Monitoring the behavior of MEO Arena roof

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Abstract

The roof structure of MEO Arena (previously known as Atlantico multipurpose Pavilion) is a pioneering example of large glued laminated timber (glulam) structures. At the time of its construction (1995) for the EXPO'98 world exhibition, this was the first large glulam structure ever built in Portugal, it had the longest single span glulam arch (122m) in the world and it was the first large timber structure designed according with an early version of Eurocode 5 (European Standard ENV 1995-1-1(1994): Design of timber structures). This timber roof structure, shaped like the shell of a horseshoe crab and covered with an oxidized zinc sheet, stands more than 40m above the arena and is independent from the concrete building underneath.

LNEC was requested to carry out systematic inspections and monitoring of the roof structure after its construction and the follow up of its performance still continues. In this scope, the geodetic monitoring set on a regular basis (twice a year) allows the assessment of three dimensional displacements of selected points of the timber arches. The analysis of this data has allowed to distinguish normal variations throughout the year from those resulting from the initial settling and climatic adjustment of the structure and will allow identify any abnormal movements that may be due to accidental or exceptional circumstances. The good knowledge of the structure behaviour has also been an important basis to a pioneer study of the behaviour of the zinc roof cover based on multitemporal InSAR techniques.

In this paper, we describe the geodetic monitoring system and an analysis of the behaviour of the glulam structure as well as of the roof cover based on the geodetic and InSAR data.

Key words: monitoring, displacement, geodetic methods, InSAR, pavilion

1 INTRODUCTION

MEO Arena, previously known as Atlantico Pavilion and, before that, during the EXPO' 98 world exhibition, as Pavilion of Utopia, was built as a response to the demand for a large space to hold events like concerts, congresses or sport activities. The roof of the Pavilion is covered with oxidized zinc sheets supported by a timber structure. It is this structure, made of glued laminated timber (glulam) arches, that makes MEO Arena one of the most emblematic buildings of its kind. At the time of its construction, 1995-1997 (Fig. 1), it was claimed to be the largest glulam structure in the world.

Fig. 1 Construction of MEO Arena

Fig. 2 MEO Arena roof

Fig. 3 Timber structure, including a section of an arch

The design of this timber structure followed the then available early version of Eurocode 5 (European standard ENV 1995-1-1 (1994): Design of timber structures). Structural Eurocodes are an initiative of the European Community that in 1975 decided to promote an action programme in the field of construction, involving the harmonisation of technical specifications.

Being an important and special structure, its construction was closely followed by the National Laboratory for Civil Engineering (LNEC) that also follows its behaviour since construction (Cruz *et al.* 2002). Systematic visual inspections and monitoring campaigns are carried out regularly intended to detect possible anomalies at early stages. The monitoring system includes a geodetic network to measure 3D displacements of targets fixed to arches of the glulam structure. A description of the system as well as an analysis of the results obtained is presented in section 2. Section 3 presents a study of the behaviour of the roof using multitemporal InSAR techniques.

2 GEODETIC MONITORING SYSTEM. DESCRIPTION AND RESULTS

The original monitoring system (Fig. 4), which was installed in 2001, consists of 21 object points (triangles with red dot in Fig. 4), and two pillars (PN, PS) for setting up the measuring equipment (tacheometers, i.e., total stations). A few years later the system was completed with seven more object points and two reference points (RN, RS). The first ones allowed to monitor more arches and also to control two arches in five points (arches 6 and 11). The reference points allow that two teams work simultaneously. Because of the regular behaviour of the structure, that has displacements according to the expected, it was decided to lighten the system: since 2014, only 18 points are monitored regularly (black triangles in Fig. 4, from Henriques *et al.* 2008).

The object points are materialized by reflector tapes:. The reference points are materialized by: i) two Kern centring devices (to assure that the tacheometer is always set up in the same position, either horizontally and vertically) permanently placed on the top of concrete pillars (PN, PS), and ii) two targets for visual pointing (RN, RS). These four points are on the two technical towers, which are massive reinforced concrete structures independent of the glulam structure, built on one end of the pavilion. These towers are the most stable structures inside the pavilion. The towers also provide areas not accessible to the public with good visibility to the arches.

