Measurement Science and Technology

PAPER

Cosmic ray tracking to monitor the stability of historical buildings: a feasibility study

To cite this article: G Bonomi *et al* 2019 *Meas. Sci. Technol.* **30** 045901

IOP Publishing Measurement Science and Technology

Meas. Sci. Technol. **30** (2019) 045901 (9pp) https://doi.org/10.1088/1361-6501/ab00d7

Cosmic ray tracking to monitor the stability of historical buildings: a feasibility study

G Bonomi[1,2,5], **M Caccia**[3,4], **A Donzella**[1,2], **D Pagano**[1,2], **V Villa**[1] **and A Zenoni**[1,2]

[1] Department of Mechanical and Industrial Engineering, University of Brescia, via Branze 38, 25123 Brescia, Italy
[2] INFN Pavia, via Bassi 6, 27100 Pavia, Italy
[3] Department of Science and High Technology, University of Insubria, Via Valleggio 11, 22100 Como, Italy
[4] INFN Milano, via Celoria 16, 20133 Milano, Italy

E-mail: germano.bonomi@cern.ch

Received 17 July 2018, revised 29 November 2018
Accepted for publication 22 January 2019
Published 1 March 2019

Abstract

A cosmic ray muon detection system is proposed for stability monitoring in the field of civil engineering, in particular for the static monitoring of historical buildings, where conservation constraints are severe and the time evolution of the deformation phenomena under study may be of the order of months or years. The stability monitoring of the wooden vaulted roof of the *Palazzo della Loggia*, located in the town of Brescia, Italy, has been considered as a case study. The feasibility, as well as the performance and limitations of a stability monitoring system based on cosmic ray tracking have been studied by Monte Carlo simulations. A study of possible systematic uncertainties is presented along with a realistic design for the construction of a measurement system prototype.

Keywords: stability monitoring, cosmic ray muons, historical buildings, tracking, alignment, position measurements, Monte Carlo simulation

(Some figures may appear in colour only in the online journal)

1. Introduction

Cosmic ray muons are elementary particles falling steadily on the Earth's surface as a consequence of the interactions of primary cosmic rays, mainly high energy protons coming from the sun and from the outer Galaxy, on atmospheric molecules [1]. The flux reaching the Earth's surface is about 10 000 μ (min m^2)$^{-1}$ and the mean muon energy is 3–4 GeV. Since muons are much heavier than electrons and do not undergo nuclear strong force, they are highly penetrating in matter and their energy may be sufficient to penetrate tens of meters of rock.

The ubiquitous presence at the Earth's surface and the high penetration capability have motivated their use in fields beyond particle physics. Since the mid-twentieth century, attenuation of cosmic ray muons has been used to produce radiographies of large and inaccessible structures in the fields of geology, archeology, speleology [2–11]. In particular, several groups are actively working in the imaging of the inner structure of volcanoes and in the prediction of volcanic eruptions [12–17]. Recently, Morishima and collaborators announced the discovery of a large 'void' in the Cheope pyramid [18].

Proposals have been presented to obtain radiographic images of the interior of large vessels with dimensions over many tens of meters, where storage or long-term structural integrity is an important issue [19]. Potential uses of cosmic ray muon radiography in industrial applications have been explored [20, 21], including the inspection of nuclear waste containers [22] and of the inner structure of a blast furnace [23–25].

In 2003 a new method was proposed [26, 27] in which the angular scattering that every muon undergoes when crossing matter is exploited to inspect unknown objects hidden inside large volumes. This technique, known as muon tomography, needs a more complex apparatus. While the absorption technique requires the measurement of the muon position and

[5] Author to whom any correspondence should be addressed.

direction only downstream of the object to be inspected, the technique based on muon scattering requires the measurement of muon position and direction both upstream and downstream, to measure the angular deviation of every single muon.

Muon tomography has been rapidly adopted for applications in the civil security domain [28–30]. It has also been proposed for the detection of radioactive orphan sources hidden in scrap metal containers [31–33], to inspect the interior of blast furnaces [34] or legacy nuclear waste containers [35]. The method has also been proposed to perform a diagnosis of the damaged cores of the Fukushima reactors [36] and, recently, the fuel melt at Daiichi 1 has been assessed by muon data [37].

A different use of cosmic rays was proposed in 2007 [38], when the feasibility of an alignment system based on muon detection, applied to the monitoring of the structural alignment of a mechanical press, was demonstrated by means of Monte Carlo simulations. In particular, it was shown that the resolution obtainable with this technique were comparable to, if not better than, those of the existing alignment methods. The major limitation of muon detection-based alignment techniques is the fixed arrival rate of muons reaching the Earth's surface, as well as their wide angular distribution around the zenith direction. This implies rather large acquisition times in order to reach the desired precision.

However, a long acquisition time is not a very limiting aspect when alignment measurements have to be applied to the survey of civil structures, such as buildings or ancient palaces for static monitoring. Preliminary studies on a monitoring system for historical buildings have been previously reported with a basic detector configuration and without taking into account systematic uncertainties [39–42].

In the present paper, the concept is further developed and detailed. In sections 2 and 3 the motivations, the general principles and the measurement procedure are presented. A case study and the implemented simulation are described in section 4. Results are presented in section 5 along with a study of the systematic uncertainties. A design for the construction of a possible monitoring system prototype is described in section 6 while the conclusions are drawn in section 7.

