THE ATLAS DETECTOR POSITIONING SYSTEM (ADEPO) TO CONTROL MOVING PARTS DURING ATLAS CLOSURE

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Abstract

ATLAS is one of two general-purpose detectors at CERN’s Large Hadron Collider (LHC). It is 46 m long, 25 m wide and 25 m in height and has a total mass of 7000 tons. During the Shutdown periods of LHC machine, intensive maintenance and/or upgrade programs are performed in the experiment. Such activities require that various large size detectors of up to 900 tons are moved from their “Run position” to a “Maintenance position”. Before the end of the shutdown, these detectors have to be moved back to the “Run position” within mechanical accuracy of 0.3 mm. The system described in this article is an upgrade of the general procedure of Detector positioning in ATLAS that is currently based on a geodetic measurement, with a delivery time of hours for the results.

A multi-disciplinary team developed and integrated the Atlas DEtector POsitioning (ADEPO) system into the already assembled experiment to control re-positioning of seven major sub-detectors. The system is based on BCAMs (Brandeis CCD Angle Monitor) as sensors in combination with prisms. ADEPO replaces partially the manual measurement and saves time in the critical path of the detector closure and increases the accuracy of the relative repositioning. In this article are treated the specification and technical constraints resulting in the system design and layout. Further are presented challenges of installation and commissioning up to the first measurement results in the maintenance period 2015/2016. The relative precision reaches up to few hundreds of mm. It is integrated in the ATLAS work flow of the movements system for the detectors and data storage in the ATLAS detector database.

INTRODUCTION

During the Shutdown periods of the LHC machine, intensive maintenance and/or upgrade programs are performed in the ATLAS experiment. Such activities require that various large size detectors are moved from their “run position” to an “open position”. Before the end of the Shutdown these detectors have to move iteratively back to the “run position” within a good accuracy. In figure 1 the names of the different detector parts are mentioned and the two Endcap Toroid Magnets are coloured in red, the two Small Wheels in green, the two Endcaps Calorimeters in brown and the two faces of the Barrel Calorimeter, which stays fix, in yellow.

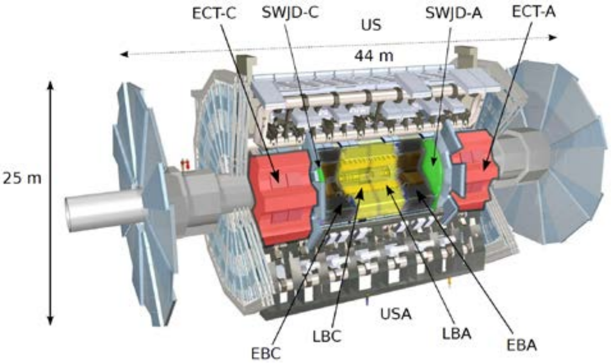

Figure 1: ATLAS overview

The system described in the article is an upgrade of the general function of Detector Positioning in ATLAS.

Although some sensors used to monitor the detector movement provide real time information related to the position of the detector, this information is partial and cannot result in the knowledge of the 3D position of the detector. The current method of positioning is mainly based on geodetic measurements by survey team which gives an off-line result within a delivery time of few hours essentially due to the time consuming access to the measured points. Despite some improvement could be done to reduce this time, the process will remain essentially iterative and therefore highly time consuming. The ADEPO system should save time and gain precision for the relative re-positioning of the detectors. For working comfort it should be at the moment of operation entirely in the hand of the technical coordination that is responsible for the detector closure.

Technical specifications

After discussions with the ATLAS technical coordination the following specifications have been agreed for the foreseen ADEPO measurement system [1]:

- Relative measurement system to measure “run” position at beginning and end of the maintenance period
- Measurement range ~50 mm in X-, Y-, Z-direction
- Accuracy: 0.1 mm in dx and dz (radial, longitudinal)
- Measurement time: less than 30 seconds

Environmental constraints

The sensors should work essentially for the closure of the experiment and a functionality as monitoring system during the run period has been added where the following constraints apply:

