COMBINED LEVELLING SYSTEMS FOR THE VERTICAL MONITORING OF A LARGE PHYSICS EXPERIMENT

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Abstract: The European Organization for Nuclear Research (CERN) is building the largest particle accelerator in the world to find out about the fundamental elements. A 27 km long accelerator ring and four experiments will be part of the new LHC[1] for which the end of installation is planned on 2007. One of these experiments, named ATLAS[2], is installed in a new huge cavern located 90 m deep below ground level, with a height of 35 m and a surface of 53 m x 35 m. One of the main problems that this experiment is facing is the ability to inspect and react to any movement in the floor level, relative to the LHC beam which is 12m higher. In addition, the assembly of the ATLAS detector is done step by step and therefore the load to the supports and to the floor changes subsequently. In order to monitor continuously at better than 50 μm accuracy the relative movements of the bedplates which support the detector, a Hydrostatic Levelling System (HLS) composed of six sensors has been installed on them. Then, at regular intervals, the position of this system is measured relatively to the LHC beam line, using vertical distance measurements with optical levelling. This paper will describe the HLS system installed as well as the methods and instrumentation used for the positioning with respect to the LHC beam line, concluding with measurements and results over more than two years.

1. Introduction

The LHC is the new 27 km long particle accelerator project at CERN in Geneva, Switzerland which will come in operation in 2007.

Large physics detectors (ALICE[3], ATLAS, CMS[4], LHCb[5]) are being installed in huge caverns at the four interaction points. These detectors aim to study very high energy collisions of proton beams with the best precision possible and are being built from many separate pieces of structure, from central tracking units, to end caps closing the system.

The performance of these physics experiments depends on the intrinsic precision of sub-detectors and of their positioning on the Nominal Beam Line of the LHC machine.

One of the main problems that the ATLAS experiment is facing is the ability to inspect and to anticipate any movement in the floor level, relative to the LHC beam which is 12 m higher.

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[1] LHC **L**arge **H**adron **C**ollider
[2] ATLAS **A** **T**oroidal **L**HC **A**pparatu**S**
[3] ALICE **A** **L**arge **I**on **C**ollider **E**xperiment
[4] CMS **C**ompact **M**uon **S**olenoid
[5] LHCb **L**arge **H**adron **C**ollider **b**eauty experiment

The next chapters describe the ATLAS experiment, the Hydrostatic Levelling System (HLS), and methods which have been implemented to monitor the floor and supporting structure stability.

2. The ATLAS experiment monitoring system

The ATLAS experiment is being built step by step in a cavern of 53 m long, 35 m large, and 35 m high. It is made of physics detectors and of a magnet system assembled in a typical onion layout. The overall dimensions of the experiment are 25 m long, 20 m diameter and the total weight is near 7000 t.

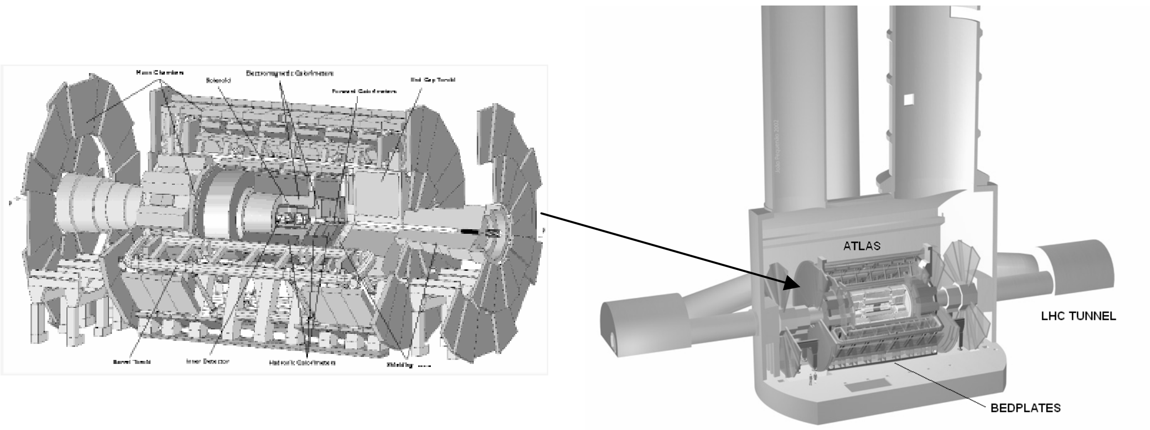

Figure 1: The ATLAS experiment

Except for the forward big wheels muon detectors fixed to the cavern walls ATLAS is supported by nine pairs of feet standing on 20 m long big stainless steel rails – the bedplates - fixed to the 5 m thick concrete floor.

According to the civil engineering simulations a long term 1mm per year heave of the floor is predicted for several years after the excavation phase due to hydrostatic pressure. In addition a short term settlement of 4 mm due to the weight of the experiment is expected.