2. Motivations

Historical buildings are landmarks of our history and represent an immense heritage for Europe in general and for Italy in particular. Their structural architectural vulnerability is a threat recognised also at regulatory institutional level. A key element of the conservation procedures is the monitoring of the structural stability, an essential entry into a continuously updated technical data sheet, hypothetically attached to each historical building. This assessment necessarily starts by the reconstruction of the static scheme of the building, which determines the path of the loads from the single structural element to the foundations and the level of stress on the various structural elements. Following this, the stability of the structure can be assessed mainly by measuring displacements or deformations, together with secondary quantities (e.g. humidity, temperature, amplitude and frequency of natural vibration modes) and by analysing the state of preservation or degradation of structural components. The deformations can be associated with the measurement of the rotation of vertical elements, the opening of cracks, the deflection of horizontal elements, the depression of the vaults, the failure of vaults or roofs. The quantification of these effects can be obtained locally by using strainmeters or globally by measuring the relative displacement between several points of the structure, one of which is used as a reference. The global survey systems, which provide the most significant information, are currently based on optical measurements, on GPS technology, on vision-based methods and on sensors, such as velocimeters and accelerometers. Details about these techniques can be found in [43–46] and references therein. A comparison with such technologies will be given in the following. The present work presents an original idea of an apparatus for the continuous monitoring of the structural stability of historical buildings, based on the reconstructed trajectories of a sample of cosmic rays. In essence, cosmic muons replace light rays of optical systems, with the primary advantage of being able to cross walls and structures between the elements to be monitored. This is a unique feature with respect to the techniques currently used.

3. The monitoring system

The design of the proposed stability monitoring system based on cosmic ray detection is described in the following. In such system, the muon tracking is provided by a well assessed detection technique in which scintillating fibers are read by silicon photomultipliers SiPM [35, 47–48]. Details about the construction of these detectors are given in section 6.

A set of three square muon detection modules, of about (400×400) mm^2 area and about 6.0 mm thickness, are positioned horizontally on an appropriate mechanical structure at a distance of 500 mm from each other. This set-up corresponds to the 'muon telescope' shown in figure 1. The mechanical structure that connects the detectors will obviously be more robust than that shown in figure 1. In particular the framework will be designed with three aspects in mind: protection against uneven thermal cycles and vibrations, arrangement of metrological verification with a high-performance coordinate measuring machine (CMM) before and after data collection, and capability to control, during data collection, crucial linear dimensions. The number of modules, also called detection planes in the following, has been chosen to allow for a minimal level of redundancy on the tracking information of the crossing muon.

Each detection module is based on two orthogonal layers of about 400 mm wide and 400 mm long, composed of 128 scintillating fibers with a (3.0×3.0) mm^2 cross section. The two layers are arranged along the x and y axes of a Cartesian reference system as shown in figure 1. They provide the measurement of the crossing position of an incident muon in the x and y coordinates with a pitch of 3.0 mm. Since the muons hit uniformly over the full surface of the scintillating fibers, the spatial resolution on the coordinate of the impact is expected to be $\sigma = (3.0\ \text{mm})/\sqrt{12} \simeq 0.9$ mm. With this granularity on the crossing point and the described geometrical dimensions, the angular resolution of the telescopes in measuring the muon direction is expected to be about 3 mrad.

The proposed monitoring system is composed by two identical telescopes, positioned one above the other, at a given distance, inside an historical building. The two telescopes are mechanically anchored to the building structure. We will refer to the two telescopes as 'lower telescope' and 'upper telescope'. Their initial horizontality is measured with standard instrumentation such as mechanical inclinometers. Floors or furniture may be interposed between them. The muon crossing point in x and y coordinates is defined as the position of the axis of the crossed scintillating fiber, on the corresponding layer, in the coordinate system shown in figure 1. For the cosmic ray muons, the three measured points on the three layers, for each coordinate, are fitted with a straight line in both telescopes. Tracks are reconstructed in the $x-z$ and $y-z$ views independently. In the following only the projection of the reconstructed tracks in the $x-z$ plane is considered.

From the reconstruction of a sample of cosmic muons, the relative position x_D and the relative inclination θ_D between the two reference frames integral with the two telescopes are estimated. Having measured (x_D^o, θ_D^o) at a given time, that we can define as 'reference', each successive measurement of the same quantities provides a control of the stability of the relative position/inclination of the two telescopes. Since the detectors are anchored to the building, the detection of a relative movement would imply a deformation of the structure.

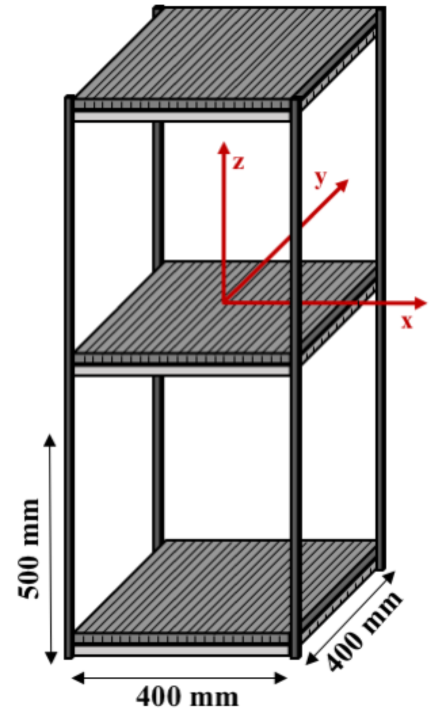

Figure 1. Structure of the muon telescope formed of three muon detection modules axially aligned at a distance of about 500 mm each other. The sensitive volume of the muon detection module is formed of two orthogonal layers of 128 scintillating fibers, (3.0×3.0) mm^2 square cross section, of about 400 mm width and 400 mm length.

3.1. Reconstruction technique

As cited above, the proposed monitoring system allows for the changes in the relative position between two telescopes to be measured, even in presence of interposing materials. The reconstruction procedure needs to take into account the multiple Coulomb scattering of the particle by nuclei [49–51]. The net angular and spatial deflections are Gaussian-distributed random variables, because of the central limit theorem. The expected value for both the angular and spatial deflections is zero while the standard deviation of the angular deflection is a function of the thickness of the material, of its density and of its atomic number. In order to reduce the impact of the multiple Coulomb scattering on the measurement of the relative position and inclination between the telescopes, a robust geometrical approach based on a minimum χ^2 estimation method has been employed. The algorithm is independently applied to both $x-z$ and $y-z$ views and is here presented for the $x-z$ case only.

