UNIVERSITY OF GRONINGEN

BACHELOR RESEARCH PROJECT PHYSICS

The VeloPix upgrade for the LHCb experiment

The automation and extension of the equalisation process for the pixel noise matrix

Author
Senne Bakker (S3055337)

First supervisor
Dr. K.A.M. De Bruyn
Second supervisor
Dr. Ir. C.J.G. Onderwater

rijksuniversiteit groningen

June 25, 2021

Contents

1 Introduction

In the time of Aristotle, approximately 350 years B.C., it was thought that everything in the Universe consisted of five elements. These elements are earth, air, fire, water and the aether. At the time, the thought of everything in the Universe consisting of 5 pure elements was revolutionary. Nowadays, much more is known about matter than was known in the time of Aristotle. We know that all 'normal' objects in the Universe are made of building blocks. For example we know that the human body is, among other things, made up from water and proteins. Water and proteins are also made up from smaller buildings blocks: molecules. When zooming in even more, we arrive at atoms and their constituents: Protons, neutrons and electrons. Protons and neutrons consist of even smaller building blocks called quarks. Quarks and electrons are the smallest building blocks we know nowadays.

However, not all of the matter in the Universe is made up from the building blocks which were just discussed. On the contrary: some of our most fundamental building blocks have counterparts. These counterparts fall in the anti-matter category. For example, anti-neutrons, anti-protons and anti-electrons also exist. They are the same and fundamentally different at the same time. For example, an electron and its counter part, the anti-electron, or positron as it is usually referred to, appear to have the same mass, but opposite charge. When a particle and its anti-particle collide, they annihilate into pure energy, usually in the form of light, or photons when referred to as a particle. The reverse process is also possible: pair formation. From pure energy, an electron positron pair can be created. Since there are only processes known that create equal amounts of matter and anti-matter, it is assumed that when the Big Bang happened, equal amounts of matter and anti-matter were created. Now, the problem is that all things that we observe in the Universe are made of normal matter. This raises a question: if there should be equal amounts of matter and anti-matter, where is all the anti-matter? This is one of the most fundamental questions in particle physics right now and that problem is usually referred to as the matter anti-matter asymmetry.

The European Organisation for Nuclear Research (CERN) is doing research on the matter anti-matter asymmetry. One experiment at CERN, the Large Hadron Collider beauty (LHCb) searches for the differences between matter and anti-matter. In the past few decades, results from experiments have shown that Nature is not the same for matter and anti-matter. The ultimate goal of LHCb is to test the Standard Model of particle physics (SM) through these differences. The SM is the basis of particle physics. It describes the smallest building blocks and the three fundamental forces, the strong and weak nuclear force and the electromagnetic force. However, it is not a complete theory. That means that not all observed phenomena can be explained by this theory. Examples of these phenomena are the matter anti-matter asymmetry and the fact that the theory of gravity is not compatible with the SM. These incompatibilities are the bridge to a new physics world: physics beyond the standard model.

Proving that there exists physics beyond the standard model, is not easy. The specific events scientists are looking for, do not occur frequently. Therefore, the detector of the LHCb experiment is upgraded. The LHCb experiment operating on the Large Hadron Collider (LHC), which is the largest and most powerful particle accelerator in the world. It works by colliding high energetic beams of protons. In these collisions, new particles are created, they are detected, processed and analysed. However, the events scientists are looking for, have a very small probability of happening and therefore the LHCb is upgraded. The goal of the upgrade is to increase the number of collisions within the detector, such that scientists can study these rare events more frequently. To process the higher collision rate, LHCb needs to upgrade its detectors. Moreover, the detectors are placed in more harsh environments with enormous amount of radiation.

Thus, the LHCb is also implementing a new detector. A major component of the LHCb that is upgraded is the Vertex Locator (VELO). The VELO is a pixel detector. It uses planes that consist of pixels to detect particles. A pixel in this sense can be compared to a small sub-plane. A small electric current starts to flow when a particle travels through a pixel and this current can be measured. However, the problem is that there always flows a current through the pixels. The current of the particle is just higher. This phenomenon is called background noise. Thus, we need a mechanism that distinguishes the particles from the hits.

All the pixels in the new detector have noise in their signal. That means that if we want a very accurate detector, we have to do something with this noise. In the end the goal is to have a better detector where all the pixels behave in the same way. To deal with this noise, an operating threshold is set. If the output signal of the pixel is lower than the threshold, it is considered noise. If the output signal of the detector is higher than the threshold, it is registered as a particle travelling through the pixel. This would be a simple and efficient solution. However, due to the fabrication process the pixels slightly deviate from each other. Therefore the output signal of every pixel is different. This output signal is referred to as the noise position. Because every pixel has a different noise position, every pixel should have its own operating threshold. Since the whole detector has almost 41 million pixels, this is not feasible. To overcome this problem, another setting has been implemented in the detector. This setting is called the trim value and it controls the noise position of the individual pixels. In total, there are 16 trim levels that can be set. The levels range from 0 to 15. These 16 trim levels are thus used to make sure that all pixels have their noise position at the same point, so that one operating threshold can be set for all pixels. Now the only problem is to find the proper trim value for every pixel, such that the detector operates efficiently. The process of finding the best trim value for every pixel is called the equalisation.

The current equalisation algorithm is not very flexible. It works with using the outer trim levels as input. These levels are thus 0 and 15 and these are used to predict the values in between. Moreover, private communications suggest that the combination used for this equalisation might not be the best one. In this thesis I will study the equalisation process in depth. I will look at how the current equalisation process works and if the algorithm can be improved by looking at the assumptions made. Moreover, I will try to extend the algorithm such that it can process any combination of trim levels between 0 and 15. Therefore, the goal of this thesis is to improve and extend the algorithm and show that it works for multiple input combinations.

