Track-based alignment in the CMS detector

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Abstract
The strategy for track-based alignment of the CMS tracking and muon detectors is presented. After an overview of the data samples used, the general alignment strategy is presented, with a focus on the procedures envisaged at the start of data-taking in 2007/8. The three currently used alignment algorithms are discussed and the first results of their application on the CMS tracker are presented, as well as studies on the alignment of the Muon detector with tracks.

20.1 Introduction

The alignment of the CMS tracking and muon detectors represents a demanding challenge, because the number of alignment parameters to be determined with high accuracy is very large. In particular, aligning the $\sim$ 15 000 silicon modules of the pixel and strip trackers with a precision which is comparable to or better than their intrinsic resolution of 10–50 μm, requires solving a problem with $\mathcal{O}$(100 000) unknowns. In addition to survey measurements at construction time and optical (laser) alignment [1, 2], track-based alignment will be a necessary ingredient to approach this huge challenge (see also Ref. [3]).

At the time of this workshop, a lot of activities related to track-based alignment were already ongoing in CMS, and are summarized in Ref. [4]. Three different alignment algorithms have been implemented in the CMS software within a common framework. Alignment studies applying these algorithms to various Monte Carlo data sets have been performed. The advantage of having several algorithms at your disposal is that the results obtained can be cross-checked using different algorithms with different systematics (see Section 20.2 on the data sets considered for alignment). Other activities related to track-based alignment are the development of a dedicated alignment stream produced during the prompt reconstruction at the Tier-0, which uses a special reduced data format ('AlCaReco'). It will enable us to run track-based alignment with a short turn-around time after the data have been taken. Moreover, a framework is being developed in order to combine the results of track-based and laser alignment with survey data. The benefits of using mass and vertex constraints, as well as of overlapping tracker modules are also studied. Further work is ongoing in order to establish observables sensitive to misalignment other than χ^2, in order to fix global transformations which leave the χ^2 unchanged.

20.2 Data samples

The following data samples are currently considered for alignment:

- *High-p_{t} muons from Z, W*
  These constitute the primary source of high-quality tracks for alignment, because of their high transverse momentum and small amount of multiple scattering in the tracker material. A compilation of the expected event rates after the HLT is shown in Table 20.1.
- *Cosmic muons*
  Cosmics are a valuable source of tracks since they are available before the first beams are in the LHC machine. They are particularly useful for the alignment of the barrel tracker and muon detectors. Estimates show that the rate for cosmic muons accepted by the L1 trigger and stand-alone muon reconstruction is around $\sim$ 400 Hz [5].
- *Beam halo muons*
  As soon as the LHC is commissioned with single beams, near-horizontal beam halo muons constitute a valuable source of tracks for the alignment of the tracker and muon end-caps. A rate of $\sim$ 5 kHz is expected per side accepted by the L1 muon trigger and stand-alone muon reconstruction [5]. A problem arises for the tracker since the muon end-cap trigger has no acceptance for radii covered by the tracker end-cap. In order to trigger beam halo muons within the tracker acceptance, dedicated scintillators will be installed.

- *Muons from J/Ψ and b hadron decays*
  Even though having a comparatively small transverse momentum spectrum, these will be very useful, in particular at the start-up of the LHC, when luminosities will be modest and muons from Z, W decays not yet available. In addition, for muons from $J/\Psi \to \mu^+\mu^-$ an invariant mass constraint can be used.
- *Isolated tracks from QCD events*
  At low luminosities this will be the only source of collision tracks which might be useful for alignment. Multiple scattering in the tracker material is clearly an issue, but studies show that these events could be beneficial at least for the alignment of the pixel detector.

