ND tests for a first assessment of mechanical behaviour of the stone-covered façades of Palazzo Ducale in Venice

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Abstract

A program of non-destructive tests carried out on the two medieval stone-covered façades of Palazzo Ducale in Venice is here described. It consisted of direct and indirect sonic wave velocity tests on site and direct tests in the laboratory on samples of the component materials. The program was set up after a preliminary historic investigation aimed to raise useful clues on the geometric, physical and mechanical features of the double-layered façades. The qualitative information provided by the sonic testing procedure was assessed by mutual comparison of the results; the reliability of the collected data was also kept into consideration by assessing the distribution of results. The reported information is going to be one of the first steps in a wide programme of multi-disciplinary control of the façades.

Keywords: sonic wave velocity test, historic masonry, Venice.

1 Introduction

Preservation guidelines for the maintenance of monumental buildings require a wide knowledge of complex general conditions, even when only a single problem has to be faced. This is the case of Palazzo Ducale in Venice, one of the most representative and valuable historic buildings of Italy. Like it happened to other historic stone-covered façades (e.g. in Genova, Ferrara and Pavia), the south façade of Palazzo Ducale (Figure 1) has recently suffered some unexpected fall of material from the external stone covering of the south façade. Thus, the Research Unit on Safety Assessment of Monuments at the IUAV University of

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Venice has set up a multi-disciplinary safety assessment program (Aldreghetti [1], Andreozzi [2]), to assess the state of preservation and to elaborate maintenance guidelines for the external medieval façades of Palazzo Ducale.

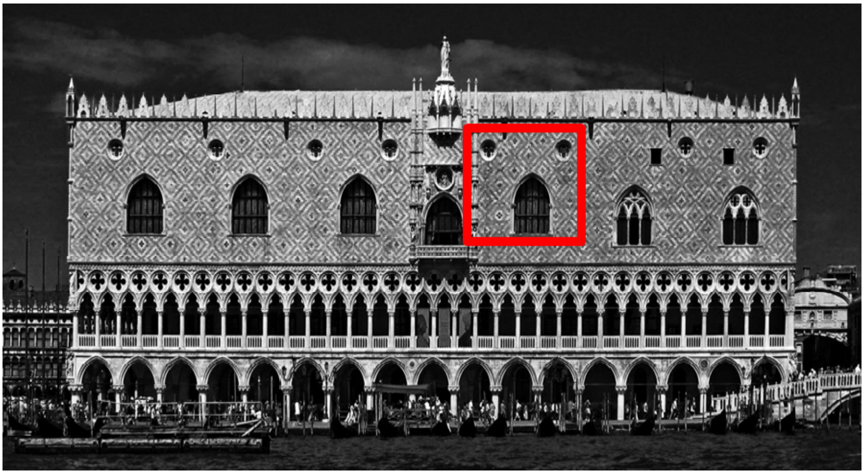

Figure 1: Venice, Palazzo Ducale, south façade – investigated portion of wall.

This program is currently in progress until October 2012; it consists of the following phases:

- detection and analysis of the past restoration works
- geometrical survey
- static, dynamic and environmental long-term monitoring
- short-term monitoring (non-destructive and micro-destructive testing)
- geotechnical tests
- numeric modelling
- physical modelling.

This paper refers to non-destructive tests performed to carry out the short-term monitoring phase, and to raise basic information about the mechanical behaviour of the stone-covered façades which will be useful for the numerical and physical modelling. In particular, a campaign of sonic velocity tests performed on the south façade of the palace is here described; the results could be compared to information from analogous tests performed in laboratory on samples of original materials.

2 Historic investigation

The non-destructive tests were programmed after inspections and historic bibliographic research on the relevant features of the monument. Palazzo Ducale consists of three main buildings facing an internal quadrilateral court. The southern one (S. Marco Basin side) was built between 1340 and 1366, and the western one (Piazzetta side) was started in 1424. They have the same façade scheme, i.e. arcades at the ground level with an upper loggia of half-span arches reaching the height of 13.70 m; then, a 12 m tall polychrome stone covering with a continuous lozenge pattern, occasionally interrupted by wide windows and a central balcony; finally, at the top, a crowning frieze indicating the roof level.

