

Alignment of the CMS Silicon Tracker

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Abstract. The complex system of the CMS all-silicon tracker, with 15148 silicon strip and 1440 silicon pixel modules, requires sophisticated alignment procedures. In order to achieve an optimal track-parameter resolution, the position and orientation of its modules need to be determined with a precision of few micrometers. Several developments of computing and data analysis have been carried out for reaching these performances. Novel tracking tools have been implemented in the alignment algorithms. Special work flows are used for a balanced statistical treatment of the data in order to fully exploit the wide range of physics candles at the LHC that can be exploited by the alignment.

We present results of the alignment of the full tracker, in its final position, used for the reconstruction of the first collisions recorded by the CMS experiment. Validation tools are used for checking the quality of the final geometries: the quantities monitored span from the basic track quantities to physics resonances. The geometry has been systematically monitored in the different periods of operation of the CMS detector.

1. Alignment concept and misalignment tools

The silicon strip tracker of the CMS experiment is by far the biggest detector of its kind ever operated. It consists of 15 148 silicon strip modules covering an area of about 200 m^2 within the tracker volume of 24.4 m^3 [1]. Individual sensors of the CMS tracking devices are designed to have a spatial resolution in the range of $10\text{--}50\ \mu\text{m}$ [2]. After assembly, without any corrective measures, the uncertainties related to their positions were estimated to be in the range of $100\text{--}500\ \mu\text{m}$ [1]. To ensure that the limited knowledge of the positions and orientations of the individual sensors, misalignment, does not degrade the measured track parameters, specific *alignment* procedures were applied to decrease alignment uncertainties.

To improve initial knowledge of module positions, precise survey measurement were carried out during the assembly of CMS. This knowledge was further refined with alignment procedures based on reconstructed tracks. In addition, a dedicated laser-based hardware alignment system exists to monitor the tracker structures on a continuous basis.

Effects of misalignment on physics results have been taken into account in simulations by using several estimated *misalignment scenarios*. The following scenarios are presented in Figs. 1 and 2:

- *perfect* alignment, where the geometry is precisely as designed,
- *SurveyLAS* alignment, where survey measurements and information from laser alignment system (LAS) are used to improve the alignment,
- *SurveyLASCosmics* alignment, where cosmic rays are used for track-based alignment, and

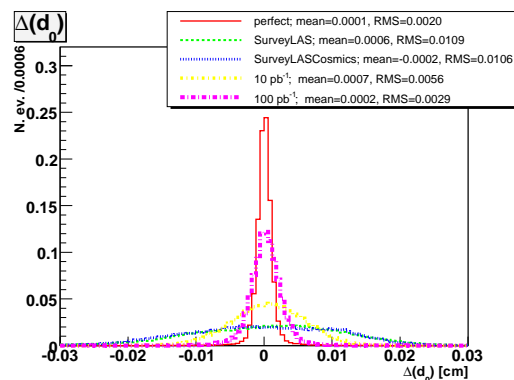


Figure 1. Example of the effect of misalignment scenarios on track impact parameter for tracks with $p_T = 100$ GeV.

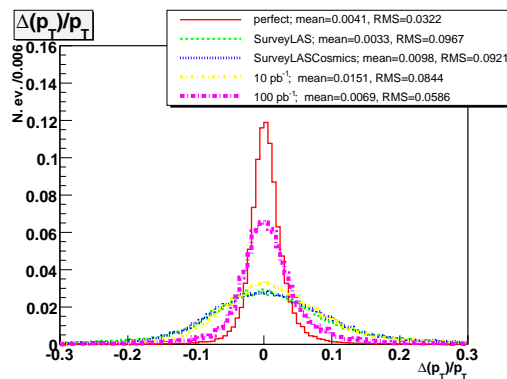


Figure 2. Example of the effect of misalignment scenarios on transverse momentum resolution for tracks with $p_T = 100$ GeV.

- scenarios corresponding to early collision data of 10 pb^{-1} and data of 100 pb^{-1} with more constrained and rare events.

In addition, scenarios created purely with alignment algorithms have been introduced lately. These scenarios have been obtained via the following track-based alignment (TBA) process: the geometry obtained with alignment with cosmic rays is taken as a starting point, and a simulated track sample produced with the design geometry is used in the alignment process. As a result, one obtains a geometry which is as close to the design (perfect) geometry as can be achieved with track-based alignment. The remaining difference would be similar to the real case: the difference between a geometry obtained with track based alignment and the true one. This helps to reproduce and study the inefficiencies of track-based alignment (especially the weak modes, discussed in Sec. 3).

