The ATLAS Detector Positioning System (ADEPO) to Control Moving Parts During ATLAS Closure

IWAA 2016 (03-07 Oct.) - Grenoble - France

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Introduction

ATLAS facts
• Length 44 m, diameter 25 m
• Weight: 7000 t
• Data: 3200 TB/year
• 3000 scientists from 38 countries

ATLAS requirements
• Regular maintenance and shut down periods
• Implies movement open/close of large sub-detectors of up to 900 t
• Manual adjustment and survey is iterative and time consuming

New ADEPO system should provide
• Near real-time results
• Speed up closure
• Precise re-positioning
• Entirely managed by ATLAS

Technical Coordination
ADEPO system specifications

- 6 detectors to be re-positioned
  - 2x ECT – 240 t
  - 2x SW – 103 t
  - 2x EB – 900 t
  - In total ~2500 t of detector are moved

- Measurement range
  - Along X : +/- 20 mm (radial)
  - Along Y: -10/+30 mm (vertical)
  - Along Z+ (side A): -10/+40 mm
  - Along Z- (side C): -40/+10 mm

- Repositioning 0.3 mm

- Measurement precision
  - 0.1 mm at 1 sigma level along XZ directions (radial and longitudinal)

- Environmental constraints
  - Resist to 1 Tesla magnetic field
  - Radiation dose of 2Gy for lifetime

- Measurement requirements
  - Measurement cycle < 30 seconds
  - Two measurement modes
    - Closure (on demand)
    - Monitoring during run time
      - Parallel to ATLAS coordinate system (shifts tolerable)

- Installed and commissioned during Long Shutdown 1 (LS1) period (2013-2014)
  => project < 2 years
Choice of layout and sensors

Layout based on experience of previous alignment systems

- BCAMs as proven camera sensors originally developed for ATLAS
- BCAMs attached to feet => max. stability
- Independency of each BCAM line
- Optical 2D measurement => less sensors
- Redundant system for error detection with 4 BCAMs and up to 8 prisms per detector
- BCAMs with protection to avoid damage
- Passive targets on mobile parts => no cabling
ADEPO System description

System is based on:
• 28 BCAMs on feet/rail system
• 44 passive targets (corner cubes)
• 1 driver and 4 multiplexers
• 24 protections
• Reference ATLAS feet/rail system
• LWDAQ for acquisition and measurement
• Movement/Positioning using push/pull system

• Adjustment concept:
  • Adjustment using additional observations (detectors rigid body)
  • Blunder detection: Application of IRLS (Iteratively Reweighted Least Square)
    • K. Jacobsen, “Block Adjustment. Institute for Photogrammetry and Surveying Engineering”, Univ. Hanover, 2002, Germany
    • Successfully tested in validation setup, still to be integrated in the present version of ADEPO

• System is considered as additional system and traditional survey is maintained!
• New references after each closure!
Validation setup and results

- Demand: 0.1 mm at 1 σ
- Repeatability: < 0.005 mm
- Displacement results: 0.04 ± 0.01 mm at 1 σ
- Verified by AT401 for detector EBA/EBC
- IRLS (Iteratively Reweighted Least Square) proved efficiency

Result of displacement test at 2.1 m → mean offset = 35 µm ± 11 µm
Installation in ATLAS cavern

- Installation and adjustment in ATLAS open position => prisms invisible, first verification can only occur after closure
- Inside detector behind layers of muon chambers
- Integration in completed detector => limited lines of sight/space
- Adjustments by AT401 in absolute system mandatory using special adapter plate
Commissioning

- Problem of hidden lines on ECT
- Hidden lines in saddle beams
  - Due to difference of as-built to 3D-model
- Concession to integration constraints with 4 BCAMs on BT warm structure
  - Movement of BCAMs on BT structure due to deformation of support structure

- Separation of flashes
- Change of flash times
- Definition of zones for BCAM measurements in case of 2 prisms
- Identified broken connector
ADEPO user interface

- Interface and server structure integrated in technical infrastructure (ATLAS network)
- GUI with 2 modes for closure and monitoring
  - Closure measurement time defined in sec.
  - Monitoring default 10 loops
- Data storage via DIP (Data Interchange Protocol) in ATLAS database
Results ATLAS closure

• Intensive use of ADEPO for closure of Technical Stop 2015/16

• Six detectors closed with in average 3 iterations of BCAM measurements
  • Maximum of 7 iterations
  • Average time for mechanical correction ~ 20 minutes

• Average difference of ADEPO results to reference position
  • 0.3 mm along monitored X, Z directions (or closer with respect to nominal values)

• Results for each detector confirmed by Laser Tracker measurements
  • Single iteration for survey
Short-term results for ECT – B-Fied on/off

• Demand from physics side for movement of ECT under magnetic field for field map

• Due to strong magnetic field no survey measurements available previously (only Muon Barrel alignment system)

• Quench at measure 200

• Back to nominal after 1 week with magnet down

• Movement of 3-4 mm with b-field of BT and ECT

• Deformation of BCAM support due to B-field
  • US-IP-Z, USA-IP-Z
Medium term results (1 month)

- One month repeatability on individual BCAMs of Small Wheel and JD C-side
- Average precision (repeatability 1 month): 2-3 µm
- BCAM lines of 1.5-3.0 m measure a detector stability within ± 0.015 mm

