

# Challenges for Mobile Hydrostatic Levelling Systems applied in accelerator environments

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## Abstract

The research for automated measurement solutions for the Large Hadron Collider (LHC) is a key point for future developments and of extreme importance for even bigger accelerators like the Future Circular Collider (FCC) where manual measurements are almost excluded due to the very large scale of the future machine. The developments for transversal measurements using close-range photogrammetry are making good progress and first results should be available from the High-Luminosity IT-String test in 2024 where a High Luminosity-LHC Triplet section will be fully tested on the surface. The R&D for the vertical measurements is still at the beginning and will combine close-range photogrammetry with mobile Hydrostatic Levelling System (mHLS) measurements. HLS are commonly used in the field of high precision measurements or long-term monitoring of vertical displacements. The basic principle is quite robust and directly linked to an equipotential surface. There are several working principles available ranging from tactile, capacitive, or optical sensors to ultrasonic sensors in different configurations. For a mobile application, a particularly suitable system is the ultrasonic system with the transducer submerged in the water. A small number of critical aspects need to be solved to be usable in the Large Hadron Collider environment. The tunnel slope and system stabilization, the temperature gradient and atmospheric pressure differences due to tunnel ventilation needed to be considered in the design of the mobile system. The final goal is to make the system available for a use on a future Survey Train in the LHC. This paper describes the principle of the system along with some specific mitigation measures and validations for the mobile application.

## MOTIVATION

Two main aspects are driving the developments towards a mobile HLS solution. The first one is the level of precision and the error propagation which does not scale linearly with the distance as optical levelling or indirect levelling does. The second aspect is the automation potential of those measurements. Those systems are very well known in permanent installations and are quite robust and reliable. However a mobile use, searching for precision, is not common. The biggest challenges are linked to the signalisation of the targets to be measured. For optical or indirect levelling, the levelling staff or target need to be oriented towards the instrument. Therefore they need to change the orientation as the measurement

Instrument advances. For the mHLS it does not matter in which direction the tube or the next sensor is oriented. Placing targets or levelling staffs on the magnets fiducials in an automated way seems very unlikely from the today's point of view. To go even further, any physical contact with the fiducials of the magnets should be avoided in view of machine safety and the later automation. The link between the mHLS measurement system and the magnets fiducials will be made by close range photogrammetry, thus avoiding any physical contact with the magnets.

## The Train Project

The future accelerator upgrades and projects like the HL-LHC or the FCC will introduce new constraints for the accelerator alignment. Time constraints, access conditions and radiation are only the most important to mention. In view of these future limitations, the CERN BE-GM Group decided to launch a new Project for a future Survey Train. The next generation of the Survey Train needs to be much more versatile than the Collimator Survey Train. This train was dedicated and limited to a very precise zone around the LHC collimators [1] whereas the new Train Project targets a general configuration in the LHC for arc- as well as straight-sections. Different studies have been made and published in the past and all those will come together in this Train Project [2]. The core technology is the close range photogrammetry with all the advantages for precise, rapid and contactless measurements.

The wire offset measurements by means of photogrammetry have been object of different studies and the next prototype is advancing very well. It will be fully tested and qualified on the HL-LHC IT Test String in 2024 which is a full featured test setup and reflecting the real HL-LHC installations. On the other hand the vertical measurements are still in the concept phase, in particular the needed automation infrastructure for the deployment of such a system. The core advantage of the mHLS would be in the signalisation or materialisation of the points to be measured as well as the error propagation being almost independent of the distance. The concept is based on two measurement heads. Both heads will carry 3 cameras, a two axis inclination sensor and an integrated mHLS. Simultaneous measurements at two positions will give the relative height difference between the heads. The 3D position of the fiducials with respect to the heads is given by close range photogrammetry. The automation of such a system is extremely challenging and therefore the first step is to fully qualify the measurement heads, thus the mHLS. Robustness and reliability are the main aspects to



be addressed as the manual use is only one step on the way to an automated system.

## SYSTEM DESCRIPTION

The system has already been presented in the past and is based on the ultrasonic HLS developed at DESY [3]. This system is particularly suitable for a mobile application as the transducer is already submerged in the water and any spill or splash water does not affect the measurement system as such. The first prototype was built to evaluate if a mobile use is feasible and that was confirmed [4]. The next step was to adapt the system for the mobile use, taking into account the constraints and particularities of the environment and the working principle.

