The CMS hardware alignment system

I. Vila[a]
for the CMS Collaboration

[a] *Instituto de Física de Cantabria (CSIC-UC), Santander, Spain*

Abstract
The different hardware-based alignment systems of the CMS detector are briefly described including its overall projected performance. Initial systems performance during the first CMS magnet operation to 4 T nominal magnetic field is also summarized.

21.1 Introduction

As its name states, the precise momentum measurement of the muon is at the top of the Compact Muon Solenoid (CMS) detector priorities; the more accurate momentum measurement is achieved by the joint use of its solid-state-based central tracker and muon system. The demanding requirements on the momentum resolution drive the need for a dedicated hardware alignment systems that will provide a fast real-time absolute and relative position monitoring of the tracking detectors to be subsequently improved by the ultimate precision of the track-based off-line alignment algorithms. In addition, the hardware-based alignment, together with static survey measurements, should complement the track-based alignment since it is sensitive to those degrees-of-freedom that can not be obtained from track algorithms [1].

The CMS hardware system consists of four systems: the laser alignment system for tracker local alignment; the muon barrel monitor; the muon end-cap monitor; and the link system for connecting muon and tracker alignment systems.

21.2 The muon alignment system

For optimal performance of the muon spectrometer [2] over the entire momentum range up to 1 TeV/c, the different muon chambers must be aligned with respect to each other and to the central tracking system to within 100–500 μm in $r\phi$. To this end, after following strict chamber construction specifications, the CMS combines precise survey and photogrammetry measurements, measurements from an optomechanical system, and the results of alignment algorithms based on muon tracks (cosmic rays and collision tracks) crossing the spectrometer.

There are several potential sources of misalignment in the muon spectrometer, from chamber production to final detector operation conditions, including: chamber construction tolerances; detector assembly and closing tolerances; magnetic field distortions; and thermal instabilities.

A Muon Alignment system was designed to provide continuous and accurate monitoring of the barrel and end-cap muon detectors amongst themselves, as well as alignment between them and the inner tracker detector. To fulfil these tasks the system is organized into different blocks: local systems of barrel and end-cap muon detectors to monitor the relative position of the muon chambers, and a link system that relates the muon (barrel and end-cap) and tracker systems, and allows a simultaneous monitoring of the detectors.

The basic geometrical segmentation consists of three r–z alignment planes with 60° staggering in ϕ. This segmentation is based on the 12-fold geometry of the barrel muon detector. Within each plane, the three tracking sub-detectors of the CMS (central tracker, barrel and end-cap detectors) are linked together.

21.2.1 Barrel muon alignment

The monitoring of the barrel muon detector is based on the measurement of all 250 DT chamber positions with respect to a floating network of 36 rigid reference structures, called MABs (Module for the Alignment of Barrel). The MAB design was optimized to achieve adequate mechanical rigidity of the structures under load, thermal, and humidity gradients. Long-term measurements were carried out showing deviations below 100 μm and 50 μrad [3]. The MABs are fixed to the barrel yoke forming 12 r–z planes parallel to the beam line, and distributed in ϕ every 60^o (see Fig. 3 in Ref. [4]). Each structure contains eight specially designed video cameras which observe LED sources mounted on the

DT chambers. Extra light sources and video cameras in specific MABs serve to connect the MABs in different planes forming a closed optical network (called diagonal connections). The MAB positions in the z coordinate are measured with respect to six calibrated carbon-fibre bars (z bars) sitting on the outer surface of the vacuum tank of the solenoid. MABs in the external wheels, YB$\pm$2, are equipped with extra alignment sensors and light sources which serve to connect the barrel monitoring system with the end-cap and tracker detectors.

The four corners of the DTs are equipped with LED light sources. Four LED holders, or forks, are rigidly mounted on the side-profile of the honeycomb structure (two per side) using the rectangular 50×65 mm^2 tube as a light passage. Each fork contains 10 LEDs, 6 on one side and 4 on the other side. The total number of light sources mounted on the DT chambers is 10 000. The position of the forks with respect to the chamber geometry (corner blocks) is measured in a dedicated bench with a precision of 70 μm. As an important byproduct the calibration also provides the full geometry, including the planarity, trapezoidity, and the relative positions of superlayers for each DT chamber with 30–50 μm precision. The individual chamber data are stored in a web-accessible database [5].

Each component, LED holder and video sensor, was individually calibrated before its assembly on the DT chambers or MABs and z bars. LED holders were measured and the position of the light centroid were determined with respect to the holder mechanics with an accuracy of 10 μm. Long-term measurements show good stability of the centroids and the light intensity distributions. CMOS miniature video sensors, containing 384×288 pixels with 12×12 μm^2 pixel size, are calibrated to absorb residual response non-uniformities and the intensity non-linearities. The video cameras consisting of a video sensor and a single-element lens assembled in an aluminium box are also calibrated to determine their inner geometrical parameters. Fully instrumented MABs, containing the necessary number of survey fiducials, were calibrated in a special bench where the whole geometry of the structure, positions and orientations of elements were determined with an overall accuracy of 70 μm and 50 μrad.