Due to the mechanical conception of the detector, the adjustment will be very difficult. The aim of the floor stability monitoring is to confirm and refine these predictions. This allows anticipating the experiment movements during the assembly phase in order to have it aligned on the LHC beam line with the nominal luminosity on 2010 as requested by the physics collaboration.

To monitor the ATLAS movements with respect to the LHC beam line a combined method has been implemented. A HLS system has been installed on the ATLAS bedplates feet used as a remote, long term monitoring tool to measure the deformations during the construction of the detector and to provide real-time observations during the operation of the experiment. The stability of the cavern floor with respect to the LHC machine geometry is measured using optical precision levelling performed at regular intervals. The HLS observations and the optical levelling measurements can be analysed together in the same geodetic network.

3. Bedplates HLS – Principle and Examples

3.1. Hydrostatic Levelling System

The HLS sensors provide vertical distances with respect to the equipotential water surface of the hydraulic network, which is the reference height. This system works according to the principle of the communicating vessels.

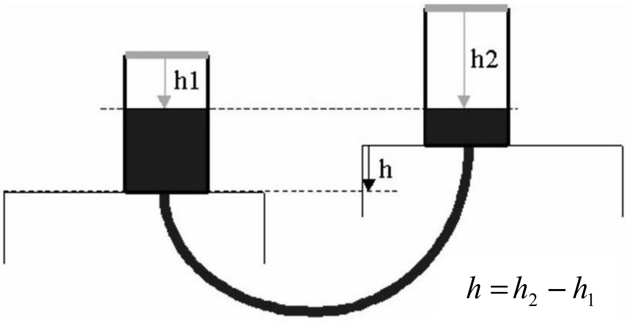

Figure 2: principle of communicating vessels

The water network is composed of vessels connected to each other by pipes, partially filled with water, allowing water and air to circulate freely. In order to eliminate the effects of the differential variations of atmospheric pressure, the whole pipe work system is only open to atmosphere at one point. To avoid salt deposition and the growth of flora and micro fauna, demineralised water is used with a biocide additive.

Sensors – associated to each vessel – determine the distance to the surface of the liquid. Several technologies are possible as for example optical, capacitive or ultrasonic measurements. [1]

At CERN, sensors based on capacitive technology are used. The measurements are based on the following principle: the sensor electrode and the target (in our case the water surface) create a capacitor. Measuring the capacitance C and knowing the permittivity and the electrode size, one can deduce the distance d from equitation (1).

$$C = \frac{\varepsilon_o \varepsilon_r S}{d} \tag{1}$$

3.2. Bedplates HLS system

The installed HLS system was originally composed of six individual sensors, three on each side of the bedplates facing each other and linked as an H-shaped hydraulic network (see figure 3). Since November 2005, one additional sensor (REF) placed in a more stable zone of the cavern allows in real-time the determination of the bedplates deformation and their movement with respect to the floor. This zone is not affected by the additional load which is installed in the cavern.

