

Integrated Vibration Analysis for Historical Dome Structures: A Complementary Approach Based on Conventional Geophysical Methods and Remote Sensing Techniques

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Abstract. The paper presents a study based on integrated non-destructive sensing methods aimed at defining the experimental vibration properties of a historical dome by using environmental microtremor measurements only. The integrated approach consists in the use of both contact and remote sensors to acquire ambient vibration data. The measurements of vibration were carried out with a high-sensitive tri-axial seismometer (Tromino) and a coherent radar system (Image By Interferometry System, IBIS-S). Five asynchronous velocimetric stations were arranged over a profile on the external side of the structure to acquire ambient vibration time-series on radial, tangential and vertical directions. In order to detect the displacements of the internal surface of the dome, the radar interferometer was positioned inside the church using three station points of measure along the main axis of the structure, with different geometric configurations for each station. With this technique, synchronous signals coming from the structure were simultaneously acquired and analyzed. Both seismic time-series and microwave signals were processed to derive the experimental vibration properties of the structure, mainly concerning the dynamic behavior of the circular dome. In addition, to evaluate the capabilities of the radar system in the indoor configuration, a Finite Element model of the structure was built, and the experimental results were compared to the numerical outputs.

Keywords: Ground-based radar interferometry · Ambient vibration tests · Non-destructive measurements · Microwave systems · Cultural heritage · Finite element modeling

1 Introduction

In the last decades, advances in ground-based radar interferometry systems have allowed the diffusion of microwave sensors to measure remotely the vibration of slender structures [1]. Many authors have proposed researches based on the use of radar sensors to measure displacement time-series on different kinds of structures, such as modern skyscrapers [2], concrete and earth dams [3, 4], bridges [5, 6], stay-cables of stay-cabled bridges [7–9], bell towers and historical structures [6, 10–17] and other

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civil infrastructures [18]. Terrestrial remote sensing techniques have been widely applied in many geological and environmental studies for the monitoring of unstable slopes [19], landslides [20, 21], mines [22], sinkholes [23] and underground cavities [24]. Main structural studies were focused on the use of terrestrial remote sensing to perform static [25] and dynamic tests [26]. In both cases, ground-based radar remote sensing provides results in good agreement with conventional techniques based on the use of contact arrays and standard devices to measure the displacements of targets [1].

In this paper an integrated non-destructive approach based on the use of contact seismic sensors and a microwave remote system is presented. The studied structure is the historical church of "Beata Vergine Assunta", in the small village of Guasila (southern Sardinia, Italy). The experimental frequency response of its ancient dome is derived from output-only measurements of ambient vibration. In order to identify most favorable operative conditions, the terrestrial coherent radar system was positioned inside the church with different geometric configurations. The tri-axial velocity sensor was installed on the outside surface of the structure in four station points, including a ground station. The comparison between microtremor traces and microwave signals allowed the identification of the main experimental vibration properties of the structure. Finally, a numerical simulation has been proposed to better interpret the experimental results obtained using both direct sensors and no-contact systems.

1.1 The Surveyed Structure

The church of the "Beata Vergine Assunta" is a central plan building located on the top of a hill dominating the rural village of Guasila. The current structure was designed in 1839 by the architect Gaetano Cima (Cagliari, 1805–1878), following the aesthetic canon of neoclassical architecture [27]. It was decided to demolish a pre-existent church, and the new structure was realized in the years from 1842 to 1852 in the middle of the urban center, in the historical sub-region of *Trexenta*. Eight large pillars divide the central main aisle from the side chapels each one communicating with two lateral paths from the main entrance to the sacristy at the rear of the church.

The pillars support the central dome of the structure with four arches and a drum. The dome, with a circular opening on the top, was closed by a cylindrical lantern later. A monumental pronaos with six columns in Doric style and two lateral pillars, surmounted by a triangular tympanum, decorates the main façade of the church. The ancient bell tower is the unique part still existing of the previous Baroque church.