2 The detector

One of the biggest research institutes of the world, the European Organisation for Nuclear Research (CERN), is based in Geneva, Switzerland. It houses the biggest and most powerful particle accelerator in the world. It was opened in 2008 and is still functioning. The particle accelerator, the Large Hadron Collider (LHC) is a circular loop of superconducting magnets that has a perimeter of 27 kilometers and lies 100 meter below the earth's surface. In this loop, high energetic particle beams are collided to get insights in the most fundamental questions in physics at the moment. The counter-propagating beams cross each other approximately 40 million times per second.

CERN hosts many experiments, of which the four main LHC experiments are: ATLAS, CMS, ALICE and LHCb. These four experiments have different purposes. The first two experiments, ATLAS and CMS, are the biggest of the four. The purposes of ATLAS and CMS are quite broad. They search for dark matter and study the properties of the higgs boson, which they discovered in 2012. The two experiments thus study the same things, but using different approaches. ATLAS and CMS use different magnet systems.

The Third experiment, ALICE, dedicates its research to heavy ions. Its scientific goal is to study the strong interactions in extreme high energy densities. At these energy densities, quarks and gluons cannot be bound by the strong interaction and thus a quark gluon-plasma forms. While the density decreases, the strong interaction creates the matter we know today: neutrons, protons and electrons. The last experiment, LHCb, focuses on beauty and charm quarks. Its primary goal is to investigate the CP violation in B-mesons interactions. B-mesons are subatomic heavy particles that consist a quark and an anti-quark, where one of them is a beauty quark.

2.1 Large Hadron Collider beauty

The 5600 tonne LHCb experiment is a 21 meters long, 10 meters high and 13 meters wide detector. Unlike the other experiments at LHC, the LHCb's detection area is not symmetric around the collision point, but focuses on the particles travelling forward. The first detector, the VELO, surrounds the collision point and the following detectors are placed behind the first one in orderly fashion. Figure 1 shows a schematic drawing of the LHCb detector.

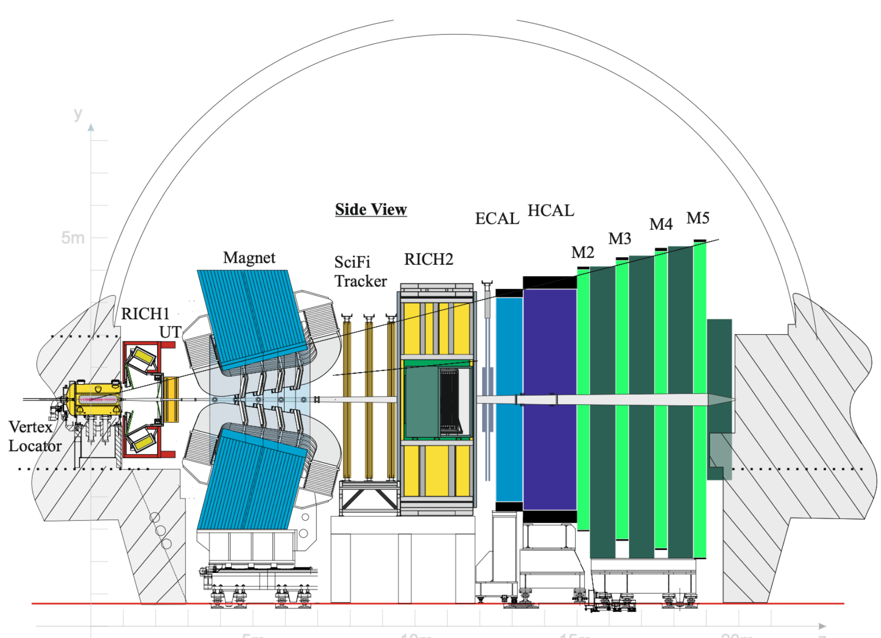

Figure 1: *A schematic drawing of the upgraded LHCb detector. [9]*

In this schematic, a couple of important components can be seen. The tracking system consists of the Vertex Locator (VELO), the Upsteam Tracker (UT), the magnet and the SciFi tracker. The particle identification system consists of the Ring Imaging Cherenkov detectors (RICH1 and RICH2), the Electromagnetic calorimeter (ECAL) and the muon detectors (M1-M5). The energy measurements are done by Hadronic and Electromagnetic (HCAL and ECAL). All these components work together to identify the particles and measure their energies and momenta. The tracking system of the LHCb experiments reconstructs the paths that charged particles follow. This is needed for momentum measurements. RICH1 and RICH2 determine the velocities of the particles by exploiting the Cherenkov effect. By combining velocity and momentum measurements, the mass of the particles can be determined. This is obviously important to conclude the nature of the particles. The hadronic and electromagnetic calorimeters determine the energy of the passing particles. The particles initiate a particle shower when entering the calorimeters. The shape and depth of the shower are used to conclude on the energy of the initial particle.

2.2 Vertex Locator

The Vertex Locator is the main tracking component of the LHCb detector, and measures the decay positions of B-mesons very accurately. It is very important, since a displaced vertex from the primary is indicative for a decay of a B-meson [4]. A B-meson is a particle that consists of a quark and an anti-quark, where one of them is a beauty quark. For this reason it is also used in the trigger system to track the interesting interactions.

The VELO detector detects particles in the following way. When a particle travels through a sensitive area of the detector, the particle ionises the path it follows. This ionisation can be measured as a flow of electric current on the pixel. This current can be measured. After it is measured it is compared with the global operating threshold, where the current below the threshold will be seen as noise.

The VELO is a major component that will be upgraded during Long shutdown II (LS2). LS2 is the period from 2019 to the beginning of 2022 where the LHC will be shut down so that the different experiments have time to implement their upgrades. The LHCb and ALICE experiments will upgrade their whole detector during LS2 whereas ATLAS and CMS will install the first part of their upgrade.