In the track-based alignment, the χ^2 -function of hit residuals is minimized not only with respect to track parameters (which is the process of track fitting), but also with respect to the alignment parameters of individual sensors (three translations and three rotations in the general case for flat sensors). To perform the minimization, two alignment algorithms are used in CMS. The Millepede II [3] algorithm is a global algorithm, which extracts the alignment parameters of the full minimization problem (both track and alignment parameters), and thus keeps the computational requirements on an acceptable level. The HIP algorithm [4] follows a local approach, which solves the minimization problem for each detector module separately, and then refits tracks and iterates over these two steps.

Prior to collisions, CMS has recorded several hundreds of millions of cosmic rays, which have also been used in alignment studies [5]. With good illumination on top and bottom of the barrel parts, an average precision of 3–4 microns of RMS has been reached for the most sensitive coordinate. In the endcap region, corresponding numbers are in the range of 3–14 microns. To accurately align also the vertically mounted sensors, also collision tracks are needed to complement the cosmic rays.

2. First alignment with 7 TeV collisions

For the first alignment with 7 TeV collision data, tracks with different topologies were combined. A selection of 1.5 million cosmic ray events and 1.7 million $\sqrt{s} = 7$ TeV collision events (corresponding to about 1 nb^{-1}) was used. A geometry prealigned with cosmic rays [5] was taken as the starting point. [6]

In case of good alignment, track-to-hit residuals are dominated by uncorrelated random effects of multiple scattering and intrinsic hit errors. The usual χ^2 distributions are presented in Fig. 3, and results with 7 TeV collision data, expected alignment at startup (MC STARTUP) and ideal situation (MC No Misal.) are compared. The χ^2 distributions are, however, sensitive only to large misalignments, and are not practical in comparison with already aligned geometries. The module-wise medians of residuals (DMR: distribution of median of residuals) are a more sensitive measure, and give good insight to the quality of the alignment, as depicted in Figs. 4, 5 and 6, and presented in more detail in [6, 7].

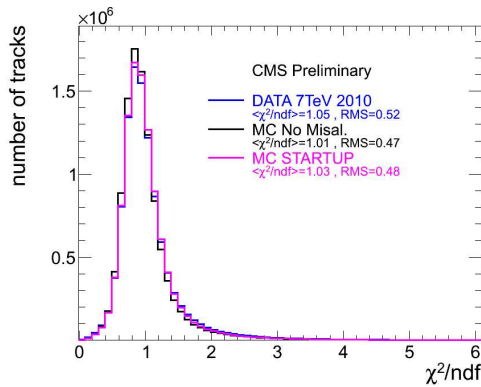


Figure 3. Normalized χ^2 distributions of the fit of the tracks.

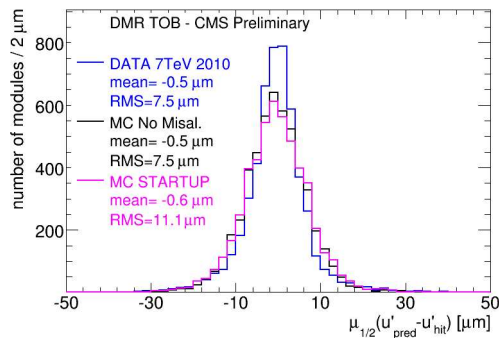


Figure 4. DMR of tracker outer barrel sensors.

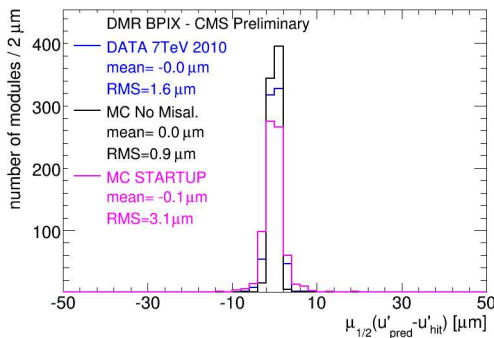


Figure 5. DMR of pixel barrel sensors.

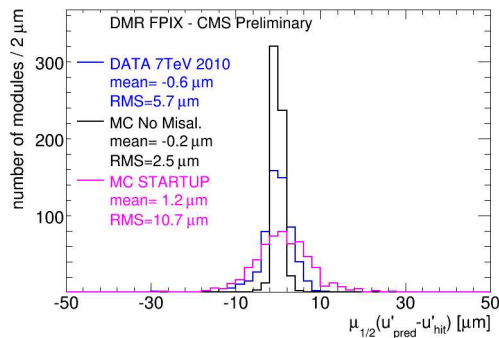


Figure 6. DMR of pixel endcap sensors.

To validate the obtained alignment constants, several tools are used: overlap studies, primary vertex fits and comparisons of track parameters of upper and lower parts of cosmic rays (track split studies).

