euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Geometrical measurement concept for the ATLAS New Small Wheel construction

Dirk Mergelkuhl[1], Jean-Christophe Gayde[1], Witold Niewiem[1], Vitali Batusov[2], Ivan Bednyakov[2], Aleksei Kuzkin[2], Andrei Pluzhnikov[2]

[1]*CERN – European Organization for Nuclear Research, Switzerland*
[2]*JINR – Joint Institute of Nuclear Research, Russia*

Dirk.Mergelkuhl@cern.ch

Abstract

ATLAS is one of the detectors of the Large Hadron Collider (LHC) at CERN and in the Long Shutdown 2 (LS2) a major upgrade of the muon forward detector with the construction and installation of the New Small Wheel (NSW) took place. Each of the two NSWs has a diameter of nearly 10 m, weighs approximately 110 t, and includes shielding parts, a mechanical support structure and 16 double wedges that are composed of multiple chambers.

The development of a dedicated surveying strategy has been necessary for the construction of the NSW to fulfil the different demands from the engineering team and the specifications of the physics detector. The concept has been prepared in cooperation with the ATLAS Technical Coordination and Collaboration. The concept includes partly the quality control and the follow-up of the assembly for different items of the NSW. The constructed detector is composed of different mechanical parts on one hand and the chambers that are sensitive parts of the detector to register data for the physics analysis on the other hand. The demanded precisions for the measurements varied between several tens of microns for reference tooling up to several millimetres for envelope issues. Mainly laser trackers have been used for the surveying tasks but in specific situation, other instrumentation has been proposed as close range photogrammetry or laser scanners.

This paper summarizes the surveying concept starting with the preparation work, adjustment of assembly tooling, the fiducialisation of components and follow-up of assembly up to the installation of the NSW in the ATLAS cavern in the second half of 2021.

Keywords: Alignment, Measuring instrument, Positioning

1. Introduction

ATLAS is a physics research experiment [1] for high-energy physics and is installed at CERN in the Large Hadron Collider (LHC) [2]. To exploit fully the detector in the high-luminosity era, an upgrade of the experiment to the higher collision rate is necessary because it creates more data and increases radiation levels. A major part of the preparation of the ATLAS detector for the High Luminosity LHC [3] is the upgrade of the Muon Spectrometer with the New Small Wheels (NSW) [4, 5], see Figure 1. After nearly 10 years of design and construction, the wheels have been lowered in the ATLAS cavern in 2021 and they have been adjusted to their run position beginning of 2022.

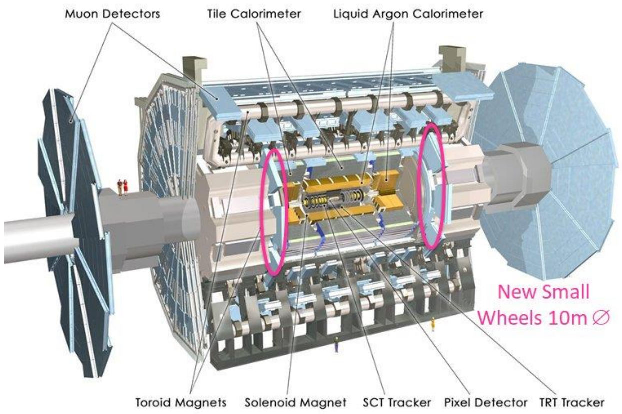

Figure 1. Overview of ATLAS experiment with highlighted NSWs.

Each of the two NSWs weighs around 110 tons and has a diameter of nearly 10 m. The sensitive part of each NSW consists of 160 chambers assembled in 16 sectors called Double Wedges that are installed on each wheel. The chambers are of two different types: four Micromegas (MM) and six small-strip Thin Gap Chambers (sTGC) per double wedge. They have been constructed in nine different countries on four continents and have been shipped to CERN for the double wedge assembly and the installation on the wheels.

Multiple challenges come along with the assembly and are of different kinds. They have been technical for the innovative chambers and their readout. A further tough task has been on the logistic side with the delivery and assembly during the pandemic. In addition, the team has been confronted to geometrical quality control at different levels. In this context, a survey strategy has been developed in the early design phase to ease the follow-up of the assembly of sectors and their installation on the wheel. This strategy takes also into account the different survey demands during the lifetime of the detector. Key interventions are the integration and positioning of the different elements to validate the correct placement and to assure the functioning of the internal optical alignment system used to correct data for the physics analysis. The alignments of the NSWs on the beamline of the LHC at the end of each maintenance period as preparation for the physics data-taking are other critical measurements.