Once the MABs were installed, the initial MAB positions on the barrel wheels were determined by photogrammetry measurements.

Based on simulation, the barrel monitoring system should provide a stand-alone measurement of the barrel chambers with an average $r\phi$ position accuracy of 100 μm for chambers in the same sector and about 250 μm between barrel sectors. The current understanding of its performance is discussed in Section 21.4.

21.2.2 End-cap muon alignment

The muon end-cap alignment system [6] is organized in order to continuously and accurately monitor the actual position of the 486 CSCs relative to each other, relative to the Tracking system, and ultimately within the absolute coordinates of CMS. Owing to the large magnetic field, the chambers mounted on the end-cap yoke undergo substantial motion and deformation of the order of a few centimetres when the field is switched on and off. The alignment system must measure and monitor the absolute positions of the CSCs in the $r\phi$ plane and in z. From simulations, the requirements on the absolute alignment accuracy were found to run from 75 to 200 μm; because of the direct coupling between r and $r\phi$ accuracy, the required accuracy in r-position is found to be $\sim$ 400 μm. The total z displacements due to the deformation of the iron yoke discs caused by the strong and non-uniform magnetic field in the end-caps require the alignment sensors to be able to accommodate $\sim$2 cm dynamic range with an accuracy of $\sim$1 mm.

The system uses a complex arrangement of five types of sensors for transferring and monitoring ϕ, r, and z coordinates. Because of CMS geometry constraints and economics, the system aligns only one sixth of all end-cap chambers. The main monitoring tools within the $r\phi$ plane are the Straight Line Monitors (SLMs). Each SLM consists of two cross-hair lasers, which emit a nearly radial laser beam across four chambers from each end, and provide straight reference lines that are picked up by two optical sensors (Digital CCD Optical Position Sensors (DCOPS) [7]. This arrangement provides references for the chamber positions relative to the laser lines.

The ϕ coordinate alignment is handled by optical SLMs and transfer lines. Transfer laser lines run parallel to the CMS z-axis along the outer cylindrical envelope of CMS at six points separated by 60° in ϕ. The SLMs run across the surface of one sixth of all the CSCs along radial directions, and link transfer lines on opposite sides of a disc. Both laser lines have a similar basic configuration: a laser beam defines a direction in space that is picked up by several DCOPS precisely mounted on CSCs or Transfer Plates to reference their own positions. Mounting accuracies due to tolerances of dowel pins and dowel holes are of the order of 50 μm. Every DCOP comprises four linear CCDs each with 2048 pixels and 14 μm pixel pitch. The CCDs are basically arranged in the shape of a square and can be illuminated by cross-hair lasers from either side. The r and z coordinate measurements are performed by analog linear potentiometers and optical distance devices in contact with aluminium tubes of calibrated length.

All analog sensors were calibrated with a 1D precision linear mover with 6.4 μm step size. The total uncertainty in the absolute distance calibration is 100 μm for r sensors and 53 μm for z sensors [8]. Calibration for optical DCOPS consisted in determining the distance from the surface of the mount hole for a reference dowel pin to the first active CCD pixel and measuring the projected pixel pitch of each of the four CCDs. This was carried out on a calibration bench where a fibre bundle variable light source at the focus of a parabolic mirror illuminated a mask with eight optical slits. A simple geometry reconstruction based on coordinate-measuring-machine data for the calibration mask and sensor mounts determined the physical pixel positions. Calibration errors were typically 30–50 μm.

21.2.3 Link alignment system

The purpose of the link alignment system is to measure the relative position of the muon spectrometer and the tracker in a common CMS coordinate system. It is designed to work in a challenging environment of very high radiation and magnetic field, meet tight space constraints, and provide high-precision measurements over long distances. A distributed network of opto-electronic position sensors, ASPDs, placed around the muon spectrometer and tracker volumes is connected by laser lines. The entire system is divided into three ϕ-planes 60° apart; this segmentation allows a direct reference of each muon barrel sector with the tracker detector and provides direct reference as well to the end-cap alignment lines in the first end-cap station, ME1. Each plane, see Fig. 4 in Ref. [4], consists of four quadrants resulting in 12 laser paths: six on each z-side of the CMS detector, generated by 36 laser sources. The system uses three types of reference structure: rigid carbon fibre annular structures placed at both ends of the tracker (Alignment Rings, AR) and at the YE$\pm$1 wheels of the end-cap muon spectrometer (Link discs, LD); and the MAB structures attached at the external barrel wheels, YB$\pm$2. The link measurement network is complemented by electrolytic tiltmeters, proximity sensors in contact with aluminium tubes of calibrated length, magnetic probes, and temperature sensors.

