Simulation of a muon based monitoring system

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ABSTRACT

In recent years cosmic rays have been suggested for civil applications. In this work a specific simulation to asses the feasibility of a muon based monitoring system for historical buildings static stability is presented. In particular the monitoring of the wooden vaulted roof of the "Palazzo della Loggia" of the City of Brescia will be described and the corresponding results will be presented.

INTRODUCTION

Cosmic rays are particles that hit the Earth surface with a rate of about 10000 per minute and per squared meter. Most of them are "muons" and are generated in reactions between the primary rays (coming from the sun and from other extrasolar sources) and the Earth atmosphere. They have a mean energy of about 3-4 GeV and they are able to penetrate even several meters of rock [1]. They have been used to investigate the intimate structure of matter and are often used in particle and nuclear physics to test and calibrate detectors. Recently various research groups have suggested to exploit them for civil and security applications [2]-[11]. Simulation of the interaction of muons with matter are clearly essential to project and design instruments and systems for such civil and security applications. In the present work a stability monitoring system for historical buildings based on the detection of cosmic ray muons will be presented. In particular the results of the simulation of a specific case, namely the study of static anomalies of the wooden vaulted roof of the "Palazzo della Loggia" of the City of Brescia will be described.

INTERACTION OF MUONS WITH MATTER

When a muon travels through a given material it is slowed down and it is deviated from its original trajectory. The mean stopping power for high-energy muons in matter can be described by $<-\mathrm{d}E/\mathrm{d}x> = a(E) + b(E)E$, where a(E) is the electronic stopping power and b(E) is the energy-scaled contribution from radiative processes (bremsstrahlung, pair production, and photonuclear interactions). a(E) and b(E) are both slowly-varying functions of the muon energy E where radiative effects are important. High energy muons can easily cross tens of cm of iron and tens of meters of rock. More information and tables can be find elsewhere [12]. For what concerns the deviation from the incoming path of the muons when crossing a given material, the underlying physics is the Multiple Coulomb Scattering (MCS) [13] [14]. The deviation angle, projected on a plane, has approximately a Gaussian distribution with zero mean value and root mean square σ that depends on radiation length X_0 and thickness x of the material and on the inverse of the muon momentum p according to the well-known formulae:

$$\sigma = \frac{13.6\ \mathrm{MeV}}{\beta pc}\sqrt{\frac{x}{X_0}}[1{+}0.038\ \log(\mathrm{x}/\mathrm{X_0})] \approx \frac{13.6\ \mathrm{MeV/c}}{\mathrm{p}} \tag{1}$$

$$X_0 = \frac{716.5\ (\mathrm{g/cm^2})}{\rho}\frac{A}{Z(Z+1)\ \log(287/\sqrt{\mathrm{Z}})} \tag{2}$$

where ρ, Z and A are the density, atomic number and mass number of the material, respectively. As an example, for muons of 1 GeV/c momentum traversing a 10 cm thickness, σ is 14 mrad for aluminum, 35 mrad for iron, 64 mrad for lead and 86 mrad for uranium.

THE SIMULATION TOOL

All the physics about the interaction of muons with matter is included in a simulation package developed at CERN and called GEANT4 [15]. Indeed GEANT4 is a toolkit for simulating the passage of particles through matter. It includes a complete range of functionality including tracking, geometry, physics models and hits. It has been designed and constructed to expose the physics models utilised, to handle complex geometries, and to enable its easy adaptation for optimal use in different sets of applications. The toolkit is the result of a worldwide collaboration of physicists and software engineers. It has been created exploiting software engineering and object-oriented technology and implemented in the C++ programming language. It is being used in applications in particle physics, nuclear physics, accelerator design, space engineering and medical physics [15]. It is the most complete, reliable and basically the *de facto* statutory software toolkit

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for this kind of simulations. Recently a new interface has been implemented that allows users to record the simulation output and to define and handle the geometry via the ROOT package [16], this new system being called GEANT4 VMC [17]. ROOT is a CERN software package specifically developed for particle physics, even though it is now used in many other fields. It has been written in C++ and it now contains all the tools required for data analysis.

