Ten Years of Three-dimensional Metrology Applied to the LHC Detectors

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The very first contacts involving survey and alignment of the LHC detectors were taken more than 10 years ago. From the very beginning, the CERN surveyors were working in close collaboration with the physicists responsible of detectors and of the inner alignment systems, specifically for Atlas and CMS. Preliminary approaches were given conjointly and approved, always preserving the survey and the possibilities of quality controls during the prototyping and the fabrications. More than 80 off-CERN geometrical operations had been carried so that the critical steps had been crosschecked by CERN directly on the fabrication premises. The poster will bring in similitudes and common features and give details of geometrical specificities for each of the four experiments

1. INTRODUCTION

The overall accuracy of detecting and the dimensions of the detectors and structures, have led the responsible persons of the construction and the installation of the LHC experiments to consider the survey very early. We also, as survey responsible persons, have understood very early that the main methodology could be continued, but it had to be adapted and proposed far in advance of any fabrication process. Then a common and very close collaboration was put in place with the various physics teams in charge of all the steps of manufacturing the spectrometer elements.

2. CONFIGURATION OF THE DETECTORS, PRECISION AND SPECIFIC SYSTEMS

The final arrangement of the inner tracking, the muon systems and the magnetic system have produced various configurations (see Figures 1 to 4).

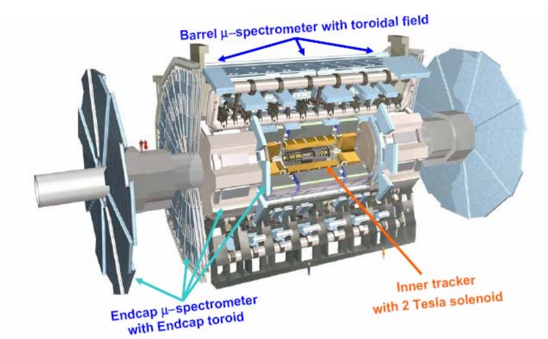


Figure 1: The ‘aerial’ ATLAS

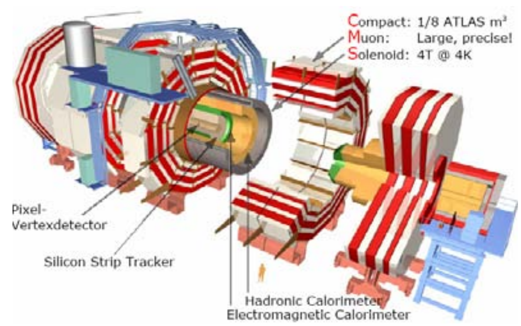


Figure 2: The ‘dense’ CMS

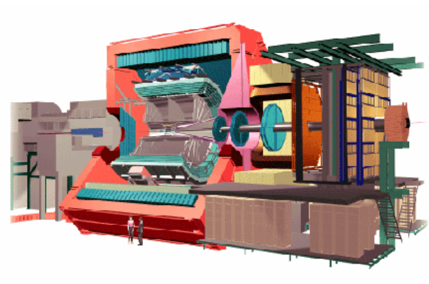


Figure 3: The ‘encapsulated ’ ALICE

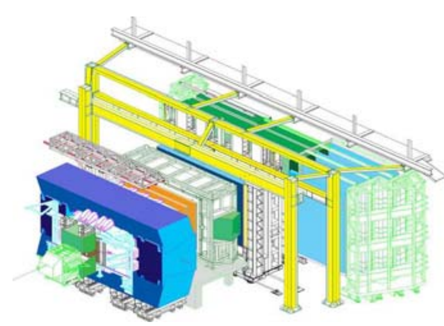


Figure 4: The ‘compressed ’ LHC-b

The general LHC experiments configuration looks like a successive and continuous group of tailored and scaled Russian dolls, each inserted into the immediate larger one, the smallest one being the most critical, the biggest being the only visible and accessible one of the ensemble (see Figure 5).

The multiplicity and the arrangement of the detection layers (i.e. the Russian dolls) have led up to a large variety of supporting structures, either as intermediate sustaining and locating means between two consecutive layers or as support for services (see Figures 6 and 7).

