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# The CMS Tracker Alignment Strategy

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## Abstract

CMS silicon Tracker alignment consists of three key components: Survey during tracker construction, measurements with the Laser Alignment System during operation and track based alignment. Methods and results are explained in detail, with a special focus on track based alignment due to its enormous complexity and numerical challenges.

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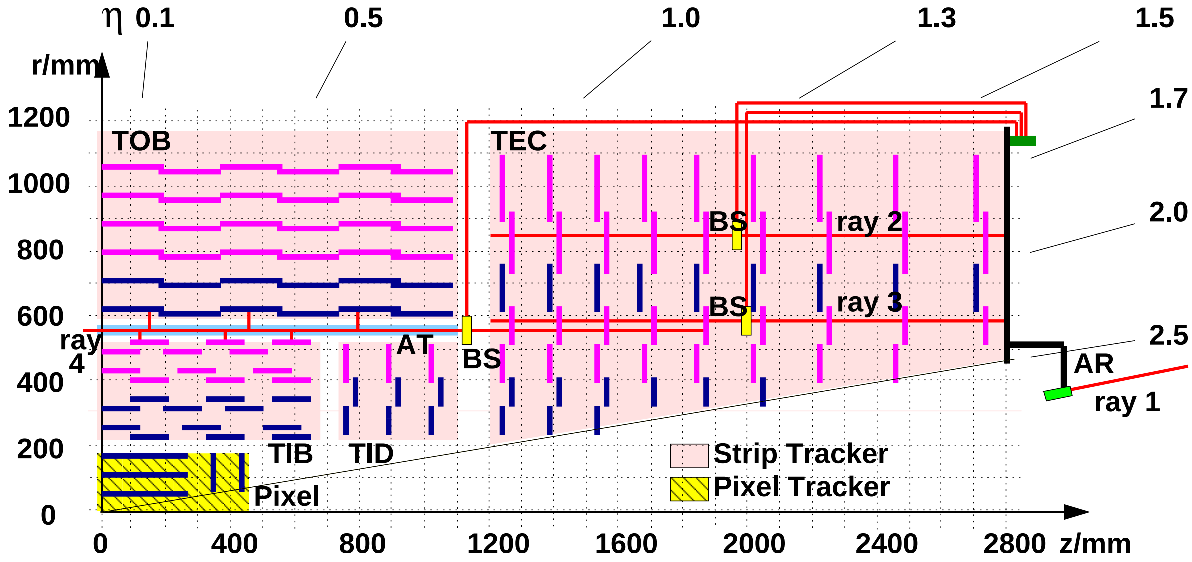

Figure 1: Overview of one quarter of the CMS Tracker in the $r$-$z$-plane. The Pixel and the Strip Tracker are shown together with the Laser Alignment System.

## 1 Introduction

The CMS Tracker [1] comprises both a silicon pixel vertex and a silicon strip tracker (Fig. 1). The Pixel Tracker is built from 1440 pixel modules with a pixel size of $100\,\mu\text{m}(r\phi) \times 150\,\mu\text{m}(z)$, amounting to a total of 66 million readout channels. With analogue signal interpolation of charge sharing induced by the large Lorentz angle $\alpha_L \approx 23°$, a single hit resolution of $10\,\mu\text{m}(r\phi) \times\ 20\,\mu\text{m}(z)$ can be reached.

The Silicon Strip Tracker comprises 15 148 single-sided silicon strip modules with strip pitches from 80–205 $\mu$m, in total 9.3 million readout channels. The single-strip resolution varies from 23–59 $\mu$m in the sensitive coordinate. For each possible track trajectory, at least four 2d-measurements are obtained by assembling two modules back-to-back with a stereo angle of 100 mrad, leading to a stereo resolution of 230–520 $\mu$m.

In order to not deteriorate the track parameter resolution and thus the CMS physics reach significantly, the position[1] of all modules needs to be known to a level of better than 10 $\mu$m for the sensitive coordinate.