Let us consider the two reference frames integral to the two telescopes, as described above. Assuming to know the z displacement between them, their relative position, in the $x-z$ view, is fully described by the spatial variable x_D, representing the relative displacement, and the angular variable θ_D, representing the relative inclination. In most of the stability monitoring problems concerning historical buildings, measurable variations of the position between the two telescopes occur over a relatively long period of time, so that x_D and θ_D can be assumed to be constant during a data taking up to few days. When a muon crosses the detection system it is independently reconstructed in the two telescopes and the reconstructed tracks are extrapolated to a common plane. The difference between the x-coordinate of the two extrapolated points $(x'_h - x'_l)$, as well as the angular difference between the track directions $(\theta_h - \theta_l)$ are then computed. In case of perfectly aligned telescopes, these variables are the net spatial and angular deflections due to the multiple Coulomb scattering, whose expected values are zero, as already said.

However, in general, a roto-translation of one telescope with respect to the other determines non-zero expected values for these variables, allowing for the estimation of x_D and θ_D from a minimum χ^2 estimation method, using the following χ^2 definition:

$$\chi^2 = \sum_i \left[\frac{(x'_{u,i} - x'_{l,i})^2}{\sigma^2_{x'_{u,i}} + \sigma^2_{x'_{l,i}}} + \frac{(\theta_{h,i} - \theta_{l,i})^2}{\sigma^2_{\theta_{h,i}} + \sigma^2_{\theta_{l,i}}} \right], \quad (1)$$

where $\sigma_{x'}$ and σ_θ are respectively the errors on the reconstructed x' and θ respectively, the subscripts u and l refer to the higher and lower detectors, and the i index runs over all the reconstructed muons in the data taking. Although more refined strategies are possible, the main advantage of this approach is that it does not require any assumption on the interposing materials.

The expected performance has been studied in the realistic case of an historical building in the City of Brescia, namely the *Palazzo della Loggia*. The stability of the roof of such a palace has been indeed monitored for ten years using a mechanical system. The performance of the proposed stability monitoring system can then be compared with the measurement requirements in this realistic case study and with the performance of the conventional method utilized. In the following section, a description of the case study and of the Monte Carlo simulations are presented.

4. The case study: the *Palazzo della Loggia* in Brescia, Italy

4.1. Overview of the case study

The *Palazzo della Loggia*, in the town of Brescia, Italy, was completed in 1574. Since then, it has cumulated a long sequence of damages, transformations, repairing interventions, some of which have generated considerable problems of structural stability of the building. The wooden vaulted roof, in particular, was completely reconstructed in 1914: its maximum elevation is 16 m, and its shape is that of an upside-down ship, with planar rectangular sides of about 25 m and 50 m respectively. The structural architecture of the vault consists of principal truss wooden arches and simple secondary arches; both are connected at the top by a truss-made wooden beam. Immediately after its reconstruction, the roof structure underwent progressive deformations of the longitudinal top beam and of the key points of the connected arches. In particular, the progressive deflection of the top beam was measured to be 190 mm in 1923, 520 mm in 1945, 800 mm in 1980.

A systematic campaign of investigation using mechanical measurement systems was performed for more than ten years, from 1990 to 2001 [52]. On four, out of the seven principal arches, three couples of wires, 2.0 mm in diameter, one of steel and the other of invar, were stretched between symmetric points at three different levels: A1–B1, at the point of connection of the arches with the building structure; A2—B2 and A3—B3, on the arch reins as schematically presented in figure 2. The wire tension was maintained by means of a system of pulleys and balance weights.

The relative displacements of the pairs of symmetric points were continuously monitored by the differential elongation of the two wires.The elongation of the two wires was measured by a mechanical measurement system based on a vernier, with a sensitivity of 1/10 mm.

Figure 3 shows the mutual displacements of the points A2–B2 of figure 2 as a function of the monitoring time, expressed in years. Cyclic seasonal deformations of the structure of the order of few millimeters are measured. In addition, superimposed to the seasonal cyclic deformations, a clear collapsing of the wooden structure of the arch is seen. The deformation trend amounts to about 1 mm per year.

It is worth remarking that the mechanical method adopted in [52] could only provide the measurement of the horizontal relative displacement of points of the wooden structure in opposite positions and not their absolute displacements with respect to a common reference system linked to the building structure.

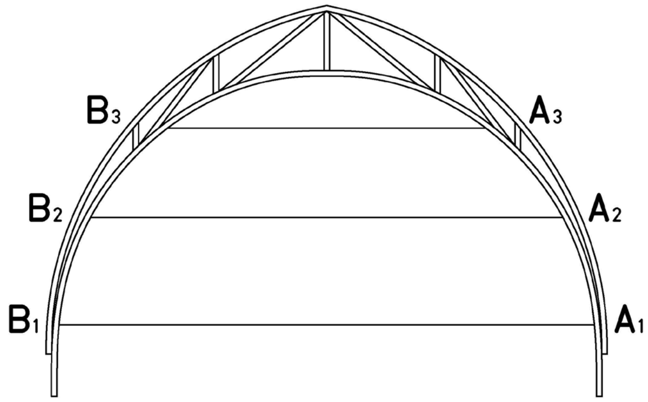

Figure 2. Schematic view of the position of the mechanical measurement systems in the wooden vaulted roof. On four, out of the seven principal arches, three couples of wires, 2.0 mm in diameter, one of steel and the other of invar, were stretched between symmetric points at three different levels, namely A1–B1, A2–B2 and A3–B3.