- Accessibility for maintenance in run configuration
- Magnetic field of 1 Tesla at BCAM positions
- Radiation dose over life time of 2 Gy
- Conception, installation and commissioning in less than 2 years
- Sensor protection withstand 1 kN
- Limited space for integration in existing detector

DESIGN CONCEPT

The system is more than an upgrade of an existing system and can be considered as a re-design. The layout changed completely as it has been visible through the last years that the most important directions to measure are X and Z (radial, longitudinal) and not the X and Y (radial, vertical) as for a previously installed system. The Y direction lost in importance as the detectors slide with air pads on stable rails that guarantee a precise vertical positioning within the stability of the civil engineering construction. Monitoring measurements have been done over more than ten years for the slab. The vertical movement of the ATLAS cavern floor is estimated to be ~0.25 mm per year. For a technical stop of 3-4 month a movement of less than 0.1 mm has to be expected.

Brandeis CCD Angle Monitors (BCAMs) have been chosen as sensors due to several advantages for the project:

- Measurement of 2 directions per sensor
- Optical non-contact measurement system
- Procurement through Collaboration as the sensors have been developed for the ATLAS Muon project
- Measurements on passive glass corner cubes
- The followed movements are perpendicular to the line of sight of the BCAMs
- Proven system for ATLAS conditions as working in the environment for 8 years

The integration of the entire system is a challenge as the ATLAS detector has been completely installed, which limits available space and lines of sight. The layout consists of 24 vertical and 4 horizontal BCAM lines and in total 44 reflectors are measured.

The distribution of the sensors has been chosen in order that the active parts are mounted on fixed part of the experiment like the ATLAS feet and that the passive target, a corner cube prism, is mounted on the moving parts of the detector to reduce integration and cabling work (see figure 2, 3).

The mechanical fixation and stability has been considered as one of the key parameters for a successful high precision measurement system. To ensure this the supporting plates of the BCAMs have been welded on the ATLAS feet and that represent one of the most stable parts of the experiment that have minimal deformation by the magnetic forces. Dedicated stainless steel covers that are independently mounted protect the sensors and the adjustable support plates of the BCAMs from external shocks. They are designed to resist forces of 1 kN to avoid accidental damages.

Due to the relative measurement concept each of the detectors is measured independently. The independence of each sensor in combination with a redundant installation increases the reliability of the system.

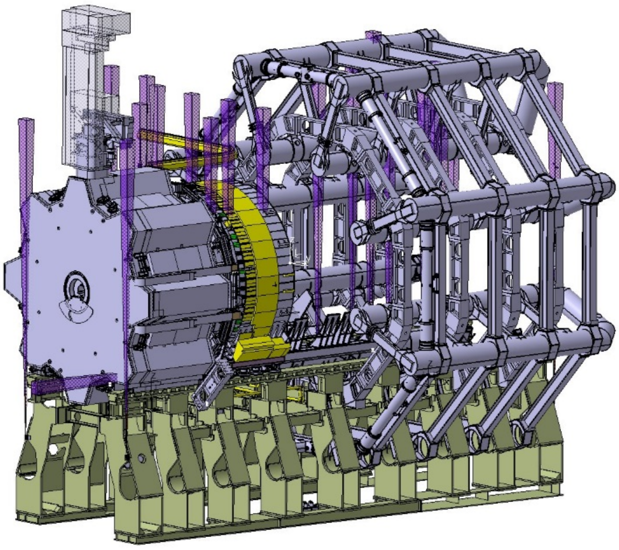

Figure 2: General layout of ADEPO system

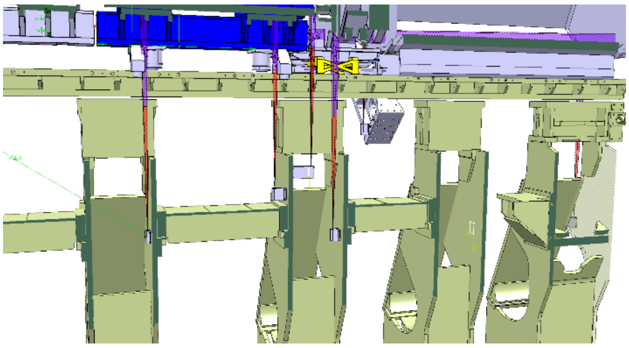

Figure 3: Detailed layout of ADEPO system

SENSOR

Brandeis BCAMs have been developed in the framework of the ATLAS experiment for the monitoring of the Muon Forward detector. Their conception has been initially done for a BCAM to BCAM use [2]. The advantage of these sensors is the resistance to the magnetic field of 1 Tesla in ATLAS and the relatively small dimension of 91 mm x 53 mm x 41 mm. The sensors have a weight of 300 g and an estimated lifetime of 10 years mainly linked to radiation in the ATLAS cavern. The readout electronics resists to 400 Gy.

