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Dynamic testing of masonry towers using the microwave interferometry

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Abstract. Microwave remote sensing is the most recent experimental methodology suitable to the non-contact measurement of deflections on large structures, in static or dynamic conditions. After a brief description of the radar measurement system, the paper addresses the application of microwave remote sensing in ambient vibration testing of two historic masonry towers.

Introduction

The most peculiar characteristic of a conventional radar is its ability to determine the range (i.e. the distance) of a target by measuring the time for the radar signal to propagate to the target and back. Although the name *RADAR* is derived from *RA*dio *D*etection *A*nd *R*anging, it is well-known [1] that a radar is capable of providing more information about the target than its name would imply and typical applications include the evaluation of the radial velocity, the angular direction, size and shape of the target.

Recent advances in radar techniques and systems has led to the development of portable radar systems [2], capable of simultaneously measuring the deflection of several points on a large structure with high accuracy. After the practical implementation of the above principles in an industrially engineered sensor, carried out by the Italian company IDS (Ingegneria Dei Sistemi, Pisa, Italy), the results of the new equipment have been validated in a joint research between IDS and Politecnico di Milano [3]-[5].

Since the development of practical methods for non-destructive testing and assessment of Cultural Heritage structures, especially in seismic prone areas, is of primary concern in many countries all over the world, the application of microwave remote sensing to ambient vibration testing of historic structures is in principle very attractive, although characterized by some potential issues: (a) the electromagnetic reflectivity of masonry is rather low; (b) the actual displacement of the structure needs to be larger than the radar sensitivity (0.02 mm, [3]).

Within this context, the radar equipment and its technical characteristics are described in the first part of the paper, and advantages and potential issues of the new technology are summarized. Subsequently, the application of microwave remote sensing to the measurement of dynamic deflections on two historic masonry towers is presented and discussed.

The radar measurement system

The radar sensor used in this work (Fig. 1) is an industrially engineered microwave interferometer (IDS, IBIS-S system) [2]-[5] and consists of a sensor module, a control PC and a power supply unit. The sensor unit is a coherent radar (i.e. a radar preserving the phase information of the received signal) generating, transmitting and receiving the electromagnetic waves to be processed in order to compute the deflections of the investigated structure. Electromagnetic signals are emitted at a central frequency of 17.2 GHz with a maximum bandwidth of 300 MHz, so that the radar is classified as K_u-band, according to the standard radar-frequency letter-band nomenclature from IEEE Standard 521-1984 [1]. The main technical characteristics of the sensor are the following:

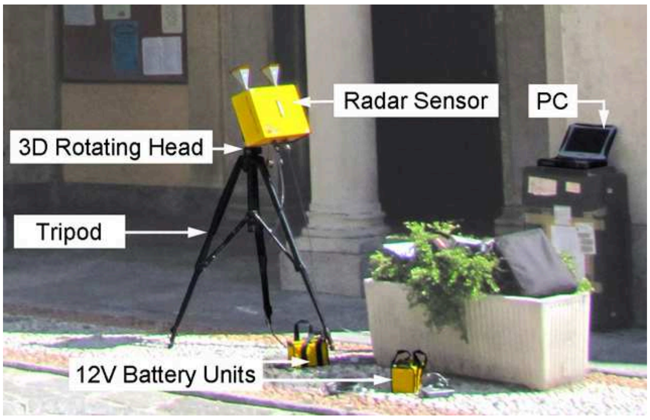


Figure 1: View of the microwave interferometer (IDS, model IBIS-S)

maximum sampling frequency:	200 Hz;
maximum operational distance:	> 500 m;
displacement accuracy:	< 0.02 mm.

Simultaneously measuring the displacement of several points on a large structure, by using a radar, involves two key steps [3]-[5]: (a) acquiring consecutive radar "images" of the structure at an appropriate sampling rate, with different points of the structure being individually observable in each image; (b) using the phase variation of the back-scattered microwaves coming from each detected target point at different times to evaluate the displacement. Hence, the main information provided by the radar technique are the synthetic image of the scenario and the time histories of the points in the scenario that characterized by a good electromagnetic reflectivity.