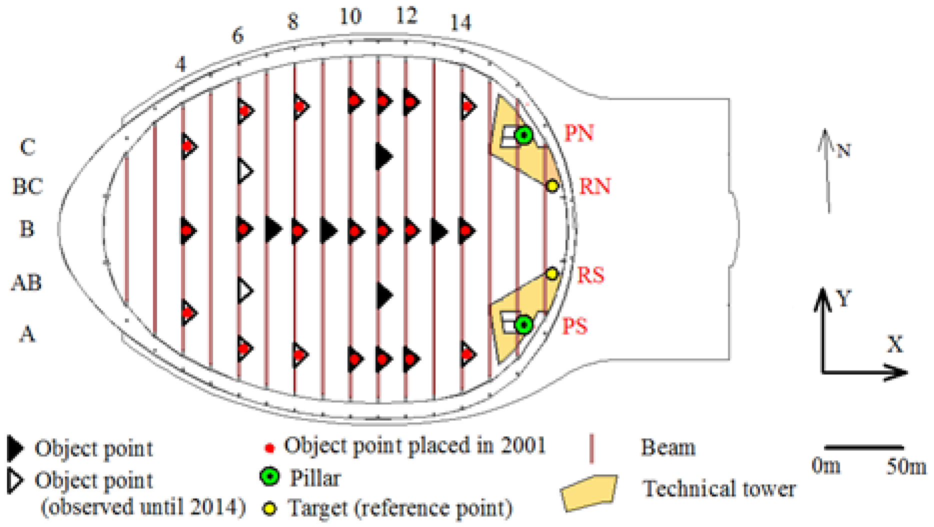
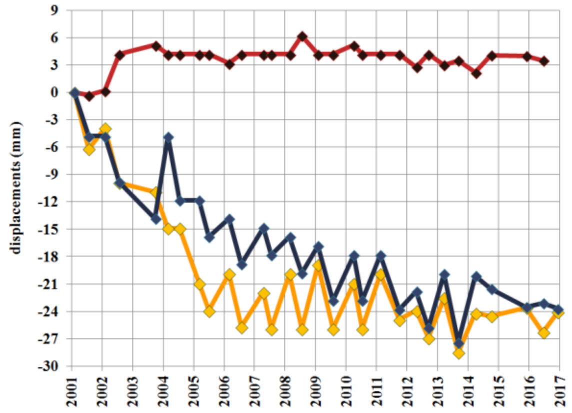


Fig. 4 The geodetic monitoring system. Location of the points and orientation of the planimetric referential

In each campaign, horizontal angles, vertical angles and distances from each pillar to all the points are measured. The equipment used in the last campaigns was a Leica TC2003. 3D displacements (dX, dY, dZ) are determined using the method of the variation of coordinates that relates the variations of the observables directly with the displacements. Figure 5 presents the three components of the displacements of point B14. All points exhibit this kind of behaviour: a combination of cyclic displacements with a linear trend. Distances between both pillars are also measured. They show periodic annual variations, smaller that 1 mm, variations that are included in the calculation of the displacements.

The factors that most influence displacements of the glulam structure are: the environment humidity and temperature, and loads, namely the loads suspended from the structure. These include a permanent metallic grid suspended from the arches and, sometimes, variable décor elements related with the shows. Whenever possible campaigns have been made in days where there were no decors.

In the year of 2008 four special campaigns were made with the unique purpose to measure the effects of loads suspended from the structure. The first two campaigns were made in July, one without the grid, the other with the grid suspended. The third and the forth campaigns, made in November, were carried out just before and after setting an especially heavy décor composed by a second metallic grid, three big screens, many spotlights and loudspeakers and heavy curtains in the back of the scenery, all suspended from the metallic grid that was up in its position on both campaigns. Figure 6 presents the corresponding displacements of point B12. In both cases, the reference of the displacements is the campaign made when there was less weight. Figure 7 presents a photo of the room during the preparation of a show where one can notice the metallic grid and suspended curtains.



