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Application of the Kalman Alignment Algorithm to the CMS Tracker

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Abstract

One of the main components of the CMS experiment is the Silicon Tracker. This device, designed to measure the trajectories of charged particles, is composed of approximately 16,000 planar silicon detector modules, which makes it the biggest of its kind. However, systematic measurement errors, caused by unavoidable inaccuracies in the construction and assembly phase, reduce the precision of the measurements significantly. The geometrical corrections that are therefore required to be known to an accuracy that is better than the intrinsic resolution of the detector modules.

The Kalman Alignment Algorithm is a novel approach to extract a set of alignment constants from a large collection of recorded particle tracks, and is applicable for a system even as big as the CMS Tracker. To show that the method is functional and well understood, and thus suitable for the data-taking period of the CMS experiment, two case studies are presented and discussed here.

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1 Introduction

The CMS Tracker [1, 2] was designed to provide precise and efficient trajectory measurements. Its mechanical structure consists of a central barrel region and two endcap regions. Inside the barrel region, which itself is divided into the Tracker Pixel Barrel (TPB), the Tracker Inner Barrel (TIB) and the Tracker Outer Barrel (TOB), the modules form concentric cylindrical layers, centered around the nominal beam line. In the endcap regions, composed of the Tracker Pixel Endcaps (TPE), the Tracker Inner Disks (TID) and Tracker Endcaps (TEC), the modules are arranged on parallel disks. The TIB, TOB, TID and TEC form the Silicon Strip Tracker. In the case of micro-strip modules, the coordinate perpendicular to the strips or, in the case of pixel modules, the more fine grained pixel coordinate is referred to as the *precise coordinate*.

The alignment strategy of the CMS Tracker utilizes three different, independent track-based alignment algorithms [3, 4]. This has several advantages, of which the possibility to validate the individual results by comparing them to each other is the most important one. The *Kalman Alignment Algorithm* (KAA) [5, 6] is one of the three methods that is used and in fact has been specifically developed for this purpose, as conventional alignment algorithms face serious problems when applied to systems as big as the CMS Tracker. The difficulties range from unrealistic computing times to numerical difficulties, usually caused by the inversion of large matrices, whereas for the KAA these matters are circumvented by design. However, it had to be proven that the method is performing properly under realistic conditions.

2 The Kalman Alignment Algorithm

The Kalman Alignment Algorithm [5, 6] analyses recorded particle trajectories to obtain a set of alignment constants. It applies the Kalman filter technique [7, 8, 9] to a global track model, that depends not only on the (ideal) track parameters but also the alignment parameters. The tracks are processed one-by-one, updating the alignment parameters at every step. A big advantage of the algorithm is how it accounts for the geometrical and statistical correlations between detector modules. The updates are not restricted to detector modules that were hit by the current track, but in principle include all detector modules at every step. For a system as big as the CMS Tracker, where this becomes impractical, the number of detector modules per update can be restricted to a manageable amount, requiring some additional bookkeeping. Furthermore, the KAA is able to include the full statistical interdependencies between all hits of a trajectory due to material effects like multiple scattering and energy loss.

However, the advantages of this approach come not for free. First of all, the geometrical correlations between the individual detector modules have to be stored, requiring a potentially large amount of virtual memory. Secondly, reading and writing the alignment parameters at every step causes a non-negligible IO overhead. Nevertheless, these problems can be successfully overcome by restricting the number of detector modules per update and careful implementation, as demonstrated by the following examples.

3 Full-scale Tracker Alignment Simulation Studies

3.1 Simulation Setup

To prove the applicability of the KAA to the full-scale Tracker under start-up conditions, keeping also in mind the resources that will be available in terms of computing power and virtual memory, detailed simulation studies have been carried out. Realistic start-up scenarios have been simulated in the course of the Computing, Software and Analysis Challenge 2008 (CSA08) [10], which tried to test – in the manner of a dress rehearsal – the full scope of offline data handling and analysis activities which will be needed for the first months of real data-taking.

