LHCb’s Real-Time Alignment in Run II

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Abstract. The LHCb collaboration has introduced a novel real-time detector alignment and calibration strategy for LHC Run II. The data collected at the start of the fill will be processed in a few minutes and used to update the alignment, while the calibration constants will be evaluated for each run. This procedure will improve the quality of the online alignment. Critically, this new real-time alignment and calibration procedure allows identical constants to be used in the online and offline reconstruction, thus improving the correlation between triggered and offline selected events. This offers the opportunity to optimise the event selection in the trigger by applying stronger constraints. The required computing time constraints are met thanks to a new dedicated framework using the multi-core farm infrastructure for the trigger. The motivation for a real-time alignment and calibration of the LHCb detector is discussed from both the operational and physics performance points of view. Specific challenges of this novel configuration are discussed, as well as the working procedures of the framework and its performance.

INTRODUCTION

The LHCb detector [1] is a single-arm forward spectrometer that covers the pseudorapidity range $2<\eta<5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the $pp$ interaction region [2], a large area silicon-strip detector (TT) located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors (IT) and straw drift tubes (OT) [3] placed downstream. The combined tracking system has momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c and an impact parameter resolution of 20 $\mu$m for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors (RICH) [4]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [5]. The online event selection is performed by a trigger [6], which consists of a hardware stage (L0), based on information from the calorimeter and muon systems, followed by software stages (HLT1 and HLT2), which apply a full event reconstruction.

The spatial alignment of a detector and the accurate calibration of its subcomponents are important elements of achieving the best physics performance [7]. The correct alignment of the VELO is needed to identify secondary vertices from the decay of particles with $b$ or $c$ quarks while a misalignment of the all tracking system would degrade the mass resolution. The improvement of alignment significantly increases the $\Upsilon$ mass resolution from 86 MeV/c$^2$ with the first to 44.3 MeV/c$^2$ with the improved alignment as is shown in Figure 1. It is clear that a more effective selection and a higher signal purity of studied channels can be achieved by a real-time alignment and calibration.

Trigger strategies

In Run I the rate of collisions was 15 MHz and it will double in Run II while the output rate of events saved on disk will change from 5 kHz in Run I to 12.5 kHz in Run II (Fig. 2). The online event reconstruction in Run I was simpler and faster than the one used offline on triggered events and did not use the latest alignment and calibration constants. In Run II, the selected events after L0 and HLT1 triggers are buffered on local disks and an automatic calibration and alignment are performed in the trigger farm within a few minutes. This online procedure enables the best possible calibration and alignment information to be used at the trigger level and provide better reconstruction performance in
FIGURE 1. Invariant mass distribution of $\Upsilon \rightarrow \mu\mu$ decay. The mass resolution is 86 MeV/$c^2$ with the first alignment (left) and is 44.3 MeV/$c^2$ with an improved alignment (right).

The real-time evaluation is performed at the beginning of run or a fill. A change of run is implemented in a few minutes when the new alignment and calibration constants are available if the difference from the previous values is significant. The constants are updated for the next run and are used online by the two software trigger stages and offline for further reconstruction and selection of events.

**Tracking alignment method**

The tracking alignment is based on an iterative procedure where the residuals of a Kalman filter fit are minimised [9, 10]. Multiple scattering and energy loss in the material together with magnetic field information are taken into account. The Kalman filter also allows particle mass and vertex constraints to be included. It is possible to align many subdetectors at once. Detector elements can be constrained to their nominal, surveyed or previously aligned position.
Given an initial alignment parameter value $\alpha_0$, the solution for $\alpha = \alpha_0 + \Delta \alpha$ is obtained by solving the set of linear equations

$$\left. \frac{d^2 \chi^2}{d\alpha^2} \right|_{\alpha_0} \Delta \alpha = -\left. \frac{d \chi^2}{d\alpha} \right|_{\alpha_0} .$$

(1)

The first and second derivatives of the total $\chi^2$ with respect to the alignment parameters are obtained by summing the contributions from all the tracks:

$$\frac{d \chi^2}{d\alpha} = 2 \sum_{\text{tracks} i} \frac{dr_i^T}{d\alpha} V_i^{-1} r_i ,$$

$$\frac{d^2 \chi^2}{d\alpha^2} = 2 \sum_{\text{tracks} i} \frac{dr_i^T}{d\alpha} V_i^{-1} R_i V_i^{-1} \frac{dr_i}{d\alpha} ,$$

(2)

where $r_i$ is the hit residuals of reconstructed particle tracks, $V_i$ is the covariance matrix of the measurement coordinates and $R_i$ is the covariance matrix of the residuals after the track fit. It is assumed that the $\chi^2$ for each track has been minimised with respect to the track parameters for the initial alignment parameter value $\alpha_0$.

The $\chi^2$ derivatives calculation can be parallelised by computing part of the sum over different events on different nodes and reconstructing the tracks. The partial sums can then be added together and Equation 1 can be minimised on a single node. For this reason two different alignment tasks are defined:

- The analyser performs the track reconstruction based on the alignment constants and evaluates the partial of the sums from Equation 2. Many samples run in parallel within the ~1700 nodes of the HLT farm. Only one sample is run per node in order not to compete with the HLT1 processes.
- The iterator collects the output of the analysers and minimises the $\chi^2$ (Eq. 1) computing the alignment constants for the next iteration.

