The CMS alignment challenge

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Abstract
The CMS tracking detectors are of unprecedented complexity: 66 million pixel cells distributed over 1440 modules in the Pixel Tracker; 9.6 million readout channels in 15 148 silicon strip modules in the Strip Tracker; 250 drift, 468 cathode strip, and 360+252 resistive plate chambers in the Muon System. All of them need to be aligned to a precision better than their intrinsic resolution in order not to degrade tracking performance. Besides being a numerical and time-intensive challenge, it is a difficult task to constrain all the possible degrees of freedom, to properly handle the large amount of data, and to face the modeling imperfections and subtle systematics the data will show once the detector is turned on. We briefly introduce the topic to set up the scene for the following articles about CMS alignment, in which more results will be presented.

19.1 Introduction
In the following sections, the alignment of the CMS tracking systems and the corresponding challenges are discussed in more detail. The alignment of the calorimeters will be carried out with respect to the Silicon Tracker, using collision data after the Tracker has been aligned. Both the complexity and precision of the calorimeter alignment are less demanding than for the tracking systems and are therefore not discussed here.

The general alignment strategy is to combine measurements from construction, from dedicated optical alignment systems using beams of laser or LED light, and from charged-particle tracks to achieve maximum precision and to reduce systematic uncertainties.

19.2 Misalignment and alignment procedure
Misalignment is usually defined as the deviation of position and orientation of an active detector element from its nominal values. There are many sources of misalignment: the precision of the detector assembly, which in general is worse than the intrinsic detector resolution, stress from the large magnetic field, thermal stress, changes in environmental humidity, and support structure dry-off, etc.

To simulate the effect of misalignment on physics analysis, misalignment has been introduced in the CMS reconstruction software by deliberately shifting detector signals that have been simulated with an ideal geometry, which is computationally less expensive than simulating a misaligned geometry. Since detectors are large compared to the misalignment, the bias due to hit loss or gain at the edges of the detectors as a result of this approach is negligible.

Two misalignment scenarios [1] have been developed, one for the first data-taking period (‘short term alignment’) with \( \mathcal{L} < 1 \text{ fb}^{-1} \) and another one for the period \( \mathcal{L} = 1 \ldots 5 \text{ fb}^{-1} \) (‘long term alignment’). In
Fig. 19.1, the transverse momentum resolution obtained for the two scenarios is compared with the ideal resolution. The final alignment is expected to restore the ideal resolution as close as possible in order not to degrade the CMS physics performance.

Alignment parameters, i.e., the correction from the nominal to the real position, are usually computed with a (linear) least-squares fit, yielding the best (linear) unbiased estimator, where ‘best’ refers to the minimal mean squared error on the parameters. The function \( \vec{f}(\vec{p}) \) predicts the measurements (i.e., the hit coordinates along the particle trajectory) as a function of the unknown track and alignment parameters \( \vec{p} \). The function is linearized by

\[
\vec{f}(\vec{p}) \approx \vec{f}(\vec{p}_0) + A \cdot (\vec{p} - \vec{p}_0), \quad A = \left. \frac{\partial \vec{f}}{\partial \vec{p}} \right|_{\vec{p} = \vec{p}_0}.
\]  

The alignment parameters are obtained by minimizing the weighted residual of prediction \( \vec{f}(\vec{p}) \) and measurement \( \vec{m} \):

\[
\chi^2 = (\vec{f}(\vec{p}) - \vec{m}) W (\vec{f}(\vec{p}) - \vec{m})^T,
\]  

where \( W^{-1} = V = \text{cov}(\vec{f} - \vec{m}) \) is the variance–covariance matrix. Computing \( \partial \chi^2 / \partial \vec{p} = 0 \) yields

\[
(A^T W A) (\vec{p} - \vec{p}_0) = A^T W (\vec{m} - \vec{f}(\vec{p}_0)).
\]  

The matrix \( A^T W A \) is huge since it contains both track and alignment parameters, with the number of tracks typically \( O(10^8) \). Because track parameters are uncorrelated with each other and not of interest in the alignment procedure, they can be resubstituted yielding an expression similar to Eq. \( \ref{eq:alignment} \) with a reduced matrix size \( N \times N \), with \( N \) being the number of alignment parameters only. The sought-after parameters \( \vec{p} \) can be computed by either diagonalizing or inverting \( A^T W A \) or solving the system of linear equations numerically.

