Precise Vertical Magnet-Girder Position Monitoring at the Swiss Light Source (SLS)

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SUMMARY

In course of a vertical realignment campaign of the Swiss Light Source (SLS) storage ring in 2011 [1] with the emphasis to minimize the vertical electron beam emittance, which is closely related to the size of the beam, it became apparent that the Hydrostatic Leveling System (HLS) can not only be used for the detection of long term settlements as it was designed for but also for monitoring deliberate girder (magnet support structure) manipulations with the remotely controlled girder alignment system of the SLS. Since then electron beam-based measurements, alignment survey data and HLS data have been compared and found to be consistent over a large range of time scales from seconds to years. A recent software upgrade has allowed a smooth integration with the SLS control system and guarantees future HLS hardware compatibility.

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1. INTRODUCTION

The Swiss Light Source (SLS) at the Paul Scherrer Institut is a 3rd generation synchrotron light source. With an energy of 2.4 GeV, it provides photon beams of high brightness for research in materials science, biology and chemistry (Fig. 1a/b).

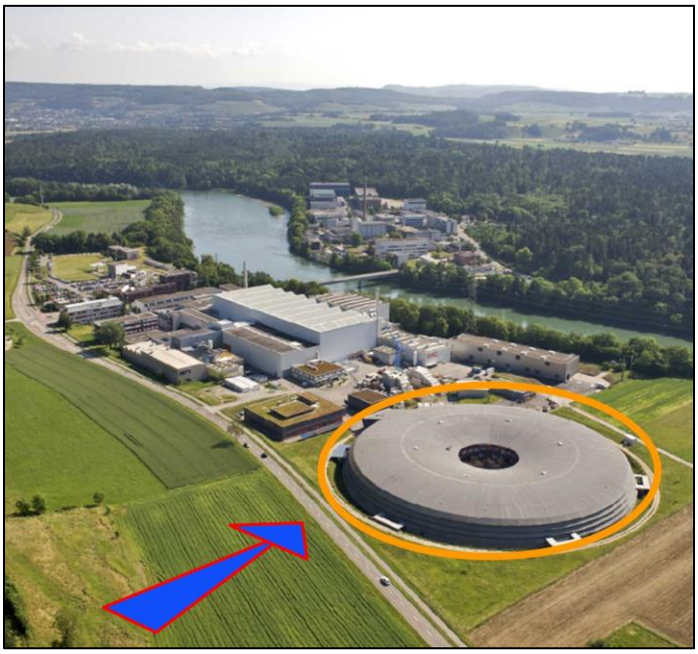


Fig. 1a): Swiss Light Source Synchrotron (SLS) at Paul Scherrer Institut (PSI), Switzerland.

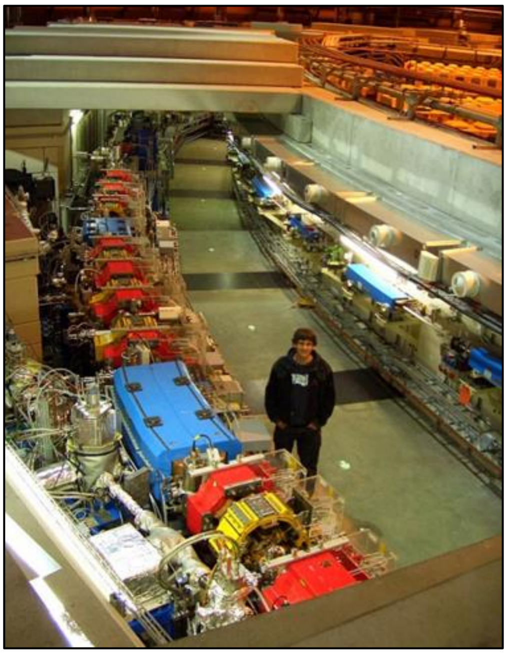


Fig. 1b): Storage ring with colored magnets in the center and photon beam line on the left side.