In the current design, the data readout is based on a trigger system. The trigger system decides which events are interesting and which are not. The reason behind this is that it is not possible to record all 40 million events per second. After the upgrade, all 40 million interactions will be read out. A new ASIC, called the VeloPix, is developed for this purpose. The new trigger system will be fully software based and thus the selection of events is more flexible [1].

In contrast to the current VELO, the upgraded VELO is a pixel detector. It will be placed closer to the beam at 5.1 mm instead of 7 mm. Moreover, the new VELO will have faster electronics and the new VeloPix to cope with the enormous total data readout. The total data readout increases with a factor 8000 to 1.2 Tb/s. The total detector consists of 52 modules that all have 12 ASICs. Thus, in the new VELO there are 624 ASICs. All these ASICs have a corresponding pixel grid of 256x256. A Schematic image of the new VELO detector can be seen in figure 2

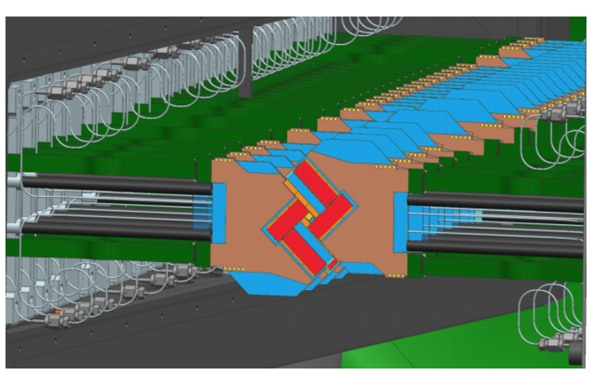

Figure 2: *A schematic image of the VELO detector [2].*

3 Background noise in the VELO

Ideally, the pixels would be calibrated perfectly and would not give output when no particles are travelling through the detector. However, this is not the case. In an environment where no detectable particles can be recorded, the VeloPix still records current, mainly due to thermal leakage. Thermal leakage is the phenomenon where electric charge carriers, such as electrons, vibrate within an electrical conductor. The vibration of the charge carriers induce the current that is detected by the VeloPix ASIC. This thermal noise is directly proportional to the temperature and thus can be reduced by lowering the temperature. This is also the reason that the detector operates at approximately -30 °.

Noise is obviously unwanted, since it disturbs the actual data. One way to deal with this, is to set a certain global operational threshold in DAC. DAC is an arbitrary unit for current and is therefore used as the value of the global threshold. The threshold makes sure that every output signal below that threshold will be regarded as noise.

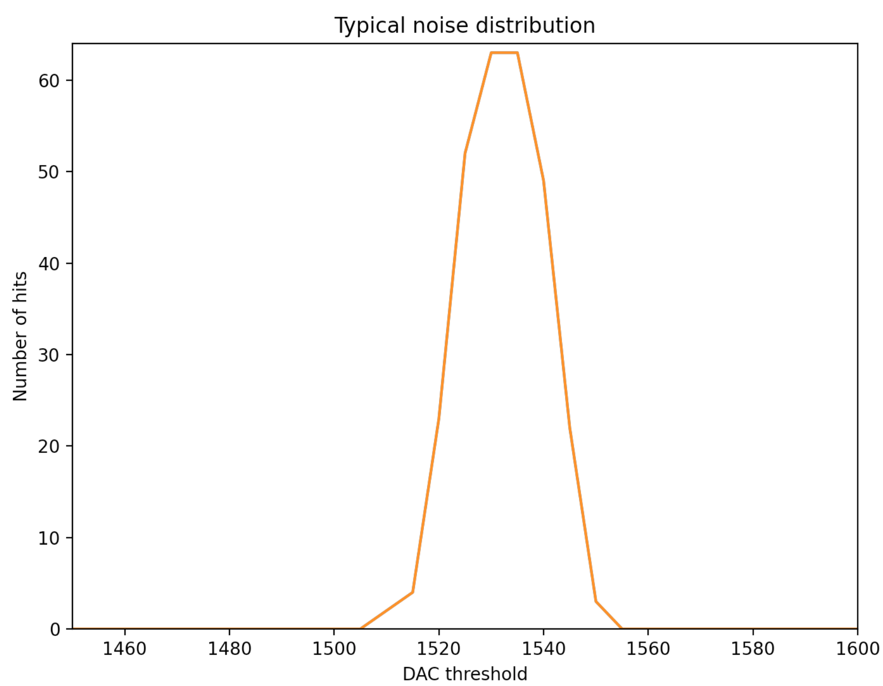

Figure 3: *A typical noise distribution of single pixel.*

To study the noise behaviour of the pixels, scans are made. A typical noise scan of an individual pixel can be seen in figure 3. The scans are made by increasing the global threshold and monitoring the response of the pixels.

However, the noise distribution in figure 3 is not unique. Due to the fabrication process, the pixels slightly deviate from each other. Therefore the pixels have a different sensitivity to thermal noise. As a result, the noise distributions of different pixels are centered around a different point. For example, in figure 3, the distribution is centered around approximately 1530 DAC. The mean of the noise distribution of a single pixel is called the pixel noise mean. For another pixel, this pixel noise mean could be 1550 DAC. Thus, a global operational threshold could fit one pixel perfectly, but could be off very much for another.

The solution to the background noise problem is a setting that has been implemented on every pixel. This setting is called a trim level. In total, there are sixteen trim levels that can be set. These levels have integer values between 0 and 15, which totals to 16 values. These trim levels determine the position of the noise distribution for individual pixels. Thus, this is the pixel specific solution that is needed to control the amount of noise in the detector.

