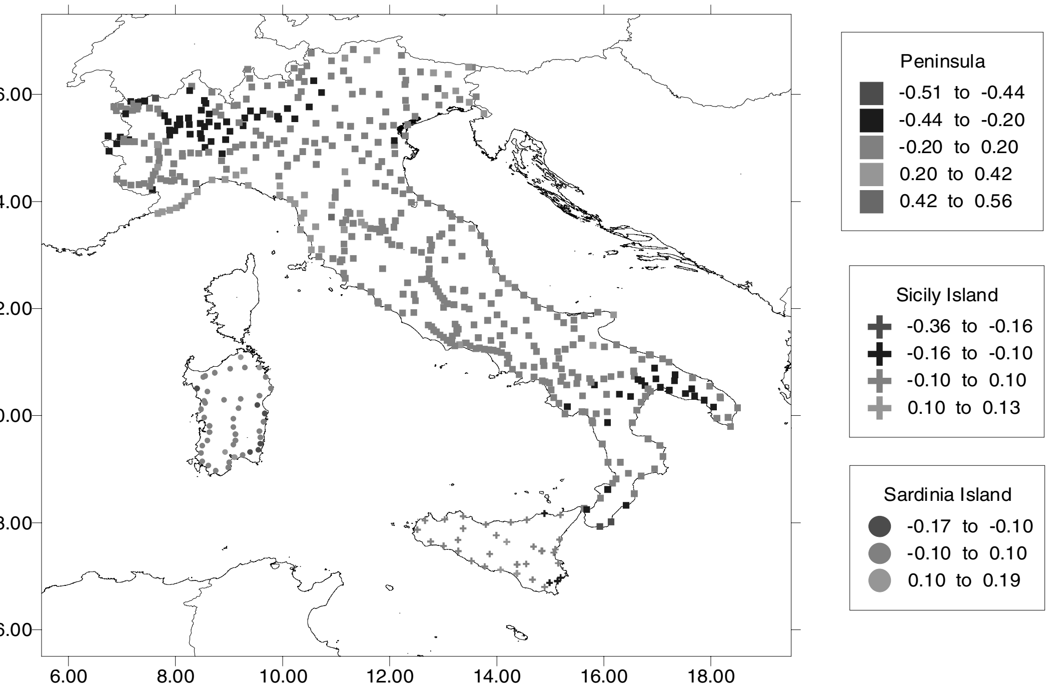


Figure 5 - Residuals between ζ_{ITG99_EGM96} *and* $N_{GPS/lev}$ *after datum shift estimate (m)*

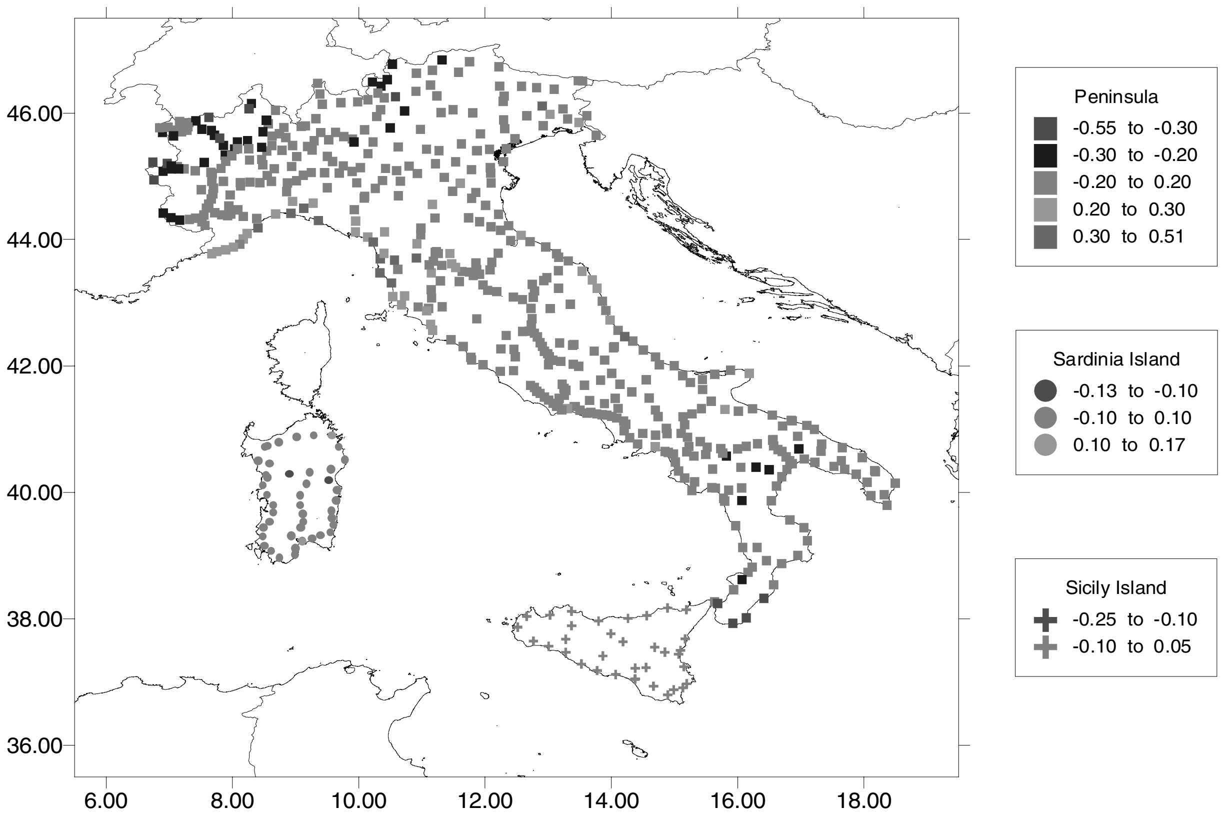
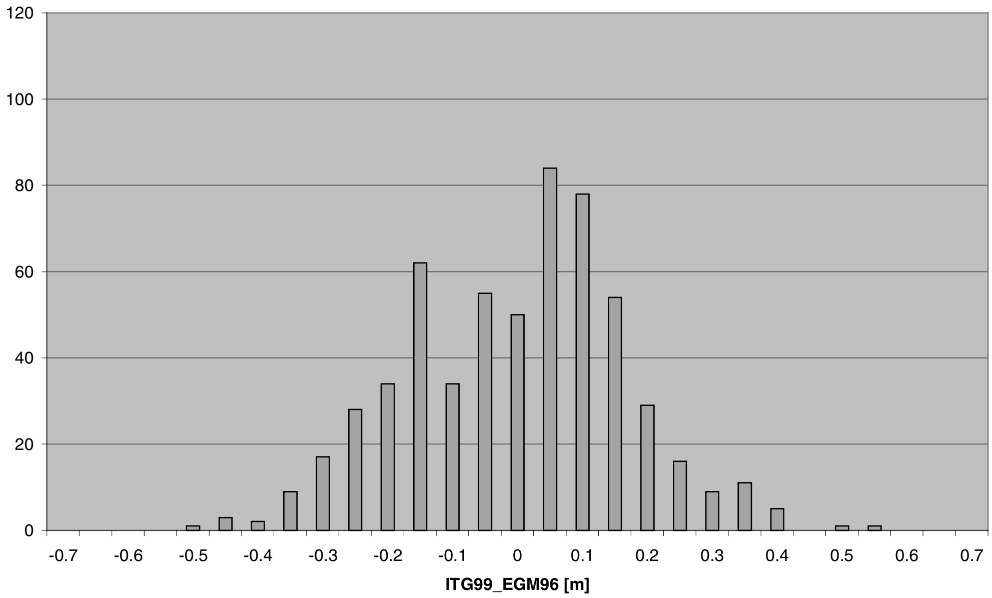


Figure 6 - Residuals between $\zeta_{ITG99\_GPM98CR}$ *and* $N_{GPS/lev}$ *after datum shift estimate (m)*

In both cases, the two models show a good agreement with $N_{GPS/lev}$ in Sicily and Sardinia while a more complex structure of the residuals is present in the Peninsular area.
This can be explained if we take into account that in this area sharp disomogeneities exist both in the orography and in leveling lines (while h is homogeneous in time and precision, this doesn't hold for H which has been measured in the continental part over a large time span).
Due to that, an error analysis on such a data set seems to be very complex. It is quite clear, and obvious, that part of the discrepancies are related to the quasi-geoid estimates. A comparison between fig. 5 and fig. 6 shows that the ITG99_GPM98CR quasi-geoid behaves better that the ITG99_EGM96 solution in the North-Western region.



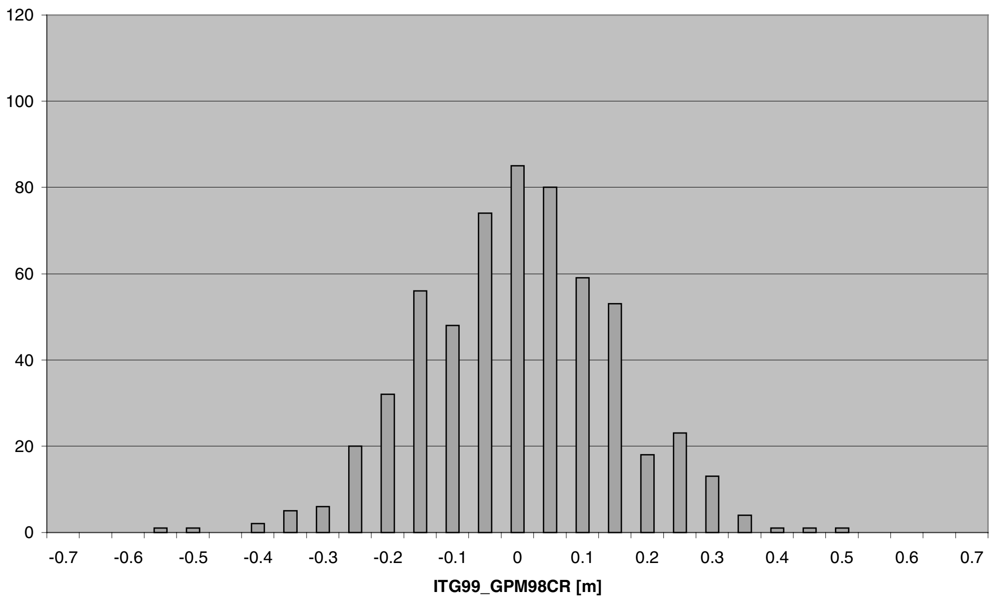


Figure 7 - Histogram of the residuals between quasi-geoid solution and $N_{GPS/lev}$ after datum shift estimate

However, in the same area, particularly along the Liguria coasts, sharp discrepancies are present between $N_{GPS/lev}$ and both quasi-geoid models, so that other possible error sources should be taken into account.
To further compare these solutions, histograms of the residuals between $N_{GPS/lev}$ and the two quasi-geoids here described are presented in fig. 7, grouping the results obtained in the three different areas.
This plots give a synthetic overview of the residuals and show that the ITG99_GPM98CR solution has the most symmetric histogram which is the only one significantly approaching a normal distribution (according to a χ^2 goddness-of-fit test with α=5%).
All these analyses prove the good quality of the ITG99_GPM98CR estimate which has been named ITALGEO99 and which is, at the moment, the most accurate quasi-geoid estimate for the whole Italy. Thus, this research task has been completely accomplished and this precision estimated geoid will be a sound basis for future researches on the altimetric datum in Italy.

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GPS AND ITS APPLICATIONS: SOME PROPOSALS ON THE ITALIAN PERMANENT NETWORK, METEOROLOGY AND DATA ANALYSIS

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Introduction

GPS applications range from geodynamic investigations to engineering applications. This wide spectrum of activities centred on GPS permanent and non-permanent networks requires a careful data management and new scientific tools leading to the best possible reliability and precision.
Particularly the Italian national GPS permanent network should be properly designed in order to ensure a uniformly precise positioning and possibly a geodynamical deformation detection at a national scale.
Thus, this project is a key project both from a geodetic and geodynamical point of view. Furthermore, cinematic real time positioning could be another important aspect of such a national network.
Also, local GPS networks, tied to the permanent one, can give valuable information on meteorological parameters, which are of extreme importance in environmental risk studies.
These aspects on GPS are revised in this paper and a new method for ambiguity resolution is presented in order to improve efficiency in data handling, an important point when processing large data sets as it is the case for GPS permanent networks.

The Italian GPS permanent network

Permanent GPS stations are nowadays the most important tool in defining a geodetic reference frame. As a matter of fact, a continuous GPS network connected to IGS produces a set of coordinates referred to the International Terrestrial Reference Frame (ITRF).
Thus, a national network of permanent GPS stations could provide GPS data and products to meet the objectives of a wide range of scientific and engineering applications.
GPS permanent stations data can be used either in post-processing or in real time applications. Post-processing applications are mainly related to cadastre, photogrammetry and filed surveying. Real time applications, which need for a master-rover radio link, are of importance for navigation purposes. So, it is important to optimise the densification of the national permanent GPS network.
In the framework of the ASI project, an optimisation of the permanent GPS sites over Italy and the design of such a network have been carried out.
Presently, the situation in Italy is nor optimal neither homogeneous if compared with other European countries.
94 GPS receivers have been activated up to now, which have been equipped with high-precision geodetic receivers. However, since GPS have been monumented and realised by many different

subjects, there are areas with a high density of permanent GPS stations and areas, which are nearly, uncovered (see fig. 1).

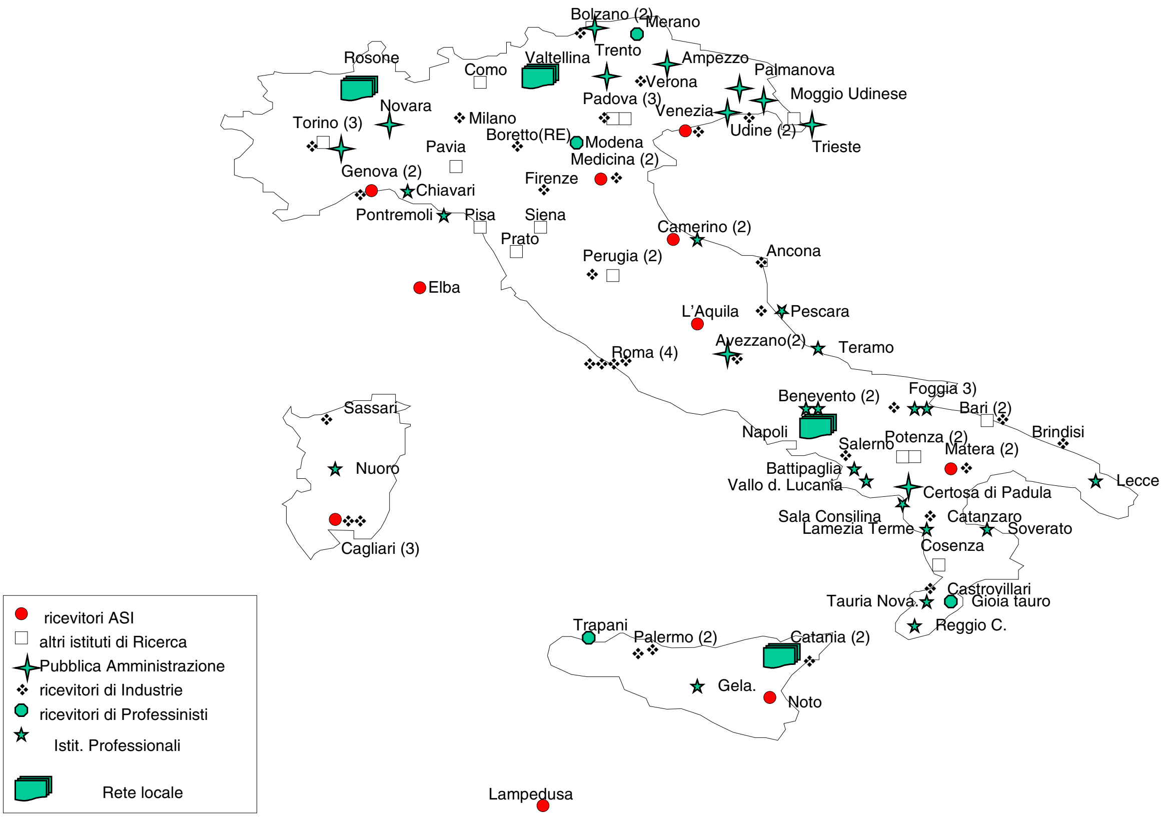

Figure 1 - The present day distribution of permanent stations in Italy

Thus, in order to properly design a GPS permanent network in Italy, different simulation scenarios with cumulative observations have been considered.

A first analysis has been done using simulated observations to estimate the position of a single receiver located in the centre of a square formed by four GPS permanent stations. The sides of the square have been assumed to be 50, 70, 90 and 100 km long. For each square, sessions from 15' to 240' have been considered: in such a way both fast-static and precise GPS measurements are taken into account (sessions have been simulated for time spans of 15', 30', 60', 120' and 240').

The simulated data have been computed using the Bernese 4.2 software (Beutler et al., 2000) with a time interval of 15', without introducing cycle slips and assuming an a priori st.dev. of 3mm both for L1 and L2. The troposphere effect have been computed using the Saastamoinen model and ionosphere has been introduced into the picture in the uniform hypothesis (Kutterer, 1998). Fixing the coordinates of the simulated permanent GPS stations and computing the coordinates of the inner points using the simulated data has done data processing. These estimated coordinates have been then compared with the simulated ones in order to evaluate the impact on the precision of the distance from the stations placed at the corners of the square.

Data processing with Bernese software has been performed using L3 double difference phase observations and the SIGMA strategy for ambiguity fixing.

The outcomes of these computations are summarised, for the 70 km and the 90 km square sides, in Table 1 and 2 (the "known" mid point coordinates have been fixed to: x=4398309.792m, y=704173.276 m and z=4550170.368 m).

minutes	x (m)	sqm x (m)	y (m)	sqm y (m)	z (m)	sqm z (m)
15	4398309.7681	0.0331	704173.2425	0.076	4550170.3791	0.0232
30	4398309.7808	0.0206	704173.2925	0.0376	4550170.3579	0.0144
60	4398309.7939	0.0012	704173.2756	0.0008	4550170.3686	0.0012
120	4398309.7921	0.0009	704173.2756	0.0006	4550170.3687	0.0008
240	4398309.7914	0.0006	704173.2757	0.0003	4550170.3682	0.0005

Table 1 - The estimated coordinates of the square middle point: square side of 70 km

minutes	x (m)	sqm x (m)	y (m)	sqm y (m)	z (m)	sqm z(m)
15	4398309.8250	0.0342	704173.1581	0.0784	4550170.3610	0.0239
30	4398309.8370	0.0204	704173.2848	0.0373	4550170.3777	0.0143
60	4398309.7906	0.0012	704173.277	0.0009	4550170.3684	0.0015
120	4398309.7903	0.0009	704173.2761	0.0006	4550170.3667	0.0008
240	4398309.7917	0.0006	704173.2758	0.0003	4550170.3686	0.0005

Table 2 - The estimated coordinates of the square middle point: square side of 90 km

Furthermore, comparisons have been expressed in terms of estimated and sampling std. as defined by:

$$\sigma_p = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$

$$S_p = \sqrt{(\hat{x} - x)^2 + (\hat{y} - y)^2 + (\hat{z} - z)^2}$$

where $\sigma_x, \sigma_y, \sigma_z$ are the Bernese std. while x, y, z are the a priori known mid point coordinates and $\hat{x}, \hat{y}, \hat{z}$ the estimated ones (those obatined using the Bernese software on simulated data).

	50 Km		70 Km		90 Km		110 Km	
minutes	σ_p (m)	S_p (m)	σ_p (m)	S_p (m)	σ_p (m)	S_p (m)	σ_p (m)	S_p (m)
15	0.0869	0.031	0.0861	0.0426	0.0888	0.1226	0.0896	0.0267
30	0.0439	0.024	0.0452	0.0223	0.0449	0.0469	0.0445	0.0291
60	0.0018	0.0006	0.0019	0.002	0.0021	0.0022	0.0019	0.0025
120	0.0013	0.001	0.0013	0.0008	0.0013	0.0021	0.0014	0.0014
240	0.0008	0.0011	0.0008	0.0007	0.0008	0.0007	0.0008	0.0011

Table 3 - Estimated and sampling std

It must be stressed that these results must be taken into account only relatively. Indeed, they cannot be considered realistic because the procedure that has been adopted for simulating and processing the data is far from reality.

However, some information can be inferred from these computations. For instance, it can be noticed that for sessions of 240’, the estimated coordinates and their std. converge to the same value while larger fluctuations are present in short sessions. This can be easily explained taking into account that for longer sessions, satellites configuration improves thus improving the coordinate estimates.
Also, by analysing table 3, one can see that S_P cannot be considered a reliable index for quantifying the solution behaviour. For short sessions it increases with the distances; then it reduces for the 100 km side length. For long sessions, is nearly constant thus being independent from the square side length.
Furthermore, the estimated std., the ones obtained by Bernese, are too precise and independent from the baseline length. Hence, in these respects, the simulation is not able to discriminate between different configurations. Processing simulated data implies a systematic error free situation, which leads to unrealistic estimates (it is well known that residual systematic errors have a strong impact on high precision GPS positioning).
To have deeper insight into the problem, real permanent GPS data have been acquired and processed.
Three baselines connecting Matera to Bari (about 50 km), Noto to Catania (about 70 km) and Matera to Brindisi (about 100 km) have been selected. 30’, 60’, 120’, 240’ and 480’ sessions have been considered, with a sampling rate of 30” during three different days.
Coordinates repeatability has been tested by comparing the shorter session estimates with respect to the 480’ estimates (Table 4).

		MATERA-BARI			**NOTO-CATANIA**			**MATERA-BRINDISI**		
		X (m)	*Y(m)*	*Z(m)*	*X (m)*	*Y(m)*	*Z(m)*	*X (m)*	*Y(m)*	*Z(m)*
30min	***Sess. 046***	0.020	0.002	0.022	0.028	-0.007	-0.002	0.050	0.172	0.137
	Sess. 055	0.021	0.005	0.026	0.104	0.041	0.143	0.006	0.086	0.060
	Sess. 059	0.019	0.009	0.018	-0.004	-0.007	-0.019	0.089	0.032	0.080
60min	***Sess. 049***	0.024	0.003	0.030	0.030	-0.005	0.004	0.033	0.163	0.071
	Sess. 055	0.027	0.007	0.025	0.102	0.057	0.130	0.118	0.033	0.109
	Sess. 059	0.028	0.009	0.022	-0.015	-0.013	-0.026	0.085	0.032	0.078
120min	***Sess. 049***	0.022	0.002	0.024	0.026	-0.003	0.008	-0.022	0.070	0.028
	Sess. 055	0.025	0.006	0.020	-0.058	0.053	0.004	0.114	0.033	0.105
	Sess. 059	0.027	0.009	0.021	-0.013	-0.014	-0.016	0.076	0.032	0.068
240min	***Sess. 049***	0.024	0.000	0.022	0.027	-0.001	0.016	-0.012	0.130	0.038
	Sess. 055	0.026	0.001	0.022	0.008	-0.007	0.005	0.113	0.028	0.106
	Sess. 059	0.024	0.005	0.021	0.007	-0.006	-0.007	0.070	0.005	0.072

Table 4 - Coordinates repeatability as a function of the session time span and the baseline length

Only for the 70 km baseline (the one connecting Noto to Catania) it is clearly visible a dependence from the session time window. The remaining two baselines show stable results (the Matera-Bari baseline) and oscillating results (the Matera-Brindisi baseline).
Furthermore, as expected, there is quite a clear dependence of the repeatability from the baseline length.
Thus, as a conclusion, one can say that the simulations and the real case processing have shown that a feasible mesh side for the planned permanent GPS network should be close to 70 km, which is also reasonable from the managing point of view.

Assessment of Zenith Wet Delay and Path Wet Delay by GPS and radiometer

Beside water vapour radiometers (WVR), recent developments in GPS data processing have allowed the estimation of troposphere water vapour with a high degree of accuracy, using a continuously operating GPS network. Under the hypothesis of a troposphere in hydrostatic equilibrium and azimuthal isotropy, from GPS radio signals, after removing the ionosphere effects, it is possible to estimate the zenith total neutral delay (TZD), and therefore to infer the zenith wet delay (ZWD) by subtracting the hydrostatic component (ZHD) computed from surface pressure measurements. The ZWD time series are then directly transformed into Integrated Perceptible Water Vapour (IPWV). This parameter, highly variable both in space and time, has a major role in the evolution of meteorological phenomena as a matter of fact from its condensation depends the formation of clouds, fogs, and precipitations. Moreover proper quantification of water vapour content is necessary for weather forecasts and for a better understanding of climate change over a wide range of spatial and temporal scales.

It's worth to note that GPS can represent a valid instrument to support the control and protection over flood hazard areas. In fact, from TZD estimates it's possible to go back to the integrated water vapour content that represents the size of the meteoric event under the hypothesis that the full amount of water vapour precipitates. This parameter is extremely useful to foresee flood events with enough advance respect to the precipitation start that can cause the flood event itself.

The advantages of the use of GPS to meteorological purposes respect to the Water Vapour radiometer – WVR, that represents a well-established technique more commonly used today, can be summarised:

- GPS can be used with any climatic condition, while radiometric measurements can not be performed in case of rain;
- GPS instruments are world-wide accessible with prices that are getting easier and extremely plain to use, while radiometer has high costs, needs of highly specialised operators to acquire and process data as well as of an accurate, complex and expensive calibration that requires auxiliary instruments (f. e. sounding balloon);
- GPS instruments have small scale and are extremely handy by now, while radiometer presents remarkable difficulties to be transported and installed.

To verify the possibility to use the GPS method for meteorological purposes three problems have been individuated and indagated:

- external coherence: validation of GPS estimated quantities by comparisons with the equivalent estimates obtained by radiometric data;
- inner coherence: validation of the coherence among GPS estimates obtained following different methods
- directional estimates: evaluation of the possibility to estimate by GPS the wet delay in any direction.

For these purposes a specific experiment has been planned and realised in collaboration with Universities of Roma, Perugia and L'Aquila. The first in Italy performed using a local network of GPS stations that observed in a permanently manner for 15 days, with the aim to perform comparisons not only in the zenith direction, but at any direction also, using the possibility of the radiometer to acquire data along the four cardinal directions and at different elevation angles.

The starting point of the experiment has been the planning and the survey of an *ad hoc* GPS network. The experiment was carried out using the following instruments: 5 GPS receivers of geodetic class (dual frequency with possibility to track full wavelength L2 carrier even in presence of Anti-Spoofing), a two-channel microwave radiometer (water vapour and liquid water) steerable both in azimuth and zenith, and 5 digital meteorological stations to measure atmospheric surface pressure and temperature with an accuracy of 0.5 - 1.1 mbar and 0.5 K respectively.

The microwave radiometer was co-located together with a meteorological station very close to the permanent GPS station of Perugia; the other 4 GPS receivers were set up at sites situated approximately along the four cardinal directions at an average distance of about 27 km from Perugia (from N to O clockwise: Montone, Assisi, Todi, Castiglione del Lago); all the sites were equipped with forced centering; these 5 GPS stations set up a local network called *Rete Umbra.* Other 3 meteorological stations were placed close to the GPS receivers, while in Castiglione del Lago a station with suitable characteristics already operating was used.

The sites of the stations around Perugia were chosen according to the following criteria: (i) to determine the ZWD-GPS gradients along the same directions sensed by the microwave radiometer; (ii) to "observe" atmospheric cones from the GPS stations (that is atmospheric cones passed through by the GPS signals received at these stations) partially overlapping each other, also in the hypothesis of data processing with a minimum cutoff angle of 20° and a "wet atmosphere" thickness of 10 km (amplitude of the cone at the top of the atmosphere of about 54 km); (iii) to avoid having stations too close to point out statistically significant ZWD gradients.

All the instruments worked permanently for about 15 days (March 27 to April 11, 2000, DOY 87–101, GPS-week 1055–1057), except short interruptions necessary to download the data.
The GPS observation sampling interval was 30'' and the minimum cutoff angle 5°. The radiometric observations were collected along cardinal directions at five elevation angles (90, 39, 30, 25, 21 degrees), performing cycles of 1 hour. Every hourly cycle includes:
- one scansion (in about 20') along the four cardinal directions (first the line South-North, then the West-East), that is repeated twice: the observations are performed, for each direction, in accordance with the 5 angles previously described in the following order: 39, 30, 25, 21 e 90 degrees;
- Zenith observation lasting 20'.

The meteorological observations have been sampled, at each site, every 10'.
The GPS data processing has been performed using the Bernese 4.2 software [Rothacher et al., 1996] and precise ephemeris, CODE and the GPS baselines adjustment was carried out by NETGPS software [Crespi, 1996].
By using GPS, radiometric, pressure and temperature data, collected during the campaign, it has been possible to estimate the total troposphere delay absolute and/or relative for the 5 stations using different instruments and methods. This has made possible to perform a first comparison between GPS and radiometer estimates (external coherence), to evaluate the coherence among GPS estimates obtained following different methods (inner coherence) and start evaluate the possibility to estimate the variation of the total content of water vapour as function of the observation direction (directional estimates).
To evaluate the external coherence of GPS, the TZD has been estimated on each station at this purpose networks of different extension have been considered. These networks have extensions bigger than that of *Rete Umbra* to completely loose the correlation of the troposphere effects observed in the different sites. Also different elaboration strategies have been used. One network considered (*Rete Nazionale*) has dimension of about 500 *km*, and includes the EUREF permanent GPS stations: Cagliari, Matera, Torino, Perugia, Graz. A second network (*Rete Europea*) with dimension from 850 to 1600 *km* has also been considered to indagate the presence of possible residual correlations among the estimates of troposphere parameters obtained at the sites of the *Rete Nazionale*. The estimation of TZD at each site has been performed every two hours bounding the site coordinates according to their mean square deviation coming from weekly EUREF solutions. To obtain ZWD from TZD, the ZHD was computed using the Saastamoinen model. For the *Rete Europea*, ZHD was also computed by a modified Saastamoinen model, which was found more correct at our latitudes. To evoid that possible geometric distorsions coming from global processing of the EUREF network invalidate the estimate of TZD, the coordinates of the EUREF sites of the *Rete Europea*, have also been determinated using only theirselves GPS observations.

The comparison between the ZWD obtained from GPS and ZWD obtained by WVR for the Perugia GPS station are represented in figura 2 for all the cases here described.

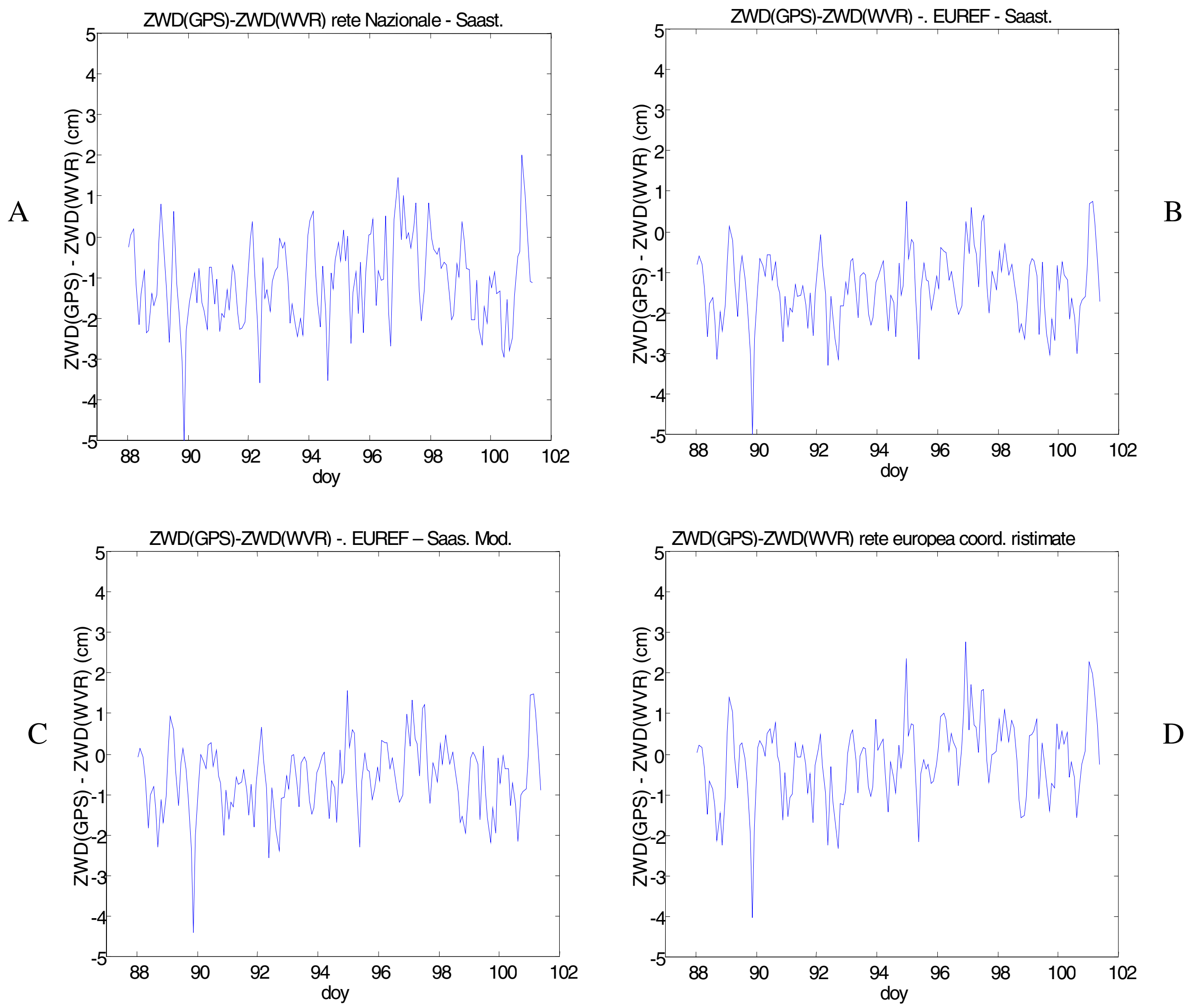

Figure 2 - Comparison of ZWD-GPS and ZWD-WVR by different methods

Concerning the GPS inner coherence analysis, in particular we estimated TZD at the four sites of the *Rete Umbra* following two different strategies:
- using GPS station of European network and considering one by one the sites around Perugia; in this case all the baselines are longer than 500 km, so we could estimate the (absolute) TZD;
- estimating the (relative) TZD at each site with respect to Perugia, fixing the TZD at Perugia at the value derived from the analysis of the European network. The comparison between the two strategies shows a good inner coherence, at a few millimetre level.

In order to check the possibility to estimate by GPS the wet delay in any direction and to relax the hypothesis of azimuth atmospheric isotropy, preliminary comparisons among directional information stemming from GPS and WVR measurements were performed. Two different approaches called *network approach* and *punctual approach* has been followed. The first considers the differences of ZWD-GPS (estimated every 30 minutes) between Castiglione and Assisi stations

(Ovest-Est direction). The comparison of this quantity with the ZWD-WVR estimated in the same direction is difficult to be interpreted (see fig. 3). There are anyway temporal intervals where it's clear the coherence between GPS and radiometric data even if there is a scaling factor, while in other periods there in no coherence between the GPS and radiometric data.

It's worth to note that in presence of high gradients, that generally happen when perturbations are present, the WVR series appears discontinuous to underline that GPS on the contrary of WVR is not influenced by atmospheric conditions, and can therefore give useful information just during evolution of meteoric events.

The punctual approach considers the visibility cone of the GPS satellites at each *Rete Umbra* site subdivided in 4 sections of the same amplitude (90°) centred along the 4 cardinal directions and processes separately data belonging to each sector to estimate TZD along the considered direction. As the GPS constellation is weak in the north directions, all the elaboration are in the direction Ovest-Est, but even in this direction the number of visible satellites is very low, and this represents the limit for this approach. At present this approach appears very difficult to be followed unless other data coming from other GPS constellations f.e. GLONASS or future GALILEO are included. At the moment it appears reasonable to develop an ad hoc software for the for the GPS data

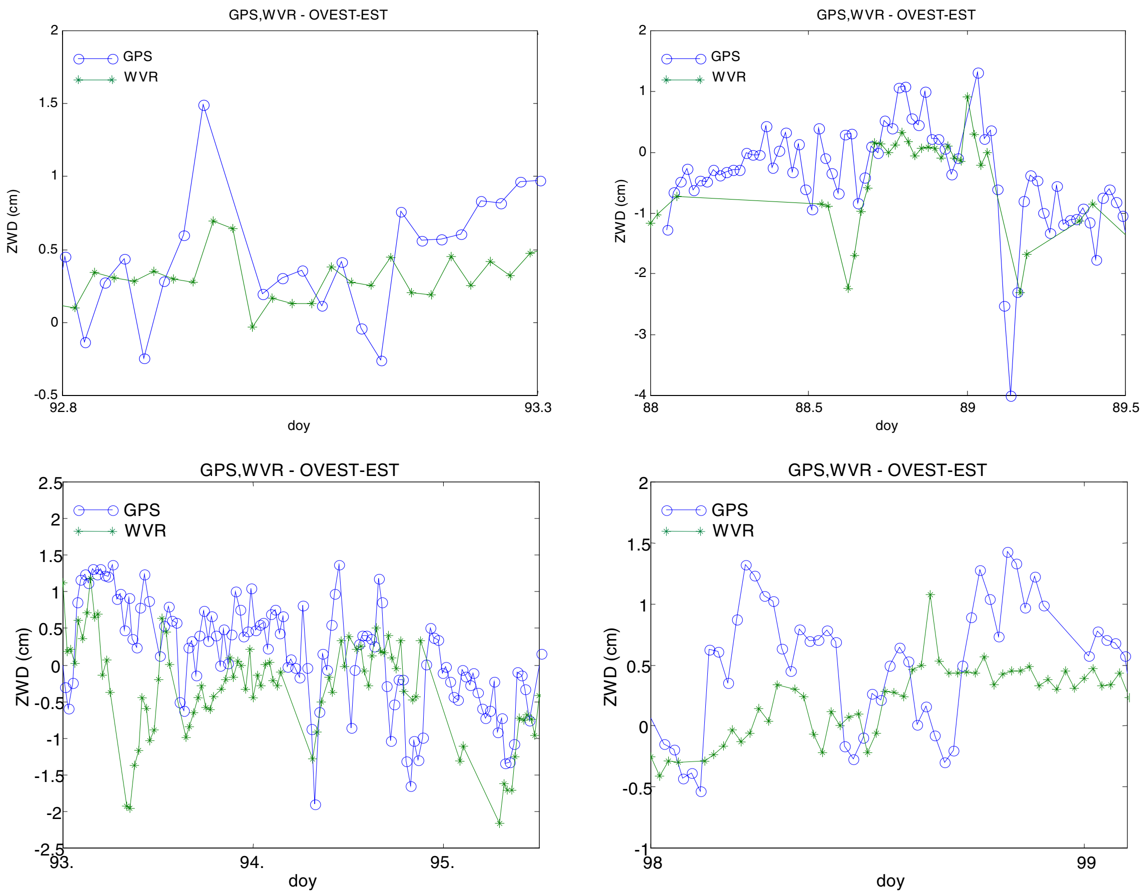

Figure 3 - Comparison of GPS and WVR in directional network approach

processing with meteorological purposes. In particular it would be worthwhile to estimate PWD coming from a single GPS satellite so that one can obtain troposphere information exactly in the direction GPS satellite- GPS receiver. Of course validation of this method would require the realisation of a new experiment where WVR can follow the GPS satellite.

The bayesian approach applied to GPS ambiguity resolution. A mixture model for the discrete-real ambiguities alternative

In the mathematical model of the double-difference GPS observation there are two groups of unknowns: baseline coordinates and initial ambiguities. According to this model the ambiguity vector should have integer components. Then the problem is to find the correct estimate for the ambiguity with integer components and the corresponding estimate for the coordinates. A usual approach to the ambiguity resolution is first to estimate coordinates and ambiguities with no constraints, i. e. floating solution and then to apply some "suitable" testing procedure to decide whether the floating ambiguity vector is compatible or not with one and only one integer estimator; in the affirmative case the estimate of the coordinates is repeated by fixing the ambiguity to the value of the integer estimator. The methods Ratio Test, FARA (Fast Ambiguity Resolution Approach)(Beutler and Frei (1990)) and LAMBDA (Least-Squares Ambiguity Decorrelation Adjustment) (Teunissen and Kleusberg (1998)) use this kind of approach. First Blewitt (1989), then Betti et al. (1993) and more recently Gundlich and Koch (2001) proposed, as alternative theory, the Bayesian approach whose main characteristics are the following:

1. yields a posterior distribution for all variables, discrete and continuous, conditional to the observed quantities;
2. takes into account the information contained in the full covariance matrix derived of the least squares adjustment, i. e. the covariance matrix of the floating solution does not need to resolve the ambiguity vector;
3. provides a solution without any further adjustment;

We have continued this work producing a practical expression for the Bayesian estimator using the Monte Carlo simulation to define the search ellipsoid in which the integer candidates are contained (Lacy et al. 2002). The Monte Carlo simulation has allowed us to obtain approximated expressions for the Bayesian solution and its covariance matrix. By studying the information and the evolution with time of the position and shape of the search ellipsoid in the bias vector space, we were urged to develop a novel enlarged model where a new variable is introduced labelling the case under analysis as an ordinary case where the bias vector has integer components, or as one of the special cases where the presence of other biases in the observations prevents us from fixing them to integer values. Of course the two cases will be discriminated only at a certain moment in time when the accumulated information becomes sufficient for that purpose.

The Monte Carlo method has been implemented in the Bamba software (Betti et al. (1996)) and applied to the baseline Herreros-Cijancos belonging to a non permanent GPS network with geodinamical purposes in Eastern Granada in the south of Spain (Gil et al. (2002)). The test baseline is about 8.5 Km long, the height difference between Herreros and Cijancos stations is close to 600*m* and measurements were taken using the same receiver and antenna, SR9500 with antenna AT302.

Data processing was performed using Bernese 4.2 (Beutler et al. (2000) and Bamba software. Only L1 frequency observations from 16h15m to 16h45m with 15s of sample rate were used. In this observation period the satellite constellation was formed by the satellites PRN 3, 17, 21, 22, 23 and 31. The satellite 23 was adopted as reference satellite because it had the highest signal/noise rate. Herrero has been adopted as reference station. CODE ephemeris from the Astronomical Institute of the University of Bern were included for the computation. Saastamoinen model with a standard atmosphere has been used for the troposphere refraction. All observations having a mask lower than 20^{o} were discarded.

The final ambiguities calculated by FARA and Monte Carlo methods have been compared. In the results obtained by FARA method we have observed a discontinuous behaviour in the ambiguity showing jumps between integer and floating ambiguities that does introduce a discontinuous behaviour in the coordinate estimator while it is noted that the Monte Carlo method is conservative and it tends little by little to one "particular" integer. Analysing this behaviour we have found that it is from the beginning that we have to build a model admitting two possible alternatives, one where the ambiguity is an integer vector and another one where the ambiguity has no integer constraints, i.e. it is generated by other effects than the simple initial ambiguity. It will then be the accumulation of information with time and the corresponding evolution of the characteristic ellipsoid that will tell us which of the two alternatives is more probable. This mixed model has been developed and in particular the Bayesian approach provides a good index, namely P_I to monitor which of the two models is prevailing with time; when $P_I \rightarrow 0$ it is the floating model which better interprets the data, when $P_I \rightarrow 1$ the opposite is true.

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DEFORMATION MONITORING USING GPS AND SAR

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Introduction

Deformation monitoring for geodynamical purposes requires high standards on data acquisition and processing.
GPS and SAR are nowadays frequently used to detect sub-centimetre movements on active faults.
However, it seems that improvements are necessary in GPS techniques to investigate effectively fault movements in the italian area where 1-2 mm/year velocities are expected.

In this respect, some improvements are presented in this paper both on a local scale (the active fault scale) and on a regional scale (using permanent GPS stations).

DInSAR also requires deeper investigation, particularly in data analysis where a new method is described to mitigate the impact of the atmosphere.

Geodynamic applications of GPS

During the three years of the project, GPS campaigns for monitoring active faults have been designed and realized. This activity has been developed both on a local scale (i.e. on specific active faults) and on a larger regional scale by means of permanent GPS stations. Due to the stringent precision requirements, local networks have been carefully monumented and GPS antenna mount was realized so to reach sub-millimetre centering.
Particularly, in the Umbria-Marche area, a GPS local network has been established and measured. The network points have been placed on solid rock, along two cross-sections perpendicular to the principal fault, comprising ten observation points (see fig. 1).
As said before point monumentation was carefully performed in order to ensure a sub-millimetre centering. At each site, a 25 cm long steel rod was fixed in solid rock and the antenna was mounted on top of this ground point using a forced stationing device (see fig. 2).
Two GPS campaigns, the first in October 1999 and the second in September 2000, have been carried out. In the first campaign, only the A transect was measured: thus the following comparisons only hold for the six points of this section.
During both campaigns, data were collected over a period of four consecutive days, with daily sessions of eight hours. The sampling rate was fixed at 15*s* and the cut-off angle at 15°.
The measurements were collected with Trimble 4000 and Trimble 4700 receivers and a combination of Trimble Geodetic and Trimble Micro-Centered antennas.

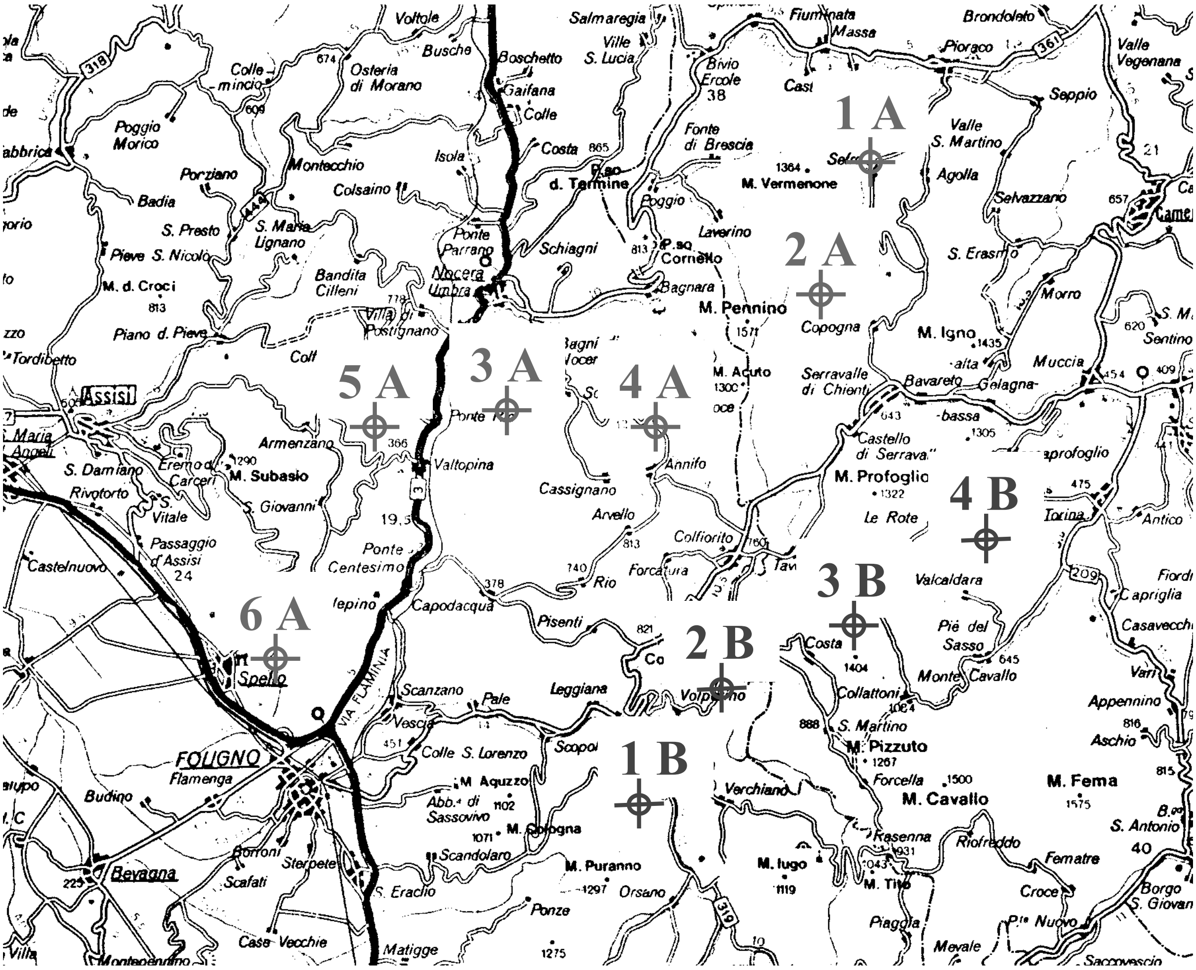

Figure 1 - The Umbria-Marche GPS network

Preliminary data analysis was performed with the Bernese 4.2 and GIPSY 2.6 software packages in order to compare different solution approaches. For Bernese, the Quasi Iono Free procedure (QIF) was selected, among the other possible options, to estimate the baselines with respect to the westernmost point of Spello (6A). In addition, tropospheric parameters were estimated on a two-hourly basis. The GIPSY analyses were based on precise non-fiducial GPS orbits, provided by JPL. In order to provide a common reference point, the position of Spello was fixed in the solutions of both years. Wet zenith delays were modeled as stochastic parameters and ambiguity fixing was applied.

In both data analysis schemes, the observations were first analysed on a daily basis, yielding full network solutions. Subsequently, the daily network solutions were combined into multi-day solutions for both years. Table 1 lists the repeatability of the daily coordinates solutions for the North East and Up components (maximum absolute difference with respect to the four days mean).

	Bernese - 1999	Bernese - 2000	GIPSY - 1999	GIPSY - 2000
Norh	2.8	4.5	3.3	3.6
East	4.9	2.6	4.2	2.1
Up	8.4	7.6	13.4	7.9

Table 1 - Repeatability of the daily solutions (mm)

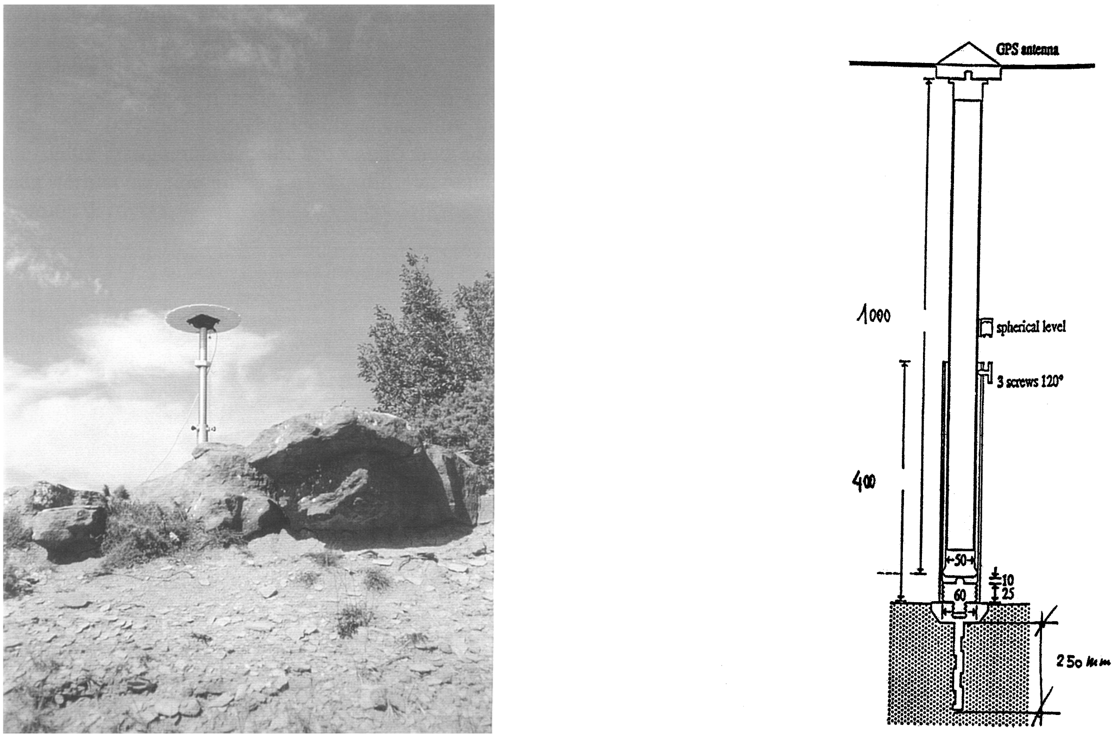

Figure 2 - The antenna mount device

As one can see, a good data quality has been obtained which is necessary in order to detect sub-centimetre/year velocities.
Baseline variations were then computed and are listed in table 2, together with their st.dev.

	Bernese	GIPSY
6A - 5A	-3.0 ± 2.0	-2.6 ± 0.9
6A – 4A	0.0 ± 2.0	0.8 ± 1.0
6A – 3A	2.0 ± 2.0	1.4 ± 1.0
6A – 2A	8.0 ± 2.0	8.2 ± 1.1
6A – 1A	1.0 ± 2.0	1.6 ± 1.2

Table 2 - Baseline length variations (2000-1999) and their formal sigmas (mm)

Although the baseline length variations are hardly significant from a statistical point of view, the agreement between the results of the Bernese and the GIPSY analyses is quite remarkable since, for all baselines, the differences are less than one millimeter.
All baseline variations are positive, except for the baseline Spello-Vallemare (6A-5A), which indicates a general trend of post-seismic extension across the fault, in agreement with current the geophysical models for the area.
So, it seems that the proposed methodology is able to reach precise results that can be applied also in other seismogenetic Italian areas.

Following the same scheme, two networks will be monumented in Calabria on two active faults. The first one will be place in the Castrovillari area while the second will be centered on Vibo Valentia (see fig. 3 and fig. 4).

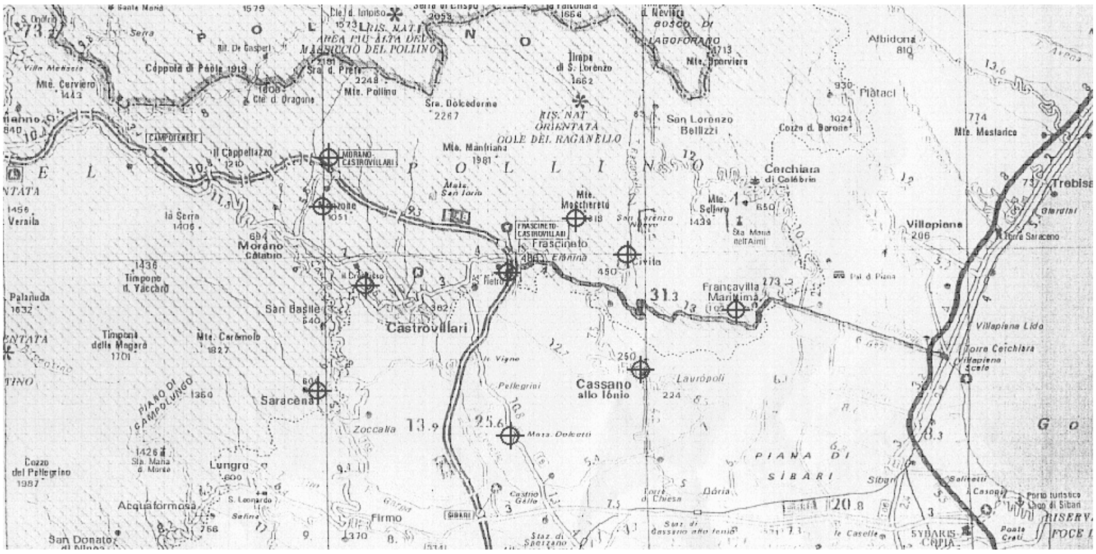

Figure 3 - The Castrovillari GPS network

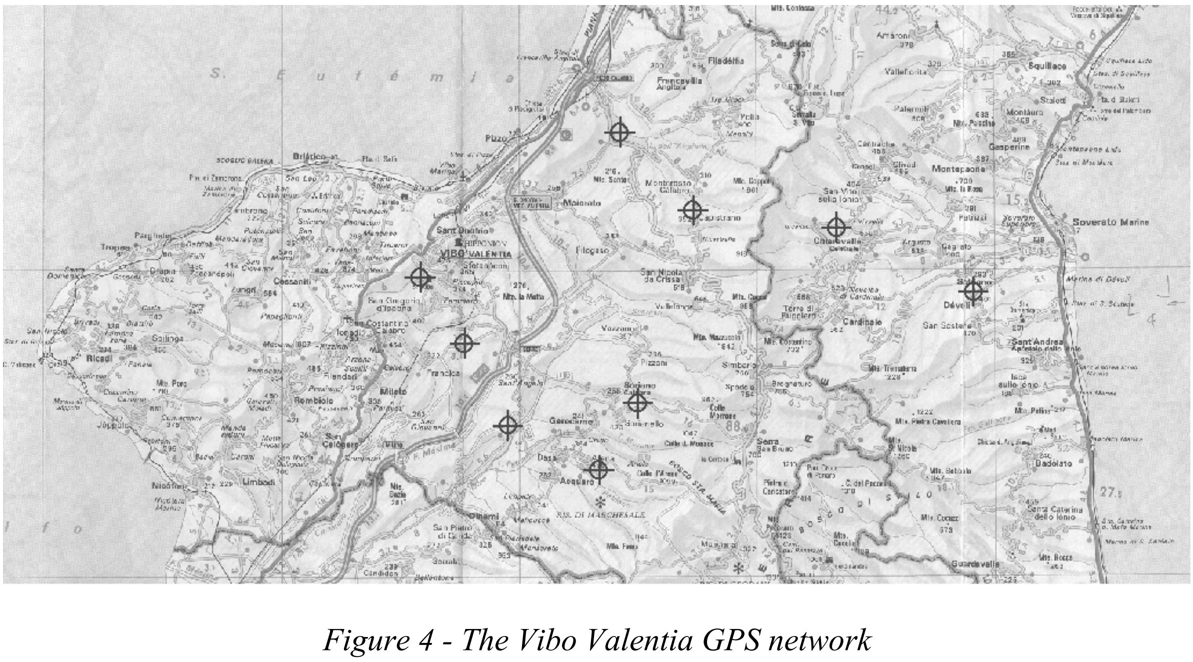

Figure 4 - The Vibo Valentia GPS network

GPS campaign will be performed in the near future on these two networks to estimate geodetic deformation to be compared with geophysical model of the two areas.

