A strategy for the monitoring of tall structures in urban area using GNSS technology

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ABSTRACT

GNSS technology has become widely used for monitoring purposes. The high precisions nowadays available have made the technique suitable also for the monitoring of structures that are usually affected by very small displacements. In this work we investigate the issue concerning the monitoring of a tall structure such as the Garisenda tower, which lay in the Bologna city centre, by using GNSS data gathered by a permanent station placed on its top. We consider the need to investigate the variations in the leaning of the structure, therefore also the position of the ground at the bottom of the structure should be known. Unfortunately it is not possible to place a GNSS receiver under a tall structure in urban context because of the too poor sky visibility. A solution would be to choose another permanent station located as close as possible assuming its behaviour coherent with the ground under the monitored structure. This hypothesis has proven not to be verified in the analysed case, where four permanent stations located within few kilometres far from the Garisenda tower were available. Therefore a strategy to combine data from the five permanent stations using a uniform strain model was developed in order to define a reference to which compare the positions given by the GNSS sensor placed on the top of the tower. The impact of such strategy will be shown and discussed in terms of mean variation of the leaning of the tower over a period of about four years.

I. INTRODUCTION

Since the GNSS technique has proved to provide repeatability of the estimated coordinates at the centimetre level or even less (Eckl *et al.,* 2001; Soler *et al.,* 2006; Barbarella *et al.,* 2018), it has become a suitable tool also for the monitoring of certain type of structures. The improved efficiency in the transmission of data to remote control centres and the lowering of instrumentation costs are two other aspects that lead to an increasing use of GNSS in structures monitoring. In some cases the main goal of the monitoring is an early warning system, which can take advantage of the capability to provide a continuous data stream given by the GNSS technology (Gandolfi *et al.,* 2017). Such applications rely on the kinematic calculation approach which do not provides the best precisions of the technique. These are conceivable for instance for suspension bridges, usually characterized by comparatively large movements. In other cases the objective of the monitoring may be the kinematic behaviour of the structure over a long period, meaning both the trends of the displacements and the periodical effects that occur because of thermal deformations, ground settling, anthropic causes and so forth (Lovse *et al.,* 1995; Hudnut *et al.,* 1998; Celebi *et al.,* 2002; Watson *et al.,* 2007).

In particular, if we consider a tall structure affected by a marked leaning, the most important parameter to be considered is probably the linear trend of such leaning, which can become critical even if its magnitude is a few mm/year only. Such trend can be represented by the average velocity of the top of the structure with respect to its base. To put a GNSS antenna on the top of a tower is a reasonable practice because good sky visibility likely guaranteed. Differently, the base of the same structure can hardly be monitored through GNSS technology too, because of the high probability to have very poor sky visibility due to urban canyons and/or lot of multipath in the satellite signals. Unfortunately, when the monitored displacements are small the ground underneath the structure cannot be assumed as fixed and the variations of its position should be discussed too.

In this work, the case of the Garisenda tower in Bologna city is discussed. The tower is one of the most important cultural heritages in the city and its structure is under investigation since the beginning of the XX century (Azzara *et al.,* 2014; Pesci *et al.,* 2011; Bergonzoni, 1989; Milani *et al.,* 2016) because of its marked leaning. The present work concerns the estimation of the variation in the leaning of the tower over time. A permanent GNSS station named BOGA is located on the top of the Garisenda and the test is based on the static processing of daily GNSS data collected for a period of about four years since October 2013. For this purpose, besides data from BOGA, four other GNSS permanent stations were considered, each one few kilometres distant from the Garisenda and thus potentially usable as stable reference for the estimation of the BOGA positions. The performed test show that none of the four permanent stations surrounding Garisenda tower should be assumed by itself as stable reference with enough confidence and an alternative method, which consider all the available data, is presented. This rely on a deformation model used for the estimation of the kinematics of the area around the tower, which can be more likely assumed as reliable reference for the displacements of the top of the structure.