When examining differences of overlapping adjacent modules, the errors of track propagation are negligible. This allows a precise study of relative alignment of adjacent modules, and since a boundary condition often exists (for instance for barrel layers), this provides an efficient constraint against weak modes like radial expansion. Figure 7 illustrates the improvements in overlaps achieved with both a survey geometry and an aligned geometry. In this study, cosmic ray events have been used, and sensor pairs belonging to the slice $80^\circ < \phi < 100^\circ$ have been considered. The survey data improves the starting geometry, and the application of alignment improves it further. The RMS of the mean of the distributions of the relative shift (scaled by $1/\sqrt{2}$) is $264 \mu\text{m}$ for the non-aligned geometry and $7.0 \mu\text{m}$ for the aligned one. [5]

Alignment of the pixel detector can be studied by examining primary vertex (PV) fits. In this method, all tracks except one probe-track are used to find the vertex, whose distance from the probe-track is then measured. The dependence on η or ϕ reveals then distortions of the alignment. Fig. 8 shows a verification of the d_{xy} distance; no significant ($> 10 \mu\text{m}$) distortion is seen when collision data were used with an earlier alignment. As a simulated example, a relative z -shift of $30 \mu\text{m}$ for each pixel half barrel generates a phi-dependence on the d_z value of the PV fit, illustrated in Fig. 9. A shift of this size would still be mechanically possible.

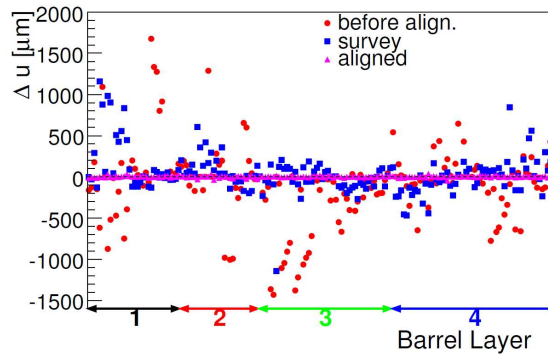


Figure 7. Validation of alignment by examination of relative shift of overlapping sensors in the sensitive direction (u) of tracker inner barrel sensors.

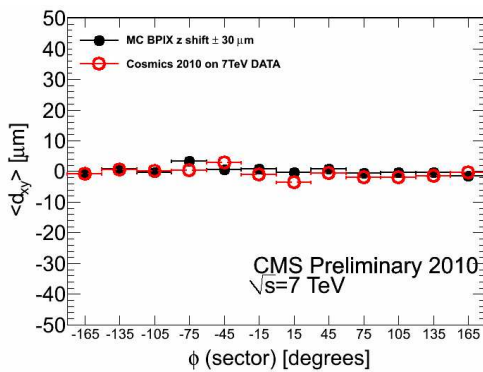


Figure 8. Alignment validation with primary vertices, d_{xy} . No significant ($> 10 \mu\text{m}$) deviation from zero can be seen when a pre-collision geometry (Cosmics 2010) is used with the 7 TeV collision data.

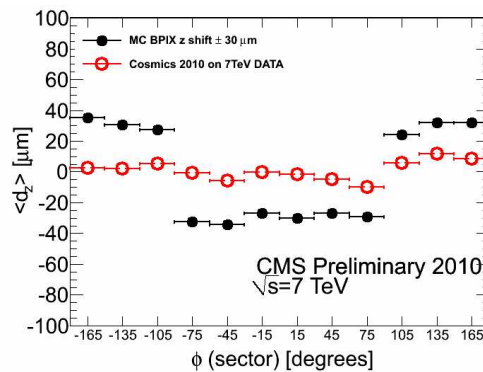


Figure 9. Alignment validation with primary vertices, d_z . No significant deviation from zero can be seen here either. The discontinuity of the filled circles at $\phi = \pm 90^\circ$ corresponds to an artificial translation between the pixel half-barrels.

As an example of the computational requirements for the HIP algorithm, alignment for the first 7 TeV collisions was carried out with:

- 30 iterations with primary vertex constraints,
- 61 jobs with minimum bias events, 27 jobs with cosmic ray events run in parallel in each iteration, 50 000 events per job,
- one job used typically 1000 s of CPU time and 20–30 minutes wall clock time, and

- total processing time was less than 24 hours.

A recent example for Millepede-II computing requirements is:

- 200 000 parameters aligned (sensor positions, rotations, bows),
- 200 000 cosmic ray tracks used,
- algorithm parallelized using OpenMP™, and
- 6 hours of wall-clock time needed with Intel Xeon, 2.83 GHz, 6 MB cache, 8 cores, 24 GB RAM.

