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THE ASSOGEO GPS NETWORK TO MONITOR SURFACE VARIATION IN THE EMILIA ROMAGNA REGION (NORTH-CENTRAL ITALY): DATA MANAGEMENT, PRODUCTS AND PRELIMINARY RESULTS

Arianna Pesci[1], Giuseppe Casula[1], Fabiana Loddo[1], Nicola Cenni[2],
Maria Giovanna Bianchi[1], and Giordano Teza[3]

[1]**INGV** (Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna)
[2]**Università di Bologna** (Dipartimento di Fisica, Sezione di Geofisica)
[3]**Università di Padova** (Dipartimento di Geoscienze)

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Introduction

The global positioning system (GPS), in both static and kinematic modes, allows a highly accurate measurement of point coordinates and therefore is widely used for monitoring both slow and fast surface deformations. The information provided by a GPS network can be used at the regional scale, to evaluate tectonic and seismogenic structure evolutions [Hunstad et al., 1999; Pietrantonio and Riguzzi, 2004], such as the estimation of deformation rates in the central Apennine chain [Pesci and Teza, 2007], or at larger scale, to monitor gravitational macroscopic effects due to, for example, rock-mass collapses, landslide activations or other instabilities [Mora et al., 2003; Tzenkov and Gospodinov, 2003; Squarzoni et al., 2005].

The accuracies of GPS measurements are generally a few millimeters for the horizontal coordinate components and sub-centimeters for the vertical ones. In fact, the elevation is highly influenced by atmospheric perturbations, involving zenith delays, which are difficult to be completely removed by means of data modeling. When referring to high accuracy, GPS surveying implies the precise measurements of the vectors between two or more receivers (baselines), the so-called relative positioning: data can be acquired on static and rapid-static conditions, which require GPS stations to be stationary.

Several permanent GPS stations continuously operate on the Italian territory, belonging to different institutes like IGS (International GPS Service), EUREF (European Reference Frame), ASI (Agenzia Spaziale Italiana), INGV (Istituto Nazionale di Geofisica e Vulcanologia) and others [Serpelloni et al. 2006; Falco et al., 2007; Devoti et al., 2008]. Due to the high efficiency of this surveying methodology, in the last few years, the number of GPS permanent stations has rapidly increased and continues to expand; the Earth Science Department of Siena University, for example, installed 8 new stations in 2003 to study the tectonic processes in the Central-Northern Apennines [Cenni et al., 2004].

Also private GPS networks planned for commercial civil proposal exist; in particular the ASSOGEO s.r.l (Italian Trimble provider), established a dense GPS network for real time positioning by means of the VRS (Virtual Reference Station) concept [Hu et al., 2003] and work is still in progress to cover the whole Italian territory with a mean size of about 20-50 km.

1. Aim of the study

At present 21 ASSOGEO stations, mainly distributed in the Toscana and Emilia Romagna regions and equipped with Trimble receivers and antennas, are operating at a 1-s sampling rate. The Emilia Romagna region, in particular, is characterized by high surface lowering movements mainly due both to tectonic effects and anthropic activities like water and hydrocarbon pumping, that are responsible for worrying subsidence phenomena [Carminati and Martinelli, 2002; Carminati et al., 2003]. The INGV is working on a complete study of these terrain surface variations, integrating spatial and ground-based geophysical techniques [Stramondo et al., 2007] like SAR (Synthetic Aperture Radar), leveling and GPS; therefore, the existence of a reliable, accurate and permanent GPS network, consisting in a large number of stations continuously operating in this area, is required.

In this work, the processing of the first ASSOGEO station data set, collected from March 2006 to February 2009, is described and some preliminary results and products are shown taking in to account the installations of commercial stations.

2. The GPS SUBER network

The considered GPS network is composed of 51 stations, 36 are located on the Italian territory, while 15 are located abroad on the Eurasian and African plates, to provide constraints on the reference frame definition; BOR1, BRUS, GRAS, HOFN, JOZE, METS, ONSA, POTS, RABT, SFER, TRO1, VILL, WSRT, WTZR and ZIMM.

Figure 1 shows the Italian part of the processed GPS network, pointing out both the ASSOGEO and INGV stations; BO03 BRAS FE01 IM01 MO01 MO02 MO03 MO04 MO05 MODE MSEL PARM PR01 RE01 SGIP.

The entire network is characterized by high heterogeneity in the quality of site monuments, with rigorous installations planned for scientific proposal, or simpler antenna anchorage systems. Some example of site monuments are: iron/steel pipes solidly connected to supporting walls with fixing screws; steel poles inserted and cemented into foundation (or supporting) walls; reinforced concrete pillars based a few meters in the ground or fixed to solid rocks. Figure 2 shows three examples for Mo05, Mo02 and SGIP stations (the latter belonging to INGV). The first example is a pole fixed to the supporting wall; the second has the antenna mounted onto a pillar reaching the roof plane; the third is a pillar created on a reinforced wall about 2 m high, with a foundation of about 1.5 m. Another cause of network heterogeneity is due to the different instruments installed in the GPS; Trimble Zephyr (with or without grand-plane), Trimble Microcentered L1/L2, Choke Ring antennas, while Trimble 5700, 4700, NETRS, 4000SSI and Leica GRX1200PRO receivers were used.