BCAMs are equipped with a CCD of 2.4 mm x 3.4 mm and 244 x 344 pixels. In addition two laser diodes (650 nm) have been integrated. The principal distance for the standard BCAMs is 72 mm and it has an opening angle of 30 mrad x 40 mrad. The working principle of a BCAM is that the relative position of the centre of a light spot is analysed as visible in figure 4.

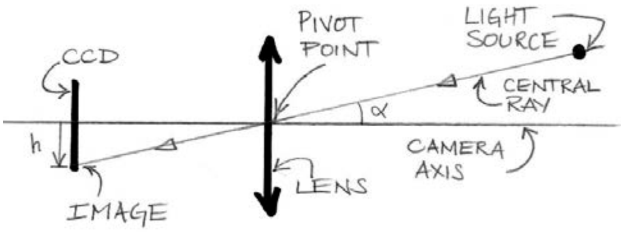

Figure 4: Optical path for BCAM prism combination [3]

In the case of use of corner cubes as reflectors the light spots correspond to reflexion of the BCAMs own flashes on the CCD-chip.

The relative precision of a BCAM is 5 µrad and the absolute precision is 50 µrad. The BCAM is delivered with a set of calibration parameters that link geometrically the chip, the isostatic mounting interface and the lens called pivot.

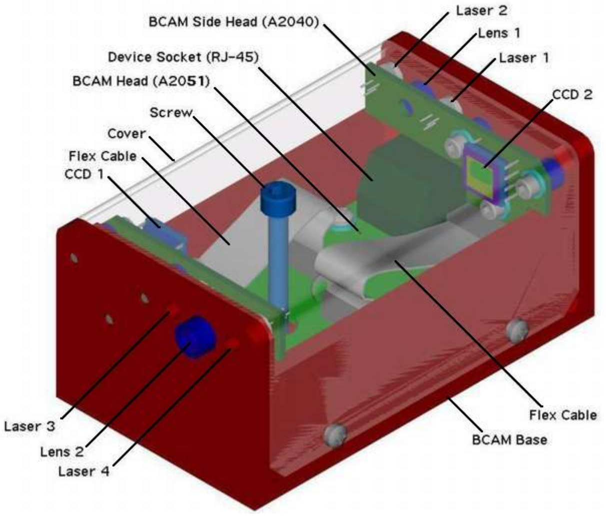

Figure 5: Double-Ended BCAM [3]

As shown in the works of Friedrich Lackner [4] and Aurelie Maurisset [5] it is possible to use BCAMs with corner cube prims as passive targets. The advantage can be seen in the reduced number of BCAMs and cabling works for the installation. The main disadvantage is that for prisms only a 2D position can be calculated precisely but the rotations cannot be calculated as in a BCAM to BCAM configuration. In addition, the precision has to be calculated for the complete optical path that is twice longer than in the BCAM to BCAM configuration.

BCAMs exist in four different variations single/double ended, blue/black. The four models permit to install BCAMs in series over longer distances. The different colours indicate mechanical mirror construction of each other.

Corner cubes

In the ADEPO system glass corner cubes with a 12.7 mm opening have been chosen instead of hollow prisms due to their cost and the limited gain in precision in a relative measurement system. Of course the systematic effects in full glass corner cubes have to be considered rigorously in the data analysis.

