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# Alignment and calibration experience under LHC data-taking conditions in the CMS experiment

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**Abstract.** Full achievement of the physics potential of the detector and timely preparation of results for conferences require a fast turnaround of alignment and calibration workflows. The CMS experiment has set up a powerful framework and infrastructure for alignment and calibration, which is based on dedicated skims providing a highly compact specific input for the various workflows computing the constants, and includes a prompt calibration concept which allows determination of highly time-dependent constants on the fly. The CMS alignment and calibration model has been commissioned step by step with cosmic muons and passed a main challenge with the first LHC high energy run and the preparation of physics results for the 2010 summer conferences. This article reviews detailed experience from this extended operation, including results from selected workflows.

#### 1. Introduction

The CMS alignment and calibration framework has been put to the real-life test in 2010, the first year of the LHC high energy run. As the machine luminosity has been ramping up, strategies have evolved smoothly bringing an increasingly complex set of workflows and dependencies into play. Various reprocessing campaigns have been conducted for which consistent sets of alignment and calibration constants have been provided. This paper summarizes the CMS alignment and calibration concept, and presents the experience and performance in the context of selected workflows.

#### 2. The CMS alignment and calibration concept

Figure 1 shows how alignment and calibration are embedded in the overall CMS offline workflow. Compact "AlCaReco" skims, i.e. datasets containing only selected events and only the specific event content relevant for the corresponding alignment and calibration workflows, are produced automatically both from the express stream and the bulk processing of all physics data. The express stream corresponds to about 10% of the physics stream bandwidth; its low processing latency of 1-2 hours opens the feasibility of a prompt calibration workflow (Section 3.4). Additional streams (denoted "Calibration" in Figure 1) contain information from laser systems and dedicated calibration triggers [1]. The AlCaReco datasets form the input for alignment and calibration workflows that operate at the CMS CERN Analysis Facility (CAF) and feed the derived constants into the conditions database.

In the management of the sizable number of alignment and calibration workflows, it is essential to account correctly for inter-dependencies. The following list contains a selection



**Figure 1.** Alignment and calibration data paths and workflows within the overall CMS offline processing scheme.

of the main workflows grouped into three levels of inter-dependency, which need to be executed in the indicated order:

- (i) Channel status calibrations (all detectors), electromagnetic (ECAL) and hadronic calorimeter (HCAL) energy scale and inter-calibration, muon system optical alignment, drift-tube chambers time pedestal and drift-time calibration, tracker gain and Lorentz angle calibrations (both for pixel and strip modules);
- (ii) Tracker alignment;
- (iii) Tracker-muon system cross alignment, muon system track-based alignment, ECAL alignment (barrel, end caps, pre-shower), offline determination of luminous region parameters. (In addition, CMS performs an online determination of luminous region parameters e.g. for monitoring purposes, which is discussed in Section 3.1.)

# 3. Performance and experience

This section discusses performance and experience for selected alignment and calibration workflows. Details regarding calorimeter and tracker calibration can be found in [1, 2].

#### 3.1. Determination of luminous region parameters

An online determination of the luminous region (also referred to as beam line or beam spot) parameters is performed at the end of each luminosity section<sup>1</sup> using two different methods, one based on impact parameters of tracks from the standard reconstruction within the full tracker, and the other using primary vertices determined with a special reconstruction with only the hits in the pixel detector. Figure 2 displays the measured evolution of the vertical beam line coordinate in a fill during which a luminosity scan took place. The plots show that the two methods are consistent and are able to track the movements of the beam well [3]. One of the main functions of this online monitoring is to provide fast feedback to the LHC operators. The beam line parameters used for final physics analysis are determined offline for optimal accuracy.

 $<sup>^1\,</sup>$  A CMS luminosity section has a duration of 23 s



Figure 2. Vertical position parameter (Y) of the luminous region as determined by the online workflow over the luminosity sections within about one hour, during a fill in which a luminosity scan took place [3].



**Figure 3.** (a) Impact parameter correlation estimator as a function of the cosine of the relative azimuthal angle between the two tracks, for two different LHC fills. The transverse luminous region width is determined as the square of the slope of a linear fit. (b) Comparison of the horizontal (X) width of the luminous region determined with impact parameter correlations and primary vertex likelihood fit methods [3].

In addition to the positional and orientational parameters, also the transverse width of the luminous region is important. Besides analysis of the primary vertex distributions, CMS uses offline an alternative method which is based on correlations of track impact parameters. For an untilted beam ellipse, the correlation between the transverse impact parameters  $d_{xy}^{(1)}$  and  $d_{xy}^{(2)}$  of two primary tracks from the same interaction can be expressed by the expectation value

$$\langle d_{xy}^{(1)} d_{xy}^{(2)} \rangle = \frac{\sigma_x^2 + \sigma_y^2}{2} \cos(\phi_1 - \phi_2) + \frac{\sigma_y^2 - \sigma_x^2}{2} \cos(\phi_1 + \phi_2), \tag{1}$$

where  $\phi_1$  and  $\phi_2$  are the azimuthal angles of the tracks measured at the point of closest approach to the beam, and  $\sigma_x$  and  $\sigma_y$  are the horizontal and vertical luminous region widths to be measured. Since this method does not require any correction for resolutions, it is complementary to the primary vertex-based method in terms of systematics. Figure 3a shows the strength of the impact parameter correlation as a function of the cosine of the azimuthal distance of the two tracks for two different fills: the slope of each fit reflects directly the squared transverse beam line width. Figure 3b displays the horizontal transverse luminous region width comparing the impact parameter correlation result with the value from the primary vertex-based method for a series of LHC fills. Both methods are using the full offline track reconstruction. The estimated systematic errors of the resulting width are at the level of a few  $\mu$ m. The very good agreement between the two methods indicates the high degree of understanding of tracking resolutions in the CMS experiment [3].

