The ATLAS muon alignment system

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Abstract
The alignment system of the muon spectrometer of the future LHC experiment ATLAS is described here. Emphasis is put on the optical system, and the fitting programs used to calculate the actual muon chamber positions. Finally, some results validating the alignment are briefly given.

17.1 Introduction

The future ATLAS experiment at the Large Hadron Collider (LHC) at CERN includes a stand-alone muon spectrometer embedded in a toroidal magnetic field. In this sub-detector about 1200 Monitored Drift Tube (MDT) chambers are being installed around the interaction point in order to cover a pseudorapidity region up to $|\eta| < 2.7$. The muon tracks will be measured by three distinct MDT chamber planes mounted at distinct points in the magnetic field.

One requirement for the spectrometer layout is an average momentum resolution of 2.5% at 100 GeV and 10% for a 1 TeV muon track. The contributions to resolution are [1]: (a) multiple scattering, (b) energy losses in the calorimeter, (c) knowledge of the magnetic field, (d) single tube resolution, (e) respective geometrical position along the measured coordinates of the three MDT chambers.

For a 1 TeV muon track, the source (d) becomes the dominant one, provided that source (e) is kept lower. The single tube resolution of 80 μm leads to a 40 μm sagitta resolution, which corresponds to roughly 10% of the sagitta. Thus, sagitta resolution due to source (e) should be kept under 40 μm.

As (e) can not be achieved mechanically, the adopted solution is to monitor deformations and the positions of the MDT chambers by means of optical sensors. The geometry used by the muon reconstruction packages is then corrected offline. The chain extending from the light caught by the optical sensors to the geometry correction factors is commonly called *alignment*.

Two alignment modes are possible: relative and absolute. In the relative mode, the positions of the MDT chambers are calculated with reference to positions previously measured by other means (straight tracks when the toroid magnet is off, for example). Two sets of optical sensor measurements are used as input: the current and the reference measurement ($m0$). In the absolute mode, the positions of the chambers are estimated using only the current measurements. This mode requires an accurate calibration of all alignment parts. The χ^2 for these two modes are:

$$\text{relative} \quad \chi^2 = \sum_i \left(\frac{(m_i - m0_i) - (s_i - s0_i)}{\sqrt{\sigma_i^2 + \sigma 0_i^2}}\right)^2 \quad (17.1)$$

$$\text{absolute} \quad \chi^2 = \sum_i \left(\frac{m_i - s_i}{\sigma_i}\right)^2 \quad (17.2)$$

where m is the current optical sensor measurement, s the current simulation, and σ the estimated measurement error. Here $s0$ is the simulation using the reference geometry. A critical step in the alignment will be when the toroid magnets are turned off or on: the MDT chambers are expected to move by several mm. The geometry difference between magnet off and magnet on should, in principle, be calculated by relative alignment only. In order to have redundancy for the difficult straight track measurement, ATLAS decided to emphasize absolute alignment as well.

In Section 17.2 the optical sensors will be presented. In Sections 17.3 and 17.4 the alignment system in the barrel and end-cap regions are shown. In Sections 17.5, 17.6 and 17.7 data acquisition and the online software are described. In Section 17.9 some examples of the alignment concept validation under real conditions are discussed.

17.2 The alignment system instrumentation

Three different optical systems are used in the ATLAS alignment: Rasniks, BCAMs and Sacams. The principle is the same for all three systems: an optical sensor looks through a lens towards a target. The sensor image is, for computer storage reasons, analyzed online and converted into four parameters:

1. translation of x with respect to the optical axis z,
2. translation of y with respect to the optical axis z,
3. rotation of angle θ_z between the target and the optical sensor,
4. magnification of the optical system.

17.2.1 Rasnik sensors

The target of the Rasnik system ([2,3]) is a chessboard-like pattern (called *mask*). The three optical elements (sensor, lens, and mask) can be placed individually and anywhere in the detector. Therefore Rasniks are 3-point alignment devices.

Rasnik sensors are monochrome CMOS sensors (VLSI Vision VV5430), with an array of 384×287 pixels and a 12 μm pixel size. The sensitivity peak lies at 820 nm. The CMOS is embedded in a custom-made electronic board, which converts the CMOS signal into a semi-differential CCIR composite video signal sent to the outside world via a RJ45 cable. The readout frequency is 7.37 MHz (LVDS). All of the electronics are placed in an aluminium die-cast housing and the optical window is covered with an infrared filter (Schott RG830) to avoid stray light which could lower the contrasts of the target image.

The mask is a thin film chromium/glass slide (< 0.5 μm), with a modified chessboard pattern back-illuminated by an array of infrared LEDs (875 nm). A diffuser is placed between the LEDs and the film, thus smoothing imperfections due to the light source shape. The chessboard square dimension D is chosen such that the image of each square is covered by at least 5–10 pixels. In ATLAS, D varies between 85 and 340 μm. This allows an interpolation of the black and white transition, lowering the translation resolution to 12 $\mu\mathrm{m}/\sqrt{N_{\mathrm{pixel}}}$. A second advantage of the Rasnik mask is that after each nine chessboard squares, a pattern of black and white squares is printed. This pattern contains information about its position on the mask. In other words, the dynamic range and the translation resolution are decoupled. The dynamic range can be increased by using larger film masks (up to several decimeters), without loss of resolution.

For a symmetric Rasnik, where the lens is positioned halfway between CMOS and mask, translation resolutions of 1 μm and magnification resolutions of 210^{-5} have been obtained.

17.2.2 BCAM sensors (*Boston CCD Angle Monitor*)

The BCAM is a camera consisting of a CCD and a lens, which looks towards one or more laser diodes. The BCAM housing also contains a set of two or four laser diodes which can be used as targets by another BCAM. Most of the time, BCAMs are used in pairs, arranged such that they are facing each other.

