Recent and future alignment challenges and solutions for both the LHC machine and experiments

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Surveyors …

Surveying or land surveying is the technique, profession, and science of determining the terrestrial or three-dimensional positions of points and the distances and angles between them. A land surveying professional is called a land surveyor. These points are usually on the surface of the Earth, and they are often used to establish maps and boundaries for ownership, locations, such as building corners or the surface location of subsurface features, or other purposes required by government or civil law, such as property sales.

Surveyors work with elements of geometry, trigonometry, regression analysis, physics, engineering, metrology, programming languages, and the law. They use equipment, such as total stations, robotic total stations, theodolites, GPS receivers, retroreflectors, 3D scanners, radios, handheld tablets, digital levels, subsurface locators, drones, GIS, and surveying software.

Surveying has been an element in the development of the human environment since the beginning of recorded history. The planning and execution of most forms of construction require it. It is also used in transport, communications, mapping, and the definition of legal boundaries for land ownership. It is an important tool for research in many other scientific disciplines.

…at CERN: surveyors are in charge of the alignment of accelerators and detectors components (EN-SMM) and land surveyors in charge of CERN patrimony and site information (SMB-SE)
Our challenges

- Size of the components
- Difficult configuration: straight and narrow
- Underground
- Scale
- In crowded area
- Severe environment...

Accuracy and precision
From a few µm to mm
Surveyors at CERN

Specific studies and activities:

• Geodesy
• Pushing standard instrumentation (calibration base for EDM measurements, calibration benches for alignment sensors)
• Development of specific instrumentation and methods → one example: the stretched wire
Stretched wire at CERN

Wire Offset measurements:

- Wire as straight alignment reference
- Radial measurements
- Wire to be protected from air currents

Wire Positioning System (WPS)

Main characteristics:

- Biaxial measurements
- Range: \( \pm 5 \) mm
- Resolution < 0.2 \( \mu \)m
- Repeatability < 1 \( \mu \)m
- Accuracy < 5 \( \mu \)m over the whole range

J-P QUESNEL et al., “Stretched wire offset measurements: 40 years of practice of this technique at CERN for aligning the accelerators of particles”, IWAA 2008, KEK, Tsukuba, Japan, 2008.
Our tool box

Software & database

Photogrammetry

R&D systems

Alignment sensors

Laser scanners

Laser trackers & total stations

Portable CMM

Romer arm

Optical & digital levels

Survey TOOLBOX

D3X

FSI

μtriangulation

WPS

HLS

BCAM

HDS6200

AT9xx

AT40x

TDA 500

TS60

TC2002
Survey and SMM

Survey mandate:

- Geodetic aspects
- Dimensional metrology of accelerator and of experiment components
- Positioning and alignment on beam lines
- Quality controls (infrastructure, installations, components)
- The R&D related to these tasks

Survey, Mechatronics and Measurements (SMM) group

The SMM Group develops and maintains a centralized competence in Survey, Mechatronic systems, tests and Measurement. The group is in charge of maintaining a competence in the development of radiation tolerant electronics, and provides support CERN wide for radiation tests and radiation monitoring for evaluating the dose to electronics installed in radiation areas. The group develops robotic platforms adapted to interventions in the accelerator environment, and deploys those solutions in collaboration with all groups in the Accelerator and Technology sector. SMM is able to provide computing support for data acquisition, data processing and data analysis, as well as for data storage related to all these activities.
Outline

*Gain time, accuracy and limit personnel exposure…*

- Recent challenges in the LHC
  - Monitoring of ATLAS detector closure
  - Remote determination of the collimators position
  - On-line alignment system on inner-triplet
- Future challenges: HL-LHC project
  - Internal monitoring
  - Full remote alignment system
Monitoring of ATLAS detector closure

Context:
- Regular maintenance and *shut-down periods*
- Implies open/close movements of large sub-detectors of up to 900 t, more particularly:
  - 2 ECT (240 t), 2 SW (103 t), 2 EB (900 t)
- Manual adjustment and survey is iterative and time consuming

