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Digital holographic interferometry method for tracking detector modules displacement

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Abstract: In high energy particle physics scattering experiments, the precision of the reconstructed particle tracks can be fundamental. For this reason, a method for detecting the displacement of tracking detector modules is developed. The modules are silicon planes mounted on a frame and used in the MUonE project, which aims at a precision measurement of the scattering angle of elastic muon-electron scattering. From the scattering angle, the hadronic contribution to the anomalous magnetic moment of the muon is extracted. To achieve the desired accuracy, the position of the tracking detector planes must be monitored. The allowable relative displacements must be less than 10 µm. To meet the specifications and to monitor as large an area of the detector as possible, a digital holographic interferometer was developed. It is based on a novel lens-less design in off-axis holographic geometry. Light from a fiber-coupled laser source is split by a fiber beam splitter, with one output used to illuminate the detector plane and the other for the reference beam. The two beams produce an interference pattern on a CMOS image sensor. To obtain relative displacement information, successive images are superimposed on an initial reference image and reconstructed by solving the Rayleigh-Sommerfeld diffraction integral taking into account the spherical wavefronts of the beams. The interference fringes that appear in the reconstructed holographic image provide a measure of the relative displacement of the detector plane compared to the initial position. The performance of the reconstruction method used was verified with the proposed setup at a real tracking station.

Keywords: Image processing; Interferometry; Detector alignment and calibration methods (lasers, sources, particle-beams); Particle tracking detectors

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1 Introduction

The latest results of the g-2 collaboration have evidenced a discrepancy between the theoretical prediction and the experimental measurement of the muon magnetic moment anomaly, $a_\mu = (g_\mu - 2)/2$. The combined results of BNL E821 [1] and FNAL E989 gives a deviation of 4.2σ from the Standard Model predictions (SM) [2]. This discrepancy in the experimental results made it necessary to further improve the calculation of a_μ. The theoretical value is calculated partly using perturbation theory with very accurate results for the dominant quantum electrodynamic (QED) part, while non-perturbative methods are used relying on experimental results for electroweak (EW) and hadronic interactions. The second largest contribution to the muon anomaly uncertainties in the SM predictions comes from hadronic vacuum polarization (HVP).

The MUonE project (CERN) is an experiment focused on extracting the HVP contribution at leading order (LO), $a_\mu^{\mathrm{HVP,LO}}$, through a precise measurement of the differential muon-electron scattering angle [3]. Indeed, a new method has been proposed to directly extract the $a_\mu^{\mathrm{HVP,LO}}$ through the $\mu e \rightarrow \mu e$ process differential cross section via the squared four-momentum transfer function in the t-channel (space-like) region as $q^2 = t < 0$ [4]. The MUonE experiment consists of a 160 GeV muon beam from the North Area at CERN, which passes through 1 meter long tracking detectors (up to 40 in the final setup) called "stations." Each station has a thin carbon target and 3 pairs of silicon 90 µm strip width sensors (2 S modules [5]) to accurately reconstruct the tracks of scattered muons and electrons and obtain the differential scattering angle. The below 10 µm precision with which the tracks are reconstructed is important. To this end, the stations are developed appropriately considering the geometry and the materials used. Thus, to achieve a competitive accuracy of $a_\mu^{\mathrm{HVP,LO}}$ (5 ppm), many parameters must be controlled and properly monitored in the experiment. For example, the uncertainty with which the tracks can be reconstructed depends on how accurately the relative distance between the Si detectors is known. To monitor this parameter and ensure that the previously measured relative distance displacement between tracking planes remains below the 10 µm requirements, a digital holographic interferometric system, the Holographic Alignment Monitor (HAM) [6], was developed.