Parallel to field campaign activities, new data analysis methods have been devised. The basic idea is to apply a stochastic filter to the double difference data in order to remove time dependent signals which are day by day uncorrelated.
In such a way, it will be possible to separate the stationary component of the signal from the time varying part which is basically related to the daily variability of the troposphere. The aim of this data processing method is to improve repeatability of the daily solutions. Preliminary tests, that have been realized on the Umbria-Marche data base, have shown that sharp improvements in daily repeatability can be reached.
However, since the results have been obtained on one baseline only, it cannot be stated that this stochastic filter has optimal properties: new tests are needed to prove the method reliability.
On regional scale, GPS permanent stations data were analyzed mainly to properly introduce correlations in the least squares adjustment procedure commonly used in handling the data.
It is well known that permanent station daily solutions are merged together to get weekly solutions which are used to infer geodynamic velocities. This is usually done disregarding correlations that exist among daily estimates.
A proper modelling of these correlations were investigated. Empirical covariances were computed using daily solutions selected in a four months window. Four GPS permanent stations included in the ASI data bases were considered (Cagliari, Noto, Matera and Medicina). These computations proved that significant correlations among daily solution exist.
Using the correct covariance matrix for adjusting the daily solutions led to a sharp increase of the st.dev. of the weekly solution which became nearly three time higher than the one obtained disregarding correlations.
Thus, these preliminary tests have shown that adjusting daily solutions must be done properly to have realistic st.dev. of the weekly estimates. This is of extreme importance when estimating geophysical relevant parameters: disregarding correlations implies too far optimistic st. dev. of the weekly solutions and unrealistic velocity parameters estimates. In the near future, this method will be extensively applied to all the ASI permanent stations data base to improve plate velocity estimates in the Italian area.
Furthermore, practical aspects on monumentation of GPS permanent stations for geophysical analyses have been investigated and pointed out.
Particularly, it has been stressed the importance of the site stability from the geological point of view. This can be checked preliminarly through geological-seismic on site investigations and by means of surveying in the area surrounding the point to ensure its stability in time (field survey can be done yearly). In this way, local site stability is verified and reliable results can be obtained. Moreover, points must be monumented on solid rock to avoid possible problems related monument instabilities (e.g. GPS permanent stations for geodynamic should not be placed on top of buildings).
Another important aspect is related to the presence of electromagnetic noise in the GPS site area: this is usually tested in the standard ASI procedure, as well as the presence of relevant multipath phenomena. Links to the ASI database through e.g. a telephone line sould be also considered an importan aspect in the selection of the site.
All these aspects will be carefully taken into account in future monumentations of permanent GPS that will be carried out in Calabria to define, at a regional scale, the present day stress of the Calabrian Arc. To this aim, a network of three permanent stations has been designed . The existing GPS station in Cosenza, handled by CNR (National Research Council), has been integrated with a permanent station in Nocara, in the northern part of Calabria. The regional scale monitoring has been then completed with the identification of a further point where a permanent GPS can be placed. This point is in the Montalto area (Aspromonte), close to Gambarie, where investigations will be done within the end of 2001 to verify if a GPS permanent site can be realized.

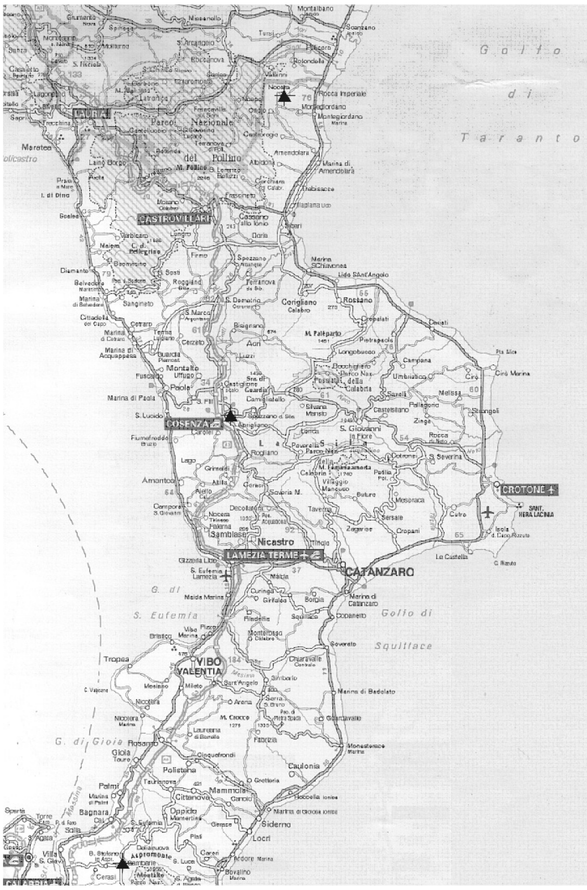

Figure 5 - The planned permanent GPS stations for the Calabrian Arc monitoring

DInSAR data filtering: a new proposal

During the three years of the project, the research was focussed on possible field experiments to compare GPS and DInSAR results and on the definition of a strategy for a proper detection of the atmospheric signal.
A field campaign has been designed to allow GPS and DinSAR comparison. This will be done in, at least in the initial stage, in two sites placed on top of two buildings nearly six kilometres apart in the area of Milano.
These two sites have been carefully monumented: they are two concrete pillars on which you can mount GPS antennas and SAR reflectors. In this way, simultaneous GPS/SAR observations will be available and a continuous monitoring will be realized. Thus, assuming that the points are stable at a sub-millimetre level, a check on the impact of unmodelled atmospheric effects will be possible, having also a croos-check between the two methodologies.
Preliminary GPS obervations on the two points have been already carried out to have precise coordinate estimates (at a sub-centimetre level) to be used in the planned GPS/SAR campaigns.
The second aspect that has been tackled is related to DInSAR signal processing. A new modelling and filtering strategy which takes advantage of the specific properties of the DInSAR obervations has been proposed.
The core of the procedure is the least square collocation filtering/prediction method applied to multiple DInSAR observations. The basic assumption is that, in multiple DInSAR observations, the atmospheric effect is temporally uncorrelated while the terrain movement phase contribution is

stationary in time. Having multiple interferograms of the same area (where e.g. subsidence is present), one can process them separately deriving from each interferogram the corresponding velocity filed. These velocity fields are then put together as input observations of the 2D estimation procedure (stacked velocity field). Then, the subsidence velocity field map is obtained through the classical LS collocation, which involves the estimation of the autocovariance function of the stacked velocity, the separation of the signal from the noise (filtering), and the prediction of the signal over location not covered by the input data (Moritz, 1978; Dermanis, 1984). The proposed procedure provides an adaptative filtering, which is only driven by the autocovariance function of the input data, without requiring any explicit modelling of the subsidence at hand: it is quite more flexible than the classical interpolation techniques, e.g. based on polynomials, etc. Finally, the analysis of the temporal evolution of the subsidence is run on the residuals of the 2D collocation filtering (i.e. the differences between the observations and the corresponding estimated signals). This analysis is typically performed on few selected locations of the deformation field under analysis (for instance, the location of the maximum deformation rate and some points of particular interest).

The performances of the proposed procedure were tested on simulated DInSAR data that roughly reproduce the characteristics of a real subsidence phenomenon: the urban subsidence of Sallent (North Catalunya, Spain), which has been extensively analysed at the Cartographic Institute of Catalonia. This subsidence, which has slow deformation rate and small spatial extent, represents a quite difficult case for the usage of the DInSAR technique. A 3D deformation field (depending on X, Y and t) has been simulated to reproduce the main feature of the Sallent subsidence field. 3D atmospheric time varying fileds were simulated and added to the deformation pattern (this signal is spatially correlated within a given interferogram but it is not temporraly correlated among different interferograms).

Furthermore 3D noise was also added together with unwrapping related errors. The results of these simulations have shown that the filtering procedure is able to detect properly the simulated deformation pattern. So, this is a step forward in DInSAR data processing which leads to a common filtering method which can be applied, with proper modifications, also to GPS data (as it was mentioned above).

In the near future, this method will be applied on a real case data set (e.g. to post seismic deformation monitoring in the Umbria-Marche region) in order to prove its reliability in detecting slow deformation rates.

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- ***Platforms kinematic positioning for mapping, photogrammetry and remote sensing***
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PLATFORMS KINEMATIC POSITIONING FOR MAPPING, PHOTOGRAMMETRY AND REMOTE SENSING

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Introduction and research topics

Navigation and positioning systems based on Global Positioning System-GPS receivers (eventually coupled with Inertial Navigation System-INS equipments) became very widely adopted in support of airborne and terrestrial surveys during last years.
These systems allow for the determination of positioning, orientation and kinematic (linear and angular velocities) parameters of the primary sensors mounted on the same platform which simultaneously collect different data sets for mapping and observing the earth surface and its modifications.
Therefore, the evaluation of performances of the positioning systems became of particular interest especially within projects devoted to land use and monitoring.
In this frame, taking into account the theoretical and experimental background of the research unit, the present project was developed, whose main topics are listed below and referred in the following sections:

- fast production and revision of DEMs and medium/large scale maps (larger than 1:10000) by low-altitude aerial photogrammetric surveys
- DEM validation techniques based on kinematic surveys
- road inventory and maintainance by surveys and images taken from suitably equipped vehicles
- monitoring of the hazards and evolution of large scale events (floodings, eruption, landslide etc.) by means of surveys from helicopter which do not require the establishment of ground control networks

In particular, during the exploitation of each topic, the following items were addressed, by the realization of the experiments described in this report:

- assessment of the performances of the moving platform used in the considered application
- specification of the optimal sensor configuration, in order to ensure the required accuracy and reduce costs
- establishment of suitable operational procedures and data processing in order to optimize system performance.

A. Highway Surveying With DGPS Based on RTCM Satellite Corrections

Recently developed models of GPS receivers (single frequency only code) results particularly suitable for accurate and reliable kinematic survey. In these new receivers the signal acquisition system is very robust against the noise that is very frequent in a typical dynamic environment. Moreover the achievable accuracy (about 1-2 meter), is quite satisfactory for most of the applications in the road sector. Among these new types of receivers, the Pro XR/XRS Trimble system was selected to carry out the experiment described in the following. This receiver uses twelve channel for tracking L1/CA code with carrier phase filtered observations. It is an integrated GPS/Beacon/Satellite Differential receiver with Everest™ multipath rejection technology. The given accuracy (RMS) for differential correction is of 50 cm plus 1 ppm for horizontal components and submeter plus 2 ppm for the vertical component. The autonomous accuracy is about 100 meters (2dRMS). These accuracy specifications apply with Selective Availability active and when at least 5 satellites are visible, PDOP is less than 6, good signal to noise ratio and the satellite elevation mask is set at 15 degrees. Accuracy specification may change if Selective Availability is deactivated or modified. The receiver is capable of receiving RTCM SC-104 standard format broadcast from a Trimble reference station or from a provider, like OMNISTAR. Ionospheric conditions, multipath signals or obstructions of the sky by buildings or heavy tree canopy may degrade accuracy by interfering with signal reception. Optimal accuracy is obtained by collecting data in an environment that is devoid of large reflective surfaces and also has a clear view of the sky, as happen along a highway. The main advantage of implementing with GPS existing road survey systems is the integrability with the sensors mounted on board, which usually includes an odometer. In such cases, the integration allows for establishing a rigorous correspondence between the relative mile chainage measured by the odometer and the absolute GPS co-ordinates. Furthermore, the odometer guarantees the continuity of the positioning when interruptions in the GPS signals occur.

Field experiments

A number of tests involving GPS receivers in various kinematics settings were conducted to assess the performance of GPS used in support of highway surveys. The main objective was to experiment the recently developed GPS Pro XR/XRS Trimble receiver for determining trajectories and reference point positions of a land vehicle dedicated to road maintenance. The performance of this single frequency receiver, equipped with internal antenna for receiving satellite transmitted RTCM correction, was evaluated by using, as reference, precisely determined positions. Different surveys were performed both in continuos kinematic and in Stop and Go mode. In order to define an accuracy range for RTCM corrected positions, the tests were conducted mounting the Pro XR/XRS system on a vehicle of the Societa' Autostrade equipped with an odometer and a geodetic dual frequency GPS receiver.
The receivers and the software adopted during tests are listed in Table 1.

RECEIVER	Trimble Pro XR/XRS (single frequency)
	Trimble 4700 (dual frequency)
	Trimble GPS TS 4800 (dual frequency)
SOFTWARE	ASPEN (acquisition and navigation)
	PATHFINDER OFFICE (differential correction)
	GPSURVEY (phase processor)

Table 1

The dual frequency receivers were used to compute very accurate co-ordinates adopted in the validation of results from Pro XR/XRS receivers and as MASTER station.
The software Aspen was used by the operator during the acquisition on the road, allowing to monitor different parameters, such as the satellite constellation and the status of satellite correction, to insert quickmarks and features and to display corrected co-ordinate and the trajectory. The performance of three different survey modes was investigated by means of the following preliminary field experiments executed with non-dedicated vehicles:
Test1 - Static GPS in Real Time with RTCM-104 correction transmitted via OMNISTAR to Pro XRS receiver;

Test2 - Differential GPS in Post-Processing with a Rover Pro XR receiver and a 4700 Trimble receiver as Base Station;
Test3 - Differential GPS in Real Time with RTCM-104 correction transmitted via OMNISTAR to Pro XRS receiver.
The Post Processing differential mode was supported by a MASTER station located in a selected site by the Centro Rilevamento Dati of the Company Autostrade. The reference point was monumented on the roof of a building and precisely measured by means of a static session using two dual frequency receivers.

Quality control of DGPS positioning

The co-ordinates of the 21 kilometre road signs were measured during different surveys:
1. Stop&Go/dual frequency receiver (4700)/post-processed;
2. Stop&Go/single frequency/post-processed;
3. Stop&Go/single frequency/ satellite transmitted RTCM corrections;
4. Continuous/single frequency/post-processed;
5. Continuous/single frequency/satellite transmitted RTCM corrections.

The level of accuracy of the two Stop&Go positioning is on the order of few decimetre, while the continuos kinematic surveys show large errors to sighting of the reference points. This is evident in the North co-ordinates corresponding to the direction of navigation, which shows a systematic error of about 8 meters.
A quality control of the GPS co-ordinates can be obtained by means of repeated measurements of the fixed baseline established between the two GPS antennas mounted on the roof. The discrepancies between an accurate estimate of the baseline length and the one estimated raw data collected during the experiments in correspondence of each reference points were computed; the mean value of the horizontal component which is of primary interest in highway survey of the baseline were:
$\Delta d = +0.54 \pm 0.42$m for Stop&Go/RTCM survey
$\Delta d = +0.38 \pm 0.32$m for Stop&Go/Post-processed survey
The experiments led to the following conclusions:
In the framework of road survey the use of GPS is necessary when the positioning has referred to an absolute reference system, which allow data representation in a mapping projection. In order to guarantee the continuity of the positioning, the presence of other sensors (odometer or platform) is still convenient. Furthermore, to maintain the compatibility with data collected during standard road survey, the extraction of a mile chainage should be considered. In general, the GPS derived mile chainage can be easily overestimated unless a more advanced procedure is implemented. With the approach adopted in this work, the mean difference observed between GPS and odometer chainage was within 3 meters.

The performance of the RTCM satellite transmitted correction for differential positioning was positively evaluated along 50 km of highway. The positional accuracy level of the RTMC mode resulted comparable to the one relative to the post-processed mode. In consideration of the major operational advantages, the RTCM technique can be efficiently adopted for road surveys requiring meter-level positional accuracy.

A configuration of a GPS based Positioning system for road survey

The experience gained during the field tests has been utilised for designing an optimal hardware and software configuration for a GPS-based positioning system, shown in Figure 1. The proposed configuration refers to the receivers and softwares adopted in the experiments (Trimble) and includes both Real-Time and Post-Processing positional capabilities.

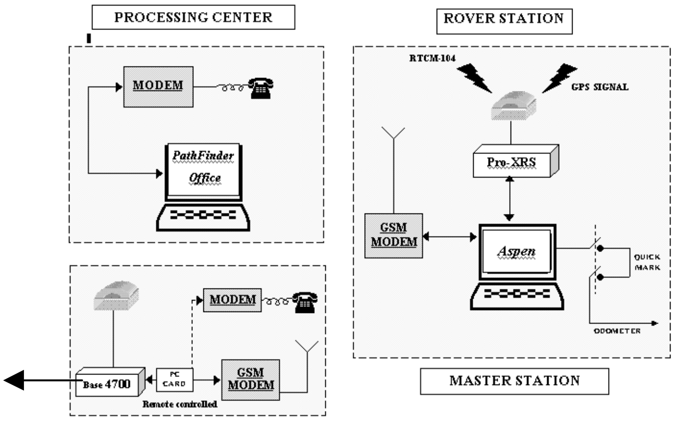

Figure 1 - A configuration of a GPS based Positioning system for road survey

B. DEM validation by GPS kinematic survey

TEST 1 :COLLI ALBANI

A relevant task for several applications in geodetic sciences is the validation of Digital Elevation Models (DEM) generated by whichever technique, mainly by analytical and digital photogrammetry, digitalization of available maps and airborne laser scanning.
The validation procedure can be divided into two steps: the internal one, that is the inner checking of the data useful to identify and remove outliers by suitable statistical techniques; the external, that is the comparison of the (interpolated) heights derived from the DEM with those estimated by a direct survey in several and possibly well distributed points.
An efficient way to perform this survey can be represented by a GPS kinematic survey. Of course, the usage of GPS forces to georeference the DEM into a realization of the WGS84 reference system (e.g. ITRF97) and requires the knowledge of a geoid model at a proper level of precision. Moreover, in order to gain the required precision (generally not higher than few meter for DEM at medium and large scale as those considered in this paper) with a good internal and external reliability of the survey, it is necessary to use three or more base permanent stations.

Data set and outline of the experiment

In this research we applied the outlined DEM validation methodology to a DEM at the nominal scale 1:10000 attaining to the Nemi lake area (Rome district, Central Italy), relevant also on the volcanological and geophysical point of view, chosen for the extreme variability of its morphology (extremely steep just around the lake inside the crater, hilly and also flat outside), wooden for its most part and about 5×5 km wide.
This DEM was generated starting from the vectorization of the contour lines of the Regional Technical Map, having an interval of 10 m. Both the vectorization of contour lines and the DEM generation were performed in the frame of MGE Integraph environment, following the standard procedure consisting in the Triangular Irregular Network generation and in the gridding according to the Nearest Neighbours algorithm. Finally, the DEM was georeferenced in the WGS84-ITRF97 and given on a cartographic UTM-WGS84 10×10 m regular grid.

The internal test

The internal test was mainly devoted to check the inner consistency of the DEM, that is to assess if there is a reasonable agreement among the main characteristics (values of height, slope and aspect) of a certain cell and those of the surrounding cells, provided the main morphologic features with breaklines of the investigated area are known. The strategy for checking this agreement is the comparison of each punctual value with the mean of the corresponding surroundings; of course, it is mandatory to define how large is the set of the values to be averaged, since the larger it is, the more reliable the test is but the less suited it is for different terrain morphologies. In this work only the height value was checked by implementing a routine in the Grid Analyst environment, particularly suited to perform operation on regular grid, and we decided to check the differences between the height of a certain cell and the mean of its 8 surroundings. The comparison was finally based on the classical Cebicev test, in order not to constrain the result to a particular distribution of the differences. We choose a 5% significance level, and the results confirm that the DEM exhibits quite good internal coherence, since the outlier percentage was below 0.85%.

The external test

The external test attains to a sample comparison between the 1:10000 scale DEM and the true terrain. In this case, a GPS kinematic survey was carried out and the obtained data were compared to DEM's information suitably interpolated in the same horizontal position. The kinematic survey was performed by equipping a car with a GPS receiver and determining the vertical offset of the antenna w.r.t. the road level with simple a local topographic survey.
Since the investigated area is almost completely covered by trees (except for the lake and the urban areas), a preliminary survey was performed, in order to assess the integrity of the GPS measurements w.r.t. the loss of lock. It was clearly shown that the phase measurements were too much corrupted by cycle slips, whilst the pseudoranges were good enough to guarantee a 3D submetric accuracy, completely suited for the external test purposes. As a matter of fact, it has to be recalled that the average accuracy of DEMs derived from maps contouring is usually around 1/3 ÷ 1/4 of the vertical interval (10 m in our experiment).
It's obvious that a crucial problem of a kinematic survey is the reliability, since every point redundancy is assured only by the geometric strength of the satellites constellation and by the power of the signal. Therefore it is suitable to use three or more master stations in order to independently estimate three or more receiver positions during the shifting and hence carrying out an inner check; moreover, this redundant configuration allows the estimation of each point accuracy.
In this experiment three master stations were considered, which are georeferenced in the WGS84-ITRF97 with a centimetric accuracy and located in a range of about 30 km centered on the Nemi lake area. Both in the master stations and on the car geodetic class dual frequency GPS receivers were used and the measurements were processed by a standard single-baseline software. The sampling interval was 10 s, the car speed was around 50 km/hour, what produced about one point each 100-150 m; all the survey took about three hours. A simple screening of the three series of positions showed that some determinations were completely out (especially in the height) by tens and hundreds of meters, so that it was necessary to adopt a robust procedure in order to identify and remove all the outliers. It was computed the mean and the median of each WGS84-ITRF97 Cartesian coordinate for each point starting from the three estimates and, taking into account our accuracy requirements, an outlier was pointed out if the absolute value of the difference between mean and median was larger than 1 m.

Finally, we reached an horizontal average accuracy of 0.3 m and a vertical one of 0.6 m; then we transformed the ellipsoidal height into orthometric ones by the most up-to-date Italian geoid model ITALGEO99 to perform their comparison with those derived from the 1:10000 scale DEM.
It is important to stress that the results obtained by the GPS survey were useful not only for the external test w.r.t. the heights but first of all to check the correct DEM georeferencing into the WGS84-ITRF97, in order to eliminate a global height inconsistency due to a wrong DEM georeferencing, which causes as larger height errors as rougher the terrain is.
We performed a bicubic interpolation in order to compare the GPS derivered height with the DEM. The differences average value was 0.8 m and the rms was 1.5 m; this result has been achieved after having rejected few outliers (~ 5%) ranging between 10 and 17 m, due to erroneous interpolation of DEM and mainly located in morphologically uneven terrain. It must be underlined the good matching globally obtained between DEM and GPS height, remarkable better than the average accuracy (2.5-3 m) suggested in the literature.

Conclusions

The external test, performed on the reference DEM, showed that kinematic GPS survey can give a remarkable contribution in DEM validation even in densely forested areas, both for correct georeferencing and for height control. Good results can be achieved provided a redundand configuration with multiple master stations is established, a suitable but quite simple robust estimation techniques is applied and a geoid model of the investigate area is available.

TEST 2 :VULCANO ISLAND

Recent technological advances in photogrammetry have now made it possible to process high resolution aerial and satellite imagery in a digital format. Airborne images may be acquired by means of film cameras and further digitized using high resolution scanners. It is also possible now to acquire airborne stereo imagery directly in digital cameras. Accurate referencing of images is performed using differential GPS positioning during data acquisition. Many applications of digital photogrammetry concern mapping and monitoring projects and research is particularly focused on the production of three-dimensional reconstruction of the surface in the form of digital terrain models (DEM). DEMs may be used to determine morphological characteristics such as slopes, volumes, or drainage patterns and integrated with multi-spectral remote sensing imagery for a large number of applications (geology, agriculture, urbanism, etc.). The comparison of DEMs relative to different epochs is potentially useful to detect and describe morphological changes on a three dimensional basis, such as deformations related to volcanic activity or determination of thickness of volcanic products. As far as terrestrial surveys, the advent of GPS has greately improved the methodology for ground deformation monitoring, allowing to collect higher accuracy and higher density data with simplified and faster operations in the field. Today this technique is often used in substitution of ground based topographical methods such as levelling or trilateration. More recently the apparition of a new generation of receivers allowed to survey geodetic networks in very short periods of time (a few minutes occupation of points in quick-static mode and a few seconds in pseudo-kinematic mode instead of one to several hours in static mode) keeping the accuracy at about 1 cm in horizontal and 2 cm in vertical. With respect with the previous way of using GPS, this new method allows further increase in the number of surveyed points and at the same time decreases the duration of the geodetic campaigns. While a GPS receiver is operated at a fixed reference station, the survey is performed with a roving GPS receiver which is left operating during the whole session of measurement on the benchmarks and during the moving between two benchmarks. In this manner, in addition to the periods corresponding of measurements at a benchmark, all the trajectory of the antenna is also recorded. With a typical sampling rate of 1 to 3

seconds, this represents thousands of coordinates recorded along a path of a few kilometres that can be surveyed in a few hours.
After the evaluation of the accuracy of our kinematic GPS measurements obtained with various field procedures (driving or walking mode), the GPS profiles are used for the assessment of the accuracy of the Digital Photogrammetry deduced DEM. On the basis of these results it was possible to establish the threshold level of deformation detectable on Vulcano by comparing DEMs relative to different epochs. On the other hand, the GPS profiles are also examinated in order to determine the areas were kinematic positioning could be successfully used for future surveys at Vulcano.

1997 Survey

A field GPS survey was carried out on Vulcano from 4 to 8 June 1997 with the aim to evaluate fast kinematic procedures for ground deformation studies and topography modeling. The differential GPS measurements were performed with full wavelength data using dual frequencies Ashtech Z12 receivers. During the survey, we acquired a series of kinematic profiles (without benchmarks) in the active crater area (La Fossa) using three mobile receivers operating continuously at a frequency rate of 3 seconds. The GPS sampling rate is fixed as a low value (1 or 3 s instead of 30 s in static mode) enabling to sample a large number of points along track, typically 1 point per meter for an walking operator. The measurements were acquired with antennas mounted on the operator's backpacks in reference to a remote station located at the volcanological observatory (baseline lower than 4 km). A total of about 6000 GPS measurements at ground level were acquired around and inside La Fossa crater area. The internal accuracy of this kinematic dataset has been estimated from the analysis of cross-over errors along the various GPS tracks. The resulting standard deviation of the differences in height determinations at almost 5000 intersection points of track lines is 4.3 cm (r.m.s. error). A complete description of the data acquisition and processing is given in Baldi et al. (2000).
Using the directly determined height (by GPS kinematic) it was possible to assess the quality of a photogrammetric DEM with a grid size of 1 meter. The control network was surveyed by using GPS receivers and computed in the ITRF94 reference system by establishing three fixed reference stations tied to the international reference network. Two of these points were used as base stations for the kinematic GPS surveys, allowing us to refer the two sets of data to the same reference system. This fact allows us to directly compare the elevations derived from the two methods. From the GPS kinematic data set, we extracted the points located within a 20 cm radius to a grid node in order to minimise the interpolation effects. Therefore, the comparison has been performed over about 6000 corresponding points mainly distributed around the top of the active cone. Two different interpolation methods (kriging and low order polynomials) were then used for extracting from the DEM the heights in correspondence of the GPS points. The two approaches provided similar results.
At a first stage, the comparison of the GPS kinematic and DEM derived heights evidenced a bias which can be mainly attributed to the offset between the GPS phase centre of the rover antenna and the ground. After the removal of the observed offset, the data show a gaussian distribution pattern where almost all the residuals are within +/- 50 centimetres and the resulting standard deviation is 18 cm. This result obtained using independently derived data confirms the high accuracy and reliability of the digital photogrammetric technique for producing DEM of areas involved in deformational processes.

C. GPS Photogrammetry

A GPS photogrammetry survey implies the use of GPS receivers both to establish the ground reference network and to determine aerial 3D coordinates of the camera positions at the instant of

exposures. The knowledge of the camera coordinates allows to introduce additional equations into the Aerial Triangulation (AT) least square adjustment procedure and, as a consequence, the number of required ground control points can be significantly reduced. Therefore, GPS photogrammetry is highly simplified in remote areas, such as volcanoes, where a homogenous ground targets network is difficult to install.
The objective of this study is to determine an optimal processing procedure for obtaining high accurate projection center positions for large scale aerial photography application. GPS measurements were collected using a multi antenna configuration both on the aircraft and on the ground. The performance of standard software's for OTF differential kinematic processing are evaluated. In order to use redundant information both rigorous combination of independently computed solutions and simultaneous adjustment of GPS observation from multiple reference stations and mobile receiver are performed. Finally, GPS derived camera projection centers are compared to results from a Aerial Triangulation (AT) adjustment.

1996 Vulcano Photogrammetric survey

The collection of images and GPS data was carried out in September 1996 using three GPS reference ground stations operating in the project area plus an additional station located about 70 km away. On the aircraft a photogrammetric camera was operating interfaced with two GPS receivers connected through a splitter to the same antenna. The flight was performed under regular operational conditions with no particular attention in avoiding signal outages during turns. The main characteristics of the Vulcano GPS-airborne photogrammetry project are listed in Table 2.

Airborne GPS Mission	
Period	**September 1996**
Location	**Vulcano Island, South Italy**
Aircraft	**Navajo**
Camera	**Wild RC 20**
Number of missions	**2 (Day 272/ Day 273)**
Hours flown	**2 (Day 272) / 3 (Day 273)**
Flight heights	**1000 m (1:5000) / 1800 m (1:10000)**
GPS receiver model	**Ashtech Z-XII / Trimble 4000SSI**
GPS acquisition rate	**1 sec / 5 sec**
Ground stations	**2 Ashtech Z-XII / 2 Trimble 4000SSI**
Cut-off angle	**10°**
Number of visible satellites	**6 / 7**

Table 2 - Main characteristics of the Vulcano GPS-airborne photogrammetry project

Kinematic GPS Data Processing

GPS kinematic solutions were obtained using both commercial and scientific software's with OTF capabilities. Different data processing strategies were used in order to select the most appropriate and effective in achieving the stringent accuracy requirements (< 20 cm). In particular, the performance of different On-The-Fly ambiguity resolution algorithms were evaluated. Performances of the different receiver models were also compared. In order to use all the redundant data, solutions obtained using the three reference stations were combined into a rigorous adjustments of kinematic vectors which connect the aircraft antenna to each reference station assumed as fiducial points with standard deviations of few millimeters. A software capable of

multi-station adjustment of undifferenced GPS observable was experimented in order to combine correctly the correlated redundant data and perform a simultaneous estimation of ambiguities and relevant parameters, like coordinates of the rover station, atmospheric correction parameters, etc..
The software's adopted for processing kinematic GPS data and including On-The-Fly ambiguity resolution algorithms are: PNAV (Precise Differential GPS NAVigation and Survey Program) (Ashtech, 1994), GEOTRACER GPS (TerraSat, 1994) and GEONAP-K (Wubbena, 1989).
PNAV, based on a Kalman filter and a smoother for combining backward and forward solution, can process all combination of GPS observable; it was used for a first analysis of the whole data set in order to access the overall quality and detect faulty observations. Results obtained from PNAV are summarized in Table 3 where the RMS of height differences are listed for each pair of reference stations. This level of repeatability can be achieved on most of the aircraft positions using standard processing procedures. In presence of a critical situation, due to unexpected disturbances on GPS signal acquired from one ground receiver (VU04), the standard procedure was not successful; manual interaction for introducing waypoints, independently computed, to constrain the solution or eliminating the affected observations was necessary.
A 1-hour dataset (from epoch 33000 to 37000), during which the images were taken, was selected for further analysis with GEOTRACER GPS and GEONAP-K. Comparing the results with PNAV, it was noted that the OTF algorithm implemented in GEOTRACER is more finely tuned resulting in a higher stability and slightly better RMSs of differences; it should be mentioned, though, that the estimated solutions presented a larger number of rejected positions. The main differences between the two software's were observed in presence of changes in the satellite configuration.

stat.1-stat.2	RCFX-VU00	RCFX-VU04	RCFX-VULC
	16.9	9.7	10.8
stat.1-stat.2	VU00-VU04	VU00-VULC	VU04-VULC
fixed solution	8.9	9.1	3.8
float solution	12.2	13.5	7.2

Table 3 - RMS (cm) of the differences between solutions from two ground stations

In order to correctly combine the redundant observations, the GEONAP-K software, capable of multi-station adjustment of undifferenced GPS observable, was experimented. Using the three reference stations on the island as fiducial ones and adopting a rigorous simultaneous dual frequency processing. High accurate aircraft positions were estimated. Results from a single-station configuration showed differences with the multi-station solution characterized by a 2-3 centimeter level RMS on the 3-D coordinates.

Comparison between GPS and AT projection centers

As the GPS antenna and the camera system were spatially and temporarily connected, the coordinates of the camera projection center can be derived by interpolating the computed coordinates of GPS antenna position at time of exposures and applying the measured spatial offset with the camera. GPS derived projection centers can act as aerial control enforcing the image processing procedure, especially where the control network cannot be very dense due to operational constraints.
In order to take advantage of the GPS aerial control and improve or at least maintain the quality of the relative mapping products, the GPS positions should fulfill specific accuracy requirements, that in case of 1:5000 photo scale are less than 20 cm. At the same time, when a conventional control network is established on the ground it is possible to estimate the complete set of image external parameters, that is position and orientation of the camera, by performing an Aerial Triangulation bundle adjustment. The accuracy of the estimated projection centers positions can be assessed

considering standard deviation of residuals on control and photographically measured pass and tie points. For this test the AT adjustment was performed over a 5-strip photogrammetric block formed by 23 selected images; using 12 ground control points it was obtained mean standard deviation values ranging between 5 and 25 centimeters (Table 4). It should be mentioned though, that the higher standard deviations for STP 2 and STP 5 can be addressed to the lack of ground control points in the corresponding images.
The triangulated projection centers of the remaining strips can be used as an independent check of the GPS positions. The GPS projection centers to be compared with the AT results can be derived both by the rigorous adjustment of the three PNAV solutions (one for each reference station on the island) or by the multi-station GEONAP-K solution. The comparison between the two solutions shows the presence of small size biases with different behavior strip by strip: the differences are about 5 centimetres for the horizontal and 10 centimetres for the vertical component.

Standard deviations			
strip	**σE (m)**	**σN (m)**	**σh (m)**
STP2	0.207	0.186	0.067
STP3	0.104	0.149	0.054
STP4	0.104	0.119	0.051
STP5	0.248	0.225	0.151
STP8	0.111	0.128	0.046

Table 4 - Mean value of standard deviations of the projection centers from AT adjustment

This indicates that the quality of airborne GPS data is high, so that we can obtain OTF position with higher accuracy both using a standard procedure and a more rigorous approach. The centimetric differences can be attributed to the different error models applied in the two software's. Should be noted that in case of a GPS-supported bundle block triangulation all the systematic discrepancies can be modeled and removed using the “shift and drift” approach. A affine transformation was applied strip by strip between GPS and AT derived projection centers: large residuals on strips 2 and 5 can be attributed to the lack of ground controls. In this case the interpretation of high accurate GPS control could be beneficial.

GPS Aided AT Adjustement

In order to assess the accuracy achievable on GPS-aided aerial triangulation adjustments, an analysis has been performed using data selected over a test area covering the central part of the cone. True terrain coordinates (ENU) of the 12 ground control points were derived from the GPS static solution of the control network. The observed image coordinates were processed with the program GAPP (GPS Assisted Phototriangulation Package) for bundle block adjustment. The solution was obtained for different cases in order to derive accuracy parameters while using a decreasing number of control points. The eliminated points were introduced into the bundle adjustment as check points and their estimated coordinates were directly compared with their true values. The comparison between the 7GCP and the 4GCP cases, in which 7 and 4 ground control points were respectively adopted, demonstrates that the use of three more ground control points does not lead to any significant improvement in the vertical component of the adjusted coordinates. This can be explained by the optimisation already obtained by the introduction of high accurate GPS coordinates for the position of the camera centres as aerial control points. Furthermore, the 4 control points selected for the 4GCP are located at the bottom of the volcano and thus can be easily established and measured. The 2GCP case may represent the practical case of minimal control since only the camera position coordinates are available from GPS and the attitude parameters are to be estimated. Ground control is necessary not only to stabilise the block but also for solving the datum problem in order to transform the coordinates into state coordinate system. The resulting accuracy for the 2GCP case are still equivalent to cases in which, in absence of GPS camera station positions, a very dense ground control model is needed.

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- ***Contribution to the design of geodetic space mission and to the use of GPS in environmental monitoring***
  (B. Benciolini, D. Sguerso, P. Zatelli)

CONTRIBUTION TO THE DESIGN OF GEODETIC SPACE MISSION AND TO THE USE OF GPS IN ENVIRONMENTAL MONITORING

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1. Introduction

The team in Trento in the field of space geodesy and related fields includes one full professor and two researcher. The group is part of the "Dipartimento di Ingegneria Civile e Ambientale". The researches developed so fare are strongly connected with the activities of the national coordination group, but most of them are also connected with the interests of other researchers of the department. Some activities requested a significant interdisciplinary cooperation.

2. Contributions to the definition of the requirements for a topographic space mission : the TOPSAT project.

Some requirements about the resolution and the accuracy of a global digital elevation model have been developed using simple linear relations and considering the application to the use of topographic heights for gravity field modeling and interpretation (Benciolini B., Sansò F., 1994).

3. Optimal frequency analysis for the inversion of the Hill's equation and comparison with other filtering methods.

In the general framework of the study of gradiometric and SST techniques it is important to analyse the data filtering of data representing the position of a LEO probe to reduce the noise level and to compute the acceleration. This is a preliminary step for the reconstruction of gravimetric information from the difference of positioning (affected by all the forces acting on the satellite) and accelerometry (affected by non gravitational forces).
The problem have been studied with synthetic data, that have been generated with a proper simulation procedure and an added noise. A realistic gravitational acceleration has been created along an arc of 6000 Km using a field with degrees between 21 and 90.
An integration procedure generated the anomalous position of a satellite along the arc. A trend has been subtracted from the data corresponding to the general solution of the Hill equations. The data of the out of plane component have been used to recover the corresponding acceleration because this component is decoupled from the others and is described by an harmonic oscillator.
The filtering of the data by means of FFT techniques is very attractive because of its computational efficiency, but in the present case it presents several drawbacks.
The numerical experiment has been developed in steps:

- empirical estimation of the power spectrum of the data;
- smoothing of the empirical power spectrum with a weighted moving average;
- direct use the smoothed empirical p.s. to filter the data with a proper choice of the variance of the noise;

OR

- modeling of the empirical p.s. with a parametric model (gaussian) and subsequent estimation.

To obtain a sensible result, i.e. an agreement between simulated and reconstructed acceleration with a mse < 1 mGal, it is necessary to smooth and dump the filter much more than what optimal theory would suggest. This shows that the applicability of the spectral procedure to the treated problem is questionable, because the performed optimization of the filter would be very difficult with real data. The conclusion is that among all the method that have been experimented the collocation is the most robust and reliable. This fact motivated an other research on the development of variance-covariance models for the treatment of vector data by collocation. The results are reported by (Benciolini B. et al., 1996).

4. Covariance function models for the inversion and filtering of vector data by collocation in gravimetry and gradiometry

Numerical analysis to invert gradiometric data has been experimented. Hill's equation is applied to synthetic but realistic low orbits.

The application of collocation always requires the estimation of a covariance function by fitting an empirical covariance function with a covariance function model.The covariance function model must be chosen from a dictionary of positive definite functions. Usually, the inversion of the orbit is obtained neglecting the cross-correlation between the components, since vector covariance function models are not available.

A vector least-square collocation software has been developed to filter significantly correlated signal. 2-D processes have been studied, in particular the conditions for positive definite covariance function models have been analyzed. Thus constrains on the parameters of some auto and cross covariance function models have been pointed out (Sguerso D., 1995).

The construction of matrix covariance function models for vector value data is treated for the application of collocation to the filtering and inversion of gravimetric and gradiometric data. A test with simulated data of the position of an Aristoteles-like satellite, obtained by the integration of the Hill's equations in a gravity field, band-limited between degree 21 and 90, has been carried out. White noise has been added to the data and radial and tangential components of the position and acceleration have been recovered by vector collocation software.

The tuning of covariance function parameters has been obtained with visual "good" fit near the origin, tails are neglected, but a compromise to fulfill the constrains on the parameters is required.

The acceleration has been estimated with an error comparable with the one in other similar experiments using the out-of-plane component only. This is probably due to the fact that a poor dictionary of vector covariance function models has been built. Thus the fulfillment of the conditions for positive definition of the covariance function models does not allow a best fit of the empirical (auto and cross) covariance functions treated independently.

Collocation has proved again to be an effective method for data filtering and transformation. The use of a rigorous model for cross-covariance functions is possible, but its real convenience must be carefully evaluated case by case.

5. SAGE

The SAGE (Satellite Accelerometry for Gravity field Exploration) project was established in 1997 for the determination of the earth gravity field by exploiting the concept of high-low satellite to satellite tracking, to obtain the low-medium coefficients of the geopotential and their time variations.

Within this project a software system for the simulation of the potential determination with the spacewise approach has been developed (Albertella et. al., 1998). In particular some tests using collocation with colored noise have been carried out. After generating signal affected by colored

noise (known thru its covariance function), its reconstruction is attempted testing different hypothesis on the available information for the noise correlation.
The collocation estimation technique, which is based on the well known partition

$$x = \varepsilon + n$$

remains valid even when both ε and *n* are regarded as processes with significant covariance function, i.e. even when the noise *n* cannot be considered white noise.
For the practical computation the following expressions must be used:

$$\varepsilon = C_{\varepsilon\varepsilon} C_{xx}^{-1} x$$

where $C_{xx} = C_{\varepsilon\varepsilon} + C_{nn}$, and $C_{nn} \neq \sigma_0^2 I$ and where the signal and the noise are not correlated, i.e. $C_{\varepsilon x} = 0$. Colored noise has been generated starting from a white noise by applying a filter of this form:

$$n = Q\upsilon$$

where *n* is the colored noise, ν is the white noise and *Q* is a matrix that satisfies the equation $QQ' = C_{nn}$.
In our simulations the *Q* matrix has been generate using the Tcholesky algorithm, and therefore it is upper triangular.
A FORTRAN program has been written to test the signal denoising when the noise is not white. Collocation technique should require a tailored formulation for the estimation formulas because the noise correlation matrix C_{nn} is not diagonal anymore, but the matrix inversion part (C_{xx}^{-1}) remains the same; therefore the computational cost remains almost unchanged.

This experiment has been carried out in three stages:

1. writing a FORTRAN program for the colored noise generation. This program generates a correlated noise with known covariance function.
2. generalizing the collocation estimation program for $C_{nn} \neq \sigma_0^2 I$.
3. performing some numerical tests on the very same data which have been used for the previous spacewise approach tests.

The numerical tests have been carried out using the general collocation programs system as setup at the Politecnico di Milano. The whole procedure is accomplished in three stages.
The orthogonal component data has been modified so that its noise has a known covariance: in our tests gaussian and spline functions have been used. As in the previous tests with white noise, the variance of the noise *n* added to the signal ε has been of 2 cm.
The tests demonstrate that in presence of colored noise the standard deviation of the difference between the estimate and the real (simulated) signal grows significantly. When the whole covariance procedure is modified so that it should be able to take the colored noise into account the result is slightly better than treating the noise as a white noise (tab. 1).

$\sigma(\hat{\delta}g - \hat{\delta})$	Case
0.9 nGal	White noise
2.3 nGal	Colored noise regarded as white noise
2.2 nGal	Colored noise regarded as colored noise

Table 1 - Orthogonal component estimation standard deviations.

As expected, when a colored noise is taken into account the standard deviation of the difference between the estimate and the real signal $\sigma(\hat{\delta}g - \hat{\delta})$ increases. The main problem is to obtain simultaneously from the empirical covariance function of the data (x) information about both the noise covariance function and the signal covariance function.

6. Kinematic GPS positioning

Several studies of GPS have been carried out within a research project aimed at setting up a suitable platform for atmospheric measurements on a light airplane (de Franceschi M. et. al. 2002, Ferrari A. et al., 1998).

Measurements of air pressure, temperature and relative humidity have been performed in various Alpine valleys up to a height of about 2500m a.m.s.l. Use of GPS facilities and specific post-processing procedures allowed careful positioning of measurement points within the explored domain. The analysis of collected data allowed detailed investigation of atmospheric vertical structures and dynamics typical of valley environment, such as morning transition from ground based inversion to fully developed well mixed convective boundary layer.

Based on data collected along flight 3D fields of the explored variables have been obtained through application of geostatistic techniques (Kriging).

The use of the GPS technique for cinematic positioning of an airplane for environmental surveys needs a specific setup for all the receivers' settings and the reference GPS network.

This kind of surveys use the continuous cinematic GPS technique with relative positioning. The OTF (On The Fly, a technique for the determination of the GPS phase initial ambiguity without requiring a static initialization) method is used to process the data but, to prevent from elaboration problems, an initialization period of about 10 minutes (where the plane stands still on the take-off strip) is required.

Using the OTF technique it is possible to process GPS data even with complete lock loss on all the satellites, provided a sufficient number of epochs with "clean" signal for at least five satellites: it is possible in this way to recover from lost locks due to external obstacles (mountains) or to quick direction changes.

One of the most relevant aspects for a good GPS positioning is a correct survey planning. In fact the geometry of the satellites constellation can change significantly with the hour or the day of flight. The presence of obstructions can change dramatically the number of visible satellite, for this reason the development of an automatic procedure for a realistic GPS planning is in progress at the Laboratorio di Geodesia (Geodesy Laboratory) of the Dipartimento di Ingegneria Civile e Ambientale of the University of Trento. This project merge the available information about the satellite positions from the almanac with the morphologic information from a digital elevation model (DEM) to automatically evaluate the number of visible satellites and the DOPs value (Sguerso and Zatelli, 1999a,b). It is possible to forecast the number of satellites and PDOP value along a full 3D trajectory of an object moving in time (Carli et al. 2000, Fruet and Sguerso, 2000). This software has been ported to a module of the Open Source GRASS GIS.

The tests carried out in the Trento area with a hybrid GPS/GLONASS Ashtech GG24 receiver show a better reliability than the GPS alone, in the sense that the number of lost positions due to insufficient number of satellites decreases from a few percent to an order of magnitude less. However a significant gain of precision (in the sense of standard deviation of the coordinates) has not been observed. These tests have suffered from setup problems, in particular for the mounting of the antennas on the plane, therefore should be considered as preliminary.

7. Realistic precision prediction in GPS applications

Several problems are connected to satellite surveying techniques. Especially for high precision survey, tropospheric effects, antenna center phase's variations and multipath effects cannot be neglected. Detection and removal of multipath effects in static and cinematic application is very important.

After an error budget analysis of GPS signal, an international bibliography research has been carry out during a graduate thesis, in cooperation with Special Study Group on Multipath mitigation (SS 1.182) of the International Association of Geodesy.

The research main topics are: multipath characterization and its effects on positioning, developments in GPS hardware and mitigation techniques.

A preliminary study about causes and effects of satellite signal reflection has been obtained for course/acquisition and carrier phase's observations. Extreme multipath interference can make useless GPS observations for precise positioning applications as well as for mobile navigation. Infact, periodic cyclic errors depend on local geometry, thus averaging during short observation sessions probably does not reduce long periodic effects.

The relation between GPS receivers' architecture for multipath mitigation and correlator bandwidth, as well as antenna techniques (ground plane, choke ring and multi antenna mitigation), has been pointed out.

Several real-time and post-processing mitigation techniques have been developed during last years, like day-to-day correlation analysis, Signal-to-Noise Ratio analysis, multipath mitigation through calibration in the local environment, multi-antenna arrays and crossing-points technique.

A schematic analysis of survey methods (static, cinematic, mobile navigation) and mitigation techniques (hardware, real-time or post-processing) has been produced. The accuracy improvement range from 25% to 65%, reducing the multipath effects to few millimeters for carrier phase and few decimeters for course/acquisition observations.

8. Automatic visibility maps of GPS satellites

A realistic forecast of the satellites visibility and their spatial geometric configuration is a key factor for the success of a Global Positioning System (GPS) survey. Planning procedure is possible with commercial software only one point at a time, for assigned temporal interval. Moreover the operator have to survey the obstacles that can hide part of the sky foe each planning point. This is very onerous in mountainous region (natural obstacle) and in the urban area (manmade obstacle) in static survey, but comes impossible in kinematic survey.

A new procedure for the realistic planning of GPS and GLONASS surveys has been set up, using the information available from a digital terrain model (DTM) and the satellites' almanac data.

This approach has been suggested by GRASS tool, based on sun-shadows algorithm, creating visibility layers satellite by satellite considering every satellites as the sun illuminating the earth.

The procedure scheme is shown in Fig. 1, composed in there principle steps.

The first step is to compute the satellites' positions on local horizon from the almanac data (input 1) at the time of the survey (input 2). An external software has been created to compute satellites' WGS84 coordinates, through reduction of the (pseudo) keplerian orbits parameters, from an almanac data in ASCII format. Satellites' relative position from latitude and longitude of the planning area center P_o (input 3) are computed.

Azimuth and elevation of each satellites above local horizon (step 1 - output) and DTM (centered on the area center P_o) are input of the GRASS algorithm r.sunmask (step 2 – input A and B) to create a binary raster shadows map of the satellite, where each pixel contains information on the availability of the satellite signal (1=available, 0=not available). The last step is performed using map algebra inside the GRASS GIS**.** It produces a global satellites' visibility map, through direct sum of each satellite layer (number of layer with "1" pixel).

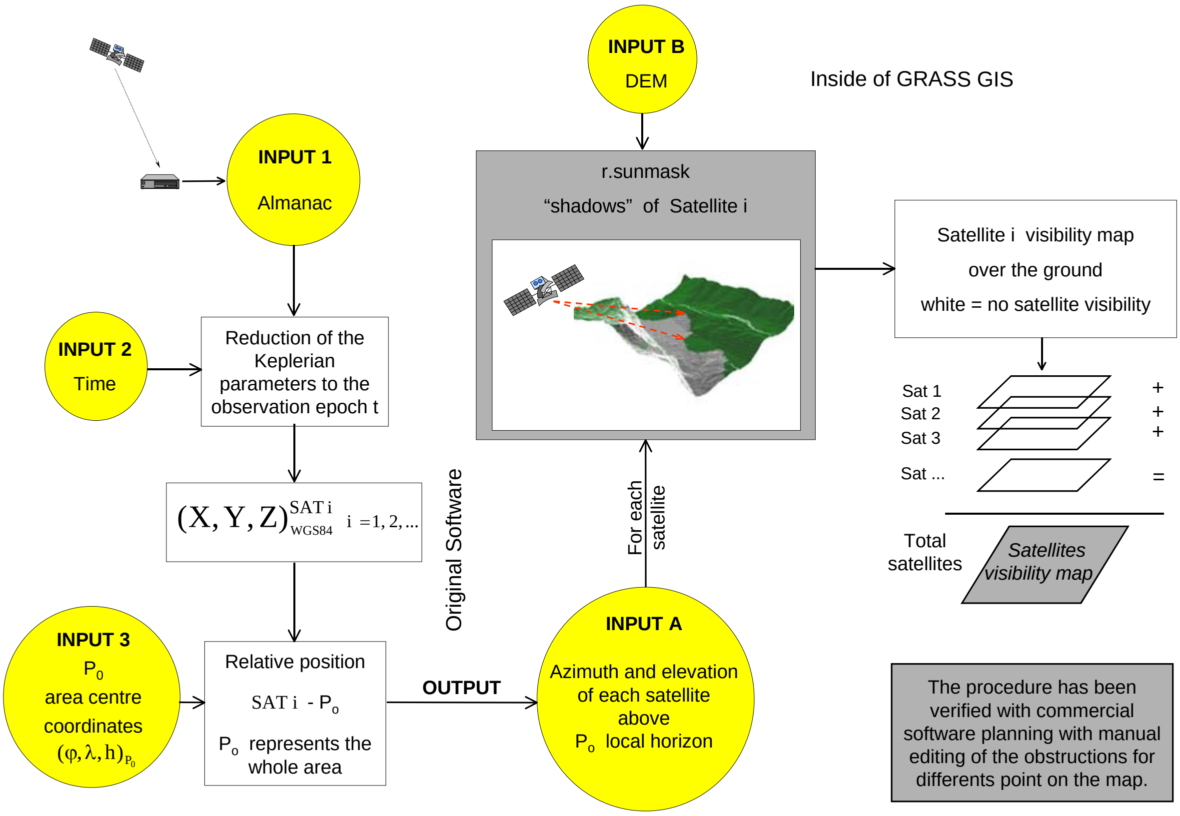

Figure 1 - Scheme of the procedure to obtain satellites visibility map.

With this procedure a satellite visibility map is obtained for the whole area and not only for a single point. The extension of the area and the reliability and accuracy of the procedure depend obviously on two kinds of approximations: compute and data approximations.

In tab. 2 the approximations due to different sources are presented, computed in term of elevation uncertainty. Their effects in term of shadow uncertainty are computed for an obstacle height of 2000 m with cut off elevation signal of 20°. Elevation variation of 1' is considered the lower level of uncertainty, due to the almanac ephemeredes source.

Shadow's variation due to almanac data and DTM uncertainty increases from 5 m to about 30 m, considering 10 m of uncertainty in eight. DTM eight uncertainty is generally lower with small spacing grid, but computational load increases considerably; a good compromise for computing speed and shadows uncertainty may be obtained with a 40 m grid spacing DTM.

The first procedure approximation comes from considering satellite signals as parallel over the whole area: this is justified from satellites' distance of about 20.000 km, that corresponds to differences of 1' at 6 km (coherent with almanac data). Consequently azimuth and elevation of each satellite above local horizon are computed only one time for the area center P_o, i.e. relative positions are considered the same for every pixel.

The difference in eight from satellites datum (WGS84) and DEM datum may be considered lower than DEM uncertainty effects, lower than 10m in terms of shadow's position.

ppapproximation type	Source	**Uncertainty** in term of elevation degree / shadow
Data	**Almanac ephemeredes**	1' / 5 m
	DEM	30 m
Procedure	Unique local horizon of the area centre P_o	1' within a 6 km radius / 5 m
	Height Different Reference Frames WGS84 (sat) and national (DEM)	< 10 m

Table 2 - Approximations.