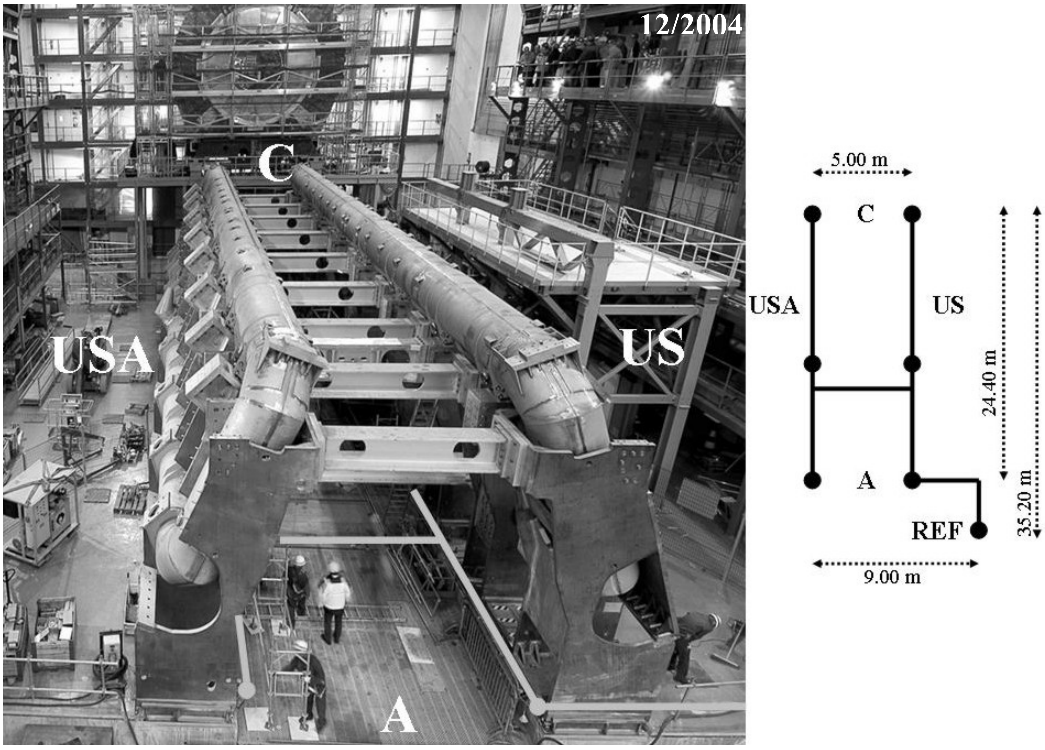

Figure 3: configuration of the bedplates HLS system

The sensors have a range of 5 mm with sub-micrometric resolution. Electronic components have been separated from the sensor due to the expected magnetic field of 800 Gauss and a radiation level of 100 Gy in the bedplates region and have been transferred to a remote electronics which can be located as far as 30 m away from the sensor itself. The electronics is expected to operate in an environment with a total radiation dose of up to 400 Gy and in a magnetic field of 300 Gauss [2]. As sensor, cable and remote electronic is one unit, they have been calibrated by the manufacturer and validated at reception.

A survey target ball interface on top of each sensor allows a three-dimensional link to classic geodetic networks as used for the floor stability monitoring. The height measurement of the sensor can therefore directly be linked via mechanical constants to other networks.

The free water surface network is made of a main hydraulic tube with an inner diameter of 50 mm, half filled with water and linked by separate water and air pipes to the sensor's vessel, named secondary hydraulic network. Each secondary hydraulic network is isolated from the main network by valves, which can be closed during the replacement of a sensor or the maintenance of the network.

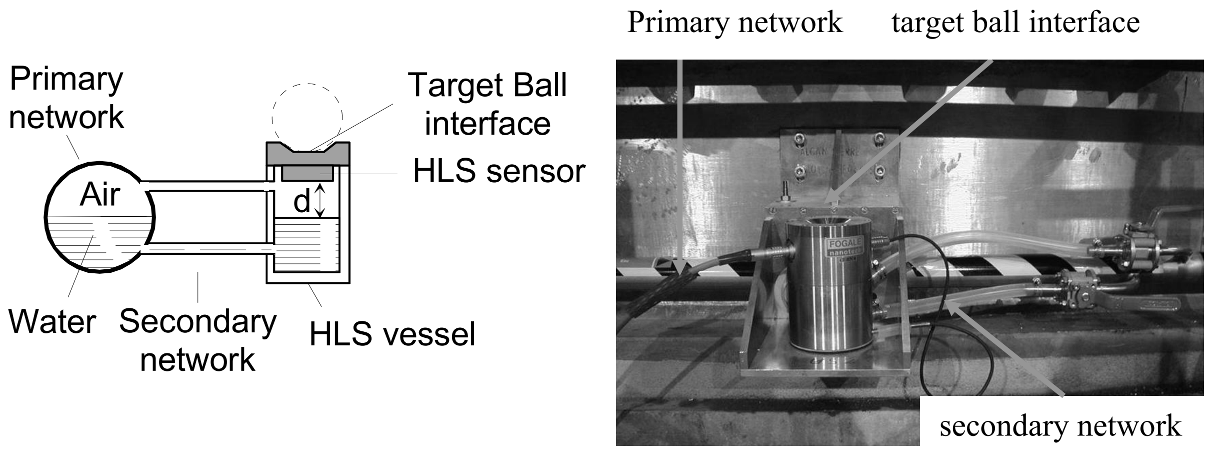

Figure 4: layout of the HLS

The sensors and their remote electronics are linked to a computer for data acquisition. Signals from the sensor's remote electronics are linked to an A/D converter, allowing the acquisition of data via RS485. The typical data acquisition interval is one minute.

3.3. HLS data and analysis

In the context of the installation phase of the ATLAS experiment, two main demands are defined:

- Online monitoring and visualisation of sensors readings
- Long-term deformation monitoring

As the system is operated in a local mode with the data acquisition on a computer, off-the-shelf software as provided by the manufacturer of the sensors can be used. For data acquisition and analysis during machine operation, a centrally hosted data base system will be implemented and analysis tools will be integrated into the central control system of the LHC.

The four main functions which can be fulfilled with the DAQ software are:

- Online visualization of the sensor's data as needed for installation tasks
- Internal correction of the measurements with temperature induced effects prior to storing in a ASCII file
- Corrected values (mm, °C) as well as uncorrected values (V) are stored in the file to allow further modelling
- Flexibility in the data acquisition intervals

The degree of analysis of the acquired data depends on the phenomena to be seen. Three types of treatments used for the analysis can be distinguished:

- **Screening** (see figure 5): in order to facilitate the visualization of the readings, a reference time t_0 is chosen. The readings of each sensor are calculated with respect to their own reference reading at t_0. This "rough" treatment allows seeing how the sensors behave in time. This treatment does not prevent from seeing the evaporation of water, which may not be considered as a drift of the sensors (see slight slope of the curves in figure 5).