II. Dataset and GNSS processing

A. *The Garisenda tower in Bologna (Italy)*

The construction of the Garisenda tower started in the XII century close to the Asinelli one (Fig.1) in the very centre of the city. The two had to reach the same height, but in 1351 the Garisenda started to tilt because of a foundation failure (Giordano, 2000). At the time its height was about 61 meters, but was soon reduced in order to avoid its collapse.

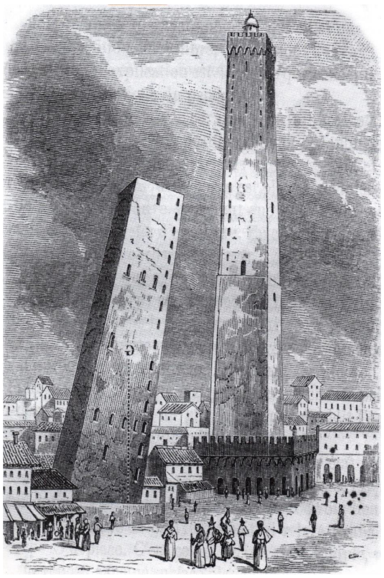

Figure 1. Portray of the Bologna two towers, Asinelli and Garisenda, during medieval age.

Nowadays the Garisenda is about 48 meters tall, with a square section having 7,5 meters sides, and is leaning for about 3,22 m toward East. Several studies and topographical surveys have been performed in order to investigate about the tower stability [Baraccani *et al.,* 2014; Capra *et al.,* 2011].

Starting from these studies several projects have been undertaken to reinforce and maintain the structure. Besides a monitoring system that was installed on the tower in the year 2011, October 2013 the DICAM department has installed a GNSS permanent station (BOGA) on the roof of the Garisenda (Fig.2) with the aim to test the effectiveness of such technology for structural monitoring purposes. The GNSS station provides raw data at 1 Hz frequency allowing also a dynamic monitoring. A sequential filtering method was also developed, improving the accuracy of the kinematic solutions [Gandolfi *et al.,* 2015].

Figure 2. The BOGA GNSS antenna installed on the top of Garisenda tower by the DICAM department since 2013.

B. *Dataset and GNSS processing*

For this test, daily 30 seconds RINEX files produced by the BOGA GNSS station were gathered from DOY 275 of year 2013 to the end of 2017. In order to estimate very accurate daily baselines, data from the closest available GNSS stations were considered too. In particular, four other permanent stations are located in Bologna, few kilometres far from the two towers, that are BLGN, BOLG, BO01 and BOL1 as shown in Figure 3.

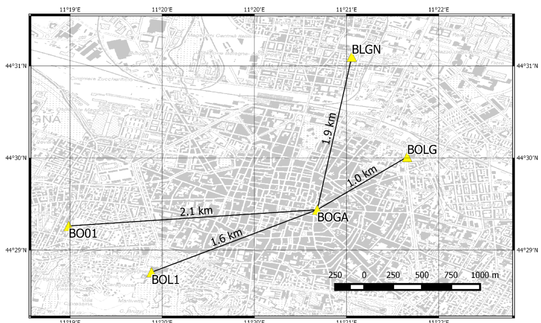

Figure 3. Positions of the Garisenda tower monitoring station (BOGA) and the four reference stations (BOL1, BOLG, BLGN, BO01) together with the relative distances.

No other GNSS stations are available in the area within ten kilometres. The more distant ones have not been considered because on one hand the higher baseline length would reduce the precision of the GNSS processing and, on the other hand, distant sites should be more probably affected by different local kinematic effect.

C. *GNSS processing and preliminary results*

The daily baselines between the BOGA station and each of the four other ones were calculated for the whole considered time span. The RTKLIB software package (Takasu, 2013) was used adopting standard parameters for static processing. IGS absolute calibration files (igs08.atx) were used for antennas phase centre variation, together with precise IGS products for ephemerids.