The pixel noise matrix is very important tool to understand what is happening with the noise. The pixel noise matrix is formed from the pixel noise mean values. Every pixel's pixel noise mean will fill an element in the pixel noise matrix. The pixel noise matrix thus has dimension 256x256 and typically looks like:

$$\begin{pmatrix} 1354 & \dots & 1338 \\ \vdots & \ddots & \vdots \\ 1301 & 1360 & 1389 \end{pmatrix}$$

When the pixel noise matrix is plotted in a histogram-like figure, it typically looks like:

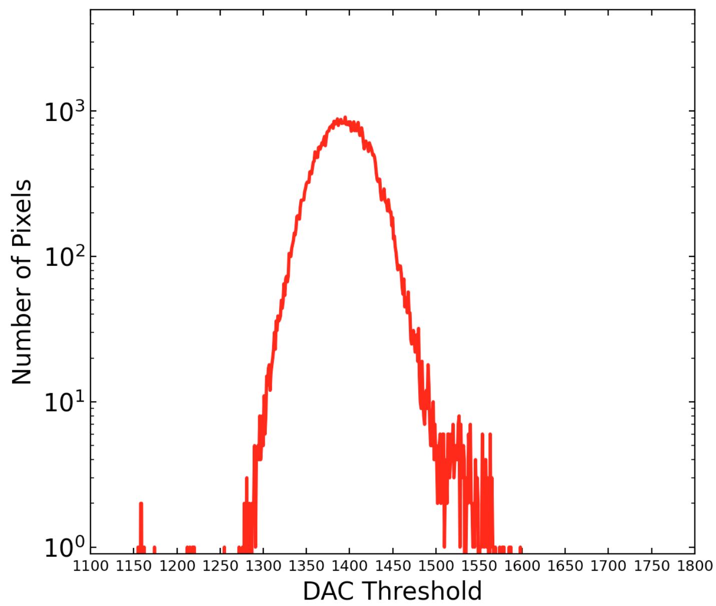

Figure 4: *The distribution of pixel noise mean values.*

4 Equalisation

The equalisation process was developed to equalise the behaviour of all the pixels. This means that every pixel should have its pixel noise mean approximately in the same position. If that is not the case, there could be pixels that have their pixel noise mean close to the global threshold. This could cause the pixel to transmit hits all the time. In the other case, where the pixel noise mean is below the global threshold, it could become inactive in the sense that also particles are suppressed by the global threshold.

To achieve the equalisation of the pixel noise mean, a code was developed. The code works in the following manner. After the input of two pixel noise matrices of two different trim levels, a global average of the pixel noise matrix is calculated. This global average of the pixel noise matrix is called the global mean of a specific trim value. It is calculated as the average of all the pixel noise mean values in the noise pixel matrix.

With these global averages, the target is calculated. The target is the DAC value where, ideally, the pixel noise mean values of every single pixel would end up. The target is calculated as the average of the global mean values of the outer two trim levels. Thus,

$$\text{Target} = \frac{\text{Global mean trim F} - \text{Global mean trim 0}}{2} \tag{1}$$

The scans that were given as input in this equalisation process were scans with the trim level set to 0 and 15.
The trim values are calculated for every pixel as

$$\text{trim value} = \frac{\text{target} - \text{pixel noise mean trim 0}}{\text{slope}} \tag{2}$$

where the slope is defined as

$$\text{slope} = \frac{\text{Global mean trim 15} - \text{Global mean trim 0}}{16}. \tag{3}$$

Then, the adjusted pixel noise position is predicted using:

$$\text{Noise position (DAC)} = \text{pixel noise mean (trim 0)} + \text{trim} * \text{slope} \tag{4}$$

to match the pixel noise mean of that particular pixel to that of the target. Thus, the noise position in eq. 4 should come as close to the target as possible. This process is repeated for every pixel in the pixel noise matrix and creates two new matrices, the pixel trim matrix and the pixel threshold matrix. The pixel trim matrix consists of the calculated trim levels for every single pixel and the pixel threshold matrix shows the predicted DAC thresholds for every single pixel. The elements of these matrices are calculated following eqs. 2 and 4.

4.1 Masking

Despite the fact that the equalisation process allows us to shift a lot of pixels towards the target, some pixels are behaving so bad that they cannot be shifted towards the target and have to be masked. This is also part of the equalisation process. Ideally, one would have as few masked pixels as possible such that the efficiency loss is minimal.

4.1.1 Conditions for masking

There are a few categories in which we divide the masked pixels.

- A: a dead pixel. Dead pixels do not react at all and are therefore useless.
- B: a pixel does not respond on the scan with the lowest trim value. The behaviour is unpredictable and therefore the pixel is masked.
- C: a pixel does not respond on the scan with the highest trim value. These pixels are masked for the same reason as category B.
- D: An invalid trim value was assigned to this pixel. When the calculated trim for a pixel is higher than 15 or lower than 0, it is masked since these levels simply do not exist.

- E: the difference between the target and the pixels noise position is too big. A pixel is allowed to be 25 DAC from the target. However, not all pixels can be shifted towards this range. The pixel could therefore be noisier than others. This makes the pixel record hits which take up bandwidth that cannot be used for actual hits.

Figure 5 shows the typical plot of the masking procedure.

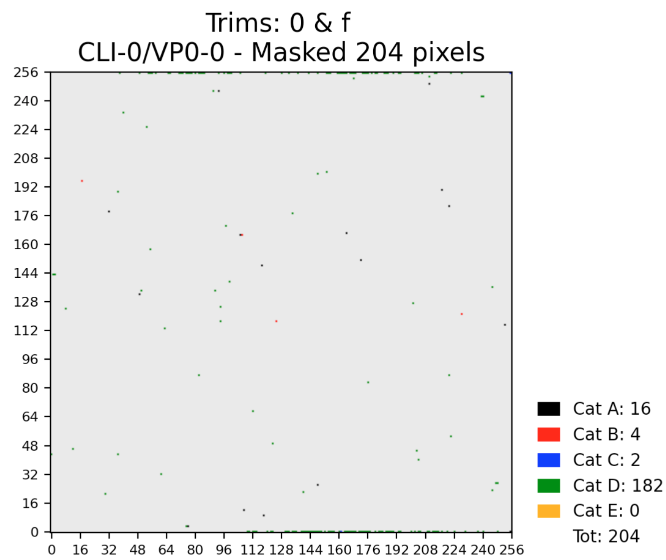

Figure 5: *a typical masking plot of the pixel noise matrix.*

4.2 limitations

The equalisation process is working properly for scans with the trim levels of 0 and 15. However, the code has its limitations.

