Stability of the Reference Frame for Structural Monitoring Applications Using GNSS

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Key words: GNSS, Monitoring, Reference Frame, Structures monitoring.

SUMMARY

Nowadays, GNSS technology can be a useful tool, not only for navigation and location aspects, but also for precise positioning applications, such as monitoring of structures. The traditional approach to GNSS monitoring is based on a relative positioning between a reference station, assumed as stable, and a rover one. The continuous monitoring based on a daily position estimation produces a time series that can be useful both for structure stability studies and for "early warning" systems. In this paper, aspects related to GNSS monitoring have been investigated using a GNSS receiver located on the top of the Garisenda tower (Bologna, Italy) since October 2013. The acquired data, amounting to a couple of years, have been processed starting from four GNSS reference stations located in the area surrounding the tower. A single base data processing has been performed, assuming each reference stations as stable, and four time series have been obtained. A comparison of the estimated mean velocities shows significant differences, probably due to some instabilities of reference stations. Therefore, a model for each reference station has been defined using Precise Point Positioning approach and the models have been considered for a new data processing. The new time series have a higher level of accuracy than the previous series.

Removing the weighted average of velocity, derived from all the RS, from the velocity of the MS, the resulting velocity can be regarded as close to the real structural movements and, in our case, the results seem to indicate that this velocity is not significant.

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1. INTRODUCTION

Nowadays, GNSS technology can be a useful tool, not only for navigation and location aspects, but also for precise positioning applications, such as monitoring of structures. This technique allows an all-weather continuous remote control, as well as a quite low cost both for instrumentations and for monumentation aspects.

The traditional approach to GNSS monitoring is based on relative positioning between a reference station (RS) and one, or more, monitoring stations (MS); repeatability and accuracy of a GNSS relative positioning depends on the distance between RS and MS. For that reason, in order to obtain high precision using L1 receivers in cases such as structural monitoring, when the expected movements are usually very small and slow, a RS has to be materialized as near as possible to MS.

For data processing, several software packages are available, both by GNSS manufacturers and by scientific institutions. Recent free and open source software packages, such as RTKLIB (Takasu, 2011) and GoGPS (Realini and Reguzzoni, 2013), are particularly interesting because they allow a much higher level of customization of the data processing and post-processing phases and, for short distances, they offer performances comparable with those of more consolidated software packages, such as Bernese (Dach et al., 2015), Gamit (Herring et al., 2006), etc…

The continuous monitoring based on a daily position estimation produces a time series that can be useful both for structure stability studies and for "early warning" systems. The time series of MS position is obtained by single base positioning, starting from a RS whose position is known and assumed as stable. The hypothesis of stability of RS means that any movements of a RS would be entirely attributed to the MS; therefore, the time series of MS position may potentially represents not only movements of the monitored structure, but also any possible movements of the RS.

In order to investigate how the choice of the RS and the initial hypothesis of RS stability affect the MS results, a case study with one MS and more than one RS can be considered; the time series of MS positions can be calculated from each RS, performing single base data processing. The monitoring results should be independent from the RS and the different MS time series are expected to be consistent with each other, regardless of the RS considered in data processing.

In this paper, the monitoring of an historical tower, the Garisenda tower in Bologna (Italy), has been considered as the case study. So, a GNSS permanent station was installed on top of the tower in October 2013, and has been considered as the MS. A particularity of this case study is the presence of four existing GNSS permanent stations located in an area of about 2 km from the tower; data acquired from the four stations were available and they have been considered as RS. Furthermore, the four permanent stations were installed years earlier than the MS, between 2004 and 2012, and the prolonged GNSS data series have been used to estimate models of RS positions, by means of Precise Point Positioning (PPP) approach and GIPSY OASIS II. The models of RS have proved useful to investigate how behaviours of RS affect the monitoring results.

