Alignment of the CMS Tracker: Latest Results from LHC Run-II

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Abstract. The all-silicon design of the tracking system of the CMS experiment provides excellent measurements of charged-particle tracks and an efficient tagging of jets. Conditions of the CMS tracker changed repeatedly during the 2015/2016 shutdown and the 2016 data-taking period. Still the true position and orientation of each of the 15 148 silicon strip and 1440 silicon pixel modules need to be known with high precision for all intervals. The alignment constants also need to be promptly re-adjusted each time the state of the CMS magnet is changed between 0T and 3.8T. Latest Run-II results of the CMS tracker alignment and resolution performance are presented, which are obtained using several millions of reconstructed tracks from collision and cosmic-ray data of 2016. The geometries and the resulting performance of physics observables are carefully validated. In addition to the offline alignment, an online procedure has been put in place which continuously monitors movements of the pixel high-level structures and triggers updates of the alignment constants if certain thresholds are exceeded.

1. Introduction
The measurement of the trajectories of charged particles, referred to as tracking, is a key ingredient of the event reconstruction at the CMS experiment [1]. To gain the best tracking performance one has to minimise the uncertainties attributed to the estimated track parameters which propagate, e.g., to the resolution of the transverse momentum of tracks. The momentum resolution for a particle has two main contributions, one originating from multiple scattering, the other from the limited precision of each hit position measurement. The latter is caused by the spatial resolution of the sensor itself, but also by the uncertainty of possible displacements, rotations or surface deformations of the sensor modules. Reducing this component to a level well below the intrinsic resolution of $10–30 \mu m$ of the silicon modules [2, 3] is the task of tracker alignment.

This report presents the results of the CMS tracker alignment using cosmic-ray data at a magnetic field of 0T and cosmic-ray and collision data taken at 3.8T before and during the operations in 2016 [4].

2. CMS tracker alignment
The CMS tracker is an all-silicon detector which consists of an inner part with 1440 silicon pixel modules and an outer part with 15 148 silicon strip modules (24 244 sensors) [1], thus providing very precise hit position measurements. However, these measurements are affected by possible
deviations from the assumed tracker geometry, resulting in enlarged track-hit residuals. Track-based alignment procedures derive the optimal set of alignment constants by minimising the quadratic sum of these residuals.

At CMS two independent algorithms are employed to fulfil this challenging task. One uses a global approach (milpeede II) [5, 6], which is a simultaneous fit of all track and alignment parameters taking their correlations into account. The other is a local fit approach (HipPy) [6], which handles the correlations in an iterative procedure. The two complementary approaches confirm each other, thereby demonstrating the robustness of the derived alignment results. The effect of the updated alignment constants on the performance in 2016 data taking is shown with respect to the outdated alignment constants from 2015, which do not take into account the condition changes during the 2015/2016 shutdown period.

The continuous alignment effort is described in the following sections beginning with the results of the 0T alignment followed by the alignment using data at the nominal field strength value of the CMS magnet of 3.8T.

The CMS coordinate system is used throughout this report. It is right-handed, with the origin at the nominal interaction point, the $x$ axis pointing to the centre of the LHC, the $y$ axis pointing up, and the $z$ axis along the anticlockwise-beam direction. The azimuth angle $\phi$ is measured in the $x$-$y$ plane and the polar angle $\theta$ is measured from the positive $z$ axis. The pseudorapidity $\eta$ is defined as $\eta = -\ln(\tan(\theta/2))$.

3. Offline alignment using cosmic-ray tracks without magnetic field

Prior to the beginning of collision-data taking in 2016, the high-level structures of the tracker, such as half-barrels and endcaps, are aligned using cosmic-ray data taken at a magnetic field value of 0T. This addresses effects accumulated during the 2015/2016 shutdown, e.g. due to temperature or magnetic-field changes, and is important to ensure reliable operation of high-level trigger and offline processing right from the start of collision data taking.