2. Methodology

The CERN Geodetic Metrology group is in charge of the geometrical infrastructure for the detector installation, the large-scale metrology works for the assembly and for the alignment on the beamline. In multiple discussions with the engineers and physicists, the needs for geometrical controls, survey and alignment are precisely defined. For the different stages where survey interventions are needed, a reasonable solution has to be found for all parties and a major step is the integration of the adjustment systems and references in the detector design.

2.1. Survey references on the NSW

For the follow-up of the assembly, survey references have been integrated on all parts of the mechanical structure to control the assembly and to define the coordinate system of each of the pieces. The CERN standard survey reference holes, see Figure 2, have been used as survey references for the mechanical structure. These are 8H7 holes that have been directly integrated in the mechanical design.

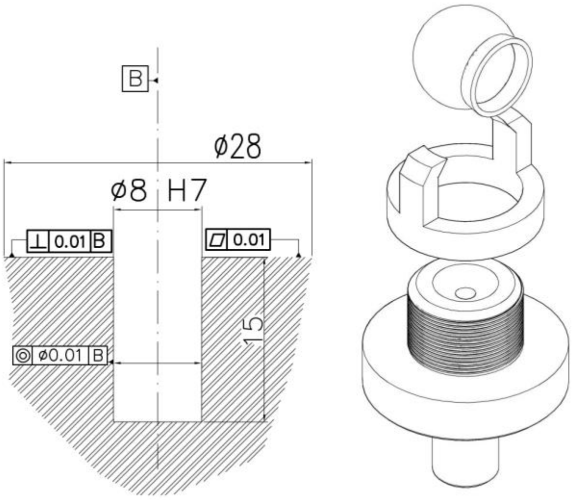

Figure 2. CERN survey reference hole and 0.5-inch survey target support.

This type of reference has appreciated flexibility as the same reference can be used for different types of measurement equipment. In addition, the integration is facilitated as no material is added, which could negatively influence the physics performance or violate the geometrical envelope of the component. The coordinates are given for the centre of the survey target that has an offset of 20.0 mm from the mechanical contact surface. The placement of the references has been chosen to provide sufficient visibility for the succeeding measurements in different configurations. Simultaneously, it should be stable and describe sufficiently well the object geometry. The needs are different for the assembly works in the surface buildings and for the placement with respect to the beamline of the LHC accelerator in the ATLAS cavern. A large number of references gets hidden following the progress of the assembly and a transfer of the geometrical references in time is necessary.

2.2. Instrumentation

The majority of the assembly measurements, in particular, the control and adjustment of assembly tooling, the fiducialisation measurements and the adjustment of sectors have been done by laser tracker AT40x [6]. The typical accuracy that could be reached is between a few tens of microns up to a few hundreds of microns and the accuracy depends mainly on the size of the objects, that have been typically 1-10 m, and on the heating and ventilation in the measurement environment. On rare occasions, close-range photogrammetry or laser scanner measurements have been used if the measurement demand justified their use. The Z+F Imager® 5016 as laser scanner has been employed for envelope measurements. The integration team checks the envelopes, in particular of the installed services, in advance to detect in the 3D mock-up possible conflicts with other parts of the ATLAS detector. The measurement precision for the 3D laser scans is at the level of a few millimetres over the detector size.

2.3. Construction of Double Wedges

Each NSW is composed of eight small and eight large Double Wedges that are mounted in an overlapping configuration as visible in Figure 3. The construction of each Double Wedge is based on the Spacer Frame as the mechanical support structure. The Micromegas chambers and a layer of small-strip Thin Gas Chambers are installed symmetrically. The relative position of the survey references for half a sector are visible in the exploded view of a large Double Wedge Figure 4. The fiducialisation of the spacer frame with its reference pins ensures the correct positioning of the Micromegas chambers. The fiducialisation measurements of the sTGC chambers with respect to the mechanical mounting points have been a condition for the precise relative angular in-plane adjustment of the sTGC wedges to a specification of 0.1 mrad on each of the Double Wedges.