Several restorations were performed during the centuries, in particular after the fire in 1577 (which destroyed the roof of the main rooms and stopped at the east side of the Room of Maggior Consiglio) and during the Austrian domain in Venice; the south and west façades had been restored mainly during the end of XIX century (1876-1890) by Eng. Annibale Forcellini, who was responsible for applying new steel ties in the loggia, re-handling previously restored zones, and substituting some stone members (capitals and even columns) in the arcade and loggia.

The two medieval façades of Palazzo Ducale (i.e. the southern and western external façades) are double-layered and 90 cm thick; they're made of a load bearing clay brick masonry wall and an external layer of stone blocks with variable thickness. The covering is finely textured in square lozenges and consists of Istrian limestone, Veronese limestone and ancient marbles; the last are used for the central blocks of the lozenges. All the blocks are about 15.5 cm high, whereas their width can be variable (i.e. 15.5, 31.0 or 46.5 cm). The joints, very skilfully and carefully executed, are 1-3 mm thick, but generally not thicker than 1 mm.

Stone-covered masonry façades are very common in Venice, since they can increase the aesthetic value of the building as well as they protect the internal load-bearing wall against the salty environment; the external layer must not be too thick so that the external façade is able to follow the masonry wall settlements.

Following Schuller [3], the façades were covered in stone only after the bearing masonry walls were completed. On the other side, the stone blocks' height is exactly equal to two masonry brick courses (Romanelli [4]), meaning that the inner wall and the outer covering could have been built at the same time. The investigations carried out during the restoration of 1997-2003, could not increase the knowledge about the construction technique of the façades of Palazzo Ducale, which nowadays is still not completely clear. Anyway, following all the available studies, it can be said that the blocks of Istrian limestone locally act as links between the external façade (cover stone layer) and the internal façade (load-bearing masonry wall): these blocks transfer the weight of external façade to the structural internal one (Fig. 2). Very few information is available on the structural brick walls behind the stone cover, since the latter was never removed in recent times, and XIX century descriptions are too poor in details.

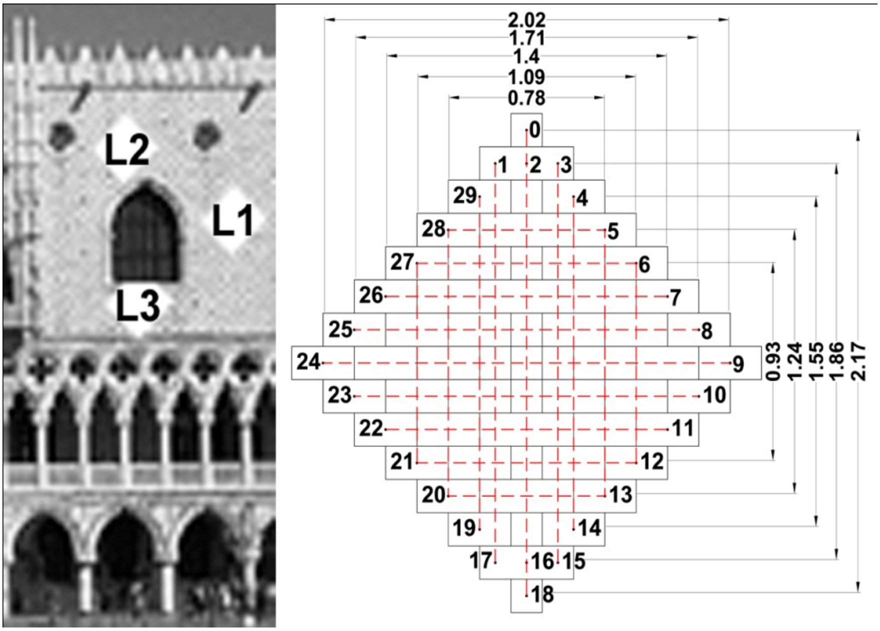

Figure 2: Location and grid of external indirect tests.

