The CMS Silicon Tracker Alignment

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Abstract

The alignment of the Strip and Pixel Tracker of the Compact Muon Solenoid experiment, with its large number of independent silicon sensors and its excellent spatial resolution, is a complex and challenging task. Besides high precision mounting, survey measurements and the Laser Alignment System, track-based alignment is needed to reach the envisaged precision. Three different algorithms for track-based alignment were successfully tested on a sample of cosmic-ray data collected at the Tracker Integration Facility, where 15% of the Tracker was tested. These results, together with those coming from the CMS global run, will provide the basis for the full-scale alignment of the Tracker, which will be carried out with the first \( p-p \) collisions.

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1 The CMS Silicon Tracker

The Compact Muon Solenoid (CMS) detector is one of two general-purpose experiments operating at the Large Hadron Collider [1]. In the central region, starting from the outside and working towards the centre of CMS, the detector consists of a precise muon spectrometer, a sampling hadron calorimeter, an electromagnetic lead-tungstate calorimeter, a superconducting coil that provides a solenoidal 4 T magnetic field for momentum measurement, and a full silicon Tracker.

The CMS silicon Tracker [2, 3] covers the cylindrical volume given by \( r < 110 \text{ cm} \), \(|z| < 275 \text{ cm}\).

In the inner part (Tracker Pixel Barrel and Endcap, TPB and TPE) is composed of 1440 pixel detectors arranged in 3 cylindrical layers and 4 discs. The pixel size is \( 100(\phi r) \times 150(z) \mu\text{m}^2 \), with an intrinsic resolution of 9 \( \mu\text{m} \) along \( r\phi \) and of 20 \( \mu\text{m} \) along \( z \) direction.

In the outer part, composed of Tracker Inner and Outer Barrel (TIB and TOB, respectively) and Tracker Inner Disks and Endcaps, (TID and TEC, respectively) there are 15148 silicon strip modules (pitch: \( 80 - 205 \mu\text{m} \)) each with a resolution of \( 20 - 60 \mu\text{m} \). These modules are arranged in 10 coaxial cylindrical layers in the Barrel region (4 layers for TIB, 6 layers for TOB) while in the Endcap region they are mounted on concentric discs (6 discs for TID, 18 for TEC, symmetrically distributed along the Z-axis).

Two layers in TIB and TOB, two rings in TID and three rings in TEC allow the measurement of second (stereo) coordinate. There two single-sided strip modules are mounted back-to-back with a stereo angle of 100 mrad. For each track from the collision point, at least four two-dimensional measurements are possible.

2 The alignment strategy

Despite the care taken during the assembly of the tracker, it is clear that the modules of the detector will not be perfectly aligned at CMS start-up. The deviations from the design positions could be up to several hundred micrometres.

For optimal resolution on the track parameters, the position and orientation of the modules need to be determined with a precision of better than a few micrometres. The large number of rigid-body parameters leads to an alignment procedure that is performed at several different levels:

1. High precision in module assembly and survey measurements. During construction and assembly of the CMS Tracker, a vast number of measurements have been performed by coordinate measurement machines (the position of sensors with respect to the carbon-fibre support is given with a precision of 10 \( \mu\text{m} \)) and photogrammetry (this step leads to a spatial resolution of about 100 \( \mu\text{m} \)), to verify the desired mechanical accuracy for all the Tracker components.

2. Laser Alignment System (LAS). This system is used to align TIB, TOB and TEC relative to each other and to monitor the relative positioning of the TEC discs. The goal of the system is to monitor the alignment on a continuous basis, allowing geometry reconstruction of the Tracker substructures at the level of 100 \( \mu\text{m} \).

3. Track based alignment. In this step tracks from a number of different sources are used to reach the resolution on the modules position of 10 \( \mu\text{m} \) along their sensitive coordinates: muons from \( Z \) and \( W \) decays, cosmic ray muons, beam halo muons, minimum bias tracks, tracks constrained at the primary vertex or by invariant mass requirements (\( Z \), \( Y \) and \( J/\psi \) decays).

The common principle of track-based alignment is the minimisation of the following \( \chi^2 \) function:

\[
\chi^2 = \sum_i^{tracks} r_i(p, q) V_i^{-1} r_i(p, q)
\]

where the residuals \( r_i(p, q) \) are defined as the displacements of hit positions with respect to the trajectory impact point of a track. They depend on the alignment parameters, \( p \) (i.e. the modules positions and orientations) as well as the track parameters, \( q \). The covariance matrix, \( V_i \), contains the measurement uncertainties.