Figure 5: What we see … what we want

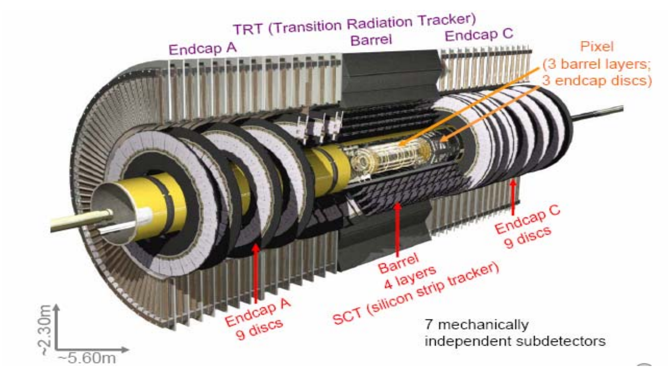


Figure 6: The ATLAS Inner detector

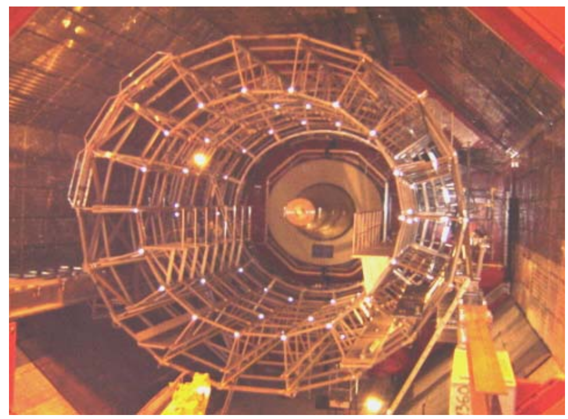


Figure 7: The ALICE TPC support structure

The relative precision of all the tracking systems setting-up, 20 microns, and the muon systems, 50 microns and 150 microns respectively for the Atlas (see Figure 8) and CMS muon chambers (see Figure 9) have justified the implementation of internal alignment devices. Survey has participated to the concept and designs of these specific systems, including prototyping, sensors positioning, calibrations of their supports, the requirements being similar to the determination of a three dimensional network [1].

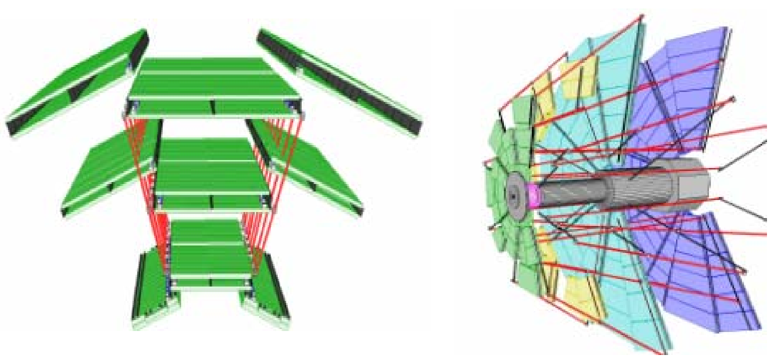


Figure 8: ATLAS barrel and end-cap muons internal alignment

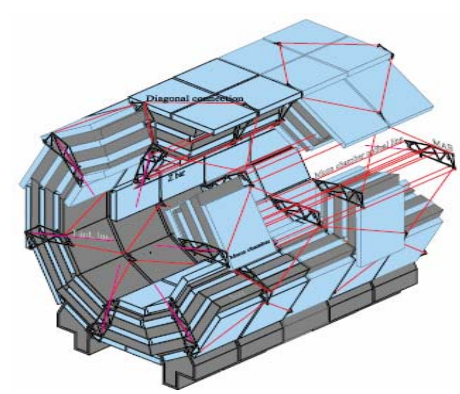


Figure 9: CMS barrel muon internal alignment

3. ADAPTED METHODOLOGY AND FIDUCIALISATION

The complexity, the necessity of a permanent alignment system, the numerous mechanical pieces have forced to organize ad-hoc discussions to identify ‘doll by doll’ the exact needs, the timescales, the necessary survey steps, the consequent working conditions and the places, the definition of the fiducials marks, their relevance, distribution and conservation regarding the required precisions and the object forms and dimensions.

