AN INTEGRATED APPROACH FOR MONITORING SOIL SETTLEMENTS AT THE VIRGO SITE*

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Abstract

The Virgo detector, currently in its 2nd generation configuration Advanced Virgo (AdV), is a Michelson interferometer aimed at the gravitational waves research and at opening a new window on the study of the Universe. It is made of two orthogonal arms being each 3 kilometers long and is located at the site of the European Gravitational Observatory (EGO), in the countryside near Pisa, Italy (Figure **1**).

Figure 1: Aerial view of Virgo Site.

After the construction of the Virgo facilities completed in 2002, over the years a steady subsidence process has been observed as a consequence of the building and embankment overloads. In consideration of the subsoil characteristics, whose surface portion is mainly formed by a 25÷60 m thickness layer of clay with limited thin layers of sands, the evolution of settlements was expected and properly considered for the design of the civil engineering infrastructures, so that the vacuum tubes can be readjusted to keep the original alignment. However, along 15 years of time life, the initial estimates of the expected displacements were continuously compared with the observed effects. The measured settlements have been regularly monitored and adopted for implementing the necessary realignment activities.

This paper reports the monitoring activities conducted over the years, mainly consisting of regular high accuracy levelling surveys, periodically integrated by GPS and classical theodolite measurements. These sets of measurement were adopted to perform the Virgo realignment procedure needed to keep the interferometer rigidly tied in a 3x3km plane.

In order to improve the knowledge on the trend of the settlements affecting the Virgo infrastructures, an analysis based on differential interferometry using satellite Synthetic Aperture Radar (SAR) data has been performed and compared with the outcome from in-situ data.

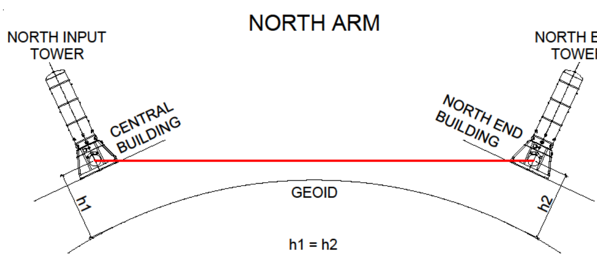
INTRODUCTION

The existence of a subsidence phenomenon in the area of the Virgo interferometer was well known since the early designing phase of the civil engineering works [1], [2]. Therefore, all the relevant infrastructures were designed taking into account this effect based on several geotechnical studies carried out considering the characteristics of the soil present in the area. Intensive geological surveys [3], [4] were performed in order properly define the soil characteristics and to model the expected settlement pattern in response to the loads. Nevertheless, the need to monitor the displacements and compare these with the expected values, as well the tight specifications set for hosting the Virgo interferometer, have required a continuous surveying activity to control the position of the buildings. Similar activities, for monitoring subsidence phenomena and supporting the realignment procedures are usually carried out in several facilities hosting scientific apparatus [5], [6], [7].

The monitoring activity is based on the requirements of two fundamental conditions for the Virgo infrastructures:

- the interferometer has to lay in a perfect plane of 3x3km dimensions for optical reasons; the tunnel axes have to be orthogonal with an accuracy of ±0.02 mrad;
- the operation of the 3km+3km Ultra High Vacuum (UHV) tubes requires that the stress induced by differential displacement of the supports on the welding lips between two adjacent modules (distance 15m) is kept under determined tolerances.

In order to apply the required correction, the vertical displacements measured along the arms were reduced in a relative reference system with respect to the optical center of the interferometer, located in the Central Building (Figure **2**).



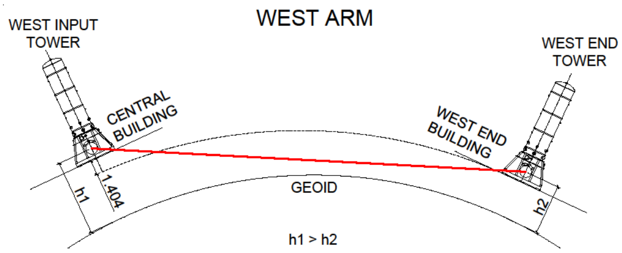


Figure 2: Schematic profiles of the two orthogonal 3km long arms forming the Virgo laser interferometer, showing the (initial) offset of the planar reference surface individuated by the laser beam (red) respect to the geoid.