Currently three alignment algorithms are available in CMS:

- **HIP.** The Hits and Impact Point algorithm [4] minimises the sum of the residuals of each aligned object, independently of the others. It takes into account only parameter correlations within a module and the track fit is repeated iteratively until convergence is reached.

- **Kalman.** This algorithm [5] is an extension of the Kalman filter used in track fitting, as it includes the alignment parameters: these are updated after each processed track. Due to the evolving statistical
correlations between the alignable objects after each update, not only the detectors which are crossed by the current track, but also all other alignable objects are updated.

- **MillePede.** The basic principle of this algorithm [6] is the minimisation of the $\chi^2$ function, which takes into account both track and alignment parameters. This allows the computation of an optimal solution to the alignment problem when all correlations are properly considered.

The ultimate alignment precision is achieved with track-based methods using data from the silicon modules traversed in-situ by charged particles. The results of the track-based alignment obtained with simulated data and with real cosmic muon tracks are presented in the remainder of this note.

## 3 Alignment using simulated datasets

During the Spring and Summer of 2008, the Computing, Software and Analysis challenge (CSA08, [7]) aimed to test the full scope of data handling, analysis activities and alignment work flow needed for LHC data taking using Monte Carlo samples. All three track-based alignment algorithms were used in this procedure. For two early LHC operation scenarios at $\sqrt{s} = 10$ TeV, samples corresponding to the number of expected events from approximately six days’ running were simulated:

- the **$S43$** scenario for operation with 43 bunches per beam at a luminosity of $\mathcal{L} = 2 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$ resulting in about 1 pb$^{-1}$ (see Table 1).

- the **$S156$** scenario simulating 156 bunches per beam at $\mathcal{L} = 2 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$, equivalent to 10 pb$^{-1}$ (see Table 1).

| $S43$ scenario | $S156$ scenario |
|----------------|-----------------|
| 6 M minimum bias tracks ($p > 1.5$ GeV) | 16k $Z \rightarrow \mu\mu$ |
| 150 k isolated muons ($p = 5$ GeV) | 3 M minimum bias tracks ($p > 1.5$ GeV) |
| 3 M Cosmics tracks ($p > 15$ GeV and >18 hits) | 1 M isolated muons ($p = 11$ GeV) |
| 1 M isolated muons ($p = 11$ GeV) | 750k single $\mu$ from $J/\psi$ decay ($p > 2.5$ GeV) |

A starting misalignment was applied to all simulated data according to the expected remaining uncertainties after survey data, LAS measurements and track-based alignment with cosmic muons have been used.

![Alignment using simulated datasets](image)

Figure 1: The difference between the true and measured values of $r\phi$ for initial start-up conditions (red curve) and after alignment with the MillePede algorithm for all strip and pixel modules using the $S43$ scenario (dashed blue curve) and using the $S156$ scenario (blue curve)
Using the track-based alignment algorithms, knowledge of module positions and orientations can be consistently improved. Figure 1 shows the differences in module position (along the most sensitive coordinate \( r \phi \)) from the ideal geometry for the start-up conditions and for those obtained from the alignment procedure with the MillePede algorithm. Using the track-based alignment results from the S43 and S156 Monte Carlo samples, the remaining misalignment along this coordinate can be estimated to be 37 \( \mu m \) and 35 \( \mu m \), respectively.

4 Alignment with cosmic muon tracks at the Tracker Integration Facility

An opportunity to gain experience in the alignment of the CMS silicon strip tracker, ahead of the installation in the underground cavern, was provided by work performed at the Tracker Integration Facility (TIF) during Spring and Summer 2007 [8].

About 15% of the silicon strip modules were operational during cosmic muon data taking in this period. Besides cosmic muon tracks, data from survey measurements and from the Laser Alignment System were also available for use in the alignment procedure. Cosmic muon events were triggered with two groups of plastic scintillators above and below the detector, while a lead shield absorbed muons with momenta below 180 MeV, in order to remove low energy muons. The magnetic field and the pixel detector were not present.