20.3 Alignment strategy

The earliest information on the tracker and muon alignment will come from survey measurements carried out during construction, as well as from the laser alignment systems. The alignment can then be improved upon with cosmic and beam halo muons. The current LHC start-up schedule foresees a 2–3 week *calibration run* at $\sqrt{s} = 900$ GeV and luminosities not exceeding $10^{29}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the end of 2007. Since no high-p_t muons from W, Z decays will be available under these conditions, minimum-bias QCD events will constitute the only source of tracks for alignment. In addition, the pixel detector will not yet be installed. If possible, a first track-based alignment of composite strip tracker structures (layers, etc.) would be performed.

During the winter shutdown 2007/8 the pixel detector will be installed and the subsequent *pilot physics run* will strive for luminosities up to $10^{32}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This will allow large statistics of high-quality muon tracks from W, Z decays to be accumulated in a short time (Table 20.1). A two-step procedure is currently foreseen to align the tracker: first, a stand-alone alignment of the pixel detector will be carried out. Second, the strip tracker will be aligned using the pixel detector as a reference system.

20.4 Alignment algorithms

Track-based alignment has proven to be the optimal method for the alignment of large tracking detectors in previous experiments. However, it represents a major challenge at the CMS because the number of degrees of freedom involved is very large: considering 3+3 translational and rotational degrees of freedom for each of the $\sim$ 15 000 modules leads to $\mathcal{O}$ (100 000) alignment parameters, which have to be determined with a precision of $\sim 10\ \mu\mathrm{m}$. Moreover, the full covariance matrix is of size $\mathcal{O}$ (100 000 $\times$ 100 000).

In CMS, three different track-based alignment algorithms are implemented in the reconstruction software, using a common software framework. Some of them have been successfully used at other experiments, others are newly developed. In the following sections, the main features and initial results of using these algorithms in CMS are summarized.

20.4.1 General software framework

Within the CMS software it is not necessary to apply (mis)alignment corrections to the geometry at the simulation step. Instead, (mis)alignment can be applied ‘on the fly’ during reconstruction. Dedicated software tools have been implemented to move and rotate parts of the tracking or muon detectors in a hierarchical way [6]. In addition, a so-called *alignment position error* can be added to the intrinsic uncertainty of reconstructed hits in order to take into account the effects of misalignment in the track reconstruction. Two dedicated *misalignment scenarios* [7] have been implemented which emulate the expected misalignment for different phases of data taking: the *First Data Taking* scenario and the *Long Term* scenario (for details see Ref. [8]). A fast track refit has been implemented in the reconstruction software, in such a way that redoing the full pattern recognition is avoided [1].

Alignment studies are performed using the reduced *AlCaReco* format, in which only the tracks used for alignment are kept in the event (e.g., the two muon tracks in the case of $Z^0 \to \mu^+\mu^-$ events). This significantly improves both the disk space needed as well as the alignment algorithm performance.

The alignment algorithms have been implemented in the standard CMS reconstruction software using a common layer of software, which provides all features that are common to all algorithms, for instance the management of alignment parameters and covariance matrices, the calculation of derivatives with respect to track or alignment parameters, input/output, and an interface to the CMS offline conditions database.

20.4.2 HIP algorithm

An iterative alignment algorithm using the Hits and Impact Points (HIP) method was developed [9]. It is able to determine the alignment of individual sensors by minimizing a local χ^2 function depending on the alignment parameters, constructed from the track-hit residuals on the sensor. Correlations between different sensors are not explicitly included, but taken care of implicitly by iterating the method, which involves consecutive cycles of calculating the alignment parameters and refitting the tracks. The algorithm is computationally light because no inversion of large matrices is involved. An alterna-

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[1] The assumption that misalignment does not change the assignment of hits to tracks was verified for the case of not too large misalignments.

tive implementation of the algorithm is designed to align composite detector structures for a common translation and rotation [10], for example pixel ladders or layers. The composite alignment involves only a small number of parameters, and therefore a rather small number of tracks is sufficient to carry out alignment already in the beginning at data-taking.

