Real-time alignment and calibration of the LHCb Detector in Run II

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Abstract. Stable, precise spatial alignment and PID calibration are necessary to achieve optimal detector performance. During Run2, LHCb will have a new real-time detector alignment and calibration to allow equivalent performance in the online and offline reconstruction to be reached. This offers the opportunity to optimise the event selection by applying stronger constraints, and to use hadronic particle identification at the trigger level. The computing time constraints are met through the use of 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 the operative and physics performance point of view. Specific challenges of this configuration are discussed, as well as the designed framework and its performance.

1. Introduction

The LHCb detector [1, 2] is a single-arm forward spectrometer covering the pseudorapidity range 2 < η < 5, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system, which provides a measurement of momentum of charged particles, with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c. The minimum distance of a track to a primary vertex, the impact parameter, is measured with a resolution of \((15 + 29/\text{p}_\text{T}) \, \mu\text{m}\), where \(\text{p}_\text{T}\) is the component of the momentum transverse to the beam in GeV/c. The tracking system consists of a silicon-strip vertex detector (VELO) surrounding the \(pp\) interaction region [3], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes [4] placed downstream of the magnet. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors (RICHs) [5]. 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 [6]. The online event selection is performed by a trigger [7], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. In Run II the rate of collision will be 40 MHz of which only 12.5 kHz will be saved on disk.
The spatial alignment of a detector and the accurate calibration of its subcomponents are essential elements of achieving the best physics performance. The correct alignment of the VELO is needed to identify secondary vertices from the decay of particles containing $b$ or $c$ quarks while a misalignment of the all tracking system would degrade the mass resolution. Figure 1 shows how an improved alignment greatly enhances the $\Upsilon$ mass resolution from 92 MeV/$c^2$ with the first alignment to 49 MeV/$c^2$ with the improved one. An exclusive selection using hadron identification criteria relies on the complete calibration of the ring-imaging Cherenkov detectors. Figure 2 shows the effect in the $B^0 \rightarrow h^+h^-$ mass spectrum of hadron identification criteria: the ratio between the signal, $B^0 \rightarrow \pi^+\pi^-$, and the combinatorial background increases by approximately a factor two and the ratio between the signal and the favoured $B^0 \rightarrow K\pi$, increases by a factor 35. Is it thus clear that using a real-time alignment and calibration during the trigger selection allows a higher signal purity and a more effective selection on the channels interesting to pursue LHCb’s physics program without increasing the overall trigger rate. This however presents an unprecedented challenge as it requires to align more than 1700 detector components and compute almost 2000 calibration constants on the fly.

![Figure 1](image1.png)

**Figure 1.** Invariant mass distribution for $\Upsilon \rightarrow \mu\mu$. The mass resolution is 92 MeV/$c^2$ with the first alignment (left) and is enhanced to 49 MeV/$c^2$ with an improved alignment (right).

![Figure 2](image2.png)

**Figure 2.** Invariant mass distribution for $B^0 \rightarrow h^+h^-$ decays [8] in the LHCb data before the use of the RICH information (left), and after applying RICH particle identification (right).
2. Trigger strategy for Run II

In Run I, the event reconstruction performed online by the trigger was simpler and quicker than the one performed offline on triggered events, and did not use the latest alignment and calibration. In Run II the LHCb trigger strategy is different as shown in Figure 3. After the hardware stage, and a first software stage (HLT1) based on a partial reconstruction, the selected events are buffered on disk while the automatic calibration and alignment is performed in a few minutes in the trigger farm. The second stage of the software trigger (HLT2) performs the same reconstruction run offline by using the same calibration and alignment.

When the new alignment and calibration are available, and a significant variation is observed, a change of run is triggered. The new constants are updated for the next run to be used online by the two stages of the software trigger, and offline, for every further reconstruction and selection. The events collected in the previous run, during the automatic alignment and calibration processing, are still reconstructed in HLT2 and offline with the previous constants for consistency with HLT1. The RICH calibration constants are updated for each run both online, in HLT2, and offline as the previous trigger stages do not rely on hadron identification requirements.