### 19.3 Muon system alignment

Figure 19.2 shows the layout of one quarter of the CMS muon system for the initial low-luminosity running. Three different detector technologies are employed, 250 drift tube (DT) chambers in the barrel, 468 cathode strip chambers (CSC) in the end-caps, and 360+252 resistive plate chambers in the barrel and the end-caps, respectively. The system contains in total nearly one million channels.

Each drift tube chamber consists of 12 planes of drift tubes, eight \( r-\phi \)-measuring planes and four \( z \)-planes. Thus each station provides a muon momentum vector, with an \( r\phi \)-precision better than 100 \( \mu \) and approximately 1 mrad in direction. One or two RPCs are coupled to each DT chamber, depending on the location. A high-\( p_t \) muon crosses up to six RPCs and four DT chambers, producing up to 44 measured points.

The CSCs are of trapezoidal shape with six gas layers. In each layer, cathode strips are radially organized with anode wires almost perpendicular to the strips. Nearly all CSCs provide overlap in \( \phi \) to provide good coverage. The fast anode wire signal of the CSCs is used for the first-level trigger, whereas the center of gravity of the image charge on the cathode strips is used to achieve maximum position resolution. Each CSC provides a muon momentum vector from six measured space-points, with a spatial resolution of typically 200 \( \mu \) and an angular resolution of the order of 10 mrad.

The RPCs provide only coarse \( (\Delta \eta \times \Delta \phi \approx 0.1 \times 5/16^6) \) position resolution, but identify the bunch crossing unambiguously due to their excellent time resolution.

It should be noted that the complete CMS muon system shrinks by approximately 0.5 cm in the barrel and 1 cm in the end-cap when the solenoid is being turned on, with a reproducibility of about 1 mm. The CMS physics goals require knowledge of the muon chamber position with respect to each other and to the central tracking system with 100–500 \( \mu \) precision. Two independent approaches are used: an optomechanical alignment system and alignment with reconstructed muon tracks.

#### 19.3.1 Optical alignment system

The optical alignment system is based on beams of LED and laser light, together with precise distance- and angle-measuring devices [2].
The layout of the optical paths in the barrel is shown in Fig. 19.3. The wire positions in the DT chambers have been measured during construction, and the chambers are treated as rigid bodies for the optical alignment. On each chamber, LED light sources are monitored on mechanical reference structures called ‘Module for Alignment of Barrel’ (MAB). The \( z \) position of chambers is determined by triangulation, and the relative \( z \) distance of the MABs is monitored by cameras on the MABs monitoring light sources on carbon-fibre ‘Z-bars’. Position and orientation of all light sources on the 250 chambers, 36 MABs, and Z-bars (\( \approx 3000 \) degrees of freedom) are constrained by 4000 measurements, providing the desired redundancy.

![Fig. 19.3: Muon alignment system for the barrel. Light paths connecting the MABs and the link to the Silicon Tracker are indicated.](image)

The link between the Silicon Tracker, Muon Barrel, and Muon End-cap is made in the two planes between the barrel and the end-caps (cf. Fig. 19.4). Twelve interleaved Straight Line Monitors (SLMs) connect the two end-caps and the outer barrel MABs, transferring six \( r\phi \) and \( r \) measurements to the end-cap iron disks. The \( z \) disk coordinate is measured with laser triangulation. Transfer to the CSC coordinates is made in the disk plane at constant \( z \), where three laser beams connect two SLMs at opposite \( \phi \) via rigid link plates, dividing one disk into six piece-of-cake like 60° segments. Transparent sensors on these CSCs in the line of the beam determine their \( r\phi \) and \( z \) position. About 23% of all CSCs are monitored with the optical system. The alignment of all the other CSCs has to be done with muon tracking in the chamber overlaps.

A successful test of one half of a CMS \( r-z \)-plane in a simplified real-scale set-up has been carried out [3], reaching a precision of \( \approx 200 \mu m \) in \( r\phi \), \( 400 \mu m \) in \( z \), and from 40 to 100 \( \mu \)rad in orientation, close to the nominal expected precision. It is challenging to prove also for larger systems, e.g., for the recent CMS Magnet Test and Cosmic Challenge, that the desired performance can be reached.