CMS utilizes dedicated data streams for calibration and alignment to enable the use of updated constants already in prompt reconstruction [8, 9, 10]. Alignment of the pixel detector, which is subject to most dense flux of collision tracks, could be carried out in *prompt calibration loop*, a 48-hour calibration loop which calculates calibration and alignment constants to be used with the full data sample. Repeated alignment with a 24-hour feedback time has already been successfully tested in a prompt alignment exercise during the cosmic run of 2009.

3. Advanced alignment studies

Future goal is to detect and control distortions to which track-based alignment is weakly sensitive. Some examples of systematic deformations are depicted in Fig. 10. Some of these deformations have a χ^2 -invariant component, which cannot be corrected with the track-based alignment. An example of the physics sensitivity study, in which these detector deformations are applied on top of the latest geometry and then partly recovered with the track-based alignment, can be found in Refs. [6, 11].

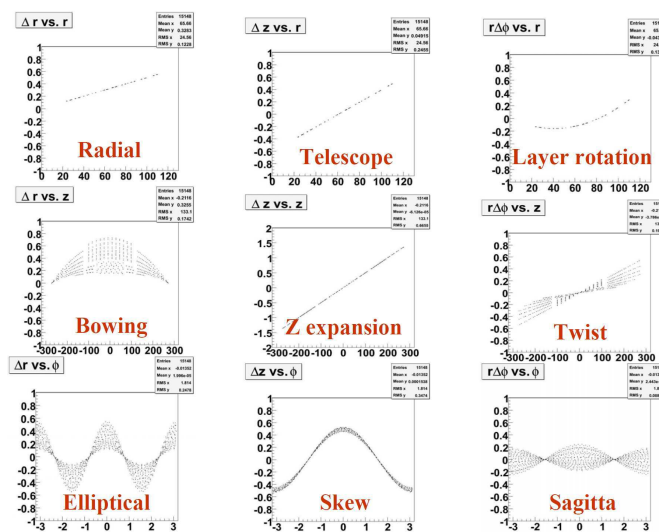


Figure 10. Examples of correlated detector movements.

An extension of the alignment of translations and rotations is to take into account also the fact that the individual sensors are not planar, but are curved to some extent, as illustrated in Fig. 11. Modules composed of two separate sensors are also prone to have an angle between the daisy-chained sensors in the outer parts of the tracker, illustrated in Fig. 12. First studies correcting these effects have been made, and as a result, the observed dependence of the residuals on the relative hit position indeed vanishes, as illustrated in Figs. 13 and 14 (from [12]).

The detection of curvature of individual sensors as well as the various validations strongly suggest that the uncorrelated misalignments have been well corrected in the CMS silicon tracker; however the systematic deformations need to be considered to avoid bias in physics results.

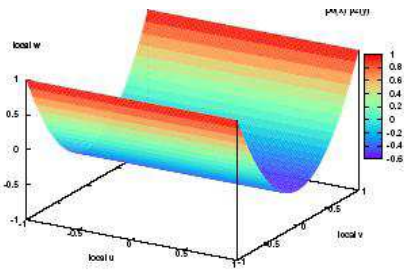


Figure 11. Example of curvature taken into account in alignment.

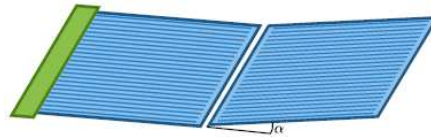


Figure 12. Illustration of a kink between two sensors in an outer barrel module.

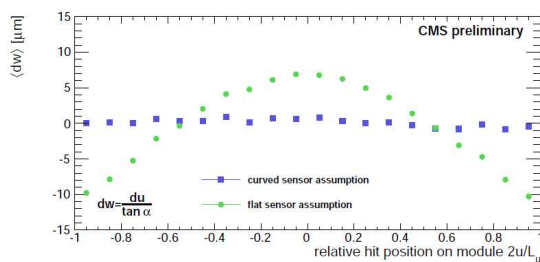


Figure 13. Average sensor deviation in the direction normal to the measurement plane estimated from the residuals for sensors in the tracker inner barrel. The deviation vanishes if sensor curvature is taken into account in the alignment process. [12]

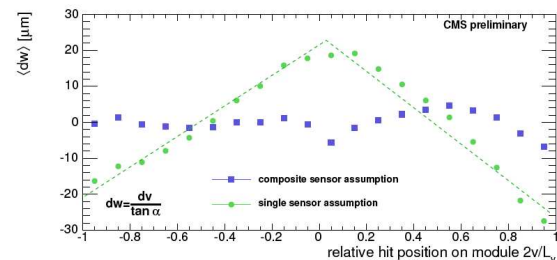


Figure 14. Average sensor deviation in the direction normal to the measurement plane estimated from the residuals for sensors in the tracker outer barrel. The deviation vanishes if the kink between sensors is taken into account in the alignment process. [12]

Acknowledgments

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