#### 3.2. Tracker alignment

The CMS tracker is the largest silicon tracker ever built, comprising about 200 m<sup>2</sup> of surface area and in total 16,588 modules. The final alignment is obtained with tracks from the full offline reconstruction traversing the acceptance of the tracker, either from cosmic rays or from pp collisions. CMS uses mainly two methods for track-based alignment: The "local" method (named HIP [4]) fits the alignment parameters of each module individually from the set of residuals determined from the track sample. All tracks are then refitted with the alignment corrections applied, and this procedure is repeated until convergence is reached. The "global" method (Millepede-II [5, 6]) performs a simultaneous fit of all alignment and track parameters. The virtues of both methods can be combined for best results.



Figure 4. Distribution of medians of residuals (DMR) for one of the local measurement directions (v)of the forward pixel sensors after alignment with 7 TeV collision data combined with cosmic muon events, in comparison with simulated data at the level of alignment only with cosmic rays ("STARTUP"), and without any misalignment.

Alignment has been performed combining cosmic ray data taken in early 2010 with the first  $nb^{-1}$  of 7 TeV collision data. The alignment is found to be significantly improved beyond the level of cosmic ray-only alignment. The addition of tracks from collisions has the largest impact in the pixel detector, in particular in its end caps, which were poorly illuminated with cosmics alone. This is visible in Figure 4, which shows the distribution of the medians of the residual distributions of the individual sensors for the pixel end caps. The RMS of this distribution is close to the one expected from simulation without any misalignment. Further details about tracker alignment results can be found in [7].

Beyond the methodology used to obtain the results mentioned above, further refinements are being implemented. Residual curvature of silicon sensors, if not accounted for, may lead to a hit



Figure 5. Mean residual bias translated to the deviation vertical to the module plane as a function of the normalized hit position on the module. Shown are the results assuming flat sensors (filled circles), and with the determined curvature parameters taken into account (squares).

bias that depends on the position and slope of the track. In addition, some modules in the CMS tracker are composed of several sensors which may slightly deviate from coplanarity, a feature described as a "kink". The optimal solution is to determine these features module by module as additional alignment parameters, which, however, leads to an increase in the overall number of parameters to about 200,000.

The successful determination of such a large set of alignment parameters has been achieved using an extended version of the Millepede-II program [6]. Figure 5 shows how a systematic residual deviation, whose dependence on the position on the sensor reflects the sensor curvature, disappears after the appropriate curvature constants, determined module by module, have been taken into account.

# 3.3. Computational aspects of the alignment workflow



**Figure 6.** Illustration of the Millepede-based alignment computing workflow. (See Section 3.3 for further details.)

The Millepede-based CMS alignment workflow (Figure 6) is structured in two steps. The first step includes all computations that proceed event by event, namely the selection of tracks and computation of residuals and their derivatives with respect to the parameters to be fitted. This step is performed in parallel in typically 100–200 jobs at the CAF. The second step executes the global fit of all track and alignment parameters and is very CPU and memory intensive. Two dedicated CAF servers each with 48 GB of memory are available for this task. In order to optimize the turnaround for this workflow, multi-threading has been introduced for the most CPU-intensive parts using the OpenMP interface [8]. On seven CPU cores, the overall execution time of a test job with 200,000 alignment parameters and about a million tracks has been reduced from 9 hours to about 1.5 hours with multi-threading.



Figure 7. Time between the end of the run and the completion of the corresponding beam line parameter objects within the prompt calibration workflow, for a series of CMS runs in October 2010.

# 3.4. The prompt calibration workflow

Several types of conditions, such as the beam line parameters, can change on short timescales. The prompt calibration concept relies on an intentional delay of prompt reconstruction during which time raw data are buffered on disk (see Figure 1), while prompt calibration workflows determine the corresponding constants on the fly from the express stream data, such that prompt reconstruction will proceed with the updated constants. Intensive tests have been performed with the beam line calibration workflow. In the first step of this workflow, the beam line fit is performed once per luminosity section using express stream AlCaReco data. In a second step, ranges with stable constants are "collapsed" into larger intervals of validity to increase the statistical precision and reduce the database storage size. Finally, the calibration object is validated and uploaded to the conditions database. Figure 7 shows the latency of the first two steps observed during constant monitoring; the constants payloads with multiple intervals of validity are available typically within 1-2 hours after the end of data-taking for a CMS run. Close to the end of the 2010 proton-proton run period, the CMS Tier-0 switched to a 48-hour-delay of prompt reconstruction, defined relative to the begin of data-taking for a run, and successfully operated the prompt calibration workflow for one week. Deployment of further prompt calibration workflows is planned, including the update of channel status conditions of various sub-detectors.

# 4. Summary

CMS alignment and calibration have been mastered in the first high energy data-taking period following the turn-on of the LHC machine. A large set of workflows have been operated successfully on dedicated alignment and calibration skims. Constants have been delivered on

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time in preparation of major conferences, and physics results of high quality have been derived based on these constants. The overall CMS alignment and calibration concept proved to be sound and efficient. Future steps will introduce additional workflows that become feasible only with increasing luminosity, resulting in improved statistical and systematic accuracy, and further extension of the set of prompt calibration workflows.

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