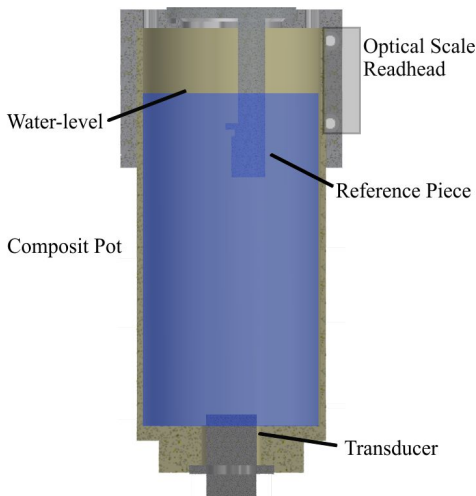


Figure 1: Section of measurement pot.

## CONSTRAINTS

A number of constraints need to be taken into account when using or designing a system for mobile use in an accelerator environment. Some of them are linked to the measurement principle and some are linked directly to the environment, others are coming up as a combination of both. We should mention:

- The connecting water tube is challenging in the accelerator environment
- The varying height differences resulting from the tunnel slope along the machine need to be compensated mechanically
- The tunnel ventilation might create a differential pressure in both vessels
- A possible temperature gradient in the vertical part of the tube will affect the measurements significantly
- The system should be reliable and robust for a daily use
- The system should be transportable and energy autonomous

Even if most of the constraints are evident, the solution is not always straight-forward and need to be addressed with all aspects in mind. There is of course no alternative to the connecting water tube. The tube needs to be as flexible as possible, robust, protected, but visible and transparent at the same time in order to locate possible air pockets inside. The out-gassing of the water can be minimized, but not be completely avoided. The height difference is known from theory and is adjusted with a vertical translation table in order to preserve the precision range ( $\pm 5$  mm) of the HLS system itself. Following the initial measurement, the system will adjust the tables to have both mHLS systems at exactly the same height. This will minimize systematic effects and in addition this precisely monitored displacement allows to verify the communication of the vessels.

The tunnel ventilation is an obligatory safety feature and absolutely mandatory. The airspeed might vary as function of the tunnel profile which creates more or less random pressure differences. Even in a shielded version the differences have reached 20  $\mu\text{m}$  of deviation. This is above the acceptable level and cannot be canceled out as this effect is not reproducible. As for a static system, the solution is clearly the use of only one venting point inside the complete system which is adding another tube and creating the risk of condensation inside the air tube. The connecting water tube is for the manual version pulled on the floor, going up to the fiducial points. So the majority of the length is following the tunnel floor and its relatively stable temperature. On the vertical parts, going up to the fiducial points this cannot be assumed as stable. The system is self calibrating for the speed of sound and therefore also for the density and temperature of the water, but only along the reference piece inside the measurement vessels. This is not valid along the tube and can create significant systematic errors. In order to rule this kind of systematic errors out, the system is permanently circulating the water inside the water circuit.

## CONFIGURATION

The configuration of the next version should allow to adress all the previously mentioned aspects. In order to take a real advantage of the HLS the measurement distance needs to be extended. That is valid for the maximum horizontal distance as well as for the vertical height difference the system could measure in one step.

### *Communication*

The electronics for the control of the translation table and the optical scale have been controlled using a USB connection which is limited to 5 probably 10 meter cable length. For the measurement of an LHC halfcell the sensors would need to be 53m apart, meaning 2x30m of cables. A protocol which is adapted to realize a reliable transmission on this longer cables is the TCP/IP protocol. The communication from the control rack to the Sensors has been switched to the TCP/IP protocol using a USB

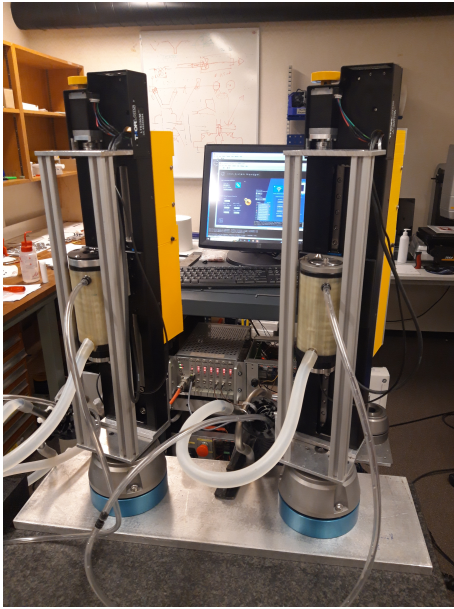


Figure 2: Picture of the mHLS today

Gigabit Network Server in both sensors. This reduced the number of needed cables to one CAT6 Ethernet cable, one 24V power cable and the coaxial cable for the ultrasonic transducer.