The positive impact of this alignment on track reconstruction is demonstrated by means of cosmic-ray tracks. The particle tracks traversing the whole detector are split at their point of closest approach to the interaction region. The resulting two sets of hits are refitted and two independent tracks are derived. For these two tracks, the normalised differences of various track quantities are studied, e.g. the distance in the transverse plane $d_{xy}$, and the pseudorapidity $\eta$ (Fig. 1). Relative displacements or rotations of the two tracker hemispheres defined by the two track halves can lead to broadened and non-central distributions of the studied quantities.

The obtained precision after alignment (green full circles) shows a clear improvement with respect to the outdated alignment constants from 2015 (blue open squares). The mean values of the distributions show a strongly reduced bias as they are clearly shifted towards zero. The decreased widths, with respect to the 2015 alignment constants, are nearly identical with the ideal behaviour (red solid line).

These improved alignment results are further refined using also collision data and cosmic-ray data at the nominal field value of the CMS magnet as is described in the following section.

4. Offline alignment using collision and cosmic-ray tracks with magnetic field

The start of collision data taking in 2016 lead to a steep and steady increase of the number of tracks available for alignment. These tracks, originating from collision events, also provide another topology and facilitate the use of additional information in the alignment procedure, e.g. mass and vertex constraints can be applied to muon tracks from Z-boson decays.

The further improved precision is demonstrated in this section using data-driven methods which validate the local precision (Sec. 4.1) or search for biases in the reconstruction of physics objects (Sec. 4.2).
4.1. Distributions of median residuals

Since the objective function used in track-based alignment targets track-hit residuals, an optimal alignment result should reflect itself in narrow and well-centred distributions of the residuals in each sensor. The corresponding median from each sensor enters the distribution of median residuals (DMRs). The width of this distribution reflects the remaining statistical alignment uncertainty. These DMRs are obtained from unbiased track-hit residuals, i.e. the track is refitted without the hit under consideration. They are monitored for all sub-detectors, as is illustrated with the pixel barrel (BPIX) and the inner strip endcaps (TID) in Fig. 2.

The distributions in Fig. 2 are obtained from one million collision events recorded with a magnetic field at 3.8T. A clear improvement with respect to the previous alignment constants manifests itself as strong reduction of the width (RMS). Especially in the BPIX (Fig. 2, left) it amounts to an improvement by a factor of 5.
4.2. Primary vertex validation

Beyond the local validation with the method described in the previous section, it is important to quantify the effect of an alignment update in terms of physics objects, e.g. to study potential biases in the primary vertex reconstruction. The method presented in the following uses unbiased longitudinal and transverse vertex-track residuals, i.e. the vertex fit is repeated excluding the track under consideration, resulting in non-correlation of track and vertex. Deviations of these mean values from zero are an indication of misalignment.

Figure 3 shows the primary vertex validation results obtained with one million collision events taken in 2016. The outdated alignment constants from 2015 (blue open squares) show clear \( \phi \)- and \( \eta \)-dependent structures. The \( \phi \)-behaviour of the residuals can be attributed to a systematic \( z \)-offset of the two pixel half-barrels, while the \( \eta \) structure indicates a relative misalignment of the pixel endcaps with respect to the barrel. All panels demonstrate a clear improvement with the 2016 alignment constants over the outdated alignment from 2015.

![Figure 3: Mean-value distributions of unbiased transverse (left) and longitudinal (right) vertex-track residuals obtained with one million collision events taken in 2016. These residuals are studied with respect to the track’s azimuth angle \( \phi \) (top) and pseudorapidity \( \eta \) (bottom). Deviations from the zero line are an indication for misalignment. The alignment update from 2016 (magenta) clearly removes biases in the primary vertex reconstruction which are visible when using the outdated alignment constants from 2015 on the same 2016 data (blue). Taken from [4].](image)

5. Online alignment

The results shown in the previous section are obtained with dedicated alignment campaigns using a large amount of tracks to determine the positions and orientations of the tracker modules. However, such campaigns require a significant preparation and computing time, thereby leading
to a potentially large delay in the update of the alignment constants used for the prompt event reconstruction.

