Identification of muons in ATLAS
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Citation for published version (APA):

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Chapter 5

ATLAS BOL commissioning

5.1 Introduction

In this chapter we present the performance of the 96 BOL muon stations, assembled and tested at Nikhef in Amsterdam. After construction at Nikhef, the MDT chambers were shipped to CERN and assembled with RPCs before being installed in the ATLAS Muon Spectrometer. During the construction and assembly, the performance of the stations was tested and commissioned on various aspects to ensure that the design specifications were met. The domain of these tests range from pure hardware issues all the way to testing the processing of large amounts of data with dedicated offline reconstruction software.

In section 5.2 the hardware components of the MDT chamber are presented, and the journey of a BOL station from construction to its final installation is followed. Section 5.3 discusses the commissioning of the MDT chambers in detail. Section 5.4 focuses on the cosmic ray data, used to commission the Muon Spectrometer and ATLAS. In Section 5.5 the hardware performance of the BOL chambers as on October 2008 is presented.

5.2 MDT electronics and services

Figure 5.1 shows a schematic overview of the MDT electronics used to read out the signal from an MDT chamber, as well as the electronics used to monitor the temperature and magnetic field. On one side of the drift tube, on the right side of the figure, the monitored drift tubes are connected to high voltage (HV). The HV is distributed over the tubes via so-called HV hedgehog cards which are mounted on the tubes.

The signal is read out at the other end of the tubes, the read-out (RO) side of the chamber. The raw tube signals are Amplified, Shaped and Discriminated, eight tubes served by one ASD chip. The ASD chip measures the deposited charge with an Analogue-to-Digital Converter (ADC) in Wilkinson ADC counts. The ADC value is used for timing corrections and monitoring of the gas-gain. The differential signal outputs of the ASDs are routed to the Time-to-Digital Converter (TDC), where arrival
times of the leading and trailing edges of the signal are stored in a buffer. Three ASD chips route the signals to one TDC chip, which in turn serves 24 MDTs. The ASDs and TDC are implemented on a printed circuit-board called a Mezzanine. BOL chambers are produced in different types of different sizes with different number of tubes, consisting of up to 18 Mezzanine elements.

The Mezzanines are controlled by a local processor, the Chamber Service Module (CSM). The CSM collects the hits from the TDC and sends them via an optical link to the Data Acquisition (DAQ) system. The CSM and the read-out electronics are powered by a low voltage (LV) power supply.

An other element in the MDT electronics scheme is the Detector Control System (DCS), which sets the chamber up for data taking by controlling the read out electronics and monitoring its condition. It monitors up to 30 temperature sensors (T-sensors) and up to four magnetic field sensors (B-sensors), mounted on each MDT chamber. These parameters are relevant for the calibration of the r-t relation which relates the time measurement to the radial distance of the hit to the wire, since the drift properties of the gas is dependent on both temperature and magnetic field. The initialization and configuration of the Mezzanines is done via the Joint Task Action Group (JTAG) protocol. This protocol programs all parameters of the ASD and TDC chips, e.g. the setting of discriminator thresholds and dead times. The DCS monitors the voltages and the temperatures of the Mezzanines as well.

The various MDT chambers are connected via the DCS box on a (CAN) field-bus for distributed control and monitoring.

An optical alignment system is deployed in the Muon Spectrometer to monitor the relative positions of the MDT stations with respect to each other, the Rasnik system [52]. The Rasnik alignment system is a set of optical paths, consisting of three elements. A led (RasLed) projects a coded mask via a lens onto a CCD camera (RasCam). The

Figure 5.1: Schematic overview of the MDT electronics.
system monitors the relative displacements of the three elements. Relative movements of each of the elements are measured by changes in the image of the mask on the camera. Analysis of the images results in a very precise (30 μm [53]) measurement of the positions and deformations of the muon stations.

The optical paths within an MDT station, connecting the high-voltage side of the station with the read-out side is called the In-plane system and measures chamber deformations. For the In-plane system, the three Rasnik elements are within the same station. Other optical paths such as the Axial system monitors the relative positions of MDT stations in the same station layer and the Projective system measures the relative positions of stations in different station layers. For these systems, one station has the RasLed mounted whereas the other station has the RasCam.