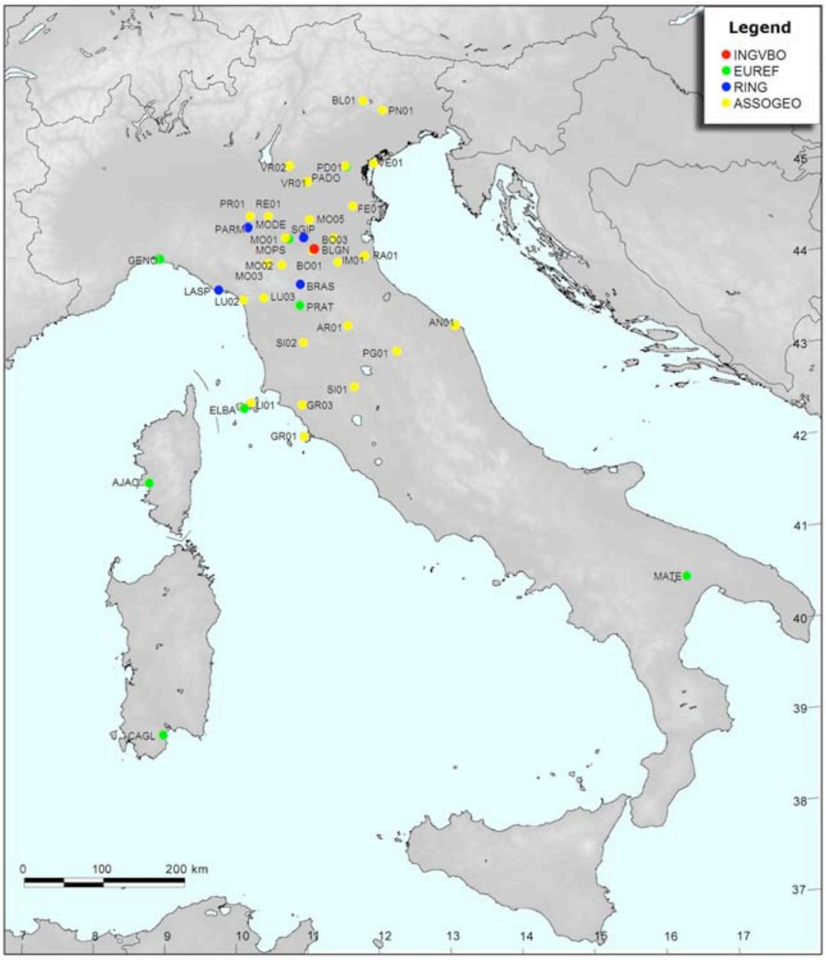


Figure 1 The Italian section of GPS network composed of CGPS belonging to different agencies.

Figure 2 Mo05, Mo02 and SGIP antenna installations.

3. The GPS server and data base

In order to compute GPS robust geo-referred solutions and to recover from errors of file downloading during the processing stage, the creation of an archive of permanent GPS stations data is needed. This archive contains the data of the ASSOGEO network and data of permanent stations belonging to the following networks; RING (Rete Integrata Nazionale Gps [Selvaggi et al., 2006]), EPN (Euref Permanent Network, [Bruyninx, 2004; Kenyeres and Bruyninx, 2004]), and IGS (International GNSS Service, [Dow et al., 2005]). To perform this task a Unix workstation based on Linux OpenSuSE 11 OS (Operating System) was set up and located in the site of INGV Bologna LAN (Local Area Network).

An automatic procedure based on BASH (Bourne Advanced SHell) scripts and on FORTRAN programs has been implemented, and it has been scheduled on a *CRONTAB* task and is periodically activated by the *CRON* daemon of the Linux System, the procedure has been set up to download three time per day the GPS data from the previously described GPS archives.

A data base has been created locally and structured with a GPS archive styled tree structure, in which the main directory represented by the YEAR (i.e 2000) is divided in sub-directories named with the DOY (Day Of Year) (i.e. 200-201-202 …) containing the corresponding data (Figure 3).

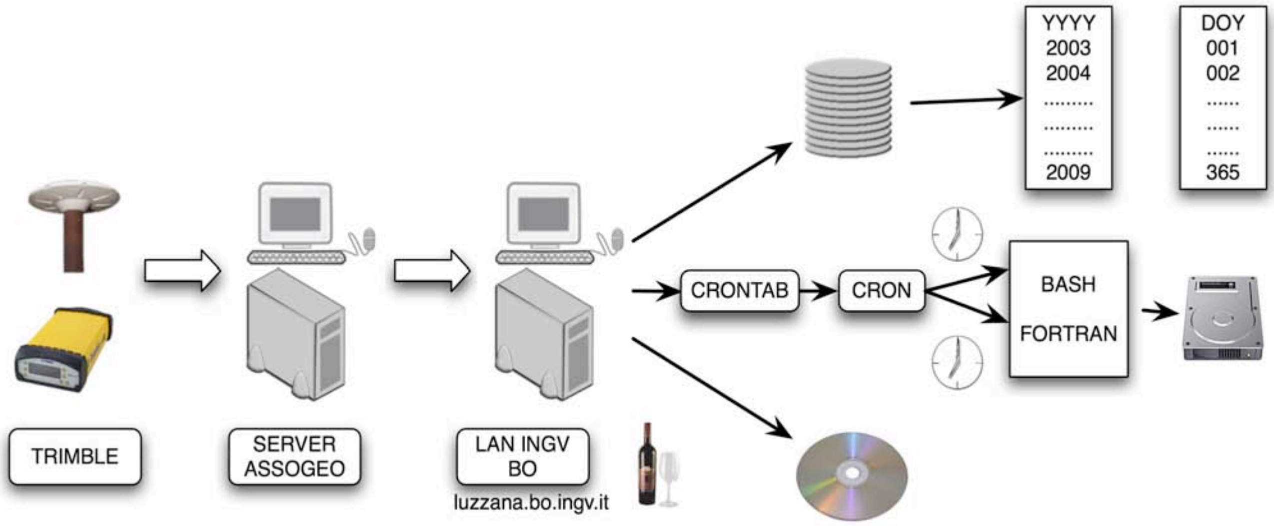


Figure 3 Downloading scheme and data organization.

The RINEX (Receiver INdependent EXchange) data after a quality check test performed by TEQC module (TEchnical Quality Check, [Estey et al., 1999]), are compressed by the Hatanaka compressor (ftp://terras.gsi.go.jp/software/RNXCMP/ [Hatanaka et al., 2003]) and subsequently archived. The metadata pertaining to all the permanent GPS stations, containing information on instrumental changes, antenna heights, monuments and so on, are downloaded and archived following the same procedures, together with precise GPS, and Broadcast IGS (International Gnss Service) orbits. Finally, all data are periodically saved on external removable Hard Disk units and successively archived on more reliable non magnetic supports like DVDs.