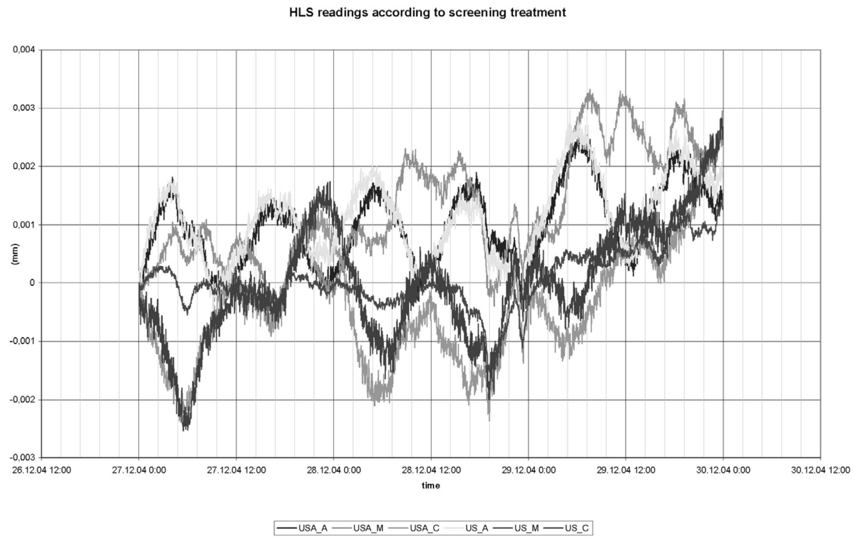

Figure 5: Screening treatment

- **Height difference** (see figure 6): Due to the principle of communicating vessels the height differences Δh_i between all sensors are continuously determined. This calculation is based on the choice of one of the sensors as reference, assumed to be the most stable and on the calculation of the height differences between this sensor and the others.

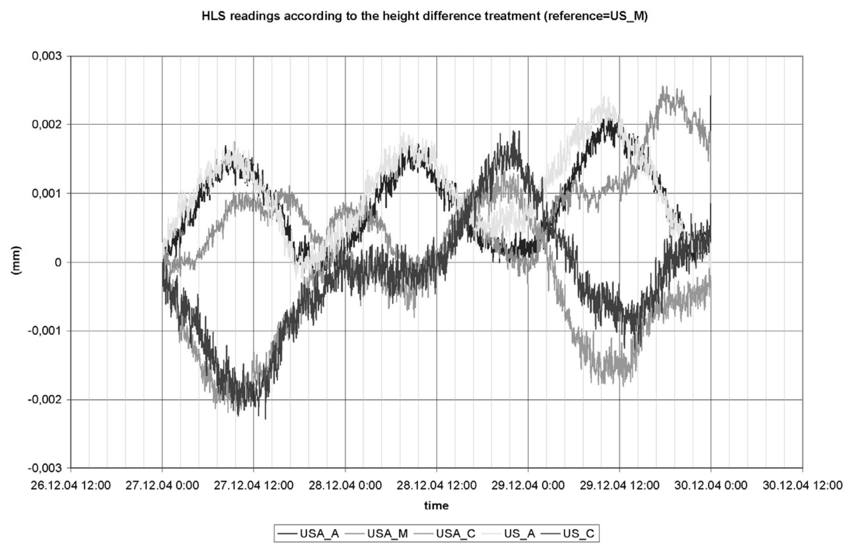

Figure 6: Height difference treatment

- **Mean plane** (see figure 7): The objective of this treatment is to calculate at each time, the mean plane of water, using the least squares compensation method, and to calculate the displacement of each sensor with respect to this plane. All problems linked to the water surface like e.g. the change of the water surface level due to external influences, evaporation or tidal effects can be hidden with this method. It is used to study long terms effects in a place with surrounding perturbations, but it does not reflect the real changes in height.