The monochrome CCD is manufactured by Texas Instruments (TC255P) and contains an array of 324×244 pixels with 10 μm pixel size. The targets are infrared laser diodes from Lumex (LDP65001), with 5 mW power at 650 nm. The CCD is placed close to the focal plane of the lens (76 mm), while the laser diode target is placed at a 0.5 to 16 m distance. The image seen on the CCD is a circular spot of light (see Fig. 17.1).

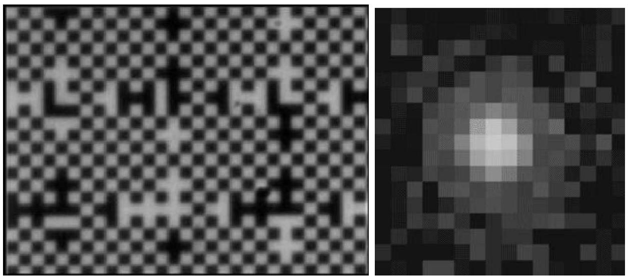

Fig. 17.1: Left: Rasnik chess board pattern seen by the CMOS. Right: Image of a LED seen by a BCAM. SaCam images are similar to BCAM ones.

Owing to the fact that the lens-target distance is much larger than the lens-CCD one, BCAMs can be considered as telescopes. The measured quantities are therefore transverse angles with respect to the optical axis. BCAMs achieve a relative resolution of 5 μrad for a target positioned at 16 m. The dynamic range of a BCAM is $\pm 16 \times \pm 21$ mrad.

If the target consists of two or more laser diodes with known separation, relative angles can be extracted which can then be converted into magnification and rotation around the optical axis. The effective longitudinal precision, using the two laser diodes of a BCAM separated by 16 mm, measures between 300 μm at 0.5 m and 75 mm at 16 m.

If BCAMs are used in pairs, the measurement of the absolute angular position of the partner can be made within 50 μrad accuracy. Another configuration of BCAM is the three-point straightness monitor. In this case, each of the outer 2 BCAMs measures the relative angular positions of two BCAMs in the centre and vice-versa. The relative accuracy is then $\sqrt{2} \cdot 5$ μrad.

As for Rasniks, captured BCAM images are analyzed online. The BCAM image analysis routine computes the centre of gravity of the image spot after subtraction of a threshold value.

17.2.3 SaCam sensors (*Saclay Camera*)

SaCams had to be built because the barrel and end-cap have different acquisition systems. Like the BCAMs, the SaCams consist of a camera containing a CMOS and a lens at fixed distance. The target consists of four back-illuminated holes, covered by a light diffuser. SaCams are therefore 2-point alignment devices. The CMOS is the same as for Rasniks (see Section 17.2.1). The lens is mounted at a distance of 80 mm. The distance of the holes are of two types: 15 $\times$ 15 mm for stand-alone targets mounted on the chambers and 35 $\times$ 50 mm for targets mounted on a camera housing. As for the BCAM, relative resolutions of 5 μrad have been achieved. The dynamic range is $\pm 22 \times \pm 29$ mrad.

17.2.4 Temperature measurement

To measure temperature, various sensor types are used: NTC, TMP37, Pt-100, and Pt-1000. Temperature sensors are mainly found on the chambers and on the end-cap alignment bars.

17.3 The barrel alignment implementation

In the barrel, the MDT chambers are arranged in projective towers. One tower consists of 3 MDTs. The innermost MDT is called BI, the middle one BM, and the outermost one BO. The barrel consists of 16 sectors in Φ. Odd-numbered sectors have 'large' chambers, even ones have 'small' chambers (leading to the abbreviations BIS, BIL, BMS, BML, BOS, BOL).

At the heart of the barrel alignment system are the projective lines which connect three chambers of one tower. The projective system works with Rasniks, where BI holds the mask, BM the lens, and BO the CMOS. Projective optical lines are pointing towards the interaction point. In the current final layout, 117 projective lines are in use. They are the backbone of the barrel alignment.

A constraint arises from the detector hermeticity. Therefore, the number of projective lines is limited to the natural passages. Thus, two out of three MDTs in the large towers are equipped with projective lines, while small chambers can not be equipped at all.

Table 17.1: The seven optical systems used for the barrel alignment.

Name	Sensor type	Total	Alignment type
Inplane	Rasnik	2110	MDT deformations
Praxial	Rasnik	2006	Plane alignment
Axial	Rasnik	1036	Plane alignment
Projective	Rasnik	117	Tower alignment
Reference	SaCam	256	Link to the Toroid
CCC	SaCam	260	Small/Large tower link
Bir-Bim	Rasnik	32	BIR/BIM link
Total		5817	

This means that MDT towers, lacking projective lines, have to be optically linked to the MDT towers equipped with projectives. Within small and large MDT planes neighbouring chambers have two kinds of optical links: small lever arm connections called Praxial (PRoximity Axial), and long-lever arms, called Axial. Both systems work with Rasniks: at each corner a given MDT is equipped with a CMOS, while the neighbouring MDT is equipped with a mask (the lens is either on one or the other MDT). Small MDT towers are connected via SaCams to the large MDT towers (this type of line is called CCC).

Another optical link connects the barrel MDTs to external points mounted on the toroid warm structure. This system is called the reference system. This system resolves ambiguities affecting the sagitta resolution. Furthermore, the reference system optically connects the eight toroid coils, forming four optical rings. These four optical rings are mounted at different points along the beam axis (two at $z < 0$, two at $z > 0$).

Many optical elements could not be positioned directly on the MDT chambers: For some projective lines in the CCC and reference alignment systems, aluminium extension plates were precisely glued to the MDT tube references. Almost one thousand extension plates have been built and have been calibrated on a CMM with a precision better than 30 microns.