3 Experimental program

The non-destructive testing campaign on site consists of superficial as well as transparency sonic tests. The former type of test puts out the velocity of the sonic wave produced by the impact of an instrumented hammer and detected by a low-frequency accelerometer set on the same surface. Tests have been performed following an orthogonal grid related to the modular texture of the stone covering in three different zones, indicated as L1, L2 and L3 (Fig. 2). The results are grouped by direction and length (which implies different materials and number of joints to be crossed by the path of the sonic wave) of each row and column of the grid; the values are illustrated in Figures 3 and 4, that include also the graphs of results' distributions $p(x)$ following the indicated formulation in which μ is the mean value and σ is the standard deviation. Generally, excluding the peak values which are about 6000m/sec, the velocity range is between 1000 and 4000 m/sec in all the three cases. In particular, L1 has a mean velocity value around 3200 m/sec both for horizontal and vertical direction, whereas for L2 and L3 the mean values lie between 1000 and 2000 m/sec. With increasing distance, the mean values of velocity decrease and the results turn out to be less scattered.

Transparency sonic tests here reported – performed by beating with the instrumented hammer while the accelerometer is set on the opposite side of the 90 cm thick wall – were performed on a portion of the wall which was free from

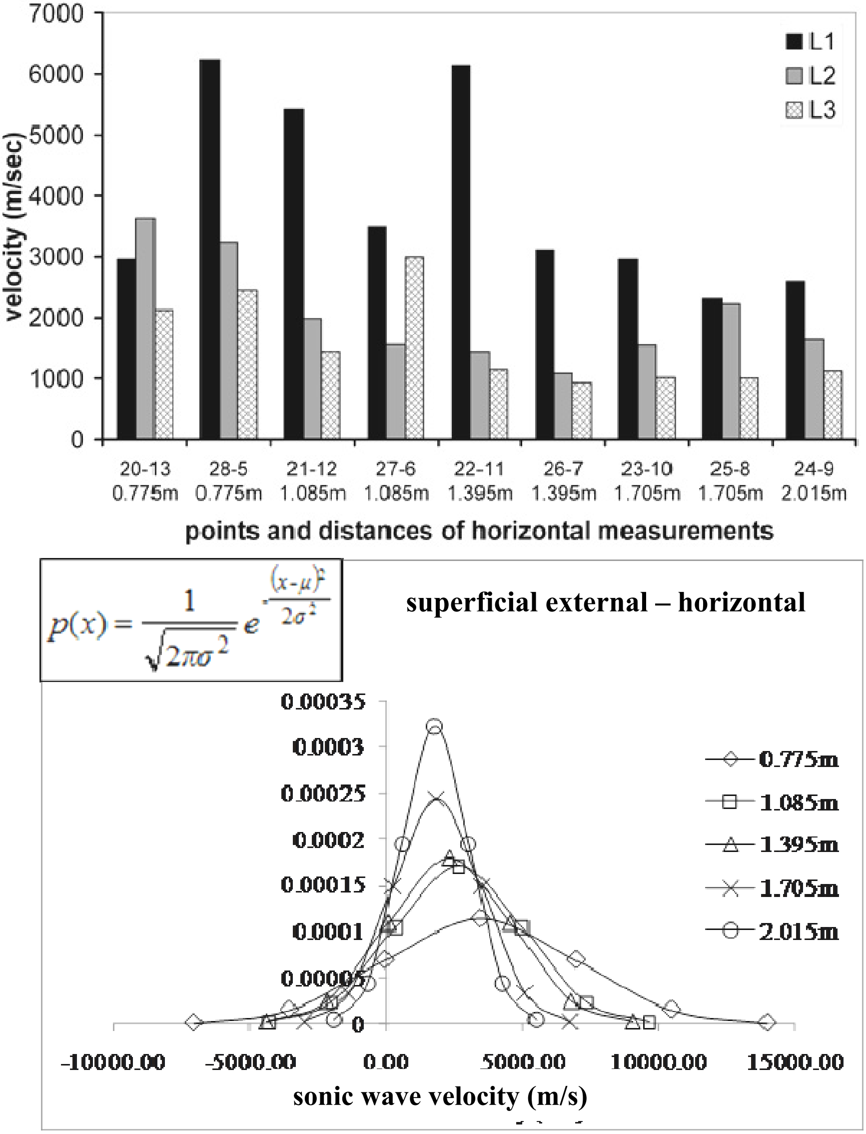

Figure 3: Superficial external tests (horizontal direction) – distribution of results.

internal claddings (Figure 5); the grid of points at which the beating were performed was drawn on the external side, taking into account the stones' texture, and mirrored on the internal side; thus, values of sonic velocity recorded from the beatings on one side could be compared to the ones at the corresponding points on the other side. Moreover, the stone which fell off from