THE IDEA

In particle and nuclear physics, muons are often used to “calibrate” the experimental apparatuses, that is to measure the relative position of different detectors with respect one to each other. Recently our research group proposed to use a similar technique for civil applications such as the mechanical monitoring of an industrial press [7]. Since muons are like (almost) straight lines and they can easily cross floors and walls of buildings, a new application for the stability monitoring of historical buildings it is now proposed and studied [18] [19]. The main component of the suggested monitoring system is the “muon telescope”, shown schematically in fig. 1(a). It is composed by a set of three muon detector modules supported by an appropriate mechanical structure and axially aligned at distance of 50 cm one from the other. Each module is composed by two orthogonal layers of 120 scintillating optical fibers with 3 mm × 3 mm cross section and 400 mm length, as shown in fig. 1(b).

The two planes of orthogonal scintillating fibers provide the measurement of the crossing position of an incident muon in the x and y coordinates, with a pitch of 3 mm. Considering a flat detection efficiency over the entire surface of the scintillating fiber, the expected spatial resolution on the hit coordinate is about 0.9 mm.

The “muon telescope” is mechanically fixed to a structural element of the building, that constitutes the reference system, with its axis aligned in the direction corresponding to the part of the structure whose displacements should be monitored. A fourth muon detector module, with the same geometry and structure of the previous ones, is positioned as “muon target” on the point to be monitored.

Thanks to their high penetrability, cosmic ray muons are able to cross the system of four detectors as well as the interposed building structures. In this way it is possible to continuously monitor the horizontal displacements of the “muon target” relative to the “muon telescope” fixed on the masonry structure of the building.

Indeed, the trajectory of a cosmic ray muon crossing the system of four detectors can be extrapolated from the “muon telescope” to the plane of the “muon target” detector, in the hypothesis that it is a perfect straight line. The difference between the muon crossing point on the ”muon target” and the extrapolated one from the ”muon telescope” allows the position of the ”muon target” relative to the ”muon telescope” to be measured. Possible displacements of the position of the ”muon target” relative to a reference position previously determined can be inferred.

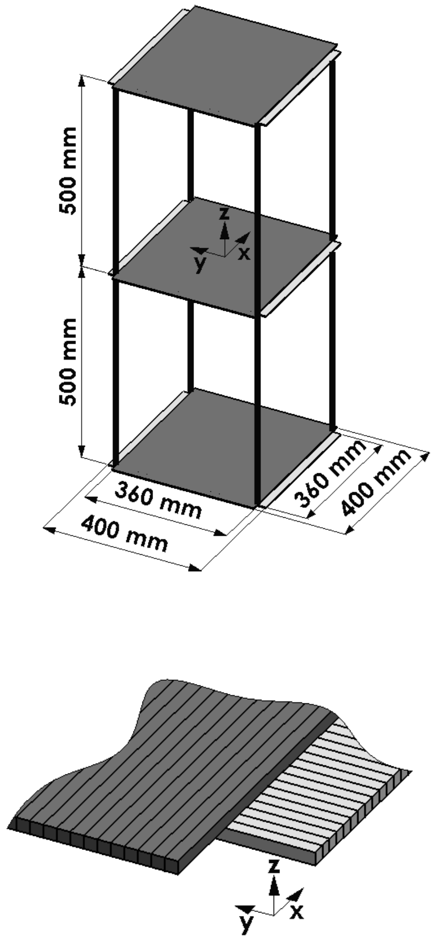

Fig. 1. (a) Structure of the “muon telescope” formed by three muon detector modules axially aligned at a distance of 50 cm each other. (b) Sensitive volume of the muon detector module formed by two orthogonal layers of 120 scintillating fibers 3 mm × 3 mm cross section and 400 mm length.