For designing, in order to adapt to the geomorphological conditions of the area, the topographic height of the beam (suspended mirror center) was the same at Central Building and North End Building, while the difference was –1.404m at West End Building. This height difference was checked in 2001, when monitoring started.

Realignment procedures have to be carried out when the relative displacement of one tube modules is higher than 5mm with respect the previous survey. This value becomes 2mm for the special modules linked to the large vacuum tube valves, close to the experimental buildings (Figure **3**).

Figure 3: End Building-Tunnel link module. Special tube support with micrometric mechanical realignment system.

TOPOGRAPHIC MONITORING

The realignment procedure for the purpose described in the previous paragraph concerns the evaluation of relative displacements. For this reason, every sets of measurements carried out over the years has been reduced in a relative reference system with respect to the optical center of the interferometer, located in the Central Building. Absolute measurements of the settlements have been also performed and described in the last paragraph.

The monitoring measurements along both tunnels (West and North Arms), carried out since 2001, include high-precision levelling (206 reference benchmarks/tunnel) and GPS surveys (11 points/tunnel).

In order to maintain the expected accuracy requirements, the following conditions were adopted:

- interdistance of 15m between the 206 benchmarks along the tunnels (Figure **4**);
- reference points materialized by accurate centering system (Figure **5**);
- staff positioned with tripod on each point (Figure **6**);
- similar environmental conditions (T and RH);
- not significant air flows in the tunnels;
- same tolerances adopted for the setup of the instruments.

Figure 4: DNA03 station in the Tunnel.

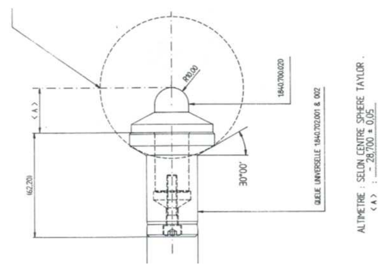


Figure 5: Accurate centering system of reference points placed on the Tunnel floor.

Figure 6: Staff on each reference point set by tripod.

The instruments adopted are the TS Leica TDA5000 for the initial survey, optical level Leica NA2+ GPM3 for the first levelling, and digital level Leica DNA03 since 2003 to now. The frequency of the measurement campaigns has been gradually decreased over the years (Table **1**), in function of the soil settling.

Table 1: Frequency of monitoring over time

Period	Frequency of monitoring	Instrument
2001	Initial survey	TDA5000
2002÷2006	6 months	NA2+GPM3 DNA03
2007÷2011	12 months	DNA03
2012÷2016	24 months	DNA03

All surveys have been reduced to the zero point located in the Central Building, named NV1 and WV1 respectively for the North and West Arm, being the main purpose the evaluation of the relative displacements referred to the optical center of the interferometer. Also the mutual position of these two main reference points has been checked by periodic accurate levelling, in order to observe the whole evolution of the interferometer.

Among subsequent campaigns, different methods of measurement (direct or alternate BFFB, aBFFB) and the inversion between the start and the end point (N206→NV1, W206→WV1) have been also adopted in order to avoid possible systematic errors, always obtaining congruent results.

The main levelling parameters are summarized in the following Table **2**, which also reports the max e min error of closure obtained among the whole measurement campaigns.

Table 2: Summary of levelling parameters

Line length	3006 m /line	
Method (NA2)	NV1(WV1)→N206(W206); N206(W206)→NV1(WV1)	
Method (DNA03)	BF NV1(WV1)→N206(W206); N206(W206)→NV1(WV1)	
Method (DNA03)	BFFB, aBFFB	
Nr. stations	205 /line	
Starting point	NV1 (WV1), N206 (W206);	
Measure type	Avg 3 of 5; chk σ/20m < 0.00005 m	
Tolerances	St > 0.5m; DBal < 0.5 m; Dmax 8m	
Max closure error	NA2	4.42 mm
min closure error		3.76 mm
Max closure error	DNA03	0.98 mm
min closure error		0.04 mm

SETTLEMENT DATA ANALYSIS

The following Figures **7** and **8** show trend diagrams generally elaborated, where last survey of the tunnel profile is compared with the theoretical design position and the tube axis profile effectively realigned, sum of the operations since the start of the realignment process. Note that in such diagrams the x-coordinate represents the progressive distance from the Central Building as rectified geoid.