5.2.1 BOL MDT testing and installation - a time line

After production at Nikhef, the BOL MDT chambers underwent a series of tests in order to ensure the best possible detector quality. The MDT electronics were checked for internal consistency and cosmic ray muon signals were used to assure the quality of the data. In further parts of this chapter we will look into the tests in more detail. During the commissioning at Nikhef, not all the elements of the electronics were mounted on the BOL chambers and part of the tests were performed with prototype electronics. Nevertheless as significant number of checks were performed at Nikhef and after successful completion of the tests, the chambers were transported to CERN.
ATLAS BOL commissioning

At CERN, for practical reasons, the BOL chambers were first stored until the chambers were further transported to the B5 assembly hall where they were reception tested to check for damage during transport. The installation of electronics was completed and the chambers were mounted with RPC detectors. The combined RPC station and BOL chamber are called stations. In the next step, the stations were tested in a cosmic ray setup to validate the data quality. At this point, malfunctioning electronics and broken wires could still be replaced. Again for practical reasons, the stations were stored until installation.

Before installation in the ATLAS cavern, the BOL stations were once more subject to a round of tests to verify readiness for installation (the Ready For Installation or RFI-tests). This was done at the surface above the ATLAS cavern, in the SX1 hall. Malfunctions could still be addressed at this point, which are very complicated after installation of the chambers where the services and electronics are difficult to reach. No new problems were found and all BOL chambers were ready for installation. After installation, the MDT chambers were regularly subjected to cosmic ray tests, as is described in section 5.4, to commission the Muon system and to integrate the other sub-systems such as the Inner Detector and Calorimeters as well. At the time of writing of this thesis, continuous commissioning efforts are still performed.

5.3 Commissioning

To ensure that the performance of the MDT chambers stated in the design report [54] were met, the chambers were extensively commissioned. Commissioning can be described in various ways, such as chronologically. Though, in this chapter, the description of the commissioning is categorized in type of commissioning, e.g. in the following three parts:

- **Hardware**: All the hardware components of the MDT chambers were tested, such as the gas system, the detector control system, alignment system and the high voltage supply for the chamber. This part also includes the read out of signals and the MDT electronics also.

- **Online software**: Besides the pure hardware aspects of the MDT chambers, the DAQ system and the overall quality of the data was tested. These tests were performed using cosmic muons mostly.

- **Offline software**: The final aspect of commissioning is the muon reconstruction software chain, which was commissioned with large data runs of cosmic ray muons. This entails the large scale data processing and the deployment of databases as well.

The following sections describe the commissioning of the MDT hardware, the online and the offline software in more detail.
5.3 Commissioning

Figure 5.3: Read-out side of the BOL MDT chamber.

5.3.1 MDT hardware commissioning

Figure 5.3 shows the read out side of a BOL MDT chamber. See Figure 1.8 for the layout of an MDT chamber. The various components discussed in the previous section such as the CSM and DCS box are indicated. In this picture, 18 Mezzanines are connected to the CSM. Besides the read out electronics and the temperature and magnetic field monitoring, the alignment system Rasnik is indicated as well. Rasnik has various components which are connected to a multiplexer, the RasMux. The inlet and outlet of the gas system are shown in the left of the picture. These various components were tested during the hardware commissioning as follows:

- A visual test was performed to verify that the chambers had no visible damage.
- The chambers were tested on gas-tightness. The drift properties of the gas mixture depend on the gas pressure. To ensure stability in the drift processes the pressure drop of the BOL chambers should not exceed 1 mbar/day. The gas-tightness is tested by measuring the pressure in the tubes for a certain amount of time. The environment temperature has a large impact on the gas pressure and is corrected for in these measurements. Practically, the pressure tests were done in two modes. First, the pressure was monitored for a couple of hours and small pressure drops were interpreted in pressure stability.
  
  Secondly, the pressure was measured after storing the stations under pressure for a long period, typically of a few months. These tests were interpreted in leak tightness. Pressure drops detected at this point were due to not properly closed valves.