Consequently this procedure produces satellites visibility map with uncertainty level lower than 1 pixel spacing DEM of 40 m.
A real example is shown in fig. 2. The realistic planning procedure points out an unexpected low satellites visibility area, where only three satellites are visible on the Adige valley axis, generally considered a good zone for a surveying (Fruet G. et al. 1999).
Therefore planning with realistic obstacles is very useful particularly in critical zones like highly urbanized area and mountain area, to plan static survey but especially for kinematic and stop&go surveys, for example for road network survey and environmental monitoring.This procedure has now been rewritten with a different approach: a first step produces an obstruction map for each DTM pixel, a second step uses this obstruction map to evaluate a map of the satellites' visibility and PDOP value.
This approach exploit the invariance of the obstruction map (unless the DTM changes): this is the heavier task but the map can be computed only once and stored for future use. It is now possible to perform a realistic planning of static and kinematic surveys with fully 3D trajectories (Carli D. et. al. 2000).
Three modules for the GRASS GIS have been created:

- r.obstruction: creates a polar obstruction map from a DTM. It provides an ASCII file, named "ostr_di_(name raster)", which contains, for every cell of the DTM map, 360 values representing the obstruction angle on the horizon for every azimuth degree.
- r.planning.static: performs a static planning for GPS and Glonass surveys using the obstruction map created with r.obstruction. If the flag [-p] is not set the program generates four different raster maps: two raster maps representing the number of visible satellites at starting time and the minimum number of visible satellites over the chosen time span and two raster maps showing the PDOP values at starting time and the maximum PDOP values over the chosen time span. The four maps are named by adding '_sat_t', '_sat_At', '_dop_t' and '_dop_At' respectively to the name of the DTM raster. If the p flag is set r.planning.static is an interactive program that allows the user, using the mouse as pointer

device, to display the number of visible satellites and PDOP value of the point currently located under the mouse pointer.

- r.planning.cinematic: performs a cinematic planning for GPS and Glonass surveys. It creates a site GRASS file from a vector trajectory. This site file contains a point for each node of the trajectory with four fields: traveling time between each point, number of visible satellite, PDOP value and height.

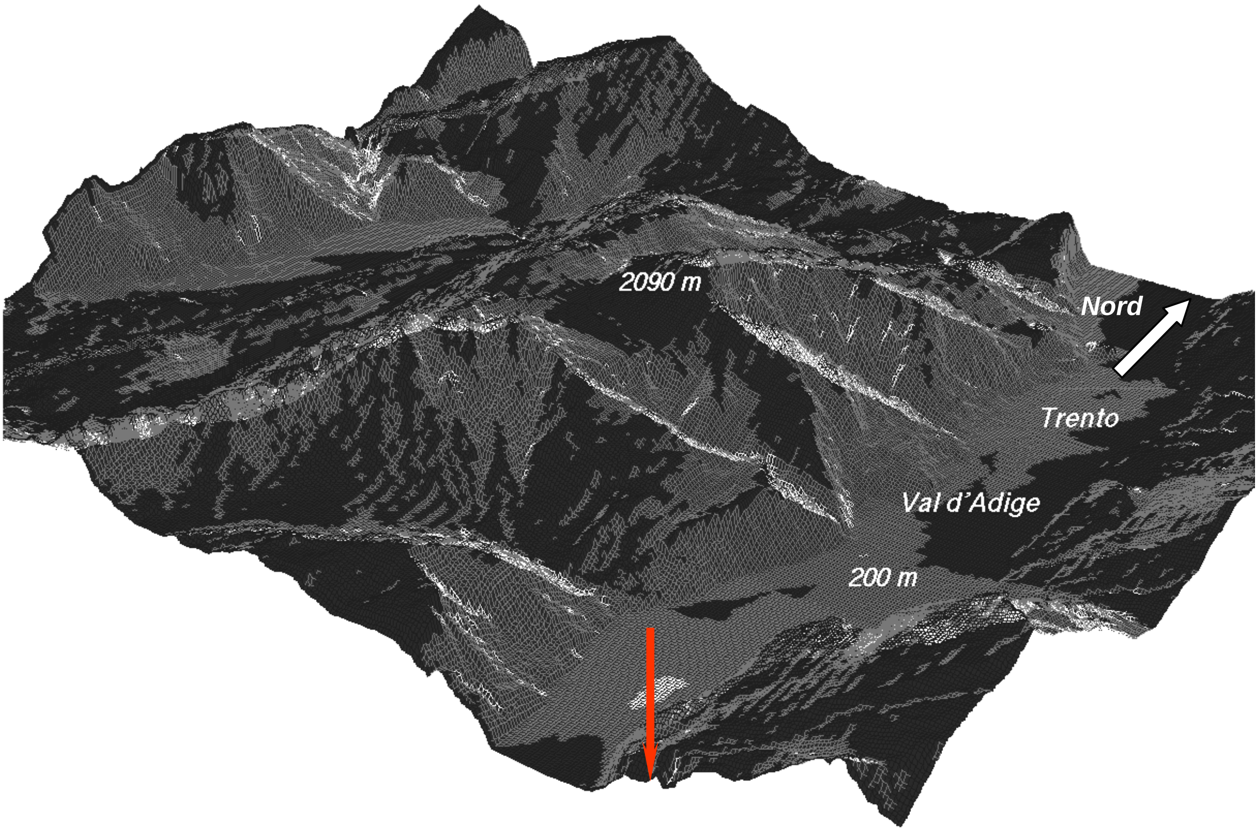

Figure 2 - Satellites visibility map for Trento area: 21-07-'99 - 12.00 GPS Time. The satellites' visibility has been subdivided in three categories: white < 4 satellites; grey 4-6 satellites; black 7-9 satellites.

This approach has been used to asses the GPS feasibility for surveys in urban areas (Fruet G., Sguerso D., 2000).

9. Multiresolution analysis

Multiresolution analysis represents a powerful tool for distributed data analysis and elaboration. It has been designed for the first time by S. Mallat and Y. Meyer in the mid 80s to create a coherent theory frame for various approximation and decomposition techniques, in particular those using wavelets bases.

Multiresolution analysis can be relevant for some geodetic applications, in particular for signal analysis and operators representation, by exploiting the possibility of an analysis which is local both in space (or time) and frequency, providing furthermore a natural way of managing data with different resolutions. Several applications of these techniques to geodetic problems has been proposed, in particular our group has investigated the use of wavelets for the analysis and use of data at different resolutions and for the fast calculation of geodetic operators.

The wavelets analysis of signals has been applied to two-dimensional problems such as image and digital terrain models multiresolution representation and compression.
A software for the wavelets analysis of two-dimensional signals has been written and tested. This software performs the discrete wavelets transformation (both analysis and synthesis) of a signal over a two-dimensional domain using different wavelets bases. Two complete programs have been written using the C and FORTRAN programming languages for DOS and X Windows/Motif systems. These programs have a graphical user interface that allows the user to interactively experiment the effect of the transformation; furthermore it is possible to apply an arbitrary transformation to the decomposition coefficients of any resolution level.
The evaluation of operators connected to the gravity field potential plays a central role in geodesy. The classical techniques differentiate between "near zone" and "far zone" with respect to the evaluation point, with the use of different formulations estimating the influence of the two different zones. In this way it is possible to solve the problem of the singularity of the operator in the evaluation point. The kernel expansion in Taylor series with respect to the radius starting from the interest point is effective for the "far zone" but can lead to divergent series near the central point, where the integration grid is usually dense. The typical integrations kernel structure in geodesy exhibits only a singularity in the central point and is smooth everywhere else: the use of the wavelets kernel representation provides a natural way to take into account such a structure by writing a sparse matrix.
A first proposal of application of wavelets to geodetic operators has been made, along with some numerical experiments, in (Benciolini et al., 1994). The operator used in the evaluation of the gravity potential in the space (in the three dimensions) by a single layer

$$T(x_P, y_P, z) = \int\int \left[z^2 + (x_P - x_Q)^2 + (y_P - y_Q)^2\right]^{-\frac{1}{2}} \rho(x_P, y_P) dx_Q dy_Q$$

has been evaluated. Numerical tests have been carried out assuming the *z* coordinate as a constant and using density ρ values on a regular grid. The value of the potential *T* is evaluated on the same grid points where the density ρ is known. Because of the regular structure of the data and the features of the operator, the associated matrix has a particular structure. Such matrix has been represented in the *non-standard* wavelets form and all the coefficients with absolute value below a threshold ($\varepsilon = 0.01$ in the numerical experiments) have been dropped. A compression ratio has been determined as the ratio between the number of remaining coefficients (i.e. coefficients above the threshold) and the total number of coefficients, while the approximation due to the coefficient dropping has been estimated by the ratio between the norm of the dropped matrix and the norm of the original one.
This experiment has highlighted some fundamental aspects of this technique:

- the compression ratio and the approximation index do not depend in a significant way on the regularity of the kernel near the origin;
- the use of very regular wavelets bases is not convenient because lower compression ratios can be achieved;
- larger matrices lead to higher compression ratios;
- the compressed matrices have regular patters and the position of the non-zero elements can be predicted before the actual calculation: it is therefore possible the use of memory efficient indexing schemes.

Other experiments have been carried out for the wavelets representation of operators (Zatelli, 1998), both one and two-dimensional.

The first experiment consists in the application of the second derivative operator to a discrete mono-dimensional signal, figure 3 shows the classical structure of the matrix representing the operator after wavelets transform.

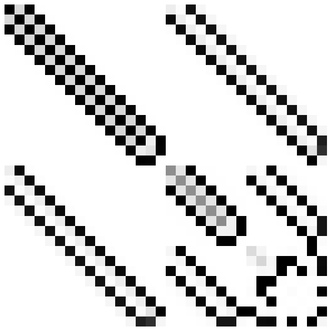

Figure 3 - Classical structure of the matrix in wavelets representation.

Several tests have been carried out using different wavelets bases (Haar, Daubechie's compact support wavelets, etc.). The results clearly indicate that higher numbers of vanishing moments for the base used lead to an apparent increase of the matrix band size, however in the latter cases the absolute value of the outer coefficients of the bands are negligible, in accordance with (Beylkin et. al., 1991).

In the second experiment a smoothing operator has been applied to a two dimensional box-like signal. The operator kernel is now four dimensional and has been written with reference to two points on the plane. The singularities scheme is now more complicate but the number of relevant coefficients remains the same. Using the kernel of the operator that represents the potential generated by a plane

$$K(P,Q) = \frac{1}{\sqrt{z^2 + (x_P - x_Q)^2 + (y_P - y_Q)^2}}$$

high compression ratios have been achieved (Benciolini et al., 1994).

These results, in particular the good compression ratios and the possibility of computing the application of an operator as a matrix-vector multiplication, suggest the possibility of the application of this technique on large scale. However, the creation of optimized programs and the direct evaluation of the sole non negligible coefficients is required.

A wavelets analysis module for the GRASS GIS is currently under development and will be used for investigate the earth surface modeling phenomena, such as erosion, at different resolution level.

10. Height coordinates in modern geodesy

The problem of the choice of a vertical datum and of height coordinates is e quite classical problem in geodesy that gained new popularity with the advent of space techniques. This is due to the global character of such techniques and to the possibility of performing a really three-dimensional and purely geometric positioning. (GNSSs provide pure geometrical information as long as the orbits are fixed).

In this frame the definition and the realisation of an height datum, the choice of proper height coordinates and the proper modelling of the observations are all relevant topics. We contributed to a research in this field, reported by Baldi et al. (1999) and Baldi et al. (2001) with a review of some height coordinates.

The relations between various kind of coordinates and between coordinates and observations have been studied. An attempt of categorization based on the geometric and physical meaning of the coordinates is presented in the following table:

Coordinates	geometrical meaning	Physical meaning	computable in Molodensky's theory
ellipsoidal height (h)	YES	NO	--
orthometric height (H)	yes	NO	NO
normal height	indirect	NO	YES
dynamic height	NO	YES	YES

Table 3 - Categorization of the coordinates.

The "geometrical meaning" is intended as a simple and evident one: only h and H are the distances of the considered point from a reference surface with a simple definition. On the other hand only the dynamic height has a precise "physical meaning". "Computable in Molodensky's theory " means that it does not require to know the density of the topographic masses.

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- ***Satellite geodesy in the solar system***
  (A. Milani, A. Rossi, D. Villani)

SATELLITE GEODESY IN THE SOLAR SYSTEM

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A unified understanding of gravity field missions

The gravity field of any planet, either large or small, can be determined from an orbiting spacecraft. Of course the techniques to do so have been developed by using artificial satellites of the Earth, but the general understanding of the problems is applicable to orbiters around other bodies, such as the Moon, the other terrestrial planets, asteroids and comets, the gas giant planets and their satellites.

The experience of our group grew from the study of high accuracy satellite geodesy of the Earth in the 1980s (see, e.g., Milani et al. 1984). In the early 1990s this experience was used to achieve very accurate geodetic solutions based on Satellite Laser Ranging (SLR) (see, e.g., Milani et al. 1995). In the mid 1990s many of the same conceptual tools were used to plan missions of Lunar exploration (see, e.g., MORO 1996, Milani et al., 1996).

In the years 1998–2001, covered by this report, the emphasis of our research was on the possibilities, opened by new sensor technologies, for extremely accurate satellite geodesy missions, both around our planet and in the context of interplanetary exploration. The new accuracies, and the possibility to achieve them even at a great distances from the Earth, required new imaginative mission designs and challenged the established algorithms and mathematical tools of satellite geodesy.

Among the examples of this, we will discuss the introduction of ultra accurate accelerometers in the design of satellite geodesy missions, and also mention the future prospects for gradiometer missions. We will present the implications of the developments in interplanetary communication technology, in particular with the use of the K-band and multi-frequency transponders. We will also discuss the implications of the new opportunities for planetary exploration introduced by the availability of advanced propulsion systems, with the Bepi-Colombo ESA mission to Mercury.

However, our contribution is not in the development of the technologies, but in learning how to use the accuracy of the new measurement methods to achieve the best results. It is the case that to this enormously increased relative accuracy of the measurements corresponds an increased complexity and difficulty of the solution algorithms. We will discuss mostly two mathematical problems arisen from this situation, which we have solved in the last few years.

These have been very successful years, because of the results of our research, but also because of the approval of the ESA missions GOCE (in 1999) and BepiColombo (in 2000). These two approved missions allow us to look at the future with confidence and with the possibility of long term planning.

This historical overview could not be complete without mentioning the most negative event of these years, namely the premature death of Paolo Farinella in the year 2000. His fundamental contributions to the development of modern satellite geodesy, such as his masterpiece studies of the non gravitational perturbation on LAGEOS-class geodetic satellites (Farinella et al., 1996), have been a model for a new generation of specialists. His deep understanding of the unity of science, and his problem-solving attitude, has been a driving force in our research, and to replace him will be difficult, maybe impossible.

Accelerometer missions

In the 1980s and 1990s, mostly under the pressure of the so called 'LAGEOS drag mystery', there has been a determined effort (in which our group was at the forefront) to model all the perturbations acting on geodetic satellites. Although some important successes were achieved, in particular in solving the LAGEOS problem with a self-consistent model of non gravitational perturbations, the case of complex-shape satellites turned out to be intractable, at least at a level of accuracy matching the accuracy of the modern position measurement techniques. This was even more true for the low orbiting geodetic satellite required to determine high resolution gravity fields.

One possible solution to this impasse came from the availability of space-borne accelerometers. The basic idea is simple: the readings of an on-board three axis accelerometer can be inserted in the right-hand side of the equations of motion, totally replacing the models of the non gravitational accelerations. The problems arising in a real implementation of this idea are less simple, including the need to take into account the displacement of the acceleration sensors from the center of mass of the spacecraft and the need to account for the apparent forces due to rotations. Nevertheless, the accelerometer data can be assumed, after some preprocessing, to directly measure the effects of the surface forces acting on the spacecraft.

The main difficulty arises because of the accelerometer calibration. In general, for each channel (corresponding to some coordinate axis) an accelerometer electronics measures some electrical quantity y which is a function of the acceleration x of the sensing element with respect to the accelerometer case, supposedly rigidly mounted on the spacecraft. The relationship among the two is expressed by a calibration formula

$$y = a\,x + b\,T + c \ldots$$

with T the temperature at the sensing head, a, b, c some calibration constants and the little dots standing for nonlinear effects, which are negligible if the accelerometer is used in the appropriate dynamic range. The constants a and b can be measured on the ground, at least for the spring-type accelerometers (Iafolla and Nozzoli, 2001); on the contrary c cannot have in space the same value as before the launch. Thus a space-borne accelerometer does not really measure accelerations, but only differences in accelerations.

Thus an accelerometer does not remove at once the problem of modeling non gravitational forces. The accelerometer data have to be considered as information on the time variation of the non gravitational accelerations, accurate only over a given frequency band. In practice, this frequency band covers the range of periods between $\simeq 10$ s and a maximum time span depending upon the hardware and the required performance. E.g., for the Italian Spring Accelerometer the calibration additive term c can be considered constant for time spans up to $\simeq 10^4$; for the very sensitive GOCE gradiometer, the calibration "constants" expire after only $\simeq 200$ s.

Specific solutions have been adopted for the different accelerometer/gradiometer missions we have been working on in the last years, such as the Italian proposal SAGE (with ISA; SAGE 1998), the ESA gradiometer mission GOCE (GOCE 1999) and the interplanetary ESA mission BepiColombo (BepiColombo 2000). The common idea is that there need to be calibration parameters among the parameters to be solved for, in such a way that they absorb, together with the decomposition of the orbit in arcs (see below), the unmeasured and unmodeled long term effects of non gravitational perturbations (and also other problems, such as the instability with time of the reference system defined by the GPS satellites).

Decomposition of gravimetry problems

The impossibility to model non gravitational perturbations at the level of accuracy required for satellite geodesy has been traditionally tackled with the multi-arc method (see, e.g., Milani et al. 1995). However, the new generation of geodetic missions has resulted in the need to solve new problems in the application of this method. The basic idea is that the orbit of a single physical spacecraft is disconnected into arcs, each one corresponding to a time span much shorter than the mission duration. Each arc has a separate set of initial conditions, as if the observations belonged to a different physical spacecraft. The observations belonging to one arc are considered to be independent from the initial conditions of another arc. That is, the initial condition coordinates are considered as *local* parameters.
Let us suppose that the vector of solve for parameters is split into two components, along linear subspaces of the parameter space:

$$X = \begin{pmatrix} L \\ G \end{pmatrix} \quad ; \quad X^* = \begin{pmatrix} L^* \\ G^* \end{pmatrix}$$

with G the global parameters, L the local ones (of all arcs). We partition the normal system in the two equations restricted to the two subspaces

$$\begin{cases} C_L\,\Delta L + C_{LG}\,\Delta G = D_L \\ C_{GL}\,\Delta L + C_G\,\Delta G = D_G \end{cases}$$

where the local-local normal matrix C_L is block diagonal, and therefore can be inverted block by block. Then it is possible to solve the normal system by substitution of ΔL, as deduced from the first equation

$$\Delta L = C_L^{-1}\,[D_L - C_{LG}\,\Delta G]$$

into the other equation

$$(C_G - C_{GL}\,C_L^{-1}\,C_{LG})\,\Delta G = D_G - C_{GL}\,C_L^{-1}\,D_L$$

with coefficients matrix C^G. If C^G is invertible, let

$$\Gamma_G = \left(C^G\right)^{-1} = \left[C_G - C_{GL}\,C_L^{-1}\,C_{LG}\right]^{-1}$$

and the solution, expressed in terms of a partitioned covariance matrix, is

$$\begin{cases} \Delta G = \Gamma_G \, D_G - \Gamma_G \, C_{GL} \, C_L^{-1} \, D_L \\ \Delta L = \Gamma_L \, D_L - C_L^{-1} \, C_{LG} \, \Gamma_G \, D_G \end{cases}$$

The conclusion is that it is possible to solve for both the local and the global parameters without computing the inverse of the full normal matrix, but by only inverting the small diagonal blocks of C_L and the matrix C^G, with a number of rows and columns equal to the number of global parameters. This allows to handle comparatively large problems without excessive computing resources.

When this classical algorithm is applied in the conditions typical of the new generation of geodetic missions, the problem of the size of the matrices arises again in a different way. In gravimetry missions aiming at determining a high resolution gravity field the set of global parameters must include at least the spherical harmonic coefficients up to some degree and order ℓ, and there are $(\ell+1)^2$ coefficients. Thus the inversion of the matrix C^G may already be a problem for reasons of computational complexity, numerical stability and computer RAM.

While preparing a full simulation of the SAGE mission we have devised a method to decompose the problem of the determination of global parameters (SAGE 1998, Section 3.5). The idea is to use a "quasi-resonant decomposition", that is to exploit the following fact. For an orbit which is exactly resonant with Earth's rotation, completing p orbits over q days (p, q integers) and coming back after this time span to the same position in an Earth-fixed reference system, the global-global normal matrix C_G can be reduced to block-diagonal by selecting a suitable ordering of the harmonic coefficient. Then for an orbit which is close to a resonance the same matrix will be "approximately" block-diagonal, that is, its coefficients outside the diagonal blocks will be comparatively much smaller. The same will be true of the matrices C^G and its inverse Γ_G. Then a well known numerical method (relaxation) can be used to perfrm the inversion iteratively, without any need to handle large matrices.

For more advanced gravimetry missions, such as GOCE, the problem of the number of parameters is even more severe. The harmonic coefficients, belonging to the global parameters, are to be solved up to degree and order $200 \simeq 250$, and thus there are tens of thousands of them: this can be solved by another application of the quasi-resonant decomposition method, which can be shown to apply also to gradiometric observations. However, the local parameters have to include, besides the initial conditions for all arcs, the accelerometer and gradiometer calibration parameters. Because of the very tight sensitivity and accuracy requirements, the calibration parameters need to increase in number up to hundreds of thousands. Thus we need to devise a method for decomposing the computation, a parallel algorithm to exploit the number crunching power, but also the RAM, of many separate processors. This method has been identified and will be the object of future research and experimentation, in the framework of the GOCE project.

Planetary exploration

The ESA cornerstone mission BepiColombo includes a Mercury Planetary Orbiter (MPO), on a polar orbit with apocenter at 1,500 km and pericenter at 400 km altitude. This spacecraft is therefore suitable for a detailed investigation of the gravitational field of the planet, provided that (1) the spacecraft can be tracked very accurately while at interplanetary distance and (2) the non gravitational perturbations resulting from the illumination from the Sun in visible light and from Mercury in the infrared (each of the two one order of magnitude above the solar illumination at the Earth's distance) are measured with an on-board accelerometer.

We have proposed a Radio Science Experiment complex, combining the informations from the ultra accurate tracking in K and X band, from the accelerometer and also from other instruments. Thanks to the enormous accuracy made possible by the development of these multi-frequency, high frequency links (Iess and Boscagli, 2001), the accuracy of the tracking of a spacecraft around Mercury is quite comparable to the accuracy used for geodetic satellites of the Earth. The accelerometer can be the same envisaged for SAGE (Iafolla and Nozzoli, 2001). The main goals of the Radio Science Experiment are as follows;

1. to measure the rotation state of Mercury, to an accuracy allowing to constrain the size and physical state of the core of the planet;

2. to measure the global structure of the gravity field of Mercury, to an accuracy allowing to constrain the internal structure;

3. to measure the local gravitational anomalies of Mercury, to an accuracy allowing to constrain the structure of the mantle, the crust/mantle interface, and characterize the mascons;

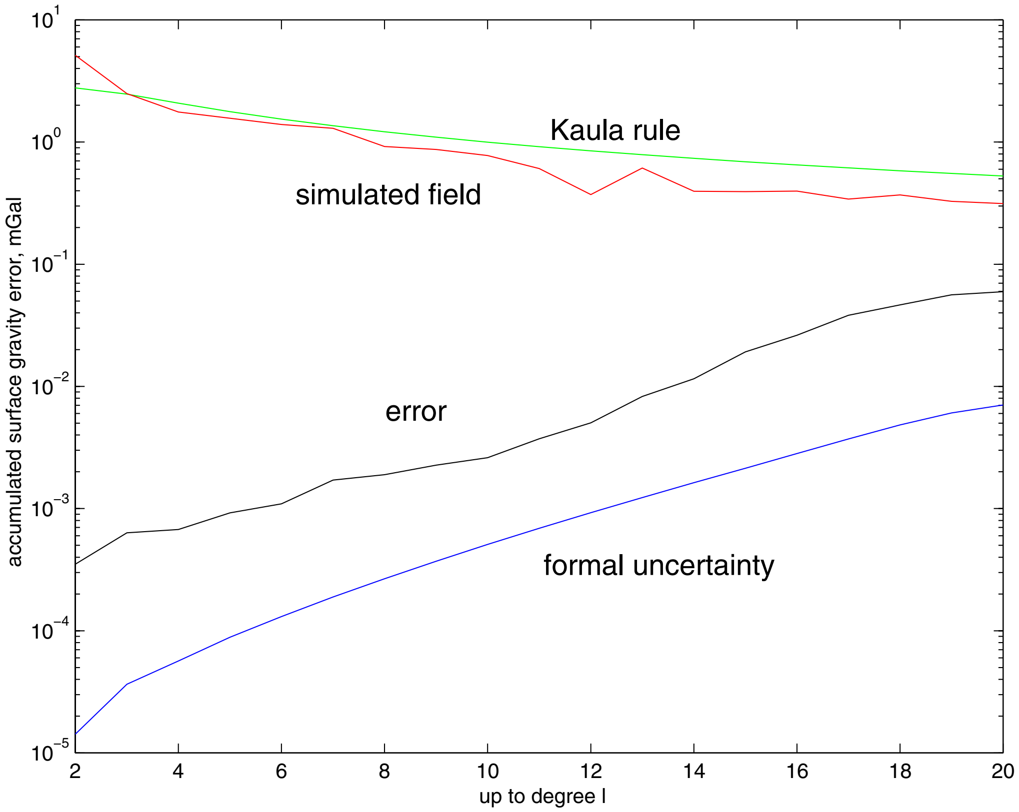
4. to measure the orbit of Mercury around the Sun and the propagation of radio waves between the Earth and Mercury in order to test general relativity to an unprecedented level of accuracy through improving constraints on the post-Newtonian parameters.

The difficulties of interplanetary missions, especially in a harsh environment such as the one around Mercury, are such that even to repeat a conventional satellite geodesy mission around another planet is far from trivial. However, there are even new, conceptual difficulties arising from the very different geometry of the spacecraft orbit and the ground stations location.

One difficulty which was vaguely known, but had not been studied in a rigorous way, is the occurrence of approximate rank deficiency (Bonanno and Milani, 2001). When the orbit of the geodetic satellite is not around the Earth, but around another planetary body, a *rank deficiency* problem arises. That is, the normal matrix for the determination of the initial conditions is poorly conditioned when the arc is very short. This can be understood as the effect of an approximate symmetry: the orbit could rotate around the Earth-planet direction without changing significantly the range and range rate. The symmetry would be exact if the planet were to remain in the same direction with respect to the Earth, and is broken by the relative motion of the planet and the Earth, but over an arc of a few hours it still holds approximately.

Even more complicated rank deficiencies occur if we take into account that the orbit of the planet Mercury (and that of the Earth) are known with uncertainties orders of magnitude larger than the accuracy possible for the BepiColombo tracking. Thus the tracking data will also contain information on the orbit of Mercury, and this in turn will provide a test of gravitation theory (Milani et al., 2001b), testing the theory of general relativity and constraining the values of the Post-Newtonian Parameters.

The overall performance of the BepiColombo Radio Science Experiment have been assessed by a full scale simulation (Milani et al., 2001a). The results for the determination of the gravity field of Mercury are summarized in the figure below; vertical scale is in milliGal (RMS value over the entire surface of the planet). The lines show as a function of the harmonic degree: from top to bottom, the expected signal as a function of the degree (Kaula's rule), the gravity signal as simulated, the actual error in the results of the experiment, and the formal error. Note that the true error is larger than the formal error because non trivial, non-Gaussian error models for both the accelerometer and the tracking measurements.



Non gravitational perturbations

We would like to mention, although briefly, the fact that our studies of non gravitational perturbation on the orbit of celestial bodies have not been abandoned, rather transformed in their field of application. Natural celestial bodies also experience non gravitational perturbations; the corresponding accelerations are small, because of the much lower area-to-mass ratio, but the time spans for accumulating the effects are much longer. This becomes relevant when he orbits of some Near Earth Asteroid are computed by using radar observations, which can be accurate to a few tens of meters in range, and a few tens of meters per day in range-rate. The effect on the orbit can be computed by using some of the mathematical tools developed for artificial satellites. We have been able to show that these effects are actually measurable, provided some asteroid is observed by radar over three different apparitions. (Vokrouhlicky et al., 2000; Vokrouhlicky and Milani, 2000; Vokrouhlicky et al., 2001).

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- ***The use of GPS permanent stations in kinematic positioning and quality control***
  (A.M. Manzino, A. Cina, T. Bellone, A. Lingua)

THE USE OF GPS PERMANENT STATIONS IN KINEMATIC POSITIONING AND QUALITY CONTROL

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Summary
In the ambit of the research project entitled: "The use of permanent *GPS stations for real time kinematic positioning*", the Turin unit concentrated principally on the aspects of "virtual stations and data diffusion from permanent stations". The main points covered in the research project were the following:

1. *RTK positioning using current permanent stations at great distance*
2. *Quality control of data from permanent GPS stations*
3. *Virtual code stations*
4. *Transmission format and the diffusion of data in real time*
5. *The use of calculated and broadcast ephemeris in static and kinematic positioning*
6. *The problems of acquiring raw code, phase data and orbital data in real time.*

1. RTK positioning using current permanent stations at great distance

One of the main problems of this type of positioning consists of the reliable initialisation of the phase measurements especially at a great distance from the station which transmits the differential correction. A substantial part of the entity of this correction depends on the non-modulated part of the clock error of the receiver, generally quartz. The limited costs and dimensions of much more stable samples of rubidium makes possible their use in portable devices. The precision of RTK measurements and the reliability of the initialisation of GPS receivers with an atomic frequency signal have been analysed.
The results of the experiments substantially met the expectations- greater precision of measurement and shorter initialisation times:
The degree of precision that can be reached at various distances from the base station were evaluated using points in a network previously measured using static techniques. The points in the network lie at distances of between 5 and 33 km from the permanent Turin centre and other points distant 67 and 92 km respectively from Turin were also taken into consideration. The alternate use of internal and external clocks enabled the calculation of the differences in the co-ordinates compared with the known values.
At a distance of 33 km from the base station it was only possible to fix the phase ambiguity by using the atomic clock. (FIX) This led to a drastic reduction in the rms differences to values of less than 1 cm, but systematic errors of more than 20 cms compared with the real-time position values were registered. In cases where an atomic clock was used the solution in which floating ambiguity (FLT) was used was less affected by systematic errors than those in which the FIX solution was adopted. The least accurate results were obtained with non fixed ambiguity and an internal clock. Phase ambiguity can be fixed even at a distance of 67 km from the base station both with an internal clock and a rubidium clock. The FIX solution, while presenting a high level of stability (average

rms of the differences ±4 cm and ±10 cm respectively for atomic and quartz clocks) does reveal sytematic errors greater than those on average found with the less stable FLT solutions.
The fixing of the phase ambiguity at these distances is clearly not significant if the various bias values are not reduced. In this respect the use of an atomic sample in the receivers provides undeniable benefits but, on its own is not a guarantee of correct fixing. For example, the current peak of solar activity is synonymous with high ionospheric delays. Doubtless, the reduction of the systematic errors which can be obtained by generating differential corrections in a network of Virtual Reference Stations, could contribute in a decisive manner to the reliability of the positions.
For example, RTK measurements were performed at Mortara (92 km from Turin) at night to reduce the effects of ionic refraction
Also in this case the fixing of the phase gives no guarantee at this distance of a correct internal solution. On average, however the systematic errors have values of about 30 cms which is better than those that can be obtained at closer distances but during the day and with internal clocks.

2. The quality control of data from permanent GPS stations

The new method proposed is by no means intended to replace traditional methods but simply to stand alongside them where these reveal certain shortcomings. This method is now feasible because of the favourable opportunities that have been created in recent years; the low cost of rubidium clocks (about $1/10^{th}$ of the cost of a receiver), the abolition of SA in May 2000, the increasingly precise (decimetrical) information about the ephemeris of satellites also at the end of the measuring day, the accurate knowledge and constant recalculation of permanent station co-ordinates and, last but not least, the improvement of the clocks used in new-generation satellites. In summer 1999 problems on the data acquired were found at the Turin GPS. These errors were almost impossible to detect using traditional methods (Teqc). Processing revealed that the data for a complete week were useless.

Let's start with the complete code and phase equations, writing, for brevity, only those for the first frequency. We shall ignore the variations of phase centre and the second level of errors.

$$P_1 = \rho + c(dt + dT) + I + d_{trop} + dm_1 + noise_{P_1} \qquad (1)$$

$$\Phi_1 = \rho + c(dt + dT) + \lambda_1 N_1 - I + d_{trop} + \partial m_1 + noise_{\Phi_1} \qquad (2)$$

It is assumed that some quantities are known to a good level of accuracy:

- ρ: it is possible to calculate it precisely using the known co-ordinates of the station and the precise ephemeris concerning satellite position;
- $c \cdot dt$: can be calculated by the interpolation of the precise calculated data provided by the satellite clocks every 15 minutes. Each epoch is common and can be precisely known thanks to the abolition of SA
- *c dT*: is common to every epoch and to the measurements of all the satellites, we can also assume that it is known because of the use of a good atomic clock
- d_{trop}: can be modelled using, for example, the Hopfield model. However it is difficult to obtain parameters for this and in the procedures developed a constant delay value on the site must be taken into account which depends on the elevation α with a function of the type $1/sin(\alpha)$.
- *I* : in theory it could be calculated some minutes before the observation, but most of the time it is subject to unpredictable fluctuations. It is normally obtained using modelling parameters inserted in the broadcast ephemeris, or else, more precisely, by means of an a posteriori estimate (after about a week) made by the data processing centres, such as, the *CODE Centre in Bern*.

It is possible to use a model to estimate the values of $\rho,\ cdt,\ I_P\ and\ d_{trop}$ we can rewrite equations (1) and (2) as follows, the terms on the right can be interpreted as residuals of nominal values.

Thus, we have:

$$P_1 - \rho - cdt - I_P - d_{trop} = B_P = cdT + dm_1 + noise \tag{3}$$

$$\Phi_1 - \boldsymbol{\rho} - cdt + I_\Phi - d_{trop} = B_\Phi = cdT + \partial m_1 + noise + N_1\boldsymbol{\lambda}_1 \tag{4}$$

The *bias*, which is the sum of the terms on the right of the equals sign and the errors due to the type of model used are defined as B_P e B_Φ . The scope of this project is to check the quality by analysing the terms B. The methods used were frequency analysis of these residuals and analysis of the filtered values with suitable mobile mean values.

From the magnitude B_P, it is possible to obtain a mean or a weighted mean value of the epoch under investigation, for all satellites. In this case, assuming that mean residual values of multipath and noise are zero, this value well represents the error of the receiver clock, common to all the satellites.

$$M[B_P] = \overline{B}_P \cong cdT \tag{5}$$

Examining the changing value of this magnitude over time it is possible to obtain a more or less precise model of receiver clock errors. The level of precision that can be reached depends on the precision of the clock itself. Normally, acceptable results can be obtained with a rubidium clock or a good quartz clock which are not always present in receivers. When using a receiver with a precise clock it is sufficient to estimate the parameters which define a straight line or, at most a parabola.

The type and precision of the information that can be obtained from these non-differentiated and non- combined quantities was examined and these quantities were then used for quality control and for detecting observation with particular data. In particular when these problems are the insurgence of wide spectrum data noise the situation is beyond repair even using double differentials and the tradition checks do not highlight the existence of the problem. This happened at Turin when a signal from a TV link entered L1, and years later, still in Turin when a caesium frequency generator stopped working and for problems with the rubidium clock.

The detection of which station in a network "swells" the differential treatment is not immediate and occurs only later when the data are being processed.

In the first case mentioned above TECQ analysis revealed a big increase in noise (wrongly interpreted as multipath), while, in the other two cases there was no large variation in the results but they were still useless. The problems were brought to light by using the method proposed in this study, i.e. the analysis of the non-combined quantities B.

3. Virtual Code Stations

So far this study has performed a series of simulations using the daily data from some permanent EUREF stations to verify their possible use for real-time positioning. So far, it has concentrated on the correction of code differentials, signal content and their spatial modellisation. The permanent GPS stations in Italy are potentially capable of supplying differential corrections to mobile receivers but the accuracy of limited by systematic errors such as spatially correlated errors of troposphere, ionosphere and ephemeris, which partly depend on the position of the stations. The distances between stations which can at times be hundreds of kilometres make the precision of the differential corrections unacceptable.

In order to limit *bias* the network stations can suitably model the effect of systematic errors in the approximate position of the mobile receiver, i.e. in a *virtual station* (VRS) very close to its actual position.
This task is concerned with the part of simulation in which the differential corrections were obtained a posteriori, using the files on the observations supplied by the nearest permanent stations. For this task a software was developed which made it possible to calculate and supply differential corrections in real time, compatibly with problems of latency and reception of network data.

The software, compiled in *visual fortran*, meets the specific requirements of the problem under examination: it calculates the orbits of the satellites and performs the absolute positioning exactly by measurement of code pseudorange. In the case of differential positioning it excludes the calculations relating to satellites which are not visible to all the network stations. The program accepts different forms of input:

- Observation files in RINEX. Format
- Broadcast ephemeris in RINEX format and precise ephemeris in SP3 format
- Real-time broadcast ephemeris and raw observations from the receiver via a serial port.

The software also has some interesting functions for data quality control:

- Tracking of satellite elevation and azimuth
- Estimate of receiver clock bias
- Estimate of ionospheric and tropospheric delay
- Estimate of float ambiguity

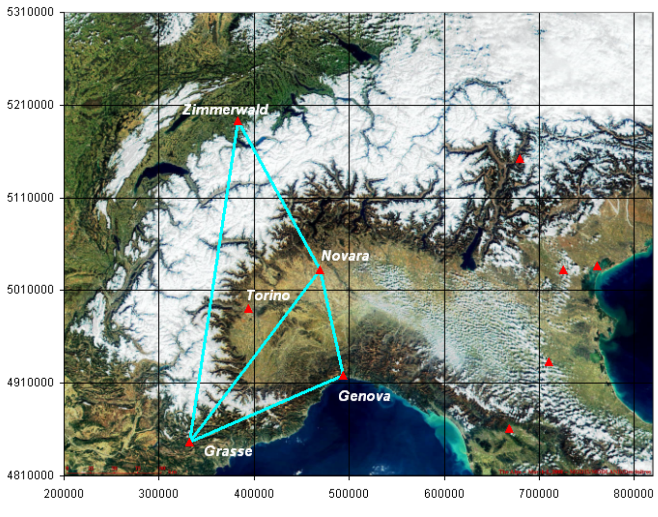


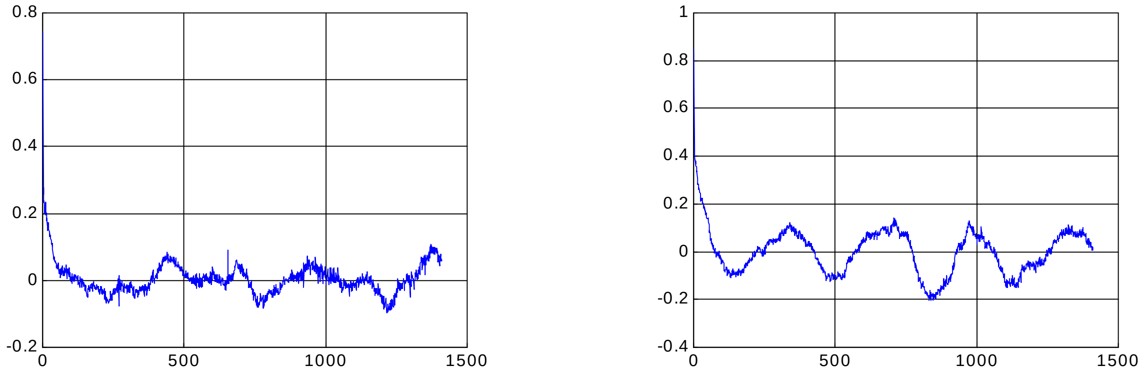
Figure 1 - The network of permanent stations used

Normally, the concept of virtual stations for differential positioning with phase measurement, but, for the moment, we have extended and applied this concept exclusively to differential positioning with code measurement. Plane and altitude errors of the measuring station are directly modelled in space and time.
For the moment this simplifies the problem and it is also makes it easier to use for non professional applications. It can also be considered to be a good initial positioning for a subsequent fixing of phase ambiguity. The study illustrates some applications involving co-ordinate correction. In the

test we used the observations from the permanent stations Novara, Genova, Grasse, Zimmerwald and Torino (fig. 1), first independently and then correlating the corrections of the first four stations in order to obtain the best possible differential positioning of the barycentric station of Turin. The distances involved are in the order of hundreds of kilometres, ten times greater than those used for RTK positioning.

From the calculation of the differential corrections performed by the home-made software and an analysis of the auto-correlation functions of the altitude corrections for Turin, calculated by the other four surrounding stations mentioned above, a signal strength of between 0.3 and 0.8 was noted. Such values indicate that the raw code data might benefit from a filtering process.

The analysis also highlights a correlation length of about 100 epochs and an oscillating course which repeats itself approximately every 300 epochs (two hours 30 minutes). This could be attributed to tropospheric aspects which are common to the differential corrections of all the stations..



a b

Figures 2 - Self correlation of the Δh corrections of Turin calculated by Grasse: a) and Zimmerwald: b)

Further research demonstrated that the correction of a station within the network can be obtained as a linear combination of the corrections of the other stations and that the coefficients can be stationary even for an entire day. For this purpose the least square sequential technique was used.

Finally, two techniques of interpolation, one simple linear method in which the weightings were functions of the squares of the distances and a second, more complex one in which it was the function of the geographical position of the virtual station and was dependent or not on the previous history of the corrections. The ideal instrument for this purpose is Kalman filtering. The second method can be used to its full potential only when the permanent station makes data available at a frequency of one second.

In short, also for differential code corrections it makes sense to speak about virtual stations even for long distances, typical of the current EUREF network. The interpolation of the corrections removes a significant pert of systematic error and increases the precision of the positioning data. It has also been shown that, in such cases, the latency is of little relevance. It has also been found that the can be modelled well with coefficients similar to weightings and that these values are stationary for long time periods (at least 24 hours). It is to be hoped that permanent stations equip themselves to provide data with a frequency rate of one second.

4. The format of the transmission and diffusion of data in real time

The main form at of the transmission of the data studied is version 2.2 of the RTCM format, also because its use is widespread. The acronym means Radio Technical Commission for Maritime Services", which is a non-profit, scientific and educational organisation based in the USA. Since it was founded in 1946, it has been concerned with all aspects or maritime radio communication, radio-transmissions for navigation and linked technologies.

The member countries are Austria, Canada, Denmark, France, Italy, Japan, Norway, Russia, UK, USA and Venezuela.

Work is done by means of "Special Committees" which produce documents known as "RTCM Recommendations". One of these is "RTCM recommended standards for differential GNSS (*Global Navigation Satellite Systems Service*) , version 2.2 published by special committee number 104 on 15/1/1998. These recommendations serve for GPS, Glonass, radiobeacons, pseudolites, etc.

The transmission can use various media:

Radio VHF, GSM, Satellite radio, DAB / DARC etc.

The "radio" transmission of codes and phases (as well as reference time) enables the *rover* to be used and the major mart of many systematic errors to be eliminated, for example:

- *Selective Availability* (1s=30m): abolished in May 2000.
- Ionospheric delay of 20 and 30m during, 3m at night.
- Tropospheric delay: about 3m at the zenith and up to 30m at 10° elevation.
- Ephemeris errors: from 50 cm to 1-3 m max with the use of calculated or predicted ephemeris.
- Satellite clock errors: according to the block to which they belong II, IIA or IIR. Kept to less than 50 cm in all cases by means of the clock corrections reading the SP3 files
- Receiver clock errors: varies according to the type of receiver and the external signal.

The study allowed us to understand the good and bad points of this type of transmission: the potential, what to pay attention to in the diffusion of data, latency times, the complexity and content of every single message.

This format and the other studies described here were the subject of a seminar day held at Turin Polytechnic in which the format and the problems of data diffusion were thoroughly illustrated to researchers from various Italian Universities(Manzino, 2001).

Concerning the points to consider in the construction of a network of virtual stations which transmit messages with this format there are three main considerations to bear in mind:

- remember to synchronise the rover receiver (or the virtual station) with the master permanent station;
- be careful not to "overcorrect" the data (there is no point in modelling the ionosphere or troposphere if the rover uses the same models for reducing bias);
- make sure that the "raw" data is used and not the "smoothed" data;
- make sure that you calculate the ephemeris of the same satellites in the same manner.

Since transmission implies latency, the rover can make clock corrections in two ways:

- by memorising the *pseudoranges* of the epochs preceding the measurements;
- by calculating the position of teh current epoch relative to the measuring position taking into account estimates of velocity.

Thus, the master station does not transmit corrected, data but raw data. Only for the transmission of "type 9" messages, in which the corrections are transmitted to groups of three satellites at a time. (and applies the correction speed also to the other satellites). For low transmission speeds it is advisable that the *reference station* be equipped with a precision clock.

All the format messages, both standard and reserved were studied as were the possibilities of expansion and the difficulties of use linked to the calculation of the corrections in a network of permanent stations.

5. The use of broadcast orbit information and precise orbit information in static and kinematic positioning.

In the course of the research activity, the algorithms for the calculation of the positions of GPS satellites were studied. This study was undertaken for operational motives, to create a software for the processing of GPS data for the generation of differential correction for "virtual station" type applications. It was necessary to consult, compare and interpret various sources in an attempt to bring together in an organic manner all the different processing procedures in order to arrive at a operational calculation procedure.

This is based on the study of reference systems starting with Kepler's orbital elements, available in the navigational message on the transformation of positions in the orbital system apparent to the ECEF system, taking into account the various disturbing effects of orbital

A fundamental first step was the understanding and exact evaluation of different time scales: normally, ephemeris time is treated in a separate manner from the time which is used to correct clock drift. The calculation procedures had to take into account all the conversions necessary for the determination of Julian dates, GPS weeks with relative days and seconds. In particular, to define the epoch of measurement one indicating parameter is not sufficient since a numerical variable, even if it is doubly precise, is not sufficient to pass from the Julian date in thousands of years to a pico-second, which is necessary to obtain the required precision on the position of the satellite and the errors to subtract in the time scale. Other effects were also taken into consideration (which are not considered in all software) such as the relative motion of the earth and the satellites in the propagation time of the signal. In the absence of SA, these effects cannot be ignored. We also studied in detail the standard forms for the transmission of navigational messages. (RINEX, RTCM).

The calculation procedures were implemented in calculation codes (written in visual fortran), and at the moment the are functional and have been verified. Later, a calculation procedure was used that was capable of determining the instantaneous position of satellites starting both from precise ephemeris and rapid ephemeris in SP3 format. These satellite positions are directly available from the ECEF system, generally with intervals of 900 seconds.

To obtain a precise interpolation to the millimetre an orbit integration program is necessary.

However, for time epochs of less than 15 secs it is sufficient to perform a polynomial interpolation

A Lagrange interpolation is applied to the four series of data and the coefficients which are determined can be applied for a long period without needing to be updated.

According to Remondi, for satellites with epoch intervals of 30 minutes a precision of 10^{-8} can be reached with a 9th degree polynomial. While for precision to the millimetre (10^{-10}), a 17th degree polynomial enables us to interpolate within an interval of 40 minutes.

The calculation of the position of the satellites starting from the various formats enabled us to compare precise orbital date with rapid and broadcast ephemeris to evaluate their precision and the degradation as a function of time. When scheduling the measuring sessions, but also for weighting the code and phase observations as a function of the elevation of the satellite, it is useful to be able to predict the visibility of the satellites, i.e. make an estimate of their position and obtain elevation, azimuth and other data relative to a point whose approximate co-ordinates. For such operations it is not normally essential to calculate the position of the satellites with extreme precision, it's thus sufficient to has almanacs of the ephemeris which contain the orbital elements without the correction parameters. The program examined also performs this type of operation. The program was then tailored so that it could use Type 17 navigation messages of the RTCM for orbital tracking by means of real time reading of the data.

In this case the IODC parameter must also be checked to make sure that its value coincides with that of IODE. It is fundamental that reference station and *rover* base the differential calculation on the same ephemeris: if the ephemeris change the technique normally used is that of calculating, for a limited period of time, the differential correction of the reference station based on the old ephemeris, whose transmission in that case is performed by the system. This enables the user to make differential corrections, to use the corrections calculated with the old ephemeris and to use the new ephemeris only when these were used by the base station. Type 17 messages are transmitted every 2 minutes if these conditions persist and until the transmission is corrected or as long as the satellite is in the area covered by the reference station.

6. Problems of acquiring in real time raw code and phase data and orbital data

For purposes linked to the calculation of the differential corrections of code and phase and for their use in a network of permanent stations we studied and partially solved problems inherent to connection and reading of raw data from a GPS receiver of a well-known and widely used brand. In particular, the collaboration with the Italian Subsidiary of the manufacturer of these receivers, a software was developed for the de-codification of some particularly interesting records in RTCM format. Other "home-made" software products were developed for the reading of raw data via the serial port of the above receiver. There is an objective difficulty in obtaining detailed knowledge about proprietary formats and user's manuals are not always very exhaustive. However, currently it is possible to decode broadcast ephemeris directly from the receiver every time they are updated, as well as the raw code and phase data and the differential corrections generated. This, albeit small result enables the procedures illustrated in this summary to be used also in real time.
Furthermore, the communications problems of a low-cost GPS receiver (only C/A code and L1) phase were solved. This is a different, but equally widely used brand and it could be used as a rover receiver.

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- ***Topographic activity for the new permanent station at the Cagliari Observatory***
  (E. Falchi, F. Resta, G. Sanna, G. Vacca)

TOPOGRAPHIC ACTIVITY FOR THE NEW PERMANENT STATION AT THE CAGLIARI OBSERVATORY

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Introduction

The local group research activity has been addressed to:

- the completion of surveys to obtain coordinates and heights in local and global reference frames

- an investigation about world-wide standards and recommendations for establishing and managing a GPS permanent station network

- the realization of a new GPS+GLONASS permanent station in the Cagliari Observatory area.

Here below the main results are summarized.

1. Levelling campaign for the orthometric height determination in the Observatory area

Many measurements involving different techniques have been carried out in the past years inside the Observatory area (SLR with mobile laser system, absolute gravimetric measurements, GPS and classic topographic measurements). It seemed so necessary to complete the knowledge of the site determining the orthometric height of the relevant points in the observatory area. Previously, the orthometric height of the marker 7545 was determined by a high precision levelling survey starting from the 3rd order benchmark of the line 75 along the SS 125 (Cagliari-Sarroch). The altitude of this benchmark is 0.81760 m. The levelling device was an electronic level WILD NA3000 with an invar bar code rod and automatic recording. The survey path was 6800 m long overcoming a gradient of about 183 m. In the same levelling a second point SELF, situated at the same pad of the marker 7545 and materialized with a benchmark, was quoted.
From these two point the levelling survey got the piers RMB1 and RMB2, where the two GPS antenna seat, it also reached the sensors of temperature and r. u. and the pressure gauge. The latter was arranged at the same altitude (± 0.10m) of the GPS+GLONASS antenna Regant-2. The altitudes of GPS piers and meteorological devices were carried out from the ancillary levelling benchmark GPSREFQ. The figure 1 shows the internal levelling point, the table 2 gives the m.s.l. altitudes of the Observatory distinctive points while fig. 3 and 4 show a sketch and a zoomed view of the two pillars.

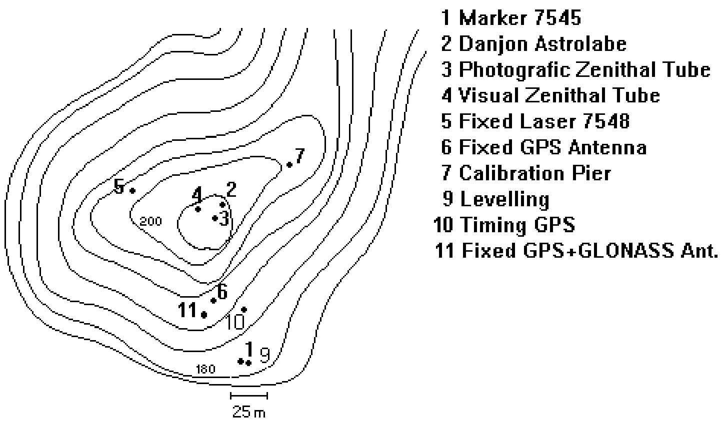

Figure 1 - Sketch of the area with the new GPS+GONASS reference station

Point	Orthometric height
Marker 7545	184.3411
SELF	184.3677
GPSREFQ	190.9406
RMB1	192.7476
RMB2	192.3540
BARREFQ	192.9286
BASE PALO	189.7409

Table 2 - Orthometric heights for points in the observatory area

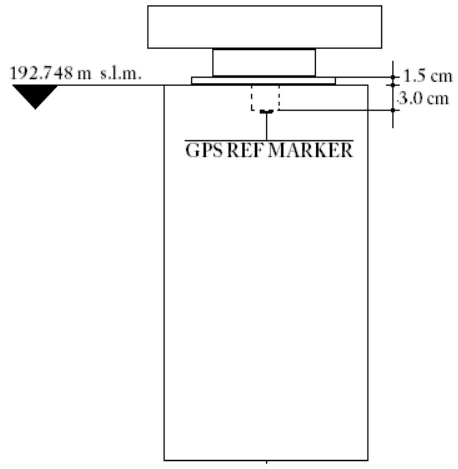

Figure 3 - Sketch and view of RMB1

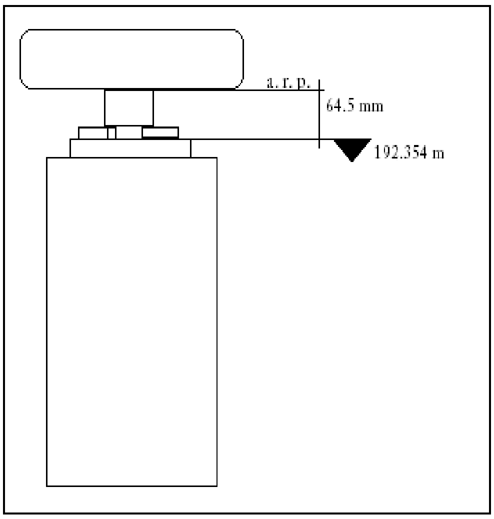

Figure 4 - Sketch and view of RMB2 with the new GPS+GLONASS reference station

2. Report on the standard for the realization of permanent stations

The study has the purpose to supply an help in the realization or specifications for permanent stations. Currently there isn't in Italy a specific normative on the subject so a world-wide investigation has been made by us, furnishing an overview of both the standards adopted and the recommendations on establishing and managing GPS permanent stations (Sanna, 2001). The most important international networks have been analysed searching for the main items regarding standard and technical recommendations. The world-wide IGS and the U.S. NGS have been used as an example. References have been inserted regarding to other networks (i. e. Germany, New Zeeland, South Africa) and to the standard compiled by UNAVCO.
The study is divided in different items discussing the choice of the site, the monumentation, the instrumentation, the connection to the local and global reference frames, the data management and user interface.
For the choice of the site the indications supplied by the IGS, keeping track of the traditional requisite of the trigonometric points so as to the specific indications related to GPS technique, are of interest.
The marker has to fulfil the standard required for the geodetic points of the first order with respect to stability, durability, maintenance for a long time term, documentation and access. The obstructions on the horizon cannot overcome the 15° of elevation, and visibility is encouraged for lower angles where it is possible (at least 7°). In order to prevent all the possible sources of obstruction, must be checked all elements, like buildings or trees, that can be build up after the installation.
The signal quality has be verified, especially in relationship to interferences due to external sources type radar, and for the multipath.
Concerning the foundation of the station preference must be given to materialization on bedrock or on soil. If the marker is materialized on a pre-existing structure, it should be degraded to a lower order. A study carried out by UNAVCO analysed the different types of monument pointing to the inherent problems. From such study emerged that the three-dimensional monument is the best type regarding multipath and the thermal expansion, it offers also an excellent stability while a disadvantage is the difficult installation compared with other typologies. Fig. 5 shows a summary of

Monument type	Multipath	Stability	Thermal expansion	Installation	Usage	Other notes
Concrete Pillar	High (duplicates ground effects)	Good	Low	Deep anchors in bedrock or soil	NGS	Difficult and time consuming installation
Deeply Anchored GPS Monument (UCSD)	Low	Excellent	Very low	Deep anchors in bedrock or soil	Basin/Range (TB installed) and networks in CA (PFO)	Difficult and time consuming installation
INVAR Rod with sleeve	Low	Good	Very low	Anchors in bedrock	Greenland perm. GPS station	INVAR is expensive
NGS Sleeve type monument	Low	Excellent	Very low	Deep anchors in soil	NOAA/NGS	Difficult and time consuming
Stainless steel pin	N/A	Excellent	Stainless steel (7-8 x 10exp-6 in/in/deg F)	Bedrock only	Majority of GPS campaigns	Simple installation

Figure 5- Summary of various monument types used in the GPS community and under development and test at UNAVCO

the study carried out by UNAVCO.
With respects of the instrumentation two choices exist: one is the employment of identical

instrumentation all around the network, taking advantage of the using of equal instrumentation; the second defines minimums requirement that the instrumentation must satisfy. The former is easy to realize when a network is set up from zero by a national agency, the latter comes from the attempt to coordinate the permanent stations managed by individual groups. Different instrumentation is found at IGS or NGS CORS, which are constituted for affiliation.
The least requirements for the instrumentation have been well summarized by NGS:
Receiver:

- Must be at least dual frequency (L1 and L2).
- Must be able to track at least 8 satellites above 10 degrees.
- Must have automatic switching between operating modes to retain full wavelength L2 when AS is on.
- Must be capable of sampling at 30-second interval.
- Must provide:
- L1 C/A-code pseudorange or P-code pseudorange.
- L1 full wavelength carrier phase.
- L2 full wavelength carrier phase.
- Pseudorange accurate to better than 0.5 meter RMS.