Clearly this is beyond the accuracy with which the huge cylindrical Tracker, 5.6 m long and 2.4 m in diameter, is constructed. Additional module position uncertainties arise e. g. from forces caused by the 4 T magnetic field, access or by cooling the Tracker to -10°C silicon operating temperature. There are potentially time-dependent contributions from e. g. out-gassing from the carbon fiber support structure in dry nitrogen, too.

Aligning (i. e. determining the position of) the 15 148 silicon strip and 1440 Pixel Tracker modules of the CMS Tracker is an unprecedented task, requiring development of novel techniques due to its computational complexity, and a well planned overall strategy.

## 2 Alignment strategy

Tracker alignment exists of three key components: Tracker survey, the Laser Alignment System (LAS) and track based alignment. Many Tracker survey measurements already exist and examples are described in section 3. They will provide, together with the experience from Tracker integration, first position corrections even before the completed Tracker operates. Since the survey accuracy depends on the surveyed objects and the survey method, some of those measurements bear uncertainties which are large compared to the Tracker resolution.

When the Tracker has been commissioned in CMS and operates, the LAS, described in detail in section 4, will constrain relative sub-detector position with a precision of about 100 $\mu$m to allow initial track reconstruction. An improved alignment will then be obtained with charged particle tracks, the most powerful tool for alignment. The Pixel Tracker will be aligned standalone with tracks from first data to the level of 10 $\mu$m, described in detail in section 5.1.

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[1] Throughout this article, “position” refers to both position and orientation.

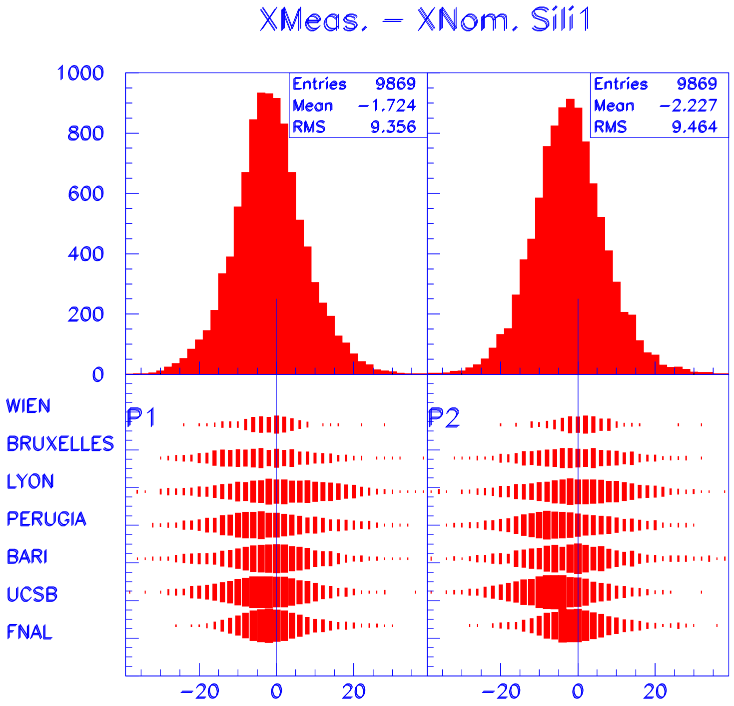

Figure 2: Accuracy of sensor placement in modules. The distribution shows the difference between measured and nominal $x$ coordinate (in $\mu$m) for all module assembly centers.

It then acts as a reference system for the Strip Tracker, which will be aligned after a high-statistics data sample of 1 $\mathrm{fb}^{-1}$ has been collected. The expected alignment accuracy of $< 20\,\mu$m is expected to last for the data taking period between 1–5 $\mathrm{fb}^{-1}$, after which a final alignment is expected.