4. GPS data processing

The GPS data processing procedure with final computation of station velocity field and strain rate is performed using the distributed sessions approach [Dong et al. 1998] by means of different software modules (Figure 4); the GPS data processing and computation of coordinates, ambiguities, atmospheric models and variance-covariance matrices (h-files), is performed with the Gamit module [Herring et al 2006a]; the data combination is performed with the Glred module of Globk package [Herring et al. 2006b]; the time series computation and screening with outliers removal and offset correction are performed automatically with the

Globk module, and then interactively verified by means of program TSVIEW [Herring, 2003]. Owing to the fact that the time series of GPS coordinates are affected by white and coloured noise an estimation of time correlated sources of errors in the computation of station positions and velocities, including monument instabilities and errors caused by orbits and atmosphere modelling is needed. In our procedure this task is preformed by means of a suitable use of the Markov noise controls applied inside the Globk processing as described by [Herring et al. 2006b]. The estimated source of errors are then verified by means of other package like TSVIEW as described by [Herring et al. 2003].

The procedure is able to account for the largest part of the white and coloured noise which affects the GPS time series resulting in one of the most realistic estimate of the rate of error which can be obtained with modern scientific GPS analysis packages, and for instance in RMS errors of coordinates and velocities that in the majority of cases can well represent the data scattering.

The definition of the reference frame, the estimation of velocity field and of Euler vector defining the Eurasian plate (rotation), are performed by means of Glorg, Plate and other modules of package Globk.

In particular, the processing procedure is based on the same distributed session multi-step approach described by [Dong et al. 1998, Herring et al. 2006a,b] and subsequently applied by Serpelloni et al., [2006] and Casula et al. [2007].

A suitable set of quasi-observations is created with the aid of GAMIT package starting from the double differenced GPS observables adjusted in the least square sense in order to compute for every GPS station involved in the computation: coordinates, ambiguities, atmospheric models, together with their variance-covariance matrices [Herring et al. 2006a].

Daily observations are created by means of GLOBK package [Herring et al. 2006b] after a robust combination process (every quasi-observation must contain at least 2 or 3 common stations), based on the assumption that combined observations are identical to solutions obtained by processing simultaneously all the GPS stations involved in the observations itself. For instance, during the combination process the Chi square parameter is checked to be less than the unit in order to verify the correctness of the stochastic model applied and eventually used for down-weighting.

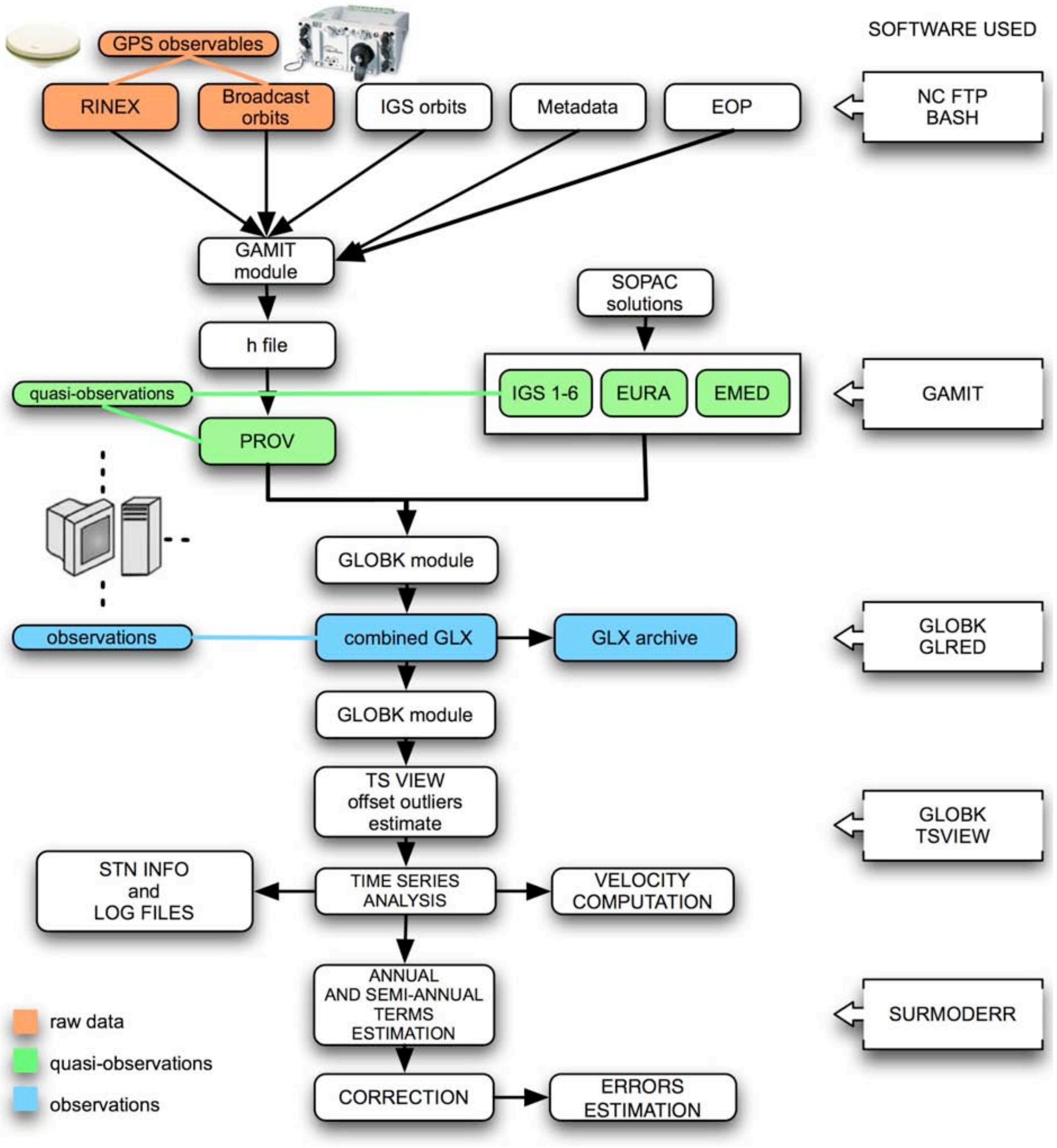


Figure 4 Flow block diagram for Assogeo GPS data processing. The raw observables, the quasi observations, and the observations are evidenced with brown, green, and blue colours respectively in the flow.

A stabilisation process is then performed by minimising the residuals between our solutions coordinates and velocities and the velocities and coordinates computed by EUREF for a set of about 40 reference stations in the IGS05 reference frame using the module Glorg (Global origin) of the package Globk.