Taking into account the distance between the laser sources of 16 mm and their diameter a minimum diameter of the corner cube of ~10 mm has been calculated and in the application corner cubes of 12.7 mm have been purchased. The corner cubes have been glued in mechanical supports fabricated at CERN. In quality control after assembly a centring offset of up to 0.3 mm has been discovered. It turned out that the intersection point of the three plan surfaces deviates from the cylindrical surface of the corner cube, which has been used as reference surface for bonding. The offset should be taken into account in case of replacement of a prism.

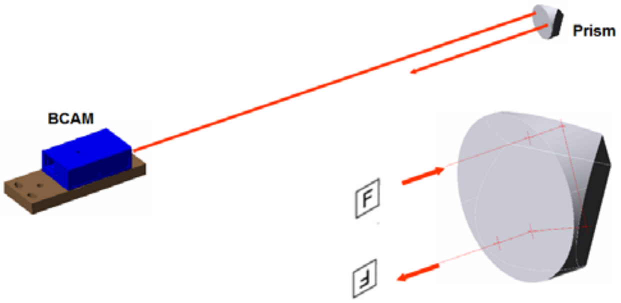

Figure 6: Optical path for corner cube

DATA ACQUISITION

The readout of the sensors is managed by the software LWDAQ that is delivered with the BCAMs. For the connection of BCAM to PC an intermediate driver is necessary. For the ADEPO system a driver of the last generation has been chosen as its acquisition frequency is three times higher than for its predecessor and speeds up the acquisition. Due to a sequential architecture of data acquisition it is mandatory that the objects are stable during the complete acquisition cycle. Following the number of connected sensors, multiplexers could be added to increase the number of BCAMs connected to a single driver up to a maximum of 80 BCAMs. All these components are connected using Ethernet cables of up to 130 meter length and the data is transferred by TCP/IP protocol. The software LWDAQ does also the image analysis including the measurement of spots on the BCAMs CCD. The acquisition can be automatized by the use of Tcl/Tk scripts. See table 1 and figure 7 for the different components of the readout system.

Table 1: Components of readout system

1 - PC with LWDAQ	**2 - Driver**
3 - Multiplexer	**4 - Black BCAM**
5 - Blue BCAM	**6 - Other sensor**
7, 8, 9 - Ethernet Cables	**10 - Power cable**

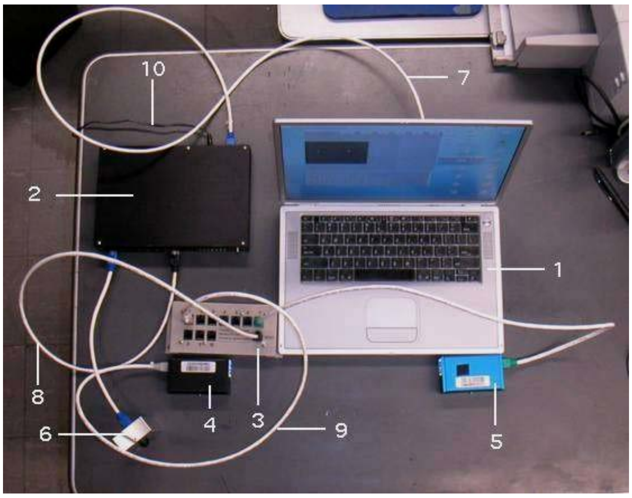

Figure 7: Connexions for BCAM system

FORMULAS

To get the coordinates of the prism in the local BCAM coordinate system the following formulas (1) need to be applied as illustrated in figure 8 [6]:

$$\vec{P}_{prism} = \frac{1}{2} \cdot \sum_{i=1}^{2} (\vec{S}_{source_i} + \vec{P}_{pivot} - (\vec{P}_{img_i} - \vec{P}_{pivot}) \cdot \frac{D}{f'}) \quad (1)$$