The necessary algorithms to align the Tracker are still under development, and the capability to align the full Tracker has not yet been shown. However, as will be described, all algorithms have been implemented in the CMS software and tested to perform well on a smaller scale, such that only the scaling to the full problem still needs to be proven. The alignment data flow has already been successfully tested in a large-scale computing exercise.

Part of the CMS Tracker alignment strategy is to supply physicists with the necessary tools, which are described in section 6, to incorporate the (expected) remaining misalignment in their physics analysis.

## 3 Detector Assembly and Survey

During construction and assembly of the CMS Tracker, a vast number of measurements have been performed to verify the desired mechanical accuracy for most Tracker components. In some cases those data allow to correct for the imperfections of the construction process, i. e. in cases where a significant amount of objects have been surveyed. One example is the measured position of sensors in modules (Fig. 2) that shows an overall accuracy of $\sigma_x < 10\,\mu$m in the sensitive coordinate. Another example is the survey of the Tracker Endcaps by photogrammetry (Fig. 3). It shows a mechanical accuracy of the endcap discs of $100\,\mu$m in the $r\phi$-plane. Both these measurements can be used to correct for the actual module position. In cases where only samples have been surveyed, the measurements will be used to estimate the position uncertainty.

## 4 The Laser Alignment System

The Laser Alignment System (LAS) uses infrared laser beams with a wavelength $\lambda = 1075$ nm to monitor the position of selected Tracker modules. It operates globally on Tracker substructures: Inner Barrel (TIB), Outer Barrel (TOB), and Endcap (TEC) discs$^{2)}$. Therefore it cannot determine the position of individual modules. The goal of the system is to generate alignment information on a continuous basis, providing geometry reconstruction of the Tracker substructures at the level of $100\,\mu$m, which is mandatory for track pattern recognition and for the

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$^{2)}$ The LAS does not include Inner Discs (TID) and Pixel.

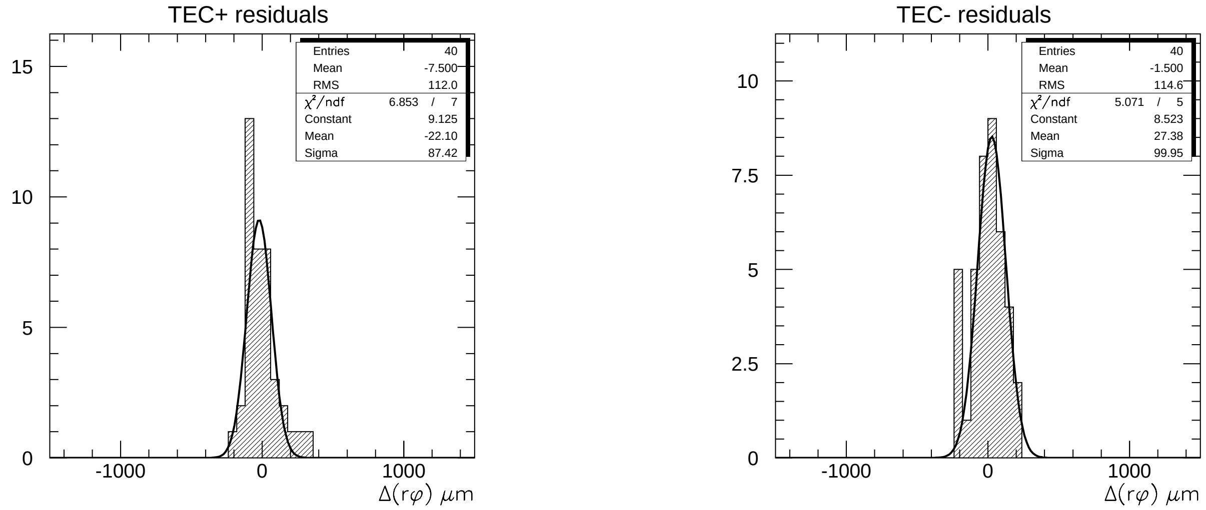

Figure 3: Residuals of Tracker Endcap mechanical structure measurements compared to the ideal cylinder (in $\mu$m).