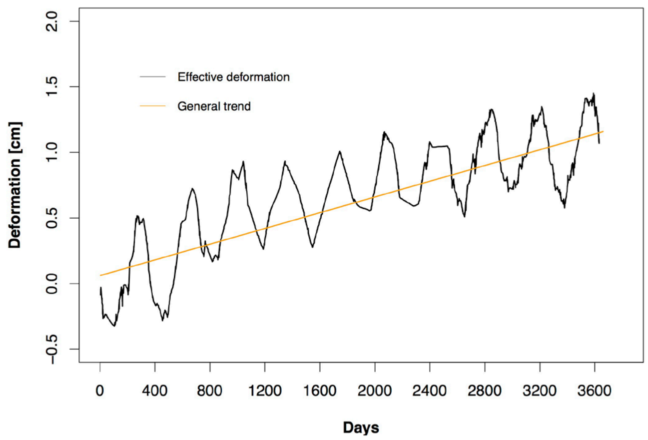

Figure 3. Elongation of the metal wires stretched between the points A2—B2 of figure 2 of the truss wooden arches as a function of time in days, as reported in [52].

4.2. The Monte Carlo simulation

The features and the expected performance of the proposed measurement system, applied to the case study, have been evaluated by means of a Monte Carlo package, based on GEANT4 [53]. The geometry and the relevant structural parts of the *Palazzo della Loggia* building as well as the structure and composing materials of the two telescopes were modeled.

In three specific simulations, the telescopes have been positioned one above the other at a different vertical distance ($\simeq$350 cm, $\simeq$880 cm and $\simeq$1300 cm). The lower telescope was placed 300 cm below a 15 cm thick wooden layer simulating the ceiling of the 'Salone Vanvitelliano' of the *Palazzo della Loggia*. In the following, we will refer to these three different configurations respectively as 'Δz(350 cm)', 'Δz(880 cm)' and 'Δz(1300 cm)'.

Finally, to test the performance of the system in real conditions, an accurate cosmic ray muon generator based on experimental data was implemented in the code to simulate the momentum, the angular distribution and the charge composition of the cosmic ray radiation at the sea level [54].

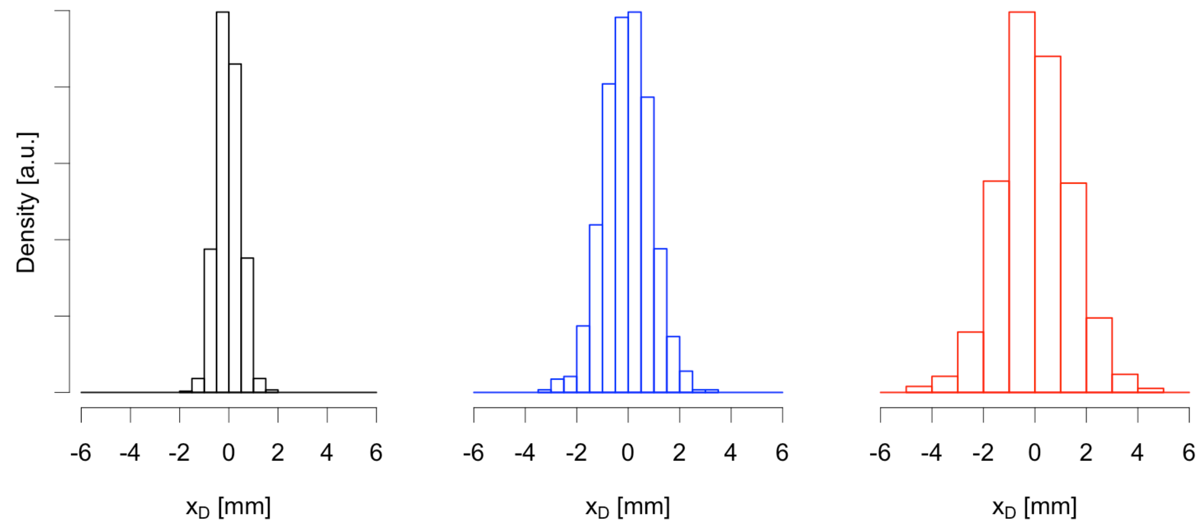

Figure 4. Distributions of the x_D for samples of 500 tracked muons for the three different configurations: Δz(350 cm) left, Δz(880 cm) center, Δz(1300 cm) right.

5. Results

With the setup described above, simulations of the tracking of cosmic ray muons through the measurement system were performed in the three configurations previously defined.

Based on the reconstruction algorithm described above, a sample of cosmic rays can provide the relative position x_D and inclination θ_D of the two telescopes. For a given number of muons, we repeated the estimation many times and calculated the standard deviation of the obtained distribution. Figure 4 shows the distributions of the statistical variable x_D for the three configurations, for a sample of 500 tracked muons. To collect the same statistics, due to geometrical acceptance and to the angular distribution of the cosmic muons, the three configurations need different time intervals: the closer the two telescopes, the shorter the time. For the Δz(350 cm) configuration this number of muons correspond to about 1.5 h of data taking, 7.5 h for the Δz(880 cm) configuration and 16 h for the Δz(1300 cm) configuration, assuming a 100% muon detection efficiency for the scintillating fibers. The standard deviation of the distributions can be considered as the resolution with which the relative position x_D and inclination θ_D can be measured. As it is evident from figure 4, given the same statistics, the standard deviation depends on the distance between the telescopes: the closer the two telescopes, the better the accuracy.

As the lower telescope and the upper telescope are perfectly aligned in the simulation, the x_D and θ_D distributions are symmetric and centered at zero. The width of the distributions is due both to the resolution of the telescopes and to the multiple scattering suffered by the muon trajectories.

5.1. Measurement resolution versus taking time (no systematics)

For a given configuration, the resolution clearly depends on data taking time. Indeed as x_D and θ_D are estimated from a minimum chi-square method, their uncertainties depend on the sample size. In the three geometrical configurations, Δz (350 cm), Δz(880 cm) and Δz(1300 cm), the expected acquisition rates of cosmic ray muons crossing the full system are respectively: 6.0 μ min^{-1}, 1.1 μ min^{-1} and 0.5 μ min^{-1}.

In figure 5 the resolution of the system is shown as a function of the data taking time for the three examined conditions and times up to 20 d.