The main goal at SLS is to produce high quality photon beams, which are mainly determined by the electron beam quality at the radiation points (small beam size and divergence). Since the vertical beam size is mainly determined by magnet misalignments a precise magnet adjustment becomes increasingly important. This requires especially provisions for accurate positioning and dynamic minimization of ground and thermally induced motion.

2. THE SLS SYNCHROTRON MACHINE LAYOUT

2.1 How the electronic beam is guided

The provision of synchrotron light of a very high quality requires the installation of a large number of magnets - a total number of 330 - to keep the electrons on their closed orbit and to make the electron beam as small as possible.

Together with the vacuum system the magnets make up the main part of the so called “storage ring”, where the stored electrons can circulate for hours. In a so-called undulator, the electron passes a periodic array of magnets with alternating polarity of the magnetic field. This forces the electrons into a “slalom” course. This together with coherence of the light concentrates the synchrotron light into discrete wavelengths, a brilliant light beam.

2.2 Layout of the magnet girders

The relative alignment of components in the storage ring of the SLS is guaranteed by mechanical means. The different types of magnets (dipoles - blue, quadrupoles – red, sextupoles - yellow) are rigidly fixed to 48 girders (Fig. 2a). The magnet mounting surfaces of the girders have been produced within a horizontal and vertical accuracy of +/- 15 µm. The girders have to be aligned very accurately, since their mechanical misalignments add significantly to the magnet misalignments on top of the girders. In order to ease the girder adjustment procedure each girder can be remotely adjusted by means of eccentric motor drives.

2.3 Girder mover system

The girder mover system (Fig. 2b) is based on five DC motors per girder allowing a dynamic realignment of the storage ring within a working window of more than ±1 mm for girder translations and ±1 mrad for rotations. The motors with worm gears provide a minimum positioning resolution of 2 µm within a motion range of 2.5 mm in vertical and 3.5 mm in horizontal direction for each mover.

2.4 HLS system

The HLS system [2] provides an absolute vertical reference for the SLS storage ring (Fig. 2c). The system monitors any relative and global vertical position change with a submicron resolution [3,4] within a working window of 14 mm. The capacitive proximity gauge based sensors measure infinitesimal altitude changes by analyzing a rectified voltage signal which depends on the distance of the electrode to a water level of the half-filled tube (Fig. 2d). They are housed in stainless steel boxes of 100 mm diameter. The dimensions of the measuring pots are optimized for maximum sensitivity and minimum influence of thermal and vibrational effects. Four pots per girder are positioned exactly above the movers to measure heave, pitch and roll (Fig. 2e) and to monitor corrections executed by the girder mover system. A total of 192 sensors are installed around the SLS storage ring [5]. They are connected by a stainless steel pipe of 25 mm diameter, which is half filled with liquid. With such an arrangement, heave, pitch and role can be calculated from the vertical positions, and corrections executed by the girder mover system can be monitored with a high precision. The most important corrections are pitch and heave which allows align the girders to a smooth polygon around the ring.