A special set-up is the Inplane system: one or more Rasniks mounted inside the MDT monitor deformations such as sagitta, torsion or width differences between opposite chamber sides. The Inplane system is the reason for the word 'monitored' in *Monitored Drift Tube* chamber. The barrel alignment set-up establishes an optical connection between 660 MDTs.

17.4 The end-cap alignment implementation

Each of the two end-cap systems consists of four wheels called EI, EM, EO and EE (see Fig. 17.2). Each wheel has 16 Φ sectors. Odd-numbered sectors are equipped with large MDTs, even ones with small MDTs.

The projective philosophy used in the muon barrel system cannot be used in the end-cap. The large number of required lines of sight would require too many penetrations in the end-cap toroidal magnets.

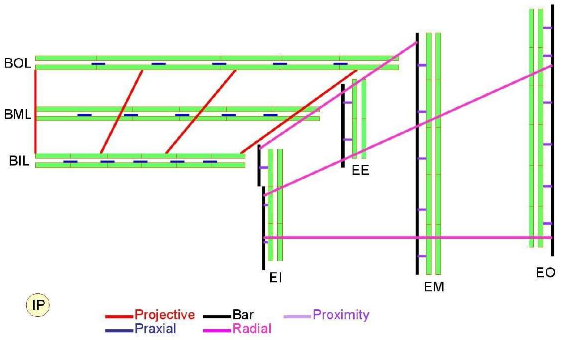

Fig. 17.2: The projective and praxial systems in the barrel; the radial and proximity systems in the end-cap

Table 17.2: The seven optical systems used for the end-cap alignment

Name	Sensor type	Total	Alignment type
Inplane	Rasnik	2048	MDT deformation
Bar Monitor	Rasnik	384	Bar deformation
Radial	BCAM	96	Bar deformation
Polar	BCAM	208	Bar to bar link
Azimuthal	BCAM	608	Bar to bar link
Proximity	Rasnik	2560	Chamber to bar link
Saloon Door	BCAM	512	Chamber to bar link
Total		6416	

The adopted solution is a grid of optically connected alignment bars using a quasi-projective alignment. The chambers are referenced to this grid. The bars are equipped with internal Rasniks and temperature sensors. Prior to installation, these bars are carefully measured using a large CMM. The subsequent shape of the bar is determined by calculations and monitored by the internal monitors. These bars can be considered as precision rulers.

The relationship between the bars is then established by a network of sensors which measure the bearing angle of light sources on the other parts of the system. Sensors used are polar, radial, and azimuthal BCAMs. The system is overdetermined and the location and orientation of each bar is determined using a fitting program.

Chambers are then referenced to the alignment grid using proximity sensors. For this purpose each small and large chamber pair is considered to be a logical unit. The sensors used are a combination of Rasnik proximity sensors and BCAMs. End-cap MDT chambers are additionally equipped with an Inplane system (see Section 17.3).

17.5 Data-acquisition system

In the barrel 5817 images and in the end-cap 6416 images will have to be read out and processed (see Tables 17.1 and 17.2). Some optical lines generate more than one image (BCAMs read one image per laser spot).

For the barrel, three custom-made multiplexer stages are used. The final image analysis is performed by a farm of nine PCs in online mode. With an average analysis time of 0.5 seconds per image, a whole acquisition cycle lasts roughly 10 minutes.

In the end-cap, a custom-made multiplexer is used. The data are analyzed by two PCs (one per end-cap). The average treatment time is estimated to be 100 ms, leading to an acquisition cycle of 10 minutes as well.

After each cycle, the data parameters are written into the ATLAS condition database (under Oracle). The conversion of the image parameters into MDT positions and deformations is made by two alignment programs [ARAMyS (Alignment Reconstruction and Simulation for the ATLAS Muon Spectrometer) for the end-cap and ASAP (ATLAS Spectrometer Alignment Program) for the barrel]. The main feature of these software packages is their precise description of the optical elements within the detector, taking into account all the individual sensor calibration constants which have previously been measured in the laboratories. Using this description, both software packages convert the current sensor measurements into MDT chamber positions using standard fitting methods. The resulting data are stored in a table in the Condition Database for later use by the muon tracking software packages.

17.6 Barrel alignment reconstruction

ASAP is a C++ code, using the ROOT framework. The inputs are:

1. Description of the spectrometer geometry using the ATLAS standard muon spectrometer description AMDB;
2. Calibration data of all the platforms, extensions and optical components used to mount the alignment system. These data are in XML format;
3. ROOT-tuple of the current alignment measurements of the sensors, which are read out from the condition database;

4. Survey results from the geometer;
5. ROOT-tuple of the temperature measurements, coming from the condition database.

The output of the ASAP is six correction factors (three translations and three orientations) which have to be applied to the nominal positions/orientations of the MDT chambers. Furthermore, the ASAP handles the MDT internal deformations, which consist of a set of eight parameters (sagitta, torsion, trapezoidal effects, as well as temperature-induced elongations). Thus, per MDT, 14 parameters are written into the ATLAS condition database for further use in the track reconstruction programs.

Some emphasis has been put on the creation of a Java server, which can be used to launch the ASAP remotely. This server permits us to visualize the status of the alignment fit via the internet. This is expected to be useful during data-taking.

17.6.1 The ASAP program

The ASAP code can be divided into three main classes, which in principle, could be used for any optical alignment and calibration problem.

Class Element: The detector description is based on a class called the Element. An Element can be a CCD, an aluminium plate, an MDT, etc. Each Element is defined by a name, an ID; a nominal, true and corrected position in space; a nominal, true and corrected rotation matrix; distortion parameters; its dimensions and finally its thermal expansion. Furthermore, an Element can have 'daughter Elements'. Daughters are Elements which are fixed to the mother. When the mother moves in space, the daughter follows that same movement. Daughters can themselves have other daughters. This concept allows us to define a tree structure of the spectrometer. Daughters are always defined in the coordinate system of the mother. An interesting feature is that trees of Elements can be created from scratch using a custom-made XML description.