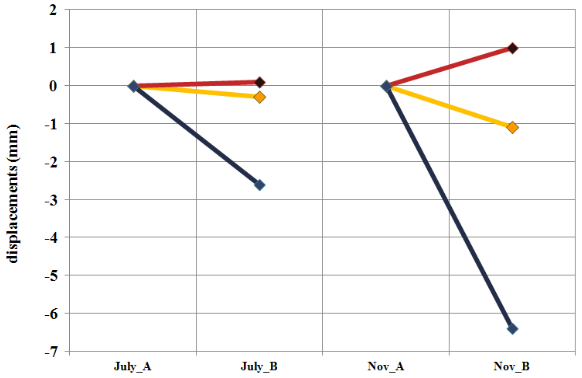
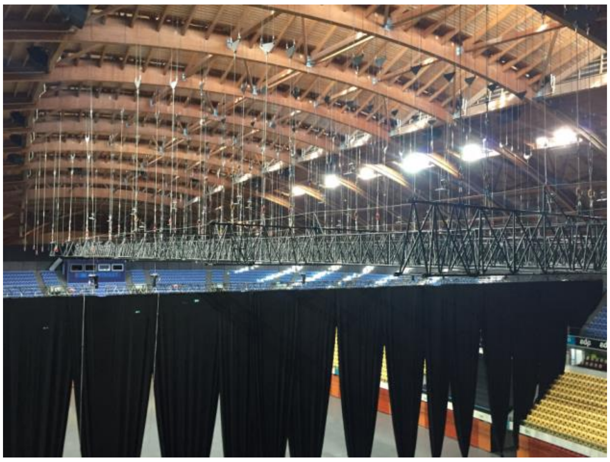


Fig. 5 Components of the displacement (point B14)

Fig. 6 Components of the displacements due to suspended loads (point B12)



←metallic grid

←curtains

Fig. 7 Photo showing the location of the permanent metallic grid and of curtains

The graph from Fig. 5 points out that, in general, displacements present regular variations added to a time effect that tends to stabilization as the structure ages. A regression model like the one presented in (1) may be used to describe the behaviour of each point.

$$y(x_1, x_2,.., x_k) = a_1 f(x_1) + a_2 f(x_2) + a_3 f(x_3) + a_4 f(x_4) + a_5 . \qquad (1)$$

In this equation y, often called response variable, stands for the variable measured (displacement component); x, the predictor variable, stands for the actions on the structure (temperature, humidity, age, etc). The coefficients a_1, …, a_5 are the unknowns, and are estimated by solving a system of equations. On each campaign a set of three equations (one for the dX, other for the dY, the third for the dZ) are set. To solve each system a minimum of five equations is necessary.

As presented in Henriques *et al.* (2013), the behaviour of the glulam structure follows an annual cyclic pattern since the beginning of observations, in 2001. This can be modelled by the sum of two terms:

$$a1\ f(x1) + a2\ f(x2) = a_1 \sin\frac{2\pi\, t'}{365.25} + a_2 \cos\frac{2\pi\, t'}{365.25} \qquad (2)$$

where t' stands for the number of days since the beginning of the year. This function has been used to represent the effect of the annual variations of temperature or humidity of the air surrounding the timber structure, and consequent shrinkage or swelling of timber.

The displacements due to time effect can be described by

$$a_3\, f(x_3) + a4\, f(x4) = a_3\,(t - t_0) + a_4\, \ln\left(1 + \frac{t\text{-}t_0}{\alpha}\right) \tag{3}$$

being t the date of the observation, t_0 the date of beginning of the phenomena ($t\text{-}t_0$ is therefore the age of the phenomena), α is chosen by the user and it causes a shift on the logarithm function results to avoid, in the first years of observations, large variations in y when changes of $t\text{-}t_0$ are small. It was chosen $\alpha = 50$ days.

After solving the three systems of equations, three sets of parameters a1,…,a5 are calculated which allows to estimate the displacement for any specific date. The chart in Fig. 8 presents: i) the displacements dZ, presented before in Fig. 5; ii) the displacements calculated using the regression model (1); iii) the effects of age (sum of the last three terms of (1)); iv) the cyclic effects ((2)).