Antenna:

- Must be at least dual frequency.
- NGS phase center variability model available.
- Capable of maintaining 1-cm stability.

Regarding the data handling NGS states:

- Data will be freely available for distribution.
- Data must be converted to RINEX 2 format using NGS-approved software.
- CORS will be operated 24 hrs/day, 365/366 days/year except during scheduled maintenance periods.
- Data will be recorded on a 30-second or shorter interval.
- Data will be stored on-line on site or at a central data facility for 7 days.

Finally the user interface has been analysed inspecting the presence of a simple ftp interface or a more user friendly web page with issues regarding the site characteristics, report on the current status or links to other reference stations and so on.
The work has been presented as an invited paper to the 5th National Conference on the Geographic Information (ASITA).

3. The new permanent station GPS+GLONASS

Besides the ASI GPS station, that is the positioning equipment formerly running at the Cagliari Astronomical Observatory (CAO), a new permanent station was placed for GPS and GLONASS observations (Fig. 6).
The first one was established by ASI for geodetics and geodynamics purposes as implementation of space-geodesy based section of the Observatory: here a fixed Satellite Laser Ranging station runs since 1993. But the growing development of the GPS and, now, the GLONASS, also in real time geodetics and topographic purposes, suggested the establishment of a new permanent station, in order to increase and improve the local survey facilities.
In addition to the ASI station purposes, the new station will allow the following tasks:

- admission to the IGLOS network
- facilities for engineering applications (the station carries out observations at 1 second sampling)

- the GLONASS system utilization in urban areas
- determination and forecasting of precipitable water vapor content, parameter required for observation scheduling at the Sardinia Radio Telescope (SRT), in construction not far away from the Observatory
- co-location between the GPS and the GLONASS systems.

Figure 6 – To the left the RMB2 pillar with the RegAnt 2 antenna, to the right the ASI reference station

For seating the GPS antennas, two piers was made inside the Observatory in addition to the internal fiducial points. The new permanent antenna was centred on the pier RMB2, built close the former antenna pier RMB1.
In order to connect the CAO internal fiducial network to the international reference frames and to check periodically the area stability, the local research unit, in collaboration with the CAO staff, established, some time ago, a control network in the surrounding of the Observatory.
As well as the geodetic connections, the international steering committees recommend to implement GPS and GLONASS stations with meteorological devices and internet facilities.
As required an ancillary meteo-rological equipment (barometer, thermometer and r. u. sensor) was installed close to the two stations. The pressure gauge was placed at the same height of the new antenna.
Here the characteristics of the new equipment follow:
- receiver GPS+GLONASS Javad Legacy-E GGD/G with input for external source of frequency (cesium)
- choke-ring antenna Regant-2 provided with protection dome and in-band interferences filtering
- proprietary management software developed on Linux OS.

The researchers plan the standardized production of observation data, surface modelling and essential parameters:

- daily issue of GPS station data, with 1 second rate acquisition and 1 week latency
- issue of meteorological data
- issue of the geoid estimate, experimentally achieved upon the whole of Sardinia
- issue of estimate of transform parameters from WGS84 to Roma40 valuable for the whole island
- issue of routines for issued data implementing on the most diffused CAD.

In the context of the new system establishment, a local server for data dissemination via internet is under construction. The connection will serve, at the same time, a WEB interface and a RTCM communication facility. The WEB pages will allow the observations data download in RINEX format and in selectable time spans. The RTCM facility will concern the real time DGPS correction data logging via cellular phones. Thanks to the acquisition of this new peculiar GPS station equipment, the local research unit, with the other research unit of Cagliari, will be able to establish a permanent station that will be very useful in topographic surveys for a lot engineering and cartographic tasks.

3.1 Determination of site coordinate in global and local reference systems.

In order to make the new station fully operational and available for surveys computing, i. e. to accomplish the above tasks, a series of topographic surveys were realised in the last year. The stations has been connected this way to both local and global reference frames.
A first determination involved the ASI reference station, whose coordinate were derived from the ITRF2000 solution.
Five days of measurements in the 1153 and 1154 GPS week were computed with the Geogenius software to obtain the eccentricities of the new station respect to the old one.
The table 2 shows the results of that computation.

ITRF2000	CAGZ	CAGL	Eccentricities
X	4893380.142	4893378.933	1.208
Y	772650.325	772649.625	0.700
Z	4004179.977	4004182.063	-2.086

Table 7 - Eccentricities of the GPS+GLONASS (CAGZ) station with respect to the ASI permanent station

CAGZ (RMB2)			
	ITRF2000	ETRF89	ROMA40
X	4893380.102	4893380.32	
Y	772650.3193	772650.2121	
Z	4004179.945	4004179.833	
φ	N 39 8 9.19949	N 39 8 9.19267	N 39 08 6.98316
λ	E 8 58 21.92284	E 8 58 21.91695	E 8 58 23.21797
h	238.0078	237.991	
N			4331861.701
E			1497676.411
H			192.3540
N			45.637

Figure 8 - Summary of CAGZ (RMB1) coordinate in global and local reference frames

Using the eccentricities already established between the ASI reference station and the marker 7545, the coordinate of the new station on the ETRF89 has been computed. Finally, applying a seven-parameters transformation, the coordinate in the local ROMA40 reference frame has been produced. The fig. 8 summarize the RMB2 coordinate in both global and local reference systems.

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- ***Applications of GPS for urban GIS and geodetic surveys***
  (G. Caroti, W. Ferri)

APPLICATIONS OF GPS FOR URBAN GIS AND GEODETIC SURVEYS

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Summary

The research, carried out in close collaboration with the University of Trieste, aimed at resuming work started in the past concerning the trajectography of vehicles with GPS and DGPS integrated with DR (Dead Reckoning) and with specific environmental sensors, the experimentations with GPS + GLONASS and geodetic research work. On this subject, we record that for example during the studies carried out from 70's onward on subsidence in the Pisa area, Prof. Palla of the University of Pisa kept to using the traditional survey methodologies, experimenting however from the 80's onward with satellite survey methods.

During the research project we were initially involved in both organising and preparing the necessary preparatory phases for subsequent on-site experiments and collaborating with other Universities with regard to common research areas. During the second phase, on the other hand, we were mainly involved in on-site experiments, data processing and result analysis.

First of all, our Trimble 4000 first series receivers were updated with a GPS system composed of a *Trimble 4000 SSI Geodetic Surveyor* receiver (also configured to work as a permanent station) with L1/L2 compact geodetic antenna, and the relative data processing software. The new Trimble Placer/DR system was purchased.

This instrumentation, together with our others (4000 SE receiver, our Department's 4x4) or in use (previous Placer/DR instrumentation), represents a sufficient operational working unit to continue the work in the navigational (trajectography) and geodetic field.

Part of the study and research aimed at gathering information on the possible integration of integrated satellite systems with cost-effective inertial navigation systems (INS) for use in urban Territorial Informative Systems.

Tests were carried out to evaluate the precision and the operativeness of these systems located in the urban area and in areas with different types of vegetation.

Indeed these areas are particularly interesting for the creation of an urban GIS geographical data bank. As are the problems related to the arrangement of cartographic surveys carried out with traditional instrumentations both in raster to be georeferenced and vectorial format.

Since the GIS requires a fast and cost-effective acquisition of data, the dynamic applications of the GPS are particularly important. Consequently the GPS can be seen as a "digitizer" and in this sense the close connection between GPS and GIS for data acquisition and updating is evident.

In particular the use of the GPS and/or of the GPS + GLONASS during the realisation and updating of the geographical data bank appears to be economical compared with traditional survey techniques (some of the causes of the unsuccessful realization of a GIS are to be found during these phases): the two survey procedures (static and dynamic) makes it possible to position points and trace trajectories.

For example, just think about the need of creating or updating small-scale thematic cartography or about areas without cartography, the plotting of places on land (road nets, service nets, use of the

ground etc.), the requirements of automatic vehicle location (bus, truck,.. etc.), the survey of atmospheric pollutants using motor vehicles equipped with special sensors, etc..
The experiments aimed at studying both positioning in environments with low satellite visibility and at surveying road geometries and street fittings as well as surveying atmospheric pollutants. This sector includes the experimental surveys of road sections on the arterial road Firenze-Pisa-Livorno, the trajectories covered by vehicles in the urban and extra-urban environment so as to realize a specific cartography, the studies carried out for the use of GPS/DR methodologies in woody areas (*Tenuta di S. Rossore*) or characterized by scarce satellite visibility (urban areas and old town centres) and the survey of atmospheric pollutants in Pisa with carbon monoxide sensors (included in the 5th Conference of the *Regione Toscana* on the environment 21/22 January 2000, Florence, "Dynamic atmospheric monitoring of pollution using the differential GPS", G. Caroti, S. Greblo, G. Manzoni, R. Pagurut).
During the research project a liaison began with the Department of Civil Engineering at the University of Florence regarding the GPS permanent station in Prato and its possible use. During the final stage of work at the station, we presented a seminar held in Prato on 17.12.99 (lecture by Dr.ssa G. Caroti on the theme "*Prato station: perspectives of use in the scientific research*"). The mutual interest in some research work resulted in the combined participation of the GPS measuring campaign aimed at controlling existing nets but also at planning and realizing an experimental polygon to be surveyed with various methods: with traditional methods and with GPS measuring campaign using the permanent station as a reference as well. There has been a cooperation with the Applied-Science Faculties of Milan for the realization and measuring of a GPS altimetrical net in the Pisa plain sharing datum points with the net established and measured at geometric levelling during the autumn winter 1998-1999. This made it possible to process and analyse the data obtained.

We report the outcome of the studies carried out on the experimentations concerning:

1. Integrated GPS with low-cost inertial systems: Placer/DR.
2. Real-time differential methodologies with radio link.
3. Location of road vehicles with GPS and GLONASS.
4. The control of subsidence in the Pisa plain with GPS measuring
5. A levelling network in the Pisa plane: a laboratory to test instruments and methods

1. Integrated GPS with low-cost inertial systems: Placer/DR

The most economical DR (Dead Reckoning) system is composed of an angular speed sensor with a piezoelectric gyroscope and of an odometer with impulse-counter. The azimut $\Delta\alpha$ variation (heading) is obtained by means of a piezoelectric gyroscope.
The experiment was carried out on stretches with various environmental conditions giving rise to GPS signal obstruction; for instance, in the pinewood of S. Rossore, Pisa (Caroti et al, 1997) where drifts of different entity are found for different causes (different motor vehicle have been used with different positions of the inertial sensor, there are different types of plants, there are thermal effects).
The most notable case of drift was analysed on this stretch using the general method of the least squares and conic approximations (Caroti, 1997). Surveys with GPS + GLONASS were carried out on the same stretch as well.
Urban and extra-urban roads were covered still in the field of tests carried out with satellite systems integrated by inertial systems. The comparison between these systems shows that the signal is frequently lost in town rather than out of town and what influence the presence of coniferous trees have on roads, as shown on the stretch of urban road in Via Giovanni Pisano and Via S. Jacopo (Figure 1) and in Via Calcesana (Figure 2) out of the city. These tests were carried out with non-

differential GPS system: the translations observed in the trajectory are due to variations in the satellite constellation used, because of the obstruction by buildings.

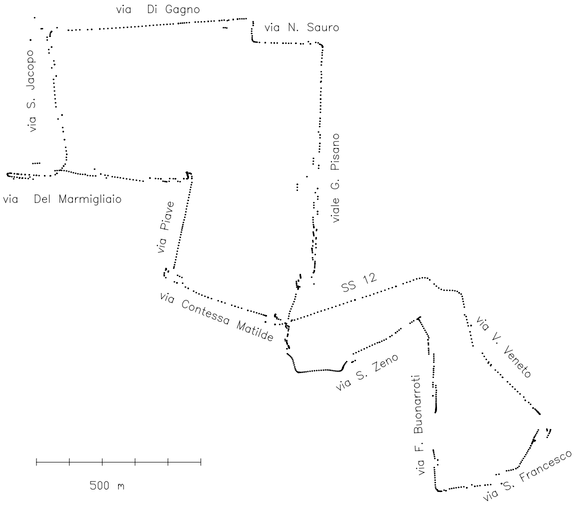

Figure 1 - City road (Pisa, old town centre)

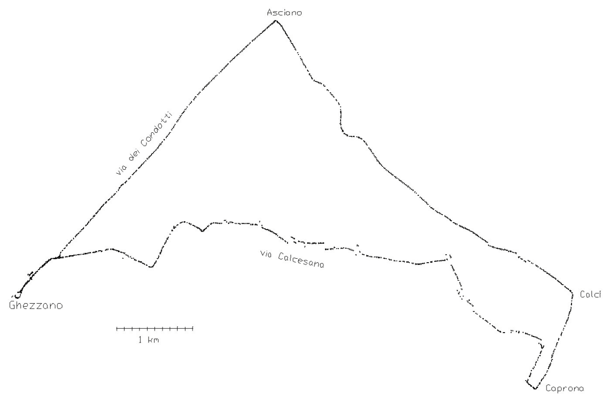

Figure 2 - Roads out of town (Pisa)

2. Real-time differential methodologies with radio link

The radio link was tested in Pisa with the master *Cetena Gruppo Fincantieri* of Genoa (long waves band, typical of radio-beacons for nautical navigation), but unfortunately this signal was received in Pisa only very intermittently and therefore it was impossible to use it. It was also tested in Milan, within the tests carried out for the positioning of trees inside the Lambro park with the IFAG master placed at Maiflingen, near Frankfurt am Main. The University of Trieste is equipped with a radio-receiver for this type of signal which was used in this experiment.
The radio-receiver of the Maiflingen RTCM data was connected to a 4000SSE Trimble geodetic GPS receiver fitted with serial input in RTCM code. During the entire static observation period, approx. 2 hours, the reception was not interrupted making GPS differential positioning possible.
A short test with the vehicle in motion was also tried but this suffered from electromagnetic disturbance of the vehicle engine that obstructed the signal received from Maiflingen (this signal is emitted to be used in Germany and is therefore weak in the North of Italy). In order to obtain a differential datum it was also necessary to stop with the engine switched off. The points surveyed in this way are reported in the chart. (Figure 3)
On the contrary, a Trimble GPS Placer receiver was used to obtain a trajectory at any rate.

3. Location of road vehicles with GPS and GLONASS systems

Satellite methods have been used for a long time to locate road vehicles. This system is convenient and cost-effective in highways and in open areas. In towns and in wooded areas and if a greater precision (of the meters) is required, the instruments and the protocol of use must be chosen with care, also taking into consideration the availability of differential correction services.
This is now common, but in practice it is essential to verify at what level of reliability the theoretical principle can be realized and applied to problems of topographical survey where a great productivity is required to guarantee its cost-effectiveness. It is referred in particular to surveys of road axes in urban areas, to environmental thematic cartography using polluting gas sensors installed on moving vehicles, to the survey of watercourses and similar applications.
For this purpose, tests were carried out under various environmental conditions, all critical for using the GPS method accurately, at least, of the meters.

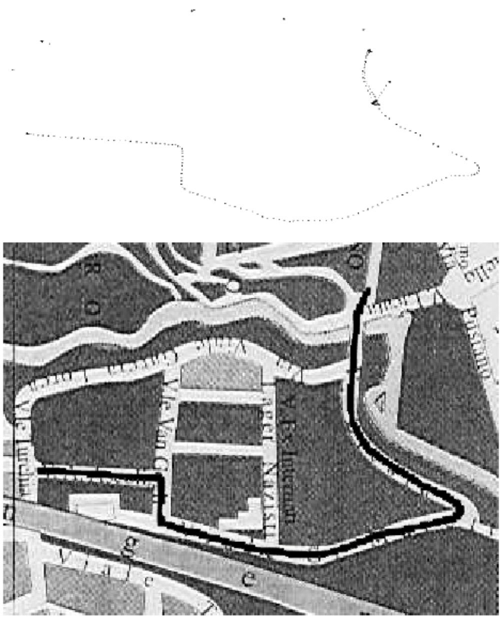

Figure 3 - Survey of the Parco Lambro in Milano

In particular, it dealt with the urban centre of Trieste and Pisa, of the Pinewood of S. Rossore. The Trieste-Venice highway was taken for comparison.
The following instruments have been used:

- GPS+GLONASS, Ashtech GG24 receiver without differential corrections;
- GPS, PLACER single receiver integrated with odometer and angular accelerometer gyroscope;
- as above but without odometer and gyroscope;
- as above but with differential corrections received by satellites for telecommunications, RACAL system;
- as above but with differential corrections received by mobile telephone; the corrections were produced by an extemporaneous local reference station and instead in the telephonic fixed net system.

The following figures show some trajectories obtained with one of the above methods superposed on the technical cartography used.
Figure 4 shows a trajectory recorded in Trieste, at the University, with differential Placer/DR through ETACS telephone connection.
Figure 5 shows a trajectory recorded in Trieste, at the University, with differential GPS+GLONASS while Figure 6, Figure 7, Figure 8 show the trajectories recorded in Pisa at the Farm of S: Rossore with non-differential Placer/DR and GPS+GLONASS.
Figure 10 represents one of the attempts at differential Placer/DR carried out in Pisa with ETACS mobile phone with master in Viale Giovanni Pisano; the continuous arc of the trajectory (in green) on the Lungarno is in differential.
To make a comparison, as has previously been mentioned, the Trieste-Venice highway (Figure 9) was chosen, which is in any case, a disturbed environment for satellite methods because of the passage of buses and trucks and of electromagnetic disturbances caused by engines.

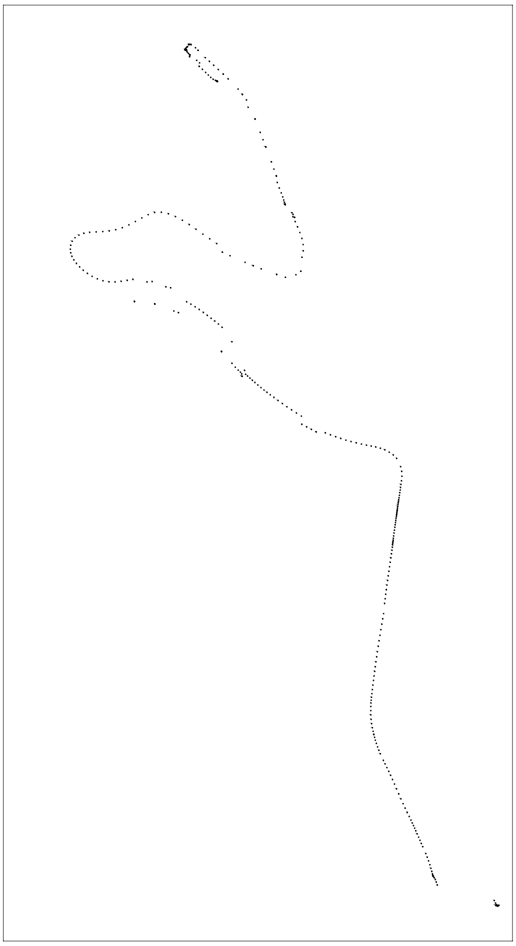

Figure 4 - Trajectory recorded in Trieste, at the University, with differential Placer/DR using ETACS phone connection

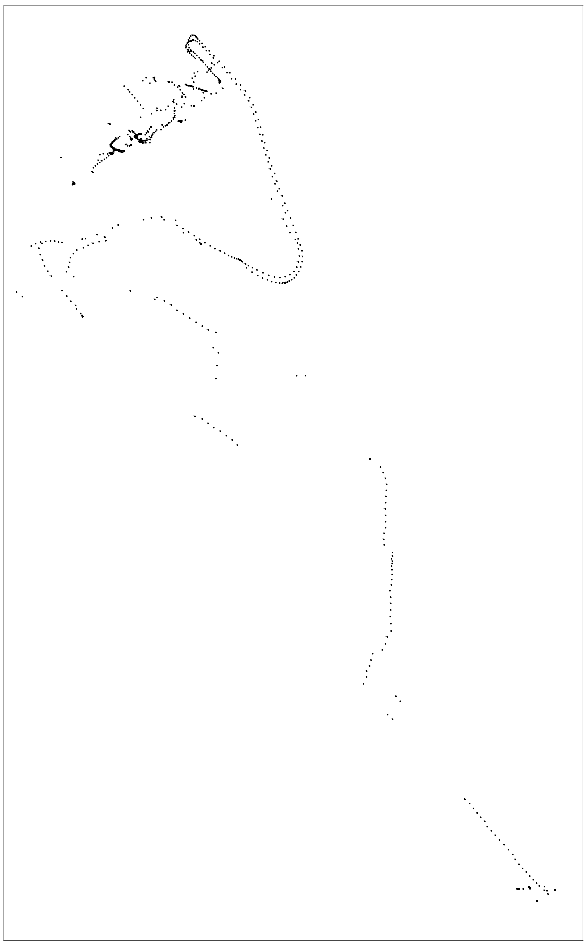

Figure 5 - Trajectory recorded in Trieste, at the University, with differential GPS+GLONASS

Figure 6 - Trajectory recorded in Pisa, at the Farm of S. Rossore (quadrilateral Via della Regina, Via Prini, via del Gombo, Viale Cascine) with non-differential GPS+GLONASS

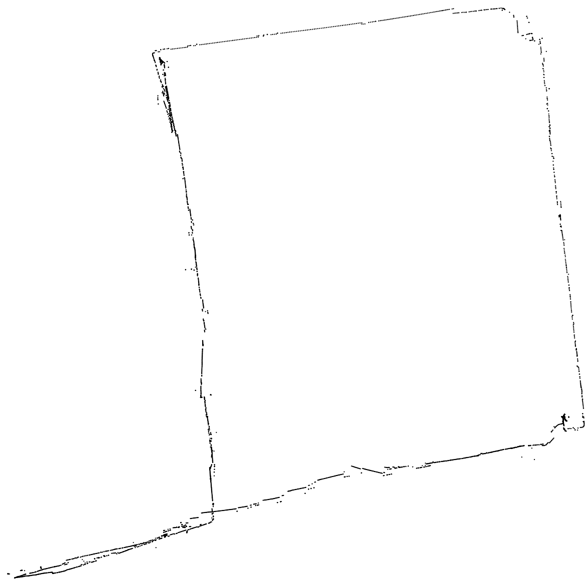

Figure 7 - Trajectory recorded still at the farm of S. Rossore (quadrilateral Via della Regina, Via Prini, Via del Gombo, Viale Cascine) with non-differential Placer/DR

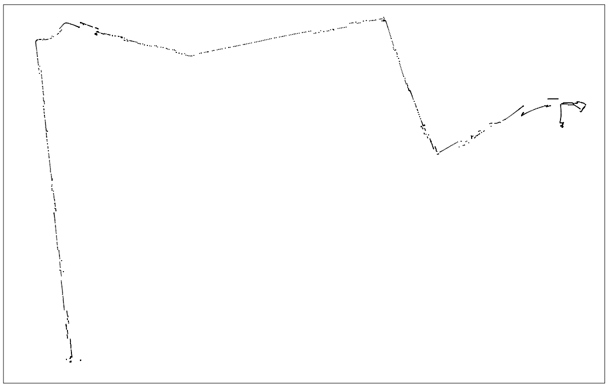

Figure 8 - Trajectory recorded still at the farm of S. Rossore at the exit from the Park with non-differential Placer/DR

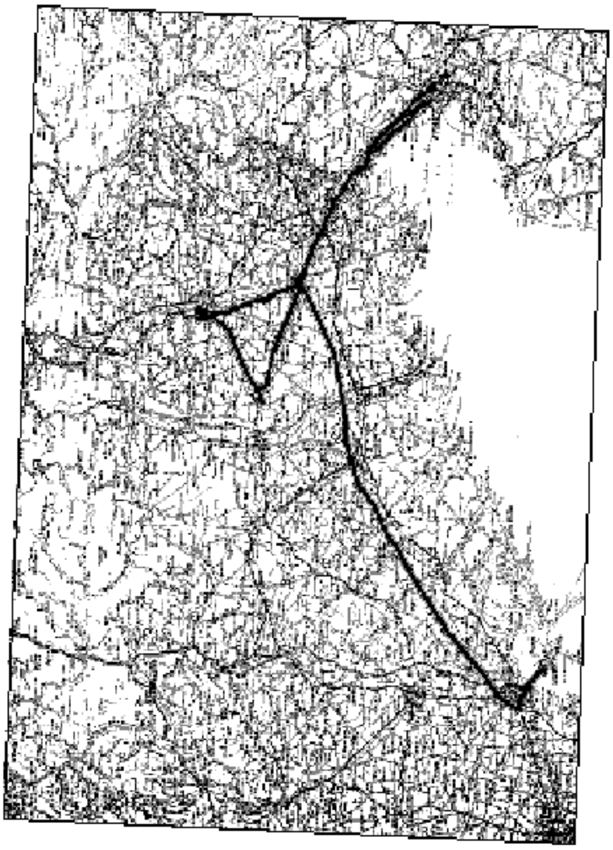

Figure 9 - Trajectories recorded on the Trieste - Venice highway (the junction surveyed is in the area of Palmanova) and on some stretches of the main road with non-differential GPS+GLONASS and with Placer without DR but differential with RACAL satellite system

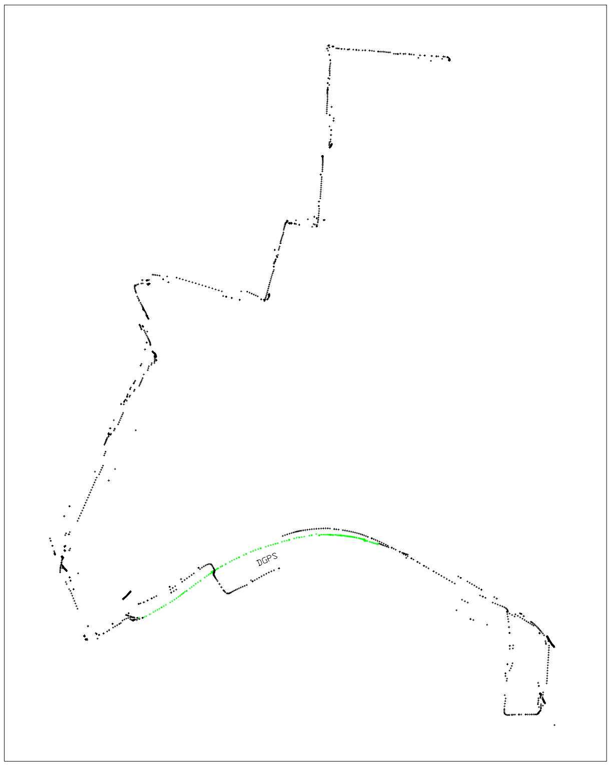

Figure 10 - Trajectory carried out in Pisa: it represents one of the attempts at differential Placer/DR with ETACS mobile phone with master in Viale Giovanni Pisano; the continuous arc of trajectory on the Lungarno is in differential

Figure 9 shows the superposition of the recorded trajectory with non-differential GPS+GLONASS equipment and the trajectory surveyed with differential GPS with the RACAL system. The location has been made with frequency of 1 Hz.

Losses of signal and transversal jumps are observed due to overtaking and due to the presence of bill boards, but in general the trajectories are correctly positioned and overlapped, with errors limited to 15 meters.

In conclusion the experiments carried out show that metrologically all the methods respond to the characteristics required: the non-differential GPS+GLONASS method is more reliable and precise than the GPS one, as was expected according to the two system's specifications cited. The differential method from RACAL telecommunication satellites is precise and reliable on the highway, but in the urban area it suffers from interruptions due to the presence of buildings. The differential method with mobile phone is precise, but suffers from interruptions in the connection, requiring the experimentation of more advanced and automatic methods of terminal management.

4. Subsidence control of Pisa plain with GPS measures

Pisa plain was, at least in the past decades, subject to a strong subsidence of mainly anthropical nature.
In 1996 some researchers of the University of Brescia and the Applied Science Faculty of Milan founded a GPS control network to evaluate the possibility of applying this method to the analysis of subsidence phenomena.
In February 2000 this network was measured again by a group of researchers of the Applied Science Faculties of Milan and of the Universities of Pisa and Parma to evaluate the entity of the altimetrical deviations in the four-year period 1996-2000.
Having evaluated the condition of the net measured in 1996, of which only two of the 12 data had been destroyed, the execution of a new campaign has been considered feasible.
Table 1 reports the parameters of the projected net, compared with those of the net in 1996.

	1996 network	2000 network
Number of bases	39	44
Local minimum, mean and maximum redundancy	0.312 0.718 0.873	0.681 0.750 0.842
Mean value of the error ellipsoids differential shaft of the coordinates φ and λ and confidence interval of the coordinate h compensated [m]	0.033 0.026	0.026 0.020
Mean value of the reliability ellipsoids differential shaft of the coordinates φ and λ and reliability interval of the coordinate h compensated [m]	0.042 0.137	0.021 0.026

Table 1 - Comparison of the networks projected in 1996 and in 2000

Having to later carry out a comparison with the figures of the measured vertexes in the first campaign, a common method was defined for data treatment to be applied both to the old and new measurements. The bases have been calculated using two different programs: Geogenius commercial software version 2.0, which adopts single-base mode, and Bernese scientific software version 4.0 which is able to solve in multi-base mode as well. The bases thus obtained were then offset – compensate using NETGPS. The calculation of the 1996 bases with Geogenius has given slightly different results from those obtained with Geotracer: the RMS of the bases' components are between 7 ÷10 mm. inclusive, while the Geogenius sqm estimate was more negative (and possibly more realistic). Network compensation was carried out still fixing point 50 (Piazza dei Miracoli) and obtaining several co-ordinates in the order of 2÷3 mm.
As regards the treatment of the bases with Bernese software, the results have highlighted two types of problems: the lack of precision of the measurements carried out during some reduced duration sessions; a network plan little suited to multi-base type treatment because of the presence of many sessions containing bases of non-uniform length. These considerations have highlighted that Bernese software is not very suitable for the treatment of data coming from a network which has not been designed for it. For this reason the 1996 network results obtained with this program have not been used for the research continuation as they were imprecise and unreliable.

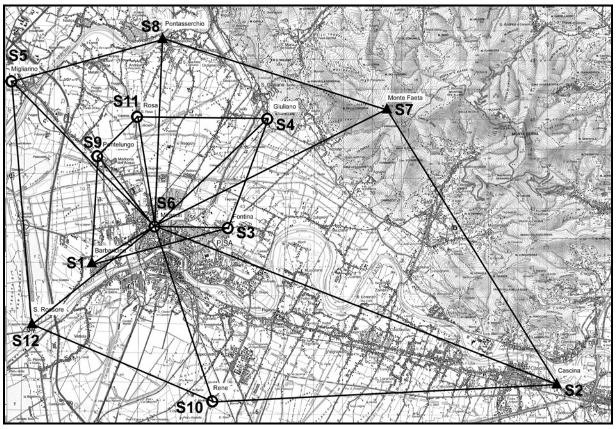

Figure 11 - GPS network vertexes and the 2000 campaign measurement chart

The designing of the 2000 network was aimed at optimising the statical control parameters as well as the precision and logistic aspects which had already been accounted for in the 1996 one. Several network models have been analysed for this purpose, among which a "star" one has been chosen (see chart in Figure 11), which adapts well to Bernware software processing.
The treatment of data obtained in the 2000 campaign have been treated in the same way as the 1996 ones. The results of the baselines calculation obtained with Geogenius have shown much repetitiveness in the two measurements of the same basis and of the variances of the better components of those obtained in 1996. The bases were then compensated with NETGPS. The Bernese treatment has supplied some very similar sqm values of vertixes co-ordinates to those obtained from bases calculated with Geogenius. This still further confirms the hypothesis of the lack of reliability of the results obtained from the 1996 data using Bernese.
After defining the coordinates of the network vertexes and the related square metres in the two periods, 1996 (Geogenius) and 2000 (Geogenius and Bernese), the differences were subjected to a statistical analysis using the Fischer test. Before doing this analysis, the networks were reported in the same reference system using the least squares estimation of one transformation corresponding to the points of the two networks compared.
The first analysis concerned the two networks treated with Geogenius in 1996 and in 2000, which highlighted minimal differences in planimetry, never exceeding 2 cm and greater than 1 cm only in two points. Differences in quota are more variable, but the Fischer test does not show any significant deformation. Therefore, it can be said that with the accuracy obtained with this GPS network it is not possible to highlight deformations smaller than 3 cm.
The second analysis concerned the comparison of the results obtained with the two types of software applied to the 2000 network. Although planimetric variability is low, altimetric ones are a lot higher. In particular the 903 point (Mountain Faeta) has a difference of 6 cm. Since statistical tests never showed any great errors, this result is considered as being the fruit of a different interpretation of the tropospherical parametres from the two programs. They have a greater influence on this point's quota determination because it has a $\Delta h \approx 800$ gradient in comparison to the other network points, located in the Pisa plain.
In conclusion, the aim of this work has been, first and foremost, to highlight some general aspects regarding the study of deformations using GPS instrumentation. The treatment programs of GPS data considerably affect the final results. This fact shows the necessity of analysing all the data with the same program. It has also pointed out that accurate network planning is essential to obtain the precision required. As regards the control of subsidence in the Pisa Plain, it can be stated that the phenomenon over the last four years has been less than that predicted at the end of the 1996 campaign. This hypothesis has been confirmed both by recent levelling measures and by a comparative analysis of the GPS measure results.

5. A levelling network in the Pisa plane: a laboratory to test instruments and methods

This work presents the results analysis of a GPS measuring campaign carried out in February 2000 in the Pisan area by researchers from the Universities of Pisa, Parma, Perugia, and the Applied-Science Faculties of Milan.
The area measured has for years been subjected to altimetric controls both with traditional instrumentation and with GPS methodologies.
The processing results of GPS measures obtained with different processing programs are analysed in the report. The effect of use of precise and transmitted ephemeredes is analysed in one of these programs.
The processing results of GPS measures are analysed in this work, in WGS84 geocentric Cartesian coordinates, carried out with different processing programs, using in particular GPSurvey, Geogenius, Geotracer, Bernese software. The influence connected to the use of precise and transmitted precise ephemeredes is evaluated as well.
The compensation of baselines was carried out with least constraints, keeping Miracoli point of known WGS84 coordinates fixed.
A first comparison was carried out on the results obtained from the Gpsurvey processing using precise and transmitted ephemeredes
Figures 12 shows graphically the comparison between the station coordinates. In general, it has been noted that the deviations are not very sensitive (the greatest values are of 3 mm).

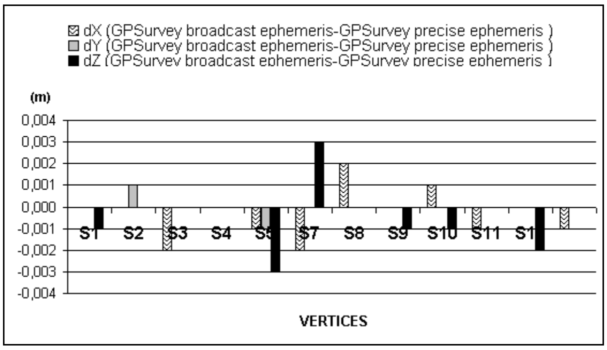

Figure 12 - Deviations on vertex coordinates obtained with data processing using GPSurvey software and transmitted and precise ephemeredes

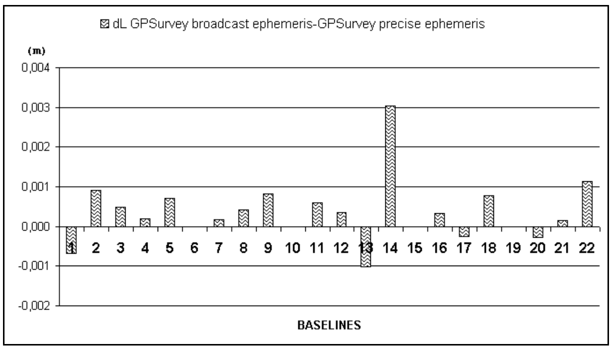

Figure 13 - Deviations among vertex baselines obtained with data processing using GPSurvey software and both transmitted and precise ephemeredes

Figures 13 shows deviations between the values of compensated baselines. The differences are of approx. 1 millimeter except for the base 14 which has a value of 3 mm; this is also the greatest deviation value.
The results of the processing using the types of software under consideration, were analysed evaluating the deviations both of the compensated coordinates of the network vertexes and of the compensated baseline values.

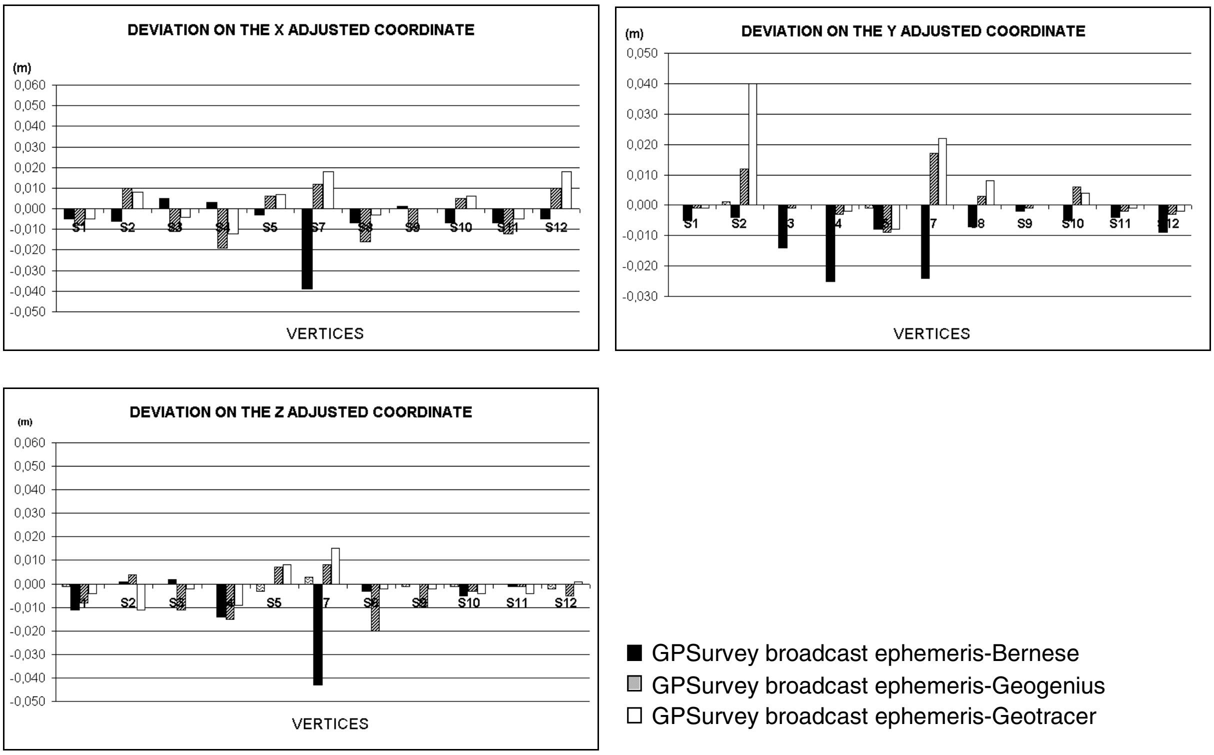

Figure 14 - Deviations on the compensated coordinates compared to GPSurvey

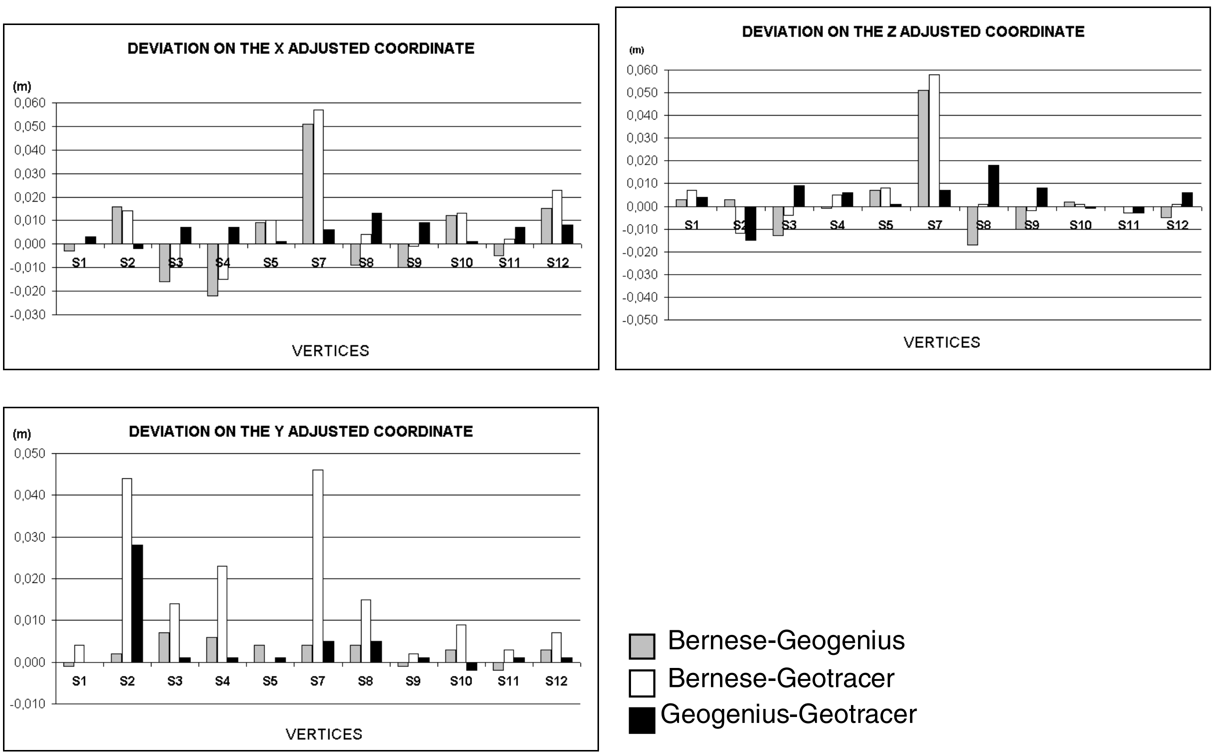

Figure 15 - Deviations on the compensated coordinates between other types of software

The analysis of diagrams of Figure 14 and Figure 15 relating to compensated coordinate deviations of the network vertexes show how such values come within a few centimeters. They are particularly evident on station 7, Mountain Faeta, which is located at approx. 850 meters contrasted with 50 - 60 meters the other vertexes.

The baseline values shown in Figures 16 and 17 also present various discrepancies between 1 and 5 cm.

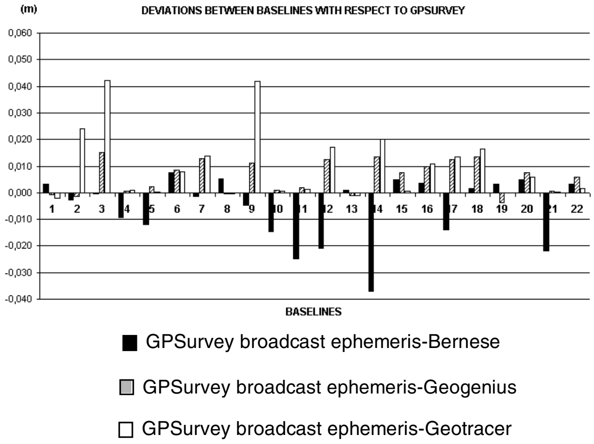

Figure 16 - Deviation between baselines compared with GPSurvey

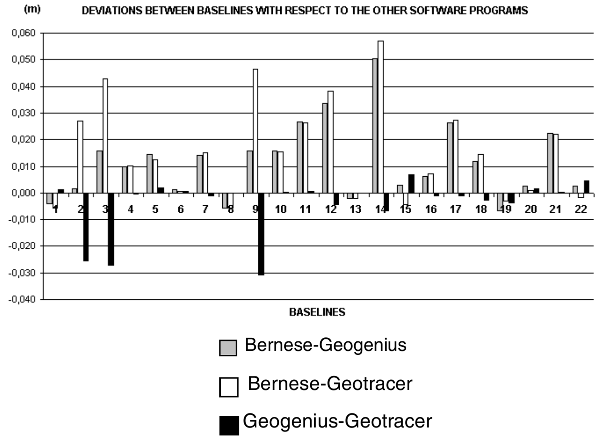

Figure 17 - Deviation between baselines compared with other software

For a global view of the result differences found in using the various software programs, Figure 18 records the global deviation from the various comparisons. In general the deviations are greater between Bernese and other software (the worse case occurs between Bernese and Geotracer), while other analyzed situations are almost equivalent.

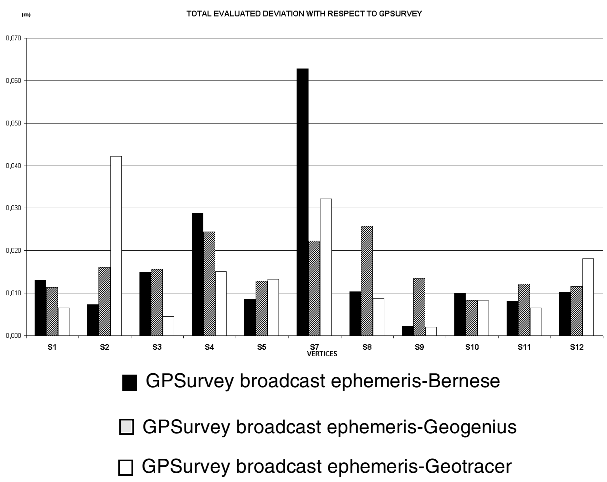

Figure 18 - Total evaluated deviation with respect to GPSurvey

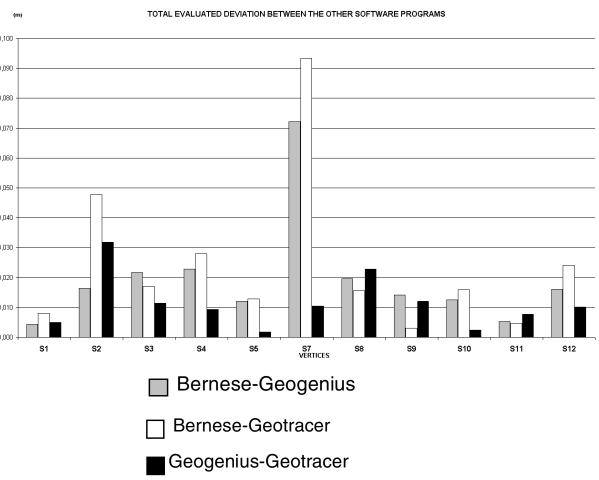

Figure 19 - Total evaluated deviation between the other software programs

It was also decided to evaluate what the results would be using the permanent station at Prato as a fixed point, as well as the Miracoli vertex, which is barycentric to the network. The Prato station is approximately 60 km from it (see Figure 20).
The processing was carried out with GPSurvey and transmitted ephemeredes. The deviations between baseline values range from a few millimeters to 2 cm and are all positive. The differences on the coordinates are the same size while global deviation ranges from 0.5 cm to 4 cm.

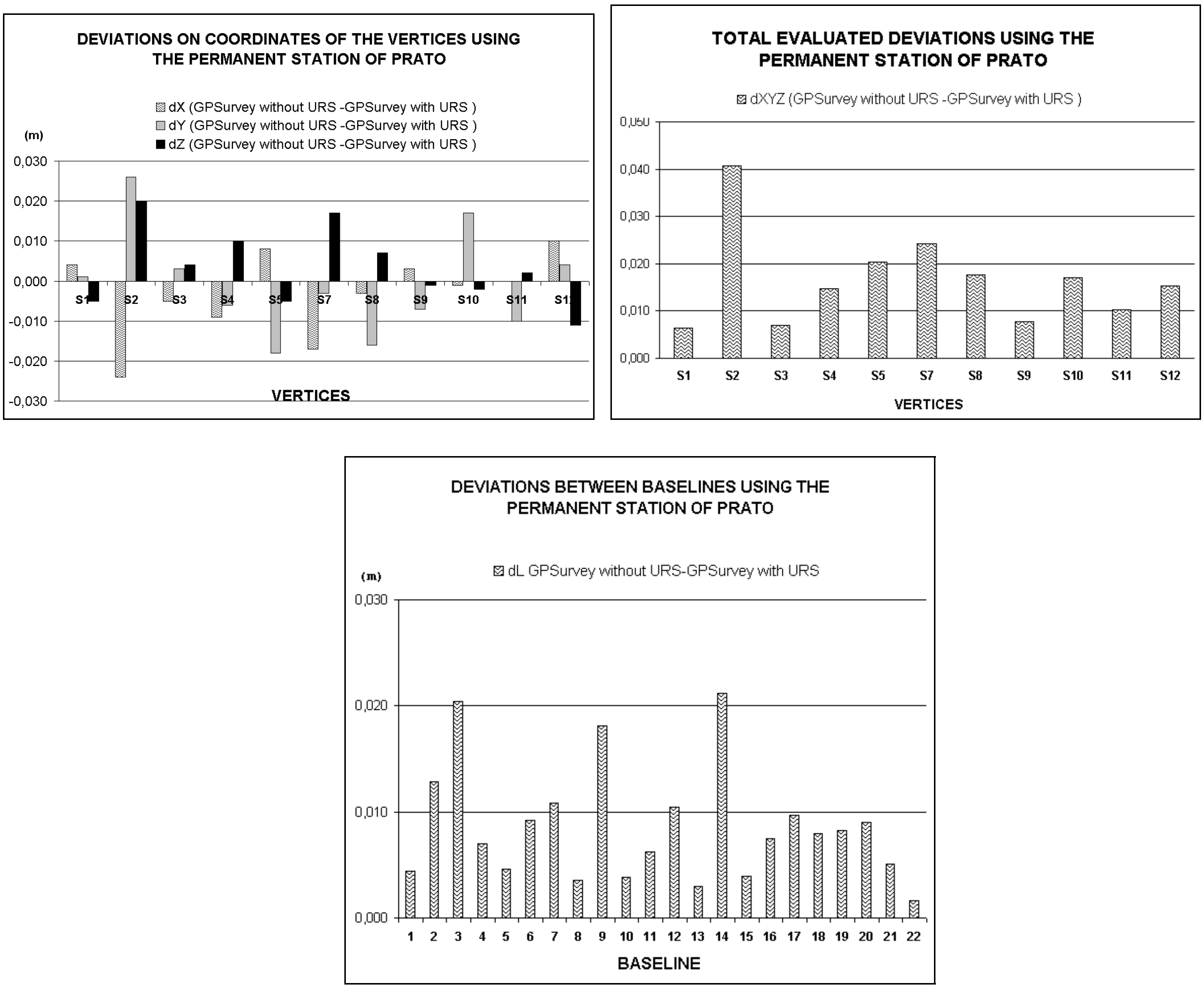

Figure 20 - Deviations, total evaluated deviations on co-ordinates of the vertices and between baselines using the permanent station of Prato

Conclusions

The differences of the results obtained by processing the measures with various software types show that the worse situation occurs between Bernese and the other softwares. This could be due to the different parameters, in particular atmospheric refractivity, that Bernese gives the operator. This will be object of close examinations.
In the other cases, the explanation can be sought in the different computational method of the baselines used by the various software.
However it can be concluded that in the monitoring of ground movements with repetition of the measures, it appears advisable to always use the same software (and the same computational options), the same network scheme, the same sessions and the same calculated baselines, the same atmospheric parameters, in particular the default ones, if the environmental variations cannot carefully be measured (for example with aerostatic probes). The introduction in software models of air temperature and pressure values measured in earth stations which may be affected by particular situations on the ground (for example thermal inversions) may lead to the onset of errors and therefore cannot represent the situation at an altitude, a more frequent repetition of the most different measurements under meteorological conditions, in such way that the effects of the refractivity variations, which cannot be measured adequately, may be treated as stocastic errors (Manzoni, 1986).

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- ***The GPS permanent station in Prato: its use for geodetic applications***
  (P. Aminti, F. Costantino, F. Sacerdote)

THE GPS PERMANENT STATION IN PRATO: ITS USE FOR GEODETIC APPLICATIONS

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Introduction

The GPS permanent station of Prato was established in 1997 on the initiative of the Civil Engineering Department of the University of Florence and of the PIN of Prato. Owing to its position, it is important both for local surveying applications and for a precise definition of a reference frame in Italy.

Its purpose was mainly for scientific applications, both for geodetic investigations, in connection to other permanent GPS stations belonging to regional networks, and for engineering studies, as for example as reference fixed station for kinematic road surveys. In addition, data with acquisition rate 5’’ and 30’’ are freely available via ftp, to be used for professional surveys.

The receiver used is Trimble 4000SSI; the antenna is Trimble Choke Ring, located on a concrete pillar on the roof of the building of PIN. This site provides both a good covering of the sky and a good quality of the received GPS signal, with a very low multipath and a rate of registered observations for elevations above 15^0 always larger than 94% and most frequently larger than 98%.

Station positioning. Remarks on reference frames

The first determination of the position of the station was carried out in 1997, by connection with two benchmarks of the IGM95 GPS network, located inside the IGM area in Florence, at a distance of about 15km. The resulting adjusted coordinates were

$$\varphi = 43^0 53'08.0114''$$
$$\lambda = 11^0 05'56.8452''$$
$$h = 120.115$$

with a rms of a few mm on horizontal components, and of about 1cm on height. The reference frame for IGM95 is EUREF89.

Since 1999, the station has been permanently connected with the ASI Center in Matera, and data are automatically transmitted every day to the GEODAF data base. The first solution was computed by the Matera Center in March 1999; the coordinates obtained were

$$\varphi = 43^0 53'08.020482''$$
$$\lambda = 11^0 05'56.851444''$$
$$h = 119.8959$$

Subsequently weekly solutions have been produced by ASI; they can be found in the GEODAF web site, even though the station is not yet officially inserted into the EUREF network. Furthermore, weekly solutions for the Prato station are also produced by the University of Padua.

The time evolution of the ASI solutions, that are expressed in the ITRF reference frame, since the beginning of 2000, is reported in Fig.1-3; it clearly shows the motion of the European plate in the ITRF frame (see for example Gatti and Stoppini 2000). Indeed, it can be seen that other European stations exhibit a similar evolution, whereas baselines are stable in time. Obviously, a similar evolution is exhibited in Padua solution. A systematic analysis of these motions for EUREF stations is illustrated for example in (Becker et al. 2000).