- The HV supply at the HV end of the muon chambers is checked to make sure that all the tubes are properly provided of HV. The chambers were tested for current leaks by applying a voltage of 3.08 kV, which corresponds to the normal
operation point, and measuring the current through the multi layers. For the 
BOL chambers, a leak current of 2 μA is expected due to small discharges at the 
hedgehog cards. High leak currents could have various causes. The HV hedgehog 
cards, turned out often to be the culprit in the system and replacing the card 
solved the problem. Sometimes, a single tube is leaking current. These problems 
are localized by disconnecting tube layers and jumpers until the leaking zone of 8 
tubes is identified. For one BOL station, dirty paths between the HV and ground 
on the end-plugs gave rise to current leaks and was cleaned.

- The read out side of the tube is tested by measuring the noise distribution 
of the drift tubes. Data is taken with a random trigger without and with high 
voltage applied to the wire. The average noise level per chamber should stay 
below an average rate of 5 kHz per tube when the HV is applied. Single tube 
noise degrades track reconstruction and rates should be kept much lower than 
the expected physical background in ATLAS. Therefore, a single tube should not 
exceed a noise rate of 40 kHz.

The HV hedgehog cards or Mezzanine cards turned out to be sources of noise and 
were replaced. In cases where this action did not help, the channel was disabled 
in the software by masking the tube.

- The magnetic field sensors (B-sensors) and temperature sensors (T-sensors) were 
read out and their data was checked on consistency. The B sensors were already 
tested and calibrated at CERN [55], for the BOL hardware commissioning the 
functionality is tested by reading out the sensors via the DCS system. Two mea-
urements are taken, one with and one without holding a magnet above the B 
sensor. Sometimes the measurement hinted at a malfunctioning sensor. This was 
always due to a broken cable or connector, which was then replaced.

- The Rasiik alignment system [52] elements mounted on the MDT chamber were 
read out and all the optical paths were tested for functionality.

Before installation, the In-plane systems are checked by analyzing the images. For 
the Axial and Projective optical paths this is not possible since the optical path 
is not yet connected. For these elements, the RasCams are tested by illuminat-
ing them with a flashlight, the RasLeds are tested by collecting the light with a 
portable RasCam. Malfunctioning elements were replaced, in practice most com-
mon malfunctions were broken cables or connectors.

After installation of the MDT chamber in ATLAS, the optical paths between the 
MDT stations were installed and checked regularly. The problems arising were 
mostly blocked optical paths by services, support or scaffolding. In few cases 
(2 optical paths) the path was given up. Since the alignment system has some 
redundancy, this has no significant effect on the Muon Spectrometer performance.

Summary reports of the RFI-tests were archived in a database [56]. Dead tubes, i.e. 
tubes with broken wires, or tubes which were disconnected, and noisy tubes, i.e. tubes
with rates higher than 40 kHz, were flagged in this database. This information was made available to the offline reconstruction software. Tubes with broken wires were repaired at this stage.

5.3.2 Online software commissioning

The online software commissioning entails the testing of the read out performance of the MDTs and the quality of the data. Data from cosmic ray muons provide an excellent mean for online software commissioning since it provides ‘real data’ for the detector and the read out systems.

Cosmic ray setups were present at the MDT construction sites where the chambers were tested before shipping to CERN. These setups typically employed a scintillator hodoscope as a trigger. At the BB5 assembly hall, the BOL stations were installed in a cosmic ray set-up, where the stations used the RPC detectors as trigger. After installation in ATLAS, the cosmic ray test were performed on an increasingly more large scale as more and more detectors were ready and included in the read out chain of the Muon Spectrometer. The organization of these cosmic ray tests will be discussed in section 5.4.

Typical MDT performances which were checked during the online software commissioning are the following:

- The charge distribution of the signal was monitored to check for possible read-out malfunctioning. Figure 5.4-a) shows a typical Wilkinson ADC distribution of an MDT tube in black. The large peak at 40 ADC counts corresponds to noise hits. These hits are ignored in the reconstruction where a requirement is imposed for hits having at least 50 ADC counts. The broader peak consists of hits caused by traversing charged particles. The gray distribution shows the ADC values for hits on segments. The noise hits were rejected ‘a priori’ in the reconstruction of segments.