In crossing the interposed materials, the trajectories of cosmic ray muons suffer multiple scattering angular deviations. At fixed momentum and at low deviation angles, these deviations follow a Gaussian law with variance depending on the inverse square of the muon momentum [13] [14]. Being these stochastic effects largely dominant over intrinsic detector resolution and geometrical conditions, statistical distributions of the difference between measured crossing coordinates in the “muon target” and the predicted crossing coordinates determined by extrapolation from the “muon telescope” are therefore necessary, in order to reduce the stochastic effects by statistical inference methods. As shown in [7], efficient unbiased estimators of the systematic displacement can be extracted from these distributions. To test the validity of the proposed method a Monte Carlo simulation based on GEANT4 has been

Fig. 2. The “Palazzo della Loggia” of the town of Brescia (1574).

performed for a specific case, that is the static anomalies of the wooden vaulted roof of the “Palazzo della Loggia” of the City of Brescia.

APPLICATION TO A SPECIFIC CASE: “PALAZZO DELLA LOGGIA”

Since its completion in 1574, the “Palazzo della Loggia” (see fig. 2, seat of the municipal hall in the town of Brescia, has cumulated a long sequence of injuries, transformations, repairing interventions, some of which have generated considerable problems of structural stability of the building. The grandiose wooden vaulted roof was completely reconstructed in 1914, with the same architectural shape and construction techniques of the original one, destroyed by a fire one year after the completion of the building. The shape of the dome is like an upside down ship which reaches in elevation a maximum of 16 m, having the planar rectangular sides of about 25 and 50 m respectively. The structural architecture of the vault consists of principal truss wooden arches and simple secondary arches, both connected at the top by a truss made wooden beam.

Immediately after its construction, the present wooden vaulted roof structure exhibited a progressive deformation of the longitudinal top beam and of the key points of the connected arches. The progressive deflection of the top beam was measured to be 190 mm in 1923, 520 mm in 1945, 800 mm in 1980 and it is visible on the top of the roof in fig. 2. Starting from 1990, a systematic campaign of investigation and monitoring of the different stability problems of the Palace (in the following “*the measurement campaign*”) has been committed by the Brescia municipality to the *“Centro di studio e ricerca per la conservazione e il recupero dei beni architettonici e ambientali dell’Università di Brescia”* [20], [21]. In particular, the progressive deformations of the principal arches of the wooden vault have been studied with a specifically designed mechanical measurement system. A progressive collapse of the wooden structure of the arch of about 1 mm per year has been measured.

SIMULATIONS AND RESULTS

The features and expected performances of the proposed measurement system were studied by Monte Carlo simulations using the GEANT4 package [15] above described. A cosmic ray muon generator based on experimental data was implemented in the code in order to simulate as realistically as possible the momentum, the angular distribution and the charge composition of the cosmic ray radiation at the sea level [22].

In order to study the performances of the proposed monitoring system, the structure and composing materials of the “muon telescope” and “muon target” were modeled as well as the relevant structures of the “Palazzo della Loggia” building.

Three configurations were considered: the first with the “muon target” located 0.50 m above the wooden ceiling of the “Salone Vanvitelliano” (this position will be pointed as “P1” in the following), at the first floor of the Palace; the second with the “muon target” located 5.8 m above the wooden ceiling (“P2”); the third with the “muon target” located 10.0 m above the wooden ceiling (“P3”). In the three different conditions the “muon telescope” was located on the vertical of the corresponding “muon target”, 3.0 m below the wooden ceiling. The ceiling of the large “Salone Vanvitelliano” was modeled as a bulky 15.0 cm thick wooden layer.

A. Position measurement uncertainty of the stability monitoring system versus data taking time

Simulation campaigns of populations of cosmic ray muons crossing the measurement system were performed for the three configurations described above. The distributions of the differences Δx and Δy between the crossing point coordinates measured by the “muon target” and the crossing point coordinates extrapolated from the “muon telescope” were calculated.