Class Sensor: Each Sensor contains an ID, a name, the current measurements, their offsets, the simulated measurements, as well as the simulated offset. Furthermore, each Sensor has a list of all Elements it depends on and a matrix called a 'transfer matrix' which relates the simulated measurements to the the positions of the Elements it depends on. This transfer matrix is a submatrix of the general transfer matrix used in the fit, which connects the response of all sensors to the detector geometry.

Class Alignment: The alignment fit is carried out using a custom-made minimization routine, which has been optimized to gain speed. This is carried out using a fit based on the inversion of a matrix, called a 'transfer matrix', which relates the optical sensor to the physical elements. The fit allows us to put constraint terms, which are mainly used to fix the coordinate system of the entire alignment set-up. Usually six coordinates are fixed. In addition, this procedure gives back relevant information, like the χ^2 contribution of each individual sensor, the number of iterations, CPU time used, and the list of the status of all sensors.

Visualization: For the alignment problems, an appropriate visualization tool proved to be vital. For this a custom-made OpenGL tool, called AtOS, developed inside ARAMyS, has been used. The advantage of this OpenGL tool is the ease with which new visualization features can be implemented. Even small movies showing the actual deformation history can be created.

Java Database Browser: This tool permits us to easily convert MySql, Oracle database tables into ROOT-tuple. *A priori*, this tools does not know what kind of data are stored in the table.

17.6.2 Testing and debugging

The ASAP was extensively tested during the test beam period (see Section 17.9) on the Barrel set-up. The different installation steps of the Barrel are followed up using ASAP fits (cosmic ray runs, toroid deformation, current in the magnet coils). Another way of debugging consists of using the ASAP in Monte Carlo mode in combination with the visualization tools.

17.7 End-Cap alignment reconstruction

17.7.1 The AraMys program

The program ARAMyS consists of about 3,000 lines of code written in C. For the χ^2 minimization in the alignment fit, the standard package MINUIT [4] is used. The use of MINUIT rather than of a private minimization routine, which might be slightly faster, makes useful information accessible for the user, e.g., about the convergence and quality of the fit, and the errors and correlation matrices of all the fitted parameters. Also, MINUIT has been used and tested for decades, and is a mature and reliable piece of software.

ARAMyS will be used in ATLAS to reconstruct the alignment of the end-cap MDT chambers. For this purpose, a bar-shape function and a chamber-shape function were implemented, to take into account deformations and expansions of alignment bars and MDT chambers, respectively. Apart from these components, the program is not very end-cap—or even ATLAS—specific, and is, in principle, suitable for any alignment problem.

Input to ARAMyS are: a description of the geometry, containing all the local coordinate systems, points, and sensors (including calibration data), as well as the alignment sensor measurements from the detector. ARAMyS outputs the reconstructed positions and rotations of all local coordinate systems with respect to the global system, and the chamber and bar deformation and expansion parameters. This information is stored in the ATLAS conditions database, for use by the detector geometry model and the muon track reconstruction routines. For debugging purposes, ARAMyS provides additional information, like the χ^2/ndf of the alignment fit, and the contributions of individual sensors to χ^2.

17.7.2 Testing and debugging

ARAMyS was developed mostly from 2001 to 2004, and was tested with data collected at a test set-up of the muon spectrometer end-cap in the H8 beam line at CERN during that period (see Section 17.9.3).

More recently, ARAMyS was successfully applied during the first phase of the construction of the real ATLAS muon spectrometer end-caps, the pre-assembly of five MDT chambers, and one alignment bar in sectors of the 'Big Wheel' (one of the end-cap wheels). ARAMyS is also being used in various calibration and test set-ups.

17.7.3 Alignment simulation

ARAMyS can also be used, during the design phase of an experiment, to simulate the performance of an alignment system design based on the foreseen network of sensors and their expected resolutions. For this application, the sensor readout values from an actual set-up are replaced by the expected measurements as calculated by ARAMyS, which are randomly distributed by an amount that reflects the intrinsic resolution and the accuracy of the mounts of individual sensor. The alignment is then reconstructed using these simulated measurements. A figure of merit is computed from the difference between true and reconstructed chamber positions. For the ATLAS muon spectrometer, the figure of merit is the width of the false sagitta distribution (the false sagitta is the reconstructed deviation from straightness of a straight track traversing a triplet of MDT chambers). The ARAMyS simulation predicts a mildly position-dependent false sagitta width in the range of 30–55 μm over the full end-cap, well in line with the specification.

17.7.4 CPU performance

Alignment reconstruction by global χ^2 minimization is a process of complexity $O(N^3)$ for N fitted parameters, where each object, bar or chamber, contributes $N = 6$ parameters for position and rotation, and $N = 9$ deformation and expansion parameters. Consequently, CPU performance becomes an issue for large alignment systems like those of ATLAS.

There are two complementary approaches to this problem. One is to optimize the code, especially the χ^2 computation, which is called $O(N^2)$ times with different values for the parameters $p_1, \ldots, p_N$. For instance, it pays to avoid recalculating unchanged quantities that were already calculated during the previous χ^2 call. MINUIT typically changes the values of only a few of the parameters p_i between two consecutive χ^2 calls and, for example, the χ^2 contributions from sensors whose positions have not changed between calls does not change, and thus does not need to be recalculated.