Special attention was given to a standardized type for fiducial marks and the choice was a 8 mm H7 hole that the detector constructors have introduced as a norm in their designs and specifications of fabrication. This facility has enabled to use targets, all with the same shank diameter but of different types and well adapted to classical surveying and close range digital photogrammetry (see Figure 10).

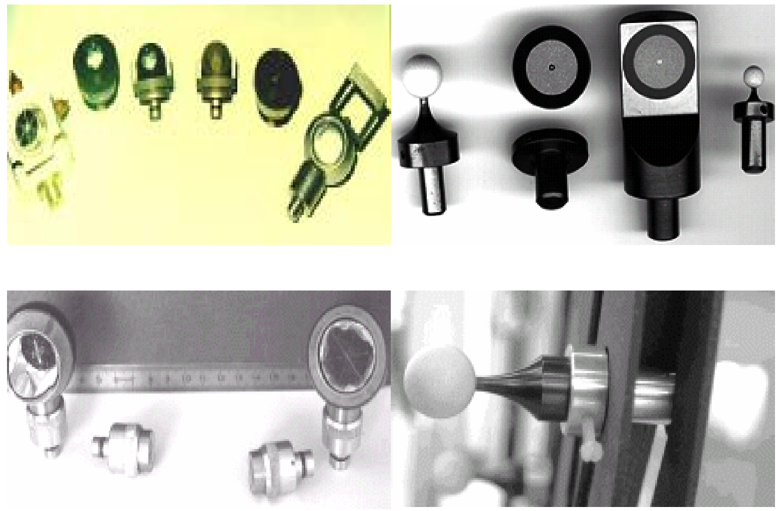


Figure 10: Various types of targets for surveying and photogrammetry

The coordinates of the reference holes are a part of the geometrical definition of each unit to be surveyed so that a full theoretical description of the positions of the detectors can be given from these data.

Nevertheless auxiliary reference marks with specific holders were necessary because of additional services hiding the official hole or for a better determination of the object (see Figure 11).

Specific benches for the calibration of the internal alignment sensing devices and outside reference marks have to be installed. Laser tracker was used for the reference grid determination and digital photogrammetry was used for determining the links between the external marks and the sensor supports (see Figure 12). Perfect mechanical correspondence between the laser tracker prism and the photogrammetry targets has been achieved so that no coordinates corrections have to be applied.

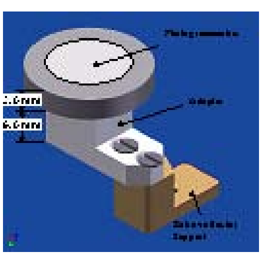


Figure 11: Target holder

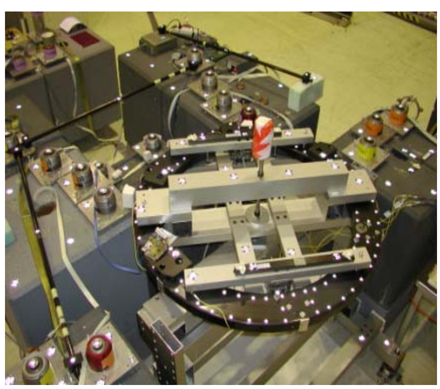


Figure 12: Alignment disk fiducialisation bench

4. GEOMETRICAL VALIDATION

The project leaders requested geometrical validations of critical items in the manufacturer premises very early, versatility, easiness and portability of our instrumentation being good guaranties for these off-CERN controls.

Geometrical assistance for dummy montages and specifically forms with outer and inner envelopes (see Figure 13) were the sharp points to control and photogrammetry proved to be the easiest measuring process since most of the objects dimensions were far out of a CMM machine acceptance (see Figure 14).