The data samples contained event signatures and rates typical for this time period, based on two representative scenarios, referred to as S43 and S156. They correspond to LHC configurations characterized by 43×43 bunches with a luminosity of $\mathcal{L} = 2\times10^{30}$ cm^{-2} s^{-1} and 156×156 bunches with a luminosity of $\mathcal{L} = 2\times10^{31}$ cm^{-2} s^{-1} respectively. The data samples were produced using a full detector simulation under the assumption of a magnetic field strength of 4 T(1) and a center-of-mass energy of 10 TeV. Misalignments and *mis-calibrations* of all detector components were modeled as expected before collisions [11, 12]. Zero suppression was applied to the readout of all detectors and no pile-up was included, since it will not play a significant role during the start-up phase.

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(1) The CMS magnet will be operated at 3.8 T.

3.2 Algorithmical and Computational Aspects

All computations have been done at the CERN Analysis Facility (CAF) [13, 14], a computing farm which will also be used in the future for alignment and calibration with real data. This is especially relevant with respect to the available memory, since the CAF computing nodes are typical commercially available machines fitted with 2 GB of RAM per core.

Bearing in mind the large number of individual detector modules, the available computing resources are a harsh constraint for the KAA. The attempt to align the full Tracker on the level of individual detector modules under these conditions would have failed, mainly because the available amount of virtual memory[2)] would not have been sufficient to store all covariance matrices representing the geometrical correlations. To overcome this issue, the Tracker was aligned in three steps, starting with the outermost silicon micro-strip regions (TOB and TEC), continuing with the inner silicon micro-strip regions (TIB and TID) and finishing with the silicon pixel detector (TPB and TPE).

All of these steps have been carried out using the scheme for a single alignment step as sketched in Figure 1: Utilizing the CMS software framework, dedicated software modules for alignment tasks (called Alignment Producers) were used to run on specially skimmed data-sets containing well isolated particle tracks (called AlCaReco). To speed up the computation, the full data sample was split and processed in parallel on individual cores. The final result was then obtained by calculating the weighted mean of the alignment constants from the independent results. This procedure was automated by using a special production system that handles, submits and monitors all jobs.

3.3 Discussion and Validation of the Results

The results of this alignment exercise were very satisfactory, showing that the algorithm itself as well as the alignment strategy perform as expected. For the *S43 alignment object*, i.e. the set of alignment constants computed from S43 data, a total of two million isolated muon trajectories from collision events, two million muon trajectories from cosmic events and 10,000 Z-decays out of the S43 data-samples have been processed. Figure 2 shows the remaining misalignment in the precise coordinates of the detector modules, projected onto the global coordinate $R\phi$, before (red) and after (black) applying the alignment constants to the misaligned geometry. The improvement is obvious, featuring an overall remaining misalignment with a RMS of $40\,\mu$m in the precise coordinate. The effects of this improvement can also be seen in Figure 3, where the tracking residuals in the TPB are shown for the case of full misalignment (red), the misalignment corrected with the S43 alignment object (black) and absolutely no misalignment, i.e. the nominal geometry (blue).

The importance of the correction of the misalignment is demonstrated in Figure 4. It shows the reconstructed transverse momenta for a sample of simulated muons with $p_{\mathrm{T}} = 100\,\mathrm{GeV}$ for the case of full misalignment (red), the misalignment corrected with the S43 alignment object (black) and absolutely no misalignment, i.e. the nominal geometry (blue). Whereas the misaligned geometry makes measurements of such high momenta impossible, the corrected geometry shows a significant improvement.

To further improve the situation, more data, preferably containing more high-momentum muon trajectories, would have to be analyzed. This was also demonstrated by processing the S156 data samples, using the S43-corrected geometry as starting point, running on two million isolated muon trajectories from collision events, two million muon trajectories from cosmic events and muons from 200,000 W- and 10,000 Z-decays. Due to the increased luminosity a larger fraction of high momentum tracks was available in the S156 data samples. To select these tracks, rather tight momentum cuts were used, which reduced the number of processed tracks. The resulting gain in precision is not enormous but distinct, as the remaining misalignment in $R\phi$ is further reduced to a RMS of $34\,\mu$m. This has a visible impact on quantities like the transverse momentum resolution, as shown in Figure 5, where the distributions for the S43 (black) and the S43+S156 (green) corrected geometries as compared. However, for an ultimate overall alignment precision of approximately $20\,\mu$m, as needed for high precision studies, clearly a larger quantity of trajectories from high energetic particles would be needed.

