Alignment strategy for the CMS Tracker

Martin Weber
on behalf of the CMS collaboration

M. Weber, I. Physikalisches Institut B, RWTH Aachen, D-52056 Aachen
E-mail: Martin.Weber@cern.ch

Abstract. The CMS Tracker measures the momentum of charged particles created in proton-proton interactions with 14 TeV nominal center-of-mass energy close to the interaction region. Its excellent single-point resolution of 9–60 µm is far below typical construction tolerances, and together with its high granularity renders the alignment a demanding task, which needs to aim at micro-meter level precision.

A strategy to align the CMS tracker with its 15 148 silicon strip and 1 440 silicon pixel modules, starting from survey measurements during construction, incorporating information from the laser hardware monitoring system and finally using collision and non-collision tracks for highest precision has been developed and is detailed in this article.

1. Introduction

The Compact Muon Solenoid (CMS) detector is one of two general-purpose experiments operating at the Large Hadron Collider [1]. In the central region, and proceeding from outwards to the center of CMS, the detector consists of a precise muon spectrometer with a standalone resolution of $\delta p_{\perp}/p_{\perp} = 8\text{--}15\%$ at 10 GeV, a sampling brass hadron calorimeter, an electromagnetic lead-tungstate calorimeter with $\delta E/E < 1\%$ for $E > 30$ GeV, a superconducting coil that provides a solenoidal 4 T magnetic field for momentum measurements, and a full silicon tracker [2, 3].

Figure 1 shows an $r$-$z$ view of the CMS Tracker. It is subdivided into four silicon strip subdetectors, the Tracker Outer Barrel (TOB), the Tracker Inner Barrel (TIB), the Tracker Inner Disks (TID), the Tracker Endcap (TEC), and two silicon pixel subdetectors, the pixel barrel and the pixel disks. All active components are housed in a cylindrical volume with a length of 5.4 m and a diameter of 2.4 m. Under nominal LHC beam conditions, the Tracker will be operated at $T = -10$°C in an atmosphere of dry nitrogen, to prevent thermal runaway due to radiation damage.

The strip tracker consists of 15 148 modules with strip pitches ranging from 80–205 µm, leading to a single-point resolution of 23–60 µm. Two layers in TIB and TOB, two rings in TID and three rings in TEC allow to measure a 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.

In the pixel detector, the 1 440 pixel modules provide $6.6 \times 10^7$ pixels of $100 \mu m (r\phi) \times 150 \mu m (z$ in the barrel, $r$ in the endcap) cell size. The high Lorentz angle $\alpha_L \approx 23^\circ$ increases the electron cloud width in the silicon bulk and thus generates charge sharing between adjacent


**Figure 1.** \( r-z \) cut through the CMS tracker. The black dot shows the collision point, the numbers on the top and right show the pseudorapidity \( \eta \) coverage of the tracker. Red boxes represent single-sided strip modules, whereas blue boxes depict two back-to-back mounted single-sided strip modules with 100 mrad stereo angle and thus allow for two-dimensional measurements.

pixels. With analog signal interpolation, a hit resolution of \( 10 \mu m(r\phi) \times 20 \mu m(z, r) \) can be achieved.

2. Alignment strategy

Starting from an initially misaligned detector, the CMS Tracker alignment strategy foresees to use survey measurements, measurements from a dedicated hardware alignment system, and track based alignment to determine true module position\(^1\).

Misaligned detectors bias measurements of track parameters and derived quantities, and deteriorates the resolution. This influences the physics reach of CMS, especially for analyses relying on track measurements. These effects can be compensated in software by a dedicated alignment process.

The precision of alignment changes with available data. Survey data (cf. section 4) naturally come first, during construction and after assembly. Data from cosmic muons have and will be recorded for (parts of) the tracker and can be used to pre-align global structures and exercise the track based alignment procedure. The Laser Alignment System (LAS, cf. section 5) can be operated before collisions and provides precise sub-detector relative position. Survey, LAS and cosmic muon data can be used in a combined alignment procedure before first beams circulate in LHC.

When first beams will circulate in the LHC, tracks from beam halo muons will be used for alignment. When first collisions will occur, charged particles originating from minimum bias events will be measured in the tracker and be used for alignment. With increasing luminosity, resonant muon pair-production from \( J/\psi \rightarrow \mu^+\mu^- \), \( \Upsilon \rightarrow \mu^+\mu^- \) and \( Z \rightarrow \mu^+\mu^- \) will become more and more important, together with cosmic muon data that will be recorded during the data taking period.