![Fig. 19.4: Optical alignment light paths in a longitudinal view of the CMS experiment, linking the Silicon Tracker with the Muon Barrel and Muon End-cap](image)

### 19.3.2 Alignment with tracks

Muon chamber stand-alone alignment with tracks is particularly challenging. This is not due to the number of approximately 5000 alignment parameters (and their correlation), because they can be dealt with existing alignment algorithms. What does make track-based alignment challenging is the large extrapolation distance in between the chambers and between the chambers and the Tracker, with a large amount of material in between. This results in non-negligible uncertainties on multiple scattering and prediction of the non-uniform magnetic field. Electromagnetic and hadron calorimeters, coil, and return yoke contribute to these uncertainties. Speaking in terms of Eqs. (19.1)–(19.3), the construction of the function \( \vec{f}(\vec{p}) \), and the variance–covariance matrix \( V \) are challenging.

Since a high \( p_t \) cutoff for muon tracks is necessary to limit multiple scattering effects, high-statistics data samples are needed corresponding to approximately one year of data taking at LHC low luminosity to achieve a precision comparable to the optical alignment system. The comparison of the two parameter sets obtained will constitute a valuable cross-check because
of their different systematics.

An earlier alignment can be obtained using a pre-aligned Strip Tracker. In this case, muon trajectories are predicted solely from the Strip Tracker, and the residuals in the muon chambers can be used directly to determine the chamber position. The \( \mathcal{O}(5000) \) parameter fit then splits into 790 fits with six parameters each, at the cost of having increased systematic uncertainties if the Strip Tracker is not perfectly aligned.

### 19.4 Silicon tracker alignment

The CMS Tracker [4] comprises both a silicon pixel vertex tracker with three layers in the barrel and two disks in each end-cap, and a silicon strip tracker with ten layers in the barrel and 3+9 disks in each inner and outer end-cap, respectively (cf. Fig. 19.5). A Laser Alignment System (LAS) allows us to measure the relative positions of the Inner Barrel (TIB), Outer Barrel (TOB), and of the end-cap (TEC) disks, but neither the Inner Disks (TID) nor the Pixel Tracker.

![Figure 19.5: Quarter view of the CMS Tracker in the \( r-z \) plane. The different Tracker partitions, and the elements and light paths of the Laser Alignment System are shown.](image)

#### 19.4.1 Laser alignment system

Infrared laser pulses with a wavelength of \( \lambda = (1075 \pm 3.5) \) nm are used to generate signals on selected Strip Tracker modules at two different radii, \( r_1 = 564 \) mm and \( r_2 = 840 \) mm in the end-cap, and on modules in the outermost and innermost layer of the TIB and TOB, respectively (cf. Fig. 19.5). At all three radii, eight beams are distributed over \( \phi \). In the barrel, the beam is partly deflected on the sensors by beam splitters in the alignment tubes (AT). In the TECs, the laser passes through special sensors with a 10 mm hole in aluminium on the back side, where in addition an anti-reflective coating is applied. Beam splitters (BS) decrease the number of sensors the beams are passing through in order to generate sufficiently high signals on the sensors within the dynamic range of the laser diode. Owing to absorption and reflection losses, the laser intensity needs to be adjusted for each layer to obtain an optimal signal-over-noise ratio, requiring a few hundred laser pulses for a complete measurement on all sensors.

The goal of the LAS is not to provide alignment parameters for individual modules but rather to determine the global Strip Tracker structure position and orientation relative to each other with a precision of about 100 \( \mu m \), which is necessary for track pattern recognition and for the High Level Trigger. Furthermore, the LAS is able to monitor relative positions with a precision \( \approx 10 \mu m \) on a continuous basis. With a trigger rate around 100 Hz, a full LAS measurement takes only a few seconds, allowing frequent measurements. Since the trigger can also be generated during physics data-taking, the LAS measurements can be used as additional input to the track-based alignment if variations on short time-scales are found.

A rigid alignment ring (AR) is mounted on the back of each TEC, providing a link to the Muon System with six laser beams distributed in \( \phi \).

It is especially challenging to extract the laser position on these TEC modules where refraction effects on the aluminium strips on the front side of the silicon sensor strongly distort the Gaussian beam shape, and to control systematic single module effects to reach ultimate precision.

#### 19.4.2 The pixel tracker

The Pixel Tracker is built from 1440 pixel modules with a pixel size of 100 \( \mu m \times 150 \mu m \), amounting to a total of 66 million readout channels. With analog signal interpolation of charge sharing induced by the large Lorentz angle \( \alpha_L \approx 23^\circ \), a single hit resolution of 10 \( \mu m \times 20 \mu m \) can be reached.