Conditions: No change of magnetic field!
Conclusion

- System installed and commissioned during LS1 2013-2014
- ADEPO has two operating modes:
  - On-demand for closing operation
  - As monitoring system (magnetic field, long-term)
- First use for relative movements during closure of LS1
- Successful use in TS2015/16 with gain of 2-3 hours for each of the 6 moving detectors during closure operation
  - Average 3 iterations using ADEPO
- Geodetic survey of detectors maintained and justified by long-term movements at level of civil engineering

- **ADEPO generates substantial gain in time, precision (relative) and comfort for technical coordination and survey team!**
Outlook

• Consolidation of few BCAM lines due to differences in 3D model with respect to the as-built construction

• Complete implementation of:
  • proposed adjustment using additional observations
  • blunder detection to identify in-valid measurements

• Acquisition of reference data after each movement during detector opening to minimize influence of mechanical deformation
  • Weight of shifted detectors represents ~2500 tons

• Possible increase of time savings at a level of ~4 hours for each single detector closure
  ➔ Up to 20% gain in ATLAS closure schedule for the technical coordination
Thanks for your attention!

Candidate Event Selected in Higgs Search Analyses

Run Number: 209109, Event Number: 86250372
Date: 2012-08-24 07:59:04 UTC
BCAM equipment

Brandeis CCD Angle Monitor – BCAM:
• BCAM resists magnetic field and radiation as developed for ATLAS Muon system
• Sensor size 344 x 244 pixel, 10 µm/pixel
• Field of view: 40 mrad x 30 mrad
• Camera focal length: 75 mm
• Minimal working distance 0.7 m
• Absolute precision 50 µrad (2D)
• Relative precision 5 µrad (2D)
• Isostatic mount system
• Delivered calibrated
• Laser diode 650 nm
Results ECT ramp up/down (short-term)

- Due to high magnetic field no survey measurements available before (only Muon alignment system)
- Demand from physics side for movement of ECT under magentic field for magentic field map
Formulas corner cubes

- BCAMs perpendicular to beam/prism (5° => error ~10 µm)
- In case of BCAM-Prism measurements the virtual source is measured at twice the distance of the real one
- Use of theoretical values for projection of D on Z axis
- In the BCAM mount system the following formula applies:

\[
\vec{P}_{prisme} = \frac{1}{2} \sum_{i=1}^{2} (\vec{S}_{source} + \vec{P}_{pivot} - (\vec{P}_{img} - \vec{P}_{pivot}) \cdot \frac{D}{f'})
\]
Formulas corner cubes

- Projection of D on Z-axis is:
  \[ D_h = \frac{\Delta S}{2 \tan \alpha} \]

- Error propagation corresponds to:
  \[ \sigma_{D_h} = \frac{D_h}{\Delta S} \sqrt{\left(\frac{\sigma_{\Delta S}}{\Delta S}\right)^2 + 8 D_h^2 \sigma_{\alpha}^2} \]

- Precision of 4 mm at 2 m results in an error of 5 um for XY directions
Validation results

Result of displacement test at 2.1 m: mean offset = 35 µm ± 11 µm
Adjustment concept

- Single detector is considered as rigid and non-deformable object
- As consequence
  - Observations are linked by constraints
  - Calculation of prism coordinates is linked by additional observations
- Equation systems for a single detector with 4 prisms:

\[
\begin{align*}
  f_1 & = \sqrt{(X_{p1} - X_{p2})^2 + (Y_{p1} - Y_{p2})^2 + (Z_{p1} - Z_{p2})^2} - D_{1-2} \\
  f_2 & = \sqrt{(X_{p1} - X_{p3})^2 + (Y_{p1} - Y_{p3})^2 + (Z_{p1} - Z_{p3})^2} - D_{1-3} \\
  f_3 & = \sqrt{(X_{p1} - X_{p4})^2 + (Y_{p1} - Y_{p4})^2 + (Z_{p1} - Z_{p4})^2} - D_{1-4} \\
  f_4 & = \sqrt{(X_{p2} - X_{p3})^2 + (Y_{p2} - Y_{p3})^2 + (Z_{p2} - Z_{p3})^2} - D_{2-3} \\
  f_5 & = \sqrt{(X_{p2} - X_{p4})^2 + (Y_{p2} - Y_{p4})^2 + (Z_{p2} - Z_{p4})^2} - D_{2-4} \\
  f_6 & = \sqrt{(X_{p3} - X_{p4})^2 + (Y_{p3} - Y_{p4})^2 + (Z_{p3} - Z_{p4})^2} - D_{3-4}
\end{align*}
\]
Blunder detection

Stability of sensors and targets is a main problem of alignment systems

- Redundant layout
  - Minimum of 8 observations for 3 unknowns
- Adjustment using additional observations (rigid detectors)
- Identification of invalid lines

The proposed mathematical approach has been successfully tested in validation setup!

• Application of IRLS (Iteratively Reweighted Least Square)
  - Based on L2–norm

\[
\begin{align*}
\text{if } \hat{v}_i < 2 \cdot \sigma_0 \text{ then: } P_i &= 1 \\
\text{else: } P_i &= k \cdot \frac{\sigma_0^2}{\hat{v}_i^2} \text{ with } k \geq 1
\end{align*}
\]
Blunder detection

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