The other approach is to make use of factorization: the property of an alignment system design which allows chamber parameters to be reconstructed by splitting the problem into subsets of objects to be aligned, without (noticeable) loss of accuracy or consistency. The muon end-cap alignment system *is* factorizable; in contrast, the barrel system (for instance) is not. It has been shown that the alignment of the two ATLAS muon end-caps, comprising about 10 000 fitted parameters in total, can be reconstructed by performing 864 'small' fits of 9 or 12 parameters each, and two 'large' fits of 384 parameters each (the latter alone consuming about half of the CPU time). This process takes, on a standard 3 GHz dual-Pentium desktop PC, as little as four minutes — without factorization, it would take weeks!

17.8 Alignment with muon tracks

In the ATLAS muon spectrometer some elements are not optically linked, or the optical connection does not have the required precision for the sagitta measurement. During common ATLAS runs, these elements can be aligned, using muon tracks passing through overlap regions between the optically precisely aligned chambers and elements without precise optical alignment.

Examples of non-optically-linked elements are: BIS8, BEE, or the barrel versus the end-cap. In addition, in order to have the best muon momentum resolution, one should align the whole muon spectrometer with respect to the inner detector.

An example of elements which are optically linked but not with the required precision, are the small MDT towers in the Barrel (the expected optical precision is roughly 400 μm). Here again tracks passing through both the precisely aligned large towers and the weakly aligned small towers can be used.

For all five cases, the alignment procedure works in two steps (see Fig. 17.3):

1. A first alignment fit is undertaken using the optical data only.
2. The output of this first fit is used by the tracking algorithm which calculates the 'pseudo-track-sensor'. In a second alignment fit, both the optical and the 'pseudo-track-sensors' are used.

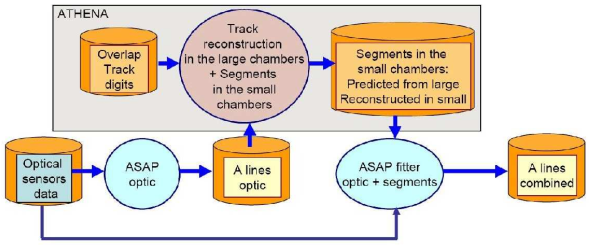

Fig. 17.3: The alignment stream when Tracks are used. Two alignment fits are needed.

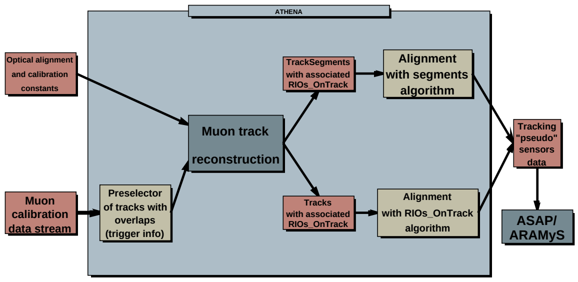

Fig. 17.4: The data flow used to calculate pseudo-track-sensors

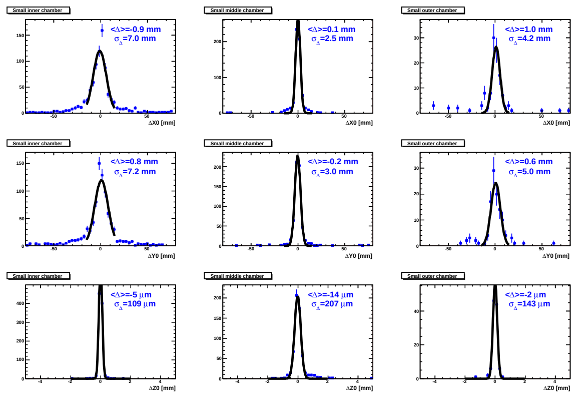

Fig. 17.5: The accuracy of the pseudo-track-sensors

For all these track-based alignment tasks, a generic algorithm within the ATHENA framework (standard ATLAS framework) is being developed. The data-flow scheme of this algorithm is shown in Fig. 17.4. The algorithm takes as input a muon track passing through overlap regions which were found by the standard muon-tracking algorithms. Then it splits the track into separate hit collections: one collection for optically-aligned chambers and several (up to three) collections for non-optically-aligned chambers. These separate hit collections are refitted using the so-called common tracking tools (tracking algorithms that were developed for the inner detector, but are generic enough to be used in the muon spectrometer). Then the refitted track from optically-aligned chambers is extrapolated into the non-aligned chambers. The differences between these extrapolated track parameters and parameters of the track refitted from corresponding non-aligned chamber hits constitute a 'measurement' from a tracking 'pseudo-track-sensor' which is used by the optical alignment reconstruction program in a global fit of the alignment data as shown in Fig. 17.4. The track alignment algorithm communicates with the optical reconstruction programs through an Oracle database interface. In the current implementation, the accuracy of tracking 'pseudo-sensors' is about 100–200 μm for the precision z-coordinate and 2–7 mm for the non-precision x- and y-coordinates (see Fig. 17.5).

In principle, the use of common tracking tools in the track-based alignment algorithm allows us to align the barrel part of the muon spectrometer with respect to the end-cap parts, and the whole muon spectrometer with respect to the inner tracker. Specific implementations of these algorithms are still under development.

17.9 Selected alignment results

17.9.1 Toroid release

The step-by-step installation of the barrel toroid has been achieved with the help of a provisional mechanical support structure (called 'the green structure' in ATLAS jargon). The support structure was connected to four coils, which are the coils of sectors 16, 4, 6 and 10 (see Fig. 17.6). After the placement of the eighth and last coil and the closure of the toroid wheel at the end of September 2005, the toroid structure had to be mechanically disconnected from this support structure. This disconnection *release* was achieved in two steps, the first one being Wednesday September 28th, the second Thursday September 29th, 2005.