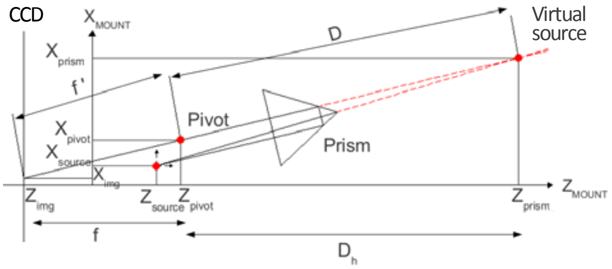

Figure 8: Light path for BCAM with corner cube

Each prism is measured by a single BCAM, which results in a non-controlled measurement. As each of the detectors is considered as a rigid assembly, the fixed relation between prisms is retained as control and can be integrated as additional constraint in a least square adjustment (2). For each of the moving detectors 4-8 prisms are installed to measure in the XZ plane. This redundancy with 8-16 measurements for 3 parameters (two translation and one rotation) permits to add an automatic blunder detection to the system (3). Statistical test based on the (ILSR) Iterative Least Square Adjustment as described by [7] has been proposed to identify damaged or dirty components in the results.

$$\begin{cases} f_1 = \sqrt{(X_{P_1} - X_{P_2})^2 + (Y_{P_1} - Y_{P_2})^2 + (Z_{P_1} - Z_{P_2})^2} - D_{1-2} \\ f_2 = \sqrt{(X_{P_1} - X_{P_3})^2 + (Y_{P_1} - Y_{P_3})^2 + (Z_{P_1} - Z_{P_3})^2} - D_{1-3} \\ f_3 = \sqrt{(X_{P_1} - X_{P_4})^2 + (Y_{P_1} - Y_{P_4})^2 + (Z_{P_1} - Z_{P_4})^2} - D_{1-4} \\ f_4 = \sqrt{(X_{P_2} - X_{P_3})^2 + (Y_{P_2} - Y_{P_3})^2 + (Z_{P_2} - Z_{P_3})^2} - D_{2-3} \\ f_5 = \sqrt{(X_{P_2} - X_{P_4})^2 + (Y_{P_2} - Y_{P_4})^2 + (Z_{P_2} - Z_{P_4})^2} - D_{2-4} \\ f_6 = \sqrt{(X_{P_3} - X_{P_4})^2 + (Y_{P_3} - Y_{P_4})^2 + (Z_{P_3} - Z_{P_4})^2} - D_{3-4} \end{cases} \quad (2)$$

$$\begin{cases} if\ \hat{v}_i < 2 \cdot \sigma_0\ then\colon P_i = 1 \\ else:\ P_i = k \cdot \frac{\sigma_0^2}{\hat{v}_i^2}\ with\ k \geq 1 \end{cases} \quad (3)$$

VALIDATION

To validate the correct function of the software and to confirm that the system is within the specifications a test setup close to scale one representing three detector parts has been constructed prior to the installation in the experiment.

Original BCAMs have been installed and adjusted so that all available lines of sight can be used. Each support plate for a BCAM as well as the prism position have been measured by AT401 at a precision of 30 µm. In the test setup different movements representative for the last centimetres during a closure have been done using a mobile frame to evaluate the reachable precision in lab conditions. See figure 9 for the layout of the validation setup.

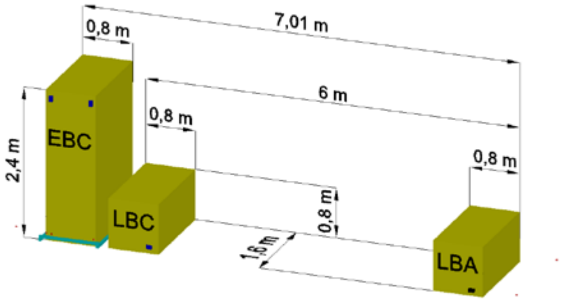

Figure 9: Layout validation setup

In the setup a distance of 2.1 m has been used for the simulation and a detector has been simulated using four vertical BCAMs in the EBC corners. The repeatability tests show excellent results (Table 2) for the installation that are below the specifications of the BCAM. For the reproducibility the result of 35 µm is impacted by the precision of the AT401 that serves as reference and the exchange of targets between the Laser tracker and BCAM measurements.

Table 2: Precision of BCAM system validation

ADEPO results (2.1 m distance)	X, Z direction (µm)
Precision Repeatability	**3.0 (1σ)**
Precision Reproducibility	**35 .0 (1σ)**

SOFTWARE AND INTERFACE

Scientific Linux CERN 6 and C++ is mandatory as development environment for a complete and easy integration in ATLAS network. The link between the main components and integration in the ATLAS infrastructure is presented in figure 10.