Firstly, private communications imply a temperature dependence on the scans with trim levels set to zero. As the VELO detector will operate in approximately -30 degrees Celsius, this is a problem. Some of the pixels do not behave in the same way they do when operating at room temperature. The solution to this problem is quite simple. For the equalisation process, a scan is used that has a trim level different from zero.

Secondly, it is not known for which trim levels the pixels behave the best. It is therefore convenient that the code can handle scans for different trim levels.

Thirdly, the correlation between the trim levels and their global mean values is not linear. From [8] we know that the actual correlation has a shape of a third degree polynomial. Figure 6 visualises this. Thus, this causes inaccuracies when calculating the best matching trim level for every pixel. The derivative of a third degree polynomial is a second degree polynomial, and therefore the slope which is used in eq. 2 is not constant anymore. Especially when the trim levels are chosen closer together, for instance trim level 8 and 9, the inaccuracies become more apparent. This can be seen in figure 7, where it is visualised that in the case of a linear slope assumption, the further we extrapolate, the bigger the error becomes.

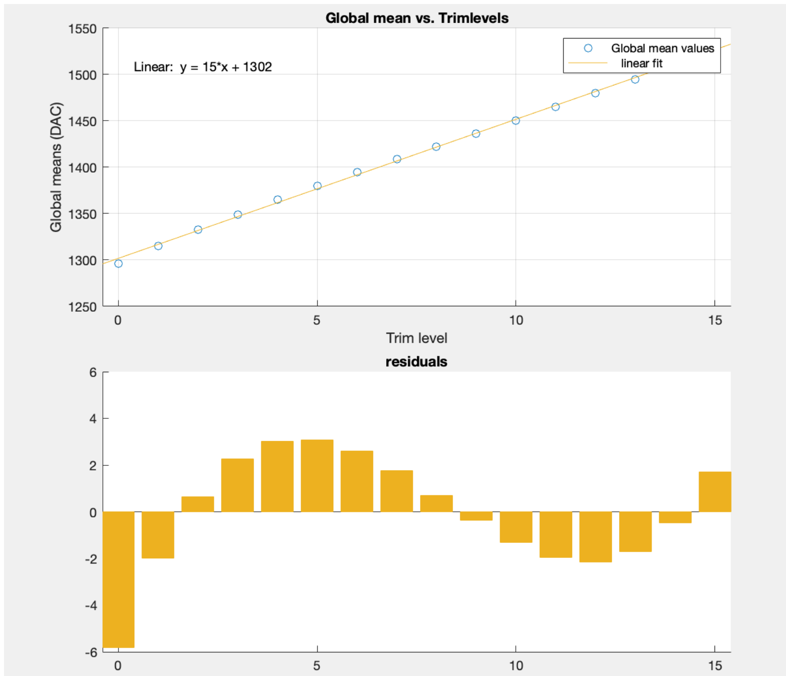

Figure 6: *The actual correlation between the global mean value and the trim levels.*

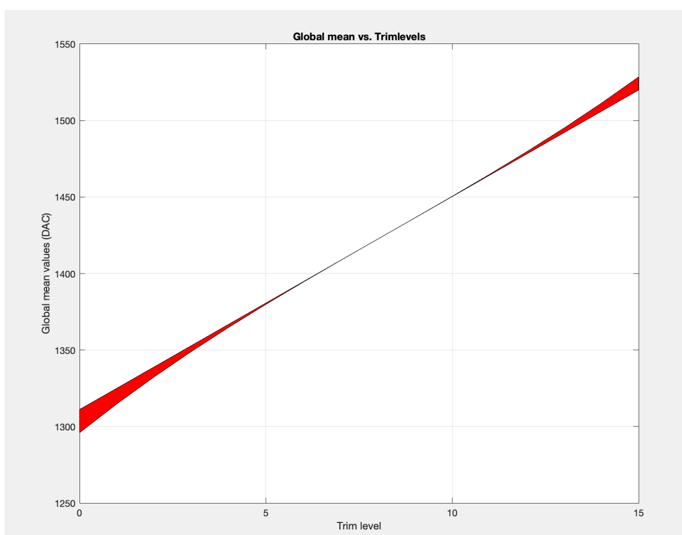

Figure 7: *If the slope is calculated with two trim values closer together, the slope becomes more and more inaccurate.*

Furthermore, the target calculation changes. Since the target was calculated as an average, the target changes with respect to scans with different trim values set. When the trim levels that were set are symmetric, for example 1 and 14, the result is approximately equal to the target that would been set if trim 0 and trim 15 were used. However, when using asymmetric trim levels, for example 10 and 15, it can be easily seen that the target calculation breaks down. Therefore, it needs to be updated.

Another problem that occurs when taking two trim levels closer together is that the global mean values come closer to the target. When this happens, a significant number of pixels have their noise positions for both scans lying higher or lower than the target. When the noise positions for both trim levels of that pixel lie higher than the target, the trim value calculated for every pixel in eq. 2 becomes negative. This means that the trim value for that pixels should be set lower than the lowest trim level that is given as input. However, since eq. 2 works using trim 0 and trim 15, the possibility of shifting down is not taking into account. Therefore, these pixels are masked by condition D. Thus, shifting the pixels down should also be implemented in the algorithm.

5 Solutions to limitations of the equalisation process

Because of the temperature dependency explained in section 4.2, the code had to be updated to handle scans with different trim levels set. Thus, the code was updated such that it could do this. The update also includes the target calculation, the calculation of the best trim value and the corresponding shifted noise position and the masking of bad pixels.