The ARs are rigidly attached to the end-cap tracker detectors, TECs, through a purely mechanical connection with the instrumented silicon volume. Three pillars, acting as support holders, connect the last instrumented disc of each TEC with the corresponding AR, at the two ends of the tracker volume. The position and orientation of the ARs with respect to TEC discs 9 and 10 were measured with a coordinate-measurement machine using the external survey fiducials, prior to TEC assembly and instrumentation. Changes in angular orientations are monitored by high-precision tiltmeters placed at the AR and TEC disc 10. Laser sources originating at the AR and running along the inner detector boundary reach ASPD sensors on the first end-cap disc, ME1, and on the external barrel wheel.

ASPD (Amorphous-Silicon Position Detectors) sensors [9] are 2D semitransparent photo-sensors, which consist of two groups of 64 silicon micro-strips, with a pitch of 430 μm, oriented perpendicularly. With >80% transmittance for the 685 nm wavelength used in the system, they allow multi-point measurements along the light path without significant distortions in the beam direction. The intrinsic position resolution is about 2 μm. The location, centre position, and orientation of the ASPD with respect to reference pins in their mechanical mount are measured with non-contact CMM with an overall accuracy of 15 μm. Distance measurement devices (optical distance sensors and linear potentiometers) already mounted in their final mechanics were calibrated using 2 μm resolution linear movers and pre-measured calibration fixtures. The total uncertainties in absolute and relative calibration [10] is below 50 μm and 20 μm, respectively, for the different sensor types. The intrinsic accuracy of the tiltmeter sensors, after calibration, is of 2 μrad; mechanical offsets inherent to the mechanical mounts and assembly tolerances are determined by survey and photogrammetry techniques.

The light sources (collimators) and specific optical devices, housed on the alignment reference structures (AR, LD and MABs), create the laser beam paths with the above defined layout. Each collimator is focused on its working distance to ensure Gaussian beam profiles along the propagation path in order to avoid beam-shape-induced bias in the position reconstruction. The adjustment and calibration [11] of the laser rays, for the AR and LD structures, is carried out in a dedicated bench instrumented with a precise survey network that mimics the nominal detector geometry. Beams are adjusted to their nominal geometry with a precision better than 100 μrad. Long-term measurements were performed after beam adjustments. Beam pointing stability, including temperature effects, was found to be better than 30 μrad. The adjustment and calibration accuracy was limited by the finite dimension of the structures combined with the intrinsic accuracy of the survey and photogrammetry measurement techniques of 50–70 μm. The outer diameter of the AR and LD, 720 mm and 1300 mm, respectively, results in a final calibration accuracy that runs from 30 μrad to 100 μrad.

Survey and photogrammetry measurements are also performed during the installation of the alignment structures in the detector. An installation precision at the level of a few mm and mrad is needed to ensure correct functionality of the system, taking into account the standard CMS assembly tolerances of the big end-cap discs and barrel wheels.

The control, readout, and data preprocessing is performed by two types of electronic boards. Analog sensor readout and laser control use standard ELMB (Embedded Local Monitor Board) cards [12]. For the readout of ASPD sensors, custom-made LEB (Local

Electronic Board) cards were developed. LEBs are intelligent imaging acquisition boards made to read and control up to four ASPD sensors. They are based on Hitachi micro-controllers. ELMB and LEB boards use the CAN communication protocol to connect the front-end electronics and the main control PC unit.

21.3 Tracker local alignment

To fulfil the full potential of the CMS tracker, a precise knowledge of the position of the silicon modules is essential. Given the intrinsic sensor resolution (23 μm to 59.2 μm), an alignment accuracy better than 10 μm is needed for all detector elements. Such an accuracy can be reached only by using a large number of reconstructed tracks.

The strategy for the alignment of the CMS tracker involves three steps [13]: mechanical construction precision and survey for all subdetector elements (TIB, TOB and TEC) — this precision amounts to a few hundred microns; Laser Alignment System (LAS), the LAS will align the TIB, TOB and the two TECs with respect to each other within 100 μm; and alignment with tracks, a large sample of reconstructed tracks will be used to achieve the final accuracy of 10 μm.

The laser alignment system employs a number of laser beams generated by diodes and detected by the same silicon sensors used as tracking detectors, see Fig. 5 in Ref. [4]. These sensors were made transparent to laser light by omitting the backplane metallization over the small area crossed by the beams. It has been verified that their electrical and charged-particle detecting properties were not affected by this modification.