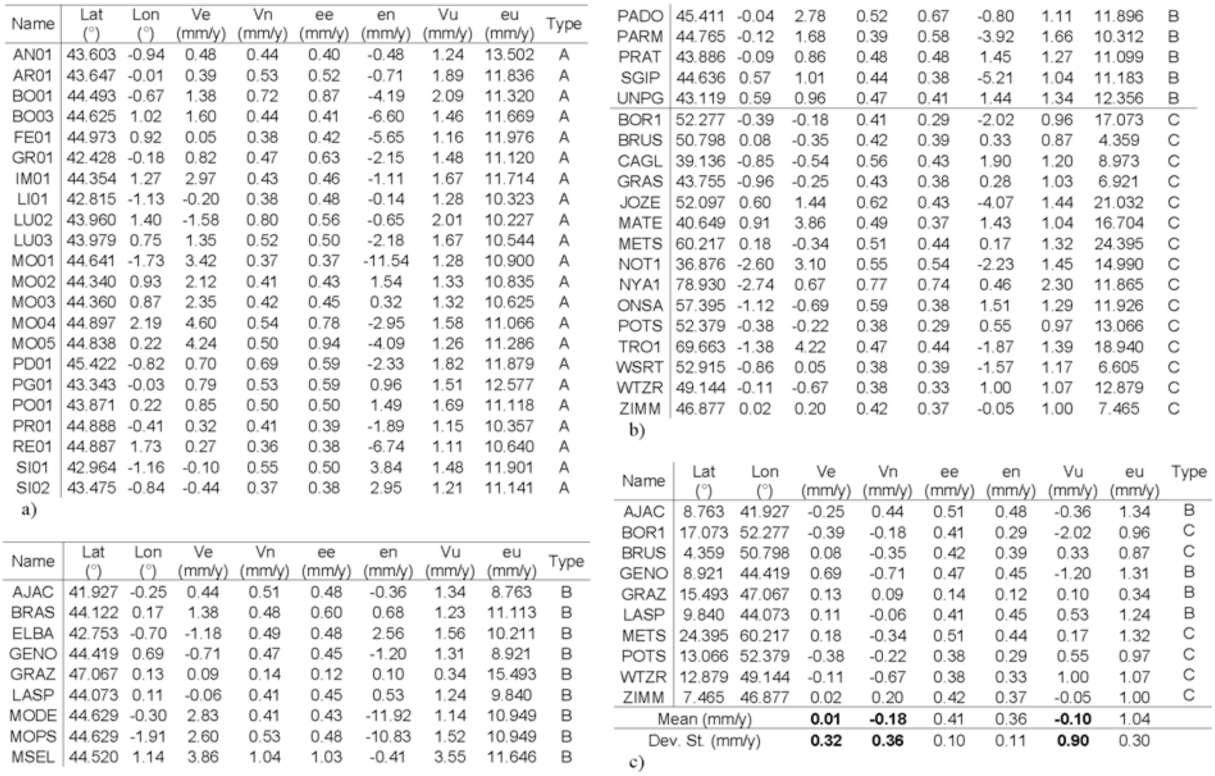
Following the previously described geo-referring stage the velocities and coordinates of the ASSOGEO network stations are transformed in the IGS05 reference frame, and an intra-plate velocity field is obtained from the IGS05 velocities by removing the inherently rigid rotation of the Eurasian Plate using the mean Euler vector computed by Altamimi [Altamimi et al. 2007]. In the last step the relative Euler pole by module plate of the Globk package is computed in order to completely remove the rigid rotation of Eurasian plate; the definition of the plate is performed using only the reference sites whose residuals resulting velocities are negligible.

5. Post Processing products

In this section a summary of the main products obtainable from data processing are shown and briefly described. In particular, the adopted procedure for velocity estimates, a post processing of coordinate time series, a computation for station reliability, the characterization of a few test sites and a strain rate computation from the available velocity pattern are cited. Actually, these results are presented only to describe the products typology and are not intended as final results but are preliminary ones.

5.1. Velocity solutions

The data belonging to the chosen 51 GPS permanent stations considered in this study, collected from March 2006 to February 2009, were processed using GAMIT software following the procedure reported above; 11 stations (BRUS GRAS HOFN JOZE METS NOT1 POTS RABT TRO1 VILL ZIMM) were processed together with the Assogeo network ones in order to optimize the network internal constrains and to facilitate the robust combination process with SOPAC regional clusters. In table 1 (a and b) the approximate geographic coordinates of GPS stations belonging to the Italian sub-network are listed together with their rms, intra-plate station velocities, velocity errors estimated with the Globk and taking into account the white and colored noise processes at 38% confidence level (1 sigma). Moreover, the intra-plate residual velocities of reference stations are listed in table 1(c).



Name	Lat (°)	Lon (°)	Ve (mm/y)	Vn (mm/y)	ee (mm/y)	en (mm/y)	Vu (mm/y)	eu (mm/y)	Type
AN01	43.603	-0.94	0.48	0.44	0.40	-0.48	1.24	13.502	A
AR01	43.647	-0.01	0.39	0.53	0.52	-0.71	1.89	11.836	A
BO01	44.493	-0.67	1.38	0.72	0.87	-4.19	2.09	11.320	A
BO03	44.625	1.02	1.60	0.44	0.41	-6.60	1.46	11.669	A
FE01	44.973	0.92	0.05	0.38	0.42	-5.65	1.16	11.976	A
GR01	42.428	-0.18	0.82	0.47	0.63	-2.15	1.48	11.120	A
IM01	44.354	1.27	2.97	0.43	0.46	-1.11	1.67	11.714	A
LI01	42.815	-1.13	-0.20	0.38	0.48	-0.14	1.28	10.323	A
LU02	43.960	1.40	-1.58	0.80	0.56	-0.65	2.01	10.227	A
LU03	43.979	0.75	1.35	0.52	0.50	-2.18	1.67	10.544	A
MO01	44.641	-1.73	3.42	0.37	0.37	-11.54	1.28	10.900	A
MO02	44.340	0.93	2.12	0.41	0.43	1.54	1.33	10.835	A
MO03	44.360	0.87	2.35	0.42	0.45	0.32	1.32	10.625	A
MO04	44.897	2.19	4.60	0.54	0.78	-2.95	1.58	11.066	A
MO05	44.838	0.22	4.24	0.50	0.94	-4.09	1.26	11.286	A
PD01	45.422	-0.82	0.70	0.69	0.59	-2.33	1.82	11.879	A
PG01	43.343	-0.03	0.79	0.53	0.59	0.96	1.51	12.577	A
PO01	43.871	0.22	0.85	0.50	0.50	1.49	1.69	11.118	A
PR01	44.888	-0.41	0.32	0.41	0.39	-1.89	1.15	10.357	A
RE01	44.887	1.73	0.27	0.36	0.38	-6.74	1.11	10.640	A
SI01	42.964	-1.16	-0.10	0.55	0.50	3.84	1.48	11.901	A
SI02	43.475	-0.84	-0.44	0.37	0.38	2.95	1.21	11.141	A

a)