Over the eastern side of the church, five buttresses were subsequently built to content lateral loads of the structure. On this side, a tall reinforced concrete retaining wall was realized, to constrain foundation terrains on the natural slope of the hill, few meters from the church. The design of the temple is clearly inspired by the shape of the Pantheon in Rome (Italy) and the eurythmic proportions of the design are probably suggested by the studies of the great Italian architect Palladio. In Fig. 1 different images of the church of Guasila are shown. Since the construction time, several problems of stability have been described (e.g. in the technical reports of architect Cima) [28]. The problems were even attributed to the low technical qualities of the materials used to build the structure, mainly consisting of local stone, marl and sandstone, characterized by weak degree of compaction and lithification [28]. Recently, the structure has been

studied in the framework of a restoration and diagnostic project based on multidisciplinary approaches [28–30]. In these studies, minero-petrographic analyses, geometric-architectural surveys, structural surveys, geotechnical and geophysical investigations were carried to implement the knowledge concerning the structural health state of the church.

2 Methods and Materials

Vibration data were acquired by means of two different measurement tools and were integrated to build a better detailed model of the experimental frequency response of the structure. Some images of the two instruments used for the dynamic surveys are shown in Fig. 2:

- Tromino 3D velocimeter (Fig. 2a);
- IBIS-S Ground-based radar interferometer (Fig. 2b).



Fig. 1. Church of Beata Vergine Assunta of Guasila (Sardinia, Italy): (a) historical image of the church (postcard of the first decade of '900, "Collezione Colombini"; (b) image from the square in front of the main façade of the church; (c) aerial perspective view of the structure.

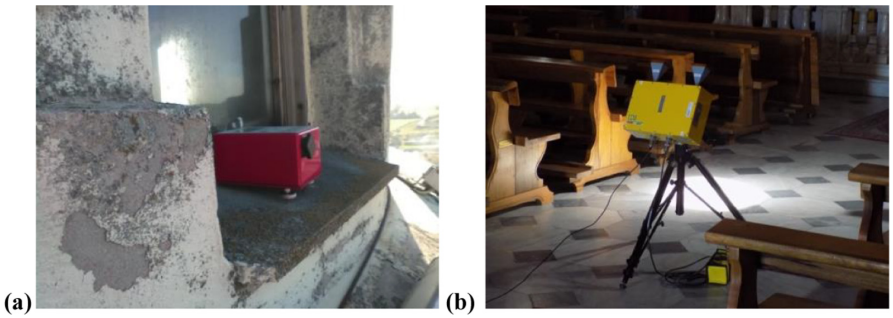

Fig. 2. Images of the instruments used for the dynamic surveys: (a) Tri-axial velocity sensor placed in the seismic station [TR05] in correspondence of the cylindrical lantern; (b) Ground-based microwave interferometer during the acquisition in correspondence to the central station [ST03].

2.1 Microtremor Spectral Analyses

Standard Spectral Ratios (SSR) method [31] has been used to analyze microtremor seismic data. This processing technique uses a reference station to filter ambient vibration data in order to isolate the contributions depending on the natural modes of vibration of the structure by the other components of microtremor. The assumption of linear dynamic behavior of the structures underlies this method. Through the SSR approach, the experimental frequency response of a dynamic system can be derived, along each component of the motion, in agreement with the following equation:

$$SSR(f) = \frac{|H_i(f)|}{|H_{ref}(f)|} \tag{1}$$

where $|H_i(f)|$ and $|H_{ref}(f)|$ indicate the amplitude spectra related to the i-th station and to the reference station, respectively.

Many authors propose the Standard Spectral Ratios method as both expeditious and effective technique. The method provides a reliable estimation of the experimental vibration properties of different types of structures, such as civil structures, ancient towers, earthquake damaged buildings and concrete dams [12, 32–34].