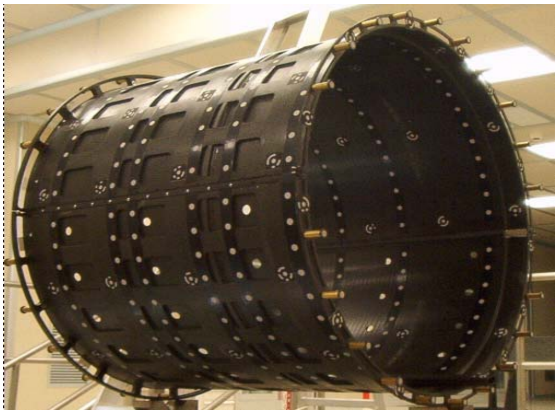


Figure 13: CMS inner tracker envelope – Italy – 2003

Figure 14: CMS half of endplate – Japan – 2000

Moreover and in addition to the geometrical controls, the behavior under load and various positions could be easily processed by photogrammetry as well, especially when connecting adjacent sides not directly accessible (see Figures 15 and 16).

Figure 15: Detail of a CMS ECAL module – Italy – 1997

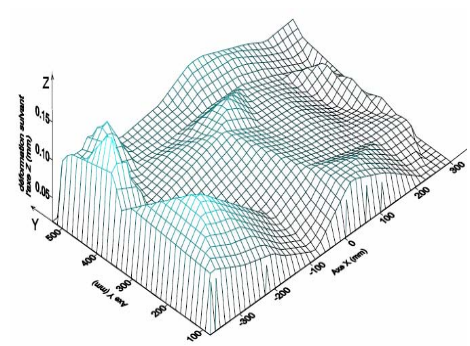


Figure 16: Deformations pattern

5. INTEGRATION AND INSTALLATION IN THE EXPERIMENTAL AREA

Every single installation is a ‘shoehorned’ operation. A primary network, linked to the specific low-betas reference system in the tunnel via the stretched wire positioning system (WPS) and the hydrostatic leveling system (HLS), both accessible inside the experimental area (see Figures 17 and 18), has been established on walls. A second even a third provisional or network on various structures linked to the primary one, permit to introduce the reference geometry very close to the detector. Regular monitoring of the networks are necessary.

Figure 17: WPS and reference network

Figure 18: HLS tube in the experimental area

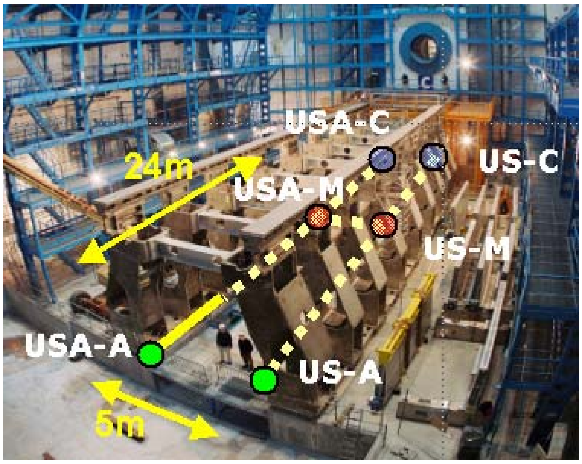


Figure 19: HLS network in the ATLAS bed-plates

Because of the small ranges of vertical adjustment in ATLAS, an additional monitoring HLS network has been implemented in the bed-plates [2] and its overall sensitivity was proved to be within 5 microns (see Figures 19, 20 and 21).