Name	Lat (°)	Lon (°)	Ve (mm/y)	Vn (mm/y)	ee (mm/y)	en (mm/y)	Vu (mm/y)	eu (mm/y)	Type
AJAC	41.927	-0.25	0.44	0.51	0.48	-0.36	1.34	8.763	B
BRAS	44.122	0.17	1.38	0.48	0.60	0.68	1.23	11.113	B
ELBA	42.753	-0.70	-1.18	0.49	0.48	2.56	1.56	10.211	B
GENO	44.419	0.69	-0.71	0.47	0.45	-1.20	1.31	8.921	B
GRAZ	47.067	0.13	0.09	0.14	0.12	0.10	0.34	15.493	B
LASP	44.073	0.11	-0.06	0.41	0.45	0.53	1.24	9.840	B
MODE	44.629	-0.30	2.83	0.41	0.43	-11.92	1.14	10.949	B
MOPS	44.629	-1.91	2.60	0.53	0.48	-10.83	1.52	10.949	B
MSEL	44.520	1.14	3.86	1.04	1.03	-0.41	3.55	11.646	B
PADO	45.411	-0.04	2.78	0.52	0.67	-0.80	1.11	11.896	B
PARM	44.765	-0.12	1.68	0.39	0.58	-3.92	1.66	10.312	B
PRAT	43.886	-0.09	0.86	0.48	0.48	1.45	1.27	11.099	B
SGIP	44.636	0.57	1.01	0.44	0.38	-5.21	1.04	11.183	B
UNPG	43.119	0.59	0.96	0.47	0.41	1.44	1.34	12.356	B
BOR1	52.277	-0.39	-0.18	0.41	0.29	-2.02	0.96	17.073	C
BRUS	50.798	0.08	-0.35	0.42	0.39	0.33	0.87	4.359	C
CAGL	39.136	-0.85	-0.54	0.56	0.43	1.90	1.20	8.973	C
GRAS	43.755	-0.96	-0.25	0.43	0.38	0.28	1.03	6.921	C
JOZE	52.097	0.60	1.44	0.62	0.43	-4.07	1.44	21.032	C
MATE	40.649	0.91	3.86	0.49	0.37	1.43	1.04	16.704	C
METS	60.217	0.18	-0.34	0.51	0.44	0.17	1.32	24.395	C
NOT1	36.876	-2.60	3.10	0.55	0.54	-2.23	1.45	14.990	C
NYA1	78.930	-2.74	0.67	0.77	0.74	0.46	2.30	11.865	C
ONSA	57.395	-1.12	-0.69	0.59	0.38	1.51	1.29	11.926	C
POTS	52.379	-0.38	-0.22	0.38	0.29	0.55	0.97	13.066	C
TRO1	69.663	-1.38	4.22	0.47	0.44	-1.87	1.39	18.940	C
WSRT	52.915	-0.86	0.05	0.38	0.39	-1.57	1.17	6.605	C
WTZR	49.144	-0.11	-0.67	0.38	0.33	1.00	1.07	12.879	C
ZIMM	46.877	0.02	0.20	0.42	0.37	-0.05	1.00	7.465	C

b)

Name	Lat (°)	Lon (°)	Ve (mm/y)	Vn (mm/y)	ee (mm/y)	en (mm/y)	Vu (mm/y)	eu (mm/y)	Type
AJAC	8.763	41.927	-0.25	0.44	0.51	0.48	-0.36	1.34	B
BOR1	17.073	52.277	-0.39	-0.18	0.41	0.29	-2.02	0.96	C
BRUS	4.359	50.798	0.08	-0.35	0.42	0.39	0.33	0.87	C
GENO	8.921	44.419	0.69	-0.71	0.47	0.45	-1.20	1.31	B
GRAZ	15.493	47.067	0.13	0.09	0.14	0.12	0.10	0.34	B
LASP	9.840	44.073	0.11	-0.06	0.41	0.45	0.53	1.24	B
METS	24.395	60.217	0.18	-0.34	0.51	0.44	0.17	1.32	C
POTS	13.066	52.379	-0.38	-0.22	0.38	0.29	0.55	0.97	C
WTZR	12.879	49.144	-0.11	-0.67	0.38	0.33	1.00	1.07	C
ZIMM	7.465	46.877	0.02	0.20	0.42	0.37	-0.05	1.00	C
Mean (mm/y)			**0.01**	**-0.18**	0.41	0.36	**-0.10**	1.04	
Dev. St. (mm/y)			**0.32**	**0.36**	0.10	0.11	**0.90**	0.30	

c)

Table 1 a) and b) Solutions in a time span of two years or more (preliminary solution); station name, geographic coordinates, velocities and associated errors are listed. A, B and C labels refers to ASSOGEO, RING and EUREF affiliations, respectively. c) Velocity residuals of the reference stations used to compute the relative Eulerian pole.

5.2. Additional automated time series analysis

An additional instrument for data analysis is provided by a specific toolbox running under Matlab 6.0 or later versions; the time series of GPS coordinates are automatically analyzed. All the functions are described in detail in the SURMODERR (SURvey MODeling ERRor) User's Guide reference manual., just discussed in Pesci et al. (2009).

The required input data file is an ASCII file containing a *N*-by-8 matrix whose columns are the vectors containing the data (y) the east, north and up coordinates (m), and related errors (m). The software was mainly conceived to simulate NPS (Non Permanent Station) data using CGPS and to define thresholds for velocity error estimates acceptance but it also allows an immediate visualization of time series and to point out their peculiarities.