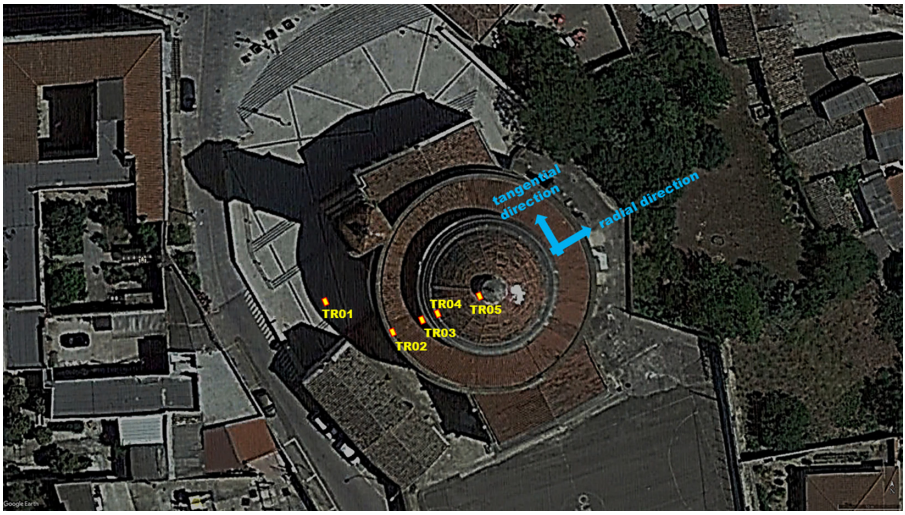

Fig. 3. Spatial distribution of the asynchronous microtremor stations (yellow rectangles) placed at the base of the structure and on it. The blue orthogonal axes indicate the local reference system utilized for the survey. (Color figure online)

An ambient vibration survey was carried out asynchronously acquiring microtremor time-series on five stations. Figure 3 shows the scheme of acquisition for the measurements. In order to identify the natural frequencies that mainly characterize the experimental dynamic behavior of the circular dome in the global complex system of the structure, SSRs were derived by monitoring three different reference stations.

This instrumental configuration aimed to put in evidence the vibration frequencies characterized by maximum amplitudes on the dome along three orthogonal directions, identified as Radial, Tangential and Vertical directions (with regards to the dome geometry in correspondence to the sensor configurations). The first reference site was chosen in correspondence to the lowest station **[TR01]**, placed at the ground surface, in the lateral parvis to the structure. This spatial position was identified in order to acquire reference signals minimally affected by the vibration of the elements of the church. Other reference stations were **[TR02]** and **[TR03]**, placed on the outside bearing wall of the structure and at the base of the circular dome. These reference stations were used to highlight the different behavior of remaining parts of the structure. Directional analyses of microtremor was performed in order to detect directional components of the structural motion. The duration of the acquisition for each measurement of microtremor was 20 min. Sampling frequency was 512 Hz.

2.2 Ground-Based Radar Interferometry: Basic Working Principles

Terrestrial remote sensing allows the measurements of the displacements without any direct array of sensors (*e.g.* velocity seismic sensors or accelerometers) installed on the structure. The displacements of different points are derived by reflected or backscattered electromagnetic signals which come back from the reflectors to the radar antenna.

The radar sensor generates microwave signals by means of the Stepped Frequency Continuous Wave (SF-CW) technique. This method uses high resolution signals [35, 36] characterized by stepped frequency waveforms over time (Fig. 4a). The displacements of the targets illuminated by the radar beam derived from the interferometric analysis [37]. The method allows to obtain time series of displacement looking at the phase shift measured between different backscattered or reflected signals coming from the same range bin.

The component of the displacement vector along the radar Line Of Sight $d_{LOS}(t)$ derives from the phase-shift $\Delta\varphi(t)$ according to the following equation:

$$d_{LOS}(t) = \frac{\lambda}{4\pi}\Delta\phi(t) \tag{2}$$

where λ is the wavelength of the signal. Interferometric processing can be used only when the sensor is based on a coherent radar system, capable to detect the phase of the received signals. Although the Eq. (2) provides a first estimation of the displacements achieved by the radar system [38], it represents a good approximation for most engineering applications.

Minimum amplitude of displacement that can be measured by means of this technique depends on the range resolution (δR) of the radar interferometer. This feature provides the capability of the radar to resolve separately two targets along the Line Of Sight of the system and depends on the signal bandwidth (B) according to the following equation:

$$\delta R = \frac{c}{2B} \tag{3}$$

where c indicates the speed of light.

For a radar system operating in *Ku* band (with central frequency of 17 GHz and wavelength λ equal to 1.76 cm) a phase variation of 1° corresponds to a displacement of 20 μm [39].

