Detecting metal elements inside the dome of Santa Maria del Fiore in Florence using cosmic ray muons

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Abstract. As part of the ongoing study of Brunelleschi’s great dome in Florence, the Opera di Santa Maria del Fiore has approved a proposal to solve the age-old problem of the possible presence of hoops or iron stirrups within the dome’s inner wall by exploiting the flux of natural muons traversing the dome. Ascertaining presence of a metal hoop in the dome would obviously be relevant to assess the static and seismic safety of the monument. The project, proposed by Dr. Elena Guardincerri from LANL and by Prof. Carlo Blasi, began in 2016 at LANL with the construction of special prototype-panels for the tracking of muons, and has expanded this year to include researchers from the Department of Physics of the University of Florence and INFN-Florence.

1. The Opera di Santa Maria del Fiore and Brunelleschi’s Dome

1.1. The activity of the Opera di Santa Maria del Fiore to preserve the dome of the Florence cathedral.

According to the tradition, the first stone of the new Florence Cathedral, designed by Arnolfo di Cambio, was laid on September 8, 1296. On the same day the institution of the Opera di Santa Maria del Fiore [1] was born. After a first phase of ecclesiastical and municipal co-management of the cathedral, the institution went, after a few decades, to a laical conduction according to schemes already in use in Florence, with its assignment to the guilds of trades. In the XIV century Francesco Talenti modified and enlarged the cathedral, adding a fourth span to the three planned.

The body of the Basilica was completed in 1380, and in 1420, after the construction of the chapels, the construction of the great dome began, which was finally entrusted to Filippo Brunelleschi. In 1934 a ministerial decree modified the organization of the Opera and sanctioned the institutional form still in force today, according to which the institution is managed by a Board of Directors made up of seven members – in part elected by the Bishop of Florence and in part by the Italian Ministry of the Interior - among which a President is elected.

Today the Opera di Santa Maria del Fiore is a non-profit organization, run according to its own Statute promulgated in 2001 and listing among its institutional goals “the promotion of culture and art”. The Opera manages, besides the Cathedral of Santa Maria del Fiore with its majestic dome, Giotto’s Campanile, the Baptistery, the new museum of the Opera, recently enlarged, the center for the Arts and Culture at piazza S. Giovanni, the palace in via della Canonica, where its offices are, and many more buildings around the Cathedral. It recently expressed its support for a project aiming at finding metal elements inside the dome by measuring the deflection of muon particles travelling through its wall.

1.2. The Dome and the argument about its hoop

Brunelleschi built the dome without explaining the rules he followed to check its geometry and to grant it stability; he did not even write memoires that could explain his beliefs and his modus operandi. For this reason the expression “secrets of the dome” has been in use for a long time. What is known today...
was deduced from the reports from the construction period, from the documents in the Opera’s archives and from studies performed during the past centuries by many researchers.

In particular, the studies following the 600-year anniversary of Brunelleschi’s birth in 1977 have been crucial, especially those by Pasquale e Andrea Chiarugi. In those years, in fact, the layout of the bricks was precisely determined: these are laid on conical beds and on spirals according to a “herringbone” pattern.

Some core samples were taken, and they proved that the masonry was carefully built throughout the entire thickness of the wall, not as in a dry stone wall; the cracks were observed and their evolution with time was studied; the system to trace and cross check the geometry by rampant centering was explained and the current monitoring system was installed, which is regarded today as the most accurate monitoring system for a monument. Lastly, the reasons for the cracks were understood. It can be argued that nowadays there are no longer big “secrets” about the construction and layout of the dome, but some important questions to be answered still remain. Among them, the most important is probably whether there is an effective hoop. Knowing whether an iron hoop or a “macigno chain” (made of large stones connected by metal clamps) are present is crucial to evaluate the safety of the dome and to determine the interventions that could be performed to grant it an adequate static and seismic stability. Such interventions would stop the slow but inexorable widening of the largest cracks, today almost 7 cm wide, affecting the entire thickness of the dome and threatening its stability.