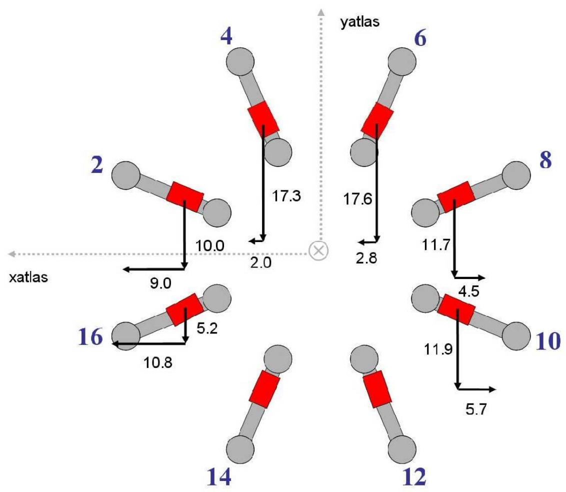

Fig. 17.6: Translation of the toroid plates, in mm, after the release (Friday, September 30th, 2005)

Previous computational simulations of the toroid release predicted an 18 mm shift of the top coils after this release. An additional 6 mm are expected once all Barrel MDT stations are in place. In order to achieve a final toroid wheel close to a circle, assuming a slight underestimation of the deformations in the FEA calculations, the coils have been assembled and hooked together with a 30 mm shift at the top.

As the expected movements of the toroid are large, this release offered a unique opportunity of cross-checking the alignment system with the simulation predictions and the geometer survey results.

The image-parameter to coil-position conversion has been achieved with the Barrel alignment program ASAP, using information from the reference plate mounted on the toroid warm structure (see Section 17.3). The input parameters were a set of $44 \times 4 = 176$ measurements, while the output are $14 \times 6 = 84$ position parameters of the plates (two out of the 16 reference plates mounted on the coils were held fixed during the fit).

For the present fit, the following components have been used: (1) the reference plate positions measured by the geometers; (2) the position of the SaCams on the reference plates as measured with a three-dimensional coordinate measuring machine. The calibration constants of each individual camera (3) were not taken into account for the present analysis. The goal of the present analysis was only to measure the relative time variation of the plates' positions. This information is available and will be incorporated in a later phase, when absolute alignment will be tested.

For the fit, the input data were grouped in 10-minute intervals, allowing us to discard spurious data points far from the average. The total analysis CPU time was about 10 minutes.

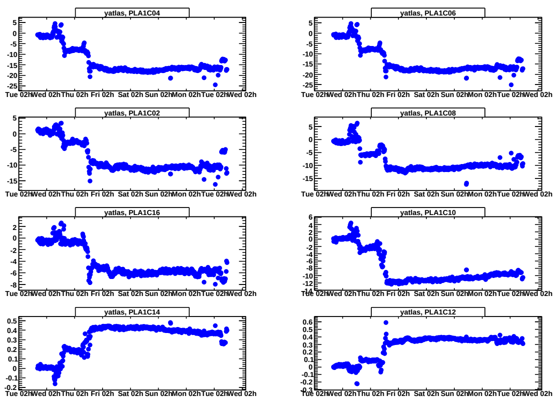

Fig. 17.7: Translations in mm along the Atlas Y coordinate of the eight plates in the wheel 1C. The Y coordinate is vertical.

The plates in sectors 12 and 14 have small displacements (of the order of some tens of microns) due to the fact that they were constrained during the ASAP fit. They form the reference position to which the other 10 plates are allowed to move. In the alignment fit, no external absolute reference is available, as is the case for the geometer survey. The constraints have been put to $\sigma_p = 1$ mm.

The toroid was released in two steps (Wednesday 28 September and Thursday 29 September), which can be clearly seen in almost all the plots (see Fig. 17.7).

Prior to the release, peaks can be observed. During installation, the jack pistons mounted on the support structure and supporting the toroid were locked at a certain position with the help of transverse screws. Then the pressure was released. Before the technicians could safely remove the blocking screws the pistons were re-pressurized, lifting the coils. Then the pressure was released again.

The second pressure release was finished Thursday 29 September at 3.30 p.m. In the y_{atlas} plots, a small peak can be observed at 2 p.m. for the sectors 16, 2, 4, and 6. For sectors 4 and 6 this peak reached 4 mm.

For the upper two coils, 4 and 6, a vertical movement of 17.3 mm and 17.6 mm, respectively, is observed, values which are well within the computational predictions. The vertical movements are 12 mm and 12 mm for coils 8 and 10, whilst coils 2 and 16 moved down by 10 mm and 5 mm.

17.9.2 Current in the toroid

An important milestone was the first current in the barrel toroid. Between October 28th and November 18th 2006, a series of tests was undertaken in which the current increased to different levels.

The movements induced were expected to be smaller than for the release (Section 17.9.1). As the turning on the barrel toroid will be a standard procedure during LHC running, the information gained here is valuable in predicting the final geometry of the spectrometer at the millimetre level.

The deformations during the current ramp-up of the toroid magnet were again followed with the reference system. In addition, the positions of several MDT chambers were followed in order to understand the movements induced.

For data-taking, the final acquisition system, consisting of nine PCs was used. All data were written in the condition database, as will be done in the actual experiment.

Expected movements of the order of 1–2 mm were observed during the current ramp-up (see Figs. 17.8, 17.9, 17.10). One interesting feature is that the egg-shape of the toroid became more pronounced (the top of the toroid went up by 2 mm at 21 kA).

One explanation for this is that not all MDT chambers were installed at this time. Since the full complement of MDT chambers was not reached, the spectrometer was still in an egg-shape at 0 kA, leading to a more pronounced egg-shape once 21 kA was reached.