The analysis of the coordinate time series of a CGPS provides: a) computation of a linear trend via a weighted or a non-weighted least square approach, as well as the generation of the corresponding detrended signal; b) time domain or frequency domain data filtering; c) analysis of residuals corresponding to low-frequency and high-frequency components of the signal; d) Fourier analysis of the detrended signal via Fast Fourier Transform (FFT). Figure 5 shows some plots provided by CGPS analysis function of SURMODERR. In particular, the time series daily data, with and without the linear trend, are shown. Some data analyses like smoothing, data filtering, FFT transforms, data subsampling and residual distribution are shown.

5.3. Station reliability check

Specific analyses are performed to investigate the quality of ASSOGEO stations in terms of results accuracy and antenna stability. As stated, these stations were disigned to provide a GPS data support during surveying, mainly planned for cartographic proposal or for short time measurement campaigns; in particular, the monument stability was not tested for long, but it is a fundamental requirement for efficient and continuous monitoring.

The approach used to check for anomalous station movements follows a simple procedure: the three coordinate components (east, north and up) are linearly interpolated, velocities are computed and series are subsequently de-trended. The rms of detrended coordinate distributions is computed for each component of each ASSOGEO stations. The same procedure is performed using the scientific available CGPS and the mean of obtained rms provided a unique threshold for each coordinate component: *thr*E, *thr*N, *thru* (figure 6).

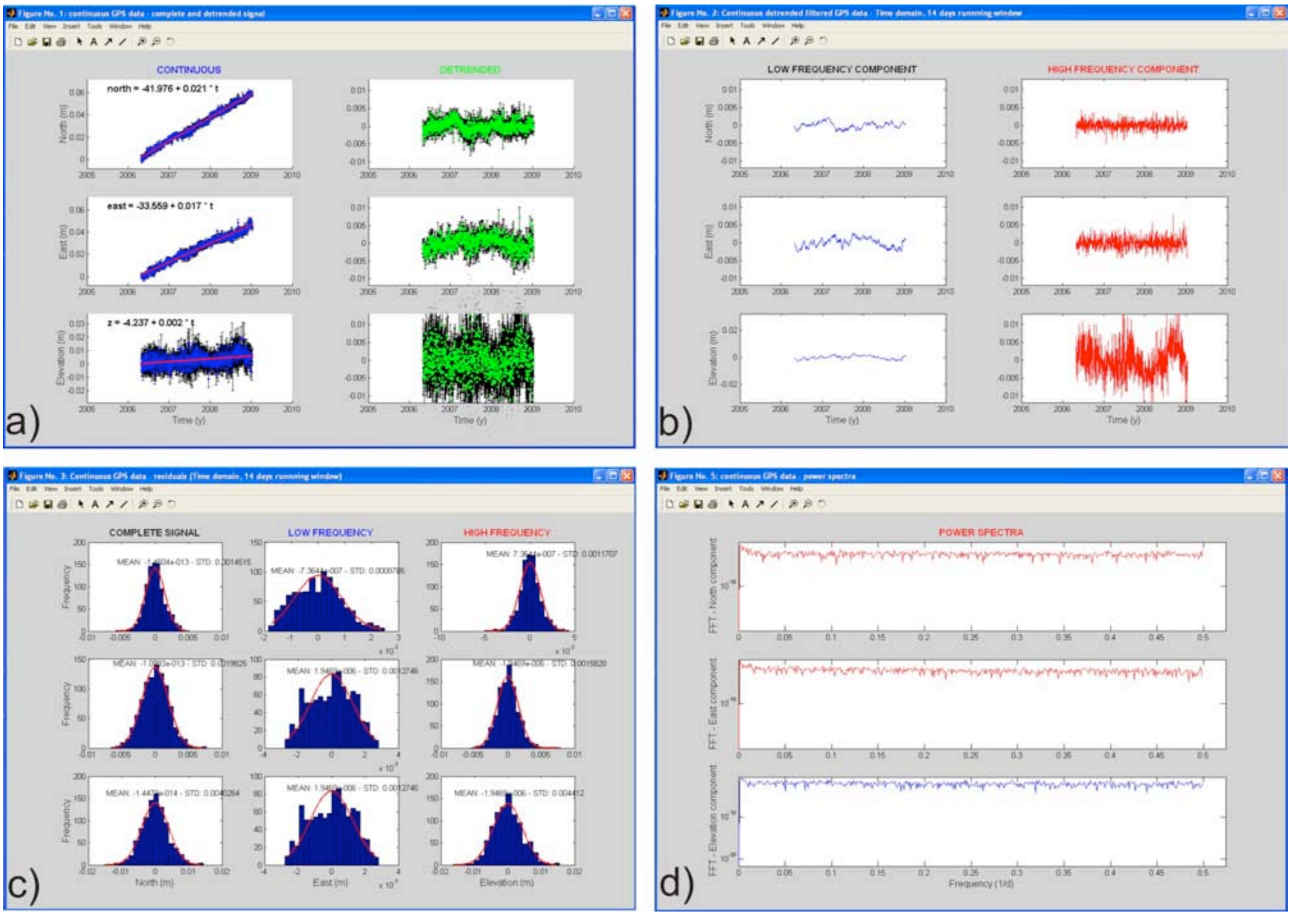


Figure 5 Default outputs of the automatic time series processing of BRAS station. A) original and detrended time series (errors are obtained from GAMIT/GLOBK processing); b) High and low frequency components forming the coordinate time series; c) the statistical distributions of high and low signals; d) FFT analysis.