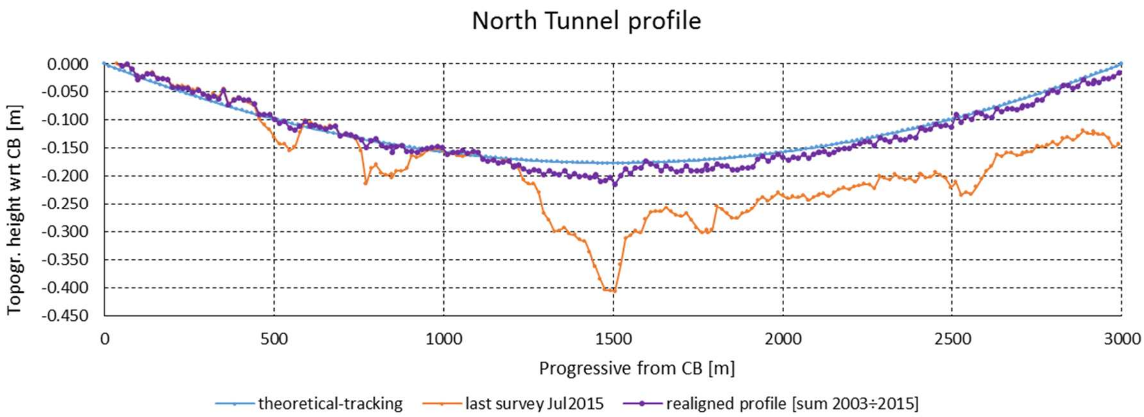


Figure 7: North Tunnel Profile: theoretical tracking curve (light blue); last survey carried out on Jul2015 (red); realigned profile made by the sum of the realignment activities over years 2003÷2015 (violet)

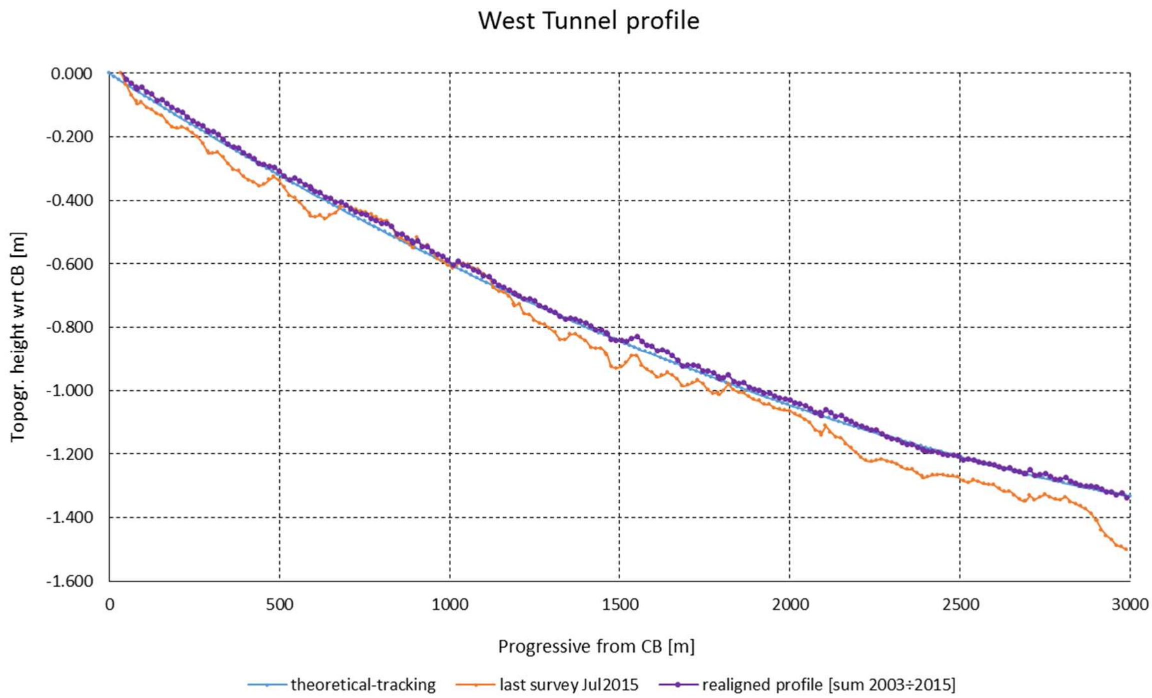


Figure 8: West Tunnel Profile: theoretical tracking curve (light blue); last survey carried out on Jul2015 (red); realigned profile made by the sum of the realignment activities over years 2003÷2015 (violet)