  The MDT stations are designed to operate in a magnetic field. Figure 5.4 shows the ADC and TDC distributions of the same MDT station shown in Figure 5.4, in an magnetic field. The electronics appear to work properly in the magnetic field.

- The drift time spectrum of the tube was monitored. The TDC value recorded is a measure for the arrival time of the first electron cluster, as discussed in section 1.2.3. Figure 5.4-b) shows a typical TDC spectrum, black for all the hits (noise hits included) and in gray for hits on segment. Hits used on segments in general have a cleaner drift time spectrum than noise hits. The leading edge of the spectrum is called the $t_b$ of the spectrum, the trailing edge of the spectrum the $t_{max}$.

  Particularly sensitive to the gas flow in the tube is the value for the drift time, $t_{max} - t_b$. The fluctuation per tube of the drift time is of the order of 20 ns. Typically time differences of 50 ns were found for stations with obstructed gas flow [57].
Hit maps were made for each tube layer. The number of hits per tube is plotted versus the tube number resulting in a map of the tube occupancy. Inefficient tubes were found as well as dead tubes. In the case of low occupancy, the gas system, HV hedgehog cards and Mezzanines were checked and if needed replaced. Dead tubes which were identified as broken wires were repaired. A more detailed analysis on BOL hit maps is presented in section 5.5.

After installation, online monitoring software GNAM [58] was taking over the task of monitoring the data quality of the MDTs and the other Muon Spectrometer technologies. GNAM is a framework which is independent of detector subsystem, e.g. Inner Detector, Calorimeters and Muon Spectrometer, interfaced to the DAQ. Detector dependent plugins decode the raw data from the detectors and provide monitoring histograms [59].
5.3.3 Offline software commissioning

Reconstruction of cosmic muons provided the most realistic test-case for the offline software system. Large amounts of cosmic data, in the order of millions of events, were processed. Various aspects from the offline software were validated:

- **Computing model.** The handling and distribution of the ATLAS data, the so-called ‘computing model’ [21] was heavily tested. Large amounts of data, several million of events, were processed by the offline reconstruction software at computer facilities at CERN, the so-called Tier-0 facility.

- **Offline reconstruction chain.** A dedicated cosmic reconstruction configuration was implemented and used to validate offline reconstruction of muons. The full software chain, as described in section 2.2, was tested. For instance, data preparation from Byte Stream to Prepared Raw Data objects were checked for internal consistency. Several problems in the hardware which were not found earlier in the hardware commissioning or online software commissioning were found and addressed at this stage. For instance, the reconstruction of cosmic muon tracks had revealed mismatches between the cabling of the detector and the software description of the cabling.

- **Software robustness.** The processing of large amounts of real data was used to validate the software robustness. For instance, the software should be able to handle incomplete data fragments from the DAQ system. Various protections in the code had to be implemented to prevent the large scale processing to crash when handling corrupted data. For example, an incomplete data fragment from the MDT read-out should be properly handled in the Bytestream conversion and not cause the reconstruction job to fail. Furthermore, rare non-standard event topologies revealed weak points in the software robustness which could be then be addressed. For example, infinite loops caused the code to hang at certain events. The very large amount of data processed at the Tier0 facility, in the order of millions of events, revealed points ready for improvement in the software. The failure rate of the processing jobs decreased from around 10% at the first cosmic runs to less than 1% in later cosmic runs. Much effort is put into maintaining this low failure rate during the running period of ATLAS.

- **Software optimization.** The large scale processing revealed parts of the code which were running slow or took too much memory. The CPU-consumption of the various algorithms in the offline software was addressed to optimize the code. It appeared that much CPU was consumed by only few events, such as cosmic shower events with complicated topologies which were not modeled in simulated data.

5.4 Muon commissioning in the ATLAS cavern

Commissioning with cosmic muons after installation of the detectors is organized in ATLAS in the so-called Milestone runs or M-runs. For the M-runs, the focus was
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on integration of the different sub-detectors (Inner Detector, Calorimeters and Muon Spectrometer), data acquisition and trigger. Dedicated data-taking periods for Muon Spectrometer commissioning are referred to as P-runs. After summer 2008, cosmic data was taken continuously until the LHC start-up. The commissioning of ATLAS is still ongoing at the time of writing of this thesis.