2. CASE STUDY

2.1 The Garisenda tower in Bologna (Italy)

In this study, two years of data acquired by a GNSS station located on the top of the Garisenda tower of Bologna (Italy) have been used. The Garisenda tower is one of the most important features of Bologna's cultural heritage, but it is notoriously affected by problems of stability and has already been monitored using different techniques (Baraccani et al., 2014). The Garisenda tower can be dated to around the last two decades of the eleventh century and during construction the foundation soil underwent subsidence phenomena (Giordano, 2000). This caused the tower, originally about 60 m tall, to tilt markedly. Today it stands at a height of 48 m and has a slope of 3.22 m towards the northeast. Therefore, several projects have been undertaken to reinforce the structure over the last decade and after completion of the work, at the beginning of the year 2011, a monitoring system[1] was installed on the tower in order to monitor its structural behavior by means of a long-base deformometer, deformometer, extensimeter, laser displacement sensor and inclinometers. In 2013, the Department of Civil, Environmental and Materials Engineering of Bologna University installed a permanent GNSS station on the roof of the Garisenda for the double purpose of monitoring the building and testing the satellite technology for this type of application. The station acquires 1 Hz GNSS data and send them via mobile phone technology to a computer server that stores all the received raw data. Starting from 1Hz data and a kinematics data processing some studies have been done concerning the possibility to improve the real time solution using sequential filtering (Gandolfi et al., 2015b).

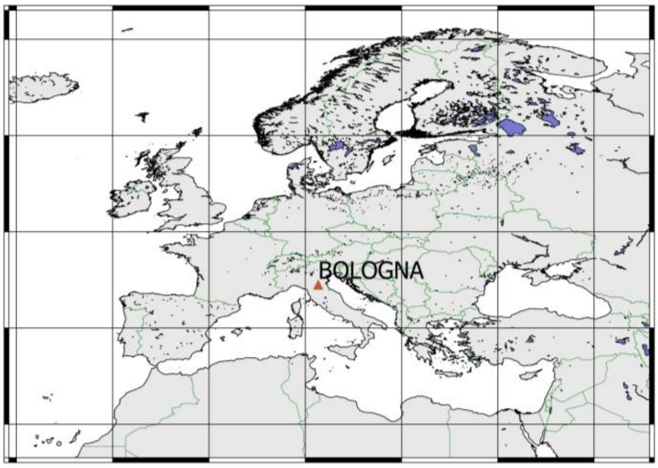

Figure 1 – On the left the "Two Towers" of Bologna and on the right the location of the town Bologna. The Garisenda tower is the shorter of the two, located on the left, and the taller one (on the right) is named "Asinelli",

[1] http://www.tecnoinmonitoraggi.it/cms_descrizione_sistema_monitoraggio.html

2.2 Data set and reference stations used for the study

As mentioned in the introduction, the traditional approach to GNSS monitoring is based on relative positioning between a reference station (RS) and one or more monitoring stations (MS), materialized at different locations of a monitored object. Positions of MS are measured from RS, assumed as stable. It is also known that repeatability and accuracy of a GNSS relative positioning, in differential data processing approach, depend on the distance between RS and MS. For that reason, in such cases as structural monitoring when the expected movements are usually very small and slow, a RS has to be materialized as near as possible to MS.
In this case study, data acquired by four existing dual frequency geodetic GNSS permanent stations located in the area surrounding the Garisenda tower were available.