In the processing the BOGA station was chosen as the master station to which fixed coordinates were imposed. Figure 4 shows the time series of the position coordinates for the easting and northing components relating to the four stations surrounding BOGA. For representation purposes the time series are referred to local topocentric reference systems arbitrarily chosen.

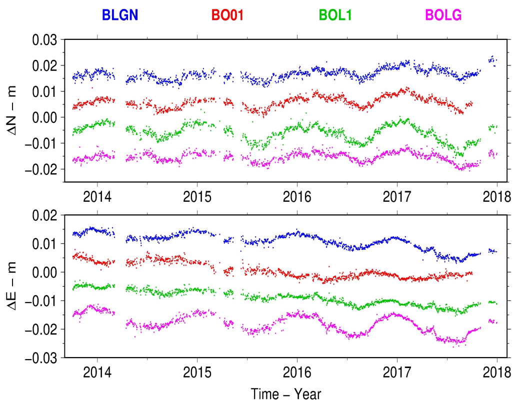

Figure 4. Time series of the daily positions of the BLGN, BO01, BOL1 and BOLG GNSS stations, from top to bottom respectively. Northing components are represented in the top panel whereas easting components are shown in the bottom one. Coordinates are calculated with respect to the BOGA station and expressed in local topocentric reference systems.

The regression straight lines for each time series were estimated for each time series after having removed outlier positions through an iterative procedure based on a three sigma rejection criteria. The slopes of these lines can be assumed to be the mean velocity components of each stations with respect to the BOGA station over the considered period. Table 1 reports the mean velocities of the four stations surrounding the Garisenda tower with respect to it. The uncertainties of the velocity parameters are also reported in terms of standard deviations.

Table 1. Columns 2 and 3 report the average velocities relatively to the BOGA station for the easting and northing component respectively. In columns 4 and 5 are the related standard deviations. All values are expressed in mm/year.

Site	V_{east}	V_{north}	σV_{east}	σV_{north}
BLGN	-2.0	1.4	0.04	0.04
BO01	-1.8	0.8	0.04	0.05
BOL1	-1.7	-0.3	0.02	0.07
BOLG	-1.2	0.2	0.06	0.04

The black arrows in figure 5 show the magnitudes and directions of the displacements for the considered stations assuming BOGA as fixed, together with the related standard error ellipses.

By using the differencing approach in GNSS processing the real measures are the baselines rather than the coordinates of a specific point and the velocities in the time series are the relative ones between two points. Therefore, it is possible change constraints and thus the interpretation of results. In Figure 5, changing the point of view, the coloured arrows represent the velocity of the top of the Garisenda tower, i.e. BOGA, having assumed as fixed the position of another station. For instance, the red arrow refers to the displacement velocity that can be found fixing the position of BOL1 station. It is worth noting that coloured arrows are all indicating an increasing leaning of the tower toward east direction. Nevertheless, from a statistical point of view and considering a 3-sigma confidence interval, the differences between the vectors are not negligible.

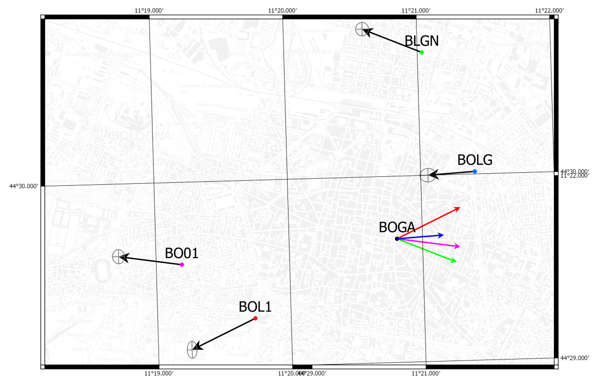

Figure 5. Black arrows represent the velocities of the four sites surrounding Garisenda tower with respect to its top (BOGA). Differently, the coloured arrows show the different estimations of BOGA displacements, each considering the position of the related station as fixed.