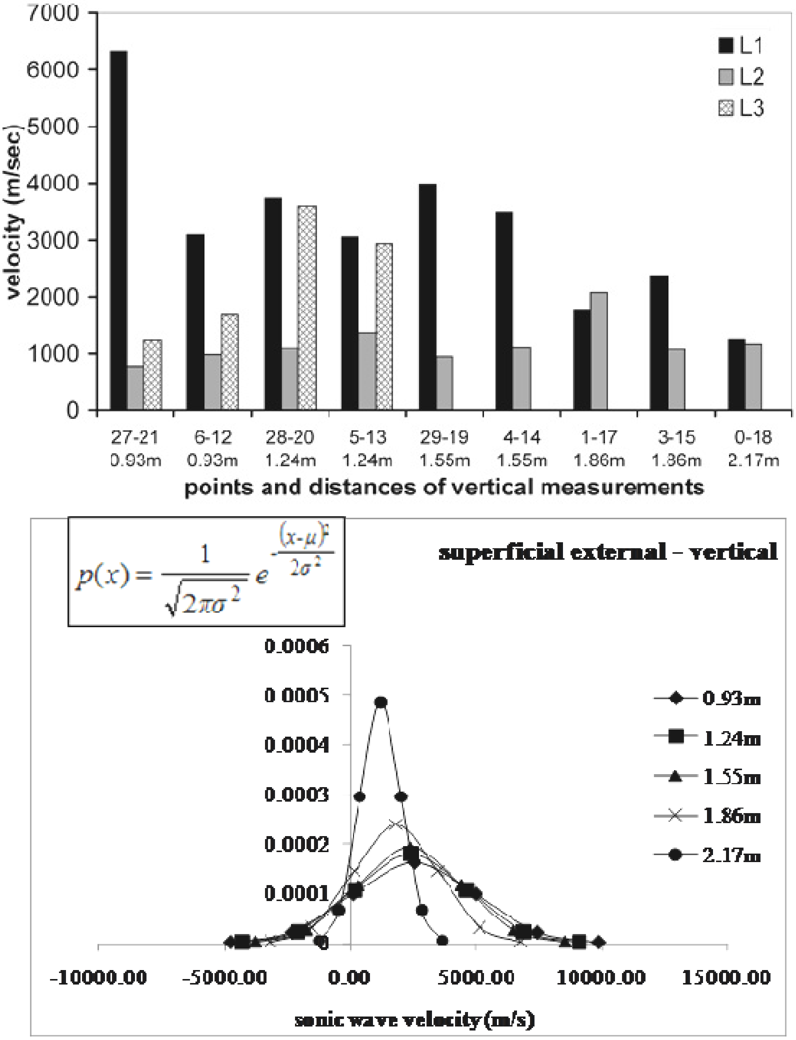

Figure 4: Superficial external tests (vertical direction) – distribution of results.

the façade was very close to this wall portion, and on both sides a crack was detected. The values of sonic velocity are mapped in Figure 6, which enlighten a good agreement between recordings from internal and external beatings; Figure 6 shows also the good distribution of results in both cases. The highest values – indicating a more compact and homogeneous masonry assembly – are clearly grouped into three zones, which refer to Istrian limestone blocks at the outer border of the lozenge. This may depend on the presence of keystones and/or on the internal state of stress above the arch window.