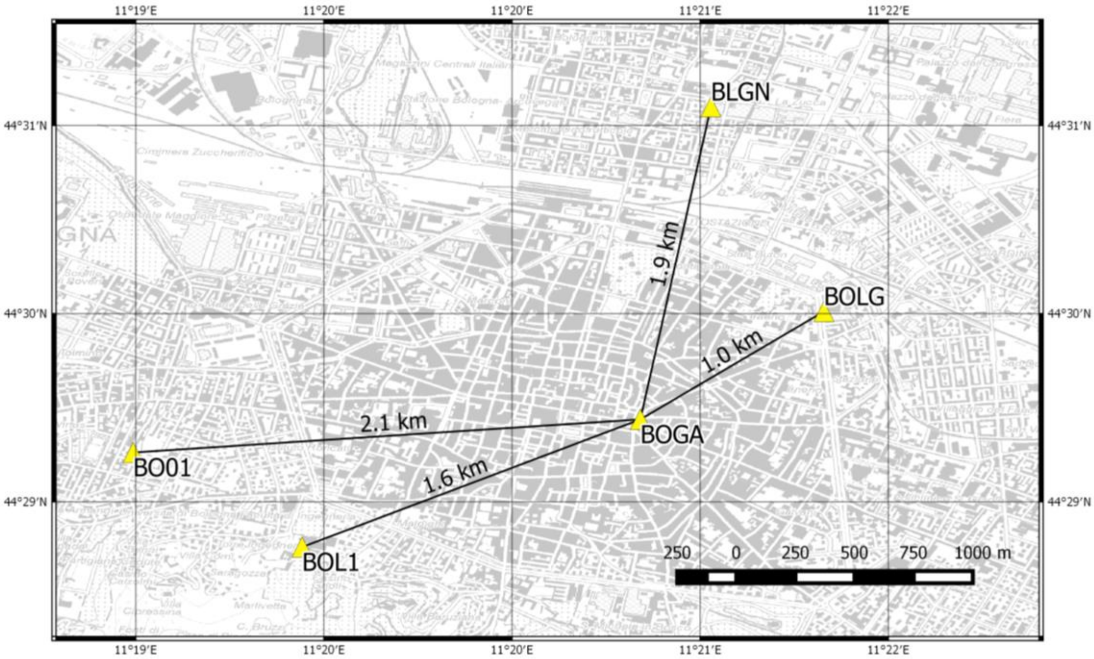

Figure 2 - Map showing the positions of the Garisenda tower MS (BOGA) and the four RS (BOL1, BOLG, BLGN, BO01)

Those four permanent stations, established at different times and for various applications and purposes, are considered as the RS.

BOL1: Dual frequency geodetic GNSS Permanent station installed on the roof of the School of Engineering and Architecture by the Department of Civil, Environmental and Materials Engineering (DICAM) of the University of Bologna in 2004, for real-time positioning applications.

BOLG: Dual frequency geodetic GNSS Permanent station installed by the Department of Physics and Astronomy (DIFA) of the University of Bologna in 2005 and part of EUREF Permanent Network (EPN).

BLGN: Dual frequency geodetic GNSS Permanent station installed by the Italian National Institute of Geophysics and Volcanology (INGV) in 2008, primarily for geodynamics studies.

BO01: Dual frequency geodetic GNSS Permanent station installed in 2012 by a private company for precise positioning applications in Emilia Romagna (Italy).

The four RS (Figure 2) are located within a distance of about 2 km from the MS on the Garisenda tower, their characteristics are listed in Table 1.

GNSS Reference Station	Receiver Type	Antenna Type and Radome	Distance from BOGA (km)
BOL1	Leica GX1230GG	Leiax 1202GG - NONE	1.6
BOLG	LeicaSR9500	LEIAT302+GP	1.0
BO01	Trimble 5700	TRM41249.00 - TZGD	2.1
BLGN	Leica SR520	LEIAX1202 NONE	1.9

Table 1 - Characteristics of each GNSS RS and their distances from the MS.

The receiver on the Garisenda tower (Rec. Type: Leica GX1230GG, Ant. Type: LEIAX 1202GG, Radome: NONE) has been acquiring data since October 2013, therefore a period of about 2 years (from 2013.7 to 2015.7) is available.

3. DATA PROCESSING AND RESULTS ASSUMING EACH REFERENCE STATION AS STABLE

GNSS data acquired by the Garisenda station (BOGA) during the 2 years period have been processed with data acquired by each RS, using RTKLIB and performing a single-base positioning. RTKLIB is an open source software package, which features several calculation modes. The RS have been assumed as stable and have been assigned fixed ITRF2008 coordinates; the main calculation parameters adopted for the data processing are listed below

- Constellation: GPS+GLONASS
- Observables: Carrier Phase
- Frequencies: L1+L2
- Positioning Mode: Static
- Filter Type: Forward
- Ionosphere Correction: Broadcast
- Tropospheric Correction: Saastamoinen
- Satellite Ephemeris/Clock: Broadcast
- Data sampling: 30 seconds

A *Perl* script has been implemented to automate the data processing phases. The results of data processing are four time series of MS positions, each referred to one of the RS.

In order to separate the plane components and the height, all results and graphs have been represented in local geodetic reference frame.
To make the reading of this paper easier, we define $BOGA_{BOL1}$ the time series of the MS BOGA obtained from the reference station BOL1; time series of BOGA obtained from the other RS are named accordingly.