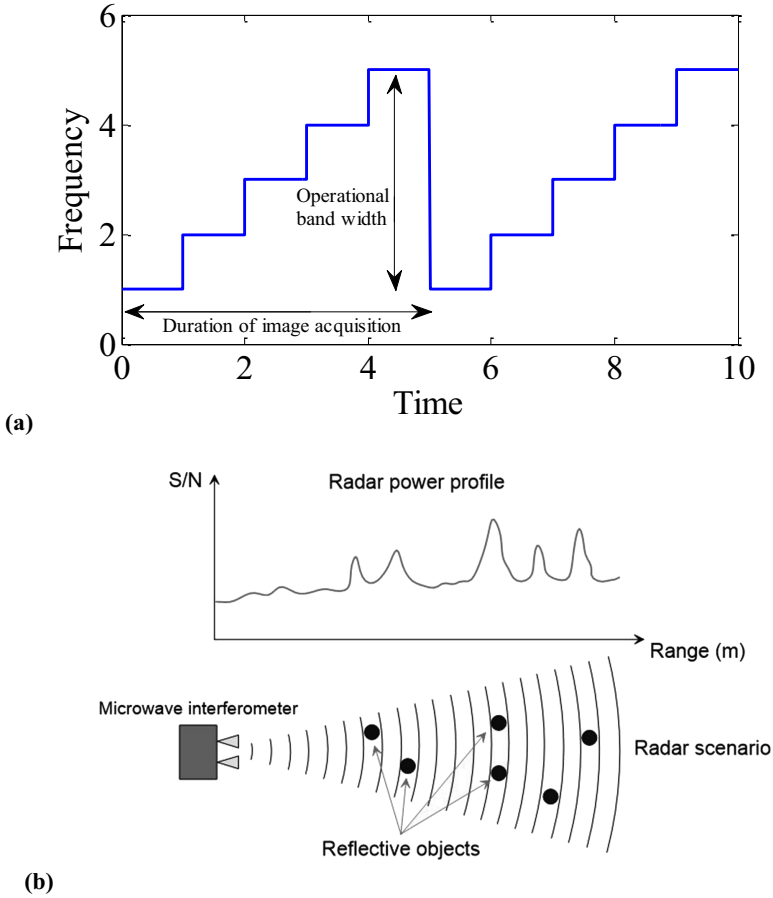

Fig. 4. (a) Illustrative spectrum of a Stepped Frequency Continuous Wave signal; (b) Schematic one-dimensional Radar Power Profile.

The microwave sensor used for the survey was the IBIS-S system (Image By Interferometry Survey, by IDS). This sensor is a coherent radar system without synthetic aperture that cannot detect the Direction Of Arrival of the reflected signals (no-DOA radar interferometer). For simple geometries, this limitation can be partially overcome by illuminating the same target element from different antenna positions. The antenna of a radar sensor is characterized by a lateral attenuation of emitted signal, with respect to the maximum axial signal, which is expressed by the azimuthal and vertical beamwidth. For the sensor used in the survey, azimuthal beamwidth has values of 17° considering a

decay of the intensity of −3 dB and of 34° at −10 dB, while vertical beamwidth is 15° at −3 dB and 45° at −10 dB. A typical spatial scenario sampled by this radar sensor is plotted in Fig. 4 jointly with the Radar Power Profile, which shows maximum amplitudes of the backscattered signals along the range distance in correspondence to the reflective objects indicated with black circles in the schematic plan view of the scenario. However, this system does not allow the estimation of the contribution of different targets positioned at the same distance (same range bin) from the radar station.