In order to oppose the centrifugal thrust and to provide an adequate hoop the Florence dome, contrary to all the major masonry domes in history, is only reinforced by a wood chain located by Brunelleschi in the space between the two shells. The chain cracked and was refurbished in the past by the Opera, whose experts were aware of its importance. The very same fact that the chain broke where the major cracks are shows its usefulness and effectiveness. The chain, made by Brunelleschi with great care and many iron clamps and nails, crosses the ribs and was probably laid based on the model of that already present in the Baptistery. In the Baptistery, however, due to the 4-5 cm wide cracks that had formed, an iron chain was added in 1514 which prevented further problems. Conversely nothing was made for Brunelleschi’s dome, despite the opinions of famous experts (among them, in primis Vincenzo Viviani) and the wooden chain has not been maintained in the last decades and fares now in a state of extreme degradation.

A survey recently performed by the technical staff of the IVALSA-CRN laboratory from San Michele all’Adige, led by Prof. Ario Ceccotti, showed how the chain is subject to a traction of about 200-300 kN in the section considered. This proves that the chain, despite its current state of decay, still has a crucial static purpose.

Figure 1: Drawings showing the conical beds upon which the bricks are laid and the tracing system based on rampant centering.
Determining the possible presence of a metal hoop would therefore be crucial for the restoration programs of the Opera; many investigations have been performed in the past with metal detectors and GPRS with unsatisfactory results, given the remarkable thickness of the dome.

The images that can be obtained using cosmic ray muons traversing the dome could help solve the problem. Two different non-invasive methodologies could be used; both are based on the detection of muons, elementary particles similar to electrons, but with a mass about 200 times larger, generated in the upper layers of the atmosphere by the interaction of cosmic radiation with the Oxygen and Nitrogen nuclei. These particles reach the ground naturally at speeds close to the speed of light and, thanks to their high mass, are able to penetrate the earth's crust like infinitesimal projectiles, reaching depths up to hundreds of meters, depending on their energy.

The former technique exploits the fact that muons are absorbed when travelling through matter, and the absorption increases with the density of the object traversed. The first use of cosmic ray muons for radiography was in 1955, when George measured muon attenuation to determine the overburden of rock above a tunnel [2]. This was followed by Alvarez et al., who used this method to confirm the Second Pyramid of Giza did not contain any undiscovered chamber above the Pharaoh’s burial chamber [3]. More recently, several groups have used muons to examine structure and geophysical features of different sites [4][5][6][7][8][9][10] and for archaeological studies [11][12].
A different method, developed at Los Alamos National Laboratory, uses measurements of the multiple scattering angle of individual muons passing through an object to create tomographic images of the object’s interior structure [13][14]. This technique was originally developed to inspect cargo containers for illicit trafficking of nuclear material [15][16][17], and has since been applied to detection of Special Nuclear Materials [18], industrial corrosion [19], nuclear reactors [20][21][22][23] and high level nuclear waste [24][25].

The two aforementioned methodologies, both proposed to be used within this project, and the measurement devices currently available are described in the following two paragraphs.

2. Imaging techniques using cosmic muons

2.1. Multiple scattering muon tomography – Los Alamos National Laboratory (LANL), USA

Multiple scattering muon tomography is a 3D imaging technique, developed at the Los Alamos National Laboratory, which exploits the measurement of the multiple scattering angle of the individual muons traversing an object to create tomographic images of its internal structure.

The method is based on the fact that muons, when travelling through materials, undergo many single Coulomb scatterings with the charged atomic nuclei. As a result, they are deviated from their initial trajectory and exit the material with a different direction from the original one. By measuring the distribution of the cosmic muons’ scattering angles after they traverse an object of interest, an image of the object itself can be reconstructed as described in [20]. The measurement of the deflection of muon trajectories requires the determination of the muons’ trajectories before and after they traverse the object of interest. This is done using two “trackers” operated in coincidence upstream and downstream of the object to be studied.
By using multiple scattering muon radiography on the inner wall of the Florence Dome we plan to identify and image iron elements inside the masonry of the dome. In order to prove the feasibility of this measurement, a demonstration measurement was performed at LANL during the summer of 2015. If any reinforcement structure is present in the masonry of the Cupola’s wall, it most likely has to be located inside the inner shell. This shell is much thicker than the outer shell, and thus plays a more important role in sustaining the whole structure.