3.1 First results and discussion

The four time series of the MS have been represented into the same graph (Figure 3), so as to compare the results obtained from the different RS. For each time series, mean velocities of the MS have been estimated. Since the main purpose of this paper is not to discuss the position determination of an unknown point but the monitoring of a point, the time series displayed in Figure 3 have been shifted of a fixed value in y-axis. This allows a better view of results and, in particular, it highlights differences between the mean velocity values, as well as the presence of signals and the scattering of each solution. The gaps in time series, evident in the graphs, have been caused by problems of the MS and interruptions of data transmission. The two vertical lines, after epoch 2014.5, mark an interval of time when the MS receiver have ben substituted with another of the same type, to allow a firmware update.

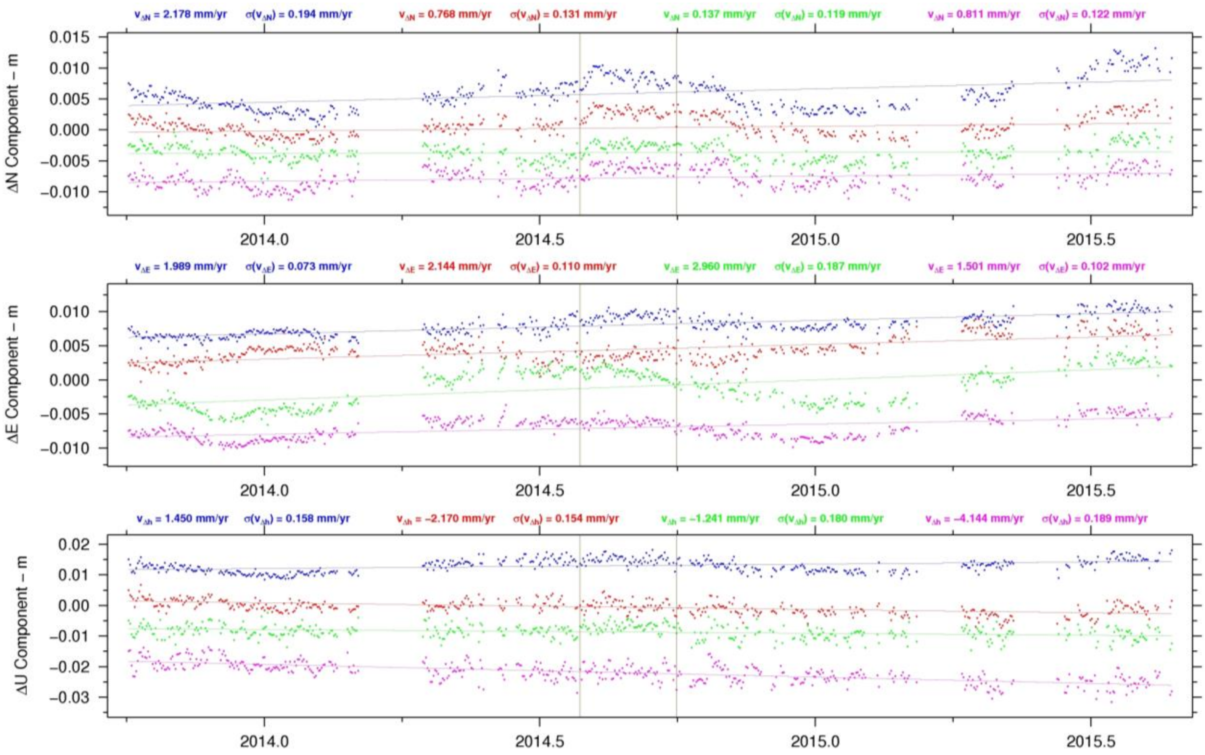

Figure 3 – Time series of BOGA, in local geodetic components, derived from RS assumed as stable. The time series are represented in different colours: $BOGA_{\mathrm{BOL1}}$ in *blue*, $BOGA_{\mathrm{BO01}}$ in *red*, $BOGA_{\mathrm{BOLG}}$ in *green* and $BOGA_{\mathrm{BLGN}}$ in *magenta*.

As Figure 3 illustrates, the four time series of BOGA show some differences, both in terms of estimated mean velocities of the MS and of signal presence.
For a better comparison of results, the estimated mean velocities of BOGA and root mean squares values are listed in
Table 2; for each local geodetic component a weighted average of velocities have been calculated and they are also shown in
Table 2. The inverse of the square of RMS has been assumed as weight.