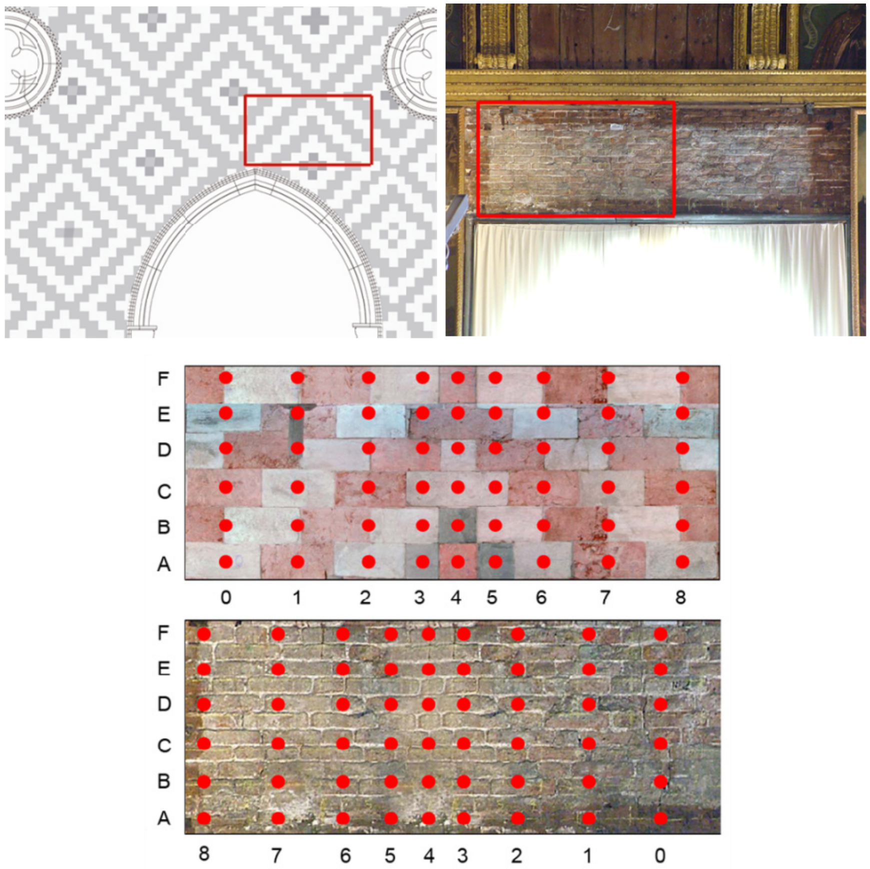

Figure 5: Location and grid of direct sonic tests.

On the internal wall portion, the indirect sonic velocity was also tested on the brick and mortar masonry; Table 1 collects the results of such tests. The high value of sonic velocity along the vertical directions likely reveals a highly compacted historic masonry.

Table 1: Superficial sonic tests on masonry.

location/direction	distance (m)	mean sonic velocity (m/s)	standard deviation
internal/vertical (masonry)	0.80	2415	1804
internal/horizontal (masonry)	1.74	1130	880

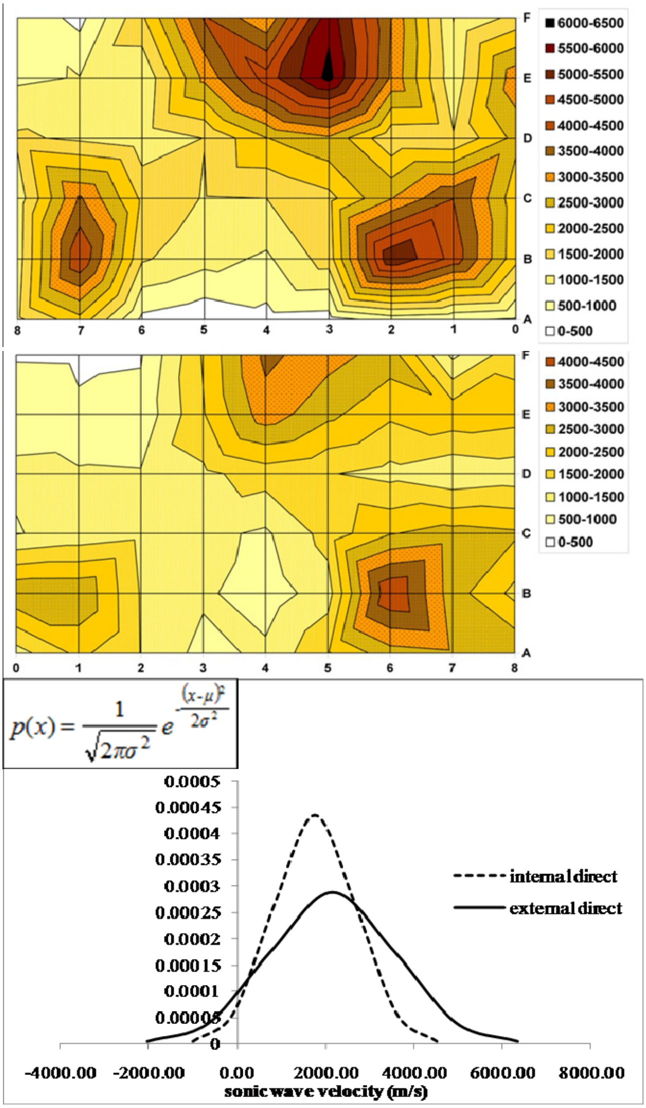

Figure 6: Direct sonic velocity tests (m/s): internal (top) and external beatings (centre), results distribution (bottom).