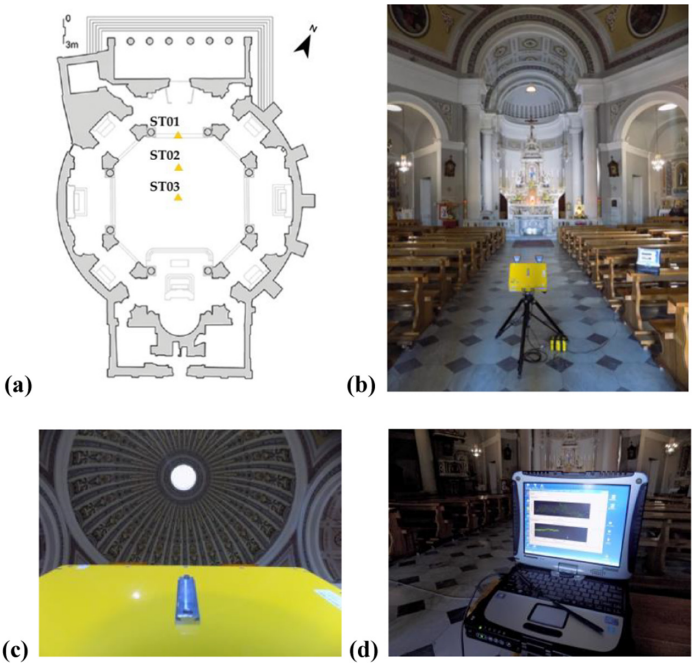

Fig. 5. Some images of the interferometric survey: (a) spatial distribution of the microwave interferometer stations (yellow triangles); (b) IBIS-S sensor during the survey, [ST02] station; (c) investigated scenario, [ST03] station; (d) experimental radar power profile and displacements time-series plotted in real time. (Color figure online)

The microwave survey was carried out using different configurations. The measurements were performed inside the church by means of three positions of the radar interferometer, indicated in Fig. 5a with yellow triangles (**[ST01]**, **[ST02]** and **[ST03]**). In order to assess the most favorable operative conditions to perform the radar survey, different configurations of measure were tested for each acquisition position (by modifying the inclination angle of the sensor head). Some images of the radar survey

Table 1. Interferometric radar stations: geometric acquisition layout.

Ground-based radar station ID	Configuration	Vertical inclination degree [°]	Duration [s]
[ST01]	**A**	85	1,200
	B	70	1,200
	C	40	1,200
[ST02]	**A**	70	1,200
	B	45	1,200
[ST03]	**A**	80	1,200
	B	65	1,200

are shown in Fig. 5. The geometric features of acquisition are reported in Table 1. Each radar station is considered in order to collect the information about a projected component of the true displacement along the Line Of Sight (LOS) direction. Combining all data, the real displacement vector can be estimated.

3 Experimental Results

3.1 Microtremor Seismic Survey

The standard spectral ratios of experimental time series, computed for the three reference stations, are reported in Fig. 6 and in Fig. 7. Starting from the analysis of the SSRs referred to the **[TR01]** station, located at the base of the structure (ground level), and looking at the vertical spectral ratios, the frequency peak with maximum amplitude is detected at the **[TR05]** microtremor station, located on the top of the dome, at a value of 7.4 Hz (Fig. 7a). The amplification effect related to this frequency is probably due to a structural vibration mode that mainly involves the body of the dome of the church, with maximum deformations along the vertical direction. In fact, this peak is not clearly visible in the horizontal components of spectral ratios, computed for the same station point (Fig. 6).

Furthermore, it is totally absent in the vertical spectral ratios, calculated for the stations positioned in the other levels of church. First two natural frequencies of vibration of the structure are recognizable at 4.0 Hz and at 4.6 Hz. These frequency peaks are clearly identified in all SSRs. The frequency peak at 4.0 Hz shows the maximum amplification along the radial component of displacement, but it is also present, although with lower amplitude, in both Tangential and Vertical components of the motion. Conversely, the frequency peak at 4.6 Hz mainly characterizes the horizontal Tangential spectral ratio and it does not show any substantial amplification along the vertical component (Fig. 7a).