Time Series	$\overline{\mathrm{V}}_{\mathrm{N}}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{\mathrm{N}}}$ (mm/y)	$\overline{\mathrm{V}}_{\mathrm{E}}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{E}}$ (mm/y)	$\overline{\mathrm{V}}_{U}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{U}}$ (mm/y)
$BOGA_{\mathrm{BLGN}}$	0.82	0.12	1.50	0.10	-4.14	0.19
$BOGA_{\mathrm{BO01}}$	0.77	0.13	2.14	0.11	-2.17	0.15
$BOGA_{\mathrm{BOL1}}$	2.18	0.19	1.99	0.07	1.45	0.16
$BOGA_{BOLG}$	0.14	0.12	2.96	0.19	-1.24	0.18
weighted average	**0.75**		**1.97**		**-1.34**	
RMS	**0.90**		**0.60**		**2.33**	

Table 2 - BOGA mean velocities, estimated for the time series obtained assuming the RS as stable, and weighted averages of velocities in each local geodetic component.

The MS position should be independent from the RS considered in the single base data processing and the four resulting BOGA time series should provide results that are consistent with each other. To evaluate the level of agreement between the time series of solutions, Pearson's correlation coefficients (Pearson, 1895) have been calculated, assuming the $BOGA_{BOL1}$ solution as reference (Table 3).

Time Series	ρ_N	ρ_E	ρ_U
$BOGA_{\mathrm{BOLG}}$	0.62	0.70	0.03
$BOGA_{\mathrm{BO01}}$	0.90	0.65	0.29
$BOGA_{\mathrm{BLGN}}$	0.59	0.64	-0.28
average	**0.70**	**0.66**	**0.02**

Table 3 - Pearson's correlation coefficients, calculated assuming $BOGA_{\mathrm{BOL1}}$ as reference, for the time series obtained with stable RS.

Figure 3 and
Table 2 show some significant differences between the mean velocities of the MS, estimated for the four time series. In figure 3, the East components appear to be one characterized by more scattered

solutions and more differences between time series signals, particularly the $BOGA_{BOLG}$ solution (drawn in green in Figure 3). The y-axis scale of the height component is different from the one of North and East, therefore some characteristics and differences may not be visible in Figure 3.
Table 2 shows that the height components have the highest value of RMS of the weighted average of estimated velocities. The correlation coefficients in Table 3 indicate that the results obtained from the four RS, assumed as stable and located close to the MS, have only a partial agreement, with the lowest values of correlation in the height component.
Most likely, those differences are partly due to the initial hypothesis of stability of the RS. With the single base data processing used, any movements of a RS would be attributed entirely to the MS, thus inducing potentially erroneous interpretations of results.
In order to take local movements and signals of RS into account and to investigate the possibility of improving the solutions' agreement, the entire dataset has been processed considering the local movements of each RS, by means of time series models of RS positions, obtained by a Precise Point Positioning (PPP) approach.

4. DATA PROCESSING AND RESULTS CONSIDERING A LOCAL TIME SERIES MODEL FOR EACH REFERENCE STATION

In a second data processing, four time series of MS positions have been calculated applying a synthetic model to each RS; as mentioned above, the RS models have been defined employing a PPP approach and Gipsy OASIS II. The RS have been installed earlier than the MS and the GNSS series of RS are all longer than the 2 years period used to calculate the BOGA solutions. For each RS, the model has been defined using all data available. For prolonged geodetic time series, PPP approach provides results comparable with those of other scientific software packages, but referred to the global reference frame (Gandolfi et al., 2015a).

4.1 Model generation using PPP and Gipsy-OASIS II software package

In order to obtain a synthetic model for each RS without introducing any direct cross-correlation between stations, a data-processing based on PPP approach represents a possible solution, as well as quite fast and accurate. Over the last few years, PPP has achieved performance levels comparable to those obtainable through the differencing approach (Griffiths and Ray 2009; Bisnath and Gao 2009), especially for GNSS permanent stations. It is known that PPP provides solutions referred to the reference frame of the orbits, which constitute the only constraint to a reference frame. Using this approach, each RS can be processed separately from the others and the result is a time series referred to the reference frame of the orbits (now IGb08 or ITRF2008). In this reference frame, a point located on the Eurasian plate moves with an average velocity of about 2.5 cm/year in North-East direction. This average motion can be removed using an S-transformation (Boucher and Altamimi, 2011), which moves the solution from the ITRS to ETRS. In this Reference System, realized through the ETRF2000, a point in Italy is characterized by a residual velocity of a few mm/year (Barbarella et al., 2013).