In figs. 3, sample distributions Δx for the three configurations are shown, for an elapsed data taking time of 15 days, corresponding to about 31.7 $\times 10^6$ cosmic ray muons crossing the “muon target” surface at the rate of 170 muons/(s m^2) [1]. The number of events in each distribution is coherent with the number of cosmic ray muons entering the geometrical acceptance of the measurement system, which depends on the surfaces of the “muon target” and of the lowest “muon telescope” modules and on their distance. The Δy distributions are not shown, since they are statistically identical to the Δx distributions.

As the “muon target” and the “muon telescope” are exactly coaxial in the simulation, the Δx distributions are symmetric and centered at zero. The shape of the distributions exhibits a central narrow peak with very long tails on both sides. This shape is due both to the intrinsic uncertainty of the “muon telescope” in measuring the direction of the cosmic ray muon and to multiple scattering angular deviations of the muon trajectories traversing the interposed materials. The latter effect dominates for large distances of the “muon target” from the “muon telescope”.

The long tails of the distributions are due in part to

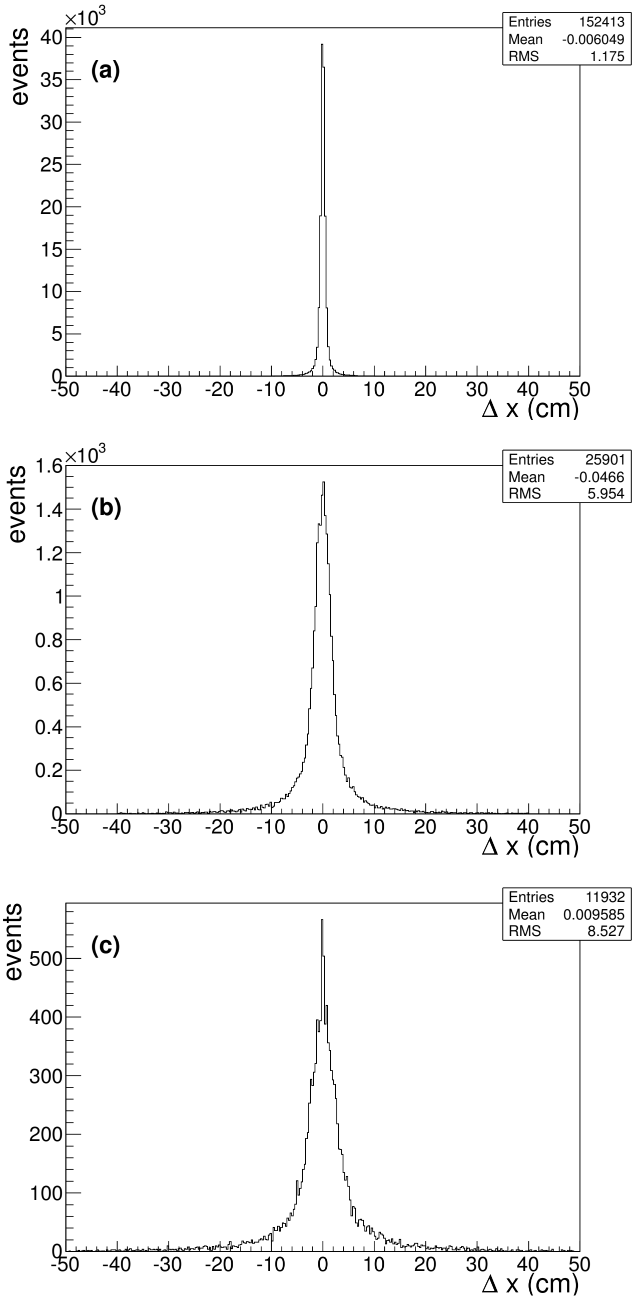

Fig. 3. Distributions of the differences Δx between the crossing point coordinates measured on the "muon target" in position P1 (a), P2 (b) and P3 (c), and the crossing point coordinates of the extrapolated muon trajectory measured by the "muon telescope", in 15 days data taking time.

low momentum muons, suffering larger deviations, and, in part, to spurious events corresponding to emission of delta rays, most of which can be discarded with a more refined data analysis. At present, the only selection applied to these bad quality events is an arbitrary cut of both tails in the three distributions, discarding about 1 % of the total events.