High Level Trigger. In addition, possible Tracker structure movements can be monitored at the level of $10\,\mu$m, providing additional input for the track based alignment.

The LAS design is illustrated in Fig. 1. Each TEC uses in total 16 beams, distributed in $\phi$ and crossing all nine TEC discs at two different radii. Here special silicon sensors with a $10\,$mm hole in the backside metalization and an anti-reflective coating are mounted. The beams are used for the internal alignment of the TEC discs. The other eight beams are foreseen to align TIB, TOB, and both TECs with respect to each other. Finally, there is a link to the Muon system, which is established by 12 laser beams (six on each side) with precise position and orientation in the Tracker coordinate system.

In the TECs, the signal induced by the laser beams on the silicon sensors decreases in height as the beams penetrate through subsequent silicon layers. To get optimal signals on all sensors, a sequence of laser pulses with increasing intensities, optimized for each silicon layer, is generated. Several triggers per intensity are taken and the signals are averaged. In total, a few hundred triggers are needed to get a full picture of the alignment of the Tracker structure. Since the trigger rate for the alignment system is around $100\,$Hz, this will take only a few seconds. Such snapshots will be taken at regular intervals, both in dedicated runs and during physics data taking.

## 5 Alignment with Tracks

Experience from other experiments has shown that collision data are not sufficient to constrain certain correlated module movements enough to obtain a unique set of alignment constants. Therefore complementary data and constraints need to be exploited. Examples are tracks from cosmic muons (with and without magnetic field) that constrain the Tracker barrel modules, or beam halo muons for the endcap. Beam gas and minimum bias events are also under consideration. Typical examples of constraints are a vertex and/or mass constraint for decay particles e. g. from $Z \to \mu^+\mu^-$ or jets, “tracks” from the Laser Alignment System, and survey constraints.

### 5.1 Pixel Tracker Alignment with Tracks

The Hits- and Impact-Points algorithm (HIP) is used to align the Pixel Tracker [2]. HIP is a local $\chi^2$-algorithm (i. e. neglecting correlations between modules) and uses biased track residuals. Therefore it needs to iterate over the track sample many times, updating the alignment estimate and refitting all tracks in each iteration. Because it neglects correlations between modules, it only needs to invert $6 \times 6$-matrices and thus is very fast. It has been used in a simulation exercise to align 504 out of the 750 Pixel Tracker barrel modules in a scenario where modules were shifted with a flat random distribution of $\pm 300\,\mu$m. The number of modules were limited by the fact that only those modules were considered that contribute to tracks with a hit in each pixel layer. The track sample were 500 000 $Z \to \mu^+\mu^-$ events corresponding to $0.5\,\mathrm{fb}^{-1}$ of integrated luminosity, and a vertex constraint was applied. The residuals (Fig. 4) show an RMS of $\Delta x \approx \Delta y \approx \Delta z, \approx 25\,\mu$m which is not yet the desired goal of $10\,\mu$m. Therefore additional track samples which are available during first data taking are under evaluation, e. g. tracks from minimum bias events.