5.1 Target calculation

Instead of calculating the target as the average of the global mean values of the two scans, it is calculated using weights. The weights are calculated based on how far the given trim levels are displaced from the middle of the spectrum. When a given trim level is closer to the target, it is given more weight to balance out the asymmetry imposed by the given input levels. Metaphorically, this process can be be compared to a seesaw.

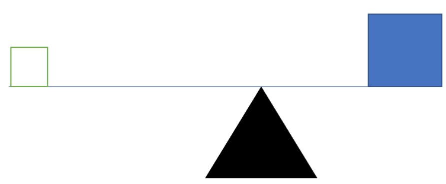

Figure 8: *The seesaw effect*

The blue weight on the right is closer to the middle of the seesaw and therefore should have more weight to balance the small weight which is further away from the middle.

5.2 Trim value and noise positions

The trim value calculation is done in the following way. First, the position of the target with respect to the noise positions of the pixels is determined. There are 5 options. The target

- lies in between the two noise positions,
- lies above the two noise positions,
- lies below the two noise positions,
- is within reasonable range from the lower noise position,
- is within reasonable range from the upper noise position.

Obviously, in the last two options, the trim level is set to the upper or the lower trim level. For the other three options and its calculations, an assumption was made. It is assumed that all ASICs follow the difference distribution shown in figure 9. The bins shown in this figure represent the difference in DAC values between the different trim levels. It is known that this is not entirely true but for simplicity sake this assumption has been made.

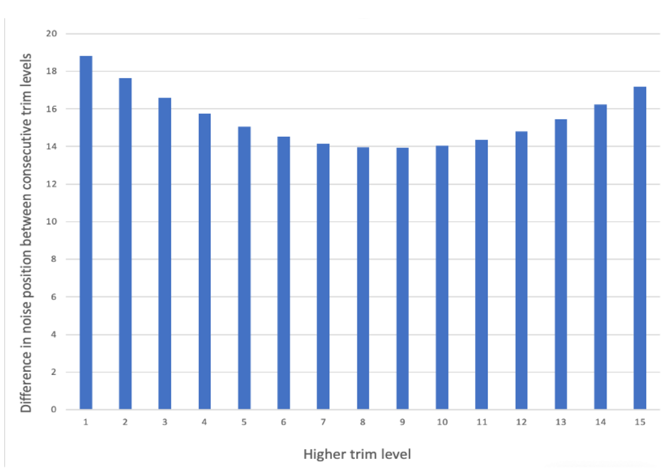

Figure 9: *The difference of the global mean values between consecutive trim levels, with the x axis representing the higher trim level of the two.*

These differences are used to calculate the trim values. This is done in the following way. First, the difference between the target and the closest noise position is calculated. Subsequently, we subtract the differences shown in 9 until the distance to the target is negligible. The number of times the bins are subtracted, are counted and therefore it is known how many trim levels the pixel should be shifted.

However, it is very rare that the shifted noise position coincides perfectly with the target and there is no residual. Therefore, if the distance to the target is within half a bin from the target, the process is stopped. The total amount of DAC units that the pixels has moved, is also counted. This is used to calculate the adjusted noise position. The adjusted noise position becomes the old noise position with the amount it has shifted and its residual taken into account.

6 Analysis

In this section, some results will be shown.

6.1 Comparing old and new results

In the figure 10 and figure 11 the comparison of the new and old masking procedure is made.