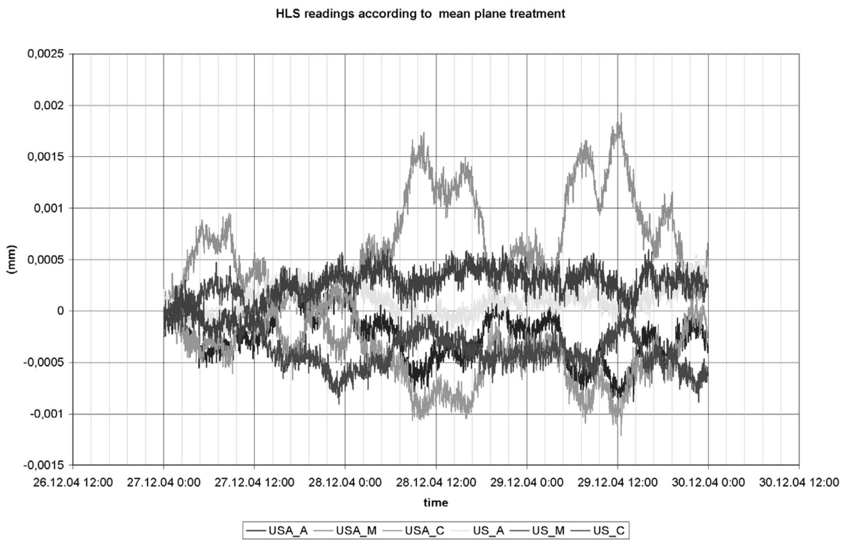

Figure 7: Mean plane treatment

The hydrostatic network can not be completely protected from influences of installation activities around. This leads to peak-to-peak waves in the system of several millimetres. During the installation of the detector, the HLS system has preferably to be used for short term observations as too many perturbations do not allow undisturbed measurements in the micrometre range. The full performance can only be maintained during periods of some days as for example during the installation of large elements as therefore the experimental area is partially evacuated. Long term observations over several weeks will be possible on a reliable base, once the machine will be in operation and installation activities have finished.

3.4. Example I: Barrel Toroid

The ATLAS experiment barrel toroid magnetic system is made of eight superconductive coils of approximately 100t each. They are as long as the experiment itself. As the load is brought into the cavern eccentric to the main detector axis, a roll effect of the bedplates was likely to occur.

Figure 8 shows the readings of the HLS sensors during the installation step of one coil. It shows a rotation of approximately 8 µm in the middle of the bedplates when the magnet is put into its final position (readings of the sensors USA_M and US_M which are symmetrical around the 0 axis of the curve) and a slight settlement on the A side. Small perturbations in the course of the measurement are due to positioning manoeuvres of the magnet, before fixing it. The first peak is caused by putting down the magnet on the central platform on the feet before tilting into its nominal position.

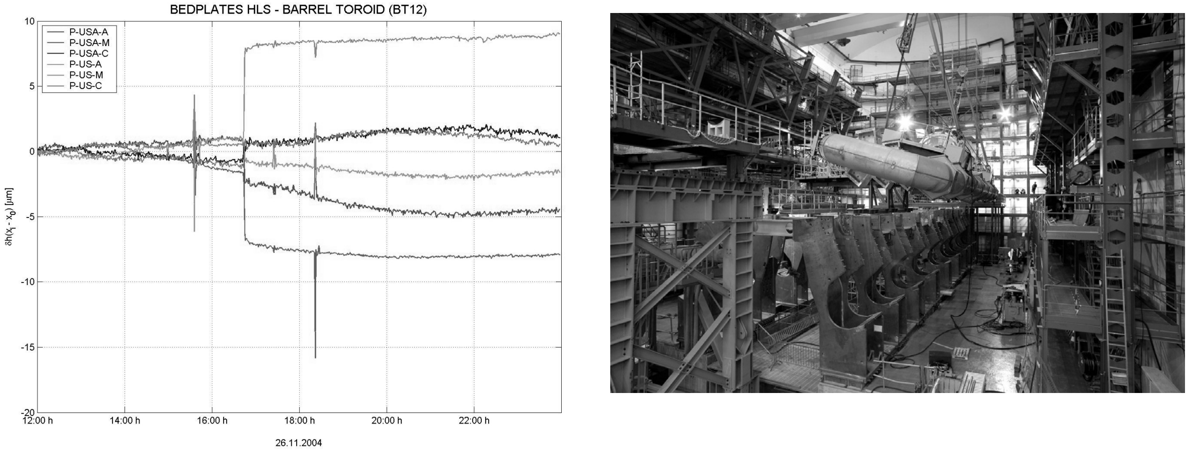

Figure 8: Barrel toroid

3.5. Example II: Tile Calorimeter

On November 2005 after the barrel toroid magnet was completed, the ATLAS Calorimeter Barrel detector, with the dimensions of 8 m in diameter and 8 m long, was brought into its final position, see figure 9. As the module has with 1.600 tons about 20 percent of the total weight of the experiment, significant deformations in the order of one millimetre were feared to occur.

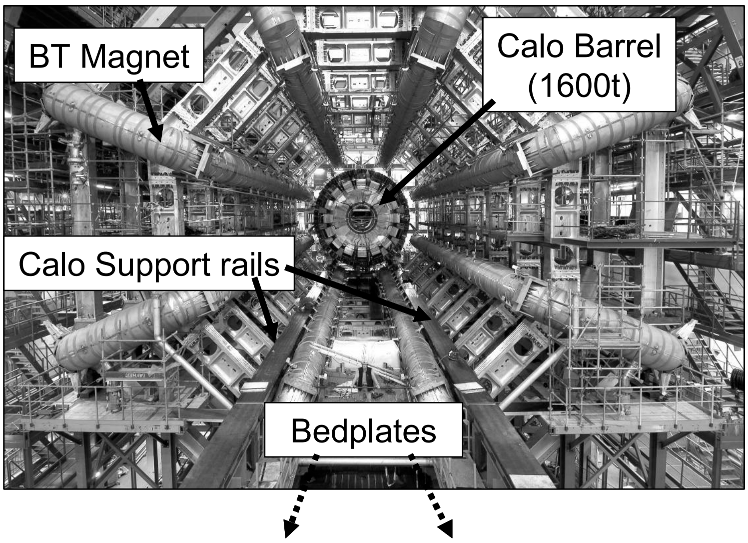

Figure 9: Calorimeter Barrel before insertion

It was asked for a measurement concept to monitor online the relative deformation at two different levels of the experiment – the rail on which the load was transported and the bedplates of the detector – in order to measure the deformation of the detector's mechanical support structure itself and of the ground where it is based on.