The amount of data collected during the years allows the evaluation of a possible scenario of the phenomenon. A best curve fitting analysis of the surveyed data has been performed for the tunnel areas showing the most pronounced effects. Particularly, these are located in the middle part of the North Tunnel (reference point N100) and in the zone of the West Tunnel next to the West End Building (reference points W199 and W200). These locations are not surprising, since those areas were interested by the major embankment overloads for the construction of the adjacent buildings. Indeed, most important settlements of the tunnels have been surveyed in correspondence of overloads on soil, related to civil works.

Several type of fitting curves have been considered and, among them, the “Michaelis-Menton” law or the logarithmic law of order 2 provided the highest value of the coefficient of determination R^2. The first curves are more coherent with the empirical formulas available in geotechnical literature.

Figure **9** shows the diagrams elaborated by the software KaleidaGraph [8] for a projection over 100 years (to be considered as $t=\infty$).

The hypnotized scenario indicates that, although realignments will continue over a very long time period, the expected subsidence ($t=\infty$) is anyhow compatible with the realignment system (i.e. the length of the adjustable feet of the tube supports) and the space present inside the tunnel.

Clearly, these “a posteriori” hypotheses are related only to the surveyed data and focused on own conditions of the Virgo tunnels and cannot be generalized. Moreover, the previous considerations are based on the hypotheses that external factors will remain constant over time (i.e. no large variations of the water deep stratum height in the area or new overloading of adjoining soil close to the tunnels).

DINSAR DATA ANALYSIS

Differential Synthetic Aperture Radar Interferometry (DInSAR) [9] is a technique based on remote sensing data able to detect ground displacements. It relies on the processing of the phase difference (Interferogram) between two temporally separated SAR images. In particular, advanced DInSAR approaches [10] [11] are based on the processing of SAR acquisition sequences collected over large time spans to generate displacement time series of permanent scatterers (PS). PS represent “targets” on the surface that are able naturally to reflect radar signal (such as structures, infrastructures, etc.) without the need of accessing to the site. The accuracy of DInSAR technique is estimated about centimeter to millimeter [12].

Long-term DInSAR deformation time series have demonstrated the capability to provide valuable information on the displacements that affecting built up area [13] [14].

DInSAR time series, obtained processing ascending and descending orbit of ENVISAT satellite from January 2003 to June 2010 (*provided by the Ministry of Environment and Protection of Land and Sea*), were analysed to understand the overall settlement affecting the area surrounding the Virgo interferometer. The results of the analysis are summarized in Figure **10,** where the RGB colour scale shows stable area (in green) and unstable area characterized by subsidence phenomena (in red).