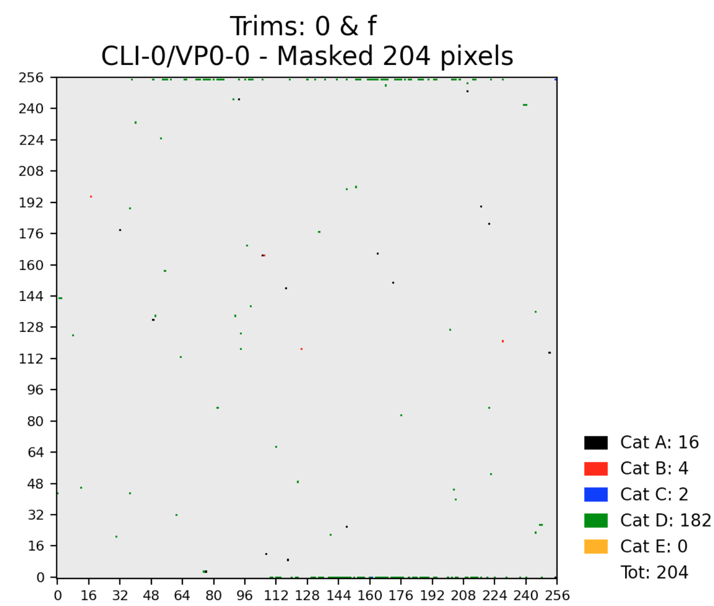

Figure 10: *The old masking procedure for trim levels 0 and 15.*

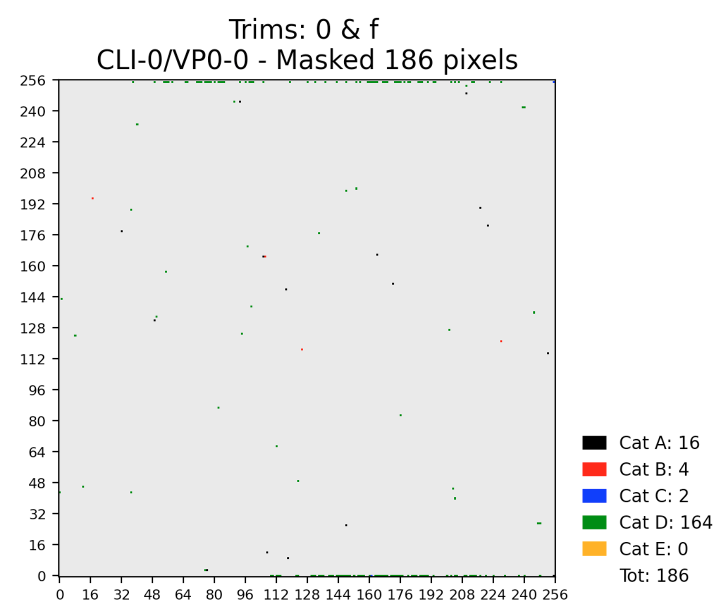

Figure 11: *The new masking procedure for trim levels 0 and 15.*

In the old algorithm, all pixels with calculated trim value larger than 15 and smaller than 0 were masked. However, some pixels that have a calculated trim value of 15.1 or -0.1 may still be in the range that is allowed. In the updated algorithm, the pixels which are in the allowed range are not masked. The allowed range is set as a maximum of 25 DAC from the target. 18 pixels fall in this category in the case which is shown in figure 10 and figure 11. In the figures below, the distributions of the equalised pixels together with the noise distributions can be seen.

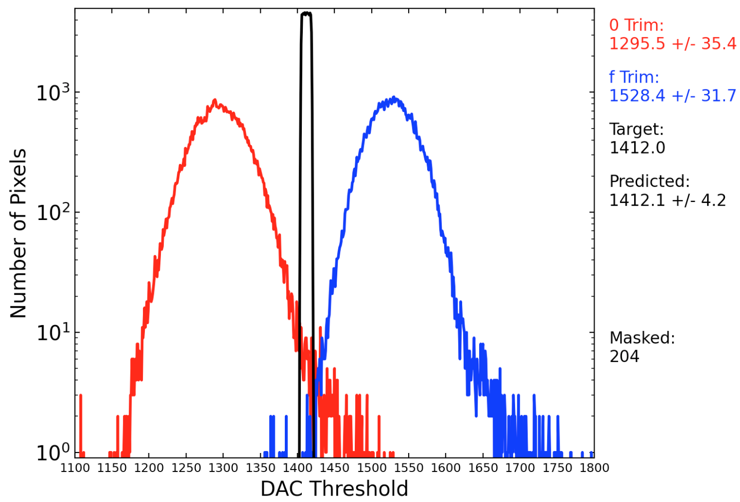

Figure 12: *The current algorithm: the plotted distributions of the trim levels 0 and 15, with the trimmed pixels being the black spike.*

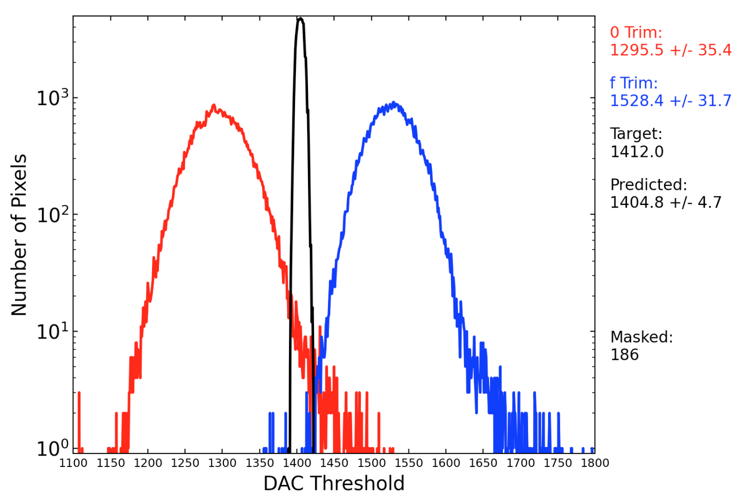

Figure 13: *The updated algorithm: the plotted distributions of the trim levels 0 and 15, with the trimmed pixels being the black spike.*

The black distribution in figures 12 and 13 represents the number of pixels which have their shifted noise position at that DAC value. In figure 13 it can be seen that the distribution is a bit wider than the distribution in 12. It is thought that this comes from the fact that the updated algorithm relies on the fact that pixels that have assigned trim value of 15.1 or -0.1 can be still be in the range. Furthermore, the algorithm takes the residuals into account. As mentioned before, it is very rare that the shifted noise positions exactly match the target. These residuals could also lead to a wider distribution in shifted noise positions.

The updated algorithm can also equalise scans with other trim values than 0 and 15. For example, figures 14 and 15 show the masking procedure and the noise and equalised pixel distributions can be seen.