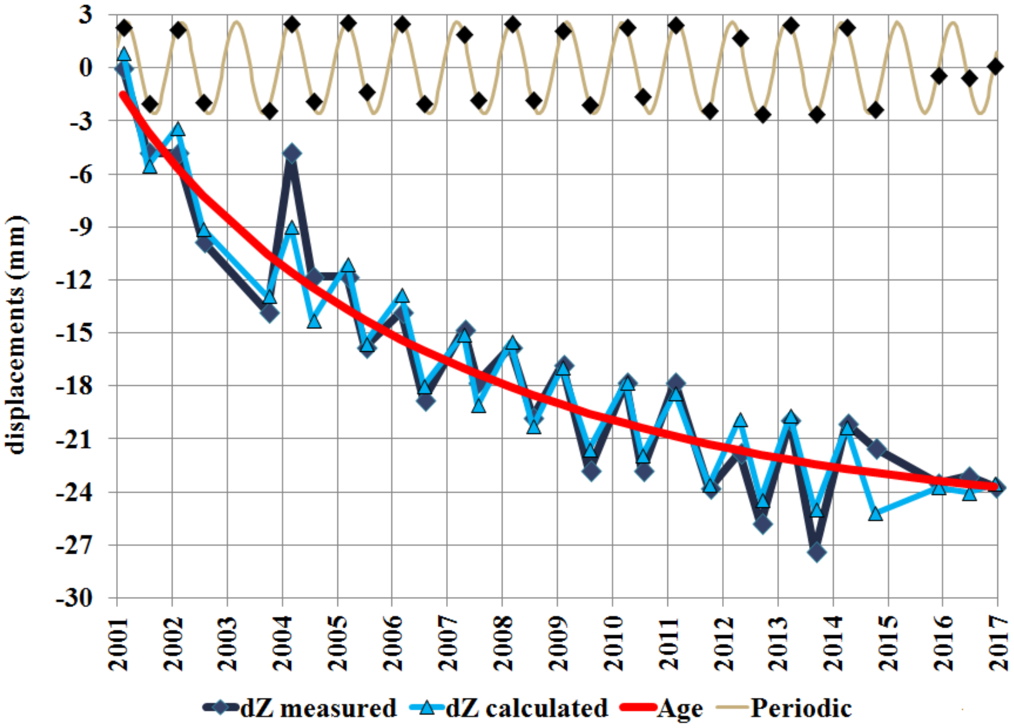


Fig. 8 – Vertical (dZ) displacements measured and calculated

From equation (2) it is possible to estimate, for each point, the displacement due to cyclic effects (see Fig. 9 and 10). One can notice that: i) displacements have Y symmetry (compare points in row A with those in row C; or AB with BC); ii) points in row B have almost no displacements in Y direction; ii) points in row AB have larger cyclic horizontal displacements when compared with points in row BC (average 20% larger); iii) points in row A have larger cyclic horizontal displacements when compared with points in row C but the difference is not significant (average 5% larger).

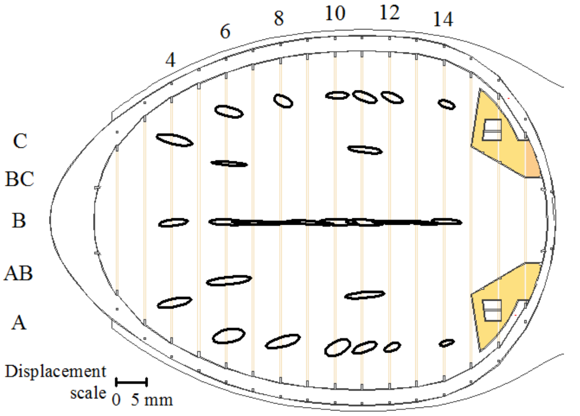


Fig. 9 Expected cyclic horizontal displacements

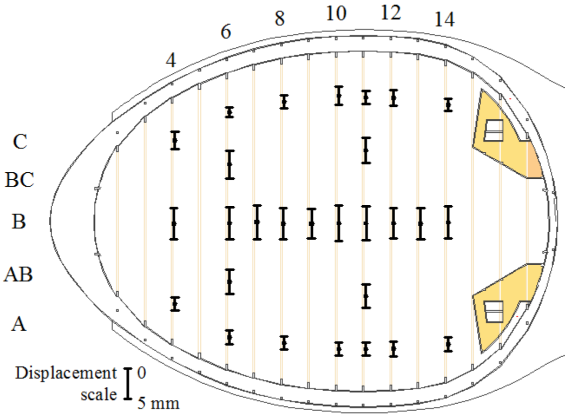
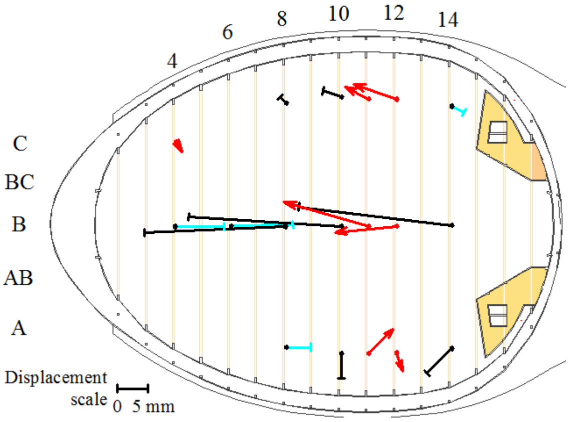