The synthetic image of the scenario, or range profile, is simply a 1-D map of the intensity of the received radar echoes in function of the distance of the target points generating the echoes themselves: the peaks in the range profile identify the position/range of the targets detected in the scenario at each time sample. It is worth underlining that the microwave interferometer has only 1-D imaging capabilities, i.e. different targets can be unambiguously detected if they are placed at different distances from the radar; hence, measurement errors may arise from the multiplicity of contributions coming from different points placed at the same distance from the radar [3], [5].

Once the interesting targets have been identified from the range profile, the sensor management software provides the time histories of the deflections corresponding to the peaks in the range profile. It is worth noting that the microwave sensor measures displacement along the radar line of sight only; hence, the evaluation of actual deflections requires the prior knowledge of the direction of motion [3]-[5].

Dynamic testing of the "Collegiata di San Vittore" bell tower: conventional and radar survey

The first investigated masonry bell tower (Fig. 2), located in the small town of Arcisate (Varese, Northern Italy), is about 37.0 m high and built in stonework masonry. The tower is connected to the Church "Collegiata di San Vittore" (XI century) on the east side and partly on the south side; the first historic document on the tower dates back to XVI century but it was probably built on a previous roman building and modified along the centuries.

As shown in Fig. 2, the tower is characterized by irregular stonework. Seven orders of floors are present, with five of them being defined by masonry offsets at the corners and by corresponding sequences of small hanging arches marking the floor levels; the last two orders were probably added in the XVIII century to host the bell trusses.

Along all sides, the tower exhibits long vertical cracks, most of them cutting the entire wall thickness and passing through the keystones of the arch window openings. These cracks are especially detected between the second-third order of the tower and the base of the belfry and show a maximum aperture corresponding to the upper end. Many superficial cracks are also diffused, particularly on the North and West fronts (Fig. 2), which are not adjacent to the church.

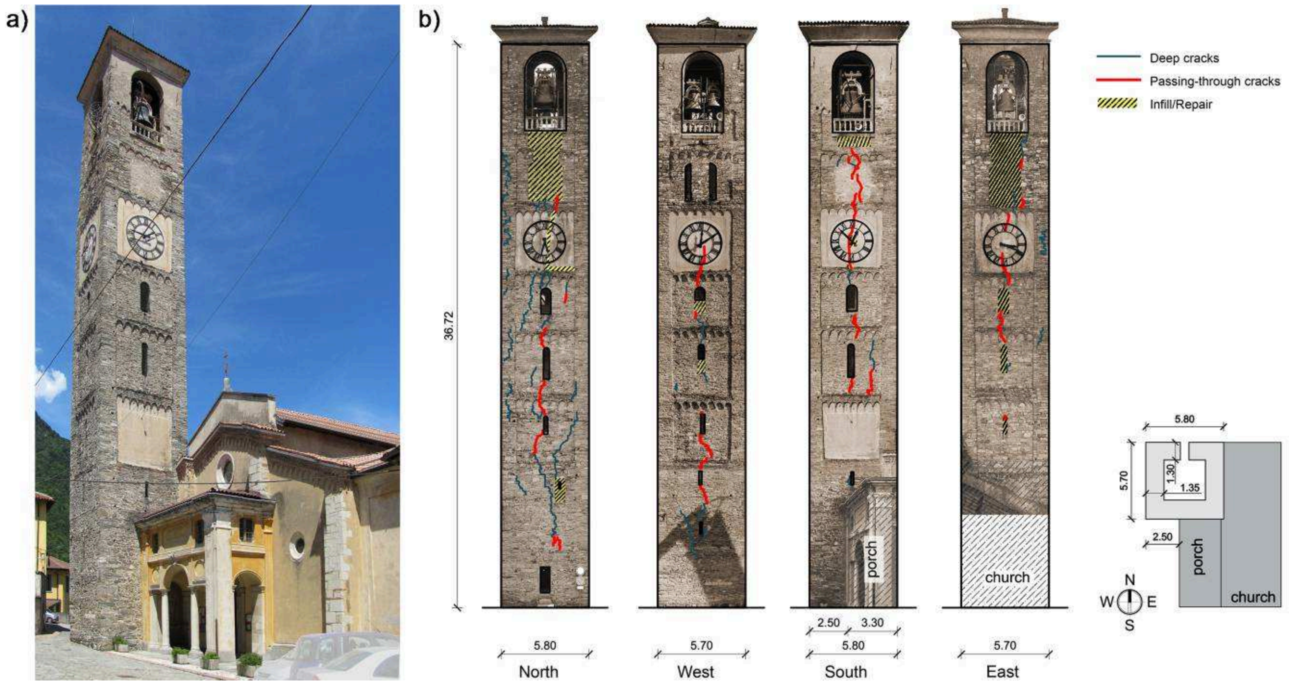
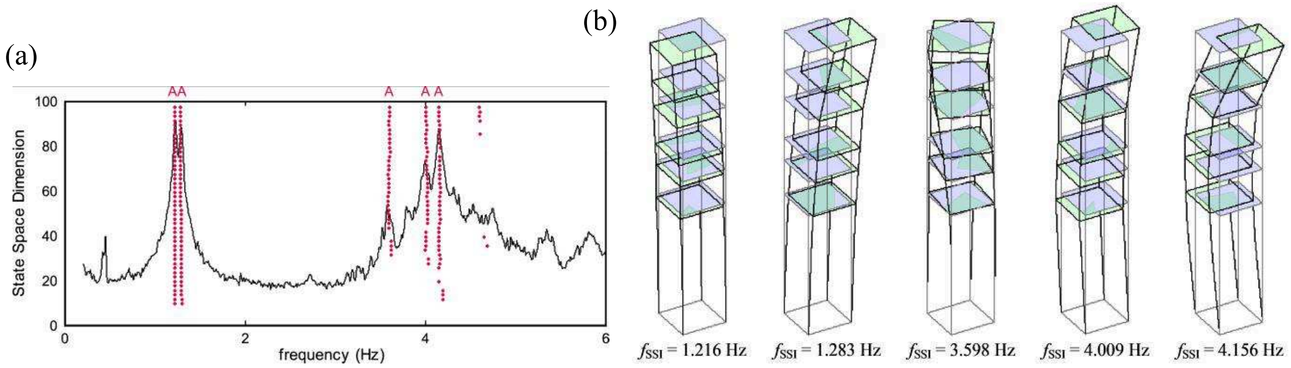