The computing times were within reasonable limits, using a moderate amount of hardware resources: For both alignment exercises a total of 10 individual cores were used in parallel. It took 15.4 h to complete the S43 alignment exercise and 6.2 h for the S156 alignment exercise.

[2)] This is not the full 2 GB mentioned before, since the analysis software framework needs a certain amount of memory on its own.

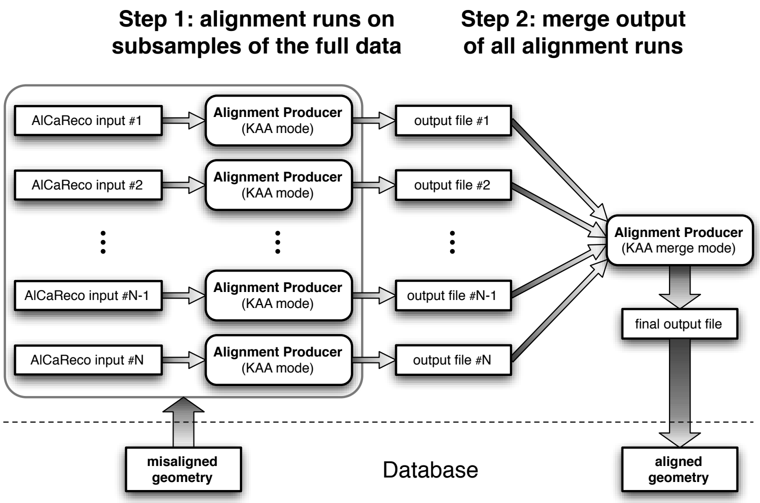

Figure 1: Workflow of the production system for a single alignment step.

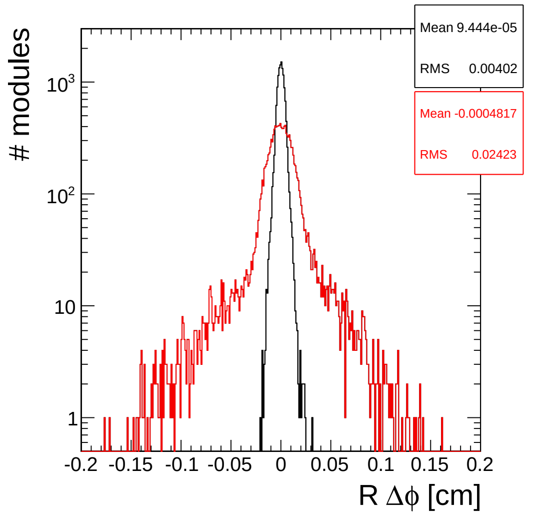

Figure 2: Initial (red) and remaining (black) misalignment after processing the S43 data.

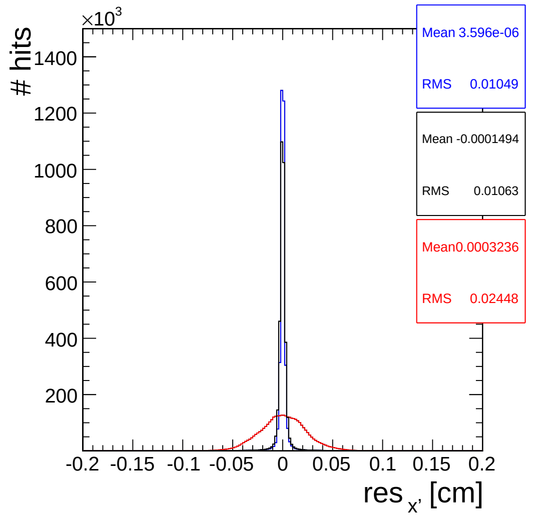

Figure 3: TPB tracking residuals for the ideal (blue), aligned (black) and misaligned (red) geometry.