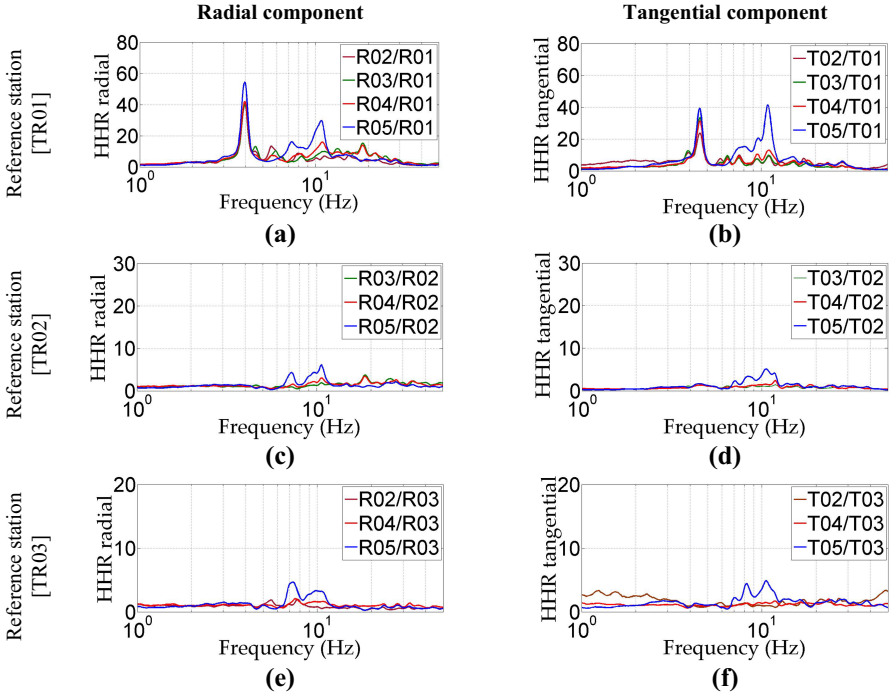

Fig. 6. Spectral ratios of ambient vibration measurements obtained by considering three different reference stations. Radial (a, c, e) and tangential (b, d, f) horizontal components of motion.

The frequency peak at 10.8 Hz is affected by significant amplitude in all components of the motion with maximum amplitude measured along both vertical and tangential spectral ratios. The spectra, filtered by means of the signal recorded at **[TR02]** station, highlight amplitude peaks at frequencies higher than 7 Hz. Probably, the first natural frequencies of vibration of the structure (4.0 Hz, 4.6 Hz) are not significantly amplified at the upper level of the church. The vertical spectral ratios clearly show the frequency peak centered at 7.4 Hz in agreement with the spectral ratios computed by the station installed at the ground level, evidencing that probably the parts of the structure between the first two reference stations, **[TR01]** and **[TR02]**, do not affect much this frequency amplification.

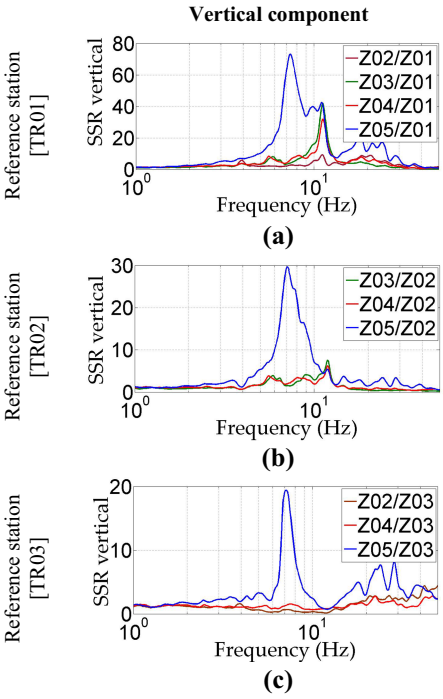

Fig. 7. Spectral ratios of ambient vibration measurements obtained by considering three different reference stations. Vertical components of motion.

3.2 Interferometric Radar Survey

In order to investigate the vibration response of the structure under operational conditions, different dynamic surveys were carried out using the IBIS-S radar interferometer. The radar survey was performed on 14 February 2020, with intense wind acting on the external side of the structure. Several geometric configurations of the radar sensor were tested with the non-trivial purpose to explore the operative capabilities of the remote sensor during the dynamic surveys, performed in indoor experimental conditions of a complex but known scenario. The position of the radar and the tilt of the antenna were modified in order to identify the most favorable geometries of acquisition. Microwave data were acquired using a sampling rate of 100 Hz over time windows of 20 min. The range resolution and the maximum range were set equal to 0.75 m and 50 m, respectively. In Fig. 8 the one-dimensional radar power profile, calculated for the configuration B in the station **[ST01]**, Table 1, is plotted. This location, settled to mainly illuminate the internal surface of the circular dome from different distances, was chosen for the preliminary analysis and the comparison with seismic data. The radar power profile that corresponds to this set of measurements is characterized by significant amplitudes of backscattered electromagnetic signals in correspondence to the range bins 29 (21.75 m, average distance from the radar system), 32 (24 m), 33 (24.75 m) and 35 (26.25 m), with a high Signal to Noise Ratio (SNR). There are also other range bins that