In order to provide a fast update of the alignment constants in response to possibly frequent movements of the high-level structures in the pixel detector due to changes of the temperature or the magnetic field, an online procedure has been put in place in 2016. It continuously monitors the offsets of the pixel half-barrels and half-cylinders of the pixel endcaps. Thus, corrections of longitudinal offsets of the pixel half-barrels as visible in Fig. 3 (top right, magenta) can be directly taken into account for the prompt reconstruction leading to an improved performance even before reprocessing of the data. The procedure is restricted to the pixel detector because the strip detector is found to be stable under the above-mentioned effects.

This procedure is part of the prompt calibration loop (PCL) of CMS [7] and is described in the following. The frequency of updates is illustrated by the time evolution of one of the monitored alignment constants.

5.1. Alignment within the prompt calibration loop

For each CMS data-taking run with more than 20000 events, an alignment is performed to derive corrections for the six degrees of freedom of six pixel high-level structures; two half-barrels and four half-cylinders of the endcaps. These high-level structure are chosen because they have a large impact on the primary vertex reconstruction performance, as described in Sec. 4.2. The offsets and rotations are measured relative to the geometry used in data processing. If these corrections exceed certain thresholds, the tracker alignment constants are automatically updated.

Figure 4: Alignment corrections for the six high-level structures in the forward (FPIX) and barrel pixel (BPIX) detector as obtained from the PCL procedure in CMS run 276318. The top row shows the shifts in global \( x \), \( y \) and \( z \) direction, while the bottom row shows the rotations \( \Delta \theta_x \), \( \Delta \theta_y \) and \( \Delta \theta_z \) around these axes. The red horizontal lines indicate the thresholds which would trigger an update of the alignment constants. In case these thresholds are exceeded, the histogram colour changes from green to orange. Taken from [4].
Figure 4 shows the results obtained in a CMS run shortly after a ramp of the magnetic field during 4th July, 2016. Offset corrections of up to 30 μm are observed in the z coordinates of the pixel high-level structures (Fig. 4, top right), i.e. along the direction of the beam pipe. Four of the six degrees of freedom triggered an update, as is visualised by the orange coloured panels where the corrections exceed the threshold indicated by the red horizontal lines.

After the alignment constants are updated the performance is clearly improved, as can be seen in Fig. 5, which shows the PCL result for a CMS run shortly afterwards with applied corrections. Only small residual offsets are visible, e.g. below 2 μm in x and y direction, and below 10 μm in z direction. Thus, the remaining offsets are in a regime where the b-tagging is not visibly degraded [8].

This set of six plots as shown in Figs. 4, 5 is routinely produced as part of the automated CMS data-quality monitoring [9].

![Figure 5: Alignment corrections for the six high-level structures in the forward (FPIX) and barrel pixel (BPIX) detector as obtained from the PCL procedure in CMS run 276.327. The top row shows the shifts in global x, y and z direction, while the bottom row shows the rotations Δθₓ, Δθᵧ and Δθz around these axes. The red horizontal lines indicate the thresholds which would trigger an update of the alignment constants. In case these thresholds are exceeded, the histogram colour changes from green to orange. Taken from [4].](image)

### 5.2. Time evolution

A typical run period of the pixel tracker PCL alignment is shown in Fig. 6 by the example of the z coordinates of the six high-level structures. It covers the period from 21st June, 2016 to 12th July, 2016, corresponding to an integrated luminosity of 7 fb⁻¹.

Typical movements during magnet cycles are smaller than 50 μm in x and y direction (not shown) and smaller than 150 μm in z direction (Fig. 6).
6. Summary

The CMS collaboration has two independent algorithms [5, 6] in place to solve the complex task of aligning 1440 pixel and 15 148 strip modules. The updates of the alignment constants in 2016 significantly improve the performance at start-up and during data taking. Tracker-geometry modifications due to changes of the temperature and magnetic field are compensated to $\mu$m level. In addition to the offline alignment campaigns, an automatic online calibration workflow is put in place, which corrects large movements of the pixel high-level structures in situ during data taking. By the application of this procedure a clear improvement of the prompt reconstruction is achieved. However, it should be noted that the more refined alignment at module level is still required to reach the ultimate performance of up to only a few $\mu$m in the pixel and also in the strip detector. Thus, the online and offline procedures are complementary approaches to obtain the results presented here.

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