For a series of consecutively arranged module layers light absorption inside each module should be enough to create a useful signal, but transmission should also be sufficient in order to reach the next layer. It was possible to link up to five module layers with a single beam, but to be able to align all nine discs of the TEC structure, a beamsplitting device had to be used which provides back-to-back beams whose collinearity is known and stable within 50 μrad.

A major challenge for this method is the improvement of the optical properties of the silicon sensors. To minimize reflection, and thus increase transmission and absorption, an anti-reflecting coating was applied on the ohmic side of the silicon sensors over the area transparent to the laser beams. The improvement in surface quality also led to uniformity of transmission and absorption and to a minimization of interference effects. The increase in transmission through application of the anti-reflecting coating is about 20%. Refraction effects are negligible at the 10 μm level.

Laser data from the first sector integrated in the TEC, involving two laser beams and 18 petals, were used to reconstruct the absolute position of the nine TEC discs with an accuracy of 50 μm, much better than the 100 μm required for the laser alignment system. This result has been confirmed by comparison with survey measurements [14].

21.4 Muon system commissioning and results from the magnet test

A crucial test of the large superconducting solenoid magnet in the CMS detector was successfully performed between June and November 2006, during which stable operation at full field (4 T) was achieved. The alignment sensors, readout, and DAQ software were commissioned during this test period for about one third of the system, instrumented at the +z side of the detector. This allowed the first full-scale dynamic test of the alignment system. The main features of the yoke displacement and deformation were studied. The most relevant results are summarized below:

– *Measurement of relative movements due to thermal changes.*
  The effects of thermal changes (day–night variations) for DT and CSC chambers were recorded for the conditions present during the Magnet Test, with the detector in the surface assembly hall and power on only $\sim$ 5% of the muon spectrometer. The relative movement measured did not exceed 50 μm over the entire test period, with changes in position showing a good correlation with temperature. Although a movement of this magnitude is not relevant from the physics analysis point of view, it shows the good resolution of the alignment system.

– *Measurement of the displacements and deformations of the yoke structures.*
  Two effects were observed. The first is the change in the original positions of the structures (the positions before any magnet operation). The displacements of the structures along the z direction towards the solenoid, of about 2.7 mm for the barrel iron and about 5 mm for the end-cap discs, seem to stabilize after the first 2.5–3 T are reached. This compression is permanent, meaning it is not reversed/recovered in subsequent magnet-off states, and it is interpreted as the final closing of the structures due to the magnetic forces acting on the iron. The second effect is the almost perfectly elastic deformations between magnet-on and magnet-off states. At 4 T, the elastic deformation of the barrel yoke, measured at the end of the +z side with respect to the plane of the interaction point, is about 2.4 mm. Despite the large over-

all compression of the barrel spectrometer, an important measurement was the stability of the barrel chambers during the whole data-taking period. The relative movements in the ϕ direction did not exceed 60 μm.

The behaviour of the end-cap disc is more complicated. Owing to the strong gradient in the magnetic field near the end of the solenoid, strong magnetic forces pull the central portions of the end-cap discs towards the solenoid. The nose is pulled $\sim$ 16 mm towards the interaction point. The various z-stops, which prevent the discs from getting pushed into each other and onto the barrel wheels, cause the end-cap discs to bend into a cone shape. The z-stops between end-cap and barrel, positioned at nearly half the disc radius, cause the side of the YE1 disc facing the barrel to compress radially around them by $\sim$ 600 μm, while expanding azimuthally by $\sim$ 800 μm. This explains the radial compression of the face of ME+1 and the larger bending angles at mid-radius than at the outer edge. End-cap disc deformations are predicted by Finite Element Analysis (FEA) using the ANSYS program [15]. The measurements are in reasonable quantitative agreement for all displacements and deformations. Note that the front z-stops, between the ME1 and barrel wheels, were not included in the FEA, which explains the difference. The difference between top and bottom is also explained by the presence of the carts that support the discs.

The rest of the end-cap stations on YE+2 and YE+3 experience a maximum bending angle relative to the vertical of $\sim$ 2.5 mrad. The disc of ME1/1 chambers, in the nose of YE+1, suffers an extra displacement towards the interaction point of $\sim$ 2.5 mm, with almost negligible distortion in $r\phi$. As is the case of the barrel chambers, with stable field, the observed relative movements were very small.

– *Detector closing tolerances and reproducibility.* The magnet test was divided into two phases, separated by a short period during which the yoke was open to extract the inner detectors, tracker, and ECAL modules. This allowed a test of the reproducibility in the closing procedure and tolerances, as well as the compatibility of measurements among the two phases. Reproducibility in the closing was at the level of a few mm, and the system was able to reproduce the same magnetic-force-induced effects as measured in the first period.

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