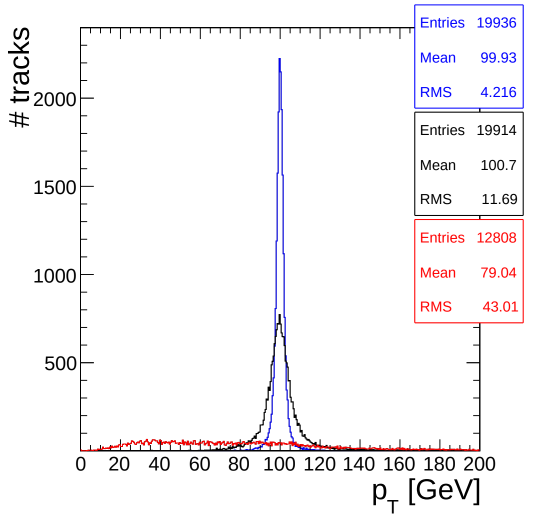

Figure 4: Distribution of the transverse momentum p_T for reconstructed tracks. The colors are the same as in Figure 3.

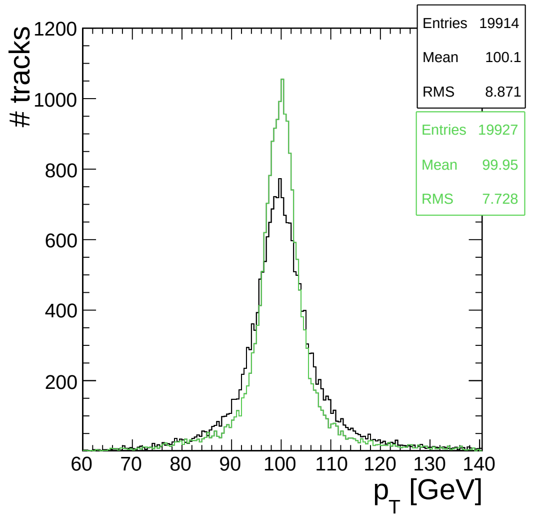

Figure 5: Improved distribution of the transverse momentum p_T for reconstructed tracks, comparing the results for S43 (black) and S43+S156 (green).

4 Results from the Tracker Integration Facility

4.1 Experimental Setup

The final assembly of the CMS Silicon Strip Tracker was carried out at a dedicated facility, referred to as the Tracker Integration Facility (TIF). Located on the surface at the CERN Meyrin site, this facility was not only used for construction, but also for testing and debugging the power supplies and the read-out electronics before lowering the CMS Tracker into the underground cavern. The Silicon Strip Tracker was operated at different coolant temperatures ranging from $+15\,^{\circ}\mathrm{C}$ to $-15\,^{\circ}\mathrm{C}$. Up to 15% of the Silicon Strip Tracker was powered and read-out simultaneously. An external trigger system was used to trigger on cosmic particles, which were subsequently used for detailed tracking and alignment performance studies [15, 16, 17]. The recorded data was analyzed with all three track-based alignment algorithms implemented for the CMS Tracker, i.e. the KAA, the HIP method [18] and the MillePede method [19]. Although in the endcap region tracks were recorded and used for alignment [20], only in the barrel region a sufficient amount of data was recorded to perform alignment at the level of individual detector modules.

4.2 Algorithmical and Computational Aspects

For alignment purposes it is beneficial to reject low-momentum tracks, for which the single hit resolution is dominated by the contribution of material effects. Since no magnetic field was available at the TIF, tight cuts had to be applied, based on trajectory estimates and fiducial errors, to get a cosmic track sample with sufficiently high momenta. In order to ease the comparability between the results of the three alignment algorithms, a common set of detector modules was defined, together with a standardized choice of which degrees of freedom should be aligned. The module selection was based solely on geometrical considerations, to exclude detector modules that were hit by the cosmic particles under large inclination angles, given the actual experimental and trigger setup.