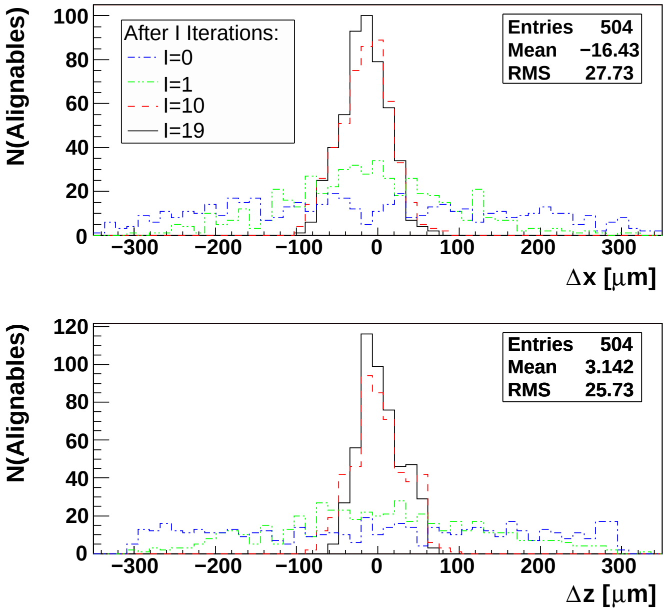

Figure 4: Residuals after Pixel Tracker alignment for 504 modules, visualized for different iteration steps.

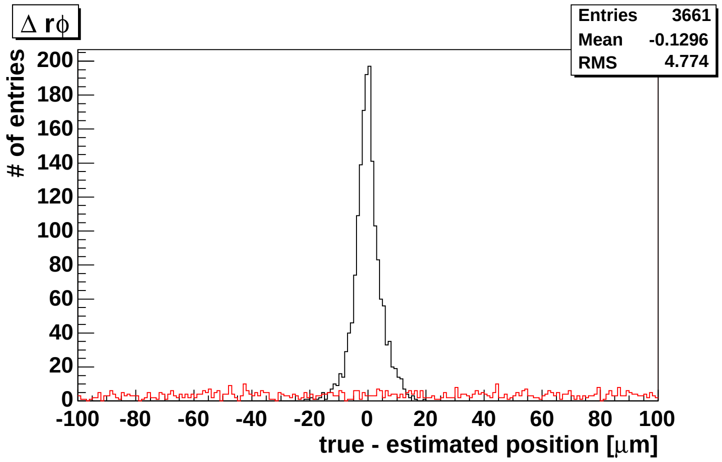

Figure 5: Residuals of most sensitive alignment parameter for Millepede II alignment.

## 5.2 Strip Tracker Alignment with Tracks

Two alignment algorithms are currently being studied. The first, Millepede II [3], is based on the Millepede I algorithm, which computes an optimal solution to the alignment problem where all correlations are properly taken into account [4]. Since Millepede I is based on matrix inversion for the solution of the system of linear equations, which is computationally expensive and poses numerical problems when applied to the full Strip Tracker, it is being upgraded with a fast numerical solver replacing matrix inversion, rendering the problem dramatically less computationally expensive, and preserving the optimal behavior.

A simulated alignment of barrel modules with 12 015 free parameters has been performed with Millepede II. 1.8 million tracks from $Z \to \mu^+\mu^-$ without vertex or mass constraint were used, while the Pixel Tracker and the outermost Tracker layer were fixed to their ideal position. The residual distribution in the sensitive coordinate is shown in Figure 5, with an RMS better than $5\,\mu$m. Results agree with the Millepede I calculation within $0.1\,\mu$m.

The second algorithm under study and in development is based on a Kalman Filter [5]. It is an optimal iterative linear least-squares estimator. “Iterative” means that the alignment estimate is updated after each track. The computational complexity of the algorithm is reduced by restricting the update to detectors which are close according to a certain metric, which introduces a certain amount of correlation bookkeeping. In a simulation study, the algorithm has been used to align 44 TIB modules in a part of the Strip Tracker. 100 000 fast simulated single muon

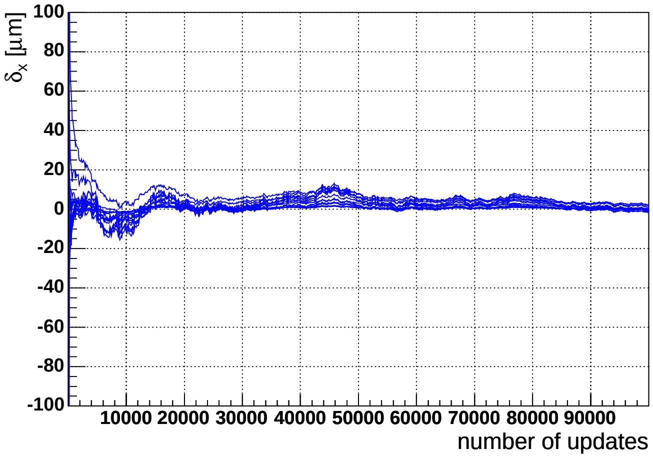

Figure 6: Residual of most sensitive alignment parameter for Kalman Filter alignment as function of the update number.