The HIP algorithm has been used [10] for the alignment of the pixel barrel modules using the First Data Taking misalignment scenario. The pixel end-caps and the strip tracker are not misaligned. The procedure has been iterated 10 times using 200 000 simulated $Z^0 \to \mu^+\mu^-$ events. Figure 20.1 (left) shows the differences between the true and estimated alignment parameters. The convergence is good, with r.m.s. values of $7(23)\ \mu\mathrm{m}$ for the $x, y(z)$ coordinates, respectively. The algorithm was also applied to a test beam set-up [11].

20.4.3 Kalman filter algorithm

A method for global alignment using charged tracks can be derived from the Kalman filter. The method is iterative, so the alignment parameters are updated after each track. It can be formulated in such a way that no large matrices have to be inverted [12]. In order to achieve a global alignment the update is not restricted to the detector elements that are crossed by the track, but can be extended to those elements that have significant correlations with the ones in the current track. This requires some bookkeeping, but keeps the computational load to an acceptable level. It is possible to use prior information about the alignment obtained from mechanical survey measurements as well as from laser alignment. The algorithm can also be extended to deal with kinematically constrained track pairs (originating from particle decays).

The algorithm has been implemented in the CMS software and studied in two small subsets of the silicon tracker: a telescope-like section of the inner and outer barrel, and a wheel-like subset of the inner barrel, consisting of 156 modules in 4 layers. The tracks used were simulated single muons with $p_\mathrm{t} = 100$ GeV. Random misalignment with a standard deviation of $\sigma = 100\ \mu\mathrm{m}$ was applied to the local x and y positions of the modules. Results from the alignment of the wheel-like set-up are shown in Figure 20.1 (right). It shows the evolution of the differences between true and estimated x-shifts for layers 1 and 2. A total of 100 000 tracks were processed. As can be seen, the speed of convergence depends on the layer. For more details, see Ref. [13].

20.4.4 Millepede-II algorithm

Millepede [14] is a well established and robust program package for alignment which has been used successfully at other experiments, for example at H1, CDF, LHCb. Being a non-iterative method, it has been shown that it can improve the alignment precision considerably with respect to other algorithms.

Millepede is a linear least-squares algorithm which is fast, accurate, and can take into account correlations among parameters. In the least-squares fit, local track parameters and global alignment parameters are fitted simultaneously. The solution for the alignment parameters is obtained from a matrix equation for the global parameters only. For N alignment parameters this requires the inversion of a $N \times N$ matrix. However, this method can only be used up to $N \sim 10\,000$ because of CPU and memory constraints. The alignment of the CMS tracker exceeds this limit by one order of magnitude. Therefore, a new version, Millepede-II [15] was developed, which offers different solution methods and is applicable for N much larger than 10 000. In Millepede-II, in addition to the matrix inversion and a diagonalization method, a new method for the solution of very large matrix equations is implemented. This minimum residual method applicable for sparse matrices determines a good solution by iteration in acceptable time even for large N. For more details, see Ref. [16].

Millepede-II has been interfaced to the CMS software and the alignment of parts of the CMS tracker has been carried out using different scenarios [15]. As an example, Fig. 20.2 (left) shows hit residuals in $r\phi$ for the new iterative method. Each individual sensor of the tracker was misaligned. The alignment procedure was carried out in the barrel region ($|\eta| < 0.9$) of the strip tracker using 1.8 million $Z^0 \to \mu^+\mu^-$ events. The pixel layers and the outermost barrel layer were kept fixed, resulting in ~ 8400 alignment parameters. The convergence is very good, and the results obtained are identical to those using the matrix inversion method, but the new method is faster by about three orders of magnitude.

Figure 20.2 (right) shows the required CPU time as a function of the number of alignment parameters for the diagonalization and matrix inversion methods, as well as for the new method used in Millepede-II. It can be seen that Millepede-II is expected to be capable of solving the full CMS tracker alignment problem within reasonable CPU time.