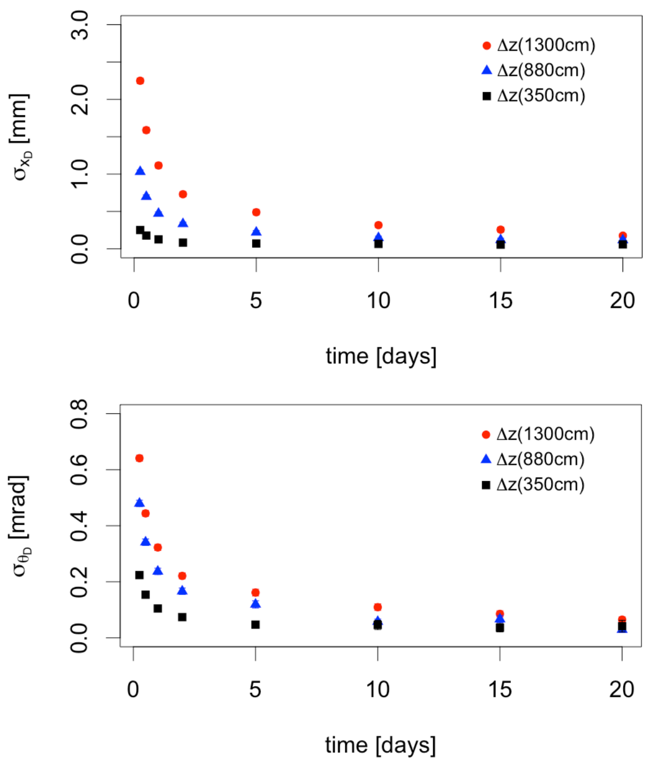

Figure 5. Resolution on the relative position x_D (top) and inclination θ_D (bottom) of the two telescopes versus data taking time, for the three different configurations: ● Δz(1300 cm), ▲ Δz (880 cm) and ■ Δz(350 cm).

5.2. Systematic uncertainties

The results presented above presume an exact knowledge of the geometry of the measurement system. Clearly this is not realistic since any mechanical structure holding the detectors has tolerances and uncertainties. In the following, the effect of the inaccuracies in the positioning of the detector planes and of the two telescopes on the precision of the measurement system itself is studied. As a first step, we investigated which are the possible effects in measuring the position and the orientation of a plane in space. While the position can easily be assessed with a resolution of ~100 µm, the horizontality of a module can be measured, with standard instrumentation such as mechanical inclinometers, with a resolution of 2 min of degree or better. When considering a rotation around the vertical axis, instruments such as magnetometers, coupled to geometrical and optical measurements, can achieve resolutions of 0.10–0.15 degrees or better.

Given such values, in a specific simulation, each of the three detection planes of the two telescopes could be positioned, with respect to the 'nominal' position and orientation, extracting a Gaussian distributed random number having as standard deviation the values reported previously. In other words, for each detection plane, six parameters such as the δx, δy, δz, $\delta\theta_x$, $\delta\theta_y$ and $\delta\theta_z$ were extracted randomly and the module was correspondently positioned inside the telescope. On top of that also the relative position and orientation of the two telescopes, relatively one with respect to the other, was also set in the same way extracting random values from Gaussian distributions with the specified standard deviations. These values have been chosen taking into account the accuracy of commercial instrumentation, but clearly they are, even if reasonable, somehow arbitrary. A different choice can lead to different systematic uncertainties. Nevertheless, when building a real measurement system, the procedure can be reversed: given the displacement measurement resolution to be reached, a limit on the accuracy on the positioning of the system can be calculated. For what concerns possible deformations of the mechanical structure holding the detection modules, that could mimic deformation of the building to be monitored, specific attention in the design and construction should be taken. In principle the effects of such deformations should be negligible compared to the error in assessing the starting geometry. Nevertheless, periodic checks on some critical linear dimensions should be foreseen during data taking.

An unrealistic assumption that was taken when obtaining the results shown in figure 5 is a detection efficiency of 100%. A more realistic assumption is to estimate an efficiency, for a single fiber to detect a crossing muon, around 80%. Since the muons need to cross all the six layers of the two telescopes, this means an overall detection efficiency of about 30%. A reduction of about 1/3 in efficiency would simply imply that to obtain the same measurement resolution, compared to the results reported above, a data taking time of three times larger is needed.

5.3. Measurement resolution versus taking time with systematics

New simulations have been run including all the sources of systematics described above and assuming an overall detection efficiency of 33%. A differential calculation has been performed assuming that any relative movement of the monitoring system, that is of the two telescopes, can be attributed to the building structure they are anchored to. Following the procedure described above, extracting randomly the position and angular parameters of the detectors, 100 different geometries, for each of the Δz(350 cm), Δz(880 cm) and Δz(1300 cm) configurations, have been defined and a specific Monte Carlo production has been run. In the reconstruction, on the other hand, the nominal geometry, where all the components of the monitoring system are perfectly aligned, has been used. The values of x_D and θ_D have been calculated twice, for two different samples containing the same number of muons. One has to be considered as the 'time zero' reference measurement (x^o_D, θ^o_D) while the other the control/monitor measurement (x^t_D, θ^t_D). The standard deviation of the distributions of the difference of such values (x^t_D–x^o_D) and (θ^t_D–θ^o_D), have been used to estimate the resolution of our system. The procedure has been repeated for different data taking times. The results are summarized in figure 6. In a day of data taking the system is capable, in the three configurations respectively, to detect displacements of ~0.3 mm, ~1.3 mm and ~3 mm and misalignments of ~0.3 mrad, ~0.6 mrad and ~0.8 mrad. It is worthwhile noting that this resolution has been calculated assuming the same data taking length both for the reference measurement and for the control measurement.