5.4.1 October 2008 cosmic muon run

The results shown in this chapter are from the data taken in October 2008. During this period, 2 million events from the run 91060 were analyzed. For this run, the full ATLAS Muon Spectrometer was read out, except for the EE stations (see section 1.2.3), which were only installed during spring 2009. For the analysis, data from the RPC trigger stream was used. Due to the poor trigger timing synchronization, only the RPCs from the middle stations were used for LVL-1 triggering. The muon trigger was set with the largest possible coincidence window and the HLT trigger passed all the events [60]. Due to several problems in the RPC trigger, the trigger and read out coverage was reduced to approximately 60%. Synchronization problems caused 11 of 64 sector logic boards to be masked. Due to broken optical links and initialization problems, some trigger towers were not operated. Finally, an entire layer of a sector was switched off due to a broken gas line.

During this period the timing of the trigger was not yet optimized, resulting in an average trigger efficiency of around 70% [61].

5.5 Hardware performance BOL

To monitor the MDT station hardware performance, hit maps of the 96 BOL MDT stations are made. These hit maps are presented in Appendix D. The results of the hardware performance, based on these hit maps are summarized in this section.

Figure 5.6: Hit map of one tube layer. Raw hits are shown by open histograms, hits on segments in gray.

Figure 5.6 shows a typical hit map of one tube layer. All the hit maps in Appendix D use this convention. Raw hits are the PrepRawData objects used as input of the reconstruction and are displayed as the open histogram. To suppress noise, only raw MDT

1During the winter shutdown, most of these problems were addressed.
5.5 Hardware performance BOL

<table>
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<th>chamber</th>
<th>ML</th>
<th>L</th>
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<td>BOL4A09</td>
<td>2</td>
<td>1,2,3</td>
<td>high voltage supply problem</td>
</tr>
<tr>
<td>BOL4A11</td>
<td>1</td>
<td>1,2,3</td>
<td>gas leak, 3 tubes need to be disconnected</td>
</tr>
<tr>
<td>BOL5A11</td>
<td>2</td>
<td>1</td>
<td>broken wire, needs to be disconnected</td>
</tr>
<tr>
<td>BOL1C13</td>
<td>1</td>
<td>1,2,3</td>
<td>draws current, probably a broken wire</td>
</tr>
<tr>
<td>BOL2C13</td>
<td>2</td>
<td>1,2,3</td>
<td>draws current, probably a broken wire</td>
</tr>
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<td>1,2,3</td>
<td>high voltage supply problem</td>
</tr>
<tr>
<td>BOL5C13</td>
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<td>3</td>
<td>high voltage connector broken</td>
</tr>
<tr>
<td>BOL6A13</td>
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<td>1</td>
<td>broken wire, needs to be disconnected</td>
</tr>
<tr>
<td>BOL5A15</td>
<td>1</td>
<td>1,2,3</td>
<td>gas leak</td>
</tr>
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<td>BOL5A15</td>
<td>2</td>
<td>1,2,3</td>
<td>gas supply blocked</td>
</tr>
</tbody>
</table>

Table 5.1: MDT station problems identified with run 91060.

hits with an ADC value of larger than 50 are taken into account for these hit maps. This cut is applied in the segment reconstruction as well. Hits on segments reconstructed by the Moore program (described in section 3.3.3) are shown in gray. The x-axis shows the tube number, running from 1 to 64, corresponding to the maximum number of tubes in one tube layer for the BOL stations. The y-axis has a logarithmic scale with a minimum value fixed at 10 and a maximum value fixed at $2 \times 10^5$.

The hit maps show clearly that some of the multilayers and tube layers were not functional during run 91060, as these (multi)layers have only a few raw hits. Table 5.1 summarizes the BOL stations with problems. Dead tubes are visible in the hit maps as well, summarized in table 5.2-a). In total, 7 multilayers, 3 tube layers and 20 single tubes were not operational during this run. This corresponds initially to a total of 1492 BOL monitored drift tubes, thus 4.4 %. In the following we describe how this number can be reduced by 'in-situ' repair of various problems.

