The alignment of the CMS Silicon Tracker

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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.

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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.

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1. Alignment concept and misalignment tools
Individual sensors of the CMS tracking devices are designed to have a spatial resolution in the range of 10–50 μm [1]. After assembly, without any corrective measures, the uncertainties related to their positions were estimated to be in the range of 100-500 μm [2]. To ensure that imperfect 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 track-based alignment procedures. In addition, a dedicated laser-based hardware alignment system exists to monitor 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, as illustrated in Figs. 1 and 2. Among others, scenarios corresponding to the situation prior to LHC startup have been included, as well as estimates for situations with early collision data (10pb⁻¹) and with data with more constrained and rare events (100pb⁻¹). Also scenarios created with alignment algorithms have been included 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 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 track-based alignment, the $\chi^2$-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 at CMS. The Millpede 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.

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

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

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 a 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 $\chi^2$ 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 $\chi^2$ distributions are, however, sensitive only to large misalignments, and are not practical in comparison of 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 alignment, as depicted in Figs. 5, 6 and 4, and presented in more detail in [6, 7].
To validate the obtained alignment constants, several tools are used: overlap studies, primary vertex fits and track split validations (cosmic rays).

When examining differences of overlapping adjacent modules, the errors of track propagation are negligible. This allows precise study of relative alignment of adjacent modules, and since a periodic 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 with a survey geometry and aligned geometry.

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

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
Figure 7. Validation of alignment by examination of relative shift of overlapping sensors in the sensitive direction ($u$) of TIB sensors. 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 application of alignment improves it further. The RMS of the mean of the distributions of the relative shift (scaled by $1/\sqrt{2}$) is $264 \mu$m for the non-aligned geometry and $7.0 \mu$m for the aligned one. [5]

Figure 8. The unbiased track-vertex impact parameter $d_{xy}$ is measured for the probe track and the refitted primary vertex.

- 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 use of updated constants already in prompt reconstruction [9, 10, 11]. 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 24-hour feedback time has already been successfully tested in a prompt alignment exercise during the cosmic runs 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. 11. Some of these deformations have a $\chi^2$-invariant component, which cannot be corrected with track-based alignment. An example of physics sensitivity study, in which these detector deformations are applied on top of the latest geometry and then partly recovered with track-based alignment, can be found in [6, 12].
Another path to improve alignment is to take also into account the fact that individual sensors are not planar, but are curved to some extent, as illustrated in Fig. 12. Modules composed of two separate sensors are also prone to have an angle between the daisy-chained sensors of outer parts of tracker, illustrated in Fig. 13. First studies correcting these effects have been made, and as a result, the observed dependence of residuals and relative hit position indeed vanishes, illustrated in Figs. 14 and 15 (from [13]).

Figure 12. Example of curvature taken into account in alignment.

Figure 13. Illustration of kink between two sensor in one outer barrel module.

Figure 14. Average sensor deviation in the direction normal to the measurement plane estimated from the residuals for sensors in the tracker inner barrel. Dependence of residuals and hit position can be seen, if curved sensor assumption is not used. [13]

Figure 15. Average sensor deviation in the direction normal to the measurement plane estimated from the residuals for sensors in the tracker inner barrel. Dependence of residuals and hit position can be seen, if assumption of composite sensor (kink) is not used. [13]

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