### *Vertical translation stages*

The stages have been updated to the mechanically stronger and more reliable LTS300 from Thorlabs. Despite the fact that these tables come with an internal incremental scale system and hall-sensor switches, the initial strategy of using a dedicated and absolute optical scale for the measurement of the vertical displacement is maintained. In this case it is a Renishaw Resolute RSLA absolute encoder system. This scale provides the needed absolute precision and is mounted rigidly to the base.

### *Tubing & piping*

The piping has been updated to be compatible with a permanent water circulation inside the system. The aim is to avoid the accumulation of gas which potentially blocks the communication, but far more important is the mitigation of a possible temperature gradient. A double hose was installed and the water is constantly circulating inside the circuit with a Y-piece just in front of the sensor vessels. In that way the water in the vessel itself is not actively circulated. The water density inside the vessel is compensated with the reference piece and a little exchange of water is still present. The water is circulated by a peristaltic or roller pump which is displacing the water without a rotating impeller. The water is pushed continuously by squeezing a flexible tube inside the body of the pump. Those pumps are often used as dosing pumps due to their precision in controlling the flow. All tubes and cables are installed in a flexible protective duct of 50 mm

diameter giving also the possibility to easily access, inspect and exchange the different cables or tubes.

## **VALIDATION TESTS**

The mHLS system itself has already been tested in the past [4]. This time the tests are focusing on the changes and mitigation measures that have been put in place especially for the use in accelerator environments. Additional points to be evaluated are the robustness, reliability and also ergonomics for a daily use.

### *Temperature Gradient*

One of the biggest concerns in the past tests was the temperature gradient which has an influence of 21ppm/K. In order to validate the circulation system it is necessary to provoke an artificial gradient in a controlled environment. The effect can be calculated from theory, measured with the mHLS system and should completely disappear with the circulation in place. However the full control of the environment is more than only challenging. In addition to the water heating and expanding inside the system, the tube expands as well. Where we expect the total volume to increase, it might even decrease due to the larger expansion coefficient of the used tubing. This is only a side effect and has no impact in the relative measurements.

The used pipe is a semi-transparent silicon hose with 10 mm inner diameter. This tube has been exposed to an IR light source on a given horizontal distance. The volumetric temperature expansion coefficient of water is not linear along the full temperature range. However in the used range from 15 to 25 °C one can assume this to be linear. If we assume that the temperature gradient along the tube is linear as well we can take the average temperature and the average volumetric temperature expansion coefficient to calculate the change of volume. In the case of the tests and a temperature difference of 10°C it was 2.07 ‰ which is representing an important systematic error on a distance of 1.2 m. We ignore the change of the total volume which is biased by the hose expansion and focus on the height differences between the two vessels. The vessels are static and are not moved at all during the measurements. A first set of measurements determines the height difference followed by the heat up of the tubing with an IR source along 40 cm of distance. The measured height difference increases with the thermal expansion of the water. With the slow circulation of 250 ml/min in place, which is corresponding to a circulation speed of 3 m/min the gradient disappears already in 30 s from the thermal images. It takes about 5 more minutes to completely mitigate the gradient and return to the initial measurements. A higher circulation rate is feasible but the vessels need to be isolated in that case in order to avoid to push water in the air tubes. The measured influence on the height difference was between 60 µm and 80 µm and 5 min of circulation brought the height difference back to the initial value within less than 10 µm.

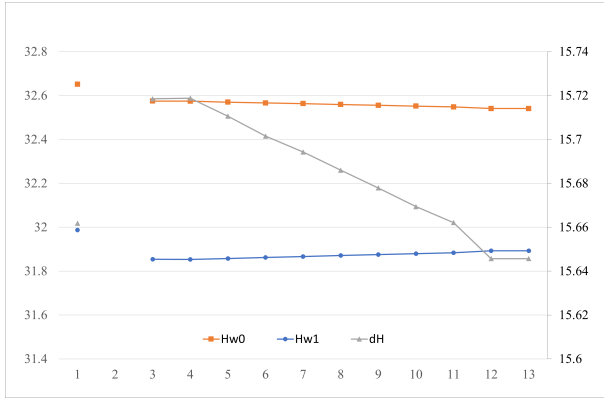


Figure 3: Influence of temperature gradient

The water inside the measurement vessels themselves is exchanged parasitically with the draft of the circuit and without any direct circulation.