Therefore, it is not possible to say which estimation is the most reliable at this level: the baseline lengths (Figure 3) range from 1 to 2.1 km, differences that are quite negligible considering 24 hours observations, and the dimensions of the standard error ellipses of the vectors are very close. The area surrounding the Garisenda may be affected by some deformation and is not clear which of the surrounding stations can better represent the displacement beneath the tower. Therefore, in the next section is presented a method for the estimation of a deformation model that approximate the displacements within the considered area. The linear velocities shown in Table 1 constitute the input data for the model.

III. METHOD

A. *Estimation of a plane strain model using GNSS reference stations*

We consider a number k of stations i, each providing a velocity vector $\boldsymbol{v}_i = \left[v_{e_i}, v_{n_i}\right]^T$. The station positions at a certain epoch t_0 are $\boldsymbol{p}_i^0 = [e_i, n_i]^T$. We also consider $\boldsymbol{p}_C^0$ as the position of the centroid of the GNSS stations. The position of each station relatively to the centroid is:

$$\boldsymbol{\Delta p}_i^0 = [\Delta e_i^0, \Delta n_i^0]^T = \boldsymbol{p}_i^0 - \boldsymbol{p}_C^0 \tag{1}$$

The position of each station i at the generic epoch j can be obtained through:

$$\boldsymbol{\Delta p}_i^j = \boldsymbol{\Delta p}_i^0 + (t_j - t_0)(\boldsymbol{v}_i - \boldsymbol{v}_c) \tag{2}$$

where $\boldsymbol{v}_c$ is the centroid velocity. Then we can use a uniform strain model (Feigl *et al.*, 1990) to parameterize the velocity within the considered area. The L matrix containing the velocity gradients has form:

$$L = \begin{bmatrix} \frac{\partial v_e}{\partial e} & \frac{\partial v_e}{\partial n} \\ \frac{\partial v_n}{\partial e} & \frac{\partial v_n}{\partial n} \end{bmatrix} \tag{3}$$

Once defined, the L matrix can be used to define velocity of each site starting from the centroid velocity and the relative position to it through:

$$\boldsymbol{v}_i = \boldsymbol{v}_c + L(\boldsymbol{p}_i^0 - \boldsymbol{p}_C^0) = \boldsymbol{v}_c + L\boldsymbol{\Delta p}_i^0 \tag{4}$$

Starting from at least three GNSS stations is possible to estimate the six unknown parameters of the model, which are:

$$\mathbf{s} = \left[v_{e_c}, v_{n_c}, L_{11}, L_{12}, L_{21}, L_{22}\right]^T \tag{5}$$

A classic Gauss-Markov model can be used considering as input the vector of the known velocities of the k stations $\boldsymbol{j}$ and the design matrix B:

$$\boldsymbol{j} = \left[v_{e_1,} v_{n_1,}, \dots, v_{e_k,} v_{e_k}\right]^T \tag{6}$$

$$B = \begin{bmatrix} 1 & 0 & \Delta e_1^0 & \Delta n_1^0 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta e_1^0 & \Delta n_1^0 \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ 1 & 0 & \Delta e_k^0 & \Delta n_k^0 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta e_k^0 & \Delta n_k^0 \end{bmatrix} \tag{7}$$

The weight matrix P should have the inverse of the variances of each velocity in the diagonal elements. The solution can be computed according to the least square criterion using:

$$\boldsymbol{s} = (B^T\ W\ B)^{-1} B^T\ W \boldsymbol{j} \tag{8}$$

The covariance matrix of the unknowns can be estimated using:

$$\Sigma_{ss} = \frac{\boldsymbol{r}^T\ W \boldsymbol{r}}{2k-6}(B^T\ W\ B)^{-1} \tag{9}$$

The uncertainty of the residuals $\boldsymbol{r}$ can be estimated using:

$$\Sigma_{rr} = s_0^2\ [W^{-1} - \mathrm{B}\ (B^T\ W\ B)^{-1}\ B^T] \tag{10}$$

The next section explains how to apply the model in order to obtain an estimated velocity for a generic site position within the considered area.