The mean value of the sample distributions represents an unbiased estimator of the position of the "muon target" relative to the "muon telescope" axis. The root mean square of the sample distribution represents the uncertainty in the measurement of the position of the "muon target" relative to the "muon telescope".

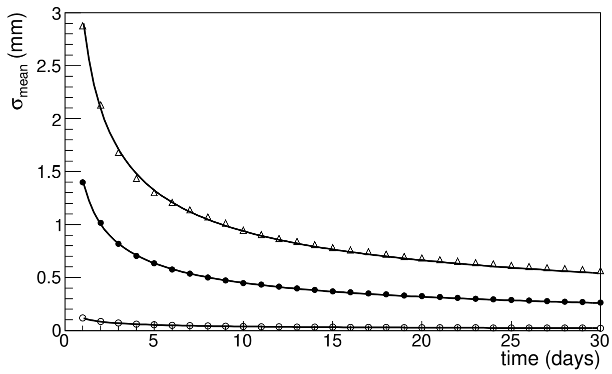

Fig. 4. Relation between the standard uncertainty on the mean value of the sample distribution and the data taking time, for the "muon target" in position P1 (○), P2 (●) and P3 (△). Each plot is fitted with the function (4).

The uncertainty on the mean value is given by the well known relation:

$$\sigma_{mean} = \sigma_{distr}/\sqrt{N_{ev}} \tag{3}$$

where N_{ev} is the number of events in the distribution. Since in the same geometrical conditions the number of events in the sample distribution is proportional to the data taking time, the measurement standard uncertainty depends only on the inverse of the square root of the data taking time. In fig. 4 the relation of the position measurement standard uncertainty and the data taking time for the three examined conditions is plotted up to a data taking time of one month.

As time increases, the measurement standard uncertainty decreases. By fitting the plots with the general relation:

$$\sigma_{mean} = C/\sqrt{t} \tag{4}$$

where C is a constant depending on the geometry and materials interposed and t is the data taking time expressed in days, the following values for the constant C are obtained in the three conditions considered: 0.12 mm day$^{1/2}$, 1.42 mm day$^{1/2}$, 2.96 mm day$^{1/2}$; the errors from the fit procedure are below 1%.

For example, in one month of data taking in position P3, where "muon target" and "muon telescope" are positioned 13.0 m far apart, a measurement standard uncertainty of the order of 0.5 mm may be achieved. The same standard uncertainty may be achieved in a week of data taking in position P2, whereas a 0.1 mm may be measured in just one day in the position P1.

As expected, the standard uncertainty of the measurement system depends on the geometrical configuration considered, since both the root mean square of the distributions and the rate of useful events collected are strongly dependent on the geometry of the system and on the amount of materials interposed. Nevertheless, although requesting different data taking times, the position monitoring of all the three inspected points by a cosmic ray tracking system could provide performances compatible with the requested precisions and with the time scale characteristic of the inspected deformation phenomenon. Typical time scales, in the case of "Palazzo della Loggia" and, in general, for historical buildings, may span over several years. Furthermore, as demonstrated in this case and unlike other monitoring systems, a stability monitoring system based on tracking of cosmic ray muons can efficiently operate also when the building points to be monitored are not reciprocally visible and are separated by solid masonry structures.

B. Measurement of seasonal deformations of the wooden vaulted roof of the "Palazzo della Loggia"

Due to the low cosmic ray rate, a monitoring system based on cosmic ray muon tracking can't provide high precision results in short time. Therefore, it can be competitive with other monitoring techniques only when the deformation under study develops over periods of months or years and the requirements for the monitoring system is to track the slow deformation with time.

This is the case of the cyclic seasonal deformations of the wooden vaulted roof of the "Palazzo della Loggia", which have been simulated with the Monte Carlo program for points P1, P2 and P3 of the roof structure. As a realistic model of the seasonal deformation, the measured displacement in point P2 on the arch reins, reported by the measurement campaign [20], [21], was adopted.