Figure 2: (a) General view and (b) fronts of the "Collegiata di San Vittore" bell tower



f_{SSI} = 1.216 Hz f_{SSI} = 1.283 Hz f_{SSI} = 3.598 Hz f_{SSI} = 4.009 Hz f_{SSI} = 4.156 Hz

Figure 3: (a) First Singular Value line (FDD), alignments of stable poles (SSI) and automatic (A) identification of natural frequencies (June 2007); (b) Vibration modes identified from ambient vibration data (SSI, June 2007)

The tower has been studied by Politecnico di Milano for a long time: previous study involved historic and documentary research, geometric survey, on-site survey of the structural discontinuities, tests of materials on site, preliminary dynamic tests in operational conditions [6]-[7], vibration-based FE modeling and continuous dynamic monitoring [7].

Two ambient vibration tests were conducted on the tower by using conventional accelerometers (June 2007 and June 2008). In both tests, the structural response was measured in 15 selected points (3 measurement points at 5 different levels).

The application of both FDD [8] and SSI [9] techniques allowed to identify 5 vibration modes in the frequency range of 0-6 Hz. The results in terms of natural frequencies can be summarized through the plot of Fig. 3a, illustrating the lower singular values (SV) of the spectral matrix and the stabilization diagrams obtained by applying the FDD and the SSI technique to the data collected in June 2007. The inspection of Fig. 8a clearly highlights that the alignments of the stable poles in the stabilization diagram of the SSI method provides a clear indication of the tower modes and those alignments of stable poles correspond to well-defined local maxima in the first SV line of the FDD technique. Fig. 3b shows the identified mode shapes (June 2007, SSI technique): dominant bending (B) modes were identified at 1.22 (B_1), 1.28 (B_2), 4.01 (B_3) and 4.16 Hz (B_4) while only one torsion mode (T_1) was identified at 3.60 Hz. It is observed that the dominant bending modes of the tower involve flexure practically along the diagonals.