Before real data can be used to determine tracker alignment, part of the alignment strategy is to estimate the alignment precision as it develops with time and integrated luminosity, in order

\(^1\) Throughout this article, “position” refers to both position and orientation.
to mimic residual misalignment effects in physics preparation studies. The alignment precision estimates will be described in section 3.

The following sections will detail the alignment strategy, not including those datasets and data taking periods that have not yet been extensively studied.

3. Estimate of alignment performance and impact on track parameters and
derived quantities

There are many reasons for a deviation of true module positions from their foreseen position. The largest single source are assembly tolerances, followed by thermal deformation during cooldown from room temperature to \(-10^\circ\)C operating temperature. Small but measurable effects, some of them time-dependent, are expected from carbon-fibre structure outgassing in dry nitrogen, stress that has been transferred from the shrinkage of the muon system when the magnetic field is switched on, and stress due to access. Deformations due to weight have partly been determined during the construction phase of the experiment, but are not (yet) used to estimate misalignment.

Based on achieved assembly precision, expected improvements from survey measurements, experience with the Laser Alignment System and Monte Carlo studies of track based alignment, misalignment scenarios corresponding to an integrated luminosity of 0pb\(^{-1}\), 10pb\(^{-1}\), 100pb\(^{-1}\) and 1000pb\(^{-1}\) have been estimated [4, 5]. The measurements and studies leading to those scenarios are described in the following sections. One should take note that these scenarios are meant to be indicative and do not include systematic deformations as can possibly be introduced during the alignment procedure (“weak modes”), \(\phi\)- and \(\eta\)-asymmetry of muons from air showers etc.

Figure 2. Expected misalignment effects for integrated luminosities of 0pb\(^{-1}\), 10pb\(^{-1}\), 100pb\(^{-1}\) and 1000pb\(^{-1}\). Left: Relative momentum resolution as a function of the pseudo-rapidity \(\eta\). Right: Mistagging rate for light and quark jets as a function of the \(b\)-tagging efficiency.

Figure 2 shows the expected impact of residual misalignment on the relative track momentum resolution as a function of the pseudo-rapidity \(\eta\), and the mistagging rate for light quark and gluon jets as a function of the \(b\)-tagging efficiency for the track counting \(b\)-tagging algorithm [6]. For scenarios with 10pb\(^{-1}\) and less of integrated luminosity large effects can be seen, whereas from 100pb\(^{-1}\) on the effect on physics results is expected to be small.
4. Survey

During the CMS Tracker construction and integration, measurements were performed to confirm the desired positioning accuracy by measuring the relative positioning of detector elements. Additionally, some parts of the detector were surveyed completely, such that the position of the active area of the silicon modules is known. The measurements typically were conducted with the help of coordinate measuring machines (CMM), photogrammetry, and theodolites. Naturally, the survey measurements follow the construction steps, and since the tracker has been built by building small parts which are assembled into larger parts, which themselves are assembled in even larger parts etc., the measurements mostly follow the construction hierarchy of the CMS Tracker.

4.1. The Tracker Hierarchies

Figure 3 shows a logical hierarchical representation of the CMS tracker structures. The CMS tracker consists of a pixel and a strip tracker. The pixel tracker consists of a barrel and two endcaps, as can be seen in Figure 1. The strip tracker is divided in two barrels, the inner and outer barrel, and four endcap detectors (inner disks and tracker endcaps (TEC) on each of the +z- and −z-end) that each consist of two separate entities (cf. Figure 1). Not all hierarchy levels that are shown in Figure 3 are mechanically decoupled from its parent and therefore play a role as an independent object in the misalignment simulation and alignment procedure. For example, the “layer” in the Strip Tracker Outer Barrel is a logical structure that is extensively used in the tracking code, whereas it has reduced meaning as a separate alignment object since it is not a single mechanical structure. Therefore, the structure of the AlignableTracker, which is used in the misalignment and alignment procedure and defines the hierarchy of alignable objects, differs from the logical view in some places. Similarly, for survey measurements there are also a few exceptions to this logical view: not all measurements were performed with respect to the next higher structure as shown in Fig. 3.

4.2. Pixel survey

The pixel endcap survey includes measurements on modules, blades, half-disks, half-layers and the endcaps. All components are surveyed completely. Measurements are conducted with coordinate measuring machines, either equipped with touch probes or camera. The typical accuracy is a few µm up to a few tenths of µm, due to extrapolation from different measurements.