For the results presented in the next section, the largest data-set for a single temperature (recorded at $-10\,^{\circ}\mathrm{C}$) was used, in order to rule out possible effects of thermal expansion. Applying the track and module selection criteria mentioned above, a total of 70,000 tracks were available to align 430 silicon strip detector modules. The associated computational effort did not make it necessary to restrict the number of detector modules at each update. Using only a single core of the CAF, the computation took less than three hours.

4.3 Discussion and Validation of the Results

Even though only a rather small fraction of all the Tracker's detector modules have been used for this study, the total number of alignment parameters taken into account is comparable to the biggest silicon tracking devices employed up to now (see e.g. [4] for a detailed compilation), thus emphasizing the value of this exercise as a benchmark test with real data.

The corrections to the nominal geometry in the innermost barrel regions were larger than previously expected. These large deviations turned out to be correlated, stemming from deformations of the barrel layers. Figure 6 visualizes such a distorted surface, where the circles show the positions of the center of the modules as described by the ideal geometry (in red) and as computed with the KAA (in black). The misalignment has been scaled by a factor 10 for better visibility; the green surfaces are merely a guide for the eye. The coordinates refer to the global CMS reference system. It should be noted, that this behavior was only observed in the inner regions of the barrel region, but not in the outer regions. The mechanical structure of the outer barrel region rules out layer-wise deformations, in contrast to the situation in the inner barrel region. This gives a further indication for the validity of the results.

A systematic validation of the results is only possible by comparing track quantities. Besides the tracking residuals the χ^2-values can be used, which are defined as the sum of the squared tracking residuals, each normalized by the error expected for the respective trajectory measurement (not including any alignment information). The χ^2-values and tracking residuals of the recorded particle trajectories should improve significantly, when the computed alignment parameters are applied to the nominal geometry. The low energy spectrum and hence strong material effects and the lack of momentum estimates for individual tracks due to the absence of a magnetic field cause the resulting distribution (shown in Figure 7) to have a very long tail; nevertheless the improvement is obvious and in good agreement with what is expected from simulation studies. Figure 8 shows the resulting tracking residuals for the precise coordinate of the detector modules for the three different alignment algorithms. The distributions are all symmetric and well centered around zero. As can be clearly seen, the KAA's performance is comparable to the other algorithms.

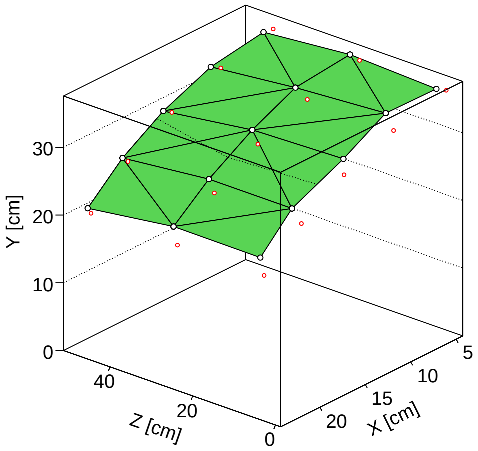

Figure 6: Visualization of the deformation of one of the inner barrel layers. Refer to the text for a detailed description.

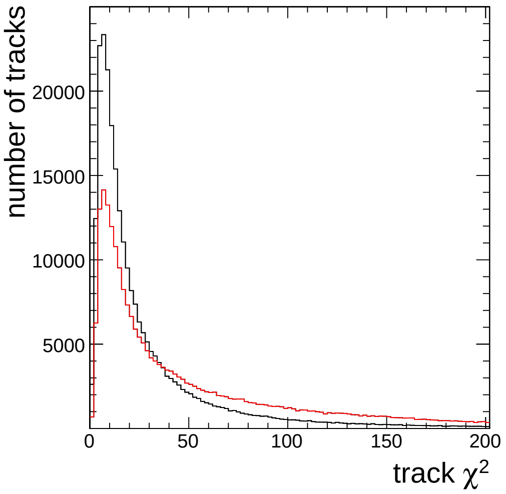

Figure 7: Track χ^2 before (red) and after (black) alignment.