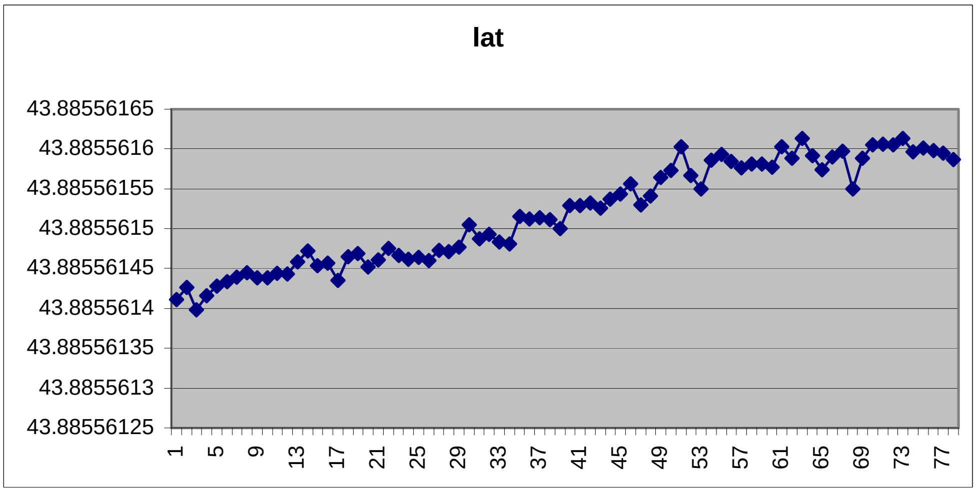

Figure1 – Time evolution of the station latitude (weekly solutions from the beginning of 2000)

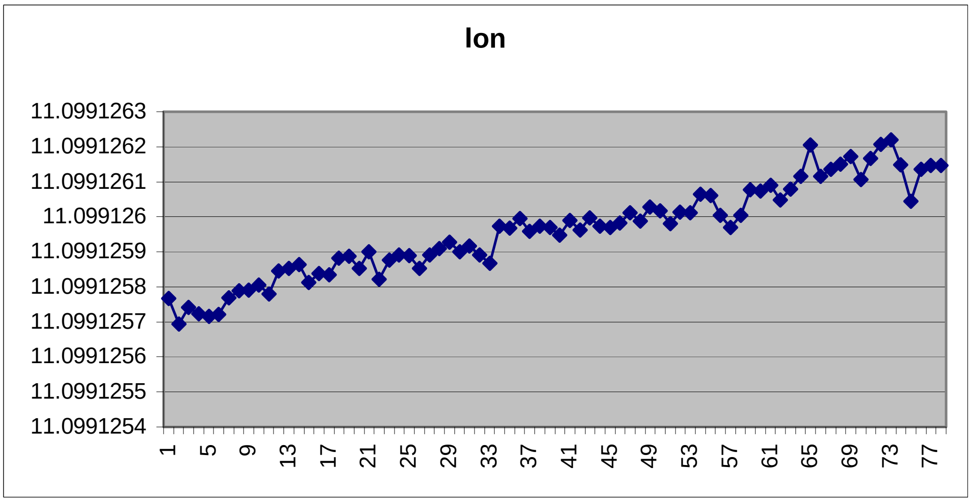

Figure 2 – Time evolution of the station longitude

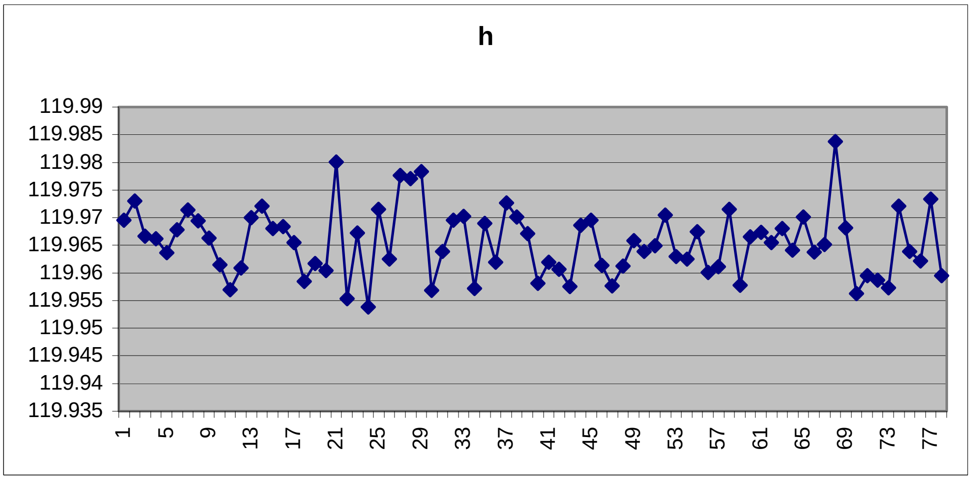

Figure 3 – Time evolution of the station ellipsoidal height

The existence of a network of high quality permanent GPS stations is obviously an essential condition to establish a reliable regional reference system, suitably connected to continental or global systems. In Italy the number of stations contributing to the network is still quite low and, furthermore, their distribution is not optimal. In addition, in view of the use of the network for geodynamical investigations, most sites do not ensure the required stability. Therefore, further work should be done both for the densification of the network and for new studies on data analysis procedures.

Scientific activities involving the Prato GPS permanent station

As remarked in the introduction, a permanent station can be widely used as a fixed reference point for local surveys, both for technical and scientific purposes. In particular, the Prato station gives support to professionals operating in the area; furthermore, in the field of scientific investigations on engineering applications of GPS, a project in cooperation with the Pisa University for kinematic GPS road surveys (within the MURST national project "Assembling, experimentation and application tests of a high productivity surveying vehicle with real time differential GNSS positioning integrated with precision INS and equipped with digital cameras and laser scanner") is in progress.

As regards geodetic applications, the Prato station has been used as reference point for a local network established in order to check the height datum in the Florence area, as a part of more general project on the geodetic use of permanent GPS stations integrated by GPS networks. A similar campaign in a different area has been carried out by a research group from Perugia University, using the Perugia GPS permanent station. The motivation for such investigations is in the growing interest in height datum studies, due to the setup of large high-precision GPS networks, together with the connection at continental level of national levelling networks, and with the growing accuracy of gravimetric geoid computations (Benciolini et al. 2001).
A GPS network of about 10 vertices was set up at points in an area whose extension was about $10km \times 10km$, close to and altimetrically connected to high precision levelling lines. All points were within a distance of 15km from the Prato station, that was used as reference fixed point for the network adjustment (see Fig.4). At the same points the geoid undulation was computed according to the Italian model ITALGEO99. It is well-known that the geoid computed with gravimetric methods is essentially based on a global model whose reference system does not coincide exactly with the GPS reference system WGS84. The transformation parameters between the two systems can be estimated using the fundamental relation $h = H + N$ from the knowledge of ellipsoidal height, orthometric height and gravimetrically computed geoid undulation of a number of points in a region.

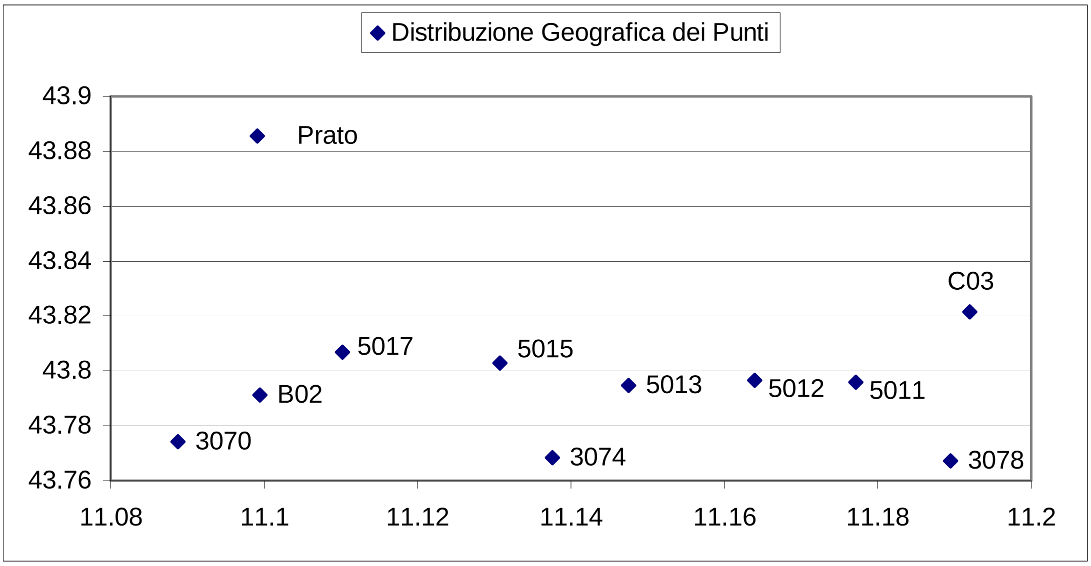

Figure 4 – Geographical distribution of network vertices

Indeed, the height datum for the whole Italian peninsular region has been checked using ellipsoidal and orthometric heights of about 500 IGM95 vertices (Barzaghi et al. 2001) and the geoid model ITALGEO99. Yet, the rsm of the residuals is as large as 15cm, too large for an accurate definition of the height datum, and systematic discrepancies presumably due to uncertainties in the heights of the national levelling network, partly measured a quite long time ago in areas affected by a relevant subsidence. Therefore, it should be expected that in small areas better accuracies could be obtained, particularly where high precision levelling lines recently measured are available.
For the computations in the Florence area, the geoid undulations at the local network points were corrected using the same reference system transformation parameters estimated from the whole Italian data set.

punto	lat	lon	h	H	N(ITALGEO99)	h-N	h-N-H
C03	43.49'17.3"	11.11'31.1"	87,37	42,313	45,213	42,157	-0,156
5011	43.47'45.5"	11.10'37.8"	81,023	35,721	45,356	35,667	-0,054
5012	43.47'47.5"	11.09'50.2"	80,985	35,628	45,367	35,618	-0,010
5013	43.47'40.7"	11.08'51"	80,857	35,57	45,402	35,455	-0,115
5015	43.48'10.4"	11.07'50.6"	86,617	41,347	45,377	41,240	-0,107
5017	43.48'24.5"	11.06'36.7"	80,026	34,756	45,380	34,646	-0,110
B02	43.47'28.4"	11.05'57.9"	81,129	35,748	45,490	35,639	-0,109
3070	43.46'27.4"	11.05'19.5"	84,705	39,159	45,618	39,087	-0,072
3074	43.46'05.8"	11.08'15.3"	81,184	35,693	45,576	35,608	-0,085
3078	43.46'02.3"	11.11'22"	91,138	45,776	45,520	45,618	-0,158

Table 1

The results are shown in Tab.1. They are not completely satisfactory: after subtracting a constant, that can be interpreted as due to a residual reference system discrepancy, residuals of a few cm are still present at some points, and a denser network in the same area should be measured in order to explain clearly the reason of these discrepancies. In addition, it has to be remarked that the Prato station could only be used as reference point for GPS measurements, as an accurate value of its orthometric height is not available.

Concluding remarks

In the first years of activity the Prato GPS permanent station has defined its role of support for local surveyors, but most of all its participation in scientific research projects. The favourable situation of the area with respect to the quality of the signal and, consequently, the good accuracy of the data, make the station fit to be inserted into regional networks for the definition of accurate reference systems. Therefore it can be expected that the station will maintain and strengthen its role in cooperation with other universities and research centres for the definition of a more accurate reference system in the Italian region, as required for geodetic and geodynamic purposes.

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- ***Geo-referencing and integration of digital images from space with remote sensored data from active sensors and geospatial observations***
  (L. Mussio)

GEO-REFERENCING AND INTEGRATION OF DIGITAL IMAGES FROM SPACE WITH REMOTE SENSORED DATA FROM ACTIVE SENSORS AND GEOSPATIAL OBSERVATIONS

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Abstract
The following research deals with problems occurring during the production of a DEM from data acquired by active sensors (SAR). All the techniques presented have been applied to images acquired during space missions (ERS-1).

Key words: telemetry, radar, (coherent) interferometric methods, surface reconstruction.

1. Methods

The Synthetic Aperture Radar (SAR) is a system that acquires data using signals in the field of the microwaves, with frequencies between 1 and 10Ghz. The employment of this range of frequencies offers some advantages, like the possibility to operate in the dark and in any weather condition, since microwaves can pass through clouds without strong attenuation, and to penetrate the vegetation and the dry land partially.

For its characteristics, SAR substantially differs from the standard radar systems and, according to its performances, is more similar to the optical systems. In fact in standard radar the targets are surveyed by transmitting an impulsive signal in the direction defined by the lobe of the antenna and measuring the time delay of the echo signal. The demanded radial resolution is obtained by transmitting very narrow signals. Instead the resolution in the azimuth direction depends on the aperture angle of the antenna, usually not very small. Assuming a constant aperture angle, the resolution in the azimuth direction obviously decreases when the distance of the reflecting point increases. Therefore, larger the distance is, more necessary becomes the use of strong directional antennas.

Therefore a standard radar system offers good performance, only if the distance is not too big, the wavelength is not extreme and the antenna is sufficiently large. If the surveying system is mounted on a satellite and a good resolution map of a specific area on the surface is demanded, the distance is so high that an antenna of enormous dimensions is required.

The wished resolution can equally be obtained with antennas of small dimensions, if the concept of synthetic aperture is used: a big antenna is simulated by an array of small antennas placed side by side. In truth, SAR doesn't consist of many distinct antennas, but only a sensor that changes position at each transmission: if in the observed zone there are not moving parts and the speed of the sensor is negligible with respect to the speed of the light, then the two methods are obviously identical.

The images are synthesized along the radial direction taking into account the shape and time of the registered signals; instead, in order to connect the data along the azimuth direction, some suitable positioning techniques are used (see figure 1).

The most common techniques of altimetric surveying, which are also the only feasible ones when using an artificial satellite as surveying station, are based on the acquisition of images of the same

zone of the surface from two different points of view (stereo-metric). Using incoherent telemetric methods, the height of a point on the surface is calculated according to the different positions of the point itself in the two images or according to the different angle from which the two orbital systems see the point on the surface.
With (coherent) interferometric methods, instead, the height is calculated comparing the phase of the images acquired from the two different points. In order to take advantage of the information contained in the phase of the SAR images, a system of two synthetic aperture radar instruments, mounted on platforms moving along parallel orbits, is required. Anyway up to now the data have been acquired by the same satellite during subsequent passages on different orbits (see figure 2).

2. Methodologies

The synthetic aperture radar (SAR) has some advantages with respect to the traditional systems. Using standard systems, only the module of the produced images is usually considered; however it is possible to gain information about the ground elevation, by comparing the phases of two images relative to the same area of the surface and acquired from different points of view. Using the information contained in the phase of the return signal, altimetric resolutions higher than those from classic telemetry systems can be reached.
This research deals with SAR data acquired from satellite. These observations are suitable for altimetry estimation, because satellites have a smooth trajectory, without fast changes of the setting, as typical of other SAR systems (for example, mounted on aircraft). In particular, it's demonstrated that, if the orbits of the two satellites with the antennas are parallel, the variations of the ground height linearly depend on the phase variations of the interferometric image.
A problem of remarkable difficulty is the fact that the phase values necessarily belong to the range ($-\pi$, $+\pi$) radiant (called main values of the phase) and, therefore, the difference between the values in two adjacent points is known with an uncertainty of 2π. This uncertainty can be solved, in a simple way, only if the phase variations are smaller than π; in the opposite case, an aliasing of the phase will occur. The construction of an algorithm for the determination of the effective phase values from the principal values (phase unwrapping or phase development), also in presence of ambiguity, was a fundamental task of this research (see figure 3).

Then the research continued in two distinct directions:

- first, using both the amplitude and the phase of SAR images, in order to identify the points with phase ambiguity with precision;
- then, combining more SAR images acquired from very different points, in order to get better solutions.

The signal to noise ratio remarkably improves if the distance between the two SAR systems increases. However, at the same time, the phase development process is much more difficult (or quite impossible), because of the greater number of areas with ambiguity. Therefore it was attempted to combine the solutions obtained from couples of images acquired from near (100 m approximately) and far (1 km to the maximum) SAR, taking advantage of the potentials of this technique. All the algorithms that have been theoretically described have already been tested with images acquired during real space missions.

3. Algorithms

According to the objectives of the research and the demanded results, the final products consist of a system of programs able to operate with interferometric SAR data too. In this sphere, some algorithms of particular interest and importance are described in the following.

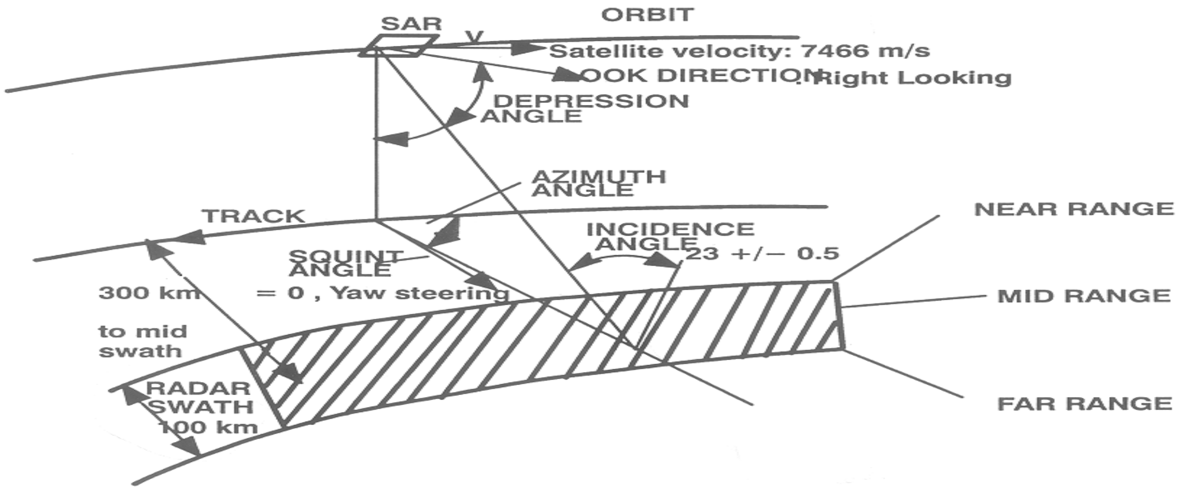

Figure 1 – Imaging geometry of SAR.

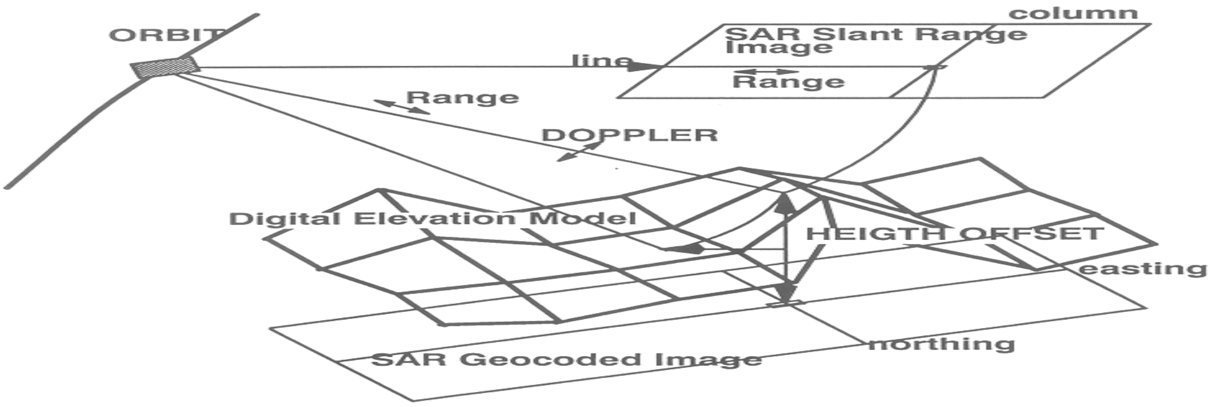

Figure 2 – Radargrammetric solution of –Geo-coding.

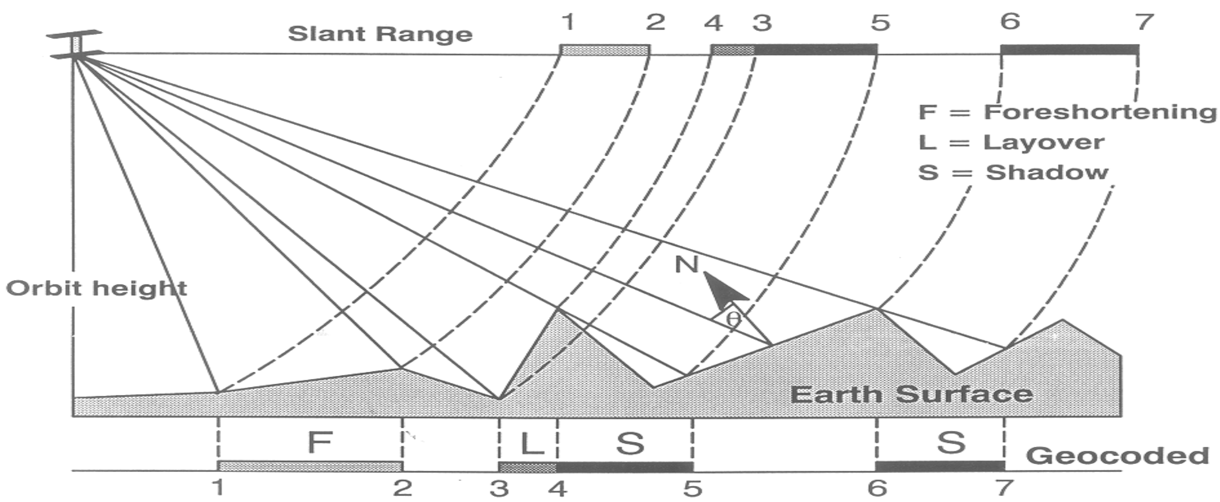

Figure 3 – Terrain distortions in SAR.

Matching algorithm:

1) shift along the image range and azimuth, because:
   - the areas investigated by the two radar are not totally coincident;
   - the distance between two subsequent points, along the range direction, is not the same for both images, since the observation points are not coincident;
   - the satellite orbits are not completely parallel;
2) data interpolation, because the shifts to apply to the points aren't usually integer values.

Unwrapping algorithm:

1) subdivision of singular points in clusters: the relative distance between points belonging to the same cluster is smaller than a certain value (in practice, the points in each cluster are so closed that it's impossible to settle which are the extremes of the real ghost lines);
2) association of all points belonging to the same cluster: as it is not possible to decide which singular points must be connected, all the singular points of the same cluster are joint together (the union between two points is set so that the circulation has opposite sign and is obtained with straight segments);
3) merging of points belonging to different clusters: search of the group of crops with minimum distance, in order to connect all the clusters (however the paths created by these crops must not generate cycles; in the opposite case, areas that can not be reached by the path of phase integration would be generated).

Geo-referencing algorithm:

1) database to be compensated with least square or robust methods:
   - schemes and methods for geospatial measurements;
   - observations from digital images from space;
   - surveyed data from active sensors;
   - points coordinates in different reference systems;
   - any available additional parameters;
2) reference system adopted for compensation of observation and pseudo-observation equations and constraints:
   - geodetic reference systems, assuming the ellipsoid as reference surface;
   - height corrections, taking into account the undulations of the geode, to transform ellipsoidal heights into ortho-metric ones.

This software package positively satisfies the required tasks, but needs to be optimized in a satisfactory way.

4. Applications

The experimental results, obtained after processing two ERS-1 images of an area in the south of Catalonia (Spain), bigger than 100 km^2 and with a maximum height difference of approximately 230 m, are rather satisfying. Although a experimental software is used not optimized for an effective operative production of digital models, the time required for manual processing is rather limited and essentially due to the preparation of the data (change of image format, reading of auxiliary data, transformations of the reference systems, etc.) and to the interactive phase of control and manual edition of the unwrapped phases. The remaining part of the operations, even if requiring some hours for calculations (as order of magnitude: 5-6 hours with a Pentium 100 MHz for an area of more than 100 km^2 and a field with about 1.5 million points), is carried out in a full automatic way.

As concerns the precision, comparing the heights in the DEM obtained from interferometry (after cartographic projection, calculation of the ortho-metric heights and re-sampling to the step of the

reference grid - see figure 4) to the heights in the corresponding DTM obtained from photogrammetry (for cartography 1:5000), the RMS error was of 9.2 m.
The differences, calculated on all the surveyed area (more than 100 km^2), contain some peaks (approximately 70-90 m, see figure 5) located in restricted areas, due to errors in the phase development. The precision is rather satisfying and of the same order of the DEM of the same area generated from a stereo-pair of SPOT images.
Although, as already mentioned, the results can be considered rather encouraging, some aspects of the procedure must be further analyzed and improved. In particular, the algorithm for interferometric phase unrolling (figure 6) can be combined with the information carried by the coherence image (figure 7).
Other aspects in the procedure to be further investigated regard the transition from the phases to the field of points. Particular attention must be addressed to the precision required in the auxiliary data (for example, orbits, control points, etc.) and to the precision of the DEM, which represents a parameter of fundamental importance for the evaluations of the employment potentialities of the final product in various applications.
In this sphere, ortho-images of the amplitude and coherence of the signal can be overlaid on the DEM, providing 3D maps or models, that can be completed by overlaying some additional vector elements of interest (parameters, toponimy, technical and/or thematic cartography, etc).

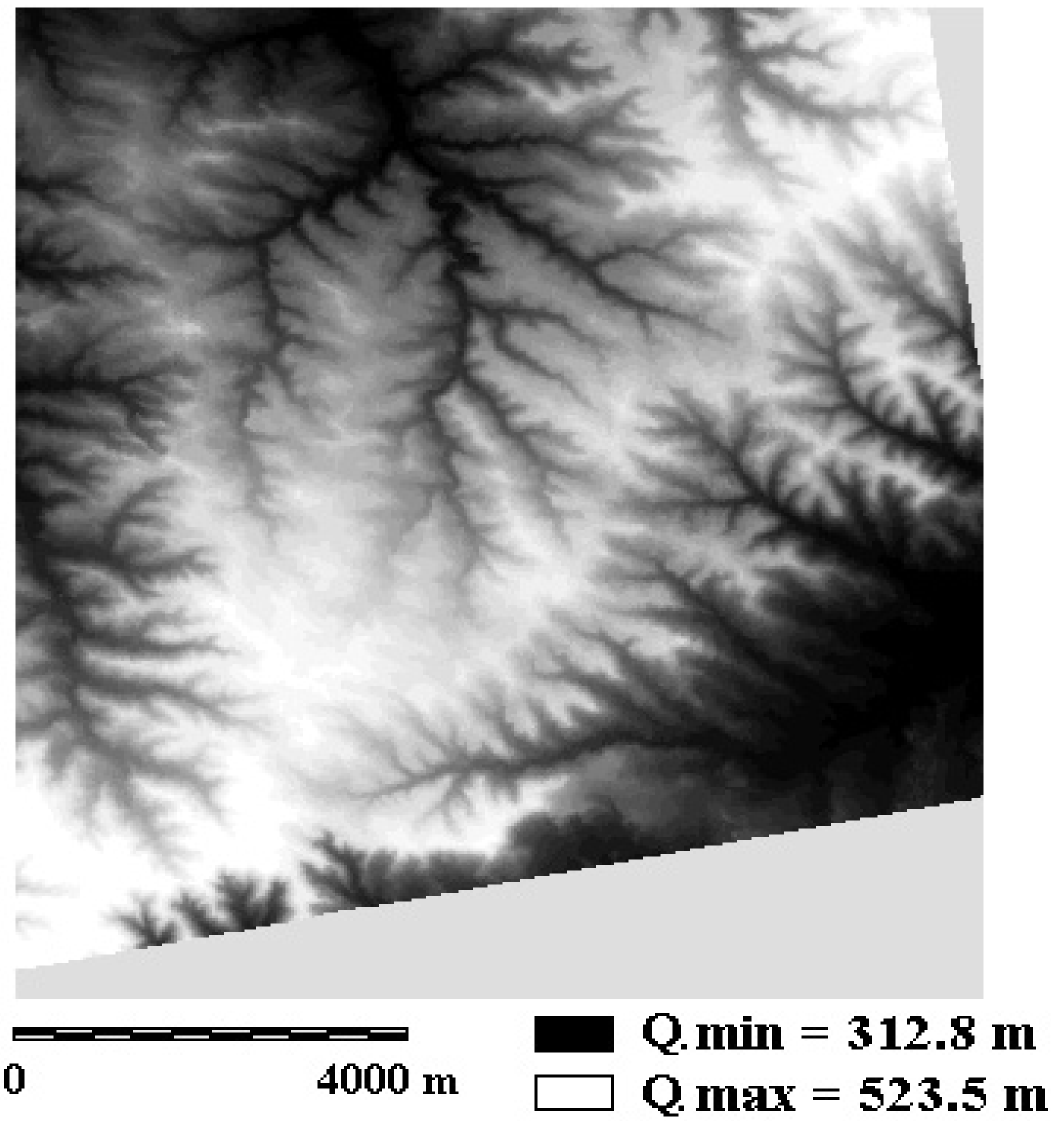

Figure 4 - DEM generated with InSAR on an area in the South of Catalonia (about 100 km^2).

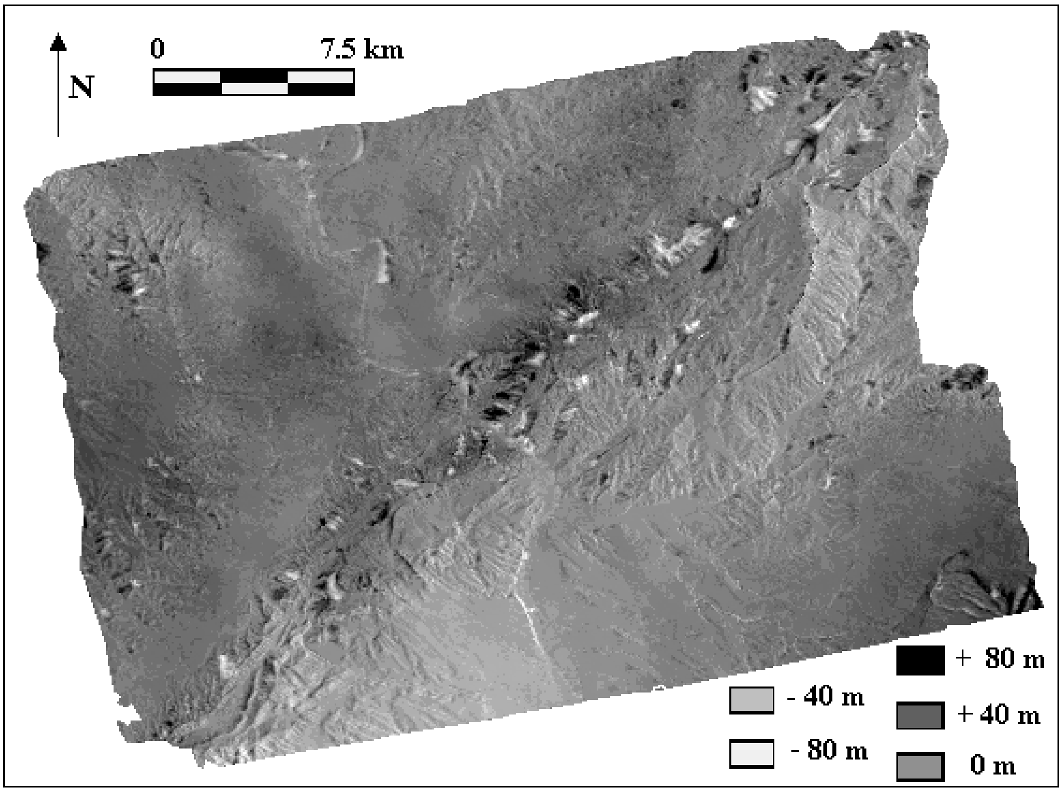

Figure 5 - Differences between reference and generated DEM.

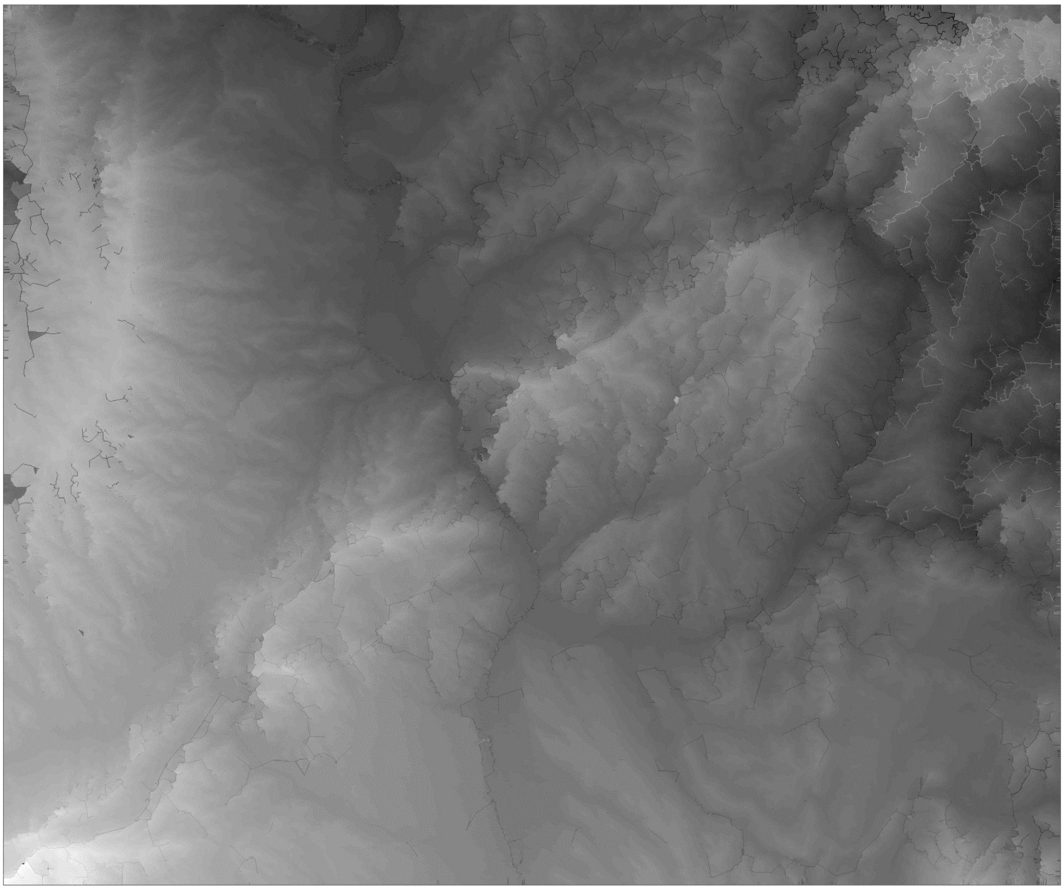

Figure 6 - Unwrapped interferometric phase.

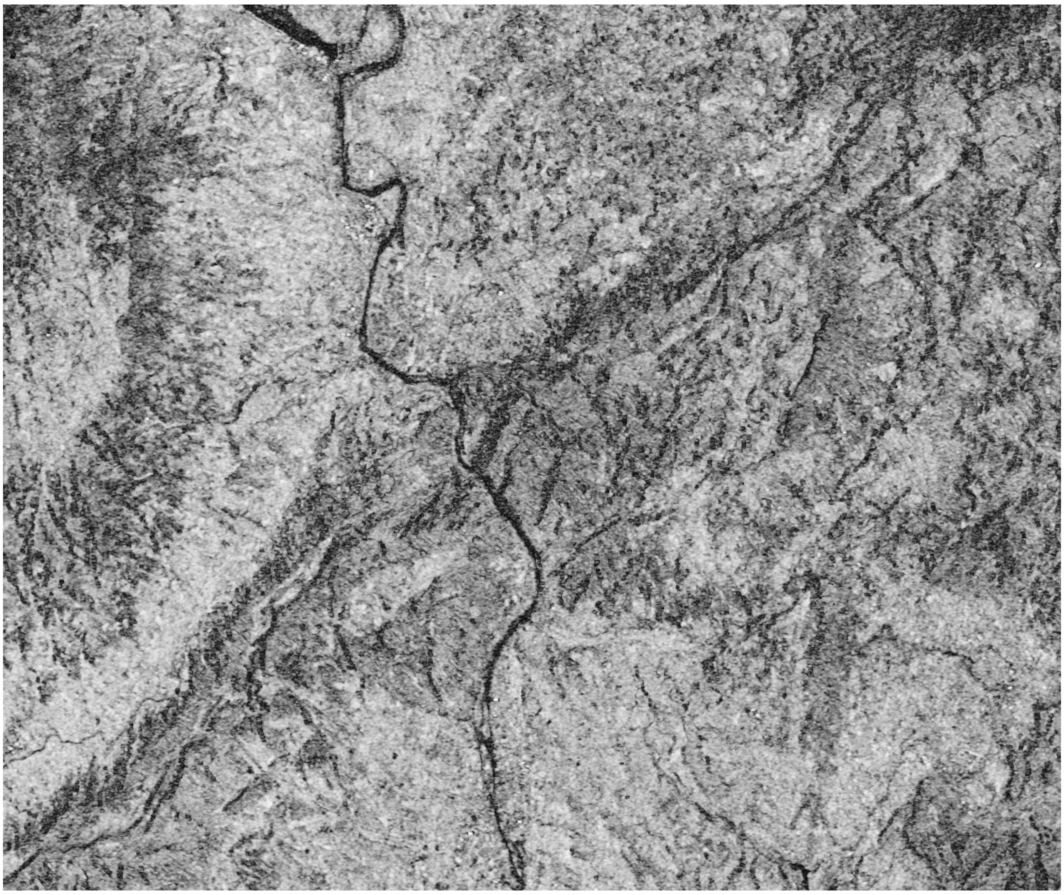

Figure 7 - Coherence image.

5. Prospective

The work done so far and the expectations of the coordination group, as risen from internal discussions, induce to suggest a significant extension of the field of interest, topic of this specific research, also according to the competencies previously acquired by the involved working group. Therefore the following topics will assume a role of interest:

- processing of images from optical satellite sensors, integration with images from microwave satellite sensors and fusion of achievable geo-referenced results;
- cartographic restitution of geo-referenced data through ortho-images with overlay of vector elements of interest, or 3D models, with texture mapping;
- filling the GIS/LIS raster first levels (orography, hydrography, settlements , infrastructures, etc.), thanks to the obtained geo-referenced information.

These topics are usually treated within geomatics. In fact nowadays all the surveying disciplines, always famous for their precision, accuracy and reliability, consider data processing as a central subject, and geomatics as a new discipline able to collect mathematical, statistical, numerical and computer science aspects of the most innovative disciplines of the field.

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- ***Use of SAR interferometry techniques for DEM generation and deformation monitoring***
  (B. Crippa, V. Barrile, L. Giacobbe)

USE OF SAR INTERFEROMETRY TECHNIQUES FOR DEM GENERATION AND DEFORMATION MONITORING

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1. Introduction

Interferometric SAR (Synthetic Aperture Radar) is a relatively new technique with important applications, such as the generation of digital elevation models (DEM), the creation of land deformation maps and the land use classification.

One of the most promising applications of interferometric SAR (InSAR) is the measurement of small surface deformations by means of the so-called differential InSAR technique (DInSAR). The SAR instrument is extremely sensitive to small relative changes in elevation occurring in the time interval between two passes over the same area. This makes possible to detect subtle changes in the Earth land and ice surfaces over periods of days to years, and over very large areas.

Several recently published papers illustrate how DInSAR can be applied to the study the deformations of glaciers, earthquakes, volcanoes and the subsidence in urban areas.

Since surface deformation may give clues to future eruptions at active volcanoes, the ability to make these measurements from space is a fundamental advance in remote sensing monitoring capability.

These studies have generated enormous interest in the Earth science community because they point to an entirely new way to study the surface of the Earth. However, further investigations are required in order to assess the actual potentialities and limitations of DInSAR.

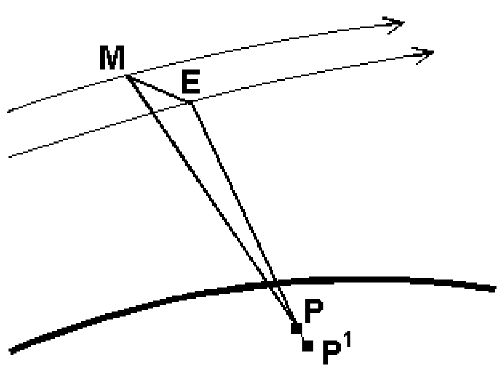

Figure 1 - D-InSAR geometry

2. The interferometric SAR techniques

A SAR system is an airborne or spaceborne imaging system. A basic element of a SAR image, a pixel, corresponds to a given portion of the terrain surface (pixel footprint). For the DInSAR procedures based on ERS images the pixel footprint is typically 25 by 25 m.

Let us assume that the change of the surface under analysis is a large-scale *coherent* change common to the footprints of several adjacent pixels. By this we assume that the change within a single pixel footprint is negligible and that the entire ground surface within that pixel footprint, as well as some adjacent ones has moved up, down, or sideways in some correlated fashion. Otherwise, i.e. when changes within single pixels occur, the DInSAR technique does not work. Let us assume that two images of the same area are available: one acquired before the movement and the other after it. Each complex SAR image contains the amplitude and the phase of the radar signal. The DInSAR exploits the information contained in the phase, and in particular in the difference of the phases contained in the two images. Referring to Figure 1, where the point on the ground moves from P to P^1, the phase difference or interferometric phase $\Delta\Phi_{Int}$ is given by:

$$\Delta\Phi_{Int} = \Phi_E - \Phi_M = \frac{EP - MP}{\frac{\lambda}{4\cdot\pi}} + \frac{EP^1 - EP}{\frac{\lambda}{4\cdot\pi}} + \Phi_{Atm} + \Phi_{Noise} = \Phi_{Topo} + \Phi_{Mov} + \Phi_{Atm} + \Phi_{Noise}$$

where: Φ_E, Φ_M are the phases of the slave and master images; E, M are the slave and master satellite positions; EP, MP are the slave-to-P and master-to-P distances; EP^1 is the slave-to-P^1 distance; λ is the radar wavelength; Φ_{Topo} is the phase component due to terrain topography; Φ_{Mov} is the phase component due to terrain movement; Φ_{Atm} is the phase component due to atmospheric effects; Φ_{Noise} is the phase noise. We consider in the following two possible cases:

- **DEM Generation**

  If there is no deformation between the two passes ($\Phi_{Mov} = 0$), and the phase component due to atmospheric effects is negligible ($\Phi_{Atm} \cong 0$) and the phase noise is smaller then the phase component due to terrain topography ($\Phi_{Noise} << \Phi_{Topo}$), then from Φ_{Topo} it is possible to derive information on the terrain topography, generating a DEM of the imaged area.

- **Deformation Monitoring**

  In case the terrain topography is known (i.e. a DEM of the imaged area is available), then the phase component due to terrain topography Φ_{Topo} can be computed and subtracted from the interferometric phase $\Delta\Phi_{Int}$, obtaining the differential interferometric phase $\Delta\Phi_{D-Int}$:

  $$\Delta\Phi_{D-Int} = \Delta\Phi_{Int} - \Phi_{Topo} = \Phi_{Mov} + \Phi_{Atm} + \Phi_{Res\_Topo} + \Phi_{Noise} \qquad (1)$$

  where Φ_{Res_Topo} represents the residual phase component due to errors in the used DEM. If both Φ_{Atm} and Φ_{Res_Topo} are negligible and the phase noise is smaller then the phase component due to terrain movement ($\Phi_{Noise} << \Phi_{Mov}$), then from Φ_{Mov} it is possible to derive information on the terrain surface deformation, generating a land deformation map of the imaged area.

2.1 A DInSAR procedure

The generation of a land deformation map starting from a pair of interferometric SAR images and a DEM of the imaged area involves a sequence of processing steps, as detailed below.

- **Step 1: Input data collection**

  As mentioned above, the DInSAR procedure requires as input the following data: a SAR image of the area, acquired before the beginning of the movement; a SAR image of the area, acquired after the end of the movement; a high resolution accurate DEM of the imaged area.

- **Step 2: SAR image registration and interferogram calculation**

  The key-aspect of InSAR lies in the pixelwise phase comparison between two SAR images (master and slave). In order to compare the phases, the images must be precisely registered, i.e. pixels with the same coordinates in the two images have to correspond to the same footprint on the ground. The registration involves the transformation from the slave geometry to the master geometry. Once the images are registered, the interferogram can be calculated. The interferometric phase equals the phase difference between the two images ($\Delta\Phi_{Int} = \Phi_E - \Phi_M$). In order to reduce the phase noise Φ_{Noise}, the interferogram often undergoes filtering.

- **Step 3: Computation of the phase due to terrain topography**

  Using the DEM and the acquisition geometry of the two images, the phase component due to terrain topography (Φ_{Topo}) is computed. In order to perform this operation an accurate knowledge of the SAR acquisition geometry is needed. This requires an accurate estimation of the parameters that describe the satellite orbits, the acquisition geometry and the SAR processing. These parameters are often known with an inadequate accuracy. The SAR acquisition geometry is refined through least squares adjustment using ground control points, that is points measured in the SAR images whose ground coordinates are known.

- **Step 4: Differential interferogram calculation**

  The differential interferogram is computed by subtracting the phase component due to terrain topography Φ_{Topo} from interferometric phase $\Delta\Phi_{Int}$, obtaining the differential interferometric phase $\Delta\Phi_{D-Int}$. If the components Φ_{Atm}, Φ_{Res_Topo} and Φ_{Noise} are negligible, $\Delta\Phi_{D-Int}$ mainly contains the information on the terrain surface deformation (Φ_{Mov}). However, the interferometric phases are only known modulo π (that is, the phase values are bounded between $-\pi$ and π). In order to derive the land deformation map it is necessary to obtain the full interferometric values $\Delta\Phi_{D-Int}$ from its principal values (phase unwrapping).

- **Step 5: Land deformation map computation**

  The land deformation map is computed by converting the full interferometric values $\Delta\Phi_{D-Int}$ (obtained after unwrapping) in vertical terrain movement and by transforming the SAR image geometry in a suitable cartographic reference system (geocoding).

- **Step 6: Analysis of the surface deformation**

  The analysis of the surface deformation is facilitated by employing more then one deformation map of the same site and of the same time interval. In fact, the data redundancy helps in separating the contribution due to terrain deformation (the signal) from the different kinds of noise (Φ_{Atm}, Φ_{Res_Topo} and Φ_{Noise}). In case the objective of the study is to monitor the evolution in time of the deformation (e.g. at times T_0, …, T_N) the above procedure has to be applied to every time interval, e.g. $D(T_1 - T_0)$, …, $D(T_N - T_0)$.

3. Discussion on the limitations of the technique

The DInSAR generation of land deformation maps is affected by some important limitations. Without going into details, some of aspects are briefly described in the following.

- **Sampling limitations**

  Land deformation monitoring represents a fairly complex task due to the 3D nature of the phenomenon at hand. Let us focus on the case the terrain surface is only subjected to subsidence, i.e. the terrain horizontal displacement is negligible. In this case the surface subsidence can be described by a variable defined in a 3D domain: two spatial components, and the time.

  A first limitation of the technique is that the SAR system is able to measure only one component of surface displacement vector, specifically the component projected onto the spacecraft-pixel-footprint vector (line of sight). This is the reason we assume the terrain is only subjected to subsidence. In this respect, the SAR measure differs from the three-dimensional measure provided by GPS survey. The great advantage of SAR is that the observations are acquired with a dense spatial coverage, rather than the sparse observations obtained in geodesy.

  A second limitation is due to spatial sampling constraints. In order to be correctly described, a spatial phenomenon has to be sampled with a suitable sampling density. The DInSAR procedures based on ERS images are characterised by a spatial sampling density of about 25 by 25 m. Taking into account the different sources of noise (Φ_{Atm}, $\Phi_{\mathrm{Re}s\_Topo}$ and Φ_{Noise}), DInSAR can monitor subsidence phenomena with a size of at least few hundreds meters. As a rule of thumb we can indicate 150-200 m as the lower bound (150 m correspond to about 6 image pixels). Additionally, as mentioned before, DInSAR can only monitor surfaces subjected to large-scale *coherent* change.

  A third limitation is due to temporal sampling constraints. In the general case the surface subsidence (Mov) may occur in a given time interval $\left(T_{End} - T_{Begin}\right)$ with a generic low (e.g. a period of slow movement followed by an increase of subsidence intensity, then a period of rest, etc.). A full description of the temporal evolution requires an adequate temporal sampling, which however is strongly limited by the availability of the SAR images. In fact, the ERS-1/2 satellites have a re-visiting period of usually 35 days (with some exceptions of 1 day and 3 days limited to given periods). This implies that subsidence phenomena with very fast evolution (e.g. with a complete evolution within one or two weeks) cannot be monitored. In these cases only the total subsidence can be measured. The re-visiting period of 35 days is usually reduced by other constraints on the orbits of two SAR passes (the orbit separation can be at most few hundreds meters, e.g. 300-400 m). This limit is due to a property of the radar interferometry: there is a loss of coherence caused by orbit separation in the direction normal to the line of sight (normal baseline $B_{\perp}$), which is proportional to the normal baseline length. Hence, it is often necessary to introduce some hypothesis on the kinetics of the subsidence (e.g. assuming that the movement goes linearly with time). In practice DInSAR can be employed to measure the general trend (e.g. the annual subsidence rate) of subsidence phenomena with slow temporal evolution.

- **SAR image quality and phase noise**

  DInSAR works with the assumption that the radar characteristics within each pixel footprint remain similar in the time between the two image acquisitions. Changes in the physical and geometric characteristics of the terrain surface between two image acquisitions reduce the degree of correlation between the SAR images (loss of image coherence). The image coherence is a good indicator of the phase quality for land deformation monitoring. It generally decreases as the time interval between the acquisitions increases. However, the evolution of the coherence basically depends on the kind of surface and the climatic conditions. Dry areas, urban areas and exposed rocks remain coherent over long time periods. On the contrary, the presence of vegetation implies a rapid loss of coherence. Geometric surface changes within single pixel footprints are another important source of image decorrelation.

The loss of image coherence constitutes one of the major problems for DInSAR. In fact, low image coherence corresponds to a very noisy interferometric phase, i.e. the inequality mentioned before ($\Phi_{Noise} << \Phi_{Mov}$) is not true. Considering large time acquisition intervals (e.g. more then 6 months) the mean image coherence is very low, i.e. the phase noise is in average very high and makes the interferometric phase useless. Exceptions are given in urban areas, where the coherence may be high, even after years due to the present of the permanent scatters.

- **Atmospheric artefacts**

In DInSAR, when deriving the surface subsidence (Mov) from Φ_{Mov}, radar signal propagation in a medium with constant refractive index is assumed. Indeed, changes in the refractive index between two image acquisitions may happen, causing distortions in the interferometric phase (Φ_{Atm}). These changes are mainly due to variations of atmospheric relative humidity, which may occur even on a kilometre scale. Other tropospheric (pressure changes) and ionospheric (Total Electron Content variations) phenomena also introduce distortions, but they usually give rise to large-scale effects.

The atmospheric effects play an important role in DInSAR. In fact, the phase component due to atmospheric effects Φ_{Atm} can often mask the component due to terrain movement Φ_{Mov}, making the interferometric phase useless. With a single InSAR pair Φ_{Mov} and Φ_{Atm} cannot always be separated: in fact, it can happen that they behave in a very similar fashion. However, this can usually be done using more pairs. In fact, Φ_{Mov} and Φ_{Atm} have different characteristics: the surface deformation is spatially and temporally strongly correlated, while the atmospheric effects are spatially correlated and temporally decorrelated.

- **Residual phase component due to DEM errors**

The differential interferometric phase $\Delta\Phi_{D-Int}$ is computed by subtracting the phase component due to terrain topography Φ_{Topo} from interferometric phase $\Delta\Phi_{Int}$. Φ_{Topo} is computed using an available DEM of the imaged area and the acquisition geometry of the two images. Errors in the DEM result in a residual phase component in the differential interferometric phase, which can degrade the $\Delta\Phi_{D-Int}$ information content. This kind of error is minimised by adopting an accurate refinement of the SAR acquisition geometry (calibration orbit) and/or by using a very accurate DEM of the analysed area.

4. Esperimental results

The esperimental part of the work has been focused on both DEM generation and subsidence monitoring. Special emphasis has been given to the quantitative aspects of these two applications.

In the **DEM generation** the analysis included the influence of different factors, like coherence, orbit parameters, terrain topography and atmospheric effects, over the DEM quality. In low coherence area there is a degradation of the precision of the InSAR point positioning and problems in the phase unwrapping: in this areas the DEM quality decrease dramatically. The orbit parameters play a important role in DEM generation. Often these parameters are not sufficient to reach the standard DEM quality, therefore an orbit calibration is need. There is a strong correlation between the type of terrain topography, related to the position of the satellite, and the corresponding DEM quality. Assumed to process images with a high mean coherence (e.g. bigger than 0.5), InSAR DEMs have quite good precision over areas characterised by gentle terrain variations. Dealing with complex terrain topography, some effects related to the SAR image distortions (foreshortening, layover and shadow) make difficult the phase unwrapping and result in spacing irregularities (i.e. "holes") in the generated grids. Atmospheric inhomogeneities during the SAR image acquisition cause distortion effects in the generated DEM. Such effects are independent of the terrain topography and the coherence and have low spatial frequency characteristics. The above described factors result in a DEM precision of the some meters (standard deviation) in areas where their influence is mitigated, while the precision decreases to several meters of standard deviationin the area where their influence is stronger. In this last case, to improve the precision of the generated DEMs, the data fusion between grids coming from ascending and descending orbits and/or the use of auxiliary data can be very useful.

The DInSAR technique may potentially offer a powerful and cost-effective tool for **subsidence monitoring**. However, different aspects of the technique have to be improved. Two D-InSAR scenarios have been considered: a single image pair and multiple observations. The first configuration is characterized by zero redundancy, and hence is completely vulnerable to atmospheric effects: it is not suitable to provide high quality standards. Nevertheless, it may provide useful information concerning the subsidence at hand. A new procedure to reduce the atmospheric effects using this configuration has been proposed (Crosetto et al., 2002a). The procedure takes advantage of the correlation characteristics of the atmospheric effects, estimated over stable areas that are located in the vicinity of the deformation area under analysis, and is suitable to applications of small spatial extent. The procedure has been tested in the analysis of a case study located in Catalonia, Spain.
The use of multiple observations (i.e. multiple interferograms) is fundamental to improve the precision, accuracy and reliability of the D-InSAR results. The redundancy of observations may be exploited to control and reduce the atmospheric effects. Furthermore, the redundancy may be used to assess, through suitable estimation techniques, the precision associated to the D-InSAR results. The fusion of multiple observations involves the 3D modelling (2D in space, plus the evolution in time) of the subsidence. Two estimation procedures based on 2D subsidence models, where a constant deformation rate over the observed time interval is assumed, have been studied (Crosetto et al., 2002b). The first procedure makes use of an explicit model of the subsidence spatial behaviour, which is described by linear splines whose parameters are estimated by LS adjustment. The data fusion procedure takes into account the weight associated with each individual DInSAR observation. The second procedure employs a more advanced modelling technique, based on the method of least squares collocation. Considering an interferogram stack, which represents a 3D - spatial and temporal - domain, the following important characteristics are exploited: the phase component related to the subsidence is highly correlated, spatially and temporally, while the atmospheric component is correlated spatially, and uncorrelated temporally. Other components can be considered mainly as white noise. Objective of the collocation filtering is to separate the "main signal" from the other components. The procedure has been tested on both synthetic and real interferometric data.