The monitoring of the displacement of the three inspected points in the wooden vaulted roof of the *Palazzo della Loggia* could provide performances compatible with the requested resolution and with the time scale characteristic of the deformation phenomenon. Typical time scales, in the case of *Palazzo della Loggia* and, in general, for historical buildings, may span over several years. Indeed, from figure 6, it is possible to conclude that the proposed stability monitoring system based on cosmic ray tracking can detect a displacement of 1 mm after an elapsed time of less than 10 d. Therefore, the proposed measurement device could be an adequate stability monitoring system in the case study considered. Moreover this system, if compared with the one used to collect the measurements shown in figure 3, has clear advantages, such as that it is not intrusive, it does not require bulky permanent installations and the presence of technical personnel for control and maintenance.

The resolution shown in figure 6 is clearly specific to the case study of *Palazzo della Loggia*. To estimate the error when measuring displacements and misalignments in different conditions, a dedicated Monte Carlo simulation would be needed, profiting of the available information on the building structure. The results of the simulation could be validated with real data in a calibration campaign to be performed after the installation of the measuring system in the operating conditions.

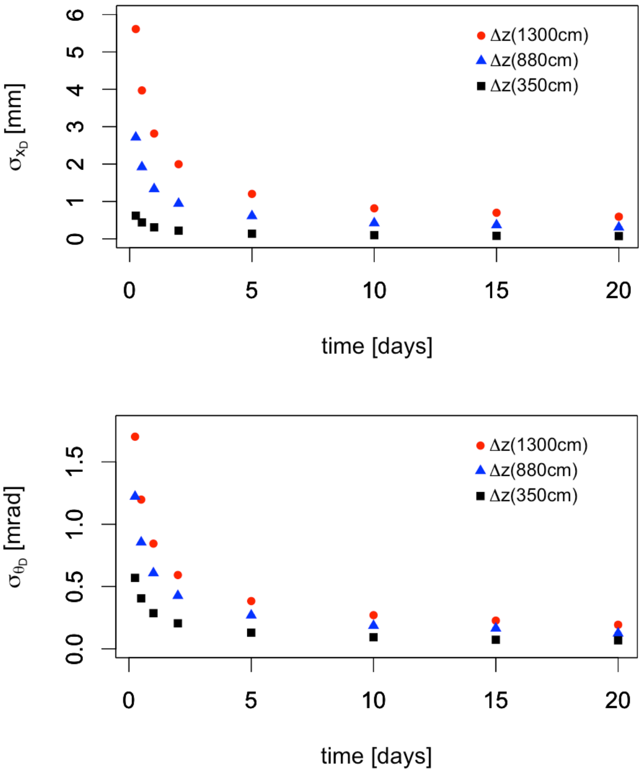

Figure 6. Same as in figure 5, but taking into account the geometrical sources of systematics and an overall detection efficiency of 30%.

In this calibration phase, the experimental data could be compared with the expected one by the simulation and a tuning of the Monte Carlo parameters be performed.

6. Design of a real monitoring system

As outlined above, the measurement system configuration is based on six detector planes, arranged in two telescopes. Each plane is made of two layers of scintillating fibers orthogonally arranged. The light generated by a crossing particle in each fiber will be detected by silicon photomultipliers (SiPM—[55] and references therein). SiPM have also been used in the development of 'cosmic ray telescopes' for Volcano tomography [15] and cargo scanning [56]. However, these applications had less stringent requests on the particle impact point resolution and used fibers of triangular shape with a pitch of 3 cm and light collection by a wavelength shifting fibre connected to the sensor. The required sensitivity for the application targeted here requires a higher granularity by one order of magnitude, shifting the main challenge to system aspects in view of a cost-effective implementation. The direct coupling of the fiber to the sensor is a key point: simulation results provide a mean value of the deposited energy equal to 500 keV. Assuming a typical light yield of 10 000 photons MeV^{-1}, an attenuation length of the order of 1 m and a SiPM photon detection efficiency exceeding 30%, a very high signal can be expected, allowing for the suppression of events due to spurious avalanches in the SiPM preserving a high detection efficiency. A preliminary test on a Teflon coated fiber with 3×3 mm^2 cross section and 200 mm length confirmed the expectations. Provided the amplitude of the signal, for the sake of system simplification the baseline design of the front-end will be based on a binary output, identifying the fiber hit by the cosmic muon in every layer. Because of the number of sensors and their density, the front-end will be based on Application Specific Integrated Circuits. Once more, because of the signal intensity, the requests on the fine adjustment of the sensor bias at individual detector level and the gain stabilization by a temperature feedback are not expected to play a significant role but the robustness will obviously be experimentally assessed. Advantages related to the read-out by sensors at both ends of the fiber will be carefully evaluated with reference to the enhancement of the noise rejection and efficiency increase versus the scaled-up cost of the system. Event triggering is also considered a minor issue since the data rate is not expected to exceed 6 events min^{-1} when the two arms are 3.5 m apart, dropping to 0.5 events min^{-1} at 13 m distance. Therefore, the baseline assumption is to run the system trigger-less, with a software event building based on time stamped pushed data. A significant advantage of the system would possibly result by a wireless data transmission to a receiving station, with processed data made available for a remote real-time event reconstruction and the relevant deformation analysis. The amount of data is not expected to be overwhelming. However, a key issue will be the choice of the transmission protocol, in view of the walls and floors interspaced between the transmitter and the receiver. The goal is to construct a prototype of the proposed monitoring system in the near future.

7. Conclusions

Cosmic ray muon detection techniques are assessed for measurement applications in the field of civil engineering and may be particularly suitable for static monitoring of historical buildings, where the evolution of the deformation phenomena under study is of the order of months or years.

For particular applications, the performances of this system may be competitive in respect to the ones of monitoring systems today widely employed and generally referred to as structural health monitoring (SHM) methods. Some examples are given in [43–46] and references therein. Conventional monitoring methods have been used with accelerometers and surveying equipment, such as the theodolite, both utilizing cabled sensors or more recently also wireless sensors and sensor networks. In recent years also vision-based systems are being studied for remote estimation of structure vibrations, greatly simplifying the measuring system installations. Optical systems based on coherent Lidars are also widely used to precisely measure the vibration velocity of remote targets. As an example they allow the monitoring of potentially damaged buildings, for their diagnosis at a safe distance after a seismic event. All these techniques are mostly devoted to measuring the dynamic response of structures and their measuring coverage are broad, that is, they are applicable for identifying high frequency ranges. However, they can hardly assess static and quasi-static displacement. For these measurements GPS-based systems are surely more indicated. They are capable of providing fast and accurate measurements of static position, and they have been used in the survey of big structures such as long span bridges.