show high amplitude SNR peaks. However, these signals do not correspond to any clearly identified structural element of the church and were discarded for the analysis. Further measurements were performed installing the sensor in correspondence to the stations **[ST02]** and **[ST03]**. The results obtained for these sets of measurements are not discussed here, but were considered to derive more information about the experimental vibration properties of the structure. The radar power profiles show different range bins characterized by intense amplitude of the backscattered signals. These signals are probably due to the presence of many lateral backscatterers, corresponding to the architectonical elements that are present on the internal walls of the structure. In addition, the curvature of the surface of the dome does not represent a single backscatterer but can be considered like as a continuous distribution of reflective points, positioned at increasing distances from the radar sensor. This feature is confirmed by the comparison among the amplitude spectra, derived from different range bins that correspond to reflective points on the structure. The radar bins with SNR higher than 40 were selected for the displacement and the frequency analyses.

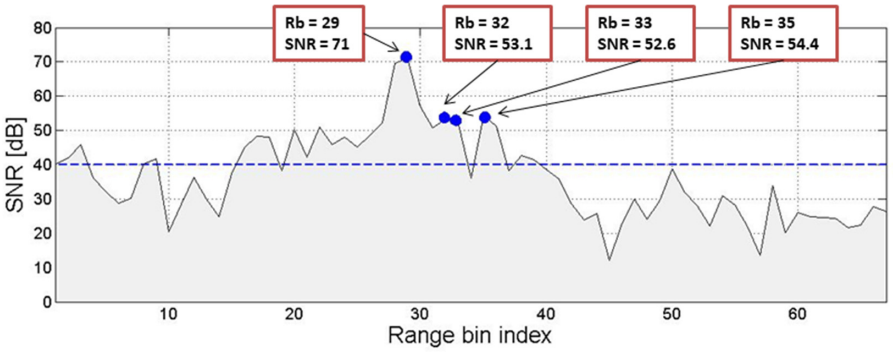

Fig. 8. Radar Power Profile corresponding to the measurement performed through the configuration B in the radar station [ST01]: blue circles indicate the range bins selected for the spectral analysis. (Color figure online)

Figure 9 shows the Power Spectral Densities functions derived from the signals corresponding to the range bins 32, 33 and 35, selected from the radar scenario of **[ST01]** station, configuration **B**. Two clear harmonic components are shown in all selected spectra. The first frequency peak recognized by the interferometric survey is centered at 7.68 Hz. This frequency peak is very close to the vibration frequency of 7.4 Hz, detected by means of the SSRs of microtremor, calculated for the vertical component of the structure motion (with different reference stations). This frequency component is characterized by high amplification in correspondence to the measurement taken on the dome of the church (**[TR05]**, lantern). This frequency can be interpreted as a natural frequency associated to a structural vibration mode that mainly involves the dome of the church. In fact, this experimental vibration mode is characterized by prevalent deformations along the vertical component of the signals.

The second frequency peak, shown by the graph in Fig. 9, is localized at 15.34 Hz. However, this frequency component was not detected by means of the microtremor measurements. All Power Spectral Density (PSD) functions, derived from the dynamic microwave surveys, do not show any frequency peaks related to the first and to the second vibration modes of the structure (4.0 Hz and 4.5 Hz). This phenomenon could be due to the low amplitude deformation associated with these vibration modes in the LOS direction of the radar.

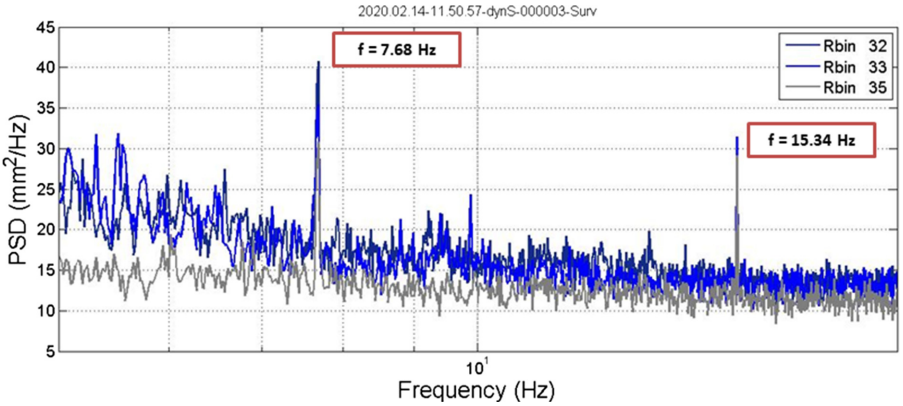

Fig. 9. Power spectral density functions derived from the range bins 32, 33 and 35, selected from the radar scenario corresponding to the station [ST01], configuration B.