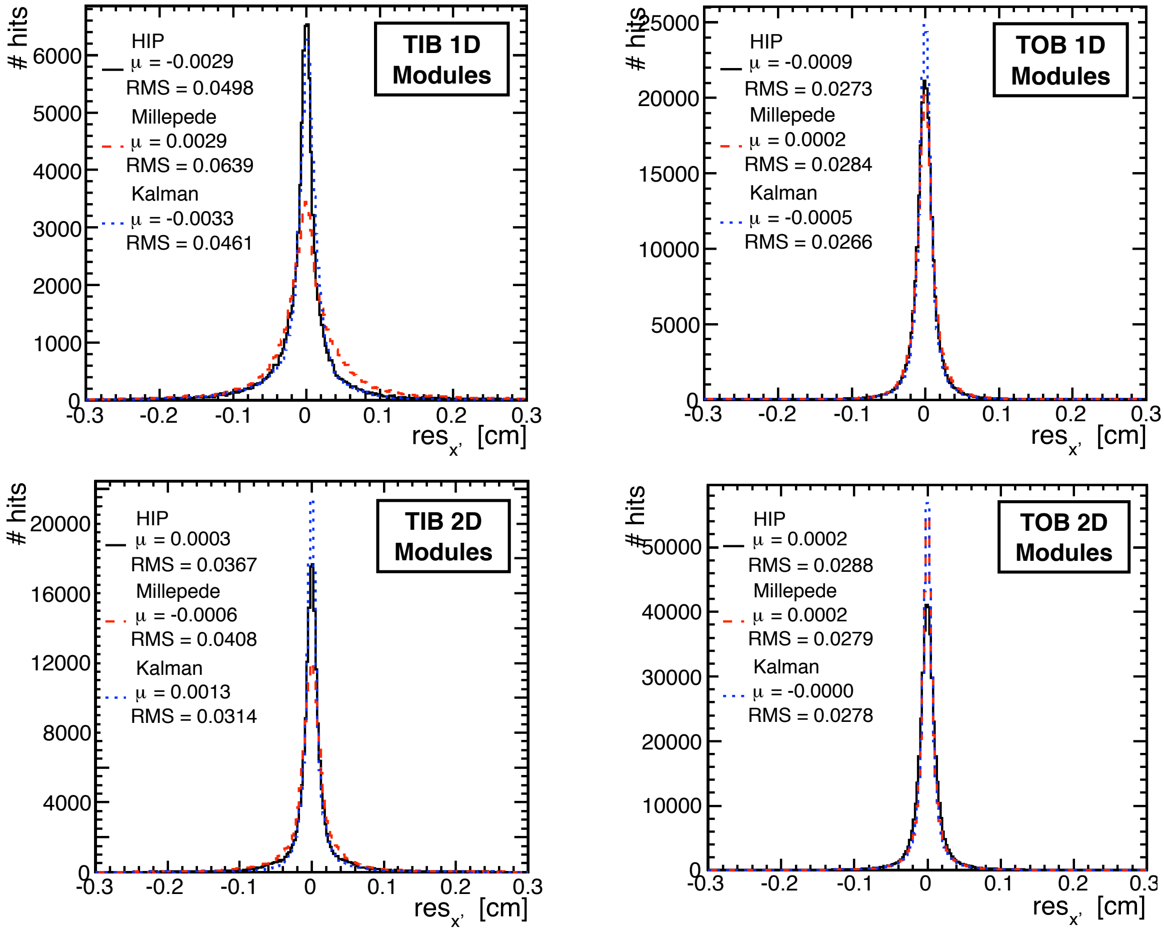

Figure 8: Comparison of the tracking residuals for the precise coordinate for the three alignment algorithms. The plots are split for single/stereo modules in the inner/outer barrel (TIB/TOB).

5 Conclusion and Outlook

Results from detailed simulation studies demonstrate that the KAA is able to align the CMS Tracker under the conditions expected during the LHC start-up phase. Moreover, it has been shown that the associated computational effort can be kept at a reasonable level by deploying the available CMS computing resources to process the data in parallel. Furthermore, an analysis of the first experimental data from cosmic particle tracks, recorded directly after the assembly of the CMS Silicon Strip Tracker, shows that the KAA is competitive to existing algorithms when applied to real data.

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