The method proposed in this work is clearly indicated for static monitoring and in this sense it is complementary to most of the SHM techinques. With respect to the GPS-based systems on the other hand it would be interesting to compare the relative performances on a test-field campaign on the same structure. The main advantage of using cosmic rays is clearly that this technique allow to monitor internal parts of buildings with high resolution even if such parts are not visible one to another.

Other appealing features of the proposed monitoring system are: (i) the use of a natural and ubiquitous source of radiation; (ii) the applicability also in presence of horizontal and/or vertical building structures interposed between the reference system and the parts to be monitored; (iii) the limited invasiveness, and the flexibility and easiness of installation of the monitoring system devices; (iv) the use of established technologies in the field of nuclear and particle physics.

Limiting features are the cosmic ray multiple scattering and the fixed rate of cosmic ray radiation, which makes this technique generally unfit for applications where promptness of response is requested. The performance of such measurement system strongly depends on the particular application under study, in particular on the building structure geometry and composition. However, the system performance in any specific situation may be easily evaluated by Monte Carlo calculations and the system can be designed accordingly.

As an example, in the case study presented in this work, as summarized in figure 6, the system is capable to detect a displacement of about 1 mm at at distance of 13 m in just few days.

The availability of muon detector modules featuring characteristics suitable to satisfy the specific application requirements is essential for the described technique to be realistically proposed. Scintillating fibers of square cross section few millimeter side read by silicon photomultipliers appear as very promising candidates, coping well the requirements of robustness, efficiency, stability and reliability, absence of any hazard, low cost that such a system should necessarily perform to be proposed for possible applications.

Acknowledgment

The authors gratefully acknowledge Prof Ezio Giuriani and Prof Alessandra Marini of the Dipartimento di Ingegneria Civile, Architettura, Territorio, Ambiente e Matematica of the Università degli Studi di Brescia for the information provided on the long-lasting study performed of the *Palazzo della Loggia* and for the invaluable advice concerning the problem of historical building monitoring.

ORCID iDs

G Bonomi https://orcid.org/0000-0003-1618-9648
M Caccia https://orcid.org/0000-0002-9499-678X
A Donzella https://orcid.org/0000-0001-7463-3431
D Pagano https://orcid.org/0000-0003-0333-448X
V Villa https://orcid.org/0000-0001-7737-499X
A Zenoni https://orcid.org/0000-0001-8649-511X

References

[1] Tanabashi M *et al* 2018 (Particle data group) review of particle physics *Phys. Rev.* D **98** 030001
[2] George E P 1955 Cosmic rays measure overburden of tunnel *Commonwealth Eng.* **43** 455
[3] Alvarez L W *et al* 1970 Search for hidden chambers in the pyramids *Science* **167** 832
[4] Caffau E *et al* 1997 Underground cosmic-ray measurement for morphological reconstruction of the "Grotta Gigante" natural cave *Nucl. Instrum. Methods* A **385** 480
[5] Menichelli M *et al* 2007 A scintillating fibres tracker detector for archaeological applications *Nucl. Instrum. Methods* A **572** 262
[6] Grabski V *et al* 2008 The use of cosmic muons in detecting heterogeneities in large volumes *Nucl. Instrum. Methods* A **585** 128
[7] Oláh L *et al* 2013 Cosmic muon detection for geophysical applications *Adv. High Energy Phys.* **2013** 560192
[8] Gómez H *et al* 2016 Studies on muon tomography for archaeological internal structures scanning *J. Phys.: Conf. Ser.* **718** 052016
[9] Marteau J *et al* 2017 DIAPHANE: muon tomography applied to volcanoes, civil engineering, archaelogy *J. Instrum.* **12** C02008
[10] Lesparre N *et al* 2017 3-D density imaging with muon flux measurements from underground galleries *Geophys. J. Int.* **208** 1579
[11] Saracino G *et al* 2017 Imaging of underground cavities with cosmic-ray muons from observations at Mt. Echia (Naples) *Nat. Sci. Rep.* **7** 1181
[12] Nagamine K *et al* 1995 Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction *Nucl. Instrum. Methods* A **356** 585
[13] Tanaka H K M *et al* 2014 Radiographic visualization of magma dynamics in an erupting volcano *Nat. Commun.* **5** 3381
[14] Ambrosi G *et al* 2011 The MU-RAY project: Volcano radiography with cosmic-ray muons *Nucl. Instrum. Methods* A **628** 120
[15] Ambrosino F *et al* 2014 The MU-RAY project: detector technology and first data from Mt. Vesuvius *J. Instrum.* **9** 02029
[16] Marteau J *et al* 2012 Muons tomography applied to geosciences and volcanology *Nucl. Instrum. Methods* A **695** 23
[17] Cârloganu C *et al* 2013 Towards a muon radiography of the Puy de Dˆome *Geosci. Instrum. Method. Data Syst.* **2** 55
[18] Morishima K *et al* 2017 Discovery of a big void in Khufu´s Pyramid by observation of cosmic-ray muons *Nature* **552** 383–90
[19] Jenneson P M *et al* 2007 Imaging large vessels using cosmic-ray muon energy-loss techniques *Chem. Eng. J.* **130** 75
[20] Gilboy W B *et al* 2007 Industrial radiography with cosmic-ray muons: A progress report *Nucl. Instrum. Methods* A **580** 785
[21] Tanaka H K M 2008 Monte Carlo modeling of a cosmic ray imaging system for non-destructive evaluation of a reinforced concrete column *NDT&E Int.* **41** 190