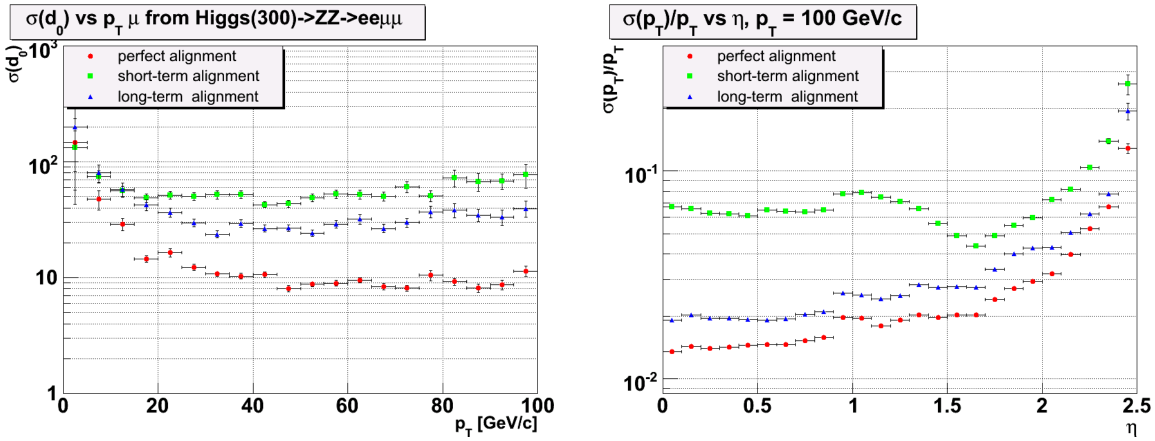

Figure 7: Impact of misalignment on transverse track impact parameter resolution as a function of transverse track momentum (top), and on transverse momentum resolution as a function of pseudo-rapidity (bottom).

tracks with $p_\perp = 100\,\mathrm{GeV}$ have been used, and the Pixel Tracker has been kept fixed as a reference. The residual RMS (Fig. 6) is about $2.5\,\mu$m.

# 6 Misalignment

CMS has estimated the module position uncertainty to be used for physics analysis in two different scenarios [6]. The first, “short-term alignment”, reflects CMS startup conditions. Here, a first pixel detector alignment with tracks is assumed, and the LAS has been used to constrain relative sub-detector position. It is expected to be valid until a reasonable luminosity $\mathcal{L} \approx 1\,\mathrm{fb}^{-1}$ has been collected.

The “long-term alignment” scenario reflects the situation after a high-statistics track sample, e. g. from $Z \rightarrow \mu^+\mu^-$, has been used to align the Strip Tracker. It reflects the data taking period from $\mathcal{L} \approx 1..5\,\mathrm{fb}^{-1}$. For the studies described in section 5.2, the Strip Tracker has been misaligned with the “short-term scenario” for Millepede and with this scenario for the Kalman filter.

The final precision with which the module position is known is expected to be better than in the “long-term alignment”, but not yet estimated.

Misalignment deteriorates the precision with which track parameters can be measured, and thus all quantities derived from track measurements are affected. Figure 7 shows two examples of the impact of misalignment on Tracker performance, namely the momentum and transverse impact parameter resolution.

## 7 Acknowledgments

I would like to thank my colleagues for many years of fruitful collaboration and the conference committee for the excellent organization and inspiring atmosphere.

## References

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