ADEPO= ATLAS DETECTOR POSITIONING SYSTEM, a ATLAS-SURVEY collaboration

Technical requirements:
- Relative measurement system to measure «run» position at the beginning and end of the maintenance period
- Measurement range ~ 50 mm in X, Y, and Z directions
- Accuracy: 0.1 mm in dX and dZ
- Measurement time: less than 30’

Environmental constraints:
- 1 T magnetic fields
- 2 Gy of radiation dose over life time
- Limited space in existing detectors

Monitoring of ATLAS detector closure

Solution = BCAM camera (Brandeis CCD Angle Monitor)

- Optical measurement system
- Measurements on passive glass corner cubes
- Already used in ATLAS

J-C. GAYDE et al., «The ATLAS detector positioning system (ADEPO) to control moving parts during ATLAS closure», IPAC 2016, Grenoble, France.
Monitoring of ATLAS detector closure

System based on:

- 28 BCAMs on feet/rail system
- 44 passive targets (corner cube Reflectors)
- 1 driver & 4 multiplexers
- 24 protections
- Application of IRLS (Iteratively Reweighted Least Square) for the data adjustment.

Integration and installation were a challenge as well.

- BCAM on feet/rail systems (fixed parts)
- Passive targets on sub-detectors (moving parts)
Monitoring of ATLAS detector closure

Results during ATLAS closure

• Intensive use of ADEPO during closure (TS 2015-2016)
• Six detectors closed with an average of 3 iterations using BCAM measurements
  • Maximum of 7 iterations
  • Average time for mechanical corrections ~ 20’
• Average difference of ADEPO results to reference position: 0.3 mm along monitored X and Z directions
• Results for each detector confirmed by Laser Tracker measurements (single iteration)

Medium term results over 1 month:

• Average repeatability over 1 month: 2-3 µm
• BCAM lines of 1.5 – 3.0 m measure the stability of a detector within ± 0.15 mm

Substantial gain of time (25%) and relative precision, for all YETS!

A BCAM system installed in LHCb to monitor the positions of the Inner Tracker stations during the LHCb dipole magnet cycles
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Remote determination of collimators position

Standard alignment measurements no longer possible in collimators area (IP3 and IP7 due to the high level of radiations)

→ Development of a remote measurement system: design of a survey wagon on the TIM train.

Remote determination of collimators position

Measurements campaign in 2012:
• 26 reference magnets
• 35 collimators
  over 500 m

Repeatability < 60 µm in altimetry and planimetry

Comparison with classical methods (levelling and wire offset measurements): 0.22 mm rms
Duration in the tunnel: a few hours (train) / 4 days at 3 persons (classical method)

Current objective: mechanical optimization and control robustness improvement for a smooth operation during LS2

Next steps: upgrade of the train for remote measurements in the LSS during LS3 for the HL-LHC project and remote measurements in the arcs for LS4.

Remote determination of collimators position

From the survey point of view: use of photogrammetry to measure the position of the wire:

Automatic wire detection

Wire position measurements

Automatic target detection

Target position determination

Target decoding

Bundle adjustment
Final calculation:
- Target precision: ± 7µm/m
- Wire precision: ± 6.5 µm/m

Remote determination of collimators position

Configuration with 4 cameras is a good compromise.

Precision of the 3D offset distance with respect to a stretched wire at a level of \( \pm 15 \, \mu m \) to \( \pm 20 \, \mu m \) for the fiducials

From the survey point of view \( \Rightarrow \) next steps:

- 4 cameras to be implemented in a carbon frame
- 2 bi-directional inclinometers added to provide link to gravity
- Chain of calculation to be automatized.
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On-line alignment system for inner triplet

Alignment requirements for the LHC:

- Stability of the positioning of one quadrupole inside its triplet: a few µm

On-line alignment system for inner triplet

What has been done in the LHC:

- Relative determination of the position of quadrupoles inside the triplet: a few µm
- Uncertainty of measurement of the fiducials of the triplet quadrupoles:
  - Radial position: ± 0.2mm (1σ) from left side to right side
  - Levelling position: ± 0.1 mm (1σ) from left side to right side
On-line alignment system for inner triplet

Linking the inner triplet w.r.t other components of the Matching Section:

- Uncertainty of measurement concerning the alignment of one triplet fiducials w.r.t the main elements of the Matching Section (MS): requested: ± 0.1 mm (1σ) but not achieved.
- For all other components of the MS: smoothing: ± 0.15 mm (1σ) over 110 m. Achieved.
- Intermediary components: smoothing w.r.t. adjacent quadrupoles. Achieved.
On-line alignment system for inner triplet

What was achieved in the LHC:

WPS data analyzed by the shift crews in the CERN Control Center to estimate the effective deflection for the triplet.

IR8 - 2015

- The triplet movement in IR8 revealed for the first time the important sensitivity to the thermal shield temperature. And by it large amplitude and fast changes ‘spoiled’ many measurements.
- In IR8 the problem came from a regulation valve that did not move correctly (not repaired, mitigated by a change of operating point).

Horizontal re-alignment of Q1.L1

Friday 6/5, noon: Q1.L1 moved back to pre-power cut position

Two ways to solve «large» movements:
- Remote re-alignment using WPS readings + motorized jacks
- Magnetic corrections using correctors
On-line alignment system for inner triplet

Lessons learnt:

Important misalignments seen due to mechanical stresses caused during cool-down

→ remote fine tuning very interesting when no access is possible anymore

WPS readings do not correlate very well with the cold mass inside the cryostat. «black box of what is inside the cryostat».

Position of the inner triplet w.r.t. other MS components not known with sufficient accuracy.

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HL-LHC project

- New IR-quads Nb3Sn (inner triplets)
- New 11 T Nb3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Major intervention on more than 1.2 km of the LHC
HL-LHC project
Internal monitoring system

• From the LHC experience: we know at the micron level the position of the cryostat, but not what happens inside \( \rightarrow \) difficult to correlate with beam.

• Displacements up to ± 0.5 mm (3\(\sigma\)) seen on the LHC dipoles after transport (EDMS 677511)

• Strong interest from BE/ABP to know more accurately than in the LHC the longitudinal position of the cold mass

• Decision to include in the baseline the internal monitoring of the inner triplet cold masses using laser interferometer (less «invasive» solution)

• Validation of the commercial solution based on Frequency Scanning Interferometry (FSI), providing absolute distance measurements

\[
\Delta\text{Phase (meas.)} = \frac{2\pi}{c} \cdot L_M \cdot \Delta \nu \\
\Delta\text{Phase (ref.)} = \frac{2\pi}{c} \cdot L_R \cdot \Delta \nu
\]

\[
\frac{\Delta\text{Phase (meas.)}}{\Delta\text{Phase (ref.)}} = \frac{L_M}{L_R}
\]
Internal monitoring system

Validation on independent benches
Performance of one line FSI & study of an alternative
- Irradiation tests
- Thermal tests
- Precision, accuracy,…

Validation on Crab cavities in SM18 & SPS
Performance target at warm, vacuum, cold, and cross-comparison with other systems

Validation on a test magnet (Dipole)
Validation of performance
- Accuracy and precision
- Long term stability
- Cryo-condensation issues

Internal monitoring system

- Pressure: ambient
- Temperature: ambient

- Isolation vacuum
- Temperature: 2 K

Internal monitoring system

- Successful cross-comparison with other systems at warm, at cold, under vacuum
- Accuracy of the absolute position of crab cavities using FSI: ±0.05 mm
- Relative position: a few micrometers
Internal monitoring system

How can we achieve a “heating” of the probes up to ~200K?

Permanent heating – by making sure that the probe stays at >=200K, no cryo-condensation should ever take place in principle. This could be achieved using the power radiated from the vacuum vessel (which is 300K “hot”).
Successful test at 4 K of the new support of targets!
Cryo-condensation issue solved!