B. *Application of the strain model for velocity estimation*

We can now consider a generic point G having position $\boldsymbol{p}_G^0 = [e_G, n_G]^T$. As for equation 4 we can estimate the velocity in G through:

$$\boldsymbol{v}_G = \left[v_{e_G}, v_{n_G}\right]^T = \boldsymbol{v}_c + L\ [\boldsymbol{p}_G^0 - \boldsymbol{p}_C^0] \tag{11}$$

We define a design matrix B_G such that $\boldsymbol{v}_G = B_G\ \boldsymbol{s}$ as:

$$\begin{bmatrix} 1 & 0 & \Delta e_G^0 & \Delta n_G^0 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta e_G^0 & \Delta n_G^0 \end{bmatrix} \tag{12}$$

Using this matrix is possible to estimate the uncertainties related to the estimated velocity of the G point by means of:

$$\Sigma_{vv_G} = B_G \Sigma_{ss} {B_G}^T \tag{13}$$

The model here described was applied assuming BO01, BOLG, BOL1 and BLGN to be the i-th stations and considering G in the position of the Garisenda tower. In the next section the obtained results are reported and discussed.

IV. RESULTS AND DISCUSSION

Using the velocities reported in Table 1 and applying equation 8 the parameters defining the deformation model for the considered area were estimated. These parameters are listed in the second column of Table 2. The table also reports the related uncertainties estimated through equation 9.

Table 2. Model parameters (eq. 5) and related uncertainties. Values are expressed in mm/year for the velocities whereas the other parmeters are scalars.

Parameter	Value	Dev.St.
$v_{e_c}\,(mm/y)$	-1.75	0.11
$v_{n_c}\,(mm/y)$	0.57	0.14
L_{11}	1.78E-07	1.64E-07
L_{12}	-2.25E-07	1.52 E-07

L_{21}	-5.01E-07	1.62 E-07
L_{22}	9.09E-07	2.02 E-07

By applying equation 11 the velocity of the ground underneath the Garisenda tower $\boldsymbol{v}_G$ was estimated. Bear in mind that all the input velocities were obtained having fixed the position of the BOGA station. Therefore $\boldsymbol{v}_G$ represents an estimation of the relative velocity between the top and the bottom of the Garisenda tower, which is also the parameter representing the increment in the leaning of the tower. In other words, the velocity of BOGA monitoring stations with respect to an estimated stable reference are the inverse of the vector $\boldsymbol{v}_G$.

Table 3. Table of the residual velocities with respect to $\boldsymbol{v}_G$ (eq. 11). These represent the displacements of the considered GNSS stations with respect to the bottom of the Garisenda Tower. All values are expressed in mm/year.

Site	Δv_e	Δv_n	$\sigma_{\Delta v_e}$	$\sigma_{\Delta v_n}$
BLGN	-0.10	-0.04	0.08	0.06
BO01	0.12	0.08	0.09	0.12
BOL1	-0.05	-0.20	0.04	0.30
BOLG	0.31	0.06	0.25	0.08
BOGA	1.55	0.08	0.19	0.22

The residual velocities with respect to G are reported in Table 3 together with the related uncertainties estimated by using equation 13 for BOGA and equation 10 for the other ones. It should be noticed that the uncertainties are quite small, but the relative velocities in the area are small too. Moreover, the hypothesis under a uniform strain model such the one used here cannot fit perfectly with the incoherent behaviour of the four available sites.