The 7 multilayers and 3 tube layers were disconnected from high voltage (HV) during this run because of various reasons. Some tube layers have a tube with a broken wire, causing large leak currents. That (multi)layer was therefore disconnected from HV. The tube layer may be reconnected when the single tube is disconnected. An other reason to disconnect a multilayer from HV was when large gas leaks were present. Falling objects in the ATLAS cavern had caused gas leaks in two BOL stations. In order to reconnect the multilayer, the leaking tube needed to be disconnected from HV. The gas supply is arranged such that three tubes are sharing one gas inlet. In practice this means that one tube leaking gas results in three tubes disconnected from the gas system, and thus from HV. Finally, in three MDT stations malfunctioning HV supplies had been identified, which will be replaced. At the time of writing of this thesis, this repair work is still in progress.

Dead tubes were recognized by empty channels in the hit maps, or channels with a lower occupancy (less than 10 %) than the neighboring channels. The stations with dead tubes are summarized in table 5.2-a). After repairing the problems summarized in table 5.1, 10 more dead channels are to be expected, adding up to a total of 30

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dead channels out of the total of 33,696 channels for the MDT BOL stations. This corresponds to a dead tube rate of 0.9 \% which is comparable to the full ATLAS MDT dead tube rate of 1.1 \% [63].

Table 5.2(b) presents a list of noisy channels. In this analysis a tube was named noisy when it had more than 3 times the amount of hits compared to the median of the other tubes in the muon station. Noisy channels were flagged in the conditions database and made available for offline reconstruction.

In sectors 1 and 9 one can observe that the tube occupancy is somewhat lower than for the other sectors. This is because of the RPC trigger which has a smaller geometrical acceptance for these sectors. The orientation of the stations in these sector with respect to the average direction of the cosmic muons give a smaller trigger rate for events passing the two sectors.

For sector 1 and 9, the segment reconstruction efficiency is lower than for the other sectors as well. This is observable by the lower fraction of hits on segment compared with the raw hits in the stations from this sector. This effect is largest for stations with a high $\eta$ value (at the sides of the spectrometer). The segment reconstruction, which is optimized for collision events, has a harder time reconstructing segments from muons traversing the station under large angles.

The segment reconstruction is constant over the whole MDT station, e.g. no tube-dependent or Mezzanine-dependent efficiency changes are observed. Such inefficiencies would have been due to mismatches between the cabling of the electronics and the mapping in the software. The BOL MDT stations appear to be properly cabled.

5.6 Conclusion and outlook

After an intensive period of Muon Spectrometer commissioning, the hardware performance of the MDT stations has been evaluated. For run 91060, 4.4 \% of the BOL MDT channels were not operational. In the following chapters, the impact of dead channels on muon reconstruction will be discussed. Muon tagging algorithms are expected to provide robust muon identification that can cope with inefficiencies in the hardware. The hardware problems will be repaired where possible and ultimately, in the best case, only about 1 \% of the 33,696 channels will be disconnected.
5.6 Conclusion and outlook

a) Station MDT L tube number

<table>
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<th>station</th>
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<th>L</th>
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<td>1</td>
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<td>3</td>
<td>43</td>
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<td>BOL2A01</td>
<td>1</td>
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<tr>
<td>BOL5A01</td>
<td>1</td>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>BOL4C01</td>
<td>2</td>
<td>1</td>
<td>25, 26</td>
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<tr>
<td>BOL4C01</td>
<td>2</td>
<td>1</td>
<td>20, 21</td>
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<tr>
<td>BOL6A03</td>
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<td>BOL2A05</td>
<td>2</td>
<td>3</td>
<td>29</td>
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<td>BOL1C09</td>
<td>1</td>
<td>1</td>
<td>52</td>
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<td>3</td>
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b) Noisy tubes; MDT channels with a rate higher than 40kHz.

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<td>3</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>BOL6C15</td>
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Table 5.2: List of MDT channels with problems: a) Dead tubes; MDT channels with less than 10% of entries compared to the median value of the other tubes in the same MDT station. b) Noisy tubes; MDT channels with a rate higher than 40kHz.
ATLAS BOL commissioning