The pixel barrel will only partially be surveyed. A survey of sensors mounted on the half-barrel ladders is proceeding with measuring the sensors relative position to each other in rφ and z. Only those ladders that are on the outer side of a shell can be accessed with the photogrammetry; modules on the inner ladders will be aligned relative to the outer ladders using tracks with help of the relatively large overlap of 2 mm. A precision of 20 µm can be reached.

4.3. Strip survey

The detail with which the strip tracker has been surveyed varies greatly between subdetectors. The TIB and TID have been surveyed completely. For the TOB, only global mounting precision of rods in the TOB wheel is available, missing values for each individual rod. Module fixation inserts on rods and the TOB wheel position in the tracker have been surveyed completely. For the TEC, information about the mounting precision of modules on petals and petals on disks is available, missing values for each individual module and petal. Full measurements are available for disk positions in the TEC and for the TEC in the tracker. The mounting precision of strip tracker elements is given in Table 1 [8]. Where survey data are available, they will be used to update initial module position. This is expected to be especially useful in the case of TIB and TID, where a full survey is available.
Figure 3. Hierarchical representation of the CMS Tracker structure, as used in alignment. (From Ref. [7])

Table 1. Estimated assembly precision (RMS, in µm) of tracker components. Values are given in between the mechanical hierarchy levels they are valid for, e. g. the position accuracy of sensors in modules is 10 µm.

| TIB  | TID  | TOB       | TEC  |
|------|------|-----------|------|
| Sensor Module | 10 | Sensor Module | 10 |
| Shell | 180 | Ring | 30 |
| Cylinder | 450 | Disc | 100 |
| Tube | 750 | Cylinder Tube | 140 (rφ), 500 (z) |
| TIBHfBarrel | | TOBhFBarrel | |
| TIBEndcap | | TOBEndcap | |
| TIBLayer | | TOBLayer | |
| TIBHalfCylinder | | TOBHalfLayer | |
| TIBModule | | TOBModule | |
| TIBShell | | TOBShell | |
| TIBTube | | TOB CMS | |
| TIBCylider | | TOBCylider | |
| TIBDisc | | TOBDisc | |
| TIBRing | | TOBRing | |
| TIBPetal | | TOBPetal | |
| TIBPetal | | TOBPetal | |
| TIBRd | | TOB Rdl | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
| TIBDisc | | TOBDisc | |
| TIBWheel | | TOBWheel | |
| TIBTube | | TOBTube | |
| TIBCMS | | TOBCMS | |
4.4. Usage of survey measurements in alignment

At first order, survey can be used to define the initial position of modules for startup reconstruction. However, track based alignment can place modules far from their true position as long as the $\chi^2$ is being minimized. In general, the covariance matrix of the alignment parameters contains small eigenvalues that correspond to only weakly measured correlated module movements. Using survey measurements in the track based alignment procedure can prevent such unwanted correlated movements and increase alignment quality. In order to achieve this goal, a survey $\chi^2$-contribution

$$\chi^2_{\text{survey}} = \sum_i \epsilon_i^T V_i^{-1} \epsilon_i,$$  

is introduced, where $\epsilon$ is the survey residual (difference between surveyed and fitted position) and $V_i$ the corresponding covariance matrix. The sum extends over all hierarchies $i$ as described in section 4.1. In the case of vanishing correlations between survey measurements the $\chi^2$ contribution of each measurement can be written in terms of the hierarchy index $i$ and coordinate $j = x, y, z$ as

$$\chi^2_{\text{survey}} = \sum_i \left[ \sum_{j=x,y,z} \frac{(R_{i,j} - r_{i,j})^2}{\sigma_{R_{i,j}}^2} + \sum_{j=x,y,z} \frac{(\Omega_{i,j} - \omega_{i,j})^2}{\sigma_{\Omega_{i,j}}^2} \right].$$

Here $r_{i,j}$ is the aligned position, $R_{i,j}$ the surveyed position with its standard error $\sigma_{R_{i,j}}$. Accordingly $\omega_{i,j}$ is the fitted rotation, and $\Omega_{i,j}$ the surveyed position with its associated standard error $\sigma_{\Omega_{i,j}}$.

Figure 4. Sketch of active Laser Alignment System components.