Next steps:
• Validation of other targets and a in-house FSI solution on the dipole
• Decision on the types of targets, viewports vs feedthrough and FSI solutions before
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  - Towards Full Remote Alignment System (FRAS)
Towards Full Remote Alignment Solution

HL-LHC alignment requirements:

Estimation of the deviation of the magnets from a laser straight line, with a quadratic sum of the following independent contributions: ± 0.27 mm:

• Fiducialisation: mechanical axis vs external fiducials: ± 0.1 mm

• Smoothing :
  • Mechanical axis of quadrupoles included in a cylinder with a radius of 0.1 mm
  • Left / right mechanical axis included in a cylinder with a radius of 0.15 mm.

• Misalignment between alignment campaigns: ± 0.17 mm (integrating ground motion, mechanical stress encountered during vacuum and cool-down phases)

Remote adjustment of the position of the main components from Q1 to Q5 (5DOF)

Towards Full Remote Alignment Solution

- Combined with an internal monitoring of the position of cold masses in the Inner Triplet cryostats using FSI system
- Motorized jacks supporting all main components.
Towards Full Remote Alignment Solution

**Kapton WPS (kWPS)**

- Based on flexible Kapton polyamide PCB with electrodes printed on the surface and covered with a layer of gold
- Sensor assembly consists of:
  - 2 aluminium blocks including connectors & screws
  - A Kapton foil glued during a simple assembly process
- First tests performed on the prototype show a micrometric repeatability of measurements over ± 5 mm of range
- Irradiation tests under way
- Next steps: accuracy and long term stability of the sensor.
Towards Full Remote Alignment Solution

«Standardized» adjustment platform
Towards Full Remote Alignment Solution

«Standardized» adjustment platform

(1) Spherical joints
(2) Flexural joints: Nitinol joints and flexible shaft
Towards Full Remote Alignment Solution

**IP1 and IP5 HL-LHC**

*Synoptic of adjustment system only*

**Baseline vs Full Remote Alignment**

- Motorized adjustment system, remotely controlled: adjustment during run, from CCC
- Manual adjustment system: adjustment during LS,YETS,TS, personnel in the tunnel, access in front of element (special for TAXS)
- Remote alignment compatible

Full Remote Alignment applied to HL baseline optics not to optimized one

Courtesy P. Fessia
Towards Full Remote Alignment Solution

After study: the full remote alignment can be deployed

Main advantages:

- It will allow the reduction of radiation doses taken by surveyors.
- It will increase the window for machine optimization.
- It will put less pressure on orbit corrector system.
- It will provide a higher machine flexibility and reduced reaction time.
- It opens the possibility to re-optimize the Matching Section.

- Endorsed last week during the 61st HL-LHC Technical Coordination Committee (TCC).
- Next steps:
  - Introduction in the baseline and preparation of associated documentation.
  - Preparation of the new layout by optimizing specific areas.
  - After study: the full remote alignment can be deployed.

Courtesy P. Fessia
Summary

Developing new devices and associated methods is a core activity of surveyors at CERN:

- Considering the alignment requirements
- The environmental conditions, the specific size of the components to be aligned
- The fact that no standard solutions exist on the market.

Surveyors have always developed their own instrumentation, tools, methods and software, considered now as standards for the alignment of other particle accelerators in the world.

R&D has allowed answering challenges for both LHC machine and experiments, and to propose very interesting solutions for HL-LHC: the Full Remote Alignment System, for a rigid remote alignment of all the components from Q1 to Q5 in the LSS.
Summary

Future colliders like CLIC or FCC will require geodetic studies, new solutions of alignment, and the automatisation of standard solutions of alignment (marking of the beam line on the tunnel floor, remote determination of the position of the components, etc.).

Developments and results achieved on the measurement train or on low cost sensors or adjustment solutions show that we are in the good direction.

We are in the good group for such developments, we just need resources and material to perform the R&D studies that will allow us solving the challenges of tomorrow.
Thank you very much