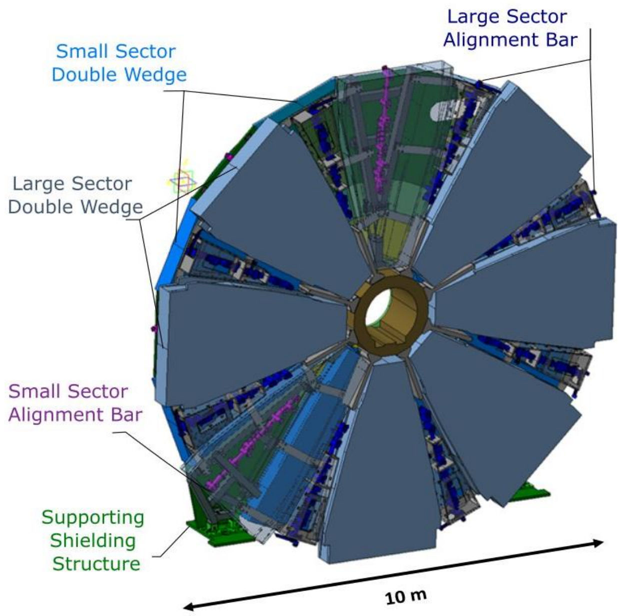

Figure 3. Large sectors (Double Wedge) small sectors (Double Wedge) with their respective Alignment Bars of small sectors and large sectors , shielding supporting structure.

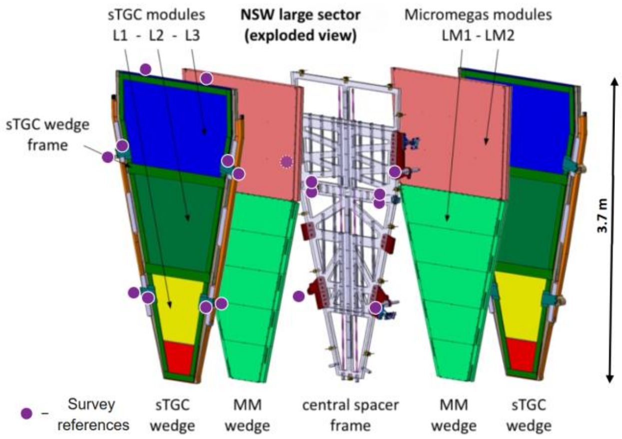

Figure 4. Exploded view of NSW Large sector Double Wedge with the spacer frame, MM chambers and sTGC.

2.4. Measurements for the New Small Wheel project

The different geometrical measurements within the NSW project can be grouped as follows and have been performed in numerous locations at CERN. The typical results are the measured 3D coordinates and the difference to their nominal values. The types of measurements are listed below and their precisions are summarised in Table 1.

a) Measurements for prototypes of the mechanical adjustment systems to confirm their correct functioning and the alignment of chamber prototypes in the test beam areas.
b) Installation and maintenance of the geometrical reference networks in the different assembly areas including the ATLAS cavern for which the coordinate system is based on the geometry of the LHC accelerator.
c) Adjustment or geometrical verification of planarity of the assembly tables for the different chamber types and spacer frames as well as the adjustment of the 2D position of the reference pins and tooling on these tables.
d) Validation of the assembly procedure for chambers and wedges on the very first elements to verify if the specifications of the assembly can be reached.
e) Follow-up of the mechanical assembly of the shielding disk and of the mechanical structures such as spokes, hub and hub-extension to validate their planarity respectively their exact 3D positioning.
f) Fiducialisation measurement of the sTGC wedges and of the spacer frames to ensure the correct positioning of the MM chambers.
g) Deformation measurements in 3D of the completed wheel after disconnection from the wall and after transport to the ATLAS cavern to validate the finite elements mechanical calculations and to confirm that the size of the deformations is acceptable for the operation of the detector.
h) Adjustment of 2 x 8 Double Wedges and Alignment Bars on each of the two NSWs, see Figure 3, and final placement of the wheels in the ATLAS experiment to be within the specification defined by the engineers and physicists for a successful operation.
i) Envelope measurements of the services for integration purpose to avoid any conflicts in later assembly stages and during the final positioning in the ATLAS cavern.

Table 1. Measurement precision (1 sigma) for ATLAS NSW assembly

#	asked (mm)	obtained (mm)	volume (m^3)	technique
a)	0.03-0.10	0.03-0.10	variable	laser tracker, photogrammetry
b)	0.3	0.10	125 x 30 x 25	laser tracker
c)	0.02-0.10	0.01-0.10	variable	laser tracker, photogrammetry
d)	0.05	0.05	10 x 6 x 3	laser tracker
e)	0.30	0.08	20 x 15 x 12	laser tracker
f)	0.10	0.05	12 x 8 x 3	laser tracker
g)	0.20	0.08	20 x 15 x 12	laser tracker, photogrammetry
h)	0.20	0.08	20 x 15 x 12	laser tracker
i)	5.0	3.0	5 x 11 x 11	laser scanner