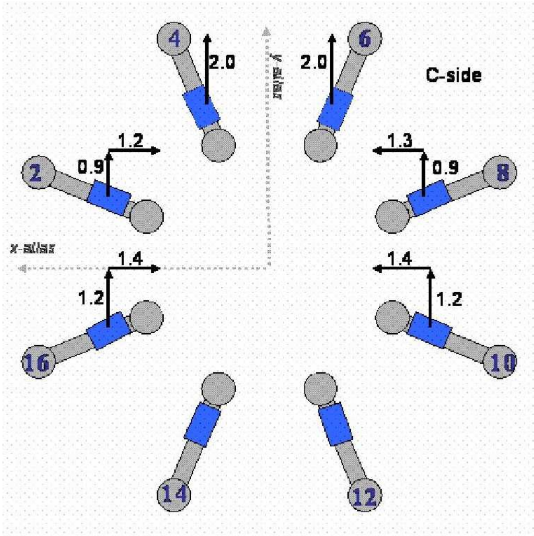

Fig. 17.8: Displacement of the various coils while 21 kA were put in the toroid

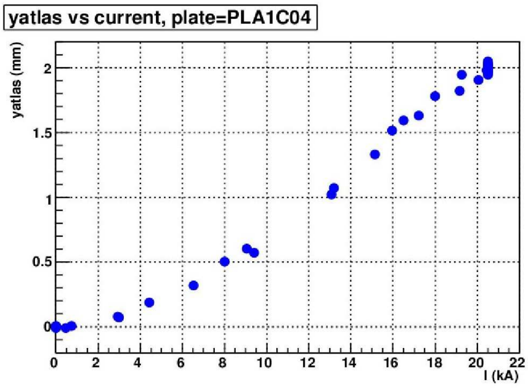

Fig. 17.9: Displacement of the upper coil versus the current in the toroid

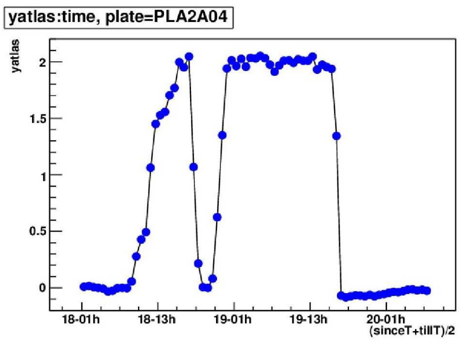

Fig. 17.10: Displacement in mm of the upper coil versus time on November 18th and 19th 2006. Two peaks can be seen, corresponding to two different ramp-ups. The end of the second peak corresponds to a fast quench of the toroid system.

17.9.3 H8 test beam set-up

In 2001, a subset of the future ATLAS muon spectrometer was mounted in the northern area of the SPS accelerator at CERN (H8 beam line) [5]. During the SPS running period, muons with momenta between a few GeV and 250 Gev were available.

This set-up is divided into two parts: the barrel and the end-cap. The barrel stand (see Fig. 17.11) consists of six MDT chambers which reproduce the geometry of the first two large barrel towers starting at $\eta = 0$ (2 BIL, 2 BML and 2 BOL MDT chambers). The end-cap stand has six MDT chambers installed on three large frames reflecting one end-cap octant (EIS1, EIL1, EMS2, EML2, EOS3, EOL3). Additionally, trigger chambers were used, called RPC in the barrel and TGC in the end-cap.

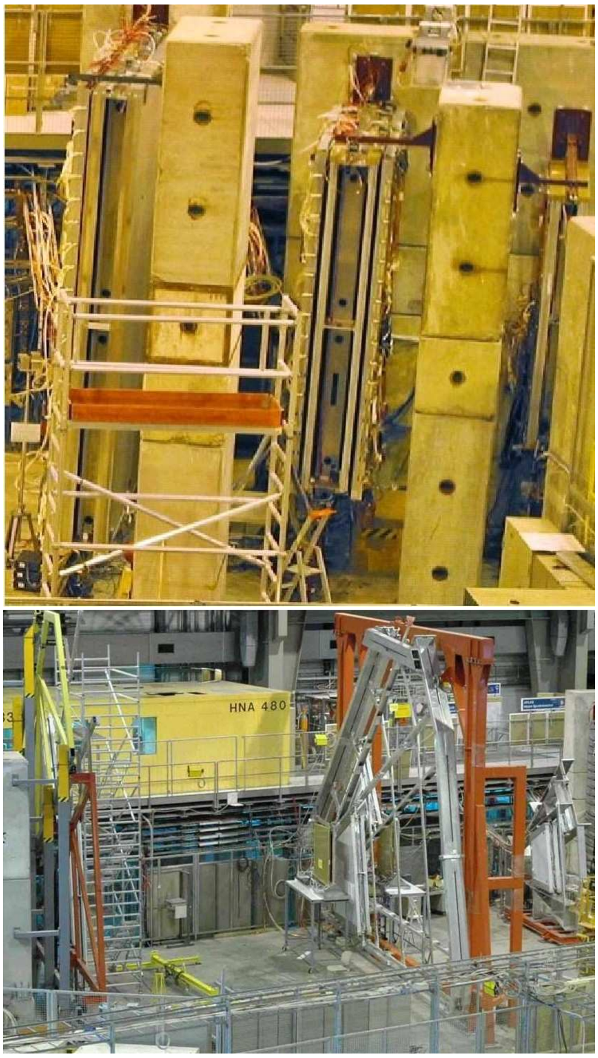

Fig. 17.11: The H8 experimental set-up. Upper figure: Barrel. Lower figure: End-cap.

Both set-ups were fully equipped with alignment sensors, which were calibrated following the ATLAS rules. In the barrel stand the toroid-to-chamber connection (called Reference) was utilized (see Table 17.1). These sensors were attached to carbon-fibre beams or mounted on the floor.