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- ***The impact of high precision space geodesy on the geodynamics of the Mediterranean***
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THE IMPACT OF HIGH PRECISION SPACE GEODESY ON THE GEODYNAMICS OF THE MEDITERRANEAN

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1. Introduction

From Gibraltar to Anatolia, the active tectonics in the Mediterranean has been studied by means of an integrated approach based on geophysical, geodetic and seismological methodologies. The aim of this study has been to gain a deep insight into the kinematics and dynamics of the crustal and lithospheric processes affecting the Mediterranean by making use of the permanent GPS data that are available in Europe and in the Mediterranean region. Major tectonic processes, such as continental collision and subduction, characterize this region that marks a broad transition zone between the African/Arabian and Eurasian plates. The counterclockwise rotation of the Africa plate with respect to Eurasia results into a NNW directed push against Eurasia itself, accompanied by lithospheric shortening in active subduction zones, in the Aegean Sea and in the Calabrian Arc.
A thin-shell finite element approach allows us to simulate the deformation pattern in the Mediterranean, by means of the appropriate velocity boundary conditions applied at subduction zones and at the southern and eastern border of the domain under study. The global plate motion model NUVEL-1A (DeMets et al., 1994) is used to account for the convergence between Africa/Arabia and Eurasia, while the relative velocities of the overriding and subduction plates at subduction zones is obtained from another family of models that, in vertical cross section, simulate the effects of the negatively buoyant density contrasts of the subducted lithosphere on the horizontal velocity at the Earth surface.
A systematic comparison between model results and the seismic strain rates obtained from the National Earthquake Information Center (NEIC) catalogue, the geodetic velocity field and the geodetic strain resulting from GPS, SLR and VLBI analyses performed by the Center of Space Geodesy in Matera, of the Italian Space Agency, indicate that Africa/Arabia vs Eurasia convergence and subduction in the Aegean Sea and Calabrian Arc are the major tectonic mechanisms controlling the deformation style in the Mediterranean. In particular, it is shown that, in order to carry into coincidence the modeled and the seismic strain rate patterns and the eigenvalues and eigenvectors of the modeled and geodetically retrieved strain rate tensors, a deep subduction in the Aegean Arc, in agreement with seismic tomography but not with the shallow one imaged by the hypocentral distribution of earthquakes, must be included in the modeling.
The modeled strain rate is in good agreement with the seismic one, in particular with the continuous pattern of high strain rate values, running along the Africa-Eurasia plate boundary, from the Maghrebian/Alpine front, through the Dinarides, to the Aegean and western and eastern Anatolia.
Studies of the deep structure reveal distinct differences between the lithosphere in the western-central Mediterranean (from Alboran to Tyrrhenian Seas) and those in the eastern Mediterranean.
The eastern Mediterranean basins are part of the African plate, formed in the Mesozoic. The western basins constitute a deformed plate boundary region of the Eurasian plate, created by back-arc extension in the Late Oligocene to recent times. The idea of a land-locked basinsetting provide

an explanation for a dynamical analysis of some Mediterranean zones. It leads to roll back and to the consumption of the oceanic lithosphere between Africa and Eurasia and to extension in the overriding plate above the subduction zones. Earthquakes in the Mediterranean are not confined to a single fault, implying that the deformation in this region cannot be described simply by the relative motion between rigid blocks. Within the broad deforming belts in the continents some large, flat, aseismic regions such as central Turkey or the Adriatic sea, appear to be rigid and can usefully be thought of as microplates.

2. Methodology

A major advance in the last decade has been made in estimating such velocity fields either from GPS measurements [McClusky et al., 2000; Devoti et al., 2001]or from spatial variations in strain rates [Jimenez-Munt et al., 2001]. Thus, for example, attempts have been made to understand how the velocity field in the Mediterranean region is related to the convergence between Africa/Arabia and Eurasia while little is known about the relative importance of the driving forces either due to pushing acting at the edge of the plate or to pulling by the foundering plate. The present research has focussed on the numerical modeling of the major tectonic processes active in the Mediterranean and on the comparison between model predictions and geodetic, seismic and stress data. The modeling includes convergence between the Africa/Arabia and Eurasia plates and the additional forces acting at plate boundaries due to subduction.

For the first time, in the present analysis we overcome the difficulties encountered in previous studies due to thesmallness of the modeled domain, that did not allow the usage of completely self consistent boundary conditions at the edges of the studied area, and we model simultaneously, for the whole Mediterranean, the effects of Africa/Arabia - Eurasia convergencefrom Gibraltar to Anatolia, including the effects of subduction in the Calabrian Arc and in the Aegean Sea and the effects of slip along the whole plate boundary separating Africa/Arabia and Eurasia. With respect o previous studies, we now have at our disposal a large amount of geodetic data that allows us to compare for the first time the modeled strain rate with the geodetic one, which permits a robust test for our hypotheses on the tectonic driving mechanisms. We use the thin-shell neotectonic modeling program SHELLS [Kong and Bird, 1995]. The thin-plate method of modeling the deforming lithosphere uses isostasy and vertical integration of lithospheric strength to reduce three-dimensional problems to two dimensions, where the horizontal velocity components do not depend on the depth. The horizontal components of the momentum equation are vertically integrated through the plate, and are solved using a 2-D finite element grid. Therefore only the horizontal components of velocity are predicted. The plane stress approach assumes the lithosphere as a thin layer with a vertically averaged rheology. This average rheology is calculated at each node of the finite element grid on the basis of the crustal and the lithospheric mantle thicknesses. We make use of the elevation and surface heat flow data to determine the lithospheric structure and its thermal structure under the assumption of local isostasy and steady state thermal regime. The elevation is taken from ETOPO-5 global dataset. The surface heat flow is taken from the global dataset of Pollack et al. [1993] completed with the data obtained by Fernandez et al.. [1998] for the Iberian Peninsula and Alboran sea. The crustal and lithospheric thicknesses agree with the seismologically retrieved ones of EurID [Du et al., 1998]. Deviations between our lithosphere thickness and the seismological one could arise from several causes: a different treatment of the lithosphere, a thermal one in our case, possible errors in surface heat flow data or the assumption of local isostasy. However, these variations in the structure of the lithosphere have small effects on the lithospheric strength and gravitational energy hich makes our lithospheric structure adequate for neotectonic studies.

Geodetic data

The geodetic data set contains 190 vector velocities, with respect to a fixed Eurasia. 33 of these geodetic velocities, grey arrows, have been obtained by the Matera Geodesy Center of the Italian Space Agency (ASI-CGS) using Global Positioning System (GPS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) data [Devoti et al., 2001]. These data have been completed in the eastern Mediterranean with the GPS measurements for the period 1988-1997 carried out by McClusky et al. [2000], black arrows, referred to Eurasia. In Devoti et al. [2001], a detailed description is provided on how the different GPS, SLR and VLBI techniques have been combined in order to obtain for each site reliable velocities. In particular, the ASI-CGS solution in Figure 1, indicated by the grey arrows, represent the residual velocity with respect to the Eurasian block obtained by subtracting the rigid motion of Eurasia expressed in the NUVEL-1A reference frame. A major characteristic of Figures 1a and 1b, from west to east, stands on three different styles for the directionof the horizontal velocity field:a generally south trending direction in the Iberian peninsula and Ligurian coast of Italy, a generally north trending direction for southern and peninsular Italy, with a rotation from NW to NNE from the Lampedusa island (LAMP), between Africa and Sicily, to Matera (MATE) through Calabria (COSE) (Figure 1a) and finally a rotation from NNW to SSW from eastern Anatolia to the southern Aegean. The NE direction in southern Italy agrees with the idea of the counterclockwise rotation of the Adriatic plate [Ward, 1994]. Besides the velocity direction, the geodetic pattern is also characterized by another major feature, dealing with the magnitude of the velocity, which shows a substantial increase from the west to the east and from the north to the south. If we focus on some details, we may notice that in central and north-east Italy the motion has a strong north component except in the Po plain, with the site MEDI showing a large east component, which is probably due to local tectonic effects, like thrusts of the buried Apenninic chain. Lampedusa, Sicily and peninsula Italy, except its westernmost coastal area, thus show a dominant north-trending component, in agreement with the major NUVEL-1A velocity component at these longitudes. Moving to the eastern Mediterranean, in Figure 1b, we can highlight high velocities, of about 30 mm/year, with SSW direction in the Aegean region and with the west directed velocities in the Anatolian Peninsula. In Figure 4b, the velocity field shows the northward motion of the Arabian plate and the counterclockwise rotation of the central/western Anatolia and southern Aegean. This rotation is bounded to the north by the NAF and its extension into the Aegean Sea. In Figure 2, the geodetic velocities are used to calculate the principal horizontal strain rates, that can be compared with the modeled ones.

Model set-up

We consider the active convergence between Africa/Arabia and Eurasia. The kinematics of these plates is governed by the counterclockwise rotation of Africa and Arabia relative to Eurasia. Several authors have constrained the relative velocity between these plates, that can be described as a rotation around an Euler pole. We use the results of the global model of plate motion NUVEL-1A [DeMets et al., 1994] to calculate the convergence between Africa and Eurasia and between Arabia and Eurasia. In this work, we have assumed Eurasia as fixed and the boundary conditions are relative to this plate. In this work, we only considered the majors faults, that approximate the plate boundary, by means of a continuous fault represented in the figures by the solid line, along north Africa, Calabrian arc, Malta Escarpment [Catalano et al., 2001], Apennines, Alps, Dinarides, Hellenic Arc and Anatolian faults, following the plate boundary. We tested different fault friction coefficients, from 0.85 to 0.01, where the friction coefficient of the continuum medium is always 0.85.

Convergence and subductions forces

In order to improve the correlation between modeled results and the geodetic velocities and seismic strain rates, we make now use of another family of models that includes the effects of subduction in the Aegean (Hellenic Arc) and southern Italy (Calabrian Arc). Within a thin plate approach, this can

be achieved by applying the appropriate horizontal velocities at the plate boundaries that simulate the effects of tectonic forces due to trench suction on the overriding plate and slab pull on the subducting plate. This implies that the plate boundary must coincide with a boundary of the model. We thus divide the model along the plate boundary and we consider separately the Eurasian plate and the African plate in order to apply the appropriate velocity boundary conditions where subductions are active.
From 3-D models of subduction [Negredo et al., 1997, 1999], where the effects of trench suction and slab pull are taken self-consistently into account, we obtain the horizontal velocities that must be applied along the trench regions, to simulate the effects of subduction. The remaining plate boundaries (north Africa and eastern Anatolia), where subductions are not active, are subject to free boundary conditions, where the only effects are those to due the lithostatic stress.
Our approach is appropriate within the assumption that the horizontal velocities induced by subductions are negligible along these plate boundaries, where subductions are not active, with respect to the horizontal velocities induced by Africa-Eurasia and Arabia Eurasia convergence along the same boundaries.

Figure 1 compares the velocities predicted by our finite element modelling that inludes the effects of convergence and subduction on the modelled horizotal velocities (black arrows) evaluated at the sites where geodetic data ara available (grey arrows). We observe that in the Calabrian arc the modeled and the observed velocity come to coincidence. We note a good fit of the velocities in the southern part of Anatolia and Ciprus Island, with some disagreement in northern Anatolia, in the velocity modulus. In fact, the modeled velocity is 9-14 mm/yr, to be compared with the observed ones of 17-22 mm/yr.North of the NAF, we note a drastic decrease in both modeled and observed velocities, indicating that this fault represents a strong discontinuity of the lithosphere. The smoother northward decrease in the velocity modulus of the model, when compared with the geodetic velocity, indicates that Anatolia has a block-like behavior in the reality, which is necessarily smoothed by our continuous rheological model.

Figure 2 portrays the eigenvectors and eigenvalues of the modeled and geodetic strain rate tensor. The western, central and eastern Mediterranean, panels a-d, have been subdivided into triangles with vertices connecting the sites where the horizontal velocity components are available. The aim is to estimate the strain rate, from the numerical and geodetic standpoint, indicative of the styleof deformation in the area within each triangle. In our approach, this is accomplished assuming that the horizontal velocity components vary linearly with distance within each triangle. This constant space gradient provides a first order approximation of the strain rate in each tectonic region embedded within the vertices of the triangles. This approximation can be improved by integrating the geodetic network with new geodetic sites. We have elected as reference point where the strain rate tensor is evaluated, the bisectors of each triangles.
The same procedure, described in detail in Devoti et al. [2001], is applied to the two series of horizontal velocity components, the geodetic and the modeled ones. In dealing with the known velocity positions at the vertices of the triangles,the solution requires the inversion of a system of linear equations in six unknowns, four tensor components plus two velocity components at the reference point. The velocity gradient tensor can be decomposed into its symmetric part and antisymmetric one, the first one providing the strain rate eigenvectors and eigenvalues, after the diagonalization procedure, while the second one provides a rigid rotation rate.
The errors associated with the geodetic strain rate tensor are obtained by means of the covariance matrix associated with the velocity components at each site. In the following panels, the eigendirections are given by two perpendicular arrows, oriented with respect to the meridian; the length of the arrow is scaled in such a way to provide the eigenvalue in units of 10^{-9} yr^{-1}. Red stands for compression and black for extension, with arrows in bold representing the geodetic strain rate and the empty ones the numerically retrieved strain rate. From West to East, we now compare the

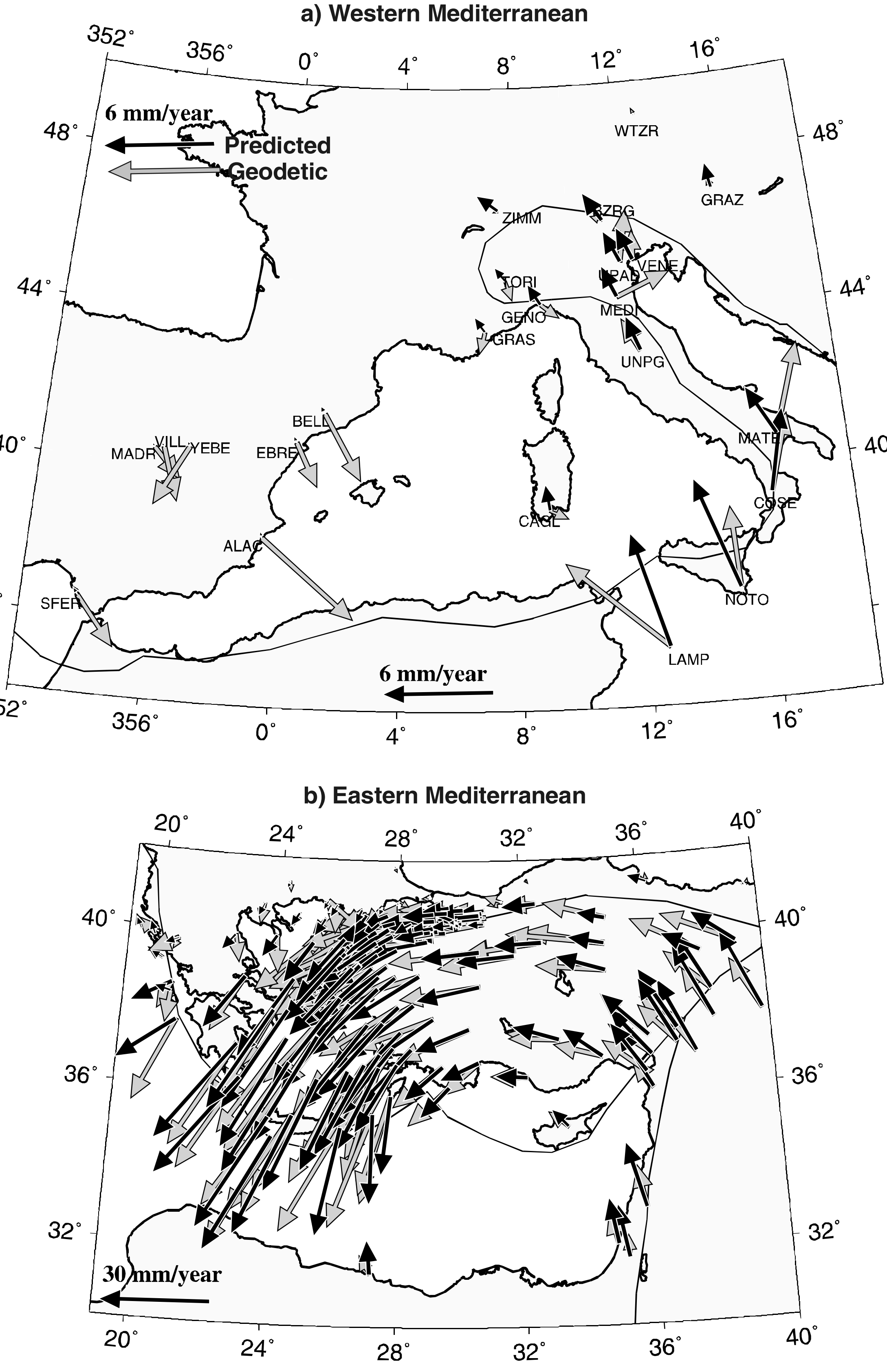

Figure 1 - Geodetic and predicted velocities resulting from the modelling, with the active convergence and subduction forces in the Hellenic (deep slab) and Calabrian arcs, decreasing the velocity from the center of the arc to the boundaries (Negredo et al., 1997) a) western Mediterranean, b) eastern Mediterranean. Grey arrows denote the geodetic data and the black ones the predictions from the model.

geodetically retrieved strain rate tensor with the numerical one In the western Mediterranean (Figure 2a), SFER-ALAC-CAGL-LAMP, compression predominates in the NNW direction. The eigendirection relative to this compression is well reproduced by the model, in particular within the triangle SFER-ALAC-LAMP, where the geodetic and modeled eigendirections agree within the standard deviation sigma, represented by the grey surface surrounding the eigenvectors of the geodetic strain tensor. In the same triangle, the modeled eigenvalue is a factor two lower than the geodetic one, indicating that the model underestimates the compression. This eigenvalue is well reproduced in the central Mediterranean, in the triangle ALAC-CAGL-LAMP.

This compression agrees of course with the idea that it is induced by the relative motion between Africa and Eurasia. South of LAMP, the geodetic compression rotates by 90° with respect to the western Mediterranean, but this compression is not reproduced by the model and the large accompanying extension is severely underestimated. In the region from LAMP to MATE, the ENE compression is now well reproduced by the model. The north trending extension is underestimated in the modeling, except for the triangle with vertices in LAMP and NOTO, where we obtain the best fit, as far as the magnitude of compression and extension is concerned. The change in strain style from LAMP to the north-east is visible also in the stress data, where from the eastern part of Sicily to the Calabrian Arc, we notice a change from thrust (compression) to normal faults events (extension) pervading the arc, particularly well reproduced by the geodetic strain rate and to a lesser extent by the modeling. In the Iberian peninsula, modeling and observation are in complete disagreement. This negative result seems to indicate that some major tectonic features are not modeled in the westermost part of the studied domain.

The eigendirections of the modeled and geodetic strain rate are best reproduced in the western part, with underestimated dominant compression, while in the eastern part of the studied area the results are the opposite, with generally well reproduced eigenvalues but with some deviation between the eigendirections. The compression that rotates by 90° with respect to the western Mediterranean, leadsto a compression which is roughly perpendicular to the Arc, which seems to be a surface fingerprint of subduction. In the center of the Tyrrhenian sea (Figure 2b), CAGL-UNPG-NOTO and NOTO-UNPG-COSE, the geodetic and the model strain rate are in close agreement, both in the eigendirections and eigenvalues.In proximity of this well modeled region, UNPG-MATE-COSE portrays the worst fit, with the modeled compression aligned with the geodetic extension, due to the mismatch, already noted, between the modeled and geodetic velocity direction of MATE.

The geodetic EW extension UNPG-NOTO-MATE, not reproduced by the model, agreeswell with the extensional tectonics perpendicular to the Apenninic chain, indicated by the normal fault events, yellow bars. The observed extension perpendicular to the chain could indicate that subduction is also active underneath the central Apennines, a process that has not been parameterized in the modeling.

In proximity of the Calabrian arc the principal strain rate is extensional (UNPG-COSE-NOTO), with a complete coherencebetween geodetic and modeled eigendirections and eigenvalues, and roughly perpendicular to the arc, probably indicating roll back of the arc itself. From the geodetic strain rate, the pentagon GRAS-TORI-UNPG-NOTO-CAGL portrays a NW compression as the dominant mechanism, changing into dominant ENE extension in the triangles CAGL-NOTO-LAMP and UNPG-COSE-NOTO. The model fits very well all these features, except the high ENE extension in the triangle CAGL-NOTO-LAMP.

If we move to the North, in Northern Italy and Alpine front,we notice a deterioration in the quality of the geodetic strain, which carries larger errors. Both in the geodetic and modeled strain rate values we notice a substantial reduction with respect to the southern values, in agreement with the reduction of deformation from South to North due to the larger distance from the Africa-Eurasia collision and subduction zones.

The eigendirections are generally well reproduced, although for TORI-VENE-UNPG and VENE-GRAZ-UNPG there is no fit with the data, with a 90° mismatch in this second triangle in the eigendirection, and the modeling predicting essentially zero strain rates in the first one. This may be due to the model, or to the quality of the geodetic strain, both possibly related to the smallness of the strain rates in the areaor to the difficulties portrayed by the large scale numerical model in dealing with small scale active tectonic features or to the effects of the hydrological cycle of the crust, not considered in our modeling. Within the pentagon ZIMM-WTZR-GRAZ-VENE-BZRG the style the compressive strain rates is well reproduced by the modeling, both in the eigendirections and eigenvalues within the error bounds, and both the geodetic data and geophysical model agree with the WSM2000 map, that portrays a cluster of thrust events in the region corresponding to thetriangle WZTR-GRAZ-VENE.The mismatch between the geodetic and modeled strain rates occurs within the two triangles VENE-GRAZ-UNPG and GRAZ-MATE-UNPG, denoting the Adriatic sector where west directed extension is predicted rather than compression, for the first triangle, and where, for the second triangle, E-W extension is not reproduced.

In the Aegean region (Figure 2c) we obtain a general improvement in the coherence between the eigendirections and eigenvalues obtained from the geodetic data and from the numerical modeling with respect to the findings of Figure 2a and 2b.

This extension fits well with the idea that the suction force induced by the negatively sinking slab in the Aegean is a major mechanism. Entering the details of this widespread extensional pattern,we notice that the largest deviation in the eigendirection occurs in the triangles LEON-7515-TWR in Greece and CAMK-BURD-7512 in western Anatolia, with a mismatch of about 90°, and in SOXO-7510-7515, with a mismatch of about 30°. Except for these three triangles, the geodetic and modeled strain rates eigendirections are in good agreement, both in Greece and western Anatolia.

The eigenvalues are also in fairly good agreement, but we notice that when a mismatch occurs, thenumerical model has the tendency to underestimate the geodetic extension, as for example in the triangle 7520 NEZA-LOGO in eastern Greece or in the two triangles in western Anatolia D7DU-CAMK-CEIL and D7DU-BURD-CAMK. The modeling has difficulties to reproduce the situation of isotropic extension for SOXO-7510-7515. In general, we obtain a fairly good agreement between the eigendirections and largest eigenvalues. Moving to the east, the NNE extension in Greece and Aegean region has the tendency to rotate to NE in Anatolia. Simultaneously with this rotation in the eigendirection of the extension, we notice that compression at right angles with respect to the previos direction, namely WNW compression, has the tendency to become the dominant mechanism once we move to the east in Anatolia.

Drawing a parallelism with the driving mechanism of extension in the Aegean region, the increase in compression to the east in Anatolia fits well with the idea that the push from the Arabian plateis a major controlling mechanism in the easternmost part of Anatolia.

It is thus clear that the peculiar pattern of extension and compression is due to the combined effects of suction induced by deep Aegean subduction and by the push of Arabia. In proximity of the HellenicArc the modeled extension parallel to the arc overestimates the geodetic one, and we notice a considerable geodetic compression perpendicular to the arc, especially in its western part, which is underestimated by the model.North of Crete, we notice in fact compression in the geodetic strain perpendicular to the arc and extension parallel to it, in agreement with the numerical model in the eigendirections (LEON-OMAL-TWR; TWR-ZAKR-7512).

The model reproduces the compressionperpendicular to the arc south of Greece (LOGO-LEON-OMAL), but not north of Crete. In this arc region, the worst fit occurs inthe westernmost part of Crete (LEON-OMAL-TWR), where predominantly WNW extension is modeled rather than NNE geodetic compression. East of Crete (TWR-7512-ZAKR) the modeled extension turns to be coherent with observations.

Deviations between the eigendirections are observed west of the Peloponnesus and east of Crete, certainly due to edge effects at the subduction zone, where the smoothing of the applied velocities that simulate the suction force are based on Negredo et al. [1996]. These results show that the major effects of the Aegean subduction are correctly reproduced, while at the edge of the plate the modeled strain rate is affected by local three-dimensional effects. In spite of that, we notice that the

intensity of the geodetic strain rate is well reproduced, denoting compression directed outward from the subduction zone and extension along the hinge line of the subdution, independently on the about 20° mismatch between the eigendirections west of the Peloponnesus and island of Crete. Figure 2, panel (d), portays the geodetic and modeled strain rate for Anatolia.
The modeled eigendirections are best reproduced in the western part, with a rotation from NNE (CAMK-D7DU-BURD) to NE (AGOK-SIVR-7587), when we move from a longitude of 28° to 32°, in good agreement with the largest geodetic eigenvalues denoting extension. Both the geodetic and modeled strain rates are in complete agreement with the cluster of normal fault events in western Anatolia, denoting extension in the NNE direction. From west to east, we notice, at least for the largest eigenvalue, a change from dominant extension todominant compression, both in the model and in the geodetic data,with an intermediate zone of reduced strain rates, centered approximatively at 33° E, in which the dominant NE extension in the west, although reduced, changes into NE compression when we move to the east.
The model reproduces well the reduction in the strain rates eigenvalues observed in the data, but in the triangle SIVR-7585-7580, in the center of Anatolia, the model eigenvectors are rotated by 90° with respect to the geodetic one, a negative results which is not unespected, due to the smallness of the strain rate. In the center of Anatolia the model thus reproduces very well the reduction in the strain rate, and the transition from extension in the west to compression in the east, but fails in the eigendirections in the center of this zone.
In the eastern part, NNW compression is the dominant mechanism, in agreement with the idea of a dominant role played by the push of Arabia.The magnitude of the largest eigenvalue is generally overestimated by the model, clearly controlled by the push of the Arabian plate. The model fails to reproduce the extension observed in the data, with a behavior that we have already observed in which our modeling, while reproducing the largest eigenvalues, has difficulties in reproducing the smallest ones. In the eastern part of Anatolia, the geodetic eigendirection is rotated counterclockwise with respect to the modeled one. This discrepancy in the eigendirections could be due to edge effects, since this region is close to the boundary where the velocity conditions are applied and modeled ones.

From Gibraltar to the east, towards Anatolia, the modeling reproduces the major features visible in the pattern of eigendirections and eigenvalues of the geodetic strain rate tensor, namely NNW compression from Gibraltar to Lampedusa, extension in southern Italy, compression along the Alpine front, the NNE extension in theAegean and western Anatolia and finally compression in eastern Anatolia. At the smaller scale, some features are well reproduced, such as the extension parallel to the Hellenic Arc, while some other features, such as the extension perpendicular to the Apenninic chain or the transition zone in central Anatolia between extension and compression, are not, indicating that the effects of local tectonic mechanisms are not properly taken into account.

The modeling reproduces also the main features of the seismic strain rate pattern obtained from the NEIC catalog, namely the belt of high seismic release in Northern Africa and the peculiar shape ofthe region of high seismic energy release embedding north-eastern Italy, Dinarides and southern Italy, the whole Aegean Sea, the western and eastern Anatolia, although the correlation between seismic data and model results must be taken with caution, as discussed above. The results shown in this study indicate that it is possible to gain a deep insight into the dynamics of the major tectonic mechanisms affecting the Mediterranean, once the basic driving processes of plate tectonics are considered within an integrated approach based on model efforts, geodetic and seismic analyses (Jimenez-Munt et al., 2002).

fig. 2a

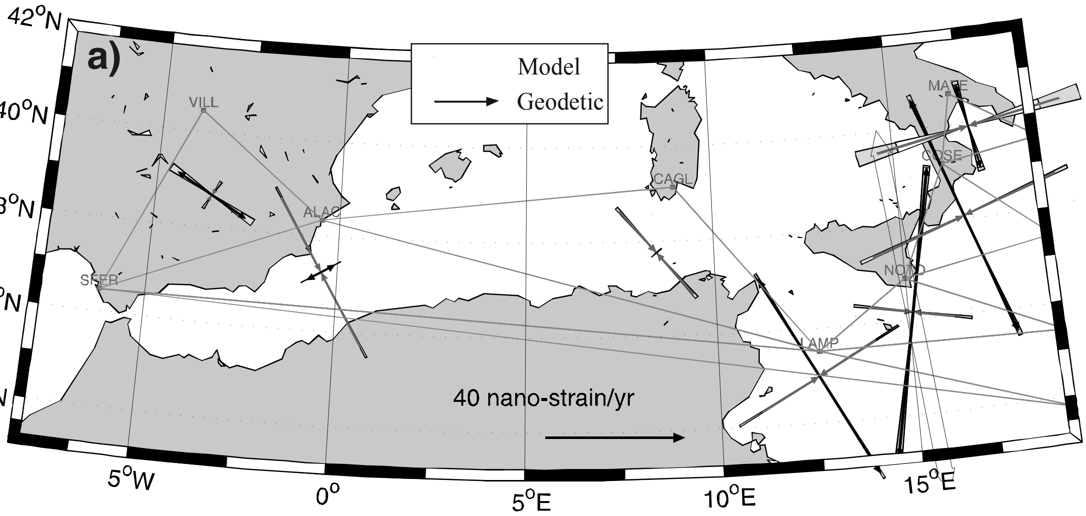
a)
Model
Geodetic
VILL
ALAC
SFER
CAGL
MATE
COSE
NOTO
LAMP
40 nano-strain/yr
42°N
40°N
38°N
36°N
34°N
5°W
0°
5°E
10°E
15°E

fig. 2b

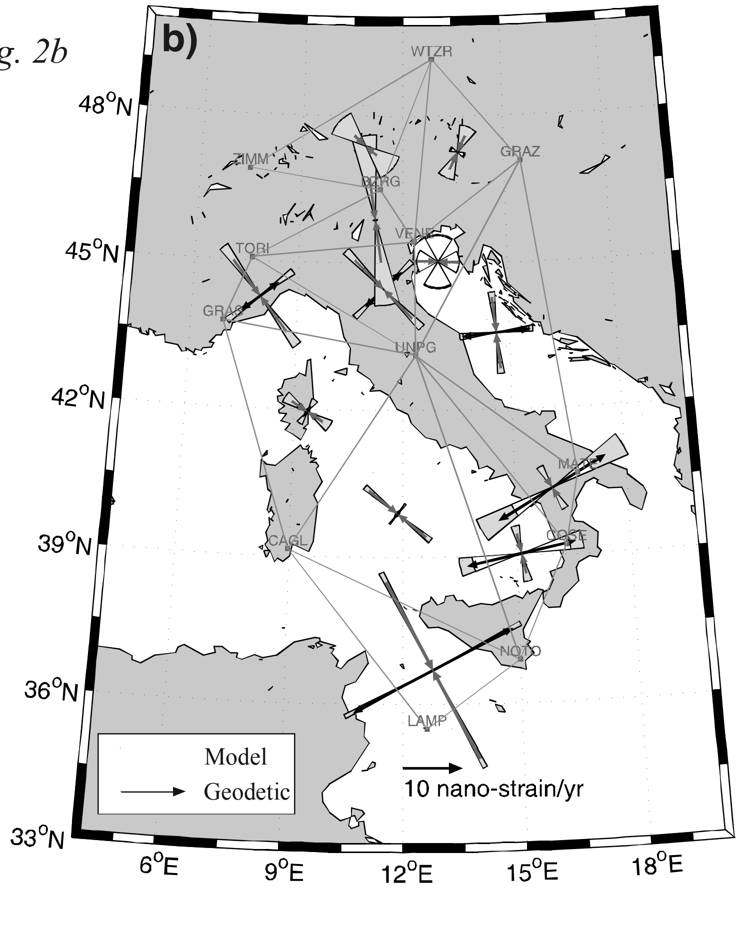
b)
WTZR
ZIMM
GRAZ
BZRG
VENE
TORI
GRAS
UNPG
MATE
COSE
CAGL
NOTO
LAMP
Model
Geodetic
10 nano-strain/yr
48°N
45°N
42°N
39°N
36°N
33°N
6°E
9°E
12°E
15°E
18°E

fig. 2c

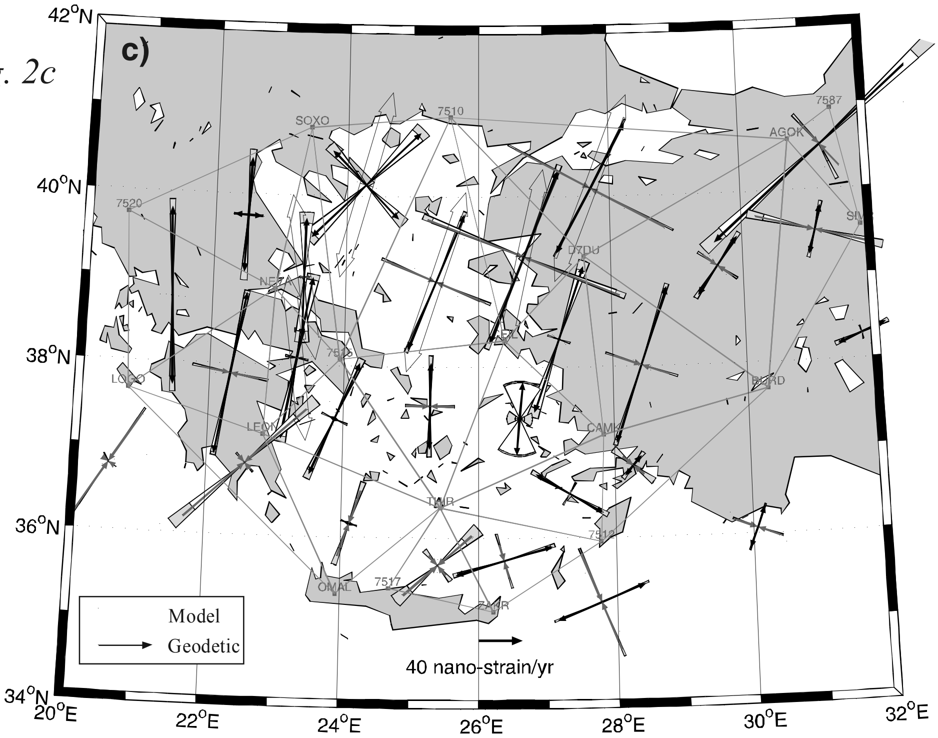

fig. 2d

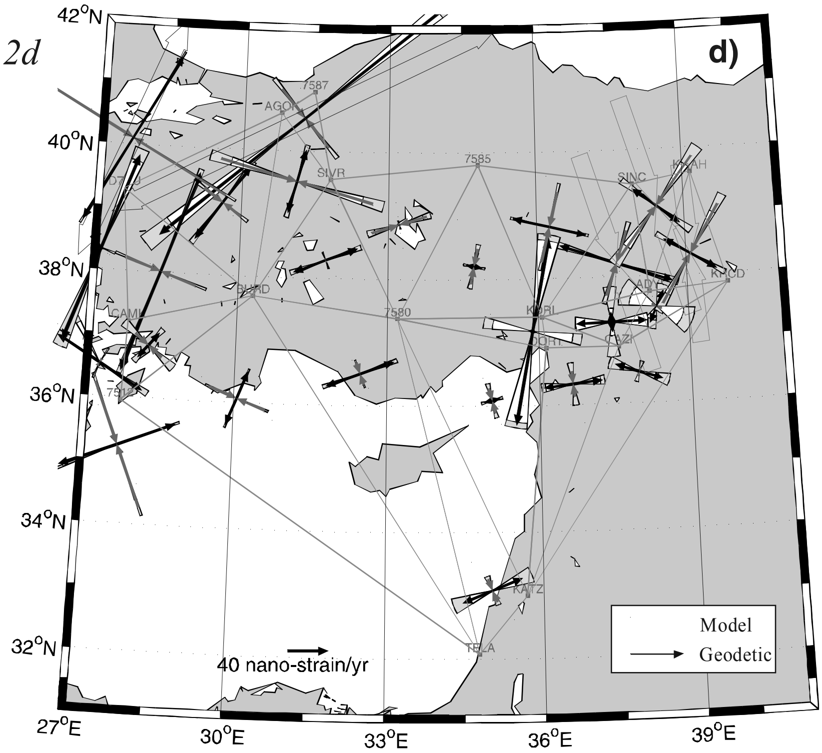

Figure 2 - Horizontal principal strain rates: geodetic ones (solid arrows) and modeled ones (empty arrows) resulting from the modelling with the associated errors. Extension is represented in black and compression in red, a) Western Mediterranean, b) Central Mediterranean, c) Aegean region and d) Anatolian Peninsula.

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- ***Quality control and validation of GPS data acquired by permanent stations***
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QUALITY CONTROL AND VALIDATION OF GPS DATA ACQUIRED BY PERMANENT STATIONS

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Introduction

The Laboratory of Geodesy, Surveying and Photogrammetry of Perugia University (D.I.C.A.) manages since October, 1997 the GPS permanent station "UNPG", part of the national ASI network and of the international networks EUREF and IGS.
By means of the conspicuous amount of data acquired during this period of time, our research group has been able to carry out interesting analyses with respect to various aspects of the GPS measurements performed by permanent stations: hardware optimisation, data quality control, bias extimation and/or removal, refinement of the data treatment and processing phases, etc.

HARDWARE OPTIMISATION

Since the UNPG permanent station has firstly entered service, a number of new instruments, accessory equipment and hardware components have been added to the installation, in order to optimise both data management and data quality.
After the installation of any component, data analyses have been performed to understand if any improvement had effectively been reached, and to optimise the installation.

Rubidium clock implementation

In May, 1999, a rubidium external clock has been acquired and installed. It has the following main characteristics:

Model: Frequency Electronics FE-5602E

Output:
sample frequency: 10 MHz ± 5 ·10-11 sine wave
amplitude: 0.5 vrms (-10% +30%) into 50 ohm load
phase noise: 120 dB at 100 Hz from carrier
signal to noise: 130 dB at 1000 Hz from carrier
harmonic distortion: -30 dBc
non-harmonic distortion: -80 dBc

Input:
supply voltage: 22.5 - 32 V dc
power: max 18 watt at 25 °C with 26 V supply
warm-up time: < 4 min to 10 MHz ± 2·10-10 at 25 °C; < 30 min to 10 MHz ± 5·10-11 at 25 °C

Stability:

long-term stability: $< 6 \cdot 10^{-11}$ first month after 14 days of continuous operation
$< 3.6 \cdot 10^{-10}$ first year (total period)
$< 2 \cdot 10^{-10}$ second year

short-term stability: $\sigma_y(\tau) = 3 \cdot 10^{-11} \cdot \tau^{-½}$ with $1s < \tau < 100s$

The rubidium oscillator is a “reconditioned” one, derived from dismissed military or industry equipments and recalibrated to match the original specifics (the frequency is compared to a Caesium sample with a $5 \cdot 10^{-12}$ uncertainty). The cost is much less than the equivalent new product, and the nominal specs are guaranteed for a certain number of years (almost five).
The external clock has been interfaced with a RF cable to the main GPS receiver (Ashtech Z-XII) of the UNPG station.

The adoption of such a stable external frequency has given an immediate improvement of the data quality. Figure 1 shows an excerpt from the TEQC summary file of the day the clock has been installed (May 19, 1999): the clock resets (“C” flags in the bottom line), which for the internal quartz clock were effected about 30 times a day, has become very sparse (one every few days). Meanwhile, the daily average clock drift has passed from about 1.2 msec/hr to a (printed) zero value.

```
   29|         --YYYYYYYYYYY-            ---IYYYYYYYYYYY-                  |
   30|        --YYYYYYYYYYYIYYYYYYYY                                         |
   31|--                           --YYYYYYYYYYYYYYYYYY-                 ----|
  CLK|C  C C  C C  C C  C C                                                |
     +--------|--------|--------|--------|--------|--------|--------|-------+
     00:00                                                             23:59
                         Rubidium clock connection

Time of First Epoch in File (year,month,day,hour) :99   5  19   0: 0
Time of Last Epoch in File (year,month,day,hour)  :99   5  19  23:59
Observation Interval for File (in seconds)        :      30
```

Figure 1 - Effect of the external rubidium clock

Meteo station

A VAISALA meteo station has been acquired and installed in proximity of the UNPG GPS receiver.
The characteristics of this equipment are the following:

HMP45A-P (humidity and temperature probe)

Measurement range: 0.8 to 100 % RH
-39.2 to + 60°C

Accuracy at 20°C: ± 2 % RH (0 to 90 % RH)
± 0.2 °C

PTU200 Class A (barometer)

Sensitivity 0.01 hPa

Both sensor are supplied with calibration certificate. The meteo station is directly interfaced with the GPS receiver through a serial cable.

Installation of a second GPS receiver

In September, 2001 a second GPS receiver has been acquired and installed on a off-centre marker at a some tenths meters distance from the main one (UNPG marker). This receiver has the function of an integrity monitor for the main station, but its more advanced characteristics will probably make it, in the next future, the primary receiver of the station.

The receiver is a Javad Legacy-E GGD, capable of performing both GPS and GLONASS double frequency measurements. Other advanced characteristics of this receiver are the following:

- 20 L1 channels + 20 L2 channels;
- multipath reduction system ;
- in-band interference rejection;
- 5 Hz real-time capability (code and phase); optionally up to 20 Hz;
- frequency input/output
- geodetic choke-ring antenna RegAnt-2 (L1 + L2, GPS + GLONASS).

Future developments of the UNPG station services, by means of this second receiver, will include the supply of differential corrections (both code and phase) to external users, for kinematic positioning and other applications, by means of radio, telephone or web connection.

Servers for data management

For data collection and management, two servers have been set up.

A first one (with Windows NT o.s.) is directly interfaced to the main GPS receiver (Ashtech Z-XII) and performs the primary data acquisition (1s sampling interval) by means of the Ashtech GBSS software. The 1s daily files are daily archived and filtered, obtaining RINEX files at 5s and 30s interval. The 30s (compressed) RINEX files are daily sent to the ASI Geodaf archive at Matera.

The second server (with Linux o.s.) acts as a "web server" for the 30s-5s-1s data distribution (site URL: labtopo.ing.unipg.it). It has been implemented after a hacker attack suffered by the main server, where the web site had been temporarily placed.

The secondary receiver (Javad) is connected to a third "interim" server, waiting for a better and definitive collocation of the GPS station accessory equipments in the Department building.

Note on the hardware purchase

Among the instruments described above, only the first two (rubidium clock and meteo station) have been acquired by means of ASI founds. All the remaining hardware components have been purchased with other funds (MURST Cofin, Laboratory external services, etc.).

SOFTWARE ACQUISITION

Beside the optimisation of the "hardware part" of the UNPG GPS permanent station, the software part has also been improved.

A first acquisition (December, 1999) by means of the funds of the present project has regarded the already mentioned GBSS (Geodetic Base Station Software) by Ashtech. It is a permanent station management software which has given the station a much better functionality with respect to the batch procedures we had adopted before.

A second important acquisition has regarded the Gipsy-Oasis II v.2.6 software, released by JPL. Two components of the research unity (D.Dominici and A. Stoppini) have attended in April, 2001 the Gipsy class organised by JPL at Pasadena (USA), thus getting the Gipsy-Oasis use licence both for Perugia and L'Aquila Universities.

It is a GPS processing software which follows a different approach from the most common (scientific or commercial) packages, using an undifferenced strategy. Thus, it is particularly appropriate for the analysis of GPS data collected by permanent stations for long periods of time.
The software is currently still under experimentation to evaluate and fully understand the differences with respect to other well-known procedures.

DATA QUALITY CONTROL

The need of a good control of the GPS data quality is particularly evident for permanent stations, collecting a relevant amount of data which are mostly to be used for scientific purposes.
The UNPG data are collected by means of the Ashtech GBSS software, and daily controlled by a routine procedure based on the TEQC software by Unavco. By varying some options and settings of the station management software, an accuracy degradation of the daily position estimates had been noticed, therefore a more refined analysis has been carried out.

The RINEX format

Most GPS high-precision applications for geodesy and surveying involve the post-processing of data collected by two or more receivers, to get the relative positions.
Although all GPS receivers measure the same GPS observables (pseudorange and carrier phase on L1 or L1/L2), each receiver maker has developed its own format for the files where the observation data are stored. In order to reduce the file size for both archive or transfer purposes, most of such formats is of the binary type.
The data processing software developed by any company for their receivers (and normally sold together with the receivers themselves) is obviously able to correctly read their original binary files (raw data). But in most cases it cannot use GPS raw data deriving from other companies' receivers.
Thus, the user is not able to use a certain company's software to process data coming from other receivers. This way, measurement campaigns involving different receivers would be impossible.
Such problems have been overtaken by means of the definition of a common exchange format. A number of software procedures have been developed, which convert the GPS raw data into a common format named RINEX (Receiver INdipendent EXchange). This format has been initially developed by the Astronomic Institute of the Berne University (AIUB) and is presently adopted in the no.2 version.
RINEX files are ASCII text files. The maximum record length is 80 characters. An excerpt of a RINEX file is given as an example in fig.2.

Problems related to the RINEX conversion of the binary files

From the list of the frequently asked questions on the Unavco web site, in the TEQC section, it has been noticed that other researchers had observed discrepancies on the GPS observables in RINEX files created with different software.
A second difference which has been noticed refers to the LLI flag (0-7) and the SNR number (0-9) which follow immediately each observation value. Those numbers, if different from zero, correspond to the fourth or fifth decimal digit of the observation value (the zeros can be given as "0" or "[blank]").

The LLI flag contains in effect up to three information levels:

- bit-0 (1) - signal loss for a satellite and a frequency (L1 or L2) - original meaning of the LLI flag;
- bit-1 (2) - moves the wave length factor to the opposite of the last recorded setting of the WAVELENGHT FACT L1/2 for that satellite and that frequency (L1 or L2);
- bit-2 (4) - anti-spoofing (A/S) is active for that satellite.

```
2              OBSERVATION DATA                        RINEX VERSION / TYPE
ASHTORIN                                 30 - JUN - 01 17:34 PGM / RUN BY / DATE
                                                            COMMENT
UNPG                                                        MARKER NAME
                                                            MARKER NUMBER
___                                                         OBSERVER / AGENCY
                   Z-XII3              CC001D0              REC # / TYPE / VERS
                                                            ANT # / TYPE
  4555176.1180   997836.4798  4337485.3565                  APPROX POSITION XYZ
        0.0520        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     7    L1    L2    C1    P1    P2    D1    D2            # / TYPES OF OBSERV
    30                                                      INTERVAL
  2000     3    31     6    57    0.000000                  TIME OF FIRST OBS
  2000     3    31    23    59   30.000000                  TIME OF LAST OBS
                                                            END OF HEADER
 00  3 31  6 57  0.0000000  0  5  9 30  4  5 29                    0.000000026
 -22402298.994 9 -17420751.40149  20613204.712    20613204.0714   20613211.0864
     -1405.374       -1095.101
 -14598254.878 9 -11357742.77947  22252916.062    22252915.8304   22252924.0184
      2508.420        1954.603
  -7843829.235 9  -6093718.24446  23418075.592    23418075.3564   23418085.6514
      1282.457         999.310
 -18856812.084 9 -14679196.76149  20329278.353    20329277.4434   20329284.4674
       570.559         444.592
  -14831443.078 9 -11532605.84447  22498853.492    22498853.0094   22498860.7244
      1461.153        1138.552
...........
```

Figure 2 - Excerpt from a RINEX file

Unfortunately, the no.2 specific of the RINEX format is ambiguous with respect to which observable should refer to a certain type of LLI flag. TEQC follows this approach:

- bit-0 (1) is properly applied only to L1 and L2 observations for each satellite;
- bit-1 (2) is applied only to L1 and L2 observations if L1 or L2, respectively, are observed in a squared mode (half wave length) for that specific satellite;
- bit-2 (4) is applied to all observation for that satellite.

To understand how other RINEX translators solve this problem is not an easy question. The method used by TEQC for fixing the SNR value (0-9) is the linear algorithm of the piece-wise Bernese, also adopted in the translators of the Bernese "family". With data deriving from receivers of the Rogue family, it is used a logarithmic algorithm also adopted in the JPL translators.
TEQC uses just a part of the possibilities of the RINEX format when it writes the wavelength factors for L1 e L2 in relation to the satellites. There will be only the default record header WAVELENGHT FACT L1/2 with possible value sets of "1 1" (double frequency receiver) or "1 0" (single frequency receiver). The squared L1 and L2 observations (half wavelength) are written only by means of bit-1 in the LLI flag.

The no.2 RINEX specific does not tell exactly how to write each observation value with refer to the significant decimal digits. The observation value is truncated or rounded? TEQC rounds internally each value to the less significant decimal digit using the C function *library floor ()*. What other translator do in such case is not known. In the nav RINEX files, it can be noticed that the TEQC translations give a further significant decimal digit if compared with a conversion of the same binary files made by means of other translators. The resulting format is in agreement with the no.2 RINEX version specific.

RINEX translation with TEQC and ASHTORIN software
From the TEQC user manual, the command lines used to convert Ashtech binary files (like the ones acquired by UNPG main receiver) are the following:

- ash d to read Ashtech download format (and dump RINEX OBS to stdout)
- ash dn to read Ashtech download format and dump RINEX NAV to stdout
- ash s to read Ashtech RS-232 format (and dump RINEX OBS to stdout)
- ash sn to read Ashtech RS-232 format and dump RINEX NAV to stdout

In the specifics of the Ashtech Z-12 RS-232 data format can be read:
The Ashtech Z-12 RS-232 data stream contains the results of a smoothing algorithm which can be applied to the pseudoranges. Normally this is not done. However, the smoothing correction can be applied by using the option +smoothing.
A bug in some earlier firmware for the Z-12 resulted in the millisecond clock resets being applied an epoch too late. If you notice periodic millisecond slips (occurring just prior to the reported clock reset times), try using the option +Ashtech_old_clk_reset during translation. This should remove the firmware artefact from the data.

For the binary to RINEX conversion with TEQC, has been used the command line shown in fig.3, without smoothing correction.

```
C:\teqc\prov_con\094>teqc +ash d bunpg000.094 > teqc094.00o
! Notice ! GPS week initially set= 1056

C:\teqc\prov_con\094>
```

Figure 3 - Command line for the RINEX translation of a binary Ashtech file operated with TEQC

The binary to RINEX conversion operated by the Ashtech ASHTORIN software is fully automatic, and the user cannot set any parameter to a custom value.

Comparison between RINEX files obtained from TEQC vs. ASHTORIN
A comparison between RINEX files obtained with the two different translators from the same binary files has been carried out by means of a procedure implemented in MathCad® and Excel® software environment, which permits to evaluate the differences between the GPS observables for any satellites.
An Excel® spreadsheet has been used to remove from the RINEX files the main header and the “secondary” headers of the observation epochs, thus separating the text fields from the observations. Two text files have been created for any RINEX file obtained through TEQC: “TDDDtesta.txt” (headers) and “TDDDdati.txt” (observations). The same, for the RINEX files obtained from ASHTORIN: “ADDDtesta.txt” and “ADDDdati.txt”. The “DDD” field corresponds to the Julian day. The data filter of Excel® has been used, imposing appropriate conditions on the first column of the spreadsheet.
To get a comparison between the two translators, a number of MathCad® sheets have been arranged to plot the differences between the observable values. Two MathCad® sheets have then been organised to show the comparison in a global summary (when possible) or in single-satellite reports when any problems had been found.

On purpose, the following functions have been implemented:

The functions “**costruzione_dati_ash**” and “**costruzione_dati_teqc**” arrange the data archived in the Excel® files in a matrix with n rows and 9 columns as follows:

- column 0: time in seconds (in the Julian day)
- “ 1: satellite identification number
- “ 2: value of the “L1” observable
- “ 3: value of the “L2” observable
- “ 4: value of the “C1” observable
- “ 5: value of the “P1” observable
- “ 6: value of the “P2” observable
- “ 7: value of the “D1” observable
- “ 8: value of the “D2” observable

An example of the input data is given in fig. 4.

testa_ASH =

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0	0	4	9	10	0	0	0	7	5	25	17	10	22	30	6	0	0	0
1	0	4	9	10	0	30	0	7	5	25	17	10	22	30	6	0	0	0

dati_ASH =

	0	1	2	3	4	5
0	-3051046.212	9	-2365708.369	$2.408 \cdot 10^7$	$2.408 \cdot 10^7$	$2.408 \cdot 10^7$
1	-3190.17	-2485.834	0	0	0	0
2	$-2.107 \cdot 10^7$	9	$-1.639 \cdot 10^7$	$2.144 \cdot 10^7$	$2.144 \cdot 10^7$	$2.144 \cdot 10^7$

Figure 4 - Example of input data for the comparison procedure

The function “**satelliti**” (fig. 5) reads the input matrix “dati” and creates a vector of matrices arranged as follows:

- the index attributed to the vector varies with the satellite to which the observable is referred;
- to each element of the main vector corresponds a matrix with rows following the output of the previous function.

```
Satelliti(dati) := | k ← 0
                   | N_righe ← rows(dati)
                   | for j ∈ 0.. 31
                   |   | for i ∈ 0.. 8
                   |   |   temp1_{0,i} ← 0
                   |   | (dati_sat_j) ← temp1
                   | for i ∈ 0.. N_righe − 1
                   |   | id_sat ← dati_{i,1}
                   |   | temp ← ((dati^T)^<i>)^T
                   |   | dati_sat_{id_sat} ← stack(dati_sat_{id_sat}, temp)
                   | dati_sat
```

Figure 5 - The function “satelliti”

The flow chart of the function "costruzione_dati" is shown in fig.6. The function, as can be seen from the flow chart, generates a matrix called "RIS" with *n* rows, where *n* corresponds to the number of observables of each satellite.

Further, a function called "**diff**", operating on the results of the functions "costruzione_dati_ash" and "costruzione_dati_teqc", creates a matrix where in place of the observables are put the differences on the observable values between the two RINEX translators TEQC and Ashtorin.

Finally, the differences found for each observable (and each satellite) are displayed in a graphic form (as seen in fig. 7 and fig. 8).

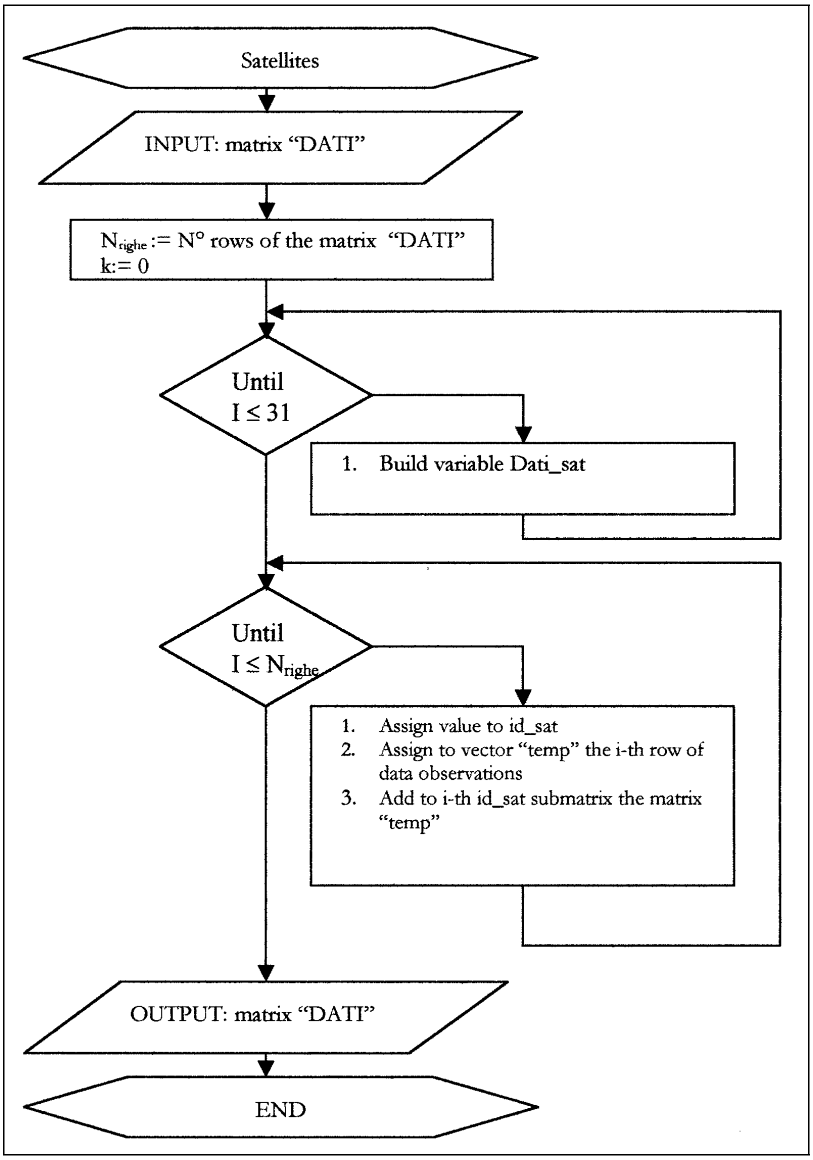

Figure 6 - Flow chart of the function "costruzione_dati"

The comparison between the RINEX files produced with the Ashtorin and the TEQC software has found significant differences. In effect, with the only exception of the L2 phase, all observables show not negligible differences.