Fig. 10 Expected cyclic vertical displacements

Concerning the effects of aging (including settling of structural joints and creep), Fig. 11 and 12 present the results of 18 of the 21 points that were placed in 2001. In the first campaigns, there was no visibility to points A4, A6 and C6. The analysis of the data showed that, for most points, the aging effect became negligible around the year 2009. However, points in arches 11 and 12 are still presenting significant displacements (red arrows). Concerning the horizontal components, one can notice that most points have moved in the same direction. When the lines have cyan colour they indicate that the displacements have already stopped but they were in the direction opposite to the ones represented with black color.



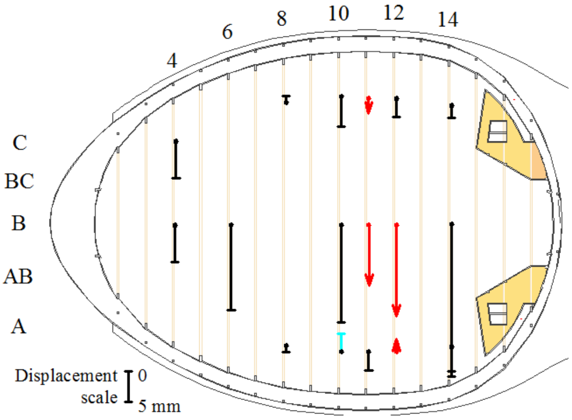


Fig. 11 Aging effect since 2001. Horizontal component *Fig. 12 Aging effect since 2001. Vertical component*

3 INSAR DISPLACEMENTS OF THE METALLIC ROOF

The displacements measured by geodetic methods have been the support to a study that started not long ago: the understanding of the behaviour of the metallic roof and its interaction with the supporting structure. The visible metallic sheets are fixed to the roof cover (timber planks) nailed to the glulam structure (see Fig. 2). Underneath, there is a layer of insulation material and another layer of (spaced) timber boards that are visible inside the building (see Fig. 3). The displacements of the roof are therefore the result of the displacements of the glulam structure combined with the movements of the roof itself. The expected opposite thermal movements of metal (roofing) and timber (supporting structure) may lead to vertical movements in opposite directions and consequent pull-off of the nailed joints which is likely to explain the observed local damage of the zinc where nails emerge.

To measure the displacements of the external roof materials, InSAR techniques can be applied. In the first study made by the authors, a dataset of 35 images (temporal resolution 11 days) of the X-band sensor on board of satellite TerraSAR-X, acquired between December

2011 and July 2013 (1.5 years), was used. The Persistent Scatterer Interferometry algorithm implemented in SARPROZ® software allowed the determination of displacements of points of the metallic roof (Roque *et al*. 2016) – the persistent scatterers (PS).

In Fig. 13 the locations of the PS are presented as well as their cumulative displacements in the direction of the sensor line-of-sight (LOS). The image acquired at 2012/08/22 was selected as master image. The reference PS is the pink point located at the upper left corner of the figure. This point was selected on the concrete platform close to the pavilion in order to minimize the relative displacements between it and the geodetic measurements reference points. During the time interval of 1.5 years the cumulative displacements of the PS on the roof vary between -2 mm (away from the sensor) and +4 mm (towards the sensor).