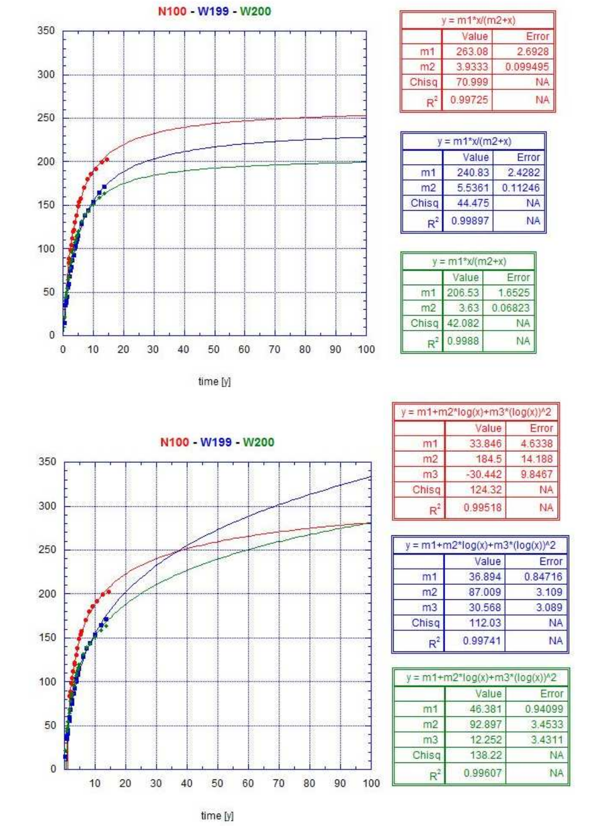


Figure 9: Best curve fitting for the highest settlements (N100-W199-W200); (top) "Michaelis-Menton" curves; (bottom) logarithmic curves.

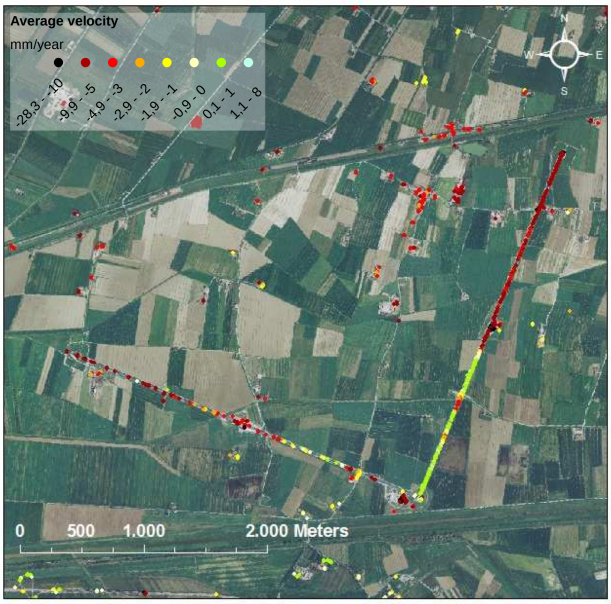


Figure 10: Average displacement maps (mm/year) obtained applying DInSAR technique on VIRGO infrastructures and its surrounding area.

The DInSAR cumulative displacements along the North and West tunnels were compared with levelling data (Figure **11**). For both tunnels, the two different techniques revealed comparable subsidence trend, as shown in Figure **11**.

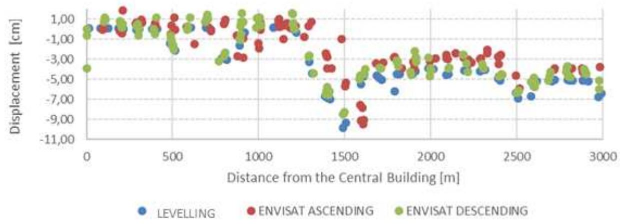


Figure 11. Comparison between levelling (in blue) and DInSAR data for ascending (in red) and descending (in blue) ENVISAT components along North Tunnel.

The displacements derived by the DInSAR data, although less accurate than the levelling ones, are characterized by larger ground coverage that allows to make an assessment of the ground subsidence phenomena at large scale. In fact, the study area is located within the Pisa alluvial plain characterized by clays and silts formations with layers of sands, peat and localized organic levels [15], where the natural consolidation processes can be accelerated by overloads at the surface. DInSAR data are useful to distinguish the subsidence linked to effects of the Virgo structures.

CONCLUSION

As widely studied and expected since the design phase, a significant subsidence phenomenon has been observed in the Virgo Area through a regular monitoring activity. Regular campaigns of high-accuracy levelling measurements were conducted over time, in order to assist the realignment procedures and fulfil the geometrical and technological specification set for the 3+3 km vacuum tubes hosting the laser interferometer. Periodically, such campaigns are also integrated by GPS and theodolite measurements for checking planimetric displacements. The monitoring dataset has permitted to quantify the evolution of a relevant subsidence process induced by the overloads of the Virgo structures acting on compressible soils at foundation. In order to understand the overall settlement process, the evaluation of the deformation patter of the Virgo Area has been performed also through the DInSAR technique. The comparison between the subsidence evaluated using DInSAR analyses and the direct measurement by levelling provided a significant coherence in the evaluation of the general trend along the tunnels.

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