The most relevant differences have been found for the P-code observables, in both frequencies. But also the L1 phase is affected with evidence by this problem.
Repeating the procedure with data acquired in different days, it has resulted that the differences remain about constant (both in value and sign).

Such differences in the code observables could be explained with the fact that TEQC, with the adopted procedure, does not take into account the Earth rotation parameters (considering them not significant with respect to the approximation of the code data).
The difference found on the L1 phase appears more “dangerous” and requires a further extension of the research, because the algorithm used by Ashtorin is not documented.

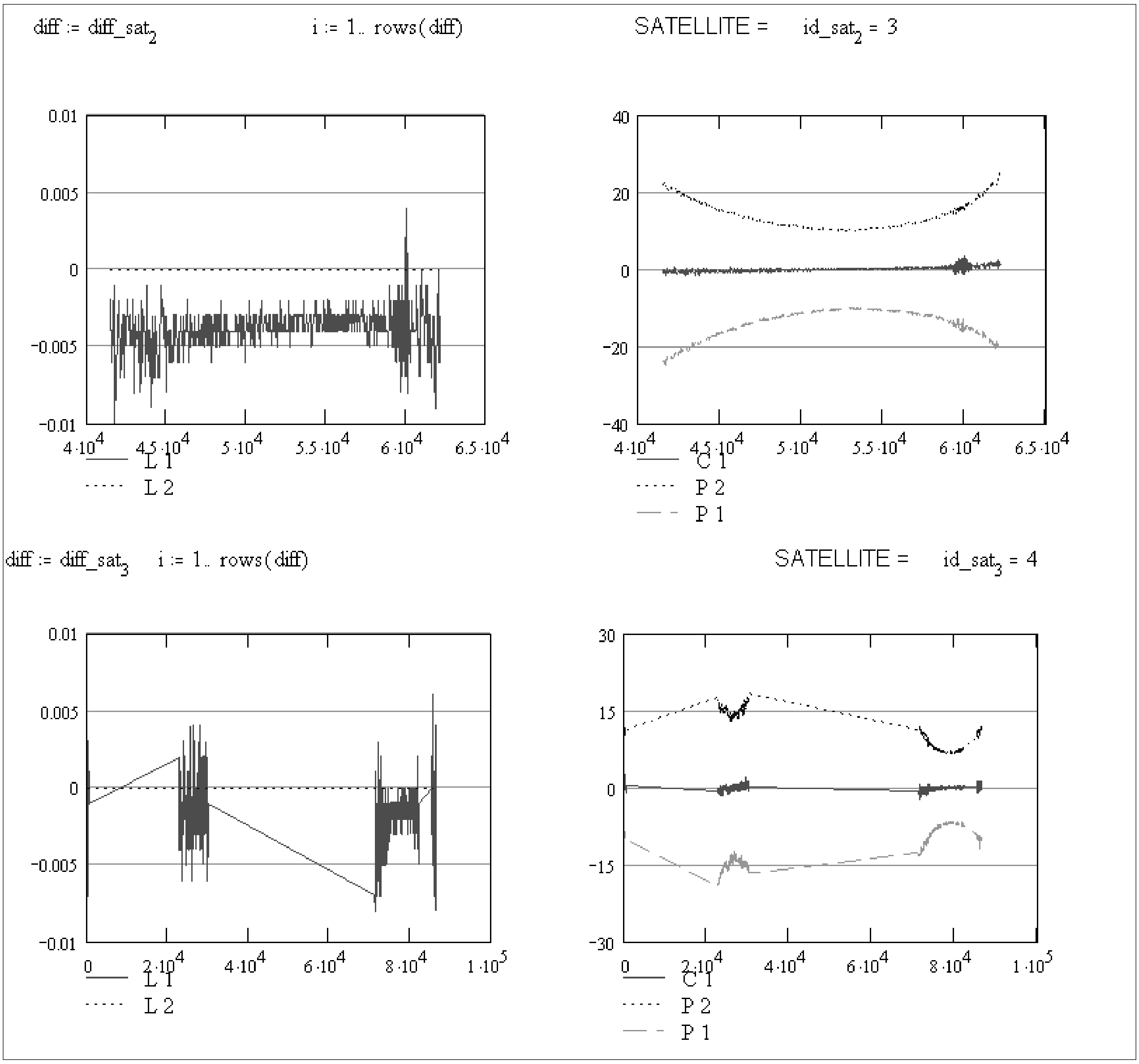

Figure 7 - Example graphics of the differences in L1, L2, C1, P1 and P2 found between TEQC and Ashtorin for two satellites (x-axis: epochs; y-axis: cycles)

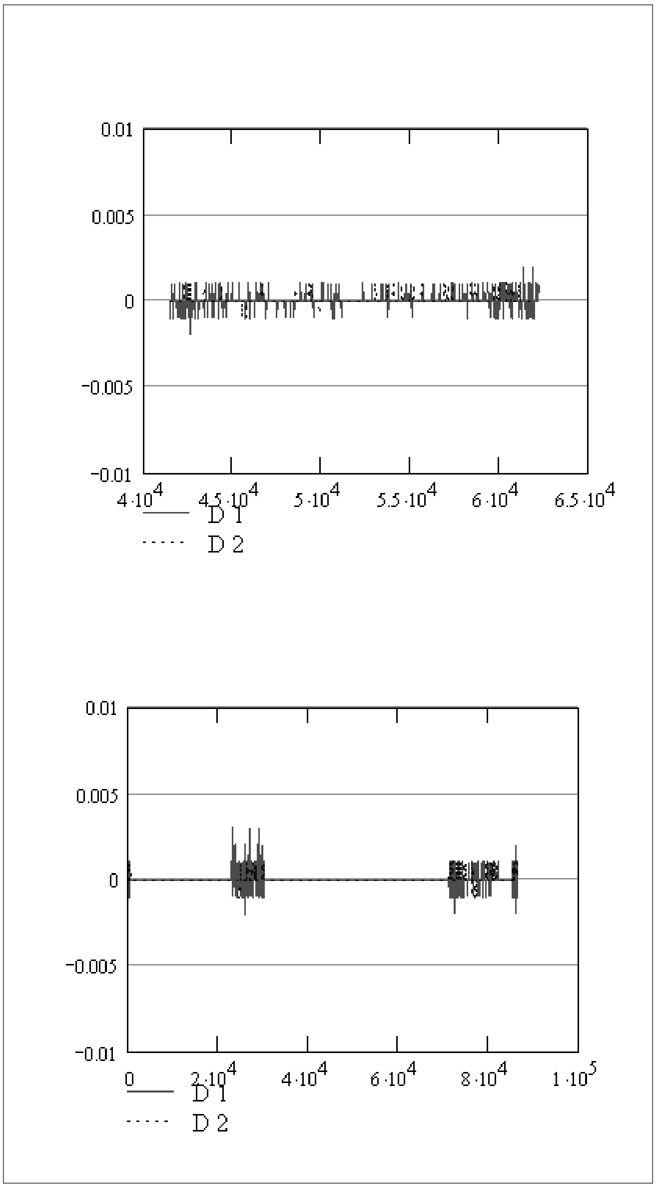

Figure 8 - Example graphics of the differences in D1 and D2 (Doppler observables) found between TEQC and Ashtorin for two satellites (x-axis: epochs; y-axis: cycles)

MEASUREMENT CAMPAIGNS

In the frame of the present and other correlated research projects, a number of measurement campaigns with many different purposes have been carried out involving the UNPG station as reference. Here will be briefly referred about the campaigns which have given some kind of improvement to the station herself (such as derivation of coordinates in a certain datum, monumentation strengthening, etc).

Local control network
In the immediate proximity of the UNPG station, a local network has been established for two purposes:
- stability control of the main marker (UNPG);
- realization of a series of auxiliary markers for the installation of secondary receivers and/or for other instruments calibration.

The network comprises 7 vertices, at a distance from the UNPG station up to some hundreds of meters (fig. 9).

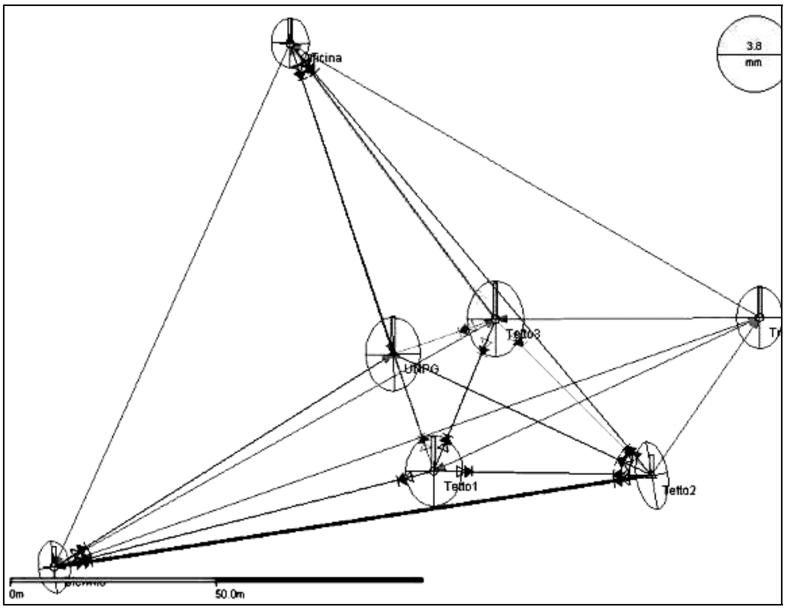

Figure 9 - Local control network (mixed adjustment)

The network has been measured both with GPS (static mode, double frequency) and classical instruments (distance meter, theodolite), then computing separate and mixed adjustment solutions.
A repetition and extension (up to some kilometres distance) of this control network is presently being carried out.

Connection of the UNPG permanent station to the IGM95 network
A measurement campaign has been performed to connect the UNPG station to the national IGM95 network, for the purpose to compute the WGS84 coordinates of UNPG.
The network (fig. 10) comprises six IGM95 vertices, at distances from UNPG up to some tenths of kilometres. The measurements have been performed by means of double frequency GPS receivers, in static mode, effecting sessions of some hours.

The WGS84 coordinates deriving from such network are congruent with the IGM95 network coordinates, which are referred to the ETRF89. For technical purposes, the IGM95 network is commonly assumed to be the Italian "realization" of the WGS84 datum.
The UNPG coordinates computed as above are intended to be used only for technical applications of the UNPG data (such as mapping or cadastral works), where the appropriate use of ITRF coordinates would present some difficulties to the users.

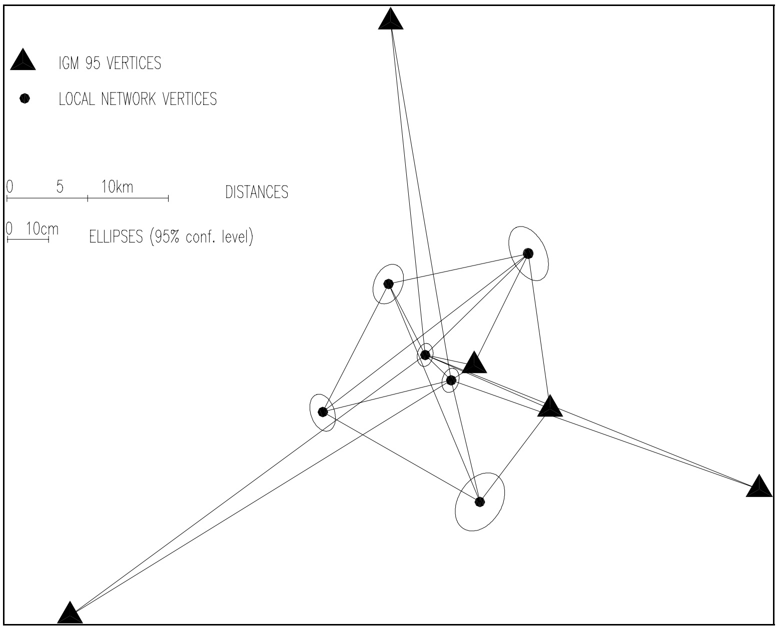

Figure 10 - Network for IGM95 connection

Connection of the UNPG permanent station to the IGM levelling network

The UNPG marker has been connected to the IGM levelling line no.12 (Arezzo-Perugia-Foligno), in order to get a better estimation of the orthometric height of the station.

The measurements have been performed with a Leica Na3003 digital level and a pair of codified invar rods.

GPS network and meteo data

In March-April, 2000 a local geodetic network has been established "around" the UNPG station, in the frame of a research aiming to the determination of water vapour content in the troposphere through GPS data, in cooperation with the ASI research unities of Milan and Rome (Betti et al., 2000).

The network is composed by four vertices, at some tenths kilometres distances from the UNPG station, beside the UNPG point itself. Long sessions (more than a week) have been effected, with continuous acquisition of meteo data (temperature and pressure) on the measurement sites.

The data deriving from this project have also been used to evaluate the effect of different tropospheric delay models (Saastamoinen, Hopfield, etc), with accurately measured meteo data, on GPS position estimations. Comparisons have also been made between solutions obtained by taking into account the measured meteo data vs. the default values (1013 mbar; 20°C) often assumed in common GPS surveys.

The processing has been made by means of the Bernese 4.2 software.

Figure 11 shows, as example, the differences on the position estimates for a network point (Montone) obtained from the same set of GPS data in three different modes: Saastamoinen model with default values (METEO STAND), Saastamoinen with measured values (METEO SAAS) and Hopfield model with measured values (METEO HOPF). Obviously, the GPS data and all other processing options are exactly the same for the three solutions.

The two models, using the measured values, show a substantial agreement on the position estimates, while the solution obtained through the default parameters is slightly different.

Similar results have been obtained for the other points of the network.

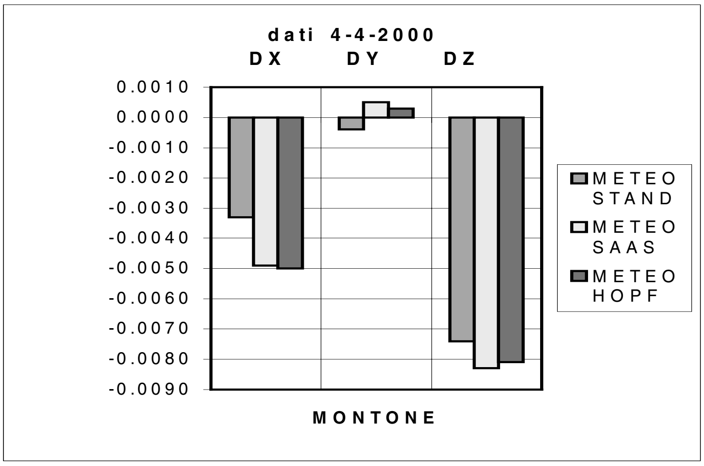

Figure 11 - Differences in a daily position estimate of Montone from the reference solution (weekly combined solution) y-axis: meters

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Research Unit
"UNIVERSITÀ DI TRIESTE"
(UNITS)

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- ***Real time differential GNSS integrated with INS and GSM position data transmission***
  (R. Cefalo, M. Lipizer, G. Manzoni, S. Martinolli, R. Pagurut, A. Piemonte, T. Sluga)

REAL TIME DIFFERENTIAL GNSS INTEGRATED WITH INS AND GSM POSITION DATA TRANSMISSION

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Summary
The main activity of the Trieste University research unit, co-ordinated by G. Manzoni, was devoted to three main items, i.e. investigation on the Real Time DGPS and RTK methods from the point of view of cost, availability and accuracy, the integration of this method with INS systems (road as well as air pollution mapping are the immediate applications), the best transmission method of GPS position data to a control centre, also in view of the implementation of a personal rescue service.

Real time DGPS and RTK
Differential and interferential GNSS (Global Navigation Satellite Systems) need to be used, better in real time, in order to get the maximum accuracy.
For this purpose, the following RTCM (Radio Technical Commission for Maritime Services) were tested in our experiments:

Low frequency carriers:
ALF (Accurate Positioning by Low Frequency) operated by Bundesamt für Cartographie und Geodesie (BKG) in Frankfurt am Main, Germany;
LF transmitter from Prague (Czech Republic); it transmits the DGPS corrections generated at the Czech Technical University (CTU) Reference Station, Prague; the signal coverage is shown in Fig.1: it covers a large portion of Central Europe; a cross marks the site where different types of corrections were tested, even if by different GPS receivers.

High frequency carrier (VHF, UHF):
DARC (Data Radio Channel)/Swift (System for Wireless Infotainment Forwarding and Teledistribution) - the RTCM and RTK emission was a service by ORF (Österreichische Rundfunk) on the FM band;
DAB (Digital Audio Broadcasting) is reported (Manzoni e Plattner, 1999, Di Girolamo, 2001, Private communication) to be continuously operational in the Bolzano area as far as regards Italy;

GPS like from Geostationary Telecomunication Satellites:
RACAL System
EGNOS (European Geostationary Overlay Service) actually under ESTB (EGNOS System Test Bed) phase, operated by ESA (European Space Agency);
WAAS (Federal Aviation Administration System**)** operated by FAA.

Having the research the Central Europe as target area, some experiences have been performed in Trieste, Bolzano, Villach and other parts of Austria.
They have been performed in cooperation with the University of Prague, the University of Warmia and Masuria and the DGPSNetz of Austria.

Figure 1- RTCM Correction Sources tested in our Experiments, and LF from Prague Signal Coverage

Activities at the University of Trieste
The main tests have been performed with:
LF transmitter in Prague,
DARC
DAB: tested in cooperation with the geodetic service of the Trentino - Alto Adige Region and the RAF Radio Service.

As mentioned before, the co-operation between these groups and the University of Trieste, has produced some experiments in Villach (Austria), Bozen, Attersee (Salzburg, Austria) and Salzburg itself, in Vienna, beyond on the routes from these cities and Trieste.
The most significant has been carried out in Villach (Faaker See), where ALF (from Frankfurt am Main) and DARC (from Villach) diffused DGPS corrections had already been received, and where it was possible to receive LW from Prague signal too. The co-ordinates of a reference point from an L1/L2 baseline solution from Trieste (100 Km away) has been calculated.
A Trimble 4000SE (RTCM input) was placed some meters away from the former receiver to be linked to the different DGPS corrections radio receivers. A previous static baseline was recorded.
Figure 2 shows the results of an experiment performed on 24th November.

24th November experiment	*LW Prague*	*ALF*	*DARC*
Ref. Point N = 5158077.40 E = 416535.96 (UTM ED50), H (WGS84) = 604.71 m			
ΔN (m)	-2.41	-4.84	-0.01
ΔE (m)	-1.30	1.90	-0.40
ΔH (m)	0.73	0.36	0.88

Figure 2- Differences between the N, E, H mean values of the three data sets and the co-ordinates of the reference points

As expected (being the source of corrections a few kilometres away only), DARC diffused RTCM corrections gave the higher accuracy.
Anyway good results and a great repeatability are also shown by distributions obtained using LW diffused corrections from Prague. This confirms the possibility to use LW transmitters to cover most of Central Europe by RTCM corrections dissemination.
For applications that require higher accuracy, local correction sources have to be adopted using higher baud rate modems.
A good repeatability has been obtained in the mean values for all the adopted systems.
Since from the earlier experiments DARC has been the most convenient system, in terms of cost and accuracy for urban or regional areas.
Hence DARC has been installed in Trieste, having the support of the private radio transmitter Radio Punto Zero, for further tests.
Moreover, the availability of periods of GIC/WAD corrections transmission from EGNOS System through Geostationary Inmarsat Satellite PNR120, allowed static and kinematic experiments (Cefalo et al., 2000, Cefalo, 2001; Cefalo, Gatti, 2001).
The following paragraphs will described such researches and results.

DARC

Thanks also to the co-operation of Dr. Herbert Doeller of the DGPSNetz , Austria, a RTCM transmitter has been installed in Trieste (Doeller H. et al. 2000). In Figure 3 the components of the systems are illustrated.
A DARC encoder TSE 760 by Sectra and a DARC receiver Sectra DRM-300 were used. The RTCM as well as the RTK output of a GPS Trimble 4000SSE geodetic receiver was sent to a PC for coding by USEP (*Universal Swift Encoder Communication Protocol*) into DARC format; then the signals were transmitted by modem into the cable telephonic network; the data were received by a GSM modem just under the FM installation, where they were inputted into the DARC coder and then into the FM unit (Manzoni G., Pagurut R., 2001).
Till now only one of the two antennas by Radio Punto Zero, Trieste, has been used. This antenna covers the town centre of Trieste so to allow the experiments in this area with the DGPS/INS vehicle described in the following. The Radioelectric Centre G.Marconi of Area Science Park as well as TIM cooperated to the measurements.

The accuracy of the DARC DGPS is within 0.5 metres, while the stand alone dispersion is within 2 metres (figure 4). The operational conditions are quite good, the antenna being installed on the roof of the Department of Civil Engineering.

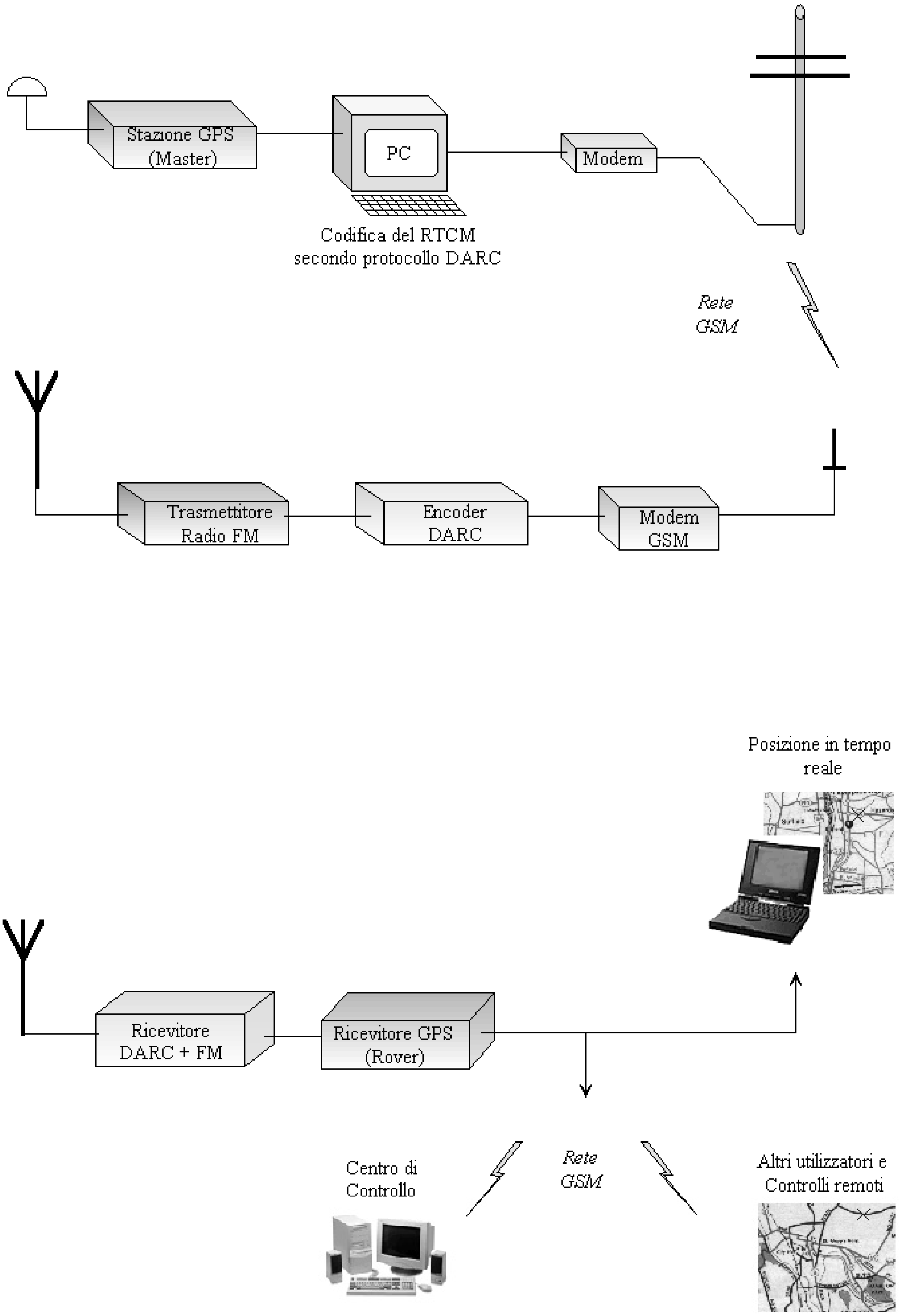

Figure 3 – DARC System

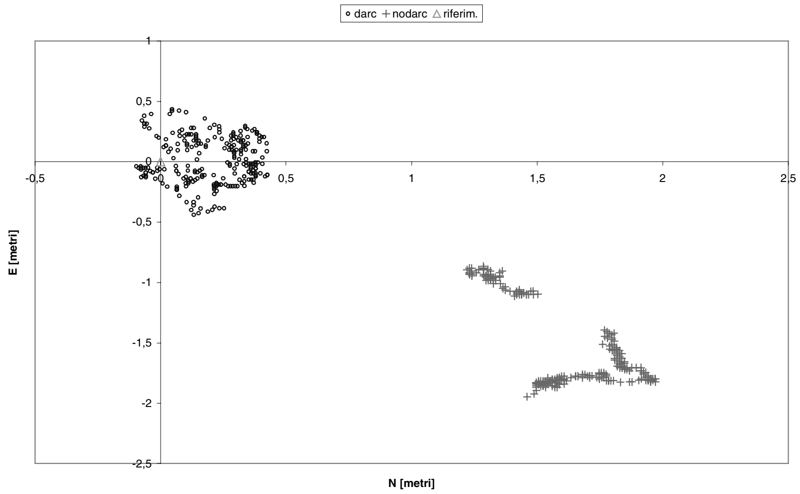

Figure 4 – Differential GPS obtained using DARC vs GPS Stand Alone

In case of DARC RTK in static mode a repeatability within 5 centimetres has been obtained.
Finally some kinematic tests have been performed.
In conclusion the DARC transmission of both the RTCM and the RTK corrections (data) has been satisfying.
In figure 3, the end device of the chain is the DGPS/INS van which is shortly shown in the following figures.

Figure 5 - GIGI (Gps Integrated with Glonass and Inertial navigation system)

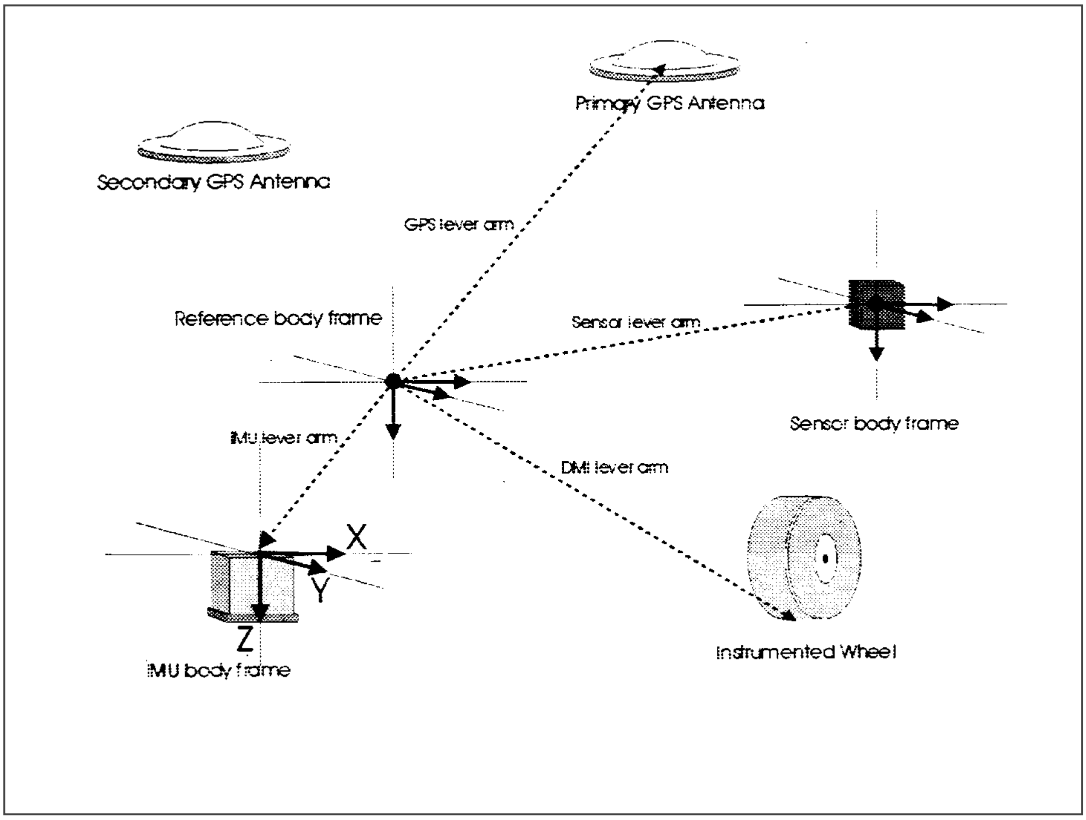

Figure 6 - Vehicle mounted Components' Scheme

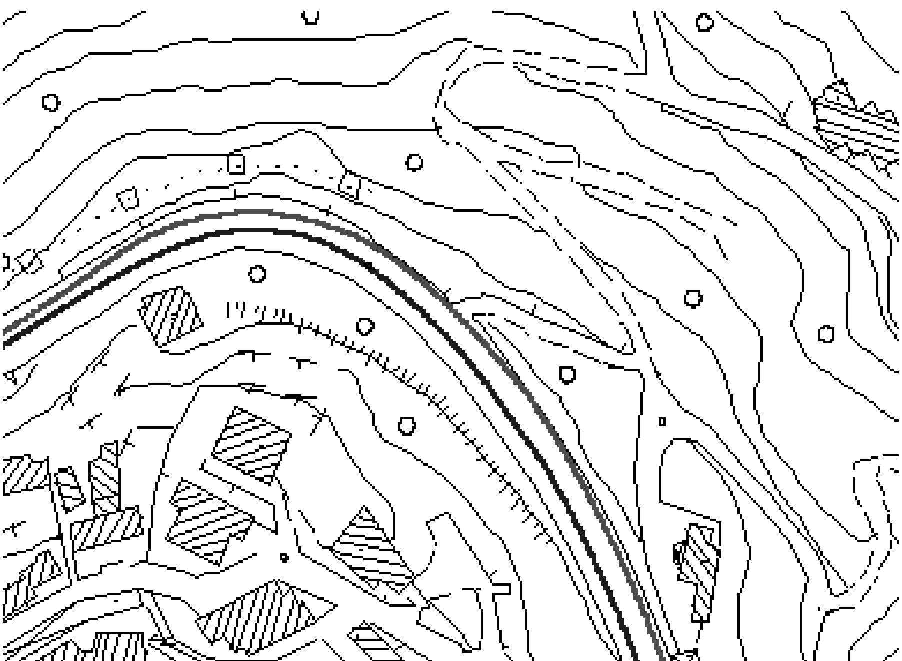

Figure 7 - Example of round trip trajectory of GIGI in DGPS/INS mode.

EGNOS

EGNOS has been reported as active from 24th April to 2000. The system uses the INMARSAT (International Maritime Satellite Organization) III AOR-E (Atlantic Ocean Region-East) geostationary satellite PRN 120 located at 15.5° W.

Two Novatel Millennium®, Canada, receivers were operated in Trieste, respectively at the University and at the G. Marconi Centre in the Area Science Park, Padriciano, Trieste, in static and kinematic mode (Cefalo, 2001; Cefalo, Gatti, 2001).

Satellite PRN120 (218° azimuth, 30° elevation from our site) was locked, but initially the EGNOS corrections have been received only in few intervals.

Then, the WAAS-FAA GIC/WAD (GNSS Integrity Channel: broadcasting of integrity information/Wide Area Differential: broadcasting of differential corrections), coming from the INMARSAT III AOR-W (Atlantic Ocean Region-West) geostationary satellite (PRN122), positioned at 54.0° W, have been received too, and the EGNOS signals became nearly continuous.

Figure 8 shows the East, North UTM WGS84 co-ordinates computed with the corrections received from the two geostationary satellites in different sessions: the distribution relative to satellite PNR122 shows lower accuracy, which fact is due to the applied ionospheric model, calculated by Wide Area Reference Stations located in the USA.

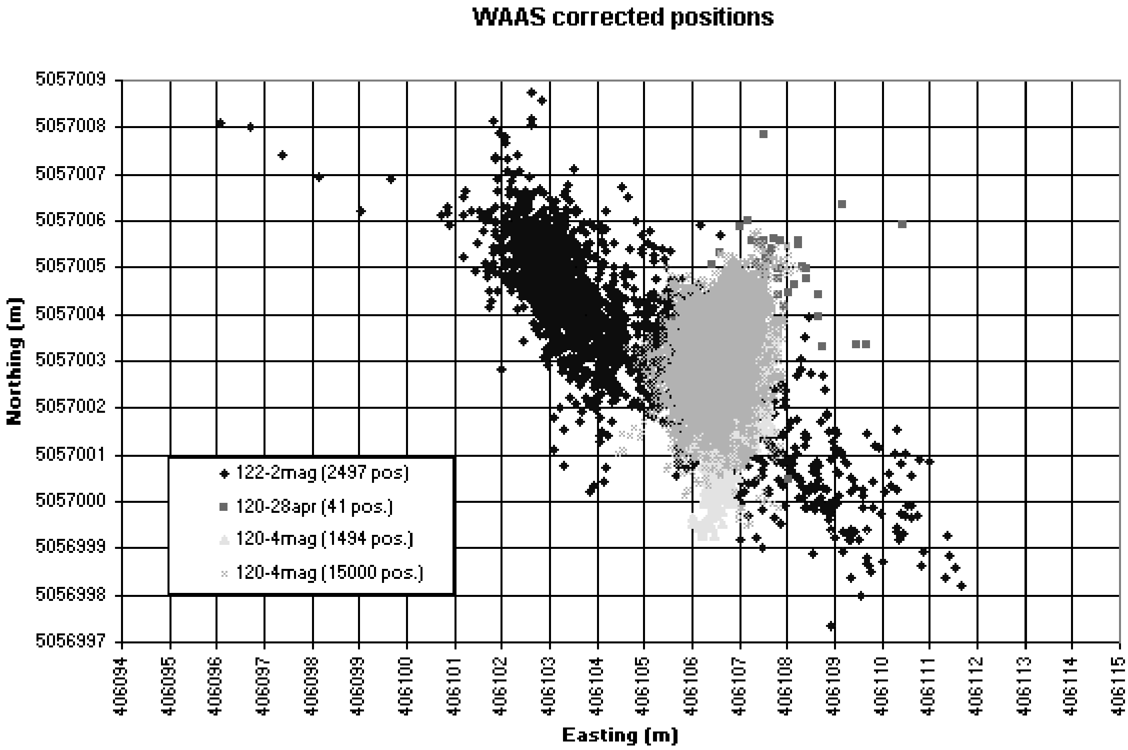

Figure 8 - Positions calculated in different sessions using WAAS-EGNOS and WAAS-FAA corrections

Conclusions

The cheapest and most reliable method for real time DGPS is the DARC one for urban area.
For extra-urban areas, the use of tele-communication satellites, EGNOS in particular, appears the best system and it is on the lines of the European Community.

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- ***Space geodesy based researches in the years 1998-2000 at Cagliari Observatory: the co-location of space techniques***
  (A. Banni, F. Buffa, L. Mureddu, A. Poma)

SPACE GEODESY BASED RESEARCHES IN THE YEARS 1998-2000 AT CAGLIARI OBSERVATORY: THE CO-LOCATION OF SPACE TECHNIQUES

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Preface

The main last achievements of CSTG (Commission on International Coordination of Space Techniques for Geodesy and Geodynamics) are the creation of the ILRS (International Laser Ranging Service) and the IVS (International VLBI Service), using the IGS (International GPS Service) structure as a template, efforts on the ISGN (International Space Geodetic Network) establishment and the organisation of the GLONASS Experiments IGEX-98.

It is remarkable that the ILRS and IVS could be set up in a comparatively short period of time. Both ILRS and IVS are technique-specific networks and their analysis centres generate well-defined products. The three services IGS, ILRS and IVS make available results in the same format, which allow it for specialised combination centres, within IERS, to come up with combined results in a much more meaningful way than it was possible before. IGEX-98 was scheduled for few months on 1998-1999, but because of new GLONASS satellites and steady and significant growth of the IGEX network it was extended. It involves microwave tracking of GLONASS and GPS satellites, and it allows for SLR support (last GPS and all GLONASS satellites have retroreflectors). It also involves coordination with other organisations, as IGS and IERS. The main task of the experiment was to measure the difference between SLR distances (as made by the stations in the ILRS network) and the corresponding distances computed by GLONASS Broadcast orbits and by IGEX precise orbits. One may conclude that the GLONASS orbits are now available in the same reference frame as the GPS satellites with an accuracy of a few decimetres.

"Strengths and weakness of space techniques" was the title of a session at the IAG (section II) Munich meeting and the following weaknesses were reported:

- Satellite geodetic techniques, in particular SLR and GPS, do not have a direct access to the inertial reference frame (but only trough the equation of motion);
- Satellite geodetic techniques are capable of monitoring changes in the inertial reference frame (which correspond to orbital accelerations (Coriolis-type)). It is thus possible to measure "length of day" (equivalent to the first time derivative of UT1-UTC), and nutation drifts in longitude and obliquity;
- The VLBI technique neither has access to the geocenter nor to the Earth's gravity field;
- Despite the fact that today we have remarkably good orbit models to account for non-gravitational accelerations always a problem when dealing with satellite microwave systems remains. Systematic differences between SLR measurements to GPS satellites and the corresponding ranges computed from IGS orbits reveal that the SLR calibration may be required.

A similar conclusion emerges from analysing TOPEX/POSEIDON data. Then it is of interest that satellite geodetic techniques would have access to the inertial reference frame, if astrometric observations were available. It would be worthwhile to take this aspect into consideration in view of the much-improved astrometric catalogues (HIPPARCOS). The above list of deficiencies let us conclude that all space techniques are required to give satisfactory answers to the questions asked in geodesy, geodynamics, and astronomy.

Over the years a number of space geodetic analysis groups have inter-compared the data sets from collocation sites starting with the VLBI/SLR comparisons done during CDP Campaigns and, more recently, with VLBI/GPS, SLR/GPS and SLR/DORIS comparisons. In general the results from these analyses have shown the agreement between the techniques to be quite low. There are a set of problems encountered by the analysts that make their work more difficult and limit their abilities to get the most out of the sets of data:

- Inadequate data sets from one of techniques for the period being analysed or insufficient numbers of global sites with collocations of techniques;
- Variations in experiment operations or ancillary measurements over time;
- Inadequate configuration control records for one or both of the techniques over time;
- Imprecise, or poorly defined or undocumented survey ties from the technique measurement point to a common ground monument;
- Survey ties derived from unsubstantiated communications without a standard format;
- Lack of a central location or system for obtaining survey ties for important collocation sites.

In order to make any formal comparison between space geodetic systems of the same or different techniques, a high precision geodetic survey must be conducted to tie the systems to a common, invariant reference point. This requires that a substantial set of ground monuments be established on and around the site. It also requires that a physical point on the space geodetic system, whether it be an SLR telescope, VLBI parabolic dish antenna, or GPS/GLONASS ground antenna, be established as the measurement point to which the technique's own data is referred. The next step is a geodetic survey to tie the measurement point to the ground monuments. The quality of this survey must be consistent with the precision assumed for the space geodetic techniques in order not to bias the results. With today's space geodetic systems these survey ties must be made with precision at the 1-2 millimetre level.
Thanks to the ASI-ARS financial support, concerning the research projects for the years 1998, 1999 and 2000, the scientific staff of the Space Geodesy section of the Cagliari Astronomical Observatory, started to study the co-location problems.

The Cagliari Observatory and collocation surveys
The Stazione Astronomica di Cagliari (SAC), formerly member of the International Latitude Service, is well suited for the study of crustal movements and euro-african tectonics because of own position and research's fields. The activities of SAC are mainly devoted to Earth oriented space research, and especially to the reduction and analysis of data based on astronomical and space geodesy techniques, such as GPS and SLR; in particular a fixed, fiducial GPS station, connected to the IGS, and a fixed SLR station, belonging to the European network EUROLAS, have been operative since almost a decade and a further new GPS/GLONASS receiver started observations in early 2001.
The fixed GPS system, established under the ASI-CGS responsibility, was made up of a Turbo Rogue SNR8100 + Dorne-Margolin choke rings antenna equipment (until July 11 2001) and now replaced with a TRIMBLE 4000SSI + TRIMBLE L1/L2 Dorne-Margolin choke rings antenna. Time series and performance concerning our GPS system are shown in figures 2 and 3.
The SLR observations were made, at first, by several mobile laser stations (belonging to the WEGENER Project) from late 1985 until late 1993 and since 1994 by means of the fixed laser station. Following the schedule of the ASI related project, the laser station was implemented in order to achieve ranging observations as far as of GPS and GLONASS satellites. Then the schedule concerned at first the Laser Station implementation with devices suitable to do ranging as

far as GPS and GLONASS satellites. I. e. updating on emission-receiving electronics and optics. But the purchase of a receiver with GLONASS spread was not achievable within the year 2000.

According to the ILRS Analysis centre reports the SLR Cagliari station performances are:
- single shot rms = 65 mm
- normal point rms = 20 mm

and in particular for GLONASS satellites:
  - precision ranging = 9 mm
  - average normal point/pass = 4
  - IGEX-98 Campaign accepted passes and n. p.

GLONASS Sat #	accepted passes	normal points
68	1	2
70	1	3
79	1	8

In advance a Unix workstation was set up with the well-known software GEODYN IIE, a training course, held by E. Pavlis, was attended by the involved researchers and an easy reference handbook was issued.

We also had surveyed and connected all the Observatory points in order to properly determine the their eccentricities with regard to the reference system defined by the different space techniques running at our Observatory.
In order to recognise the relative positions of the main benchmarks of our Observatory, we have made several surveys of the local network with both classical and space geodesy techniques. The relevant points of Cagliari Observatory are shown in figure 1 and described in table 1.

Surveys on the relevant points in the observatory and on some first order Italian Network benchmarks were performed by either classical topographic observations or static GPS measurements:

- The COB surveys include azimuth angles, zenith angles, EDM distances, and for the relative adjustment, performed by GEOLAB software, fixed points are 7545, Pier 7 and one high.
- The static GPS surveys adjustment was also performed by GEOLAB software, with 7545 as fixed point.
- The network adjustments are referred to the year 1994, and the coordinates we use for the fixed point 7545 are from SSC(JPL)95P02 and SSC(CSR)95L01 sets.
- Besides we translate coordinates to ITRF94 reference by means of transformation parameters published on IERS TECHNICAL NOTE 20 (March 1996).

The first analysis about the connection between the coordinates carried out by GPS and SLR techniques were shown at the first international conference on Co-location (GEMSTONE) in Tokyo.

Preliminary computation and analysis of co-locations about points 7545 and 7548, obtained by GEODYN software and absolutely locally defined, are reported below. Data we used are the Satellite Laser Ranging observations performed in common-view from January to March 1994. In fact during the period from October 1993 till March 1994 the NASA TLRS1 mobile laser station worked at the Cagliari Observatory (7545/WEGENER campaigns), meanwhile our fixed laser station (7548) became operative and we were able to reach several LAGEOS passes in common view.

In the following tables the main results obtained in the computation of the collocations and of the transformation parameters are reported. Recently the Italian "Istituto Geografico Militare" computed the new Italian Network (IGM95), based on ETRF89 campaign.

IGM coordinates of Observatory points, together with transformation parameter between WGS84 and Gauss-Boaga Projection.

POINT	N/sigma	E/sigma	H/sigma
1 –7545	4331813.196/0.000	497665.449/0.000	229.946/0.000
5 –7548	4331942.154/0.005	497583.998/0.017	252.111/0.021
7 - PIER	4331961.795/0.000	497702.209/0.000	245.665/0.000
8 - PIER	4332173.400/0.018	497872.345/0.016	274.691/0.000
2 - ASTROL.	4331931.801/0.004	497651.810/0.007	254.986/0.045\
3 – PZT	4331921.889/0.005	497646.670/0.007	256.531/0.046

Adjusted coordinates from classical observations - Reference system WGS84 UTM32 - Fixed stations (SSC(JPL)95PL02 SOLUTIONS): 7545, PIER 7, Height PIER 8

POINT	X/sigma	Y/sigma	Z/sigma
1 - 7545	4893398.014/0.000	772673.423/0.000	4004140.999/0.000\\
5 - 7548	4893347.293/0.017	772582.879/0.017	4004255.039/0.014\\
7 - PIER	4893311.638/0.000	772696.972/0.000	4004266.240/0.000\\
8 - PIER	4893175.318/0.013	772847.703/0.014	4004448.798/0.014\\
3 - PZT	4893353.528/0.035	772647.346/0.009	4004242.120/0.029\\
2 - ASTROL.	4893345.360/0.034	772651.259/0.008	4004248.836/0.028\
dXdYdZ 7548-7545	-50.721	-90.544	114.040
SLOPE DISTANCE	154.195		

Adjusted coordinates from static GPS observations - Reference System WGS84 UTM32 - Fixed stations (SSC(JPL)95PL02 SOLUTIONS) : 7545, PIER 7

POINT	N/sigma	E/sigma	H/sigma
1 - 7545	4331813.196/0.000	497665.449/0.000	229.946/0.000
5 - 7548	4331942.156/0.002	497584.000/0.001	252.104/0.003
6 - GPS	4331859.156/0.001	497644.889/0.000	238.415/0.001
7 - PIER	4331961.793/0.001	497702.209/0.001	245.585/0.002
6bis - PIER	4331856.719/0.001	497645.390/0.001	237.957/0.002
POINT	X/sigma	Y/sigma	Z/sigma
1 - 7545	4893398.014/0.000	772673.423/0.000	4004140.999/0.000
5 - 7548	4893347.287/0.002	772582.880/0.001	4004255.037/0.003
6 - GPS	4893379.051/0.001	772649.592/0.000	4004182.004/0.001
7 - PIER	4893311.578/0.002	772696.962/0.001	4004266.189/0.001
6bis - PIER	4893380.142/0.002	772650.272/0.001	4004179.824/0.001
DXdYdZ 7548-7545	-50.727	-90.543	114.038
SLOPE DISTANCE	154.194		

Preliminary 7548 coordinates from SLR data (GEODYN EII)
Fixed Stations (SSC(CSR)95L01 solution): 1181, 1884, 7805, 7810, 7811, 7824, 7831, 7833, 7834, 7835, 7836, 7839, 7840, 7939, 8834, 7545

POINT	X/sigma	Y/sigma	Z/sigma
1 – 7545	4893398.031/0.000	772673.384/0.000	4004141.057/0.000
5 – 7548	4893347.240/0.494	772582.644/0.498	4004255.255/0.496
DXdYdZ 7548-7545	-50.791	-90.74	114.198
SLOPE DISTANCE	154.450		

ETRF89 coordinates (WGS84 UTM32)

POINT	N	E	H
1 – 7545	6437.10.00	38913.35.00	229.98
6 – GPS	6483.05.00	38893.17.00	238.39
TRANSF. PARAMS	d = 13.9 ppm T = 152.47 4.54 13.53 R = 1.620" -2.107" -1.069"		

ITRF4 Coordinates from IERS Technical Note 20 - Transformation parameters SSC(JPL)95P02

POINT	X	Y	Z
1 – 7545	4893398.013	772673.400	4004141.042
5 – 7548	4893347.286	772582.857	4004255.080

ITRF4 Coordinates from IERS Technical Note 20 - Transformation parameters SSC(JPL)95I01

POINT	X	Y	Z
1 – 7545	4893398.036	772673.392	4004141.063
5 – 7548	4893347.245	772582.652	4004255.261

From the above tables then it results that COB surveys solution coincides with the static GPS one. There is consistency between the two solutions and the use of eccentricities referred to WGS84 reference is correct.

By using global solutions and their relative transform parameters we can tie the Observatory network to the International Terrestrial Frames, through internal benchmarks belonging to different techniques, such as mobile Laser, fixed Laser, fixed GPS antenna, fixed GPS/GLONASS antenna and, in the near future (within 2004), the new VLBI radiotelescope (64 meters) that will built 40 Km apart from the Cagliari Observatory.

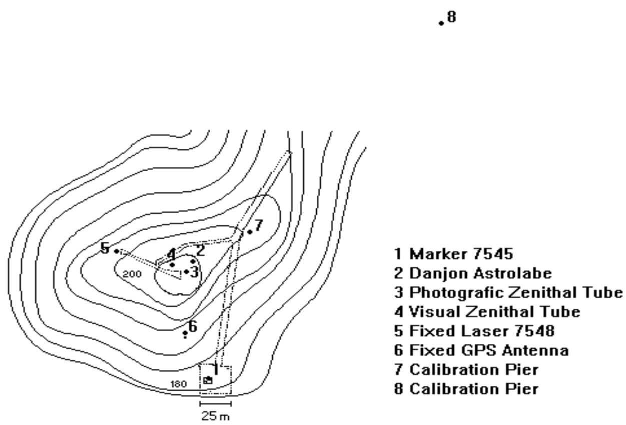

Figure 1 - The local network at the Cagliari Observatory

N.	Name	Number/Campaign
1	Marker 7545	7545/WEGENER/CDP, 12725M002/ITRF, IGM/234903
2	Danjion Astrolabe	
3	Photographic Zenithal Tube	
4	Visual Zenithal Tube	
5	Fixed SLR Station	7548/WEGENER/CDP, 12725S013/ITRF
6	Fixed GPS Antenna	12725M003/ITRF, 69/EUREF
6bis	Fixed GPS/GLONASS Ant.	
7	SLR Calibration Pier	
8	Geodetic Pier	234902/IGM
9	Levelling Benchmark	
10	Timing GPS Ant.	

Table 1 - Relevant geodetic points at the Cagliari Observatory

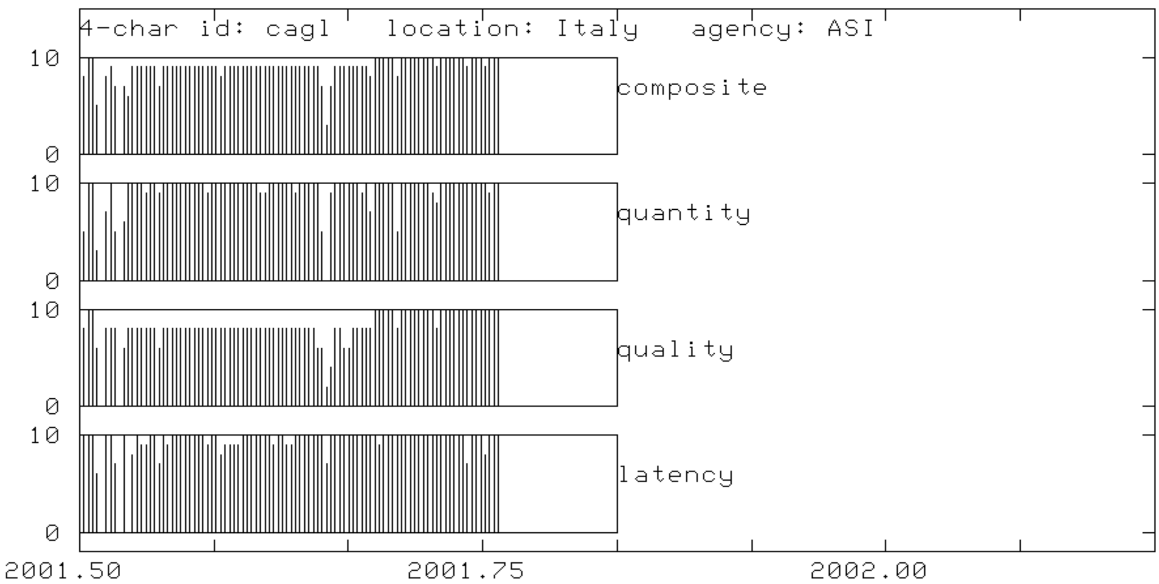

Figure 2 - Cagliari GPS station performance example (http://igscb.jpl.nasa.gov/igsnet)

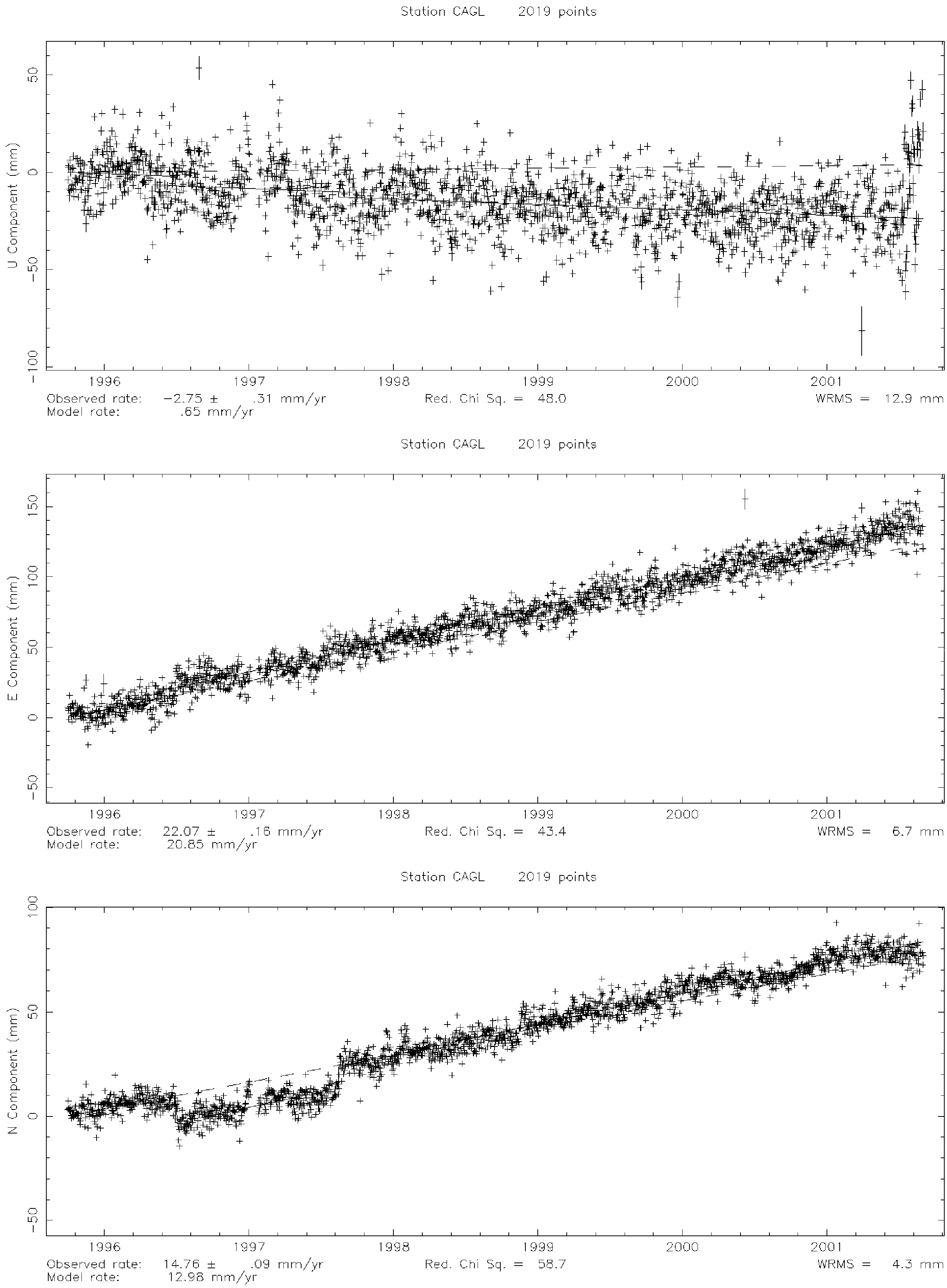

Figure 3 - Time series of the geodetic coordinates (http://geodaf.mt.asi.it/DATA/GEOD/GPSD/GEODETIC_SOLUTIONS/TIME_SERIES)

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- ***GPS, SAR and laser scanning activities in the Neapolitan volcanic areas***
  (V. Achilli, S. Borgstrom, C. Del Gaudio, G. Salemi, V. Sepe)

GPS, SAR AND LASER SCANNING ACTIVITIES IN THE NEAPOLITAN VOLCANIC AREAS

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Introduction

The Operating Unit of Padua University is hosted at the Engineering Faculty by the Prof. Vladimiro Achilli. Former the same OU was hosted at the Osservatorio Vesuviano – Naples. The people involved in the phase 1 (Naples) and in the phase 2 (Padua) are the same ones, coming from the Osservatorio Vesuviano, the Padua University (DAUR), the Bologna University (DISTART), The Udine University (DIGE).