The sonic tests performed in laboratory are a part of a wider destructive and non-destructive testing programme which is now in progress. The stone samples are of the same types and age of the façade covering; the samples of masonry (bricks with mortar joint) are taken from an internal wall of the palace which dates back to the same age of the south façade. Table 2 reports the results of the laboratory tests, the mean value and the standard deviation. Istrian stone shows

Table 2: Laboratory sonic tests.

samples	mean sonic velocity (m/s)	standard deviation
Istrian limestone	2486	2326
Veronese limestone	1121	1048
Brick and mortar	682	379

the highest values of sonic wave velocity, while, as it could be expected, the values of the masonry are relatively low.

A final comparison was made among the most significant values collected in this non-destructive testing programme is illustrated in Table 3, which collects the highest and lowest values resulting from direct tests on the wall assembly and on samples of the three single materials in laboratory; a direct sonic velocity value for brick and masonry was calculated from the mean indirect wave velocity along the horizontal direction, using the following eqn. (1) (Cianfrone [5]):

$$V_l = 0.58 \cdot V_t \tag{1}$$

where V_l and V_t are respectively the longitudinal and transversal velocity, resulting in a higher value than the one measured in laboratory (last row of Table 3). As it can be seen from the peak values, the range of results of the direct sonic tests on the wall is very wide, since higher values than those of the stones' samples were registered in some cases; this is likely due to the internal stress state of the wall in such cases.

Istrian limestone has a more than two times higher mean value of sonic wave velocity than Veronese limestone, but the ranges of velocity of the whole wall section in the two cases (first two rows of Table 3) are not so different. Thus, a greater influence of the velocity of brick-mortar masonry layer can be inferred in the sonic wave velocity of the whole wall assembly.

The lowest velocity values resulting from direct sonic tests can be associated to the thinnest (7–8 cm, as above said) stone covering; the available information gives no certainty about the greatest thickness of the stone blocks.

Table 3: Comparison of direct sonic velocity values.

material		velocity (m/s)	
tests on site	wall (Istrian limestone at the external side) – external beatings	min 447	max 3203
	wall (Veronese limestone at the external side) – external beatings	min 434	max 3629
	wall (mean value, external beatings)	1772	
	wall (mean value, internal beatings)	2160	
	brick and mortar masonry	1948	
tests in laboratory	Istrian limestone	2486	
	Veronese limestone	1121	
	brick and mortar masonry	682	

4 Conclusions

This paper collects the first results of a non-destructive testing programme involving the external walls of Palazzo Ducale in Venice. The following final remarks can be made about the above presented results:

- The direct tests on the south façade wall have given useful information on the internal structure of the double-layered wall of brick and mortar masonry and covering stones. The wide range of results of direct sonic tests is very probably linked to the different thickness of the stone blocks. Currently, the information raised through this testing campaign allows to assess the distribution of thickness in a qualitative way, and to individuate with likeliness the position of keystones.
- A further aim is to get an esteem of the effective thickness of the stone covering, which is variable and, as it could be inferred from the direct sonic tests here reported, is greater at the outer border of the lozenge modulus. Other kinds of tests – such as endoscopy – will help clarifying and quantifying the thickness of the keystones.
- The zones of highest direct sonic wave velocity (5000–6000 m/s) of the investigated wall panel can also reveal the internal stress state pattern; this interpretation of results may also be supported by comparing these values to those of the stones' samples.
- The direct sonic wave velocity of the brick and mortar masonry layer was assessed in laboratory with tests on brick-mortar samples, and analytically evaluated from the experimental value of indirect sonic wave velocity. The latter value, being significantly higher, is probably due to the compactness and state of compressive stress of the historic structural brickwork.
- The reliability of the test results could be assessed with the graphs of distributions. Generally, it can be said that direct tests have shown a good distribution; indirect tests have flatter distribution curves which become sharp with increasing distance of measurement.

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