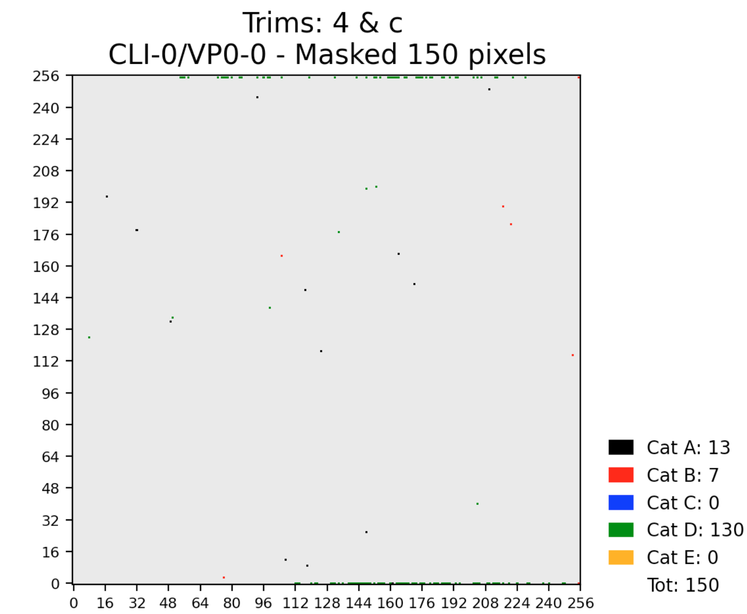

Figure 14: *The masking procedure for trim levels 4 and 12*

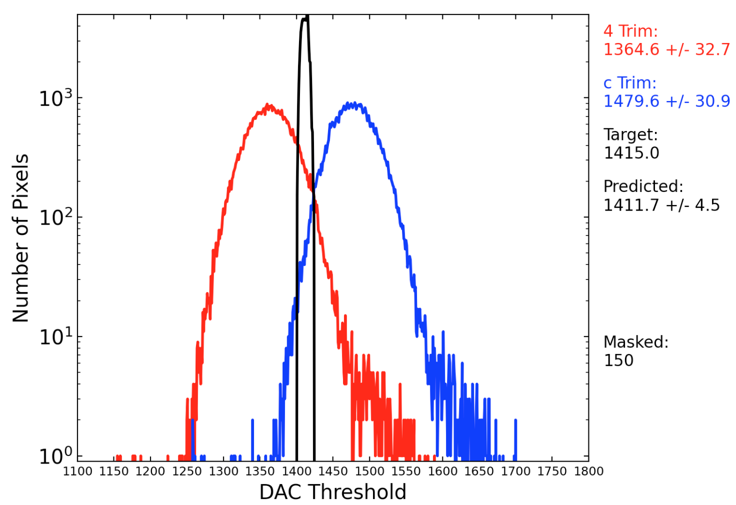

Figure 15: *The plotted distributions of the trim levels 4 and 12, with the trimmed pixels being the black spike.*

In these figures, it can be seen that less pixels are masked than with the 0 and 15 trim. This raises a question. Since the number of masked pixels in figure 10 is higher, how reliable is the number of masked pixels in figure 14? In the case of the equalisation for the 0 and 15 trim, the algorithm only has to interpolate, since the two trim levels are the boundaries. Thus, you would think that this is the best option. There are multiple reasons for the number of masked pixels being lower. When trim levels are chosen closer together, the algorithm has to extrapolate, with no 0 or 15 trim for reference where to stop. The third order polynomial that is implemented, is not followed perfectly by all pixels [8]. Thus, when calculating the trim levels and corresponding DAC values, some pixels may be assigned values that are actually outside the boundaries set by the 0 and 15 trim.

7 Future prospects

Ideally, we could input scans for every trim level. In this way the best trim level for every pixel could be determined instead of calculated. However, 16 scans take very long to process and this is not ideal since the algorithm will be used on a regular basis and the algorithm has to run for almost every ASIC in the detector. Therefore, some other options are discussed.

7.1 Fitting function

Firstly, one could input 4 scans, which is the optimal number of scans [8], with 4 different trim levels set. With these 4 scans, it is possible to fit a third degree polynomial through the raw data of every pixel. Thus, for every single pixel in these scans, the noise positions for every trim value can be calculated more accurately. This should improve the accuracy for the equalisation process. In this report, the assumption is made that all ASICs follow the distribution shown in figure 9. However, in reality the noise positions of the single pixels, of the same trim level differ. The fitting function would therefore also solve the problem of the different ASICs.

7.2 Slower algorithm

Secondly, the algorithm is not as fast as it used to be. During this project approximately 15 functions were created that are called for all of the 65536 pixels. Some functions may be combined to give less calls and speed up the calculation.

8 Discussion and conclusion

Because of the temperature dependency of scans with trim level set to zero, the equalisation algorithm had to be more flexible. Thus, the algorithm was extended take scans with any trim level as input. There were a few limitations in the old algorithm. One of the biggest problems was that when the target DAC value was lower than the pixel noise position, the trim level would automatically evaluate to a negative number. This means that the pixel should be shifted down with respect to the lower trim value. However, this was not implemented in the old algorithm, but is in the new algorithm. Furthermore, the third degree polynomial from [8] and a new way of calculating trim values and predicting the shifted noise positions was implemented.

When looking at the masking plots, it is noticeable that when scans are used with trim levels that are closer together, for example trim levels 4 and 12, the number of masked pixels are decreased. This may be caused by the fact that the calculations are more fragile when the trim values of the scans are chosen to be closer together. This fragility is probably caused by the fact that the new algorithm uses extrapolation.

Overall, the updated algorithm is slower, but more precise. It takes into account the correlation between the global mean values of different scans with respect to the trim levels and it gives more precise calculations of the predicted trim levels for single pixels.

9 Acknowledgements

I would like to thank Kristof de Bruyn for his help with this project and his useful input. I also would like to thank Kristof for his quick responses and for providing me with more data when needed. Also, the weekly meetings with the VSI LHCb group every Thursday were both interesting and helpful.

10 Appendix A: The code

The source code can be found by clicking the link below.
https://github.com/SenneBakker/Thesis

References

[1] A. Obłąkowska-Mucha and T. Szumlak. Tracking system of the upgraded LHCb. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 824:62–63, 2016. Link.

[2] E. Buchanan. The LHCb vertex locator (VELO) pixel detector upgrade. *Journal of Instrumentation*, 12(01):C01013–C01013, jan 2017. Link.

[3] LHCb Collaboration. LHCb VELO Upgrade Technical Design Report. Technical report, Nov 2013. Link..

[4] J Libby. VELO: the LHCb vertex detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 494(1):113–119, 2002. Link.

[5] Jeroen J. van Hunen. The LHCb tracking system. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 572(1):149–153, 2007. Link..

[6] Karol Hennessy. LHCb VELO Upgrade. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 845:97–100, 2017. Link..

[7] L. Diamante. Transforming LHCb: What's in store for the next two years? Feb 2019. Link..

[8] M. Vos. Predicting the noise position for unmeasured trim levels. June 2021. Bachelor thesis.

[9] Various writers. Framework TDR for the LHCb Upgrade: Technical Design Report. Technical report, Apr 2012. Link.