5. The Laser Alignment System

The Laser Alignment System (cf. Figure 4) operates at a wavelength of $\lambda = 1075$ nm and is designed to provide relative TEC disk position and relative TIB vs. TOB vs. TEC position with a precision of better than 100 $\mu$m and 100 $\mu$rad and monitoring at the 10 $\mu$m level. Additionally it provides a link between the tracker and the muon system with less than 150 $\mu$m and less than $< 60 \mu$rad resolution. In the TECs, eight beams are distributed equally in $\phi$ at radii 564 mm...
and 840 mm. The incoming laser beams are divided in two beams of opposite direction with the help of beam splitters (BS) in disk 6. The beams penetrate from layer to layer through the silicon detectors in a laser-light semi-transparent opening of approximately 1 cm radius in the backside metallization, inducing a signal in the silicon modules. A special anti-reflective coating reduces reflection to be $\leq 6\%$ and increases transmission to $13 - 20\%$. In the barrel eight beams are unequally distributed in $\phi$ between TIB and TOB. They pass through five layers in each TEC. They run in alignment tubes (AT) between TIB and TOB and are partially deflected by semi-permeable mirrors into six modules in the innermost layer of TOB and six modules in the outermost layer of TIB, allowing relative sub-detector position measurements. Several measurements are taken for each beam. The intensity of the laser beams is subsequently adjusted to reach an optimal signal to noise ratio in each module.

During the integration of one TEC in Aachen [11], the performance of the Laser Alignment System has been evaluated by comparing to survey and alignment with tracks from cosmic muons [12]. Measurements for the disk positions in $x$ and $y$ as well as the rotation angle $\gamma$ around the disk axis are shown in Figure 5. An overall agreement of better than 50 $\mu$m in $x, y$ and 40 $\mu$rad in the rotation angle $\gamma$ is obtained from the data.

![Figure 5. Comparison between alignment with tracks from cosmic muons, the Laser Alignment System, and survey. Coordinates of the aligned disk $x$- and $y$- positions are given as well as the rotation angle $\gamma$ around the disk axis. Shown values are relative changes with respect to ideal position.](image)

6. Track based alignment
6.1. Alignment data flow
Figure 6 shows the alignment data flow. Part of the data recorded by CMS and selected by the High Level Trigger (HLT) are used for alignment purposes. This includes data from special calibration and alignment runs as it is the case for the Laser Alignment System, and collision events that are of interest both for alignment and physics analysis. These events are reconstructed with low latency at the CMS Tier-0 [13], called “prompt reconstruction”. A special reduced event format is written to the CMS Analysis Facility (CAF). All physics events are being stored in a large buffer for 24 hours. At the CAF, the reduced event data are input to the alignment procedure (LAS and track based alignment). Alignment parameters are determined, validated and saved to a database. The alignment procedure needs to be ready before 24 hours have passed, in order to be used for the reconstruction and production of AOD of all physics events.
6.2. Alignment algorithms

CMS has developed three complementary alignment algorithms for track based alignment. The main objective is to solve quickly and reliably the system of linear equations of order $O(100000)$. The first algorithm is an extension to the well-known global Millepede algorithm [14] that takes all correlations into account and has been shown to successfully align the most sensitive 50000 parameters [15]. The second is a novel approach using a Kalman Filter [16], which bridges the gap between global and local algorithms by taking into account only the most important correlations. In addition the HIP [17] algorithm, which takes into account only parameter correlations within a module, has been developed in parallel. In this algorithm, correlations between modules are dealt with implicitly by iterating the alignment many times. All three methods are expected to be able to provide alignment constants for the full silicon pixel and strip tracker.

6.2.1. HIP

In a Monte Carlo study [18], the HIP algorithm has been used to align 504 from 750 pixel barrel modules, where the reduced number comes from the requirement that tracks need to have hits in each pixel layer. Tracks from 500000 $Z \rightarrow \mu^+\mu^-$ events have been used, and a precision of 25 $\mu m$ has been reached. The left part of Figure 7 shows the differences $\Delta x$, $\Delta y$ and $\Delta z$ between the true and calculated positions as a function of the iteration, and their distribution before alignment and after 1, 10 and 19 iterations, respectively. Improved results can be obtained by using longer tracks in a full tracker alignment approach.

6.2.2. Kalman Filter

The Kalman Filter alignment algorithm has been used to align 44 TIB modules with 100 000 single muon tracks with a $p_T > 100$ GeV [19] in a Monte-Carlo study. The pixel detector has been fixed and used to determine the coordinate system. The evolution of the alignment parameters as a function of the processed track number can be seen in the right part of Figure 7. TIB modules were misaligned initially with an RMS in the most sensitive coordinate $x$ across the strips of 120 $\mu m$, and the achieved precision after alignment is 2 $\mu m$.