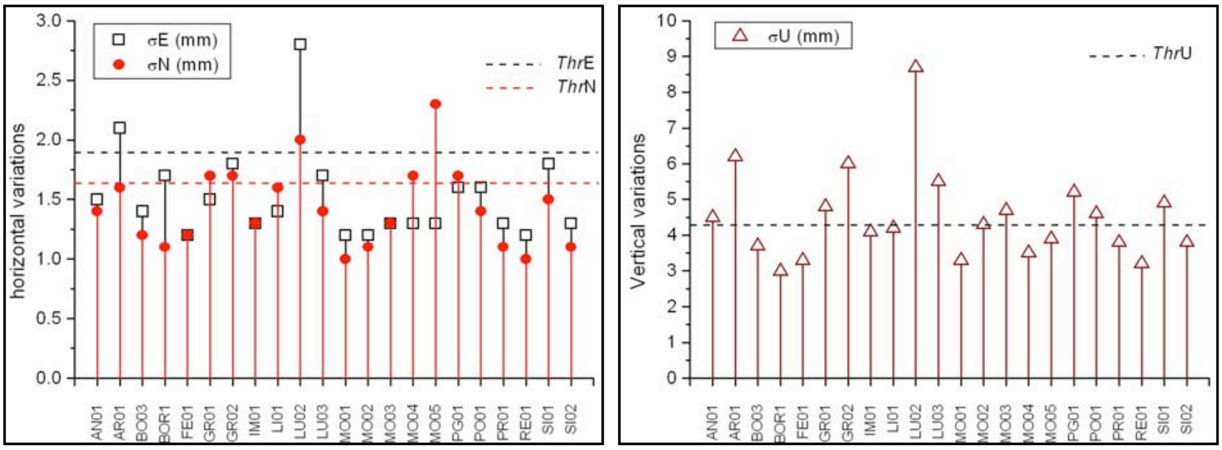


Figure 6 Plot of the rms from ASSOGEO detrended coordinate time series. The mean coordinate rms from data analysis of the scientific CGPS of the network (dashed lines) are overimposed. The check shows values exceeding the thresholds so corresponding stations are flagged and successively analyzed.

Using these values, the quality check for ASSOGEO GPS station stability starts: the rms of coordinate exceeding the thresholds could indicate that data are affected by large noise and anomalous antenna movements or should be characteristic of a local terrain effect. Figure 6 shows an example of stability check performed on a first data set collected in 1.5 year time span. In this example, three stations exceeds the thresholds for the horizontal coordinate reliability check: AP01, LU02 and MO05.

5.4. Area characterization: Modena area

This area represent an interesting example for local terrain variation monitoring; two stations MODE and MO01 are considered, installed in the in the city of Modena at a distance of about 4 km; first belongs to INGV while the second is an ASSOGEO station.

The two vertical time series are shown in figure 7 and shows similar trends. Moreover, the low component of the signals were separated, compared and a coefficient of correlation was computed as 0.97078 demonstrating a strong correlation. On the contrary, the same computation performed over the high frequency (> 14-days) led to a very low correlation (0.082).

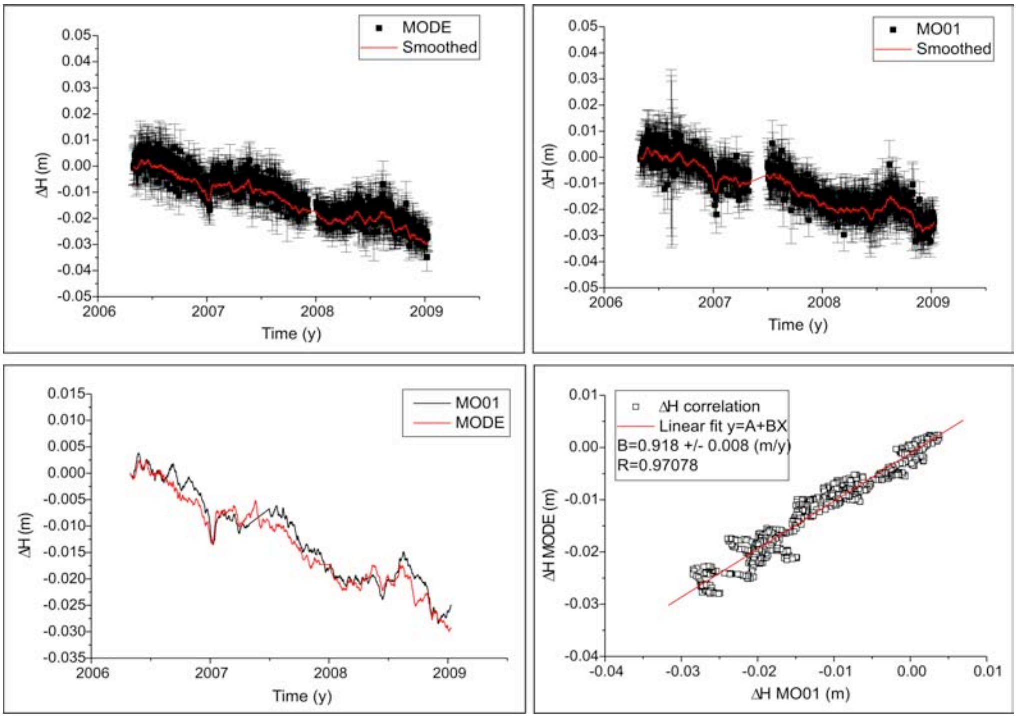


Figure 7 MODE and MO01 time series, smoothing and data correlation.

5.5. Area characterization: Apennine area

In the Apennine area MO02, MO03 and BRAS stations are considered. These stations lie in a mountainous environment and are characterized by height differences of about 100 m. Also in this case, a simple signal analysis was performed separating high and low frequencies, computing correlations and observing the smoothed series behaviors; resulting zero-positive trends suggest an uplift. Figure x shows the computed linear trends of smoothed time series, in agreement with velocity estimates obtained during the data processing that are 0.0014, 0.0015 and 0.0013 m/y.