In this framework, some activites were performed either as research activities either as measurements campaigns:
GPS: campaigns of static measurements in the Aeolian Islands together with other geophysical and volcanogical surveys, including classical photogrammetric and INSAR observations, to detect and describe the geodynamics of these islands arc for geodynamic applications and monitoring of crustal deformations.
INSAR: georeferencing problems, comparison between different DTMs, monitoring of crustal deformations by Sar with an application to an area on the Vesuvius.

Geodetic and geophysical data integration

A very interesting topic was developed about the spatiotemporal GIS techniques for the management of geodetic and geophisics temporal series in the Neapolitan Volcanic area.
On the island of Ischia (one of the Neapolitan volcanic areas) some networks have been founded from the Osservatorio Vesuviano for the geodetic and geophysics surveillance and monitoring.
The use of the GIS strategy results winning for the management of these temporal series, but it sets a series of problems:

- simple transfer of data between database of different GIS
- use of the same software on database multiples of GIS
- compatibility of the knowledge between different products GIS
- support of different products DBMS with a single product GIS.

Therefore, there is particularly necessity to have more defined data models for volume- and time-orientated data structures, for both gridded and object data.
Another problem is difficulty to manage and to visualize fine-dimensional data that have often scattered in one or more dimensions; in this case a GIS has to incorporate methods of interpolation to allow the consumer to visualize the natural variation of the data tracking them in the space and in the time (four-dimensional space).

Laser Scanning

Having a good quality DTM in Neapolitan area is coming out from the importance of geological morphology and environmental risks of zone. The area is considered one of the more active volcanic zone in Italy and it has monitored for long years.

Airborne laser scanning, recently, is one of the best method to obtain a reliable DTM with precision could reach one decimetre. The system mainly consist of two sensor group: the first is Laser Range Finder and its used for measuring the distance from the sensor to the terrain surface. GPS and INS (Inertial Navigation System) constitute the second group and determine the position and altitude of the Laser Range Finder at the time of measurements.

Many factors could affect the precision of the laser system used and, consequently, the precision of the derived DTM. The main factors are:

1. The range accuracy which mainly could affected by:
   - Non-parallel alignment of the send and receive parts of the sensor.
   - Inaccuracies in the measurement of the pulse path time.
   - Variation in the rotation speed or oscillation of the mirror.
2. Position accuracy which depends on many factors such as satellite configuration, multipath and distance between reference-rover receivers.
3. Altitude accuracy, which is related to INS quality and could be affected by:
   - alignment errors.
   - impurity in the accelerometer.
4. Time offsets, to obtain a good and accurate three dimensional positioning. Orientation, position and range are required to be taken at the same time in the same coordinate time system (all measurements should be synchronised).
5. Coordinate system, which depends on the coordinates transformation between WGS84 to National or local system and also on the geoid measurements.

Naturally, there are more complex relations among these factors and the flight height, the scan angle, the terrain topography, the land cover and the control points used for coordinates transformation.

Due to all above mentioned factors, and new prospect field problems it has been mandatory to perform some experiments at selected areas before performing entire surveying of whole area.

The aim of these experiments was to evaluate the DTM precision using data acquired at different heights above the ground and estimate the economic aspect of the method (cost/time factor).

DTM acquisition and generation

In this work some experiments performed by airborne laser scanner at Neapolitan area have been performed. Consequently some important points have been noted:

- the lateral coverage used in laser strips should be taken in consideration to be at least 15%, due to the wind condition during the helicopter surveying (Fig. 1);
- the precision of 10-20 cm of the obtained DTM (Fig. 2) is good enough for many engineering applications and it depends on the flight height;
- the performed surveying at 750 m with 540 m wide strip and 1point/m^2, reduces the time survey and consequently the total cost.

The transformation of the ellipsoidal height to orthometric height should be examined carefully taking in consideration all factors that could affect the result such as the distribution of control points around the interested area and the geoid undulation.

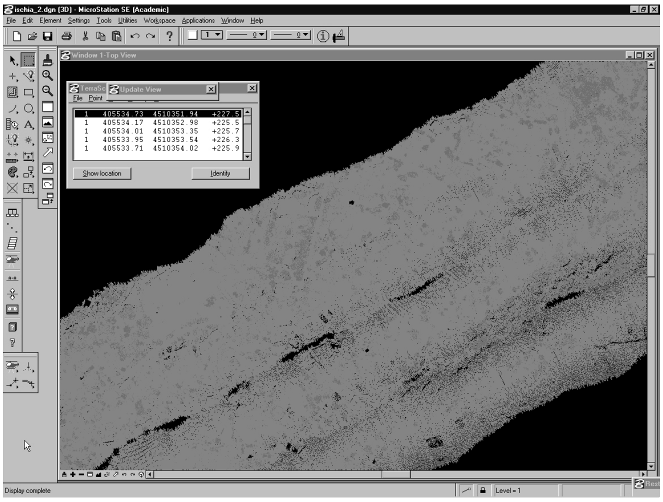

Figure 1 - Lateral gaps between some strips due to helicopter tilt (roll) during survey, with a 10% lateral coverage.

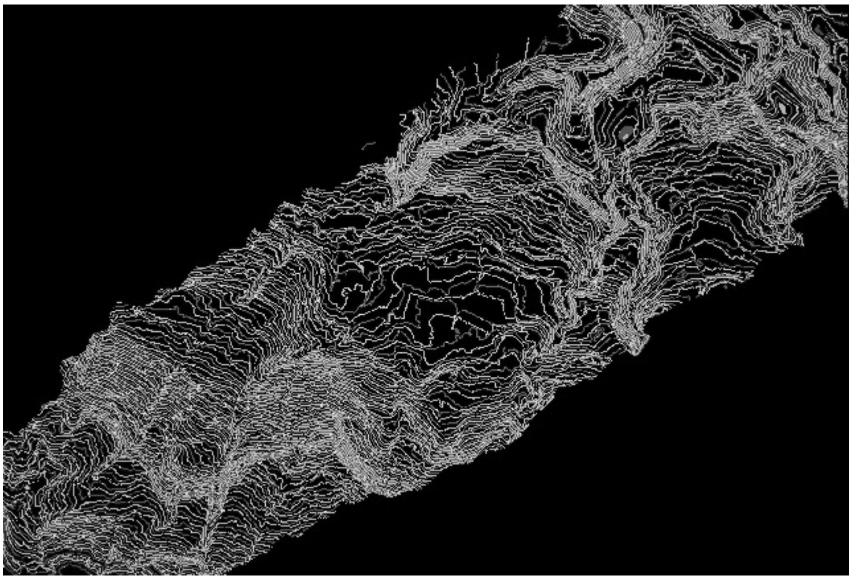

Figure 2 - Contour lines at Ischia Island as computed by Terra Modeller programm.

GPS measurements campaigns

This research is related to Global Positioning Systems applications on volcanic areas in order to monitor small ground deformations.

We stress out the GPS performances in continuous static acquisition. The Survey and Geomatic Laboratory of the Padua University monitor two GPS networks on italian volcanic areas: the first one, on the Euganean Hills (NE of Italy) with 9 vertexes which cover a 300 Km^2 area, the second one on the Aeolian Islands (SW of Italy) with 8 vertexes on 1500 Km^2 area.

We approach this study from the network establishment to the data processing, in order to compare different temporal sessions. Double frequency geodetic GPS receivers were adopted with relative-static positioning using carrier phase measurements. In the processing phase, data coming from the GPS permanent stations are used.

To compare results of different and not directly comparable sessions, also using “historical” data, we adopted the seven parameters Helmert’s transformation (3 translations, 3 rotations and 1 scale factor).
A network of permanent GPS station was installed in the Neapolitan area to supply GPS georeferentation to all the geodetic and geophysical activities (Fig. 3)

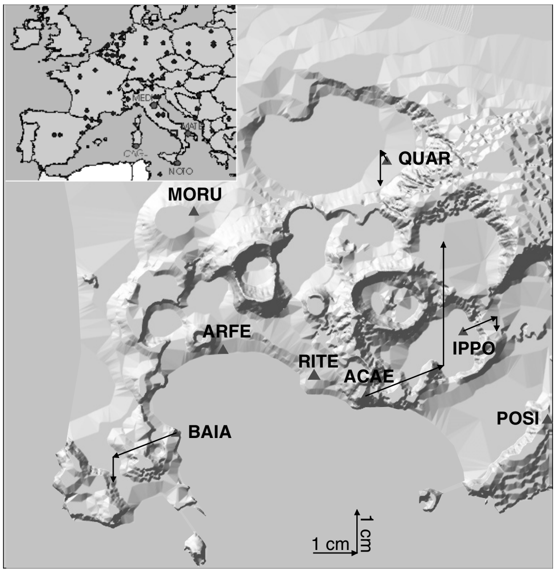

Figure 3 – GPS permanent network in the Neapolitan area.

Integration of SAR interferometry with classical geodetic techniques for ground deformation.
Phlegrean Fields are an active volcanic area, which was interested by historical activity (Mt. Nuovo eruption, on 1538) as well as by strong bradyseismic crises in 1969/72 and 1982/84. Since January, 1985, Phlegrean Fields are undergoing a subsidence phase, with small uplifts occurred in 1989, 1994 and, more recently, from March, 2000.
From these events, the importance of a careful geodetic monitoring of a densely populated area. A valid approach to the problem of the geodetic surveillance of an active volcanic area, which guarantees reliable results, consists in the combined use of different geodetical methodologies, either based on ground networks (in which the final result is an high resolution but *punctual* datum), or on the use of airborne/spaceborne sensors (with a lower resolution, but an *areal* information).

Geodetical monitoring by the Osservatorio Vesuviano in the Phlegrean Fields area, is carried out at present by continuous and periodical networks (Fig.4):

- GPS continuous and periodical networks, with 36 3D vertices (yearly measured), eight of which at present equipped for continuous acquisition.
- Tiltmetric continuous network, with four stations; for the next future, the network will be completed by four *borehole* tiltmeters.
- Spirit leveling network, with more than 300 benchmarks on about 120 km of leveling line; the network is yearly measured.

Recently, some experiments were carried out, in order to obtain a Digital Terrain Model (DTM) of a little extension area (Solfatara volcano) by Laser Scanning technique.

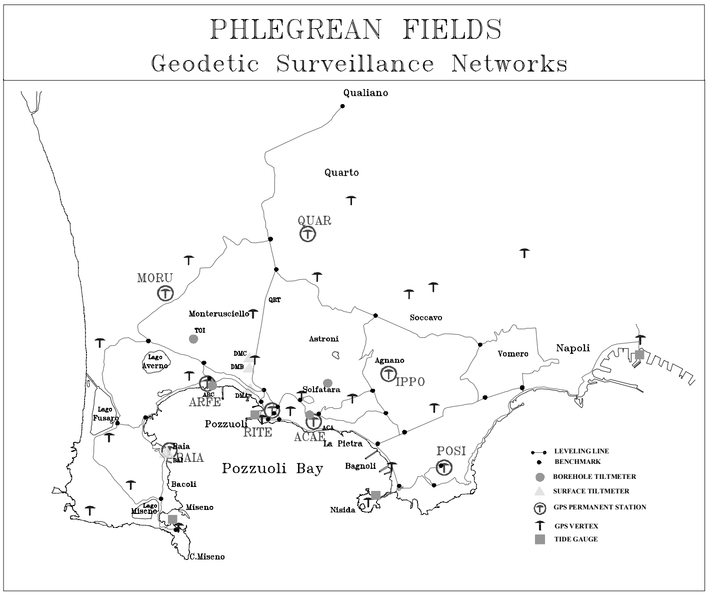

Figure 4 - Geodetical surveillance networks - Phlegrean Fields

The trend pointed out starting from March by GPS and tiltmetric continuous networks suggested the use of SAR Interferometry (InSAR), in order to get an areal information on the uplift acting in the area. In this case, the complexity of the deformation field of the area was confirmed by data analysis, which points out different deformation patterns comparing ascending and descending orbits (ERS2). The amplitude of the whole uplift is well recorded in the 2000/03/02-2000/07/20 interferogram, in which almost two fringes (Fig.5) indicate a line of sight deformation of about 5 cm (see also Fig. 6)

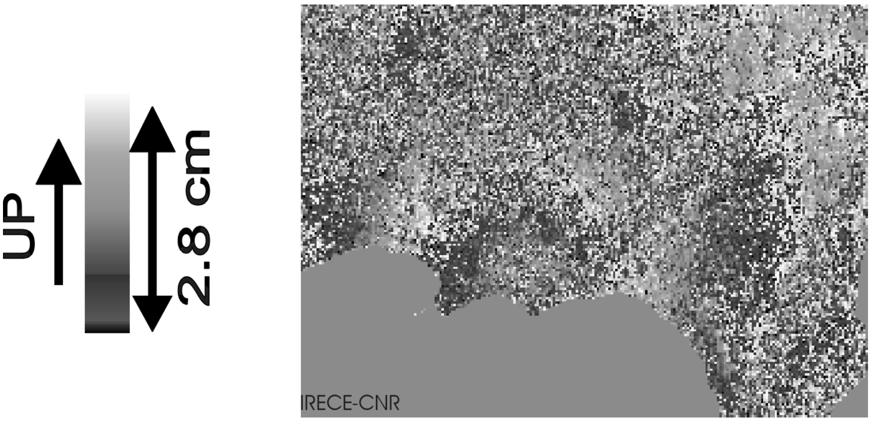

Figure 5 - 2000/03/02-2000/07/20 interferogram (ERS2 - descending orbit) - Phlegrean Fields

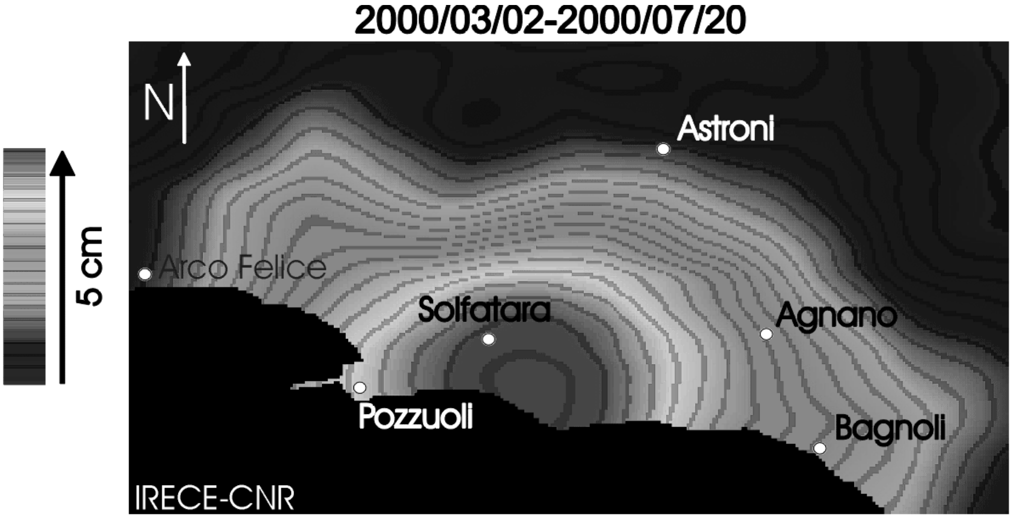

Figure 6 - Deformation map from InSAR data (ERS2 - descending orbit) - Phlegrean Fields

The value of ground deformation seen in the 1999/09/09-2000/07/20 interferogram (about one fringe, which corresponds to about three cm of line of sight deformation) (Fig.7) is absolutely consistent with the results of spirit leveling measurements in the same time interval, indicating in this case a maximum vertical deformation of 3.5 ± 0.5 cm on the coast line near Pozzuoli.

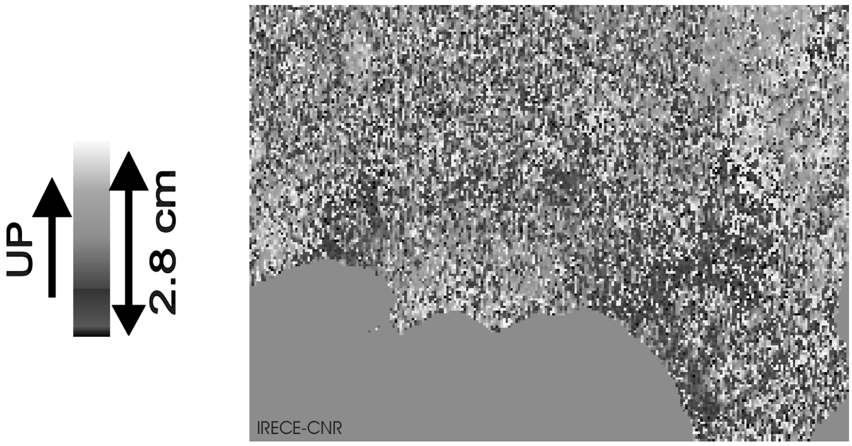

Figure 7 - 1999/09/09-2000/07/20 interferogram (ERS2 - descending orbit) - Phlegrean Fields

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- ***The use of GPS for meteorological applications and tide-gauges measurements***
  (L. Balestri, M. Boccolari, S. Fazlagic', S. Pugnaghi, R. Santangelo, M. Zucchi)

THE USE OF GPS FOR METEOROLOGICAL APPLICATIONS AND TIDE-GAUGES MEASUREMENTS

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I. TIDE-GAUGES MEASUREMENTS

Eleven tide-gauges have been selected in collaboration with Istituto Idrografico Nazionale among tide-gauges with uncertainties on their heights. The selected sites are: Trieste, Venezia, Marina di Ravenna, Ancona, Pescara, Bari, Otranto, Civitavecchia, Lampedusa, Genova e Cagliari.

Tide-gauges are usually characterized by two outer studs, see for example Figure 1: the first, horizontal, near the tide gauges cabin and the second vertical, perpendicularly fixed to the cabin with the instruments.

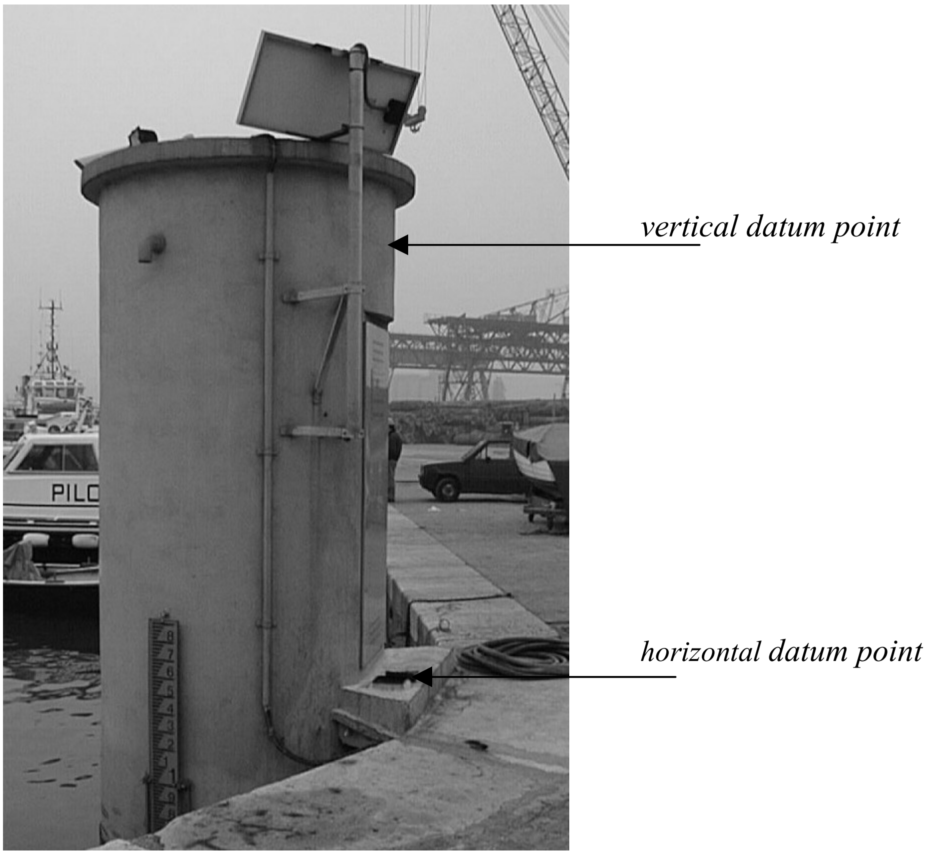

Figure 1 - Ancona site

GPS and gravimetric measurements have been executed at horizontal datum point for six hours. To obtain precise coordinates of the tide-gauges, GPS data have been elaborated relatively to the

nearest GPS permanent stations. Data processing has been performed using the Bernese software. Relative gravimetric measurements have been carried out with Autogravimeter Scintrex CG-3M.
An important check has been performed on tide-gauges coordinates obtained by GPS data collected under very different relative humidity conditions to verify coordinates repeatability.

II. SUN PHOTOMETER AT LAMPEDUSA

In the framework of the MAGIC (*Meteorological Applications of GPS Integrated Column Water Vapour Measurements in the Western Mediterranean*) European Project (Haase et al., 1999; Haase et al., 2000) a sun photometer has been installed (27 June 2000) at the ENEA (Ente per le Nuove tecnologie, l'Energia e l'Ambiente) base of Lampedusa Island (Italy). The base is located very close to the lighthouse of Capo Grecale (Fig. 2).

Figure 2 - Lampedusa Island - Capo Grecale.

The lighthouse has the following coordinates: East Longitude 12° 37.9'; North Latitude 35° 31.0'; Altitude about 45 m. The ENEA base is at about 100 m from the lighthouse and the sun photometer is on the roof of the base. In Fig. 3 it is possible to see the sun photometer during the installation and, behind it, the lighthouse of Capo Grecale.

Figure 3 - The lighthouse from the roof of the ENEA base.

The sun photometer is a completely independent instrument. The big box on the right of the sun photometer (Fig. 3) contains the electronics, the battery and all the electrical connections. A solar panel on the door of the box (Fig. 4) produces the needed power supply. A portable PC collected the measurements performed during year 2000. This sun photometer is part of AERONET (AErosol and RObotic NETwork) program and in the next future the data will be transmitted to NASA by means of METEOSAT satellite. The electronics drives the azimuth and zenith motors (vertical and horizontal white cases respectively; shown in Fig. 5), which permit to aim the sun. At the end of the two collimators, always in Fig. 5, there is the optical head and the filter holder wheel.

Figure 4

Figure 5

Sun photometer measurements

The sunphotometer is a CIMEL 318-2 using five different interference filters; the central wavelengths are reported in the following table. Three polarized measurements are performed at 870 nm.

Channel #	**1**	**2**	**3**	**4**	**5**
λ (nm)	**1020**	**870**	**670**	**440**	**936**

Sunphotometer measurements are based on Bouguer's law. Since the exponential attenuation law is valid strictly for monochromatic radiation Bouguer's law is not valid for the 936 nm channel (strong water vapour absorption band). According to Halthore (1997) the atmospheric transmission in the water vapour band can be modelled as a two parameters expression:

$$J_\lambda = R \cdot J_{0,\lambda} \cdot e^{-m \cdot \tau_\lambda} \cdot e^{-a \cdot w^b} \quad [1]$$

$$\tau_\lambda = \tau_\lambda^R + \tau_\lambda^A \quad \text{and} \quad w = m \cdot WV \quad [2]$$

Where:

τ_λ^R is the Rayleigh (or molecular) optical thickness

τ_λ^A is the Aerosol optical thickness; estimated by interpolation between 870 nm and 1020 nm channels

WV is the water vapour vertical column abundance

GPS Zenith Tropospheric Delay

In Lampedusa village, at only few km from the ENEA base, an ASI (Agenzia Spaziale Italiana) GPS receiver is working on the roof of the Capitaneria di Porto (Lat. 35° 31' 3.8" N, Long. 12° 34' 2.7" E).
The ASI GPS zenith delay and the sun photometric data of the period June-September 2000 have been compared.

Assuming (Thayer, 1974):

$$ZTD = ZDD + ZWD \quad [3]$$

Where:

ZTD is the Zenith Tropospheric (Total) Delay
ZDD is the Zenith Dry (or better hydrostatic) Delay
ZWD is the (so called) Zenith Wet Delay

$$ZTD = \int \left(k_1 \cdot \frac{p_d}{T} + k_2 \cdot \frac{e}{T} + k_3 \cdot \frac{e}{T^2} \right) \cdot dz \quad [4]$$

$$ZDD = \int k_1 \cdot \rho \cdot R_d \cdot dz = \int \frac{k_1 \cdot R_d}{g} \cdot dP \approx 2.2768 \cdot P_0 \quad [5]$$

$$ZWD = \int \left((k_2 \cdot R_v - k_1 \cdot R_d) \cdot \rho_v + \frac{k_3 \cdot R_v}{T} \cdot \rho_v \right) \cdot dz \approx \frac{PW}{\Pi(T_m)} \quad [6]$$

Where k_1, k_2 and k_3 are empirical constants (Bevis et al., 1994); P_d and e are the dry air and water vapour partial pressure; T is the air temperature; ρ and ρ_v are the humid air and water vapour density respectively, R_v and R_d are the gas constant for water vapour and dry air respectively; PW is the precipitable water (or integrated water vapour) and finally $\Pi(T_m)$ is a function of the vertical mean temperature.

The ZTD data were obtained from the ASI GPS measurements. The HIRLAM (High Resolution Limited Area Model) forecasted pressure at the ASI receiver antenna altitude gives ZDD so ZWD was estimated (Vedel et al., 2001). HIRLAM is an NWP model developed jointly by a number of European meteorological institutes. It is the NWP model used operationally at Danish Meteorological Institute.
On the basis of the integrated water vapour estimated by HIRLAM and taking into account that 1 mm of precipitable water corresponds to about 6.3 mm of zenith-wet delay (Bevis et al., 1992), it was seen a mean bias of about 10% (sun photometer high). The quoted bias has been recently seen (Ingold et al., 2000; Schmid et al., 2001).
Independently by the bias the scatter plot between the sun photometric data and the ZWD derived from the GPS measurement shows the behaviour of Fig. 6. The standard deviation (σ) is about 10 mm (Pugnaghi et al., 2001); in Fig. 6 a confidence interval of 95% (2 σ) is shown. The quoted

standard deviation of about 10 mm have been found by other author using different techniques (Betti et al., 2000; Pacione et al., 2000).

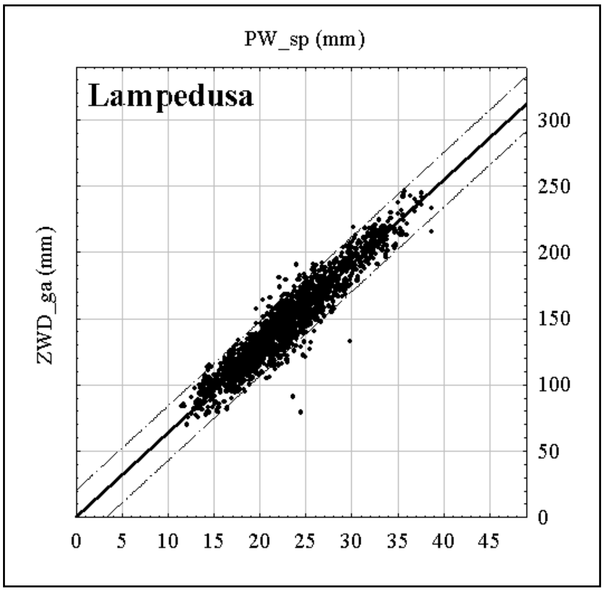

Figure 6 - 27 June 2000 - 17 September 2000
GPS ZWD versus sun photometric PW data

Matera station
In Matera there is the centre of ASI. Here are co-located a well-monitored GPS receiver and a standard meteorological station. The ASI site is on a wide flat at about 500 m of altitude. These characteristics should permit to have a good data set. The reduced (respect to sea level altitude) aerosol optical thickness and precipitable water should permit better instrumental measurements (for both sun photometer and GPS). The validation of the GPS data by means of the sun photometer should make possible comparisons with meteorological predictions and non-predicted local extreme meteorological events.

III. DETECTION OF METEOROLOGICAL INCONSISTENCIES BY GPS

1) Objective
This work aims to assimilate integrated meteorological measures as those obtained by GPS receivers with conventional meteorological measures in upper air as those provided by a standard meteorological database, e.g. the database of Deutscher Wetterdienst (DWD) currently received in real time by Osservatorio Geofisico in Modena (Italy). Meteorological fields, from database, allow computing the corresponding integrated measure performed by GPS. A comparison shows possible inconsistencies in near real time.
The amount of detected inconsistencies (measured mean divided by standard deviation) is a quality warning about the products (forecasts) emitted by such database. Obviously this quality warning

concerns possible errors of meteorological fields used in forecast models, without demanding that this quality warning may concern also mechanisms used in the model.

2) Summary of GPS activity within EEC Project MAGIC, during MAP-SOP (Mesoscale Alpine Program -Special Observing Period)

The proposal, which will be discussed later, uses GPS data observed in Padua and Medicina (near Bologna) during MAP-SOP (since September 1 1999 and November 30 1999). Two GPS receivers have been considered since they allow using a Double Difference Technique (better explained later) which increases precision of GPS analysis.

Receiver in Padua was chosen since it was rather close to the chosen MAP site in Verona, where about 100 balloons were launched and tracked on command of a forecaster team. As second receiver was chosen the one in Medicina (near Bologna), since balloons are currently launched in Capofiume (near Bologna also) every day. Therefore upper air information above Capofiume is currently received and assimilated by Meteorological Centers, so that their disseminated meteorological fields (for instance by DWD) was received and currently available.

In conclusion: one site (Medicina) could be considered meteorologically well known, whereas in the other site (Padua) meteorology obtained by balloons could be compared with meteorology obtained by GPS observations. These last observations were assimilated by a suitable (Hugentobler et al., 2001) GPS Program ("Bernese" Program) which requires knowledge of two satellites and two receivers (one of which could be considered meteorologically known) whereas the other was meteorologically known only after a radio-sounding.

Tropospheric delay, which is an integrated meteorological information, evaluated by meteorological profiles obtained by balloons in Verona, has been compared with the corresponding tropospheric delay observed by GPS in Padua (not very far from Verona).. The agreement was good.

3) "Ionofree" combination of the two GPS signals emitted by a GPS satellite

Each GPS satellite emits two signals, each having its own frequency. A suitable combination of such signals is called "ionofree" signal of that satellite. With a good approximation, "ionofree" signal doesn't need any correction during its travel across ionosphere, whereas it undergoes to refraction when it travels across neutral atmosphere. Refraction depends on meteorological conditions along the traveled trajectory but it doesn't depend on frequency (no dispersion). Obviously in void "ionofree" signal travels with the speed of light.

4) GPS observable

Due to a sophisticated procedure starting time tI of a GPS signal from a GPS satellite I, and arrival time tA ($>$ tI) of the same GPS signal down to GPS receiver A , are appropriately recognized as belonging to the same signal. Travel time lag is measured by phase ranging: therefore such time observable measured by phase ranging, has an intrinsic phase ambiguity.

Moreover time lag or observable

$$O = (tA - tI) \qquad [7]$$

has further errors due to unknown constants in both satellite and receiver clocks. In conclusion observable O should be written as:

$$O = [(tA + kA) - (tI + kI)] \qquad [8]$$

where kA and kI are unknown constants. Unknown constants disappear if a Double Difference of Observed Phases is used i.e. :

$$DDO = [O(I,A) - O(I,B)] - [O(J.A) - O(J,B] \qquad [9]$$

where DDO means Double Difference of Observed Phases.

5) Constraint if no neutral atmosphere were present

If no neutral atmosphere were present, so that GPS signal would move with the speed of light (= c), the following constraint exists:

$$c\ DDO = DDL \qquad [10]$$

where DDO means Double Difference of observed phases (neglecting any problem concerning phase ambiguity) and DDL means Double Difference of Travel paths from satellites: I, J to receivers A, B. At any epoch distances between receiver and satellite are fairly well known, due to rather well known orbits of satellites, under the assumption that receiver don't move (no ocean loading). With self-explanatory symbols:

$$DDL = [L(I,A) - L(I,B)] - [L(J,A) - L(J,B)] \qquad [11]$$

6) GPS signal traveling across a neutral atmosphere (mainly troposphere)

When a GPS signal travels across a neutral atmosphere, i.e. a refractive atmosphere, undergoes to an extra-delay T', which exceeds the delay of a signal having the speed of light, due to a velocity lower than that of light. It is useful to convert extra-delay T' into a length T:

$$T = c\ T' \qquad [12]$$

GPS signal travels mainly vertically from satellite. A GPS wave-front, during its propagation along a line element having the same propagation direction of the wave, undergoes to a longitudinal extra-delay T° proportional to the length of the line element traveled. Longitudinal extra-delay T° (as length) depends on meteorological parameters existing along that line element. Extra-delay from a satellite (say I) to a receiver (say A) is equal to extra-delay along the direction of emitting antenna from I to a point A' which lays in the direction of propagation ; A' and A lay with on the same wave front, so that their delay is equal:

$$T(I,A) = T°(I,A') \qquad [13]$$

Obviously T(I,A) or T°(I,A') are obtained by integrating extra-delays along each line element.
If receiver is not located along the vertical propagation line, extra-delay T has the following approximate expression:

$$T(I,A) = T°(I,A')\ f \qquad [14]$$

where f is a suitable mapping function, which depends on the configuration of emitting antenna, and of meteorological fields (Bisnath et al., 1997).
In first approximation, it depends on zenith angle: z , only (angle between vertical line from satellite towards Earth and line of sight from satellite to receiver). For very small zenith angles:

$$f = 1/\cos(\text{zenith angle}) = 1/\cos z \qquad [15]$$

Lack of knowledge of exact expression of mapping function, implies that evaluation of T is rather uncertain under slant conditions.
For completeness extended expression of DDT is shown:

$$DDT = [T(I,A) - T(I,B)] - [T(J,A) - T(J,B)] \qquad [16]$$

7) Constraint in neutral atmosphere
Therefore previous constraint (in Double Difference Technique) must be suitably modified into the following one:

$$c\, DDO = DDL + DDT \qquad [17]$$

DDO is obtained by phase ranging; DDL is obtained by known orbits of satellites. DDT needs some attention. A DDT° can be obtained, by using formulas involving upper air meteorology, under the assumption that the direction of propagation of GPS outgoing wave (emitted downwards from GPS antenna on board of satellite vertically) coincides with the line satellite/receiver. In principle DDT° is made up by two parts: a hydrostatic part (dry part) and a wet part.
If the line of sight (satellite/receiver) is slant, i.e. if there is a zenith angle: z, between the vertical line (direction of antenna) and the line of sight, a slant DDT has to be considered. This new DDT is obtained by multiplying the two previous dry and wet parts of DDT° by the corresponding mapping function (dry and wet) These mapping functions depend mainly on zenith angle z. For small zenith angles (i.e. for near vertical line of sight) each mapping function can be approximated by 1/cos z. Knowledge of upper air meteorology ,necessary to compute DDT°, can be obtained, for instance, in the following two ways:

1) by Meteorological Database disseminated by Meteorological Centers (e.g. by DWD) and received in real time;
2) by ground meteorological measurements in real time, suitably extrapolated towards upper air, e.g. by a formula suggested by Saastamoinen.

These two possible choices for evaluation of extra-delay DDT° are foreseen in the “Bernese” Program to be discussed in next Section. The two choices provide, for most epochs, close results.
For slant line of sights, “Bernese” Program provides, in particular, the following two options (Niell, 1996):

1) a dry Niell mapping function;
2) a wet Niell mapping function.

8) “Bernese” Program in order to adjust previous data epoch by epoch
Previous three terms in [17] are adjusted by “Bernese” Program by a suitable fit which takes into account phase ambiguity also, and provides finally an unbalance or a Double Difference Residual (DDR).
If the fit were perfect DDR would be zero. Upper air meteorology of days analyzed by “Bernese” Program, during MAP-SOP, was:
1) measured at ground and suitably extrapolated to upper air ;
2) obtained by Meteorological Database disseminated by DWD.
It seems preferable to use meteorological fields provided by DWD database since they are expected to represent better upper air conditions.
14 days, belonging to the MAP time series of observations have been analyzed by “Bernese” Program so that their DDR is available versus time.

9) Pairs of satellites observing a pair of receivers, at each epoch: zenith cut-off

At any epoch there are several satellites which observe a pair of receivers in sites A and B, say 5. Therefore there are several pairs of satellites which provide different values of DDR according to the chosen mapping functions. In order to avoid management of uncertain DDRs, due to uncertain mapping functions, it would be preferable to choose near vertical satellites or small zenith angles. However, with such choice, only very few satellites would be accepted. Therefore a compromise is necessary. A zenith angle smaller than 60 degrees, for each zenith angle of the considered pair of satellites, observing the two receivers in A and B ,seems a reasonable compromise. Actually each zenith angle is not so high, so that the mapping functions available in “Bernese” Program should approximate reasonably the real but somehow unknown mapping functions. Certainly this choice of a cut-off angle implies a significant reduction of pairs of satellites observing simultaneously receivers A, B at that epoch.

With such choice, at any day, not more than two pairs of satellites are simultaneously present.

10) Evolution of DDR versus epoch and for periods of consecutive epochs

Since DDR fitted by procedure previously outlined in [17], fluctuates pretty much, it is better to consider values averaged over several consecutive epochs, during which the satellites remain unchanged. Actually it happens that reception of a same pair of satellites lasts several epochs (more than 2 epochs are chosen). During that period, every DDR should vanish. Therefore it is preferable to consider the mean value of DDR: m, and the standard deviation of the mean: s, for that period.

For all 14 days previously mentioned, GPS has been observed continuously, and meteorological data from DWD database have been obtained. Due to uncertainty in mapping functions both dry and wet Niell were considered, so that two types of DDR have been obtained for every epoch: a dry DDR and a wet DDR.

In Figures from 7.1 up to 7.2, with suitable colors, evolution of m and s is shown, for every period of consecutive epochs with the same satellites observing, for the two possible mapping functions. In the same plot, anomalous periods having: $(m/s)^{**}2 > 9$ are suitably labeled by using a red color.

They mean that a certain inconsistency exists between measured data (DDO from GPS), orbital data (DDL), and meteorological fields (DDT as obtained by DDT° or by meteorological fields and by mapping functions).

11) Anomalous periods

Anomalous periods are present in evolution of dry DDR. However such cases, often, are not confirmed by corresponding wet DDR. Therefore anomaly is probably due to use of an imprecise mapping function (dry Niell).

However there are some periods (rather short) for which both dry and wet Niell are simultaneously anomalous (doubly red). These period suggest a sort of a warning due to the inconsistency.

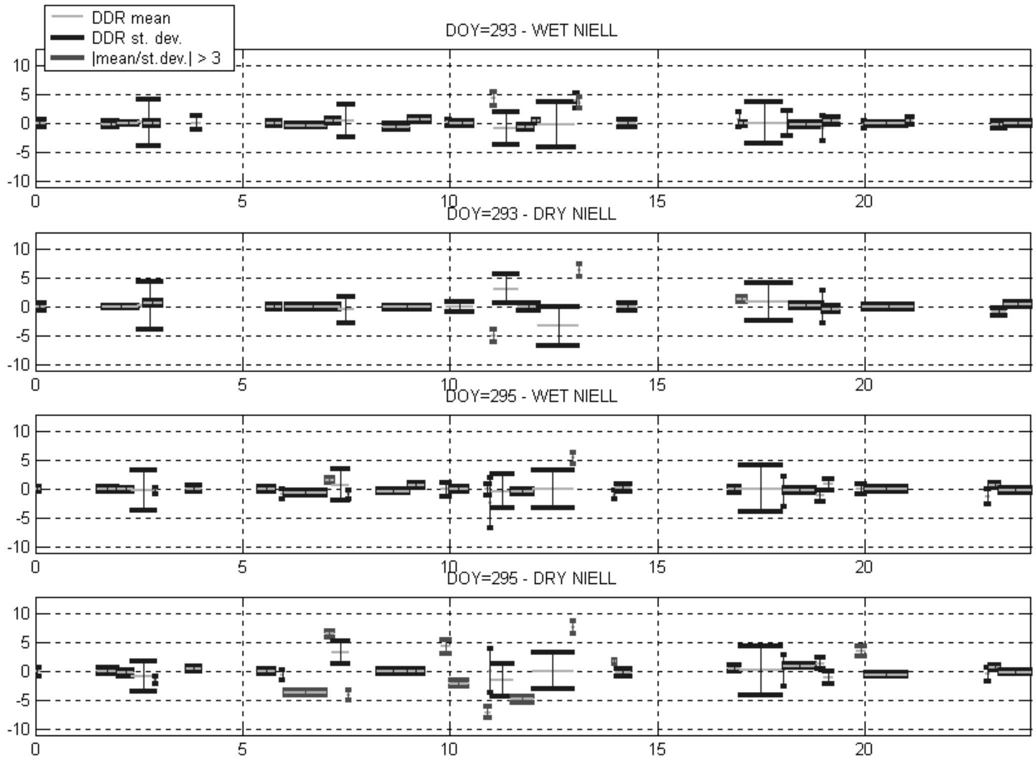

Figure 7.1 – DDR and St. Dev. Calculated using Meteorological data and Wet and Dry Niell Mapping function for DOY 293 and 295 (20th Oct. and 22nd Oct. 1999) for GPS Stations Padova and Medicina

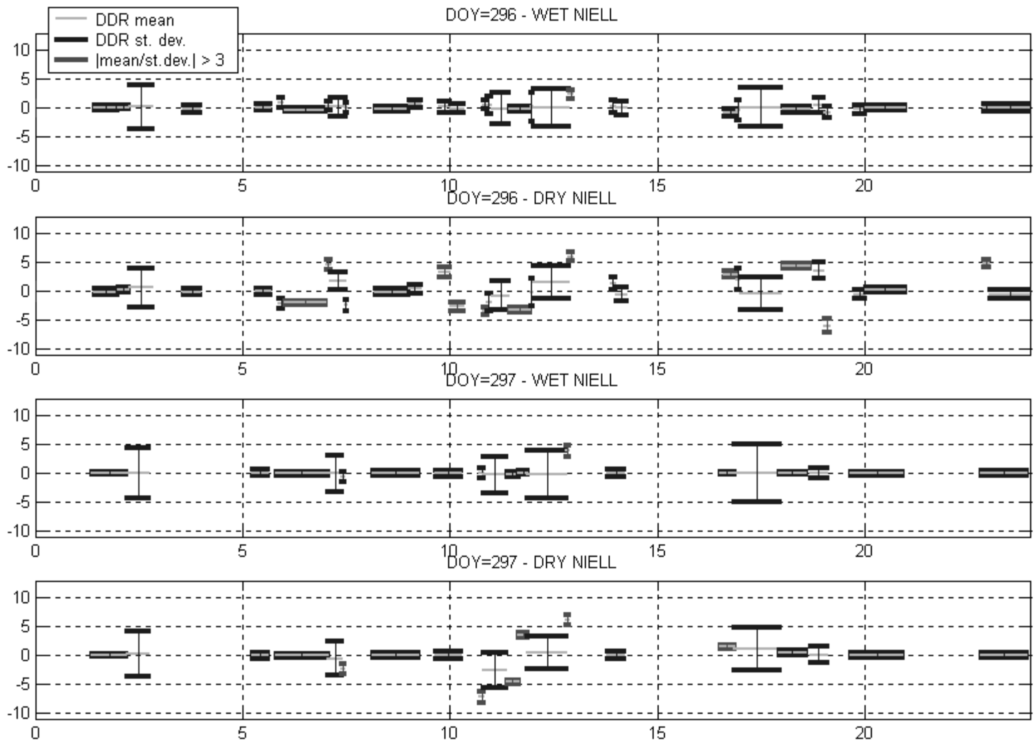

Figure 7.2 – DDR and St. Dev. Calculated using Meteorological data and Wet and Dry Niell Mapping function for DOY 296 and 297 (23rd Oct. And 24th Oct. 1999) for GPS Stations Padova and Medicina

Conclusion

These “doubly red” cases are not frequent and for rather short periods of time. It may not be excluded that a better mapping functions could further reduce such inconsistencies.
However these cases could be real conditions of imprecise knowledge of upper air meteorology such to deserve a real warning about products (forecasts) obtained by such imprecise meteorological fields. Actually amount of mean divided by its standard deviation may provide a quality factor of emitted forecasts.
A study with more statistics and correlation with meteorological events is envisaged.

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- ***Measurements and methods of high precision space geodesy: precise orbit determination of low-earth orbiting satellites through GPS and accelerometry***
  (S. Casotto, A. Zin, B. Padovan)

MEASUREMENTS AND METHODS OF HIGH PRECISION SPACE GEODESY: PRECISE ORBIT DETERMINATION OF LOW-EARTH ORBITING SATELLITES THROUGH GPS AND ACCELEROMETRY

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Simulation of Precise Orbit Reconstruction using Accelerometry
The primary objectives of the first phase of the study were (1) the upgrade of the software code `POP` (Padua Orbit Processor) for the precise determination of the orbits of Earth satellites through the analysis of the phase observables of the Global Positioning System (GPS) and (2) the simulation of the reconstruction of the orbit of an Earth satellite on the basis of the measurements obtained by an accelerometer carried onboard.

As far as the first point is concerned, the mathematical models of the measurements were defined, both for the phase and the pseudorange observables. In so doing an accurate mathematical model was introduced of the fundamental oscillator. Variations of the basic observables known as the single (SD) and the double (DD) differences were also defined, together with their partial derivatives with respect to parameters such as the transmitter (GPS SV) and receiver (user) positions, their three-dimensional velocities, the oscillator polynomial model parameters. The results of this phase of the research are covered by a CISAS report.

The second phase of the first objective consisted in the implementation of the measurement models into the precise orbit determination software POP. The implementation of the models was verified through a quality control scheme.

The second objective was tackled in a similar manner in two steps. In the first step the definition of the mathematical model of the measurement obtained from an electrostatic accelerometer positioned at the center of mass of a satellite was developed. The model also accounts for a series of error sources which include scale factors, couplings between readouts along different axes, and misalignements among the axes themselves. The full model is therefore fairly complete since it can well describe the functional behavior of a capacitive accelerometer. In the second step the implementation of the model into `POP` was carried out. In practice, this implied a modification of the external force modeling in such a way that the user could disable the use of the non-gravitational forces acting on the surface of the satellite and activate in its stead the reading of the accelerometer data from a file for use within the numerical integration module. Some problems were encountered in adjusting the high rate at which accelerometer data are available and the integration time step, which cannot be made extremely small as this would require.
The orbit determination program POP, upgraded as described above, was later used in the context of the Phase A study of the ASI small mission SAGE. In order to carry out a simulation study—`POP` does provide a simulation capability—other upgrades to the software code had to be implemented. Thus the capability of simulating acceleration measurements along a reference, or

truth trajectory was added in. This was made possible by adopting the best non-gravitational forces model available within POP and generating the truth acceleration values while integrating the trajectory under the action of the full force model. These values were then made more realistic by corrupting them by the addition of a noise term. The noise term had to be generated itself and this called for a big simulation effort in order to generate noise according to the spectral properties characteristic of the accelerometer hardware. A large literature search was carried out to identify methods for the digital generation of colored noise of given power spectrum. The method adopted was based on an innovative algorithm proposed by J. Kasdin in 1995 for the discrete generation of noise characterized by a PSD function with the typical inverse proportionality to some real power of the frequency, which is exactly was needed in the present case.

The verification of the simulated data required great computational effort since the most critical part was the generation of data at the low frequency end of the spectrum over periods of the order of 10^5 s. In order to make sure that the spectral characteristics were correct, data had to be generate for at least one order of magnitude more, so that time histories of the order of 10^6 data points had to be handled and processed. The measurements thus corrupted were then used in the (simulated) data reduction mode of the POP orbit processor. The results have shown that the SAGE orbit can be reconstructed within the error budget allocated for POD. The recovery of the Stokes coefficients of the Earth's gravitational field can thus be accomplished within the accuracy established by the mission objectives.

More detailed reports on the techniques and results obtained in this phase of the research can be found in *SAGE: Phase A Final Report,* in the thesis of A. Zin and in the paper presented at the *Spaceflight Dynamics Meeting* of the *American Astronautical Society* held at Brackenridge, Colorado, in 1999 (see the Publications section below).

Refinements and Applications to CHAMP
The objectives of the second phase of the study (cfr. Product Description section of the proposal for 1999) were (1) the continuing upgrade of the POD software tools in order to be ready for the handling and processing of the tracking and payload data of the GOCE mission, (2) the experimentation of the tools so developed on the real data obtained from the planned (at the time of proposal writing) mission CHAMP.

The upgrade of the Precise Orbit Determination software system needed for its use with real data form the CHAMP mission were mainly necessary in that part of the system known as `GPS_PP`, the data pre-processor. Its function is to accept the raw tracking measurements in some predefined standard format (e.g., the international RINEX standard for GPS data) and convert them into a form which is acceptable for processing by `POP`. This means a basic reformatting step, but mainly the application of a series of corrections to the data, which account for the propagation of the signal through the atmospheric medium, the identification of data corruption such as cycle slips in the case of phase data, possible time retagging of the measurements, and combination of the measurements between different space-to-Earth links to form single or double differences in order to get rid of most of the clock errors. All these capabilities were reviewed and properly adjusted in `GPS_PP`. Another important activity in this regard has been the introduction into the software system of the capability to handle attitude data which are ancillary to the payload data distributed by the CHAMP Science Data Centre. Attitude data are necessary in the orbit determination problem in order to compute the center of mass correction. This is the correction which needs to be applied to any tracking measurement of a metric nature between the satellite and the observer in order that the measurement be referred to the center of mass of the spacecraft (whose position is obtained through the integration of the equations of motion) and the center of phase, or the emission/reception/reflection point on the satellite. In the case of GPS, the reception point is fixed

within the satellite frame, and such is supposed to be the center of mass (corrections to its location varying as a function of fuel consumption can also be applied, if available). The center of mass/center of phase correction can be found by properly projecting the three-dimensional correction vector onto the line of sight between the transmitter and the receiver. This is only possible if the attitude of the satellite is known with sufficient accuracy. The CHAMP attitude data were available in terms of quaternions. This meant that a series of routines had to be written in order to handle such format and transform into more the usable Euler angle information.
Figure 1 below shows the motion of the body-fixed CHAMP frame in an inertial system. It is seen that the Earth-pointing attitude is maintained on average, but the cross-track direction exhibits deviations of the order of a few degrees.
The processing section of the software system was also upgraded in order to handle the CHAMP orbit, which shows the unusually low altitude of about 450 km. Since POP is a dynamical orbit computation system—as opposed to kinematic or reduced-dynamic systems—the parameterization of the orbit requires special attention. In particular, when accelerometer data are not used, but recourse is made to atmospheric density and radiation pressure modeling, the associated parameters must be taken as valid over very short arcs, namely of the order of one or two orbits. This upgrade is still ongoing. However, preliminary results show that DD phase data can be fit to about 7 cm, in line with the results obtained by other analysis groups working on the same data. The results are encouraging, although the goal is to go down to a fit at the level of 2 cm.

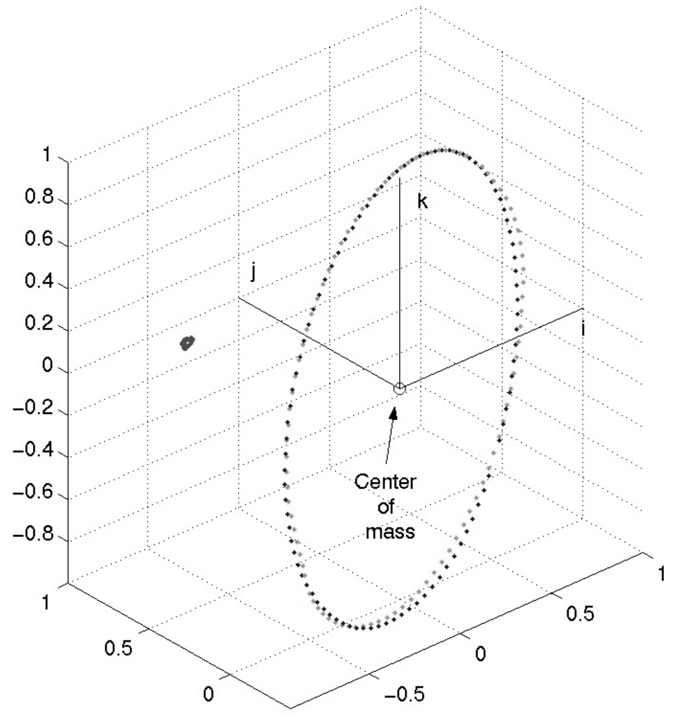

Figure 1 - Attitude motion of CHAMP

Spheroidal Harmonics Modeling of the External Potential
The Padua Research Unit was not funded in the third year of the project, i.e. for the proposal submitted in response to the 1999 call. However, research was carried out on the topics proposed, since those investigations have direct bearing on the approach to specific items of concern in modeling the gravitational field. In particular, one area of interest is the *downward continuation* to the surface of the Earth of the gravitational field, whose coefficients are derived by processing

measurements obtained at satellite altitude. In this respect, research was carried out in gravitational field representation methods alternative to the usually adopted spherical harmonic approach. A series of papers were presented dealing with the harmonic representation of the field based on spheroidal geometries. This implies the use of spheroidal harmonics, where solutions of the second species of the Associated Legendre Equation are needed. This topic was investigated and routines for the generation of such functions were written. The investigation on the convergence of the downward continuation of the satellite-derived representation to the true values of the gravitational field are still ongoing.

Software Produced

Upgrades of `POP` and `Gps_pp` were introduced as described in the text above. A new program called `PointP` was written to process dual-frequency pseudorange data from static and kinematic GPS receivers in order to obtain their instantaneous, or point positions. This application can be used to generate coarse spacecraft positions which in turn are used to fit a preliminary orbit to feed into `gps_pp` for further processing the phase data. The input to `gps_pp` is GPS RINEX data files (of either static platforms or orbiting receivers, as in the LEO case) and IGS precise ephemerides (in SP3 format) for GNSS satellites. The use of precise GPS orbits allows an accuracy improvement of about 40% w.r.t. the utilization of ephemerides contained in the navigation message. `PointP` initializes the position of a static receiver using a database of ITRF position coordinates. If the position is not available, as always happens in the case of an orbiting receiver, the initial estimate is assumed to be the center of the Earth. After a maximum of five iterations, the convergence of the process is reached. The solution is reached through a Weighted Least Squares Estimate, where the weights can be set by the user. The accuracy of the positioning achieved by the method is of the order of a few meters in the static case, and of a few tens of meters in the kinematic case (the same is true for the clock errors).

Other pieces of utility software were also written, among which we list `ch_read.f90`, which extracts and reorders quaternion data from GFZ CHAMP data files, `q2ea.m`, which computes and visualizes the motion of the body-fixed frame in the inertial or in the RTN systems and determines maximum attitude angles of pitch, roll and yaw, `quaterfft.m`, which filters quaternions to reject clear outliers through the application of an FFT, determines for every epoch the c.o.p.—c.o.m. vector in the inertial frame, `quaternion.F`, a subroutine of `gps_pp` which simply reads the `quaterfft`-generated file of the c.o.p. —c.o.m. vector and rotates it to the RTN frame.

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