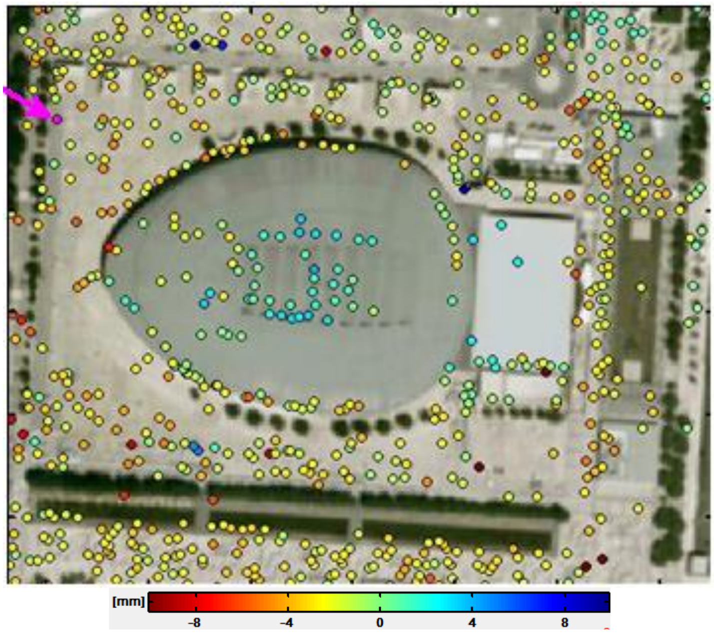


Fig. 13 Cumulative displacement map for PS; Product source TerraSAR-X © DLR <2015>

Fig. 14 presents the displacements of a point of the glulam structure monitored by geodetic methods (B13) and the closest PS to its vertical. The results presented (Roque *et al*. 2016) are: i) the geodetic displacements of point B13 in the LOS direction; ii) the displacements of this point for each SAR image acquisition date calculated by applying (1), the regression model, also in the LOS direction; iii) the InSAR displacements of the closest PS. The three sets of displacements have as reference the date of 2013/03/18, chosen because this geodetic campaign is the closest to a SAR image acquisition (only one day apart). To transform the geodetic displacements into the LOS referential, two transformations were applied: the rotation from the referential X0Y (see Fig. 4) to WGS84 UTM 29N and the projection to the LOS direction, through the heading and the radiation incidence angles.

4 CONCLUSIONS

The geodetic monitoring system placed inside MEO Arena to determine the displacements of the glulam structure that covers the main room of this pavilion, has been a valuable help to analyse the behaviour of this important Arena of the city of Lisbon. The analyses of displacements suggest that the structure has a regular normal behaviour. The analysis will be complemented with the development of a numerical model of the timber structure to predict the roof response to specific applied loads.

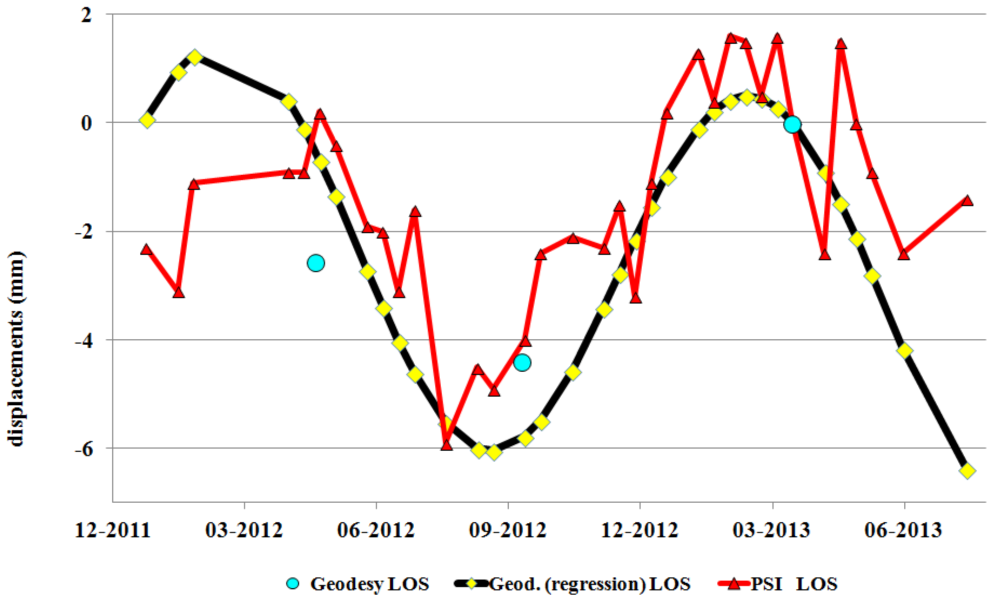


Fig. 14 Geodetic displacements of point B13 and InSAR displacements of the closest point on the metallic roof

The collection of data on the timber roof movements allowed, through a regression model, to estimate the general displacements of the structure any day of the year, information that is crucial to support the undergoing studies to analyse the behaviour of the metallic roofing based in SAR images. Persistent Scatterer Interferometry allows access to the behaviour of several points on the roof with a high observation frequency and also contributes to the monitoring of the area surrounding the pavilion.

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