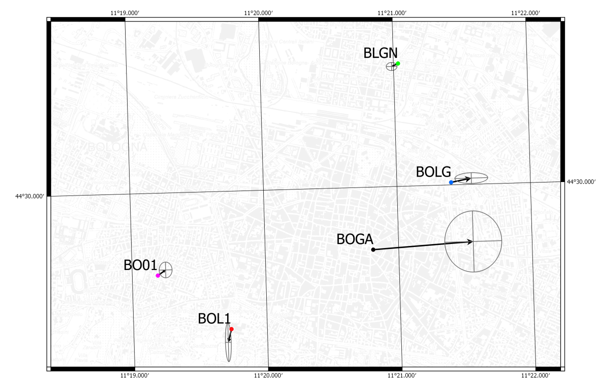

Figure 6. The arrows represent the velocity vectors obtained having fixed the position of the ground underneath the Garisenda tower.

Finally, Figure 6 shows the vectors of the velocities for the five considered GNSS stations with respect to a reference located under the Garisenda tower. A comparison between the vector of BOGA with the coloured ones reported in Figure 5 shows that the new estimation of the variation in the leaning of the tower is more close to the one that would have be found considering the BOLG station (blue vector) as reference. In fact, BOLG is the station closest to the Garisenda, therefore its influence on the estimation of the model in the position of BOGA is higher. Nevertheless, if we compare the deformation of the tower estimated using the model, that is 1.5 mm/year easting and 0.08 mm/year northing, with the deformation estimated using BOLG as reference, 1.2 mm/year easting and -0.2 mm/year northing, and we consider a 2-sigma confidence iterval, the difference is statistically not negliegible.

Finally, the presented method can in principle be applied also to position solutions estimated using techniques different that the GNSS differenced processing. For instance, even estimating the positions of BOGA by using a PPP (Precise Point Positioning) approach and transforming the coordinates into the ETRS89, the result could not have been representative of the variation in the leaning of the tower. This because it is known that some areas such as Italy and Greece are affected by residual velocities even with respect to the Eurasian plate that are several mm/years (Barbarella et al., 2018). Therefore, also performing a PPP processing, a computation of a model similar to the one here presented should be performed starting from the time series of the coordinates of the other sites surrounding the Garisenda tower (Poluzzi et al., 2019).

V. Conclusion

The focus of this work is the monitoring of tall structures in urban areas by means of GNSS instrumentation. The case study here presented concerns the Garisenda tower, one of the most important cultural heritages in Bologna city. The tower is characterized by a marked leaning that is still increasing and should be carefully monitored. A GNSS permanent station named BOGA was placed on the top of the tower providing data since DOY 275 of year 2013. In this work the daily data gathered until the end of 2017 were used.

Four other GNSS permanent stations are present in the area few kilometres far from BOGA, that are BOL1, BOLG, BO01 and BLGN. In a common approach to the monitoring one of these sites would have been chosen as a stable reference and the daily baselines linking to BOGA calculated. Then, the linear trend of the coordinates of BOGA could have been assumed to be the velocity of the top of the tower with respect to its base, which represents the increasing in the leaning of the structure.

Such processing was performed considering each of the four available stations as reference and the results in terms of velocity of the top of the Garisenda are shown in Figure 5, referring to the coloured arrows. The differences between the vectors are significant, also in statistical terms, and it is hard to define which one can be considered the most reliable.

Therefore, a different approach has been introduced, based on the definition of a linear strain model that aims to represent the deformations present in the area. In particular, the goal of the model has been the definition of a stable reference position characterizing the ground underneath the Garisenda tower. The model takes into account the velocities of the four stations surrounding BOGA and its implementation is carefully described in section three.

The velocity of BOGA station with respect to the model reference was calculated and is shown in Figure 6, together with the related standard error ellipse and the residual velocities of the other stations with respect to the same reference. The variation in the leaning of the tower estimated using the strain model is mostly similar to what found using the closest station (BOLG) as reference, with a difference in terms of magnitude of 0,3 mm/y (about 22%).

The choice of a stable reference is one of the most important aspects in monitoring in general, and it become more and more complex the smaller are the monitored quantities. When the chosen reference has displacements of not negligible magnitude with respect to those of the monitored object, then the approach here presented can be a viable solution in order to obtain more reliable results. This is true also if considering coordinates estimated from GNSS data using the PPP approach instead of the differencing one.

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