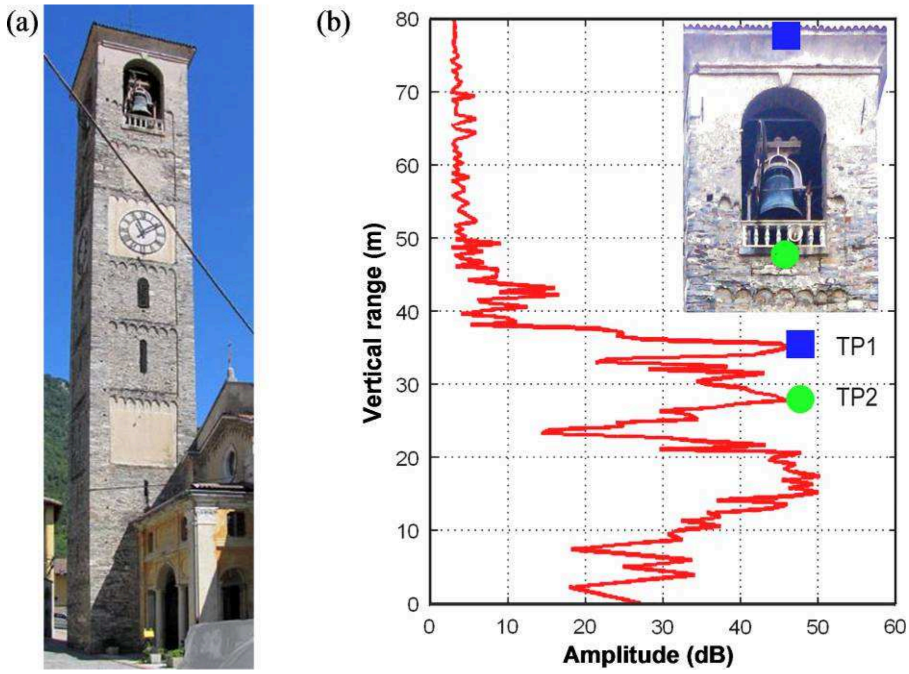


Figure 4: (a) Radar position in front of the tower South side; (b) Range profile of the test scenario

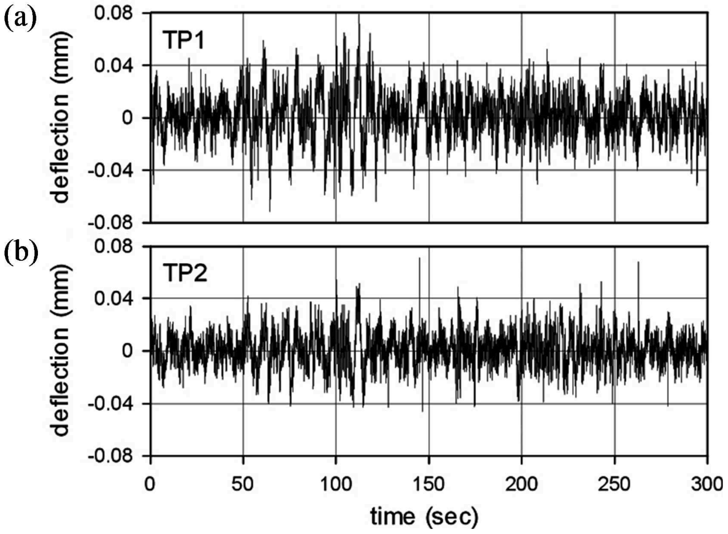


Figure 5: Typical deflection time series measured by the radar at: (a) TP1; (b) TP2

The dynamic test was repeated on July 2011 by using the microwave remote sensing. During the radar survey, the ambient excitation was very low and only provided by micro-tremors. Fig. 4a shows the radar position (at a distance of 6.40 m from the South side wall and inclined of 70° upward). Radar data were acquired at rate of 200 Hz over a time window of 3600 s.

The range profile of the test scenario is presented in Fig. 4b: it is observed that after some close and neighboring peaks at the height of 10-20 m (vertical range), two well defined peaks clearly identify the position of the "corner zones" denoted as TP1 and TP2 in Fig. 4b and corresponding to the top cornice and the projecting stone sill of the belfry opening.

The analysis of the results obtained by the radar sensor first involves the qualitative inspection of the deflection measurements. Figs. 5a-b show an example of the displacement time-histories measured at TP1 and TP2, respectively. It should be noticed that, as it has to be expected at the low level of excitation that existed during the tests, the recorded displacements are very low, with the maximum amplitudes ranging between 0.079 mm (TP1) and 0.071 mm (TP2); in addition, the deflection time histories seems rather "noisy". On the other hand, the deflection amplitude exceeds 2-4 times the sensor resolution (0.02 mm, [3]): hence, significant results have to be expected in terms of natural frequencies and modal amplitudes at target points TP1 and TP2.