Stand-alone alignment of the Pixel Tracker is only possible with tracks, since it is not reached by any laser beams from the LAS. This is challenging because tracks can be constructed from only three measurements in the barrel and two measurements in the end-cap (plus overlaps). Since most of these measurements need to be used to estimate track parameters, the statistical power of each track on the determination of alignment parameters is lower than in the Strip Tracker. Therefore vertex or mass constraints need to be used in multi-track events. Also the momentum resolution in the Pixel Tracker is, because of the small curvature of high \( p_T \) tracks, much worse than for the Strip Tracker. In this case, the momentum estimate from the (even misaligned) Strip Tracker can be taken.

A Pixel barrel stand-alone alignment with 504 out of 720 modules has been performed with the HIP algorithm [5], the reduced number being due to the requirement of hits in each Pixel layer. 200 000 \( Z \rightarrow \mu^+\mu^- \) events have been used and a common vertex constraint for the two tracks is employed. A resolution of \( \approx 25 \mu m \) for the three spatial coordinates has been
reached (Fig. 19.6). It will be challenging to increase the precision by employing complementary data sets to reach a precision better than the Pixel resolution, and to include modules on tracks with only two hits. Studies including the Pixel end-caps are ongoing.

Fig. 19.6: Residuals after Pixel Tracker alignment for 504 modules, visualized for different iteration steps

19.4.3 The strip tracker

The Silicon Strip Tracker comprises 15,148 single-sided silicon strip modules with strip pitches from 80–205 $\mu$m, in total 9.6 million readout channels. The single-strip resolution varies between 23 $\mu$m and 59 $\mu$m in the sensitive coordinate. For each possible track trajectory, at least four 2D-measurements are obtained by assembling two modules back-to-back with a stereo angle of 100 mrad, leading to a stereo resolution of 230–520 $\mu$m.

When aligning all six degrees of freedom for each module, the matrix $A^TWA$ of Eq. (19.3) is of size $90,888^2$, and the solution via diagonalization or inversion, for which algorithms of order $O(N^3)$ exist, becomes impractical because of computing time and numerical precision. It is expected that the time needed for inversion on one conventional CPU is of the order of one year, and even using quadruple precision in the inversion, is not sufficient to obtain a correct solution.

Therefore CMS is pursuing the development of novel alignment algorithms. Two techniques providing unbiased alignment estimates are under investigation. The first is an extension of the well-known Millepede algorithm, replacing the matrix inversion by a fast numerical solver [6]. The second is a novel approach using a Kalman filter [7], where the alignment is updated iteratively after each processed track, and the inversion is necessary on a very small matrix with size of the number of measured parameters per track only. Both methods are expected to be able to provide alignment constants for the full Strip Tracker. Current studies use the Pixel Tracker as a reference system, under the assumption that it has already been aligned to a precision of at least 10 $\mu$m. Both algorithms are still in development, and it will be challenging to have them implemented and well tested for CMS data-taking. However, they have been successfully tested in parts of the Strip Tracker, proving the ability to align the full Strip Tracker [6, 7].

Another challenge is to obtain a unique solution to the alignment problem. Tracks from collision data, i.e., originating from the interaction point, are not able to constrain all parameters at the same time. There are a number of correlated module movements, called ‘weak deformation modes’, which give rise to a different set of track and alignment parameters but otherwise leave the $\chi^2$ of Eq. (19.2) unchanged. Typical examples are a curl in the $r\phi$ plane as a function of $r$ (cf. Fig. 19.7), leading to a charge asymmetry, and correlated shifts along $z$ as a function of $r$, mimicking a boost of the centre-of-mass system. In order to constrain these modes, different data samples like cosmic rays or beam halo muons need to be used, and constraints to the data applied, like, for example, common vertex fits for multi-track events, mass constraints from, for example, $Z \rightarrow \mu^+\mu^-$, or incorporating survey or LAS constraints in the alignment fit. The possibility of obtaining a unique solution in the Strip Tracker has not yet been shown, also on account of the experimental state of the algorithms, and thus remains a challenge.

19.5 Summary and outlook

CMS alignment is a challenging task, especially for the Strip Tracker which will soon be the largest Silicon Tracker ever constructed. Many studies have just begun and proven to work, such as the alignment data flow that has been successfully tested in the CMS Computing, Software and Analysis challenge this year [8]. Still, many challenges lie ahead of us, both regarding opti-
c al alignment systems and track-based alignment. One of them is to extrapolate the current studies to the full CMS scale.

Even with the best possible preparation, the data will certainly hold surprises, like other HEP experiments in the past. It will be exciting when the full detector is commissioned and recording data, and we look forward to computing the first alignment parameters.

References