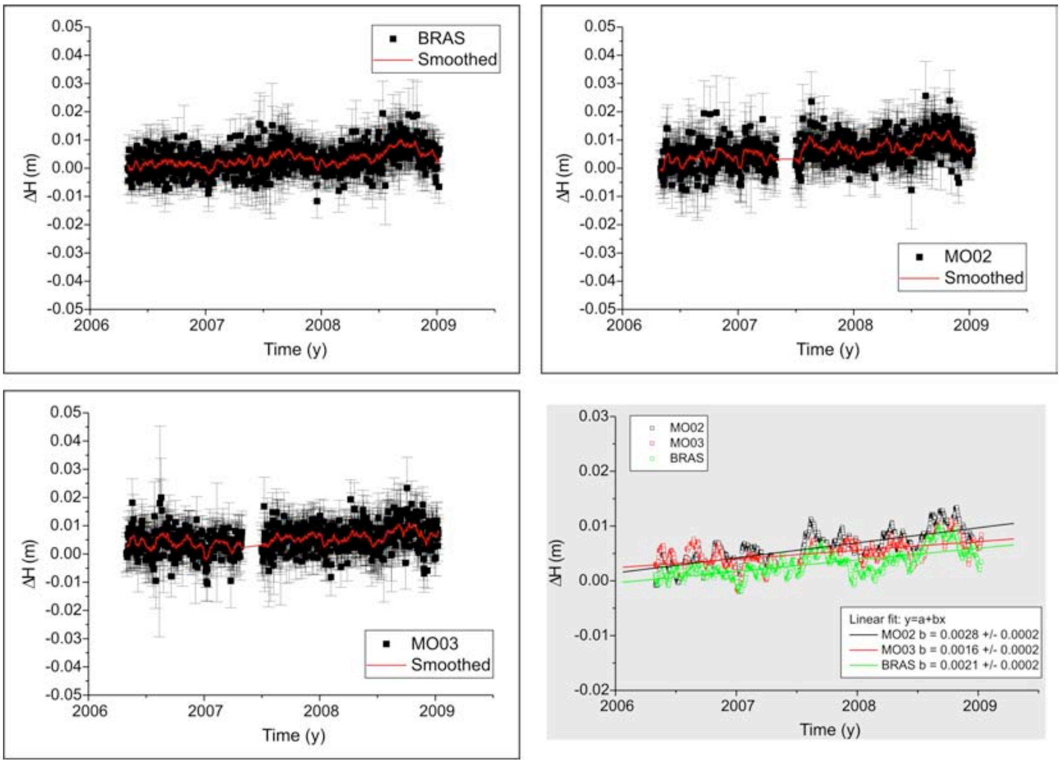


Figure 8 Apennine time series, smoothed data and linear trends.

5.6. Strain computation

Starting from the velocity field periodically computed, a preliminary automatic estimate of the strain rate is performed, following the theory of Feigl et al. 1990. Figure 9 shows a recent result. The strain rate tensors are shown inside several triangles created using the vertices of ASSOGEO stations (Delaunay triangulation method). The maxima of the strain rate are evidenced in the area of the Northern part of the Network and are superimposed to the epicentre of the 23th December 2008 earthquake of 5.1 local Magnitude occurred in the Parma district, showing a compressive trend (Figure 9).

Also in this case, the results have to be considered as a mere application of a tested methodology. The velocity field used to compute strain rate is not still reliable, due to the short observation time. Anyway, this is one of the obtainable post processing products periodically provided.

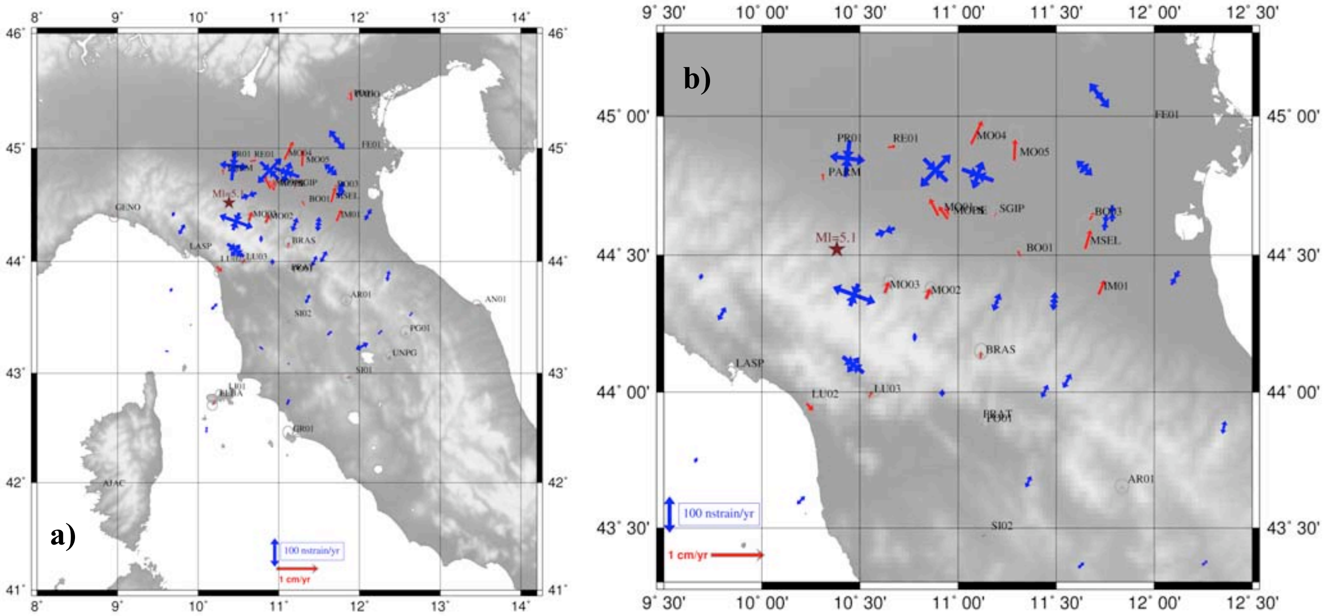


Figure 9 Results of the automatic strain rate computation; (a) the whole Assogeo Network, (b) the Emilia Romagna region and surroundings; the epicentre of the earthquake occurred on the December 23th 2008 is shown (brown star).

6. Conclusions

The synergy between INGV, Bologna University and ASSOGEO company led the integration of data collected from GPS stations conceived for different application and following different criteria providing a dense GPS information in the Emilia Romagna region. The GPS data belonging to ASSOGEO commercial network are continuously downloaded, collected, formatted and processed to monitor the surface variations in the Emilia Romagna territory. In particular, a wide and dense network is considered, composed of ASSOGEO and INGV CGPS integrated with other IGS stations.

The GAMIT/GLOBK software version 10.3 was used, leading to accurate station coordinate and velocity estimates in the ITRF reference frame, together with corresponding errors. The coordinate time series were analyzed, station velocities were estimated and residuals time series were obtained with de-trending operations.

Automatic procedures for data analysis and management are planned to provide the network velocity field, the corresponding strain rate pattern, the station coordinate stability check and data for local and specific analysis of horizontal and vertical measured movements.

Some evidences are detectable also from preliminary results; for example, common trends and strong correlations for vertical movements is measured at the stations installed in Modena city and the same rate for vertical uplift of stations in the Bologna Apennine.

The short mean inter-distance between stations and the high density of the integrated GPS network make it possible the realization of an efficient monitoring system at both local and regional scale.

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