Millepede-II has also been used [17] to investigate the global correlations between alignment parameters for the CMS tracker. It turns out that in certain cases these correlations can be very high (above 99%). Studies show that it is very important to combine samples of tracks with different topologies, such as collision tracks and cosmics, in order to reduce these global correlations.

20.5 Muon alignment

The CMS Muon system consists of 790 individual chambers with an intrinsic resolution in the range 75–100 μm. Excellent alignment of the muon system is particularly important to ensure efficient muon triggering and good track momentum resolution at large momenta, where the resolution is dominated by the muon detector.

For optimal performance of the muon spectrometer over the entire momentum range up to 1 TeV, the different muon chambers must be aligned with respect to each other and to the central tracking system to within 100–500 μm. To control misalignment during commissioning and to monitor further displacements during operation, which can be of the order of 1 mm, the CMS will combine measurements from an optical-mechanical system with the results of track-based alignment [18]. Two approaches are pursued: alignment using tracks which are extrapolated from the tracker, and a standalone muon alignment (Fig. 20.3).

20.6 Conclusions

The alignment of the CMS tracker and muon detectors constitutes a significant challenge because of the large number of parameters ($\sim$ 100 000 in the tracker), as well as the high intrinsic resolution of the detectors.

Even though LHC operation is still more than one year away, a lot of activities related to track-based alignment in the CMS are already ongoing. The initial results obtained with the three alignment algorithms considered are very promising, although a realistic alignment of the full tracker at the sensor level is yet to be demonstrated. In addition, real data from tracker test set-ups and from the *Magnet Test and Cosmic Challenge* are being studied for alignment. Work is ongoing on improving further the alignment software and strategy, in order to be well prepared once the first collisions are delivered by the LHC.

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Table 20.1: Anticipated rates of $W^{\pm} \to \mu^{\pm}\nu$ and $Z^0 \to \mu^+\mu^-$ events after HLT in 2008

Luminosity	10^{32} cm^{-2} s^{-1}		2×10^{33} cm^{-2} s^{-1}		
Time	Few weeks	6 months	1 day	Few weeks	One year
Integrated luminosity	100 pb^{-1}	1 fb^{-1}		1 fb^{-1}	10 fb^{-1}
$W^{\pm} \to \mu^{\pm}\nu$	700 k	7 M	100 k	7 M	70 M
$Z^0 \to \mu^+\mu^-$	100 k	1 M	20 k	1 M	10 M