The central part of the system is the ADEPO Server that runs the ADEPO Client Display to choose a configuration and the program LWDAQ. The data acquisition works via Tcl/Tk scripts and the BCAM driver to access the BCAM sensors. The image analysis and calculation of 3D coordinates is performed on the ADEPO server. The last step is the final storage in the ATLAS database using the Data Interchange Protocol and data supply to potential end-users.

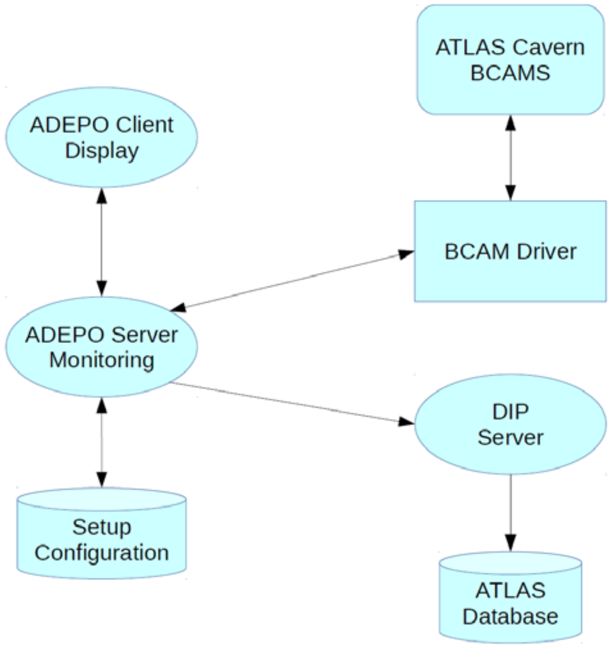

Figure 10: Scheme of adopted architecture

INSTALLATION

The installation procedure has been modified with respect to the specifications as absolute adjustments of the BCAM support plates have been possible. This guarantees the orientation of the BCAM coordinate systems to be parallel to the ATLAS coordinate system. This is a major point if voluntary displacements of a sub-detector are requested from physicists with respect to a previous position. The mounting plates have been adjusted prior using AT401 laser tracker. The isostatic mounting interface has a length of 0.1 m and the measurement distance from BCAM to prism is 1.3-11 m creating a large lever arm. As consequence the coordinates, measured by the BCAMs, have a limited absolute precision.

Installation areas have been extremely difficult to access as they are deep inside the detector behind two layers of muon chambers. Measurements could only be carried out thanks to a small and light weight laser tracker that permitted a comfortable, manual transport and installation on temporary supports inside the ATLAS detector.

The entire installation and adjustment of equipment has been done in the maintenance configuration during the Long Shutdown 1 (LS1). The detectors are opened at least 3.1 m what creates challenges to insure visibility once all detectors are closed. The passive reflectors are installed mechanically based on nominal values from the ATLAS 3D-model, which increases the risk. Differences of the as-built construction with respect to the 3D-model based on construction drawings can be discovered only once all detectors are closed and in run position at the end of LS1. Particularly the installed services can differ significantly from 3D-model.

MEASUREMENT RESULTS 2015/16

Missing reference data for the BCAMs reduced the benefit of the system for the closure of the ATLAS experiment at the end of LS1. However the ADEPO system could be used to control the size of relative movements in the different iterations and already speeded up the process and showed its potential. A complete test of the system had to wait until the closure at the end Technical Stop 2015/16.

Short term results (closure)

ADEPO confirmed its potential and an average of three iterations of BCAM measurements has been necessary for the six mobile detectors to get a satisfactory position. In an exceptional case up to seven iterations have been necessary for correct positioning.

The ADEPO results have been verified and confirmed by a laser tracker measurement. The offsets in the monitored directions that are X and Z have been at the level of 0.3 mm with respect to the previous detector position or closer than previously to the nominal position.

The measurement system uses a standard measurement time of 30 seconds.

Medium term stability and precision

Over a period of 30 days the measurement stability for different detectors is at the level of ± 15 µm if the magnetic field didn’t change during the period (figure 11). The 1σ precision for an individual BCAM is ~3 µm.