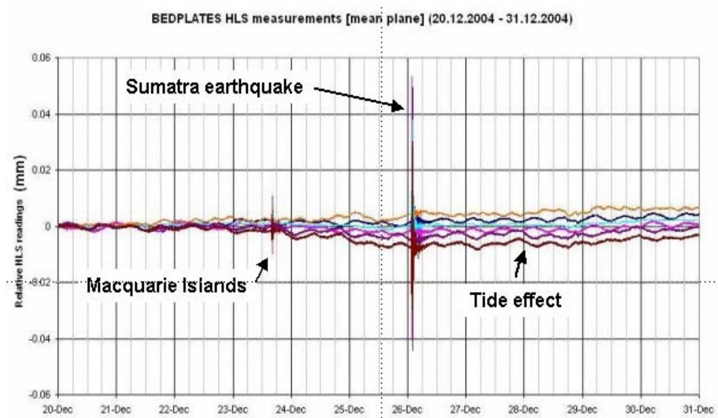


Figure 20: Recording of the ‘tsunami’- December 2004

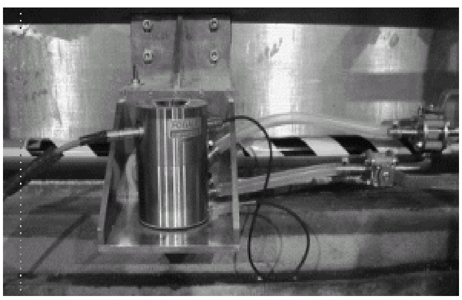


Figure 21: HLS vessel, sensor, water and air tubes

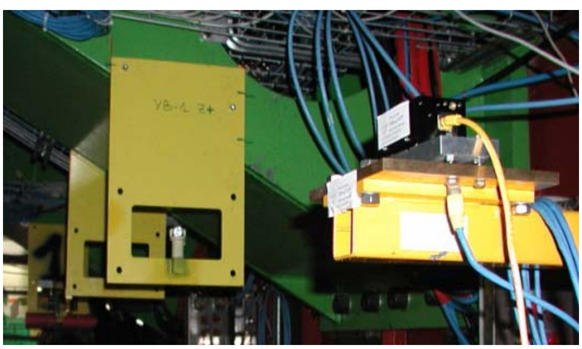


Figure 22: BCAM, prism and survey corridor in CMS

Similar systems and some others as complementary ones will be installed in CMS, specifically to ensure the periodical opening and closings of the magnet. Four lines of BCAM’s (Brandeis Camera Angle Monitoring) [3] are being installed, the positions of the cameras on the central yoke wheel and the prisms on the others wheels and end-caps and being referred to all the detectors (see Figure 22).

Once the initial position of every detector has been determined, the subsequent survey operations will be devoted to the periodical reference networks monitoring. The HLS’s and BCAMS’s as permanent survey ‘eyes’ attached to the supporting structures will provide information as the internal alignment systems and the off-line data will do too.

6. NETWORKS ANALYSIS AND SPECIFIC TECHNICAL FEATURES

Due to the losing of geometrical links because of the detectors installation, the robustness of the primary network in the experimental area degrades continuously and an adaptive Kalman filtering (AKF) process has been tested and will be applied to adjust three-dimensional networks subject to deformation and changing configuration [4].

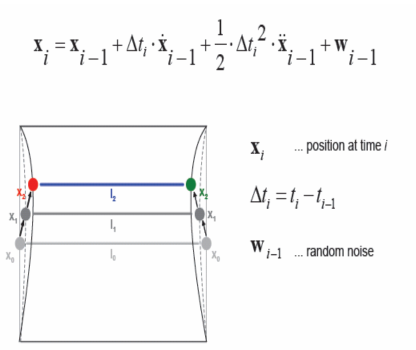


Figure 23: Kalman filter basics

The network is interpreted as a kinematics system (see Figure 23) considering position, velocity and acceleration, and is modeled by an ensemble of a correct system description and a changing network configuration matrices associated to information on the reliability. The adaptive filter is based on the introduction of an innovation matrix representing the mismatch between actual measurements and the best prediction based on the system model and previous measurement data.

Comparisons with results obtained by single-epoch least squares adjustment (LSA), not considering a kinematics setup, show that the performances of the AKF are less affected when some points are poorly determined and a single position becomes more accurate when applying the AKF (see Figures 24 and 25).