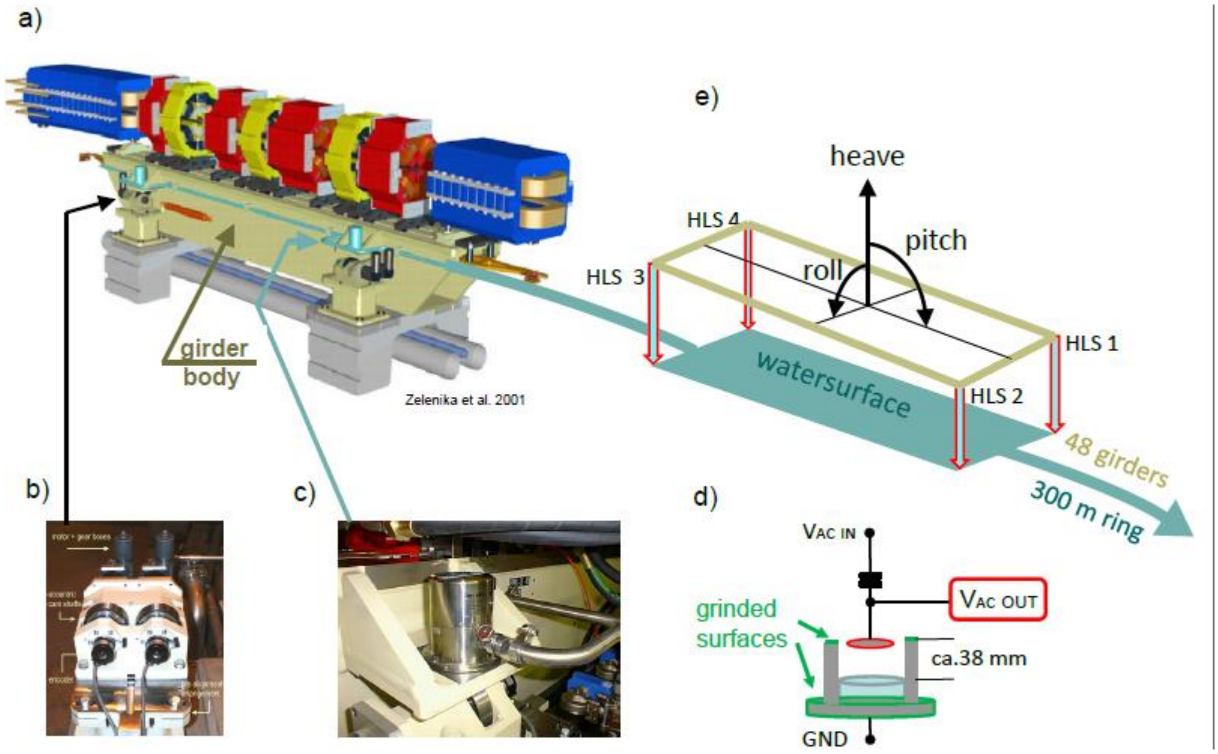


Fig. 2) Girder carrying the bending, focusing and dispersing magnets (a). The girder body (beige) is mounted on four 'legs' with movers which can shift the girder in the vertical axis (b). This vertical movement is monitored by a HLS sensor at each mover (c). Capacitive proximity gauge based sensors are employed (d). Heave pitch and roll is calculated (e).

3. NEW ONLINE SOFTWARE – A STEP TOWARDS THE NEXT GENERATION SYNCHROTRON "SLS-2"

At the SLS a LabView software from National Instruments is used on a Windows computer (presently Windows 7). 192 Level sensors and 192 Temperature sensors are scanned and recorded every second. Pitch and roll of 48 girders as well as heave of all girders are calculated and plotted simultaneously on a screen attached to the computer.

The data output is realized by a ringbuffer with all data in binary and in ASCII format (1 sec sampling rate) and a selectable sampling rate in Excel format (default 1 hour sampling rate). All recorded data are stored on the computer hard disk as well as on an external Synology NAS (Network Attached Storage) drive. An EPICS I/O server running on the HLS PC allows retrieval of all data by the EPICS based SLS control system.

3.1 Overview screen: Heave, pitch and roll of 48 girders

The overview screen (Fig. 3) allows a fast review of the system state. This window shows the pitch, roll and heave values for all girders. All 48 Girders are displayed in a ring.
The 'System State' field (center bottom) shows the overall state of the tree state groups ('Signal Monitoring', 'Communication' and 'Water Level Control'). Three green lights mean the system