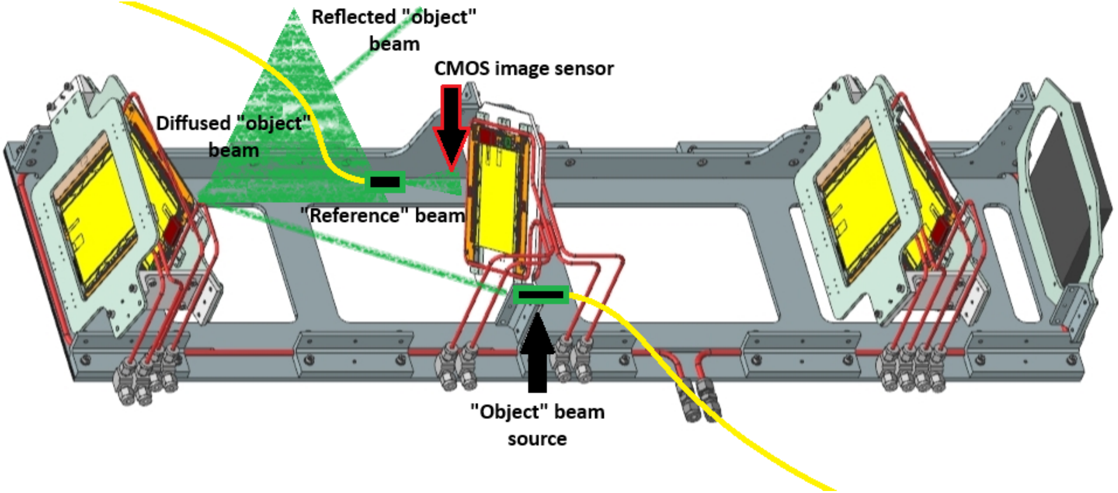

Figure 1. Schematic diagram of the Holographic Alignment Monitor mounted on a MUonE station showing the main parts of the system and their positions. It can be seen that two types of radiation are scattered from the object (2S module) due to the high reflectivity of the silicon surface. From the point of view of the incident light, the CMOS image sensor is located in the lower left corner of the adjacent detector plane, where the "reference" beam source is also located with a special mount. The "object" beam source is also mounted with a special bracket in the upper right corner of the same plane as the sensor, correctly aligned with the center of the 2S module [6]. For the description of the station refer to the text. Reproduced with permission from [6].

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2 Holographic Alignment Monitor

The Holographic Alignment Monitor is a fiber-coupled optical system. It is a off-axis digital holography method used for time-dependent interferometry. In figure 1, a drawing of the MUonE station is shown, showing from right to left the main parts: the target (in black) and the three pairs of tracking modules (the yellow surfaces in the CAD[1]). Also on the figure 1 the scheme of the holographic system is described. The principle of digital off-axis holography data acquisition is also shown. It basically consists in recording the intensity of the two electromagnetic waves, one of which comes directly from the fiber-coupled laser as the "reference" beam, while the other comes from the diffused beam of the illuminated object. The setup uses a 532 nm laser source that is properly split, with 90% of the beam power used for the "object" beam. The system does not require any type of lens or collimators, so it can be easily and smoothly integrated with other setup, in this case the MUonE station, along with the fibre-coupled laser source. The off-axis geometry also provides more degrees of freedom and is more customizable. The raw hologram recorded by the sensor must be reconstructed. In classical holography, reconstruction is achieved by re-illuminating the recorded hologram (typically on a light-sensitive plate) with the reference beam, which projects the reconstructed image at the same distance at which it was recorded [7]. In digital methods, a similar approach is followed. The reconstruction process described earlier is described by the Rayleigh-Sommerfeld diffraction integral: each point in the raw image acts as a small aperture to which the reference beam diffracts, forming a field of spherical waves. By digitising the integral and

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[1] However, in each pair of 2S modules, only the left one is clearly visible.

using appropriate approximations, the reconstruction formula can be expressed as [6]:

$$\Gamma(k, l, d_o, d_r)_{\text{MPR}} = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \tilde{h}(m, n, d, d_r) \times \exp\left[-i2\pi\left(\frac{mk}{M} + \frac{ml}{N}\right)\right], \tag{2.1}$$

called *Minimal Phase Reconstruction* (MPR), where

$$\tilde{h}(m, n, d_o, d_r) = h(m, n) r(m, n) \times \exp\left[\frac{i\pi}{\lambda}\left(\frac{1}{d_o} - \frac{1}{d_r}\right)(m^2 \Delta x^2 + n^2 \Delta y^2)\right]. \tag{2.2}$$