[22] Stanley S J *et al* 2008 See inside: The development of a cosmic ray muon imaging system to aid the clean up of the UK´s nuclear waste legacy *Ann. Nucl. Energy* **35** 507
[23] Nagamine K *et al* 2005 Probing the inner structure of blast furnaces by cosmic-ray muon radiography *Proc. Japan Acad.* B **81** 257
[24] Gilboy W B *et al* 2005 Industrial thickness gauging with cosmic-ray muons *Radiat. Phys. Chem.* **74** 454
[25] Sauerwald J *et al* 2012 Investigation of the coke network and cohesive zone by muon tomography *Proc. 6th Int. Congress on the Science and Technology of Ironmaking (Rio de Janeiro, Brasil)* p. 1371
[26] Borozdin K N *et al* 2003 Radiographic imaging with cosmic-ray muons *Nature* **422** 277
[27] Schultz L J *et al* 2007 Statistical reconstruction for cosmic ray muon tomography *IEEE Trans. Image Process.* **16** 1985
[28] Morris C L *et al* 2008 Tomographic imaging with cosmic ray muons *Sci. Glob. Secur.* **16** 37
[29] La Rocca P *et al* 2014 Search for hidden high-Z materials inside containers with the Muon Portal Project *J. Instrum.* **9** 01056
[30] Armitage J *et al* 2014 First images from the cript muon tomography system *Int. J. Mod. Phys. Conf. Ser.* 27 1460129
[31] Pesente S *et al* 2009 First results on material identification and imaging with a large-volume muon tomography prototype *Nucl. Instrum. Methods* A **604** 738
[32] Bonomi G *et al* 2014 Muon tomography as a tool to detect radioactive source shielding in scrap metal containers *Int. J. Mod. Phys. Conf. Ser.* 27 1460157
[33] Marton E *et al* 2014 Muons scanner to detect radioactive sources hidden in scrap metal containers (MU-STEEL) *Final Report* European Commission RFCS (https://doi.org/10.2777/75975)
[34] Calliari I et al 2018 Study of the capability of muon tomography to map the material composition inside a blast furnace (Mu-Blast) Final report, Eur. Commission RFCS https://doi.org/10.2777/24858
[35] Clarkson A *et al* 2014 GEANT4 simulation of a scintillating-fibre tracker for the cosmic-ray muon tomography of legacy nuclear waste containers *Nucl. Instrum. Methods* A **746** 64
[36] Borozdin K *et al* 2012 Cosmic ray radiography of the damaged cores of the Fukushima reactors *Phys. Rev. Lett.* **109** 152501
[37] http://world-nuclear-news.org/RS-Detectors-confirm-most-fuel-remains-in-unit-2-vessel-2907164.html
[38] Bodini I *et al* 2007 Cosmic ray detection based measurement systems: a preliminary study *Meas. Sci. Technol.* **18** 3537
[39] Zenoni A *et al* 2014 Historical building stability monitoring by means of a cosmic ray tracking system (arXiv:1403.1709v1)
[40] Donzella A 2014 Stability monitoring of a historical building by means of cosmic ray tracking *Il Nuovo Cimento* C **37** 223
[41] Bodini I *et al* 2014 Monte Carlo simulations of a stability monitoring system based on tracking cosmic rays *Proc. IX Congress of National Group of Mechanical and Thermal Measurements (Ancona, Italy, 11–13 September) p* 33
[42] Bonomi G *et al* 2014 Simulation of a muon based monitoring system *Proc.—28th European Conf. on Modelling and Simulation* pp 41–6
[43] Lynch J P and Loh K J 2006 A summary review of wireless sensors and sensor networks for structural health monitoring *Shock Vib. Dig.* **38** 91
[44] Lee J J *et al* 2007 Development and application of a vision-based displacement measurement system for structural health monitoring of civil structures *Smart Struct. Syst.* **3** 373
[45] Im S B *et al* 2011 Summary review of GPS technology for structural health monitoring *J. Struct. Eng.* **139** 1653
[46] Valla J M *et al* 2014 Remote modal study of reinforced concrete buildings using a multipath lidar vibrometer *J. Struct. Eng.* **141** D4014005
[47] Greim R *et al* 2009 A high-resolution scintillating fiber tracker with SiPM array readout for cosmic-ray research *Proc. of the 31st (ICRC Lódź)* p. 1569
[48] Stanca D *et al* 2012 Preliminary results of plastic scintillators detector readout with silicon photomultipliers for cosmic rays studies *Rom. Rep. Phys.* **64** 831
[49] Moliere G Z 1947 Theorie der Streeung schneller geladener Teilchen I. Einzelstreeung am abgesschirmten Coulomb-Feld *Z. Naturforsch.* **2a** 133
[50] Moliere G Z 1948 Theorie der Streeung schneller geladener Teilchen II. Mehrfach und Vielfachstreuung *Z. Naturforsch.* **3a** 78
[51] Bethe H A 1953 Moliere's theory of multiple scattering *Phys. Rev.* **89** 1256
[52] Bellini A *et al* 2007 *Il Palazzo Della Loggia di Brescia—Indagini e Progetti per la Conservazione—Convegno Storia e Problemi Statici del Palazzo della Loggia di Brescia, ottobre 2000* (Brescia: Starrylink editrice)
[53] Agostinelli S *et al* 2003 GEANT4: A Simulation toolkit *Nucl. Instrum. Methods* A **506** 250
[54] Bonechi L *et al* 2005 Development of the ADAMO detector: test with cosmic rays at di↵erent zenith angles *Proc. 29th Int. Cosmic Ray Conf. (Pune) vol* 9 p 283
[55] Renker D and Lorenz E 2009 Advances in solid state photon detectors *J. Instrum.* **4** P04004
[56] Riggi S *et al* 2013 Muon tomography imaging algorithms for nuclear threat detection inside large volume containers with the Muon Portal detector *Nucl. Instrum. Methods* A **728** 59