3. Discussion

It should be noted that the construction of the NSWs is a first and has not been preceded by any full-scale prototype. The assembly procedures and methods had to be adapted to the learning curve. Especially the beginning of the mechanical sector installation suffered from the lack of experience and several works had to be reiterated. Even if a detailed measurement list with the corresponding accuracies has been defined in advance, modifications in the assembly procedures, to cope with unexpected situations, ended up with additional survey tasks. This has been the case due to repair of chambers after their arrival at CERN or because of defects in sectors that have been discovered during commissioning. In this case, it has been necessary to disassemble the sector for modification. The mechanical assembly procedures have been partly too optimistic and the expected mechanical precision could not always be achieved. In several cases, additional survey interventions could solve mechanical problems. The insufficient stability of the assembly tooling used for the chamber integration and the sub-optimal mechanical integration of the survey reference marks on sTGC chambers can be mentioned here as examples of problems overcome thanks to additional measurement intervention.

In several of the work zones, the measurement conditions are far from perfect stabilised laboratory environmental conditions. The temperature gradients caused by the seasonal variations in surface buildings result in significant changes due to the size of the objects. The NSW is composed of different materials like steel and aluminium, thus the thermal expansion of the entire structure is a complex question. Temperature differences in the assembly areas of up to a maximum of 15°C between measurements in winter and summer cause stress in the structure. The changes in size and form are partly visible in the measurement results. The typical temperature changes in between measurements are significantly smaller and reach rarely more than a few degrees Celsius. In this case, the differences are noticeable for the measurement system but not critical for the assembly.

3.1. Deformation measurements of the completed NSW

During the assembly, the mechanical structure has been gradually charged by the installed sectors and services. As the NSW has been bolted to the wall during the assembly for stability and safety reasons, the deformations have been limited to less than 2 mm. Additional significant movements up to 7 mm on the hub extension in the centre of the wheel and up to 15 mm have been visible for points on top of the wheel at the moment of the disconnection from the wall. Despite these movements, the deformations are limited to +/-1 mm at 1 sigma based on the results of the best-fit transformation. The transport and lowering in the cavern has caused further deformation i.e. of +/- 5 mm at the feet level due to the different load distribution. Even if the mechanical engineers had calculated the expected deformation in advance, it has been neglected during the assembly on the surface. The decision has been justified by the limited deformation in the plane of the sectors and that the demanded quality of the sector positioning has been +/-2 mm to ensure that the sensors of the optical alignment system of the muon spectrometer are within its measurement range.

3.2. Alignment of the NSWs on the nominal beamline

The ATLAS cavern has a size of 53 m x 30 m x 35 m and is located nearly 100 m underground. The geometrical network used for the survey and alignment of experiment parts in the cavern is referenced with respect to the geometry of the LHC accelerator in the tunnel. Due to the installed shielding and detectors, the link of the accelerator tunnel and the experimental cavern is guaranteed by the survey galleries (UPS14/UPS16), see Figure 5. A dedicated monitoring system measures the relative alignment of the last magnets located in the accelerator tunnel at each side of the experiment and provides, via a dedicated transfer alignment system, references for the geometrical network in the ATLAS experimental cavern [7]. The frequency of the network measurements is reduced to once a year due to its complexity as well as the required time and effort. Nevertheless, a regular update is mandatory as the civil engineering structures like the tunnel and cavern are constantly exposed to long-term deformations at a sub-millimetre level per year.

Due to the dimension of the assembly, practical issues became challenging such as the access to the geometrical reference points and their visibility from stable stations of the laser tracker. The achieved measurement precision of the final alignment of the NSWs with respect to the LHC nominal beamline is on the sub-millimetre level despite the challenging conditions.

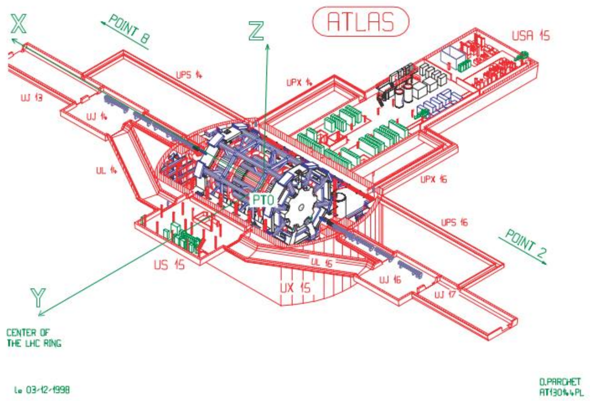

Figure 5. Layout of ATLAS cavern and LHC accelerator.