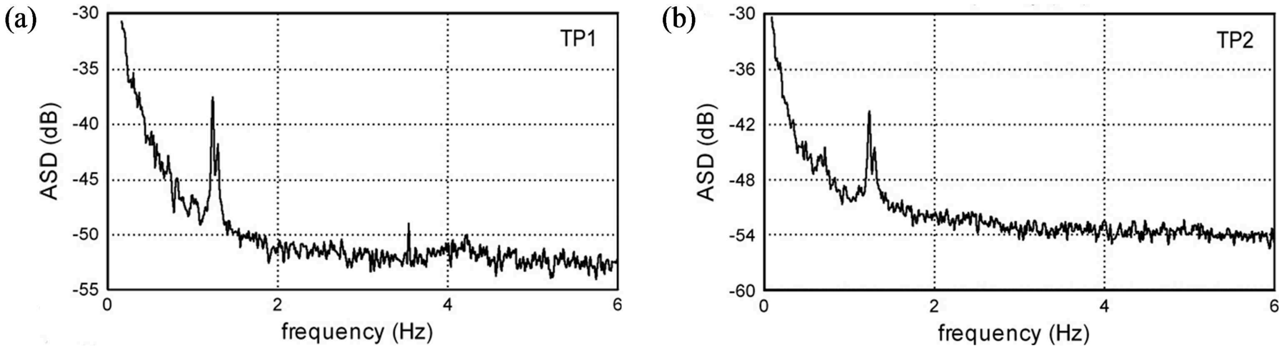


Figure 6: Auto-spectra (ASD) of the displacement data measured by the radar at: (a) TP1; (b) TP2

Data processing in the frequency domain provides the auto-spectral densities (ASD) illustrated in Fig. 6. The inspection of the ASDs highlights the presence of two well defined peaks at 1.240 and 1.299 Hz, corresponding with excellent accuracy to the modes B_1 and B_2, previously identified (Fig. 3); it is worth underlining that also the ratio between the modal deflections at TP1 and TP2 exhibits a very good agreement with the results of previous tests.

Radar-based dynamic testing of the "San Domenico" bell tower

More recently, taking advantage of an extensive post-earthquake assessment carried out by Politecnico di Milano on the tallest historic tower of Mantua, a quick radar survey was performed on the "San Domenico" bell tower (Fig. 7), about 30 m high and placed in the same town.

The two fronts of the tower shown in Fig. 7 were surveyed by microwave remote sensing; for each radar position, deflection data were acquired at rate of 200 Hz over a time window of 2400 s. As in the previous case study, the response corresponding to the top of the structure was recorded. The auto-spectrum of the displacement at the top of the tower in the 2-4 plane is shown in Fig. 8 and exhibits four well defined spectral peaks at 1.135, 1.306, 7.263 and 8.643 Hz. The first two dominant frequencies were also clearly identified from the response in the orthogonal 1-3 plane, thus indicating that the lower vibration modes of the tower involve biaxial bending or coupled bending-torsion behavior, as it has to be expected from the building structural architecture (Fig. 7).

It is further noticed that vibration modes, with natural frequencies of 1.15 and 1.30 Hz and characterized by modal deflections in both planes 1-3 and 2-4, were identified in other studies [10] from the rough analysis of low-sensitivity accelerometer data.