Using GIPSY OASIS II software package, the data processing of the four RS has been performed and each solution was transformed in ETRF2000.
Average velocities of each RS have been estimated with the method described; the values are shown in
Table 4 and are useful for some later analyses.

GNSS reference stations	$\overline{V}_N$ (mm/y)	$\sigma_{\overline{V}_N}$ (mm/y)	$\overline{V}_E$ (mm/y)	$\sigma_{\overline{V}_E}$ (mm/y)	$\overline{V}_U$ (mm/y)	$\sigma_{\overline{V}_U}$ (mm/y)
BLGN	2.18	0.04	1.91	0.03	2.46	0.15
BO01	2.83	0.05	1.14	0.05	3.74	0.17
BOL1	2.54	0.06	1.49	0.03	-0.48	0.11
BOLG	3.20	0.06	0.77	0.07	1.41	0.17
weighted average	**2.60**		**1.51**		**1.29**	
RMS	**0.44**		**0.53**		**1.87**	

Table 4 - Average velocities of RS, derived from PPP modeling, and weighted averages of velocities in each local component.

4.2 Final results and discussion

The complete models of RS, described in 4.1, have been applied to the time series obtained by the first data processing performed assuming the RS as stable. The results of this second processing are four new time series, where local movements and signals of RS are taken into account. In order to assess the influence of the RS models on MS results, the new time series of BOGA have been represented in local geodetic frame and analyzed like the previous time series, computing mean velocities and correlation coefficients. The new time series have been represented into the same graph (Figure 4). Estimated mean velocities of the MS and their respective root mean square values are listed in
Table 5, weighted averages of velocity values in each local components are also reported.
Table 6 shows the Pearson's correlation coefficients, calculated assuming the $BOGA_{BOL1}$ solution as a reference.