6.2.3. Millepede

A full detector alignment with the Millepede alignment algorithm involving 44432 parameters has been performed with simulated data [20], assuming data available
Figure 7. Left and middle plot show results from alignment of 504 pixel barrel modules with the HIP algorithm and tracks from $Z \rightarrow \mu^+ \mu^-$. Left: Deviation of module position as a function of HIP iteration. Middle: Histogram of module position at HIP iterations 0, 1, 10 and 19. The right plot shows results from alignment of 44 TIB modules with single muon tracks and the Kalman Filter algorithm.

Corresponding to 500 pb$^{-1}$: 500,000 events from $Z \rightarrow \mu^+ \mu^-$ with vertex and mass constraint, 3 million single muon tracks from $W \rightarrow \mu\nu$ and 25,000 tracks from cosmic muons. The results are shown in Figure 8 and compared to the initial misalignment (short term) and to a predicted long term misalignment. A precision of about 10 µm, better than predicted, can be reached for barrel modules, whereas the performance in the endcap modules is with 23 µm close to the predicted value. In the pixel detector, a precision of 1.2 µm can be reached for most sensitive coordinate $r \phi$ in the barrel, compared to 2.5 µm in the endcaps.

Figure 8. Full tracker alignment with the Millepede algorithm. The overall precision of the most sensitive coordinate $r \phi$ is shown a) for barrel modules and b) for endcap modules, respectively.
7. Conclusions

The CMS tracker alignment strategy uses survey, laser alignment and track information to achieve highest possible precision at any time. A successful full tracker alignment has been performed with the Millepede algorithm. The strategy foresees feedback within less than 24 hours during data taking in order to be able to reconstruct data with fresh alignment constants. CMS will thus be well prepared for exciting physics discoveries as soon as collision data arrive.

Acknowledgements

I would like to thank my CMS colleagues for their support in preparing the presentation and this document.

[1] CERN-2004-003, Vol 1 ‘The LHC Main Ring’.
[2] CERN/LHCC 98-6, ‘The Tracker Project Technical Design Report’.
[3] CERN/LHCC 2000-016, ‘Addendum to the CMS Tracker TDR’.
[4] I. Belotelov et al., CMS NOTE 2006/008, ‘Simulation of Misalignment Scenarios for CMS Tracking Devices’.
[5] T. Lampén et al., CMS NOTE, in preparation.
[6] A. Rizzi, F. Palla, and G. Segneri, CMS Note 2006/019, 2006, ‘Track impact parameter based $b$-tagging algorithm in CMS’.
[7] E. Widl, private communication.
[8] CMS Collaboration, ‘The CMS experiment at the CERN LHC’, Submitted to the Journal of Instrumentation (JINST).
[9] M. Stoye, these proceedings.
[10] E. Widl, these proceedings.
[11] R. Bremer né Brauer, ‘Integration of the End Cap TEC+ of the CMS Silicon Strip Tracker’, Ph. D. thesis, RWTH Aachen (2008). (urn:nbn:de:hbz:82-opus-23365).
[12] D. Sprenger, Diploma Thesis RWTH Aachen, 2008.
[13] CERN/LHCC-2005-023, ‘The Computing Project Technical Design Report’.
[14] P. Schleper, G. Steinbrück, M. Stoye, CMS Note 2006/011, ‘Software Alignment of the CMS Tracker using MILLEPEDE II’.
[15] M. Stoye, CERN THESIS 2007-049, ‘Calibration and Alignment of the CMS Silicon Tracking Detector’.
[16] E. Widl, R. Frühwirth, W. Adam, CMS Note 2006/022, ‘A Kalman Filter for Track-based Alignment’.
[17] CMS V. Karimäki, A. Heikkinen, T. Lampén and T. Lindén, Conference Report 2003/022, ‘Sensor Alignment by Tracks’, In Proceedings of the CHEP2003 - International Conference on Computing in High Energy and Nuclear Physics, La Jolla, San Diego, California, USA, March 24-28.
[18] V. Karimäki, T. Lampén, F. P. Schilling, CMS Note 2006/018, ‘The HIP Algorithm for Track Based Alignment and its Application to the CMS Pixel Detector’.
[19] E. Widl, R. Frühwirth, W. Adam, CMS Note 2006/022, ‘A Kalman Filter for Track-based Alignment’.
[20] G. Flucke, P. Schleper, G. Steinbrück, M. Stoye, CMS Note 2008/008, ‘A Study of Full Scale CMS Tracker Alignment using High Momentum Muons and Cosmics’.