In the equations (2.1) and (2.2), we have all the information we need for a magnitude- contrast representation of the recorded hologram $h(m, n)$, with $m[0, M-1]$ and $n[0, N-1]$, since the data has $M \times N$ pixels recorded by the sensor. In the formula, λ is the wavelength of the laser, $\Delta x \Delta y$ corresponds to the pixel size of the sensor used, and d_o and d_r are the distances between the sensor and the object and the reference beam $r(m, n)$, respectively. The equation (2.1) is a discrete Fourier transform and can be converted to a Fast Fourier Transform (FFT) algorithm in computer language, while the acquisition information is inserted with the equation (2.2). Since the MPR is a complex field, the real part is extracted and a magnitude contrast image is displayed when the absolute value is taken. Figure 2 shows a schematic process of reconstruction where the real field has three diffraction orders 0, 1 (real image) and -1 (virtual image). While in photography the data contains only the amplitude information (intensity) of the radiation recorded by the sensor, in holography the phase information is also preserved. This property enables holographic interferometry. Soon after the discovery of holography, interferometric applications were tested [8]. In the case of the HAM system, the principle of time-dependent interferometry is very simple. Using the previously described acquisition methods, a first raw image is acquired at time t_0 and a later one at time t_1. By combining the two images, a holographic interferometric image $h_1^i(x, y)$ is acquired, which is mathematically described as the sum or difference $h_1^i(x, y) h_{t_0}(x, y) \pm h_{t_1}(x, y)$. If there is a displacement between them interferometric fringes are formed on the reconstructed hologram.

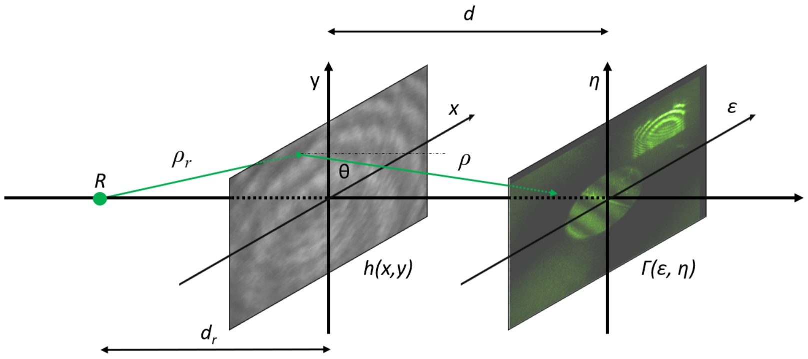

Figure 2. Holographic reconstruction scheme showing the re-illumination of the raw holographic data $h(x, y)$ by the "reference" wave R at distance d_r. The reconstructed field $\Gamma(\epsilon, \eta)$ is then formed at distance d from $h(x, y)$ [6]. Reproduced with permission from [6].

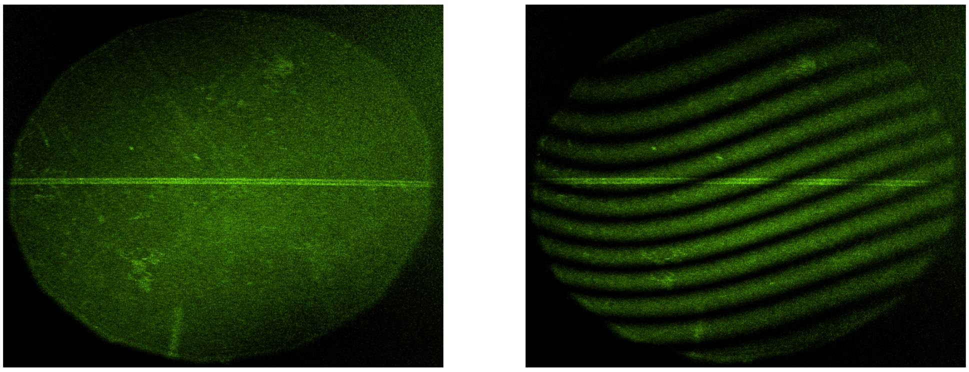

Figure 3. Reconstructed interferometric holograms using the HAM system during night data taking: the left one at the start of the night and the right at a later time.

3 Results

The Holographic Alignment Monitor is used to monitor the relative displacement between tracking modules. A circular portion ($\approx$ 5 cm in diameter) of the Si sensors is illuminated. The computation time to capture and reconstruct the hologram is $\approx$ 2 s. Tests were performed with the HAM system, exploiting the temperature drop during the night to monitor the displacement caused by the linear thermal expansion of the material (aluminium) of the mock-up MUonE station used. Figure 3 shows two reconstructed interferometric holograms: the left one at the beginning of the data acquisition and the other one at a later time. The first shows no fringes, i.e., no displacement, while the second shows 11 fringes. Since a fringe forms at a displacement of $\lambda/2$, the number of fringes in the reconstructed hologram shows a displacement of $\approx$ 3 µm [6].

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