This strategy has several advantages: firstly it minimises the difference between the online and offline performance, allowing to use a more effective trigger selection that can take advantage of the hadron identification information. For example Charm physics is limited by trigger output rate contraints; using hadron identification in the trigger allows to have an higher selection efficiency and purity for the double Cabibbo suppressed modes and, at the same time, satisfy the output rate contraints by pre-scaling the more abundant Cabibbo favourite modes. Secondly it ensures the stability of the alignment quality and hence of the physics performance. Finally, as in Run II the last level of the trigger performs the same reconstruction as the one performed offline [9], it will be possible to run some physics analyses directly on the output of the trigger using the special stream of data known as Turbo stream [10].

Figure 3. Trigger strategy for Run II: after the hardware stage and a first software stage based on a partial reconstruction, the selected events are buffered on disk while the real-time calibration and alignment are performed. The second stage of the software trigger performs the same reconstruction performed offline using the same calibration and alignment.
3. The real-time alignment procedure

Two main kinds of tasks are defined: alignment tasks and calibration tasks. The real-time evaluation of the alignment and the calibration uses for each task a dedicated data sample selected by HLT1, and is performed at regular intervals: either at the beginning of the run, fill, or less frequently depending on the task. They are performed in a few minutes using the nodes of the trigger farm and the alignment or calibration constants are updated only if the difference from the previous values is significant, to ignore a random fluctuation due to the different input data sample used.

3.1. Tracking alignment

The tracking alignment is based on an iterative procedure where the residuals of a Kalman track fit are minimised. The magnetic field and material effects are taken into account and information from vertices and particle masses can also be used as constraints to avoid global distortions \[11, 12\].

Given a set of tracks reconstructed using the alignment parameters \(\alpha_0\), the new set of alignment constants can be found solving the system of equations

\[
\alpha = \alpha_0 - \left( \frac{d^2 \chi^2}{d\alpha^2} \right)^{-1} \left| \frac{d\chi^2}{d\alpha} \right|_{\alpha_0},
\]

(1)

where the derivatives of the total \(\chi^2\) with respect to the alignment parameters are obtained by summing the contributions from all the tracks:

\[
\frac{d\chi^2}{d\alpha} = 2 \sum_{\text{tracks}} \frac{dr^T}{d\alpha} V^{-1} r,
\]

\[
\frac{d^2 \chi^2}{d\alpha^2} = 2 \sum_{\text{tracks}} \frac{dr^T}{d\alpha} V^{-1} R V^{-1} \frac{dr}{d\alpha}.
\]

(2)

Here \(V\) is the covariance matrix of the measurement coordinates, \(r\) is the track residuals (the distance between the hit position and the track intercept point), and \(R\) is the covariance matrix of the residuals. It is assumed that the \(\chi^2\) has been minimised with respect to the track parameters for the alignment \(\alpha_0\).

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

- The analyser performs the track reconstruction based on the input set of alignment constants and evaluates the partial of the sums from Equation (3). Many instances run in parallel within the ~ 1700 nodes of the HLT farm. In order not to compete with the HLT1 processes just one instance is run per node.
- The iterator collects the output of all the analysers and minimises Equation (1).

The behaviour of both the analyser and the iterator are defined by the finite state machine in Figure 4. 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:

$$\Delta \chi^2 = -(\alpha - \alpha_0)^T \frac{d\chi^2}{d\alpha} \bigg|_{\alpha_0} = -(\alpha - \alpha_0)^T \text{Cov}(\alpha_0)^{-1} (\alpha - \alpha_0)$$  \hspace{1cm} (3)

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

Figure 4. Finite state machine which defines the behaviour of the alignment tasks.

The VELO is made of two halves that during the data taking are at approximately 8 mm away from the nominal beam position. During the beam injection at the beginning of a fill the halves are retracted by 29 mm until stable beam is declared.

The VELO halves are moved using stepper motors and their position is read from resolvers mounted on the motor axes with an accuracy better than 10 $\mu$m. An automated closure procedure positions the VELO halves around the beams using the response of the hardware 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 beams 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.

Figure 5 shows for a subsample of the Run I dataset the variation of the misalignment between the two halves, estimated by taking the difference of the positions of the primary vertices reconstructed separately with tracks in each half of the VELO. In a perfectly aligned detector the mean of this difference should be zero. The average variation in Run I is $\sim 4 \mu$m while the maximum variation is $O(10 \mu$m), which is more than the $O(2 \mu$m) precision of the track based software alignment procedure [13]. The alignment of the VELO is evaluated at the beginning of each fill in a few minutes. From Run I experience, an update of the VELO alignment parameters is expected often but not for each fill.