A concrete wall having the same equivalent thickness (in terms of the effects of the material on the muon flux) as the inner wall of the Dome was built. More details about this measurement can be found in [26].

Three iron bars were placed inside this mock-up wall. The bars had rectangular or square cross-sections with different cross sections, the thinnest was 2 cm x 3 cm. The LANL Mini Muon Tracker (MMT [27]), was used to perform the demonstration measurement. The detector consists of two trackers made of aluminum drift tubes. The two trackers were deployed on opposite sides of the wall and collected data for 35 days. An image of the vertical plane passing through the iron bars was reconstructed and the resulting image is shown in the left insert in Figure 5. All the three iron bars are visible, including the thinnest one. For comparison, a Monte Carlo simulation of the same experimental set-up was performed and its data was analyzed with the same analysis technique. The areal density image obtained from the Monte Carlo simulation is also shown in Figure 5. The good agreement between the data and the simulation demonstrates that the technique is well understood and that the performances of future measurements can be confidently predicted. This measurement furthermore demonstrates that iron elements inside the inner wall of the dome of the Florence Cathedral could be located and imaged using a pair of muon trackers similar to those used to perform the aforementioned measurement.

We are therefore assembling two trackers made of carbon fiber drift tubes closed by conductive plastic endcaps: the trackers are modular, made of elements small and light enough to be hand carried to the base of the dome through the narrow spiral staircases leading there. Each tracker is made of 576 drift tubes, each one having a diameter of 2.54 cm and a length of 122 cm. Each tube has a 20 μm diameter anode wire at its center. The tubes are grouped in modules of 24. Each module has been assembled and tested at the Los Alamos National Laboratory. The modules will be filled with a mixture of Ar, CF₃ and ethane and operated at 1 bar of pressure. The overall size of each tracker, including the electronics, will be 137 cm × 137 cm × 30.5 cm and its weight will be around 130 kg. A mechanical drawing of a single tracker is shown in Figure 6 and a picture of one tracker, showing also the aluminum frame that holds together the tube modules, is shown in Figure 7.

The timing of the tiny (few fC) charge pulses produced at the anode wire of each tube will be read out by custom electronic boards, currently being designed by the Department of Physics and Astronomy at the University of Pennsylvania, and the information used to determine the trajectory of each muon crossing the trackers. The existing image reconstruction software developed by LANL will then be used to obtain radiographic images of the volume between the two trackers. Once the trackers are fully

Figure 6: Mechanical drawing showing one of the two LANL trackers and its constituent modules
assembled and tested they will be shipped to Florence and deployed and operated on two opposite sides of the inner wall of the dome of Santa Maria del Fiore.