The HLS system was upgraded with one additional sensor in order to have a reference sensor in a zone which was likely not to be affected by the installation.

Figure 10 shows the relative deformation of the ATLAS bedplates during the installation of the tile calorimeter.

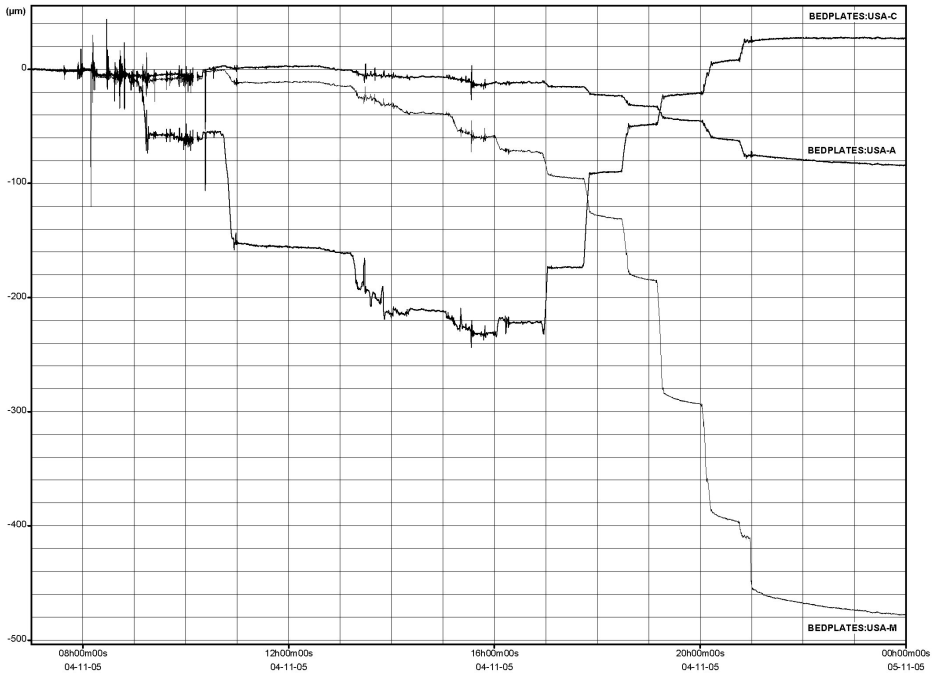

Figure 10: HLS monitoring during Calorimeter installation

A staircase-like effect can be seen for the three different sections of the bedplates as the load is transported in steps of one to two meters to the centre of the experiment (M position) starting from an outside position on the C side; see positions indicated in figure 13. The applied load causes a temporary deformation of 200 µm which is reduced to its original value after the transition of the load. The middle section is affected by 500 µm once the tile is in place.

3.6. Example III: Earthquakes

Sometimes, the HLS sensors monitor phenomena which were not expected. As shown in figure 11, the readings recorded by the sensors at the end of the year 2004 revealed two perturbations: one on December 23 starting at 15:45 UTC and the other on December 26 at 01:23 UTC. Seeing these unusual and punctual readings on December 26, we immediately wondered whether they were connected with the earthquake off the Indonesian coast. This hypothesis was confirmed by an expert from the Laboratory for studies on Geological Risks in Geneva.

The epicentre of the Sumatra quake was 9.700 km from CERN. The primary P waves, which are the fastest waves propagating at a speed of 6 to 8 km/s, took about 20 minutes to reach

CERN, which is consistent with the first perturbations recorded by the sensors at 1:23 UTC. The earthquake occurred at 0:58 UTC [3].