The behaviour of both the analyser and the iterator are determined by the finite state diagram in Figure 3. After the initial configuration, a run controller issues the start transition to the analysers which read the initial alignment constants and run on the events assigned to them and then go the paused state. When all the analysers are paused the run controller issues them the stop transitions during which the analysers write on a fixed location of a shared file system the partial sums that they computed and go back to the ready state. The run controller then starts the iterator which reads the output of the analysers, combines them and computes a new set of alignment constants. The run controller then issues another start command to the analysers for a new iteration of the alignment procedure. The iterations continue until the difference of the $\chi^2$ between two successive iterations falls below a threshold. The reason for this is that the change in the total $\chi^2$ is equivalent to the significance of the alignment correction [11]:

$$\Delta \chi^2 = -(\alpha - \alpha_0)^T \frac{d \chi^2}{d\alpha} \Bigg|_{\alpha_0} = -(\alpha - \alpha_0)^T \text{Cov}(\alpha)^{-1} (\alpha - \alpha_0)$$

(3)

where $\text{Cov}(\alpha_0) = \left. \left( \frac{d^2 \chi^2}{d\alpha^2} \right) \right|_{\alpha_0}^{-1}$ is a covariance matrix for the alignment parameters.

Alignment of the LHCb detector

**VELO and tracker alignment**

The VELO is made of two halves that open during LHC filling and close at the beginning of each fill when the beams are declared stable.

The VELO halves are moved using stepper motors. The position is read from resolvers mounted on the motor axes with an accuracy better than $10 \, \mu m$. An automated closure procedure has been developed to position the VELO halves around the beams using the hardware failures or corruption and the measured positions of the beams. By considering the two independent beam profiles compiled by each half, the VELO is observed to close symmetrically around the beam to an accuracy of better than $4 \, \mu m$. As the VELO is closed for each fill, its alignment may change with the same frequency.

The VELO alignment is evaluated first and, since the alignment of the VELO can change for each fill, in case a significant variation of alignment parameters is found, a change of run is performed and the new alignment constants
are used for the following run. An update of the alignment parameters of the VELO is expected often but not for each fill.

Figure 4 shows the stability of the VELO halves alignment during the first fills of Run II. Each point is obtained running the online alignment procedure and presents the difference between the initial alignment constants and the new ones computed by the alignment. It is normal that the alignment constants evaluated for two different fills may vary due to statistical fluctuations even without real movement as different input data samples are used. A maximum variation is a comparable with the $O(2 \mu m)$ precision of the alignment procedure.

The tracker alignment is performed at the beginning of each fill after the alignment of the VELO. The sub-detectors aligned are the TT, the IT and the OT. The alignment constants are updated at every change of the magnet polarity or after the technical stops to account for any change in detectors condition during the time. These alignment constants are expected to change every few weeks and, if a significant variation is found, the new alignment parameters are applied to the following fill.

The left Figure 5 shows the stability of the IT boxes alignment during the first fills of Run II. Each point is obtained running the online alignment procedure and presents the difference between the initial alignment constants and the new ones computed by the alignment. The alignment constants evaluated for two different fills may vary due to statistical fluctuations even without real movement as different input data samples are used. A $\Delta x$ variation of about $O(50 \mu m)$ is smaller than the $O(75 \mu m)$ precision of the alignment procedure. The right Figure 5 presents the convergence of alignment of the IT boxes obtained on fill 3835 starting from 2012 tracker alignment. Each point shows the $x$ variation of the each IT boxes with respect to the previous iteration. The alignment of each IT boxes is converged after 10 iterations.
Both RICH detectors have two sets of mirrors: photons are reflected off a primary mirror onto a secondary mirror, from where they are deflected out of the LHCb acceptance onto the photon detection plane.

The RICH mirror alignment has the same general procedure of the tracking alignment: there is a task performed in parallel by the analysers while the calculation of alignment constants is performed by the iterator on a single node. The alignment of the RICH mirror relies on the fact that a misalignment of the mirrors causes the Cherenkov ring on the Hybrid Photon Detector (HPD) plane to be shifted with respect to the position expected from the momentum of the incoming track. The misalignments are extracted by fitting the variation of the Cherenkov angle ($\theta$) given by:

$$\Delta \theta = \theta_x \cos(\phi) + \theta_y \sin(\phi)$$

where the extracted $\theta_x$ and $\theta_y$ are the misalignment on the HPD plane and $\phi$ is the polar angle measured from the vector that defines the distance of the point where the track hit the detector and the reconstructed centre of the Cherenkov ring [4].

The analysers perform the photon reconstruction and fill $\Delta \theta(\phi)$ distribution histograms for each pair of mirrors on different events. The iterator collects all the histograms and combines them. Then the iterator fits the combined histogram by Equation 4 and extracts the alignment constants. The procedure is performed until the variations are below a threshold. The alignment constants are determined at the beginning of each fill. Figure 6 shows the distribution of $\Delta \theta$ as a function of $\phi$ before and after the mirror alignment for one mirror.

![Figure 5](image1.png)

**Figure 5.** The variation of $x$ position of the IT boxes with respect to the alignment during the Run II data taking as a function of a fill number (left) and as a function of an iteration number (right).

![Figure 6](image2.png)

**Figure 6.** Difference between the measured and expected Cherenkov angle $\Delta \theta$ as a function of the polar angle $\phi$ before (left) and after (right) the mirror alignment for one mirror.
Conclusion

An automatic real-time alignment and calibration strategy is introduced by LHCb in Run II. Data collected at the start of the fill are processed in a few minutes and the output is used to update the alignment. The same framework is used to perform finer calibration less frequently and to monitor the alignment quality of various sub-detectors. This procedure allows a more stable quality of the alignment, more effective trigger selections and offline-online consistency. A dedicated framework has been put in place to parallelise the alignment and calibration tasks on the multi-core farm infrastructure used for the trigger in order to meet the computing time constraints. Physics analyses can be performed directly on the trigger output with the same offline-online performance.

REFERENCES