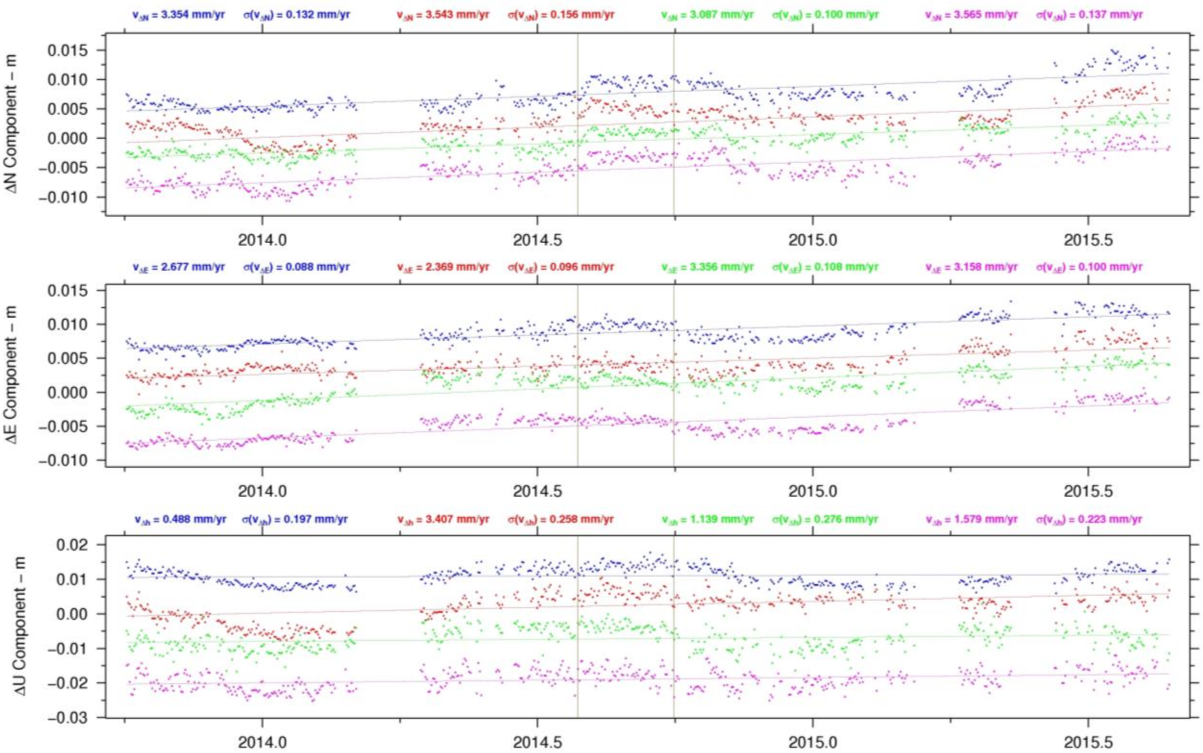

Figure 4 – Time series of BOGA, in local geodetic components, derived from the four RS and considering the RS models. The time series are represented in different colours: $BOGA_{\mathrm{BOL1}}$ in *blue*, $BOGA_{\mathrm{BO01}}$ in *red*, $BOGA_{\mathrm{BOLG}}$ in *green* and $BOGA_{\mathrm{BLGN}}$ in *magenta*.

Time Series	$\overline{\mathrm{V}}_{\mathrm{N}}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{\mathrm{N}}}$ (mm/y)	$\overline{\mathrm{V}}_{\mathrm{E}}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{E}}$ (mm/y)	$\overline{\mathrm{V}}_{U}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{U}}$ (mm/y)
$BOGA_{\mathrm{BOL1}}$	3.35	0.13	2.68	0.09	0.49	0.20
$BOGA_{\mathrm{BLGN}}$	3.56	0.14	3.16	0.10	1.58	0.22
$BOGA_{\mathrm{BO01}}$	3.54	0.16	2.37	0.10	3.41	0.26
$BOGA_{BOLG}$	3.09	0.10	3.36	0.11	1.14	0.28
weighted average	**3.32**		**2.85**		**1.49**	
RMS	**0.23**		**0.45**		**1.27**	

Table 5 - BOGA mean velocities, estimated for the time series obtained considering the RS models, and weighted averages of velocities in each local geodetic component.

Time Series	ρ_N	ρ_E	ρ_U
$BOGA_{BOLG}$	0.82	0.81	0.39
$BOGA_{\mathrm{BO01}}$	0.88	0.90	0.68
$BOGA_{\mathrm{BLGN}}$	0.81	0.88	0.37
average	**0.84**	**0.86**	**0.48**

Table 6 - Pearson's correlation coefficients, calculated assuming $BOGA_{\mathrm{BOL1}}$ solution as reference, for time series obtained with RS models

Mean velocities of BOGA (Table 5) have been estimated for time series calculated considering synthetic RS models referred to the ETRF2000 reference systems; for this reason, the values of mean velocities in local components amount to a few mm/year.

Compared to the mean velocities in Table 2, the values shown in Table 5 are more similar and, in each local component, the root mean squares values of weighted average velocity are lower, especially for North and height component.

As mentioned before, MS solutions should be independent from the RS considered in data processing and each time series should give the same results for the BOGA station.

Table 6 shows correlation coefficient values that are overall higher than those of the previous results (Table 3), particularly in height component. Such increase suggests that considering the RS models, and thus taking into account movements and signals of RS, results in an improvement in the level of agreement between the four solutions.

Obviously, these results (Table 5) don't represent movements of the structure where the MS is located, but they represent movements of the structure together with the residual velocity of the ETRF2000 in the area of study. A rigorous procedure to remove residual velocity of the ETRF2000 cannot be defined. However, considering the respective locations of RS and MS, a weighted average velocity based on the mean velocities of each RS can be computed (Table 4); these RS velocity values can be subtracted from the velocities of MS in Table 5 and a quasi-residual velocity of the structure can be estimated (Table 7).