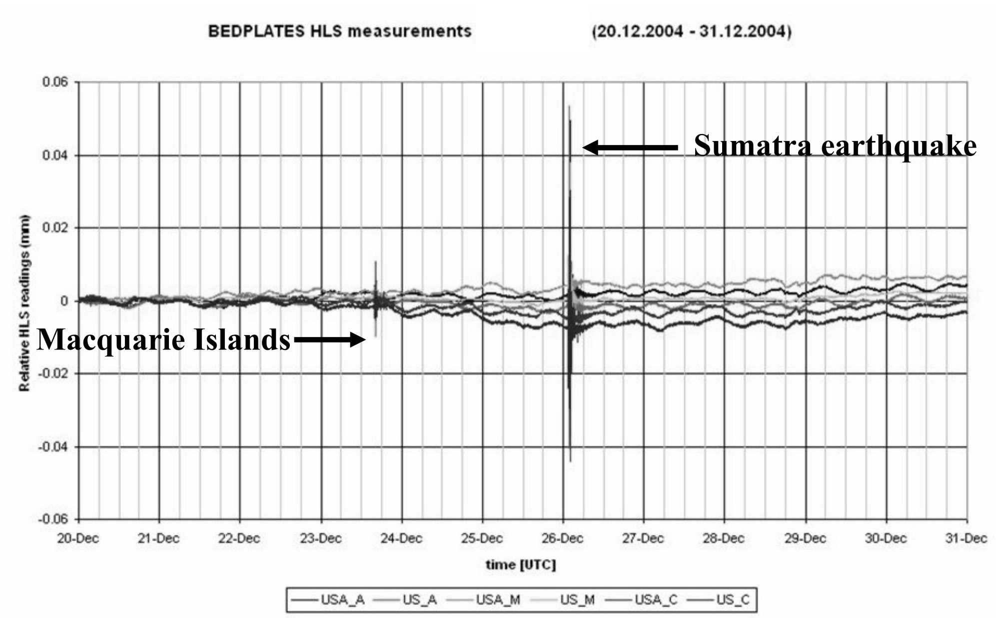

Figure 11: Tsunami earthquakes (Dec. 26, 2004)

The first perturbation, which occurred at 15:45 UTC on December 23, was also due to an earthquake, at 14:59 UTC near the Macquarie islands located between Australia and Antarctica, which measured 8.1 on the Richter scale.

The waves detected by the HLS system do not reflect the real displacement of the system. They show in fact the amplifying effect of the main hydraulic network as the water can easily loop up waves.

3.7. Combined levelling systems

The HLS measurements are an excellent tool to detect relative movements in the ATLAS bedplates. Even with the perturbing influences of installation activities in the cavern, the demanded 50 μm accuracy can be obtained. The combination of continuous measurements with the HLS system and discontinuous epoch-wise levelling measurements allows the integration of the relative HLS measurements into an absolute coordinate frame, e.g. with respect to the machine system.

Note that comparisons of the relative levelling between the HLS target ball interfaces obtained by optical and hydrostatic levelling are similar within 0.1 mm (comparison limited by the optical levelling precision).

The next chapter shows the methods used for the epoch-wise levelling and the positioning with respect to the LHC beam.

4. Cavern floor stability

4.1. Layout

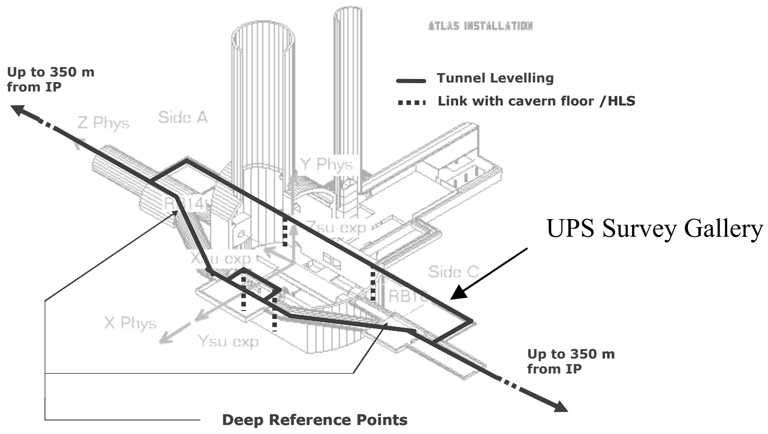

Figure 12: Optical Levelling path

The base points of the optical precise levelling – carried out using a precise Leica NA2 level and classical invar staff - are 2 deep references placed in the tunnel on both sides of the experiment and which are independent of the tunnel floor, see figure 12. The deep references consist in 16 m long invar bars fixed to the bed rock at their bottom part and sliding in a tube. A reference socket is placed at the top of each bar at the tunnel floor level in order to allow the measurement.

In order to inspect the tunnel stability around the cavern zone – some civil engineering works were also performed in this area – the levelling includes the tunnel reference points on a distance of 350 m on each side. These points are placed in the tunnel floor every approximately 40 m and they are used for the machine magnets installation.

The measurements are transferred to the cavern through two UPS survey galleries on one side and through communication doors on the other one. Another set of 20 reference points are distributed on the cavern floor along profiles near the experiment and also close to the walls. See figure 13.