The circulation needs to be stopped 20 s before a measurement and for the transport of the system as the valves are closed in that state. If we assume a circulation in standby mode which corresponds to 30 %, one can exclude the development of a temperature gradient along the tube.

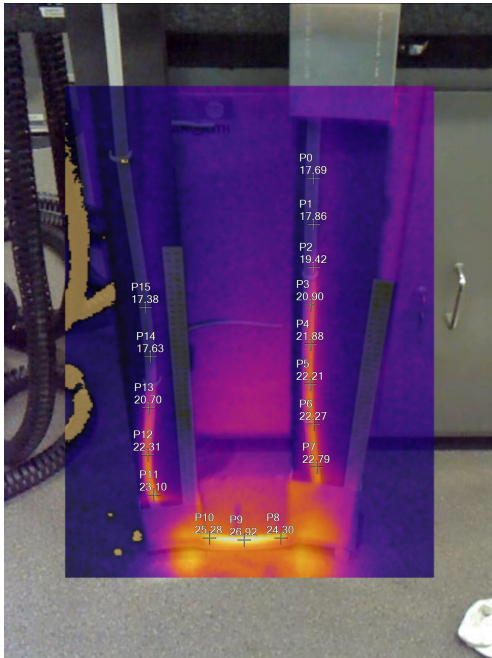


Figure 4: IR Image of temperature gradient

### Ventilation effects

The tunnel ventilation is a mandatory safety feature and cannot be modified. The approximate volume is 22000 m<sup>3</sup>/h which is representing, depending on the section of the tunnel, an airspeed of 1 m/s. Previous tests have shown that the influence of the ventilation can reach up to 100 μm in the measured height difference [4]. This effect needs to

be ruled out completely in order to make the mHLS system usable in the LHC environment. The classical method is a dedicated air-tube linking the vessels. That tube need to be flexible, but without any risk of blocking or pinching the tube. Water evaporation and condensation inside the air-tube were a concern in the beginning of the tests. Initially a flexible filter with a textile membrane should help to reduce or avoid any condensation inside the air-tube. With a relatively stable temperature, almost no condensation could be observed inside the air-tube. Spill water is a problem during transport and could still be solved with a membrane. Further tests should show if the membrane can be made transparent for the measurements. The risk of a blocked or partially blocked air-tube is however existing. Depending on the amount of water inside the tube, the communication of the vessels can be partially or even fully blocked. A validation of the communication is done prior to all measurements. After the pre-alignment, one of the vessels is moved by a precise value monitored by the optical scales. The system should respond to that change within the measurement precision. If this is not the case the measurements are biased by an obstruction either in the water-tube (no response at all) or in the air-tube with a partial response to the movement.

### OUTLOOK

Reliability and robustness are the two main aspects to be ensured in order to continue towards an automated measurement solution. From the hardware side the system is now ready for the first real and manual measurements in the LHC machine. The software needs to be updated with automatic control and validation processes. Movement response, response time as well as correlation of the observations between both vessels are criteria to validate the measurements and detect problems with the system. Those criteria need to be implemented in the automatic control and validation procedures. The next steps will be dedicated to the infrastructure around this measurement method. The remote handling of the mHLS system is challenging, even if absolutely no physical contact with the magnets is needed or foreseen. Today the systems are linked by a protective chain of 50 mm diameter. That chain is dragged on the tunnel floor which is not an option for the automated solution. A real management system for the tubing will be needed in the future. The handling of the sensor heads needs to be automated using a sequence which allows also the exchange of the leading system to minimize further systematic effects. The development of the mHLS sensor head will profit from the progress on the prototype for the transversal measurements by photogrammetry. The basic photogrammetric system as well as the procedures and calculations will be very similar and we are looking forward to combine all the efforts on the individual components into a final system. Although we are on the way to an automated measurement system, there are a lot of exciting challenges ahead of us during the coming years.

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