Time Series	$\overline{\mathrm{V}}_{\mathrm{N}}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{\mathrm{N}}}$ (mm/y)	$\overline{\mathrm{V}}_{\mathrm{E}}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{E}}$ (mm/y)	$\overline{\mathrm{V}}_{U}$ (mm/y)	$\sigma_{\overline{\mathrm{V}}_{U}}$ (mm/y)
$BOGA_{\mathrm{BOL1}}$	0.76	0.46	1.16	0.54	-0.81	1.88
$BOGA_{\mathrm{BLGN}}$	0.97	0.47	1.64	0.54	0.28	1.89
$BOGA_{\mathrm{BO01}}$	0.95	0.47	0.86	0.54	2.11	1.89
$BOGA_{BOLG}$	0.49	0.46	1.84	0.54	-0.16	1.89
weighted average	**0.78**		**1.37**		**0.36**	
RMS	**0.22**		**0.45**		**1.25**	

Table 7 - Quasi residual velocities of the Garisenda tower

5. CONCLUSIONS

Some aspects concerning the stability of reference frame, in particular when dealing with structural monitoring, have been investigated in this paper. The monitoring of an historical tower, the Garisenda tower located in Bologna (Italy), has been selected as a case study. The particularity of this case is the availability of four GNSS dual frequency permanent stations in an area of about a 2 km from the tower. The four stations have been considered as RS in single base data processing, to obtain four time series of the MS; the four solutions are expected to be consistent and independent from the RS. Under the hypothesis of stable RS, the results show significant differences, both in terms of mean velocity and in terms of internal variability; the differences are also supported by low values of Pearson's correlation coefficient, calculated between each solutions and the solutions obtained by BOL1 RS. These results seem to indicate that the initial hypothesis of stability of the RS affects the solutions, which may represent not only any possible movements of the monitored structure but also possible movements of the RS. In order to consider this aspect, each RS has been processed using PPP approach and synthetic models of each RS movements have been produced. Each model has been applied to the time series of the MS obtained by the first data processing. The new time series show improvements in terms of mean velocity and signals, additionally, the improvements are supported by an overall increase in Pearson correlation coefficients. Obviously, since the models have been generated from a PPP solution of each RS, the synthetic models are referred to an ITRS reference frame and have been subsequently aligned to the ETRS89 reference frame, applying transformation parameters. In the ETRF2000, the coordinates are not characterized by a zero-velocity but by an average velocity that represents the residual intraplate velocity of the area. Therefore, the MS is characterized by a velocity that can be view as vectorial sum of two components: the structural movement vector and the intraplate residual velocity vector. In this case, the velocity of the MS is about 3.3, 2.8, 1.4 mm/y in North, East and Up component respectively and is consistent with the intraplate residual velocity. Removing the weighted average velocity derived by all the RS from the velocity of the MS, the resulting velocity can be regarded as close to the real structural movements and, in our case, the results seem to indicate that this velocity is not significant.

The adopted approach can be particularly important when an investigation of very small and slow movements is required; when the entity of movements is very high, in studies of movements of a structure or a part of territory, such as landslides, these considerations can represent a second order problem.

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BIOGRAPHICAL NOTES

Maurizio Barbarella received the Degree in Physics cum laude in 1971 at the University of Bologna. He has been full professor of geomatics at the universities of Ancona and Rome and is currently full professor at the University of Bologna. His current research interests concern monitoring of structures and of territory with various surveying techniques, such as high-resolution satellite images, Terrestrial Laser Scanner, GNSS.

Stefano Gandolfi received the Degree in Physics (with laude) in 1993 and the Ph.D. in Geodetic and Topographic Sciences from the University of Bologna in 1997. He is currently associate professor of geomatics at the University of Bologna and coordinator for the MSc degree in Environmental Engineering Study Program. His scientific interests are concentrate on the definition and maintenance of regional reference frames and on the use of GNSS data for monitoring deformation processes of structures and territory.

Lucia Cacciamani received her MSc degree in Environmental Engineering at the School of Engineering and Architecture at the University of Bologna in 2015, with a thesis on Surveying Techniques for Territorial Monitoring.

Luca Poluzzi is a Ph.D. student in the School of Engineering and Architecture at the University of Bologna, Italy. He received his MSc in Civil Engineering at the School of Engineering and Architecture at the University of Bologna, Italy. His current research interests include monitoring of structures through GNSS technology, the analysis of GNSS time series, creation of sequential filter to improve the accuracy of the GNSS kinematic time series, creation of automatic procedures for GNSS data processing.

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