In fig. 5 the curve corresponding to the assumed seasonal deformation (the same for the three points) is shown as a continuous line. The results of the simulated measurements of the position of the "muon target", displaced following the assumed structure deformation, are shown; sampling rates of one week, two weeks and one month respectively for points P1, P2 and P3 have been used. It is evident the ability of the proposed measurement system to follow seasonal structural displacements of few millimeters and, consequently, also systematic ones.

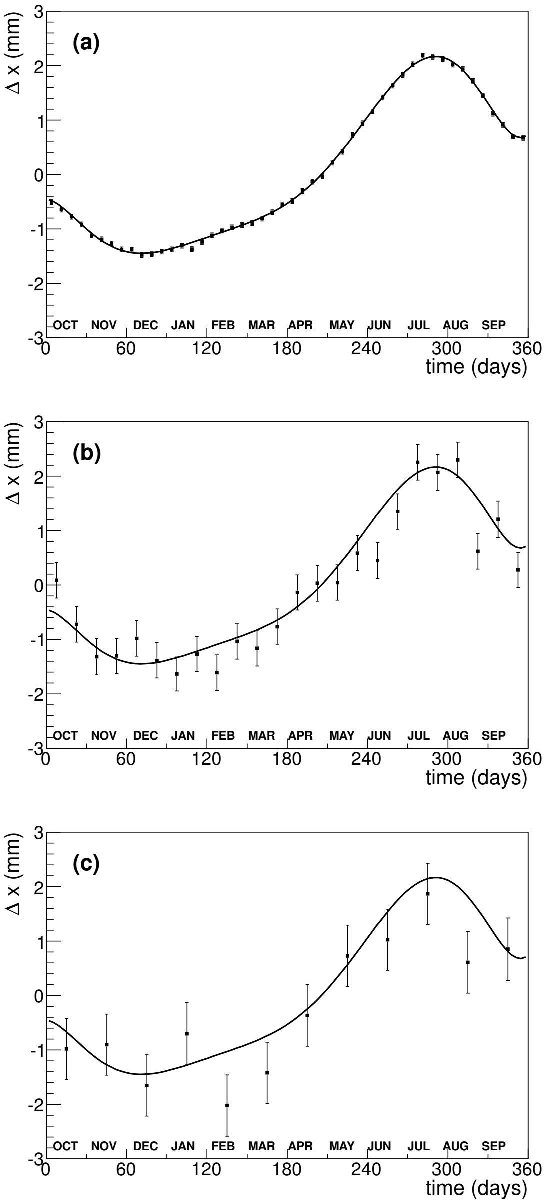

Fig. 5. The seasonal deformation evaluated by the measurement campaign [20], with superimposed the result of the simulation measurements with the sample mean of the position of the "muon target" displaced following the assumed structure deformation, with sampling rate of one week for position P1 (a), two weeks for position P2 (b) and one month for position P3 (c).

CONCLUSIONS

Cosmic ray muon detection techniques for stability monitoring of historical buildings have to deal with the low rate of muon events and with the stochastic nature of the deviations of the muon trajectories due to multiple scattering in crossing materials.

However, due to the very slow evolution of the deformation phenomena that may characterize the behavior of historical building structures, as in the case illustrated in the present work, these constraints do not really constitute a severe limitation for the employment of the proposed method.

Conversely, the ability of muons to penetrate large thicknesses of material suffering only small deviations of the trajectories offers a new possibility to perform the stability monitoring of parts of the building physically and optically separated by solid structures, as walls or floors.

For particular applications, these performances may be competitive in respect to the ones of monitoring systems today widely employed as laser scanner and theodolites, which make use of visible light, or as global position system based methods, hardly applicable to monitor with high resolution internal parts of the building. In addition, whereas the performances of monitoring techniques based on pendulums, inclinometers and extensometers provide measurements of deformation or strain in specific point positions, a global and simultaneous muon monitoring system may be constituted exploiting compact muon detectors distributed in different positions inside the building.

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