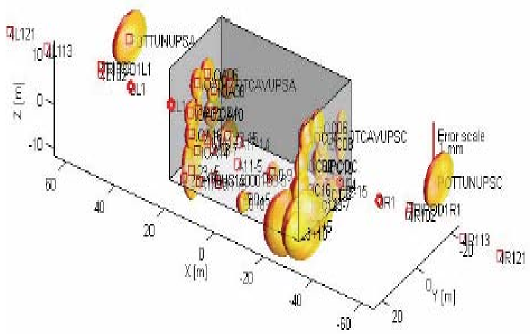


Figure 24: Error ellipsoids after LSA

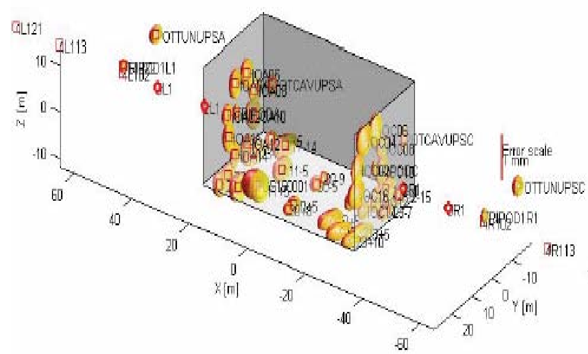


Figure 25: Error ellipsoids after AKF

As specific technical features, the photogrammetry Aicon 3D Studio software enables the determination of the principle distance and the principle point for each image (see Figure 26) and the option FiBun (Finite elements Bundle) models the sensor flatness via a raster-wise grid, the correction being as a plane vector for each grid point and the curvature constraints as pseudo-observations (see Figure 27). The final enhancement of relative precision is 30 % and the option is regularly used for a favorable distribution and a good number of object points [5].

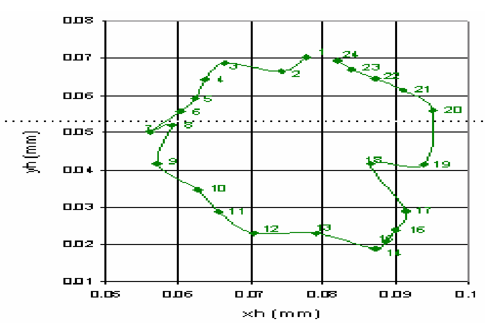


Figure 26: Movement of principle point

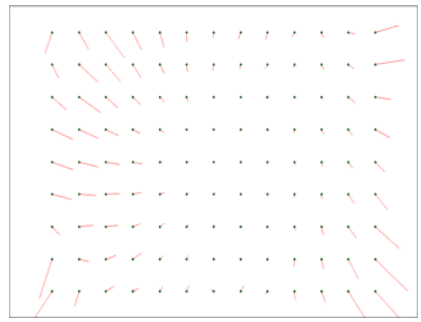


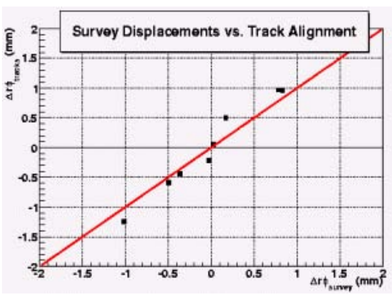
Figure 27: Correction grid -raster width 2.35 mm-maximum 8 microns

7. CONCLUSION

The most exciting features during these last ten years were certainly to learn and to teach.

Learning and understanding the various steps of survey required in and off-site CERN and integrating them in a proper working and resources planning. In addition to the numerous in-site installations areas at CERN, about 80 off site geometrical interventions have been carried out, each of them needing an attentive understanding of the demands and careful attention to the logistics. Some of them are now episodes of the group history (see Figure 28).

Figure 28: An episode of the group history - South Korea 2001



Learning to identify the real responsible persons and adapt the instrumentation, the measuring processes and the controls to the required precision (see Figure 29).

Teaching the responsible persons our methods and the persons in the field our practical needs for safe working conditions. That has implied participations and presentations to the far in advance detectors construction workshops, technical management and integration boards.

Figure 29: Survey versus Alignment (Cosmic rays in CMS)

Learning and teaching to apply new concepts and means of measuring. The HLS's and BCAM's are perfect examples of now well incorporated and complementary to survey instrumentation systems in the experiments.

Acknowledgments

The authors wish to thank their close collaborators. No such a review would have been possible without their motivation over these last 10 years.

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