3.3. Optical Alignment System of the NSW

The alignment precision of the different parts of the Muon Spectrometer is essential for the detection and analysis of the muon particle tracks in the detector [8]. Due to temperature changes and long-term deformation of the cavern, the different parts of the spectrometer composed of various materials move well above the 50 microns. This is the precision demanded by the physicists to exploit fully the capacities of the NSW chambers. In addition, the strong magnetic field of the Toroid magnets in run configuration creates forces reaching over 12000 kN [9] and deforms the mechanical structure. It provokes changes in the relative position of the different parts of the muon spectrometer. To cope with these influences and to provide continuously valid data during the operation of the detector, an internal optical alignment system is integrated to monitor these movements and to recalculate the relative 3D position of all chambers [10]. The strict geometrical follow-up of the sector assembly and installation has been necessary to ensure the correct functioning of the fragile high precision chambers and to keep all sensors of the optical alignment system within their measurement range. The backbones of the system are the calibrated Alignment Bars as shown in Figure 3. They are equipped with sensors to allow the optical connection between the bars and to measure the chamber positions relative to the bars. The bars themselves are equipped with internal optical and thermal sensors such that the shape of the bar and the position of all sensors on the bar are known with adequate accuracy [11]. In combination with measurements taken by the muon spectrometer based on particle tracks from collisions, with the magnet system switched off, the optical alignment system can provide corrections for the physics analysis [12].

4. Summary

The assembly of the NSW and the associated survey works took around five years after several years of preparatory discussions with the different teams spread over several countries around the world. A large variety of measurements and more than 250 survey interventions have been necessary for the completion of the NSWs. Each of the measurements of the more then 1500 reference points is documented with a survey report in CERN's Engineering Data Management Service. The adapted instrumentation met the demands specified by mechanical engineers and physicists. A few values of the specifications had to be modified to fit the geometrical quality of the wedge assembly and the environmental condition of the measurements. The measured deformations globally fitted well to the calculation of the mechanical engineers. Due to different delays and unexpected situations that generated a large number of unplanned survey works, the workload has been very intense especially in the last two years with a survey team working on a daily basis for the project. With the alignment of the NSWs to their physics run position beginning of 2022, a further milestone of the project has been achieved and the physics data taking will start later this year. The optical alignment system now takes over the monitoring of the position of the chambers in the internal geometry of the NSWs. In parallel, it measures the position of the NSWs in the ATLAS muon spectrometer and any deformation during the operation of the detector. The geodetic metrology is still asked at the end of each maintenance period to adjust the wheels with respect to the nominal beamline.

References

[1] Aad, G. et al., 2008, The ATLAS Experiment at the CERN Large Hadron Collider, *Journal of Instrumentation*, Volume **3** S08003

[2] Evans, L. Bryant, P. , 2008, LHC Machine, Journal of Instrumentation, Volume **3** S08001

[3] Rossi, L., Brüning, O., 2015, Introduction to the HL-LHC Project, Geneva, Switzerland

[4] Lefebvre, B., 2018, ATLAS Collaboration, "Muon Spectrometer Phase-I Upgrade for the ATLAS Experiment: the New Small Wheel project", Conference on the Intersections of Particle and Nuclear Physics, Palm Springs, USA

[5] Kawamoto, T. et al., 2013, ATLAS collaboration, New Small Wheel Technical Design Report, CERN-LHCC-2013-006, Geneva

[6] Leica Geosystems. 2010, Leica Absolute Tracker AT401 White Paper, Unterentfelden, Switzerland

[7] Coosemans, W..Mainaud Durand, H.,Marin, A., Quesnel, J-P., 2002, The alignment of the LHC low beta triplets : instrumentation and methods, Proceeding of the 7th International Workshop on Accelerator Alignment, Spring 8, Japan

[8] Aefsky, S. et al., 2008, The Optical Alignment System of the ATLAS Muon Spectrometer Endcaps, *Journal of Instrumentation*, Volume **3** P11005

[9] Badiou, J. P. et al., 1997, ATLAS barrel toroid: Technical Design Report, Geneva, Switzerland

[10] Dushkin, A., 2015, NSW Alignment Layout Alignment Bars and BCAMs Design, Indico, USA

[11] Amelung, C. et al., 2005, Reference bars for the alignment of the ATLAS muon spectrometer, *Nuclear Instruments and Methods in Physics Research A* , volume **555** 36-47

[12] Amelung, C., Bauer, F., Giraud, P-F., 2020, Performance of the muon spectrometer alignment in 2017 and 2018 data, ATL-COM-MUON-2020-058, Geneva, Switzerland