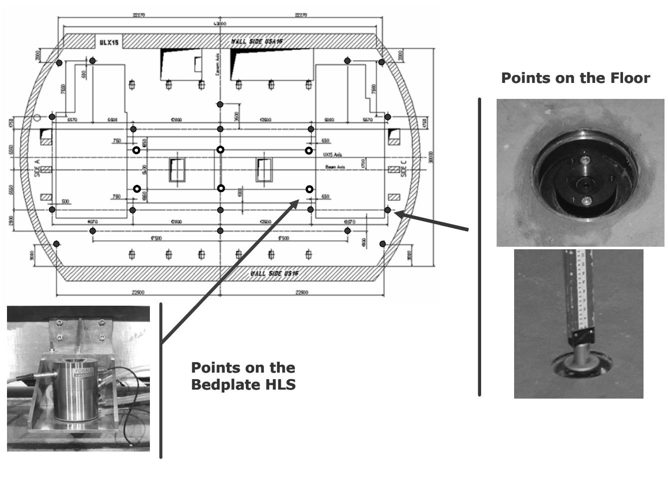

Figure 13: Reference points on the floor

These points and the HLS Bedplate sensors are linked to the tunnel geometry via 4 vertical paths in the corners of the cavern, see figure 12.

Special brackets are installed at top (tunnel level) and bottom (close to cavern floor level) of these paths. Vertical distances are measured between them - using a Leica TC2002 calibrated instrument - with a precision better than 0.2 mm. This measurement is made in a relative way in order to avoid systematic errors due to instrumental constant influence. These brackets are then included in the tunnel and cavern floor optical levelling.

According to the configuration and to the redundancy of the measurements, the level of the points after least square calculation is obtained with an accuracy of 0.2 mm (1 sigma) with respect to the tunnel geometry datum. Then the precision of the difference of level between two epochs is of 0.3 mm (1 sigma).

In small area such as the bedplates region the difference of level between points measured in the same epoch is 0.1 mm (1 sigma).

4.2. Stability measurements and results

From August 2003, nine stability measurements have been performed regularly and when special events occur such as the 1600 t Calorimeter Barrel installation.

From August 2003 to March 2005, a heave of the cavern floor was seen. The movement is not equally distributed on the floor surface, see figure 14. An average movement of +1.0 mm was measured on the central zone, near the experiment feet with a maximum at +1.2 mm. The outer points of the cavern floor moved up of +0.5 mm.

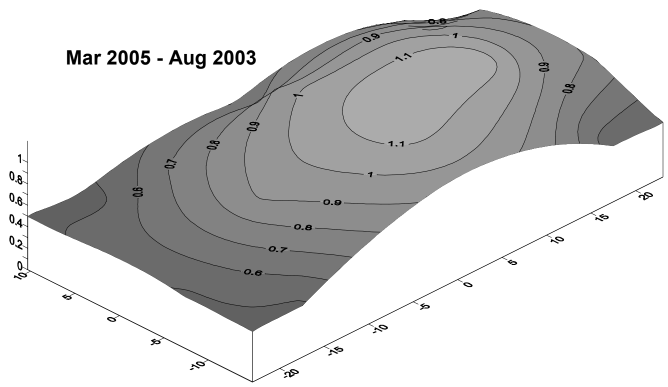

Figure 15: 3D view of the Cavern floor deformation from August 2003 to March 2005

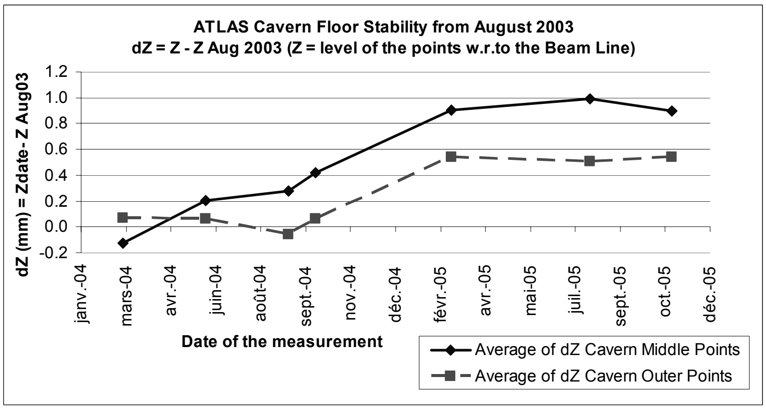

Figure 16: Cavern floor deformation from August 2003 to March 2005

From March 2005, the floor seams more stable, see figure 16. This corresponds to a period of heavy pieces installation, mainly the Barrel Toroid Magnet assembly and the Calorimeter Barrel insertion. During this period, the weight increased up to 50% of the total load.

5. Conclusion

The combined survey of the ATLAS stability using optical levelling and HLS Bedplate system is of importance in the help to the physics responsible persons in charge of the detector assembly. The obtained values are included in the detector alignment decisional process together with some other parameters such as the supporting structures behaviour and the sub-detectors internal deformations due to the working temperature (some detectors are working in cryogenic conditions).

The HLS system, designed and installed to follow the relative movements of the bedplates at better than 50 μm accuracy, has proved that it can monitor expected or unexpected deformations in the micrometer range, which is very promising for long term observations once the machine will be in operation.

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