The other components of the tracking system do not move before each fill. However movements were observed when turning on the magnet. In addition some variation over time was observed, partially correlated to the magnet polarity which is reversed periodically. The alignment procedure is run at the beginning of each fill after the alignment of the VELO. These alignment constants are expected to change every few weeks.
The alignment procedure of the muon stations is also run at the beginning of each fill but only serves as monitoring, as its alignment is not expected to vary except in case of hardware intervention.

3.2. Rich Mirror alignment

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 follows the same general procedure of the tracking alignment: there is a task performed in parallel by the analysers while the computation of the alignment constants is performed by the iterator on a single node. The RICH mirror alignment relies on the fact that a misalignment of the mirrors causes the Cherenkov ring on the photodetector plane to be shifted with respect to its expected position. The projected track coordinate is not at the centre of the ring, thus the Cherenkov opening angle ($\Theta$) varies as a function of the azimuthal angle ($\phi$) in the photodetector plane:

$$\Delta \Theta = \Theta - \Theta_0 = T_x \cos(\phi) + T_y \sin(\phi),$$

(4)

where $T_x$ and $T_y$ are the components of the misalignment of the projected track coordinate with respect to the expected position and $\Theta_0$ is the Cherenkov angle calculated from the momentum of the track and the refractive index of the radiator \([14]\). The analysers perform the photon reconstruction and fill histograms of the $\Delta \Theta(\phi)$ distribution for each pair of mirrors on different events. The iterator collects all the histograms and combines them. It fits the combined histogram by Equation (4) and extracts the alignment constants. Figure 6 shows for one mirror the distribution of $\Delta \Theta$ as a function of $\phi$ before and after the mirror alignment.

**Figure 5.** Misalignment between the two VELO halves in each run, evaluated by fitting the primary vertices separately with tracks in each half of the VELO. The run numbers shown here span the period of the last four months of operations in 2010.

**Figure 6.** Difference between the measured and expected Cherenkov angle $\Delta \Theta$ as a function of the azimuthal angle $\phi$ before (left) and after (right) the mirror alignment for one mirror \([5]\).
4. The real-time calibration procedure
The evaluation of the new calibration constants does not require an iterative procedure and can be obtained by fitting the relevant distribution on a single node.

4.1. RICH calibration
The RICH automatic calibration consists of calibrating the RICH refractive index and the Hybrid Photon Detectors (HPDs) images. Both these calibrations are evaluated and updated every run.

The refractive index of the gas radiators depends on the ambient temperature and pressure, and the exact composition of the gas mixture and so can change in time. These quantities are monitored to compute an expected refractive index, but this does not have a high enough precision and needs to be corrected. The distribution of the difference between the reconstructed and expected Cherenkov angle is fitted to extract the scale factor to correct the expected refractive index.

HPDs are used to detect Cherenkov photons. They consist of vacuum tubes separated from the radiator gas by a quartz window and a photocathode. The photoelectrons produced are focused onto a silicon pixel array using an accelerating voltage [14]. The anode images are affected by magnetic and electric fields, and so are cleaned and a Sobel filter [15] is used to detect the edges. Figure 7 shows the anode images before and after this process.

![Figure 7. RICH HPD anode images, before (left) and after (right) the cleaning and applying the Sobel filter.](image)

4.2. Global time alignment of the outer tracker
In the straw tubes that compose the outer tracker, the drift time measured may be different from the time estimated from the distance of the track to the wire. This is mainly due to the difference between the collision time and the LHCb clock and is common to all modules. A delay in the electronic readout, different for each module, may be partially responsible for this difference, but its contribution is small in comparison and constant in time, thus it can be calibrated offline. The automatic procedure is performed every fill and computes a single parameter which accounts for the global time alignment by fitting the distribution of the difference between the measured and the estimated time (Figure 8).

5. Conclusion
In Run II the new scheme for software trigger at LHCb allows the alignment and calibration to be performed in real time. Data collected at the start of the fill are processed in a few minutes and the output is used to update the alignment, while the calibration constants are evaluated for
Figure 8. Fit to the distribution of the drift-time residuals of outer tracker hits used to estimate the global time shift between the collision time and the LHCb clock.

each run. This procedure allows a more stable alignment quality, more effective trigger selections and offline-online consistency. A dedicated framework has been put in place to parallelise the alignment tasks on the multi-core farm infrastructure used for the trigger in order to meet the computing time constraints.

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