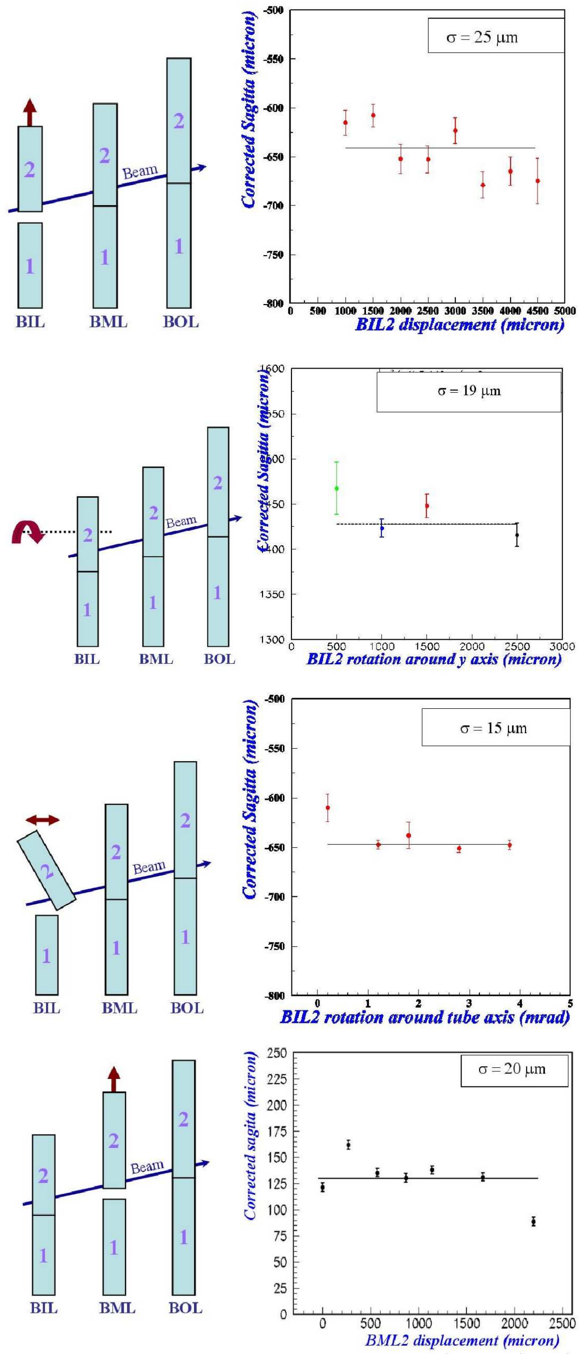

Fig. 17.12: Controlled movements of the barrel MDT chamber in H8. The four plots show the residual sagitta once the alignment correction issued from Asap have been taken into account in the muon tracking package MuonBoy. The lowest plot is a chamber movement undertaken in 2002.

The alignment data acquisition and processing were developed and commissioned on a step-by-step basis. Both are implemented today using final design components. All data is stored automatically in the condition database.

In 2002 and 2003, acquisition runs were performed, with controlled chamber movements along and around various axes. Owing to the large dimensions of the support structure, thermally-induced movements could also be studied for the end-cap. A detailed analysis can be found in Ref. [6].

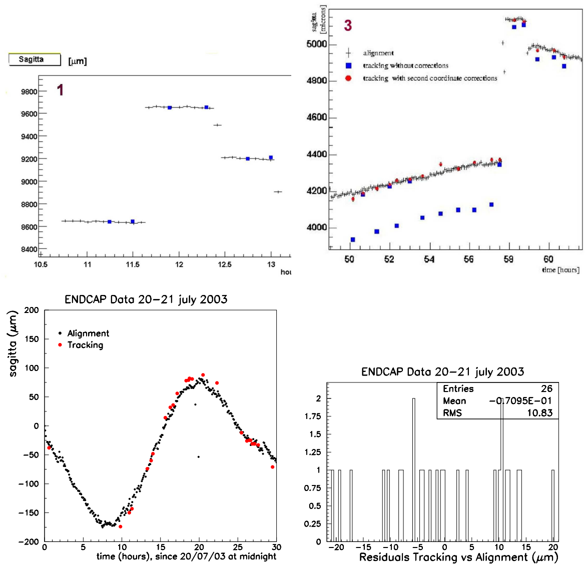

Fig. 17.13: Controlled and thermally induced movements of the end-cap MDT chambers in H8. The upper two plots show the sagitta calculated by the ARAMyS alignment package compared to those calculated by the Moore muon tracking package. The lower two plots show the ARAMyS sagitta compared to the MuonBoy sagitta. A r.m.s. of 11 μm has been achieved for these thermally induced movements.

The barrel chambers BIL2 and BML2 were moved on different occasions. For certain runs the beam was deviated such that it impacted at different chamber points. The reconstructed geometry was fed to the muon tracking software MuonBoy. The residual sagitta after the muon reconstruction are shown in Fig. 17.12. For the four chamber movements shown here, the sagitta residuals have a dispersion of about 20 μm in relative mode. The offset is non-zero and is due to the precision with which the geometer could determinate the initial MDT positions (in 2003 the MDTs were covered with RPC trigger chambers, thus leading to a degradation of the precision).

For the barrel, no absolute alignment has been tempted so far, as some of the sensors are not yet fully calibrated. As shown in Fig. 17.13, the reconstructed muon sagitta using the Moore or MuonBoy tracking package are compared to the ones predicted by the alignment program ARAMyS. After second coordinate corrections coming from the trigger instrumentations, the reconstructed sagitta are close to the predicted one. At present, all end-cap optical sensors used in H8 are fully calibrated and the absolute alignment accuracy of the end-cap is estimated at 40 μm.

17.10 Conclusion

The relative alignment concept for a detector subpart has been tested and validated for both end-cap and barrel regions, using controlled MDT chamber movements and straight muon tracks coming from the SPS muon test beam.

Acknowledgement

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