The magnetic forces of the Barrel Toroid are above 1000 kN and influence the position of the Endcap Toroid as visible in figure 12. Movements at the level of 3-4 mm are visible in figure 12 and could not be measured before with geodetic survey techniques. The magnetic forces cause less movements on the other detectors that are steel structures. In the monitoring mode the movements caused by the ramp up or ramp down of the ATLAS magnetic field influences the precision of the measurement results that decreases but stays within the specification of 0.1 mm.

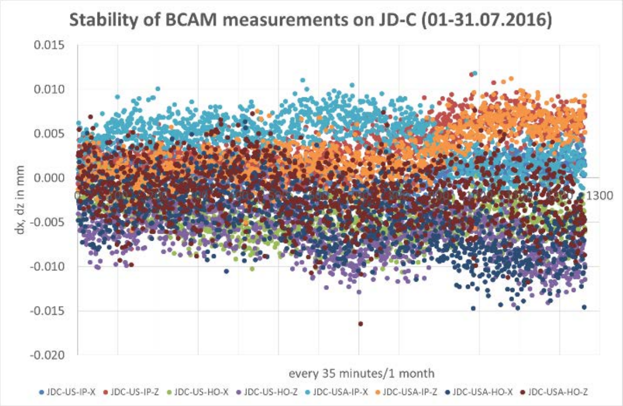

Figure 11: BCAM measurement stability over 1 month

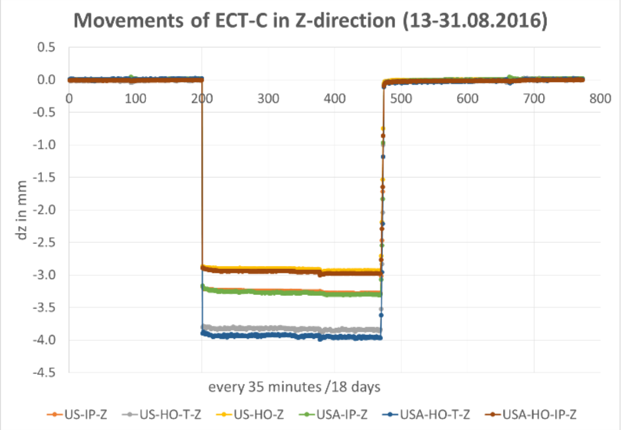

Figure 12: Sigma during magnet ramp up/down

CONCLUSION

The Technical Coordination of ATLAS appreciated ADEPO as valuable tool that has saved 2-3 hours for the closure of each of the six detectors at its first use. In the future the saving could be, thanks to the confidence in the system, at a level of ~4 hours per detector. Over the complete closing procedure of three weeks the gain in the schedule for the technical coordination could represent up to 20 % of the total time.

The time saving for the survey team represents, depending on the detector, up to 25 %. This is possible thanks to the reduction of iterations to the strict minimum of one. In addition the survey intervention that has been so far on the critical path of the detector closure operation can be registered in the future as shadow operation in the planning. ADEPO increases at the same time the comfort of the implicated teams as the intervention time is reduced and is more flexible requires less coordination.

The independent control of ADEPO by the maintained geodetic measurement is justified to detect long-term movements at the level of civil engineering as cavern floor that limits the potential of a relative alignment system.

OUTLOOK

The differences of ATLAS model with respect to the as-built necessitate further interventions to modify several horizontal lines to deal with the lack of visibility. In addition the complete implementation of the proposed adjustment and error detection using the least square algorithm should facilitate the automatic interpretation of results based on sigma values and a priori knowledge of theoretical values.

During the opening procedure reference measurements should be acquired after each detector movement to get reference data of best quality regardless of the mechanical deformations caused by detectors of over 2500 tons shifted on the rails and feet structure.

ACKNOWLEDGMENT

We would like to thank the different ATLAS technical coordinators Marzio Nessi, Beniamino Di Girolamo and Ludovico Pontecorvo for their support of the project.

Many thanks to technical coordination team, Julien Migne, Frederic Rosset, Cedric Sorde and Nikolay Azaryan for their participation.

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