4 Numerical Results

A three-dimensional preliminary Finite Element (FE) model of the main central body of the church was realized to compare the experimental results with the outputs of the numerical simulation and to better evaluate the correspondence between the synthetic dynamic response of the model and the interferometric radar results.

The dynamic simulation was performed using the software Autodesk Inventor. The geometry of the structure was simplified and the discrete model was built using 145,814 nodes and 85,525 elements. The eight central pillars that support the upper part of the structure and the central circular dome were included in the model. Furthermore, lateral structural elements were inserted in order to simulate the horizontal constraint action due to the chapels of the church. The material properties (density and elastic modulus), were assigned in agreement with the scientific literature and taking into account specific analyses done on the samples of building materials [31].

Preliminary results highlight that the dynamic behavior of the model shows a vibration mode characterized by significant deformations along the vertical direction (Fig. 10). The deformations corresponding to this natural mode (frequency of 7.16 Hz) mainly regard the circular dome and the upper part of the model. The preliminary numerical outputs show a good agreement with the experimental results.

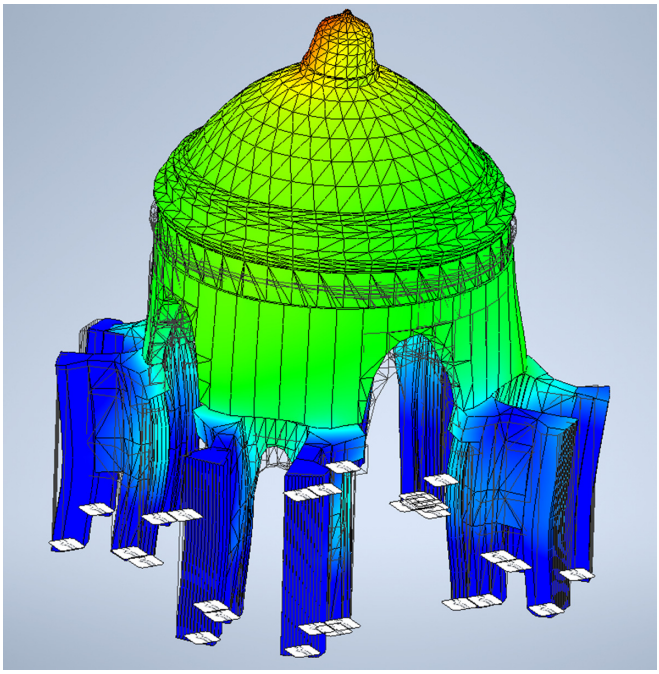

Fig. 10. Preliminary numerical dynamic analysis: synthetic mode shape with maximum deformations detected in the top of the structure.

5 Conclusion

Thanks to the integration of non-destructive methods based on conventional velocity sensors and terrestrial remote sensing systems, the experimental dynamic study of a historical structure was proposed. The complementary approach was utilized to perform the dynamic characterization of the dome of the church of "Beata Vergine Assunta" in Guasila. Spectral analyses of microtremor were used to derive the main vibration properties of the structure starting from five asynchronous stations of environmental noise. Microtremor spectra showed high amplification effects at frequencies of 4.0 Hz, 4.6 Hz and 7.4 Hz for the radial, tangential and vertical components of the motion. Ground-based radar interferometry surveys were performed inside the structure. Interferometric results show that the experimental datasets contain the contribution of a natural mode of vibration, that mainly characterizes the upper part of the structure (circular dome) at the frequency of 7.68 Hz. Preliminary numerical outputs derived from the Finite Element analysis show a good agreement with the experimental results of the surveys. Future studies will be performed to improve the analysis of the interferometric data and to implement a more detailed Finite Element simulation.

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