2.2. Muon absorption radiography - Department of Physics and Astronomy and INFN, Florence, Italy

Unlike the tomographic technique presented in the previous paragraph, based on the measurement of the deflection of muon trajectories, the muon absorption radiographic technique is based instead on the measurement of the degree of absorption of the cosmic ray muons crossing the material under examination. The Department of Physics and Astronomy of the University of Florence and the INFN section of Florence have started since 2009 a new development of the methodology, initially declining it to the sole volcanological area. This activity, stimulated by similar studies proposed by the Japanese group of Prof. H. Tanaka [28], took shape in the INFN Mu-Ray R&D project and in the subsequent “Progetto Premiale” (reward project) MURAVES [29], funded by the Italian Ministry of Education, University and Research (MIUR). The main purpose of this project is the validation of muon radiography as a standard prospection tool for Volcanology, by means of a detailed study of the internal structure of Vesuvius. The project involves the Italian INFN and INGV research institutes. Starting from 2012, the Florence research group has started a parallel study aimed at the possible application of this methodology in other research fields, in particular focusing on case studies of archaeological and geological interest. Concerning the dome of the Florence cathedral a particle detector of the latest generation (analogous to a classic optical telescope) will be used to measure the natural muon flux in two different experimental configurations: 1) with the detector installed inside the dome, pointing to the zone of interest and 2) with the detector placed outside the dome and pointing to free sky along the same direction of the previous case (reference measurement). The comparison of the two measurements makes it possible to highlight cavities or dense areas (like metal structures) hidden inside the predominant material constituting the volume under examination. The Florentine proponent group has already constructed a detector suitable for the use within this project, called MIMA (Muon Imaging for Mining and Archeology).

The MIMA detector consists of a cube-shaped hodoscope, about 50 cm in length, housed on an altazimuth mount to be easily oriented in space, thus defining precisely the measurement direction. The approximate total mass is 70 kg. In Figure 8 the instrument is shown in different phases of its development and use for measurements performed in real sites of interest. The MIMA detector consists of six detection planes, each of them made of 21 bars of scintillating material, optically shielded with respect to each other by means of a reflective film. The bars, 40 cm long and with an isosceles triangle section with a 4 cm base, are arranged alternately with the right angle directed upwards or downwards, so as to form practically homogeneous flat structures, 2 cm thick, as shown in Figure 9. The crossing of these planes by a muon gives rise to the production of photons along the muon paths inside the struck bars. The light signals thus generated propagate within each affected bar and are partly collected by SiPM photosensors (silicon photomultipliers), low-consumption optical devices of the latest generation, installed at both ends of each bar (see Figure 10).
The information provided by the SiPMs for each bar crossed by a muon allows reconstructing a coordinate along the muon trajectory. Thanks to the particular spatial arrangement of the scintillating bars, inherited from the MINERVA experiment [30] at Fermilab (USA), the trajectories of the muons cross always at least two adjacent bars for each plane of the detector.

This allows reconstructing a coordinate along the muon trajectory with a spatial resolution of about 3 mm, exploiting the information on the relative intensity of the signals released by the two adjacent bars (a sort of barycenter of the measured signals). The MIMA hodoscope consists of a total of three pairs of x-y scintillating planes, i.e. three planes with parallel bars, arranged for the measurement of the coordinate along the x-axis, and three planes with the bars rotated of 90° compared to the previous ones, for the measurement of the coordinate along the y-axis, orthogonal to the previous one. The measurement of three points of passage of the muon allows uniquely and reliably identifying the real straight trajectory traveled by the particle.

On the basis of previous experiences, the study of the dome (of the order of a few meters thick wall) with the detector located 1-2 meters from the internal surface requires approximately an exposure time of at least a few weeks, with the currently available apparatus (MIMA).

The spatial resolution of 3 mm obtainable with a single scintillating plane allows reconstructing the muon trajectories with an angular resolution of about 10 mrad. Considering a structure placed at 2 meters from the detector, this angular resolution allows in principle to carry out a measurement of the structure’s details with a spatial resolutions of about 2 cm. By moving the detector away from the volume under

Figure 8: Left: the MIMA muon hodoscope at the INFN-Florence laboratories. Center: installation at the Galleria Borbonica in Naples. Right: measurement at a river bank in collaboration with geologists of the University of Florence.

Figure 9: Details of the structure of the detection planes of the MIMA hodoscope.
Left: passage of a muon through two adjacent bars.
Right: arrangement of the scintillating bars in pairs of x-y planes (in the example only two pairs of three are represented).
examination, the spatial resolution obtainable increases (worsens) linearly with the distance. We believe that the installation of the MIMA hodoscope close to the internal surface of the dome, does not present critical problems. Once installed the detector can be safely left running for a few weeks without the need for any on-site maintenance.

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