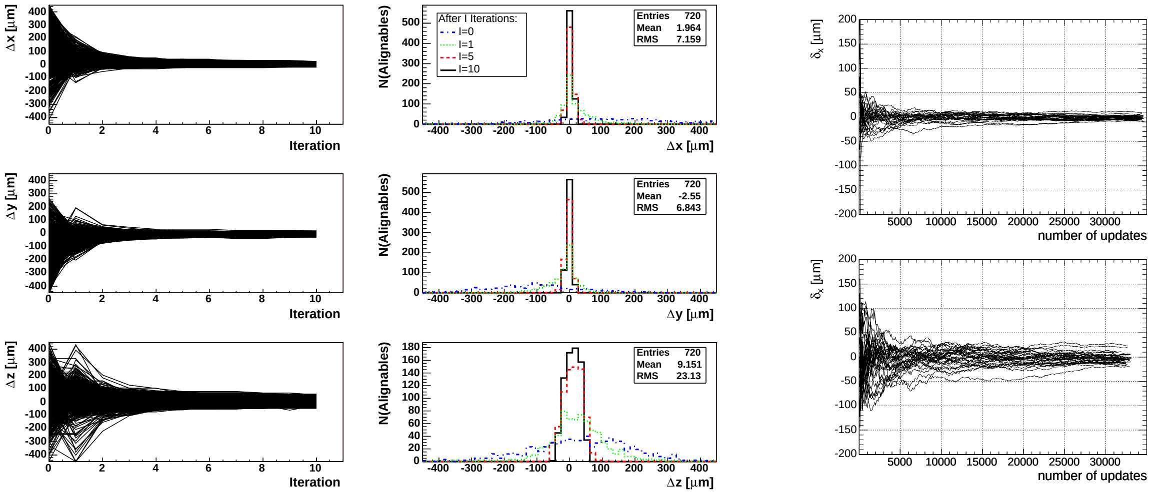

Fig. 20.1: Left: Alignment of the Pixel barrel modules with the HIP algorithm. The residuals in global coordinates are shown as a function of iteration, and projected for 0, 1, 5 and 10 iterations. Right: Kalman filter alignment. Residuals in local x for TIB layers 1 (top) and 2 (bottom) as a function of the number of processed tracks.

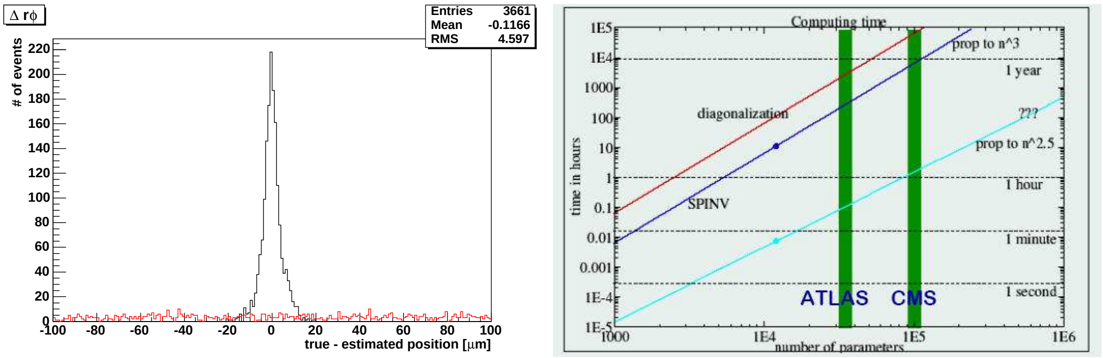

Fig. 20.2: Millepede II: Left: Residuals in $r\phi$ in the strip tracker barrel before (red) and after (black) alignment using Millepede II. Right: CPU time as a function of alignment parameters for matrix inversion (blue) and Millepede II.

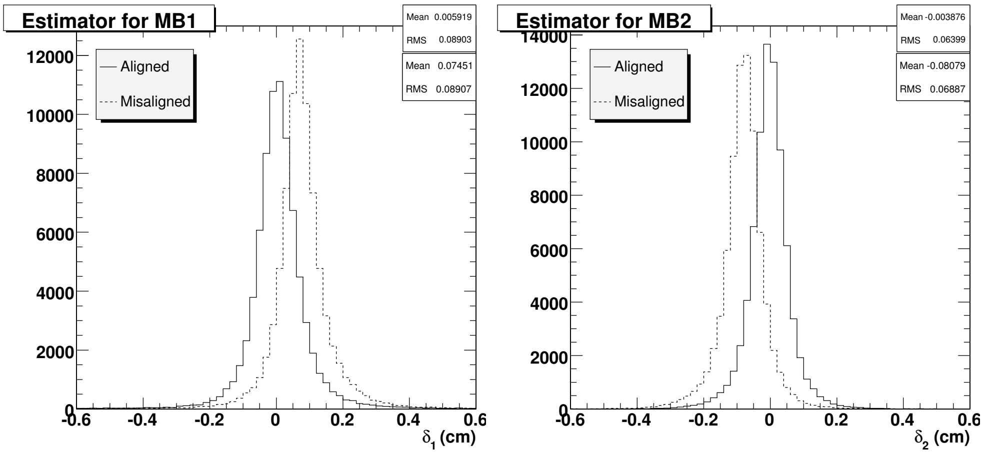

Fig. 20.3: Muon alignment: $r\phi$ estimator for muon chambers in different wheels for aligned (solid line) and ± 1 mm displaced samples of $W^{\pm}$