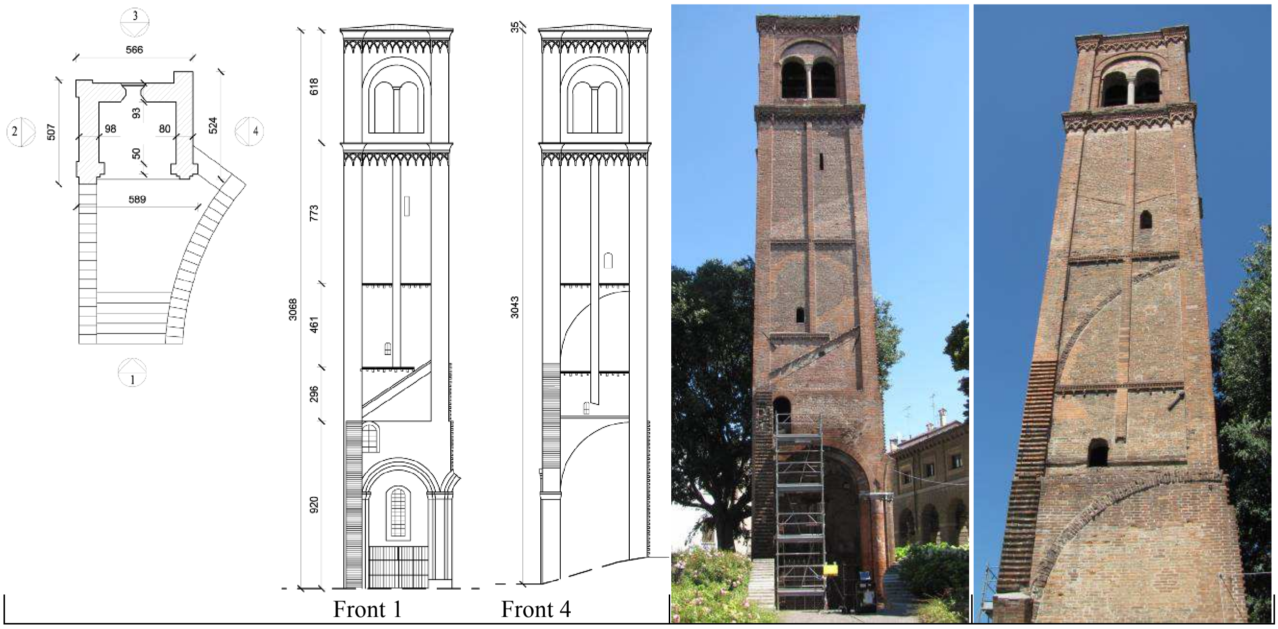


Figure 7: "San Domenico" bell-tower: general arrangement and fronts 1 and 4 (dimensions in cm)

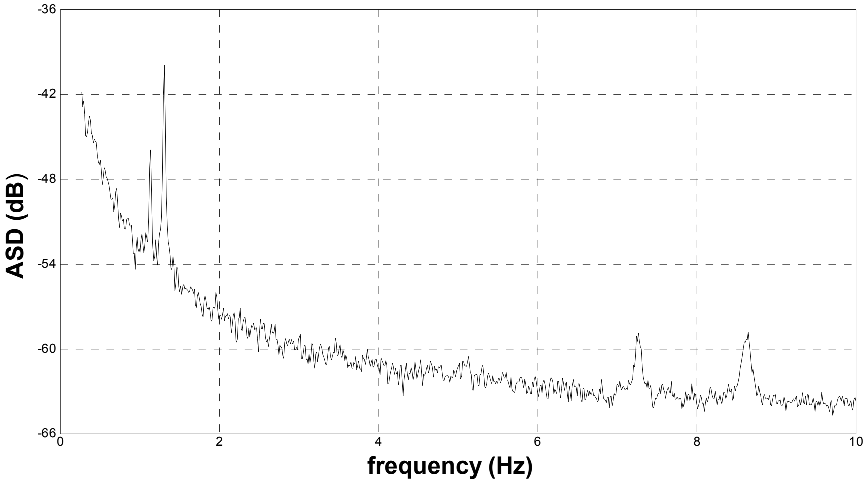


Figure 8: Auto-spectrum of a displacement time-history recorded on the San Domenico bell-tower

Conclusions

The paper is focused on the application of microwave remote sensing to the measurement of dynamic deflections on two masonry towers.

The experimental results, in terms of natural frequencies, turned to be as accurate as that obtained with conventional accelerometers, even with the extremely low level of ambient excitation that existed during the test. On the other hand, the application of microwave remote sensing to historic structures – although promising and in principle very attractive – turns out to be characterized by some potential issues: (a) the electromagnetic reflectivity of masonry is rather low; (b) historic structures (such as towers or churches) generally exhibit few "corner zones" effectively reflecting electromagnetic waves; (c) the actual deflection of the surveyed structure needs to be larger than the radar sensitivity.

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