In total, five million events were recorded at varying coolant temperatures ranging from \(-15^\circ\) C to \(15^\circ\) C and in different mechanical conditions (TEC disks at \( z < 0 \) were inserted during data taking).

Input data for the track-based alignment were carefully selected: only events with one single muon track in a region defined by the fiducial scintillator positions were considered. Tracks were required to be of good quality with a normalised \( \chi^2 \) below 4.0 (assuming initial misalignment uncertainty in quadrature) and to consist of at least five well defined and isolated hits.

Figure 2: The absolute track \( \chi^2 \) values for the design (black solid line) and survey (red dashed line) geometries as well as that (blue dashed line) from HIP track-based alignment. No Alignment Position Errors (APE) have been applied.

Figure 2 shows the distributions of track \( \chi^2 \) values assuming design geometry, geometry based on survey information, and the geometry determined after alignment. Compared to the design geometry, the use of both survey data and results from track-based alignment significantly improves track quality, as visible in the decrease of the mean values with respect to the initial (Design) value.

The RMS of the residuals distributions can be used to estimate alignment resolution in the aligned barrel region via comparison with simulation. Different misalignment scenarios have been applied to the ideal Tracker geometry used in reconstructing the simulated data until the RMS values are found to be similar to those observed in each layer in the data. The modules in TIB and TOB have been randomly shifted in three dimensions according to Gaussian distributions. As can be seen by figure 3, using a misalignment with standard deviations of 50 \( \mu m \) and 80 \( \mu m \) in the TOB and the TIB, respectively, the RMS of the residual distributions per layer agree with the data after alignment, such that these numbers can well be taken as an estimate of the size of the remaining misalignment.
Figure 3: Hit residual means in local x’coordinate (left) and RMS (right) in the ten layers of the barrel tracker, i.e. four layers of TIB and six layers of TOB, shown in data before track-based alignment (red full circles), after track based alignment (HIP, red full squares), in simulation with ideal geometry (blue open circles) and in simulation after tuning of misalignment according to data (blue open squares).

5 Alignment with cosmic muon tracks at the CMS Global Run

After installation underground in December 2007, the Tracker was involved in a new challenge, together with other subdetectors: the CMS Global Run. In a configuration with no magnetic field and with the whole Tracker operating together with all other CMS subdetectors for the first time, cosmic ray data was taken, which was used to perform an alignment of all the Tracker components, leading to promising results.

During the first period the modules on the TEC disks at \( z < 0 \) and the pixel modules were not in the readout, while during the second period the whole Tracker was active, collecting about 600k tracks useable for alignment. Since all of these events were taken in a configuration without magnetic field, a track momentum of 1 GeV was assumed in the reconstruction of the tracks during the first period. This was increased to 5 GeV for the second period of data taking. Using the experience gained from TIF data, a first full Tracker alignment with real data was performed using both HIP and MillePede algorithms: the former using tracks and module survey constraints, the latter using only tracks. Both approaches lead to improvements in terms of \( \chi^2 \) of the tracks and hit residual distributions. A further validation of alignment constants determined using Global Run and an attempt to estimate the achieved alignment precision in TIB and TOB was performed using the mean value of residuals as shown in figure 4.

Figure 4: The mean of the residuals for modules collecting more than 100 hits. The plots show a comparison of the residuals from data assuming the design geometry (blue) and using the aligned geometry from HIP algorithm (red) for TIB (left) and TOB (right). The corresponding distributions from Monte Carlo are also shown (black).
Only modules with more than 100 hits (52% in TIB and 70% in TOB) are included in the distribution, making it less sensitive to multiple scattering. The RMS should therefore be indicative of the remaining misalignment, which is estimated to be about 30 $\mu$m in TIB and 47 $\mu$m in TOB. A comparison with the corresponding Monte Carlo distribution using the ideal geometry is also shown, giving an indication of the statistical uncertainty coming from the amount of data used (21 $\mu$m in TIB, 25 $\mu$m in TOB).

6 Conclusions

The CMS Tracker alignment strategy foresees to use survey, laser alignment and track information to achieve the highest possible precision. Computational issues and alignment workflow were successfully tested using CSA08 simulated data giving an indication of the achievable statistical precision. A successful track-based Tracker alignment, first at TIF with about 15% of the Tracker active and afterwards during the first phase of the CMS Global Run with the whole Tracker switched on, has been performed using the first collected cosmic tracks, leading to promising results.

References

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