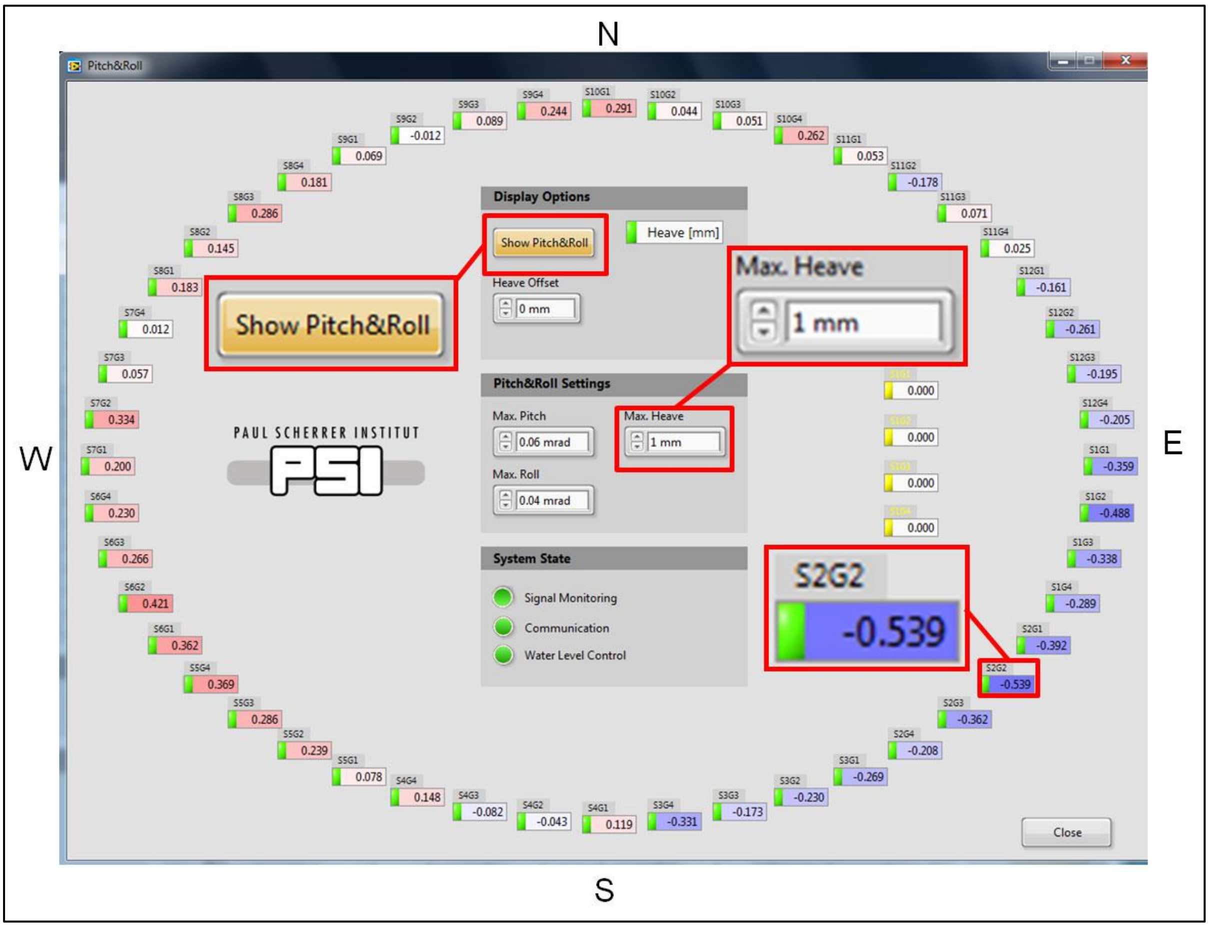
function is OK. Detailed information about the corresponding state group can be displayed in a separated window by selecting the corresponding menu.

In the ‘Display Options’ field (center top) it can be switched between heave or pitch & roll. At the right of the switch-button the currently displayed motion axis is shown for all girders.

In the heave view (Fig. 3) one square represents one girder. The displayed value is the average value of all 4 HLS sensors of each girder.

In the ‘Settings’ field (center) the displayed colors can be changed by adjusting the “Max. Heave” value. If the value exceeds the maximal deviation (positive or negative), the LED on the left lights red.

Please note the difference in the background colors in the western (positive values > red colors) and the eastern section (negative values > blue colors) of the ring, stating a tilting of the SLS concrete base plate of almost 1 mm during the last 10 year (since 2005).



Heave Offset: 0 mm

Max. Pitch: 0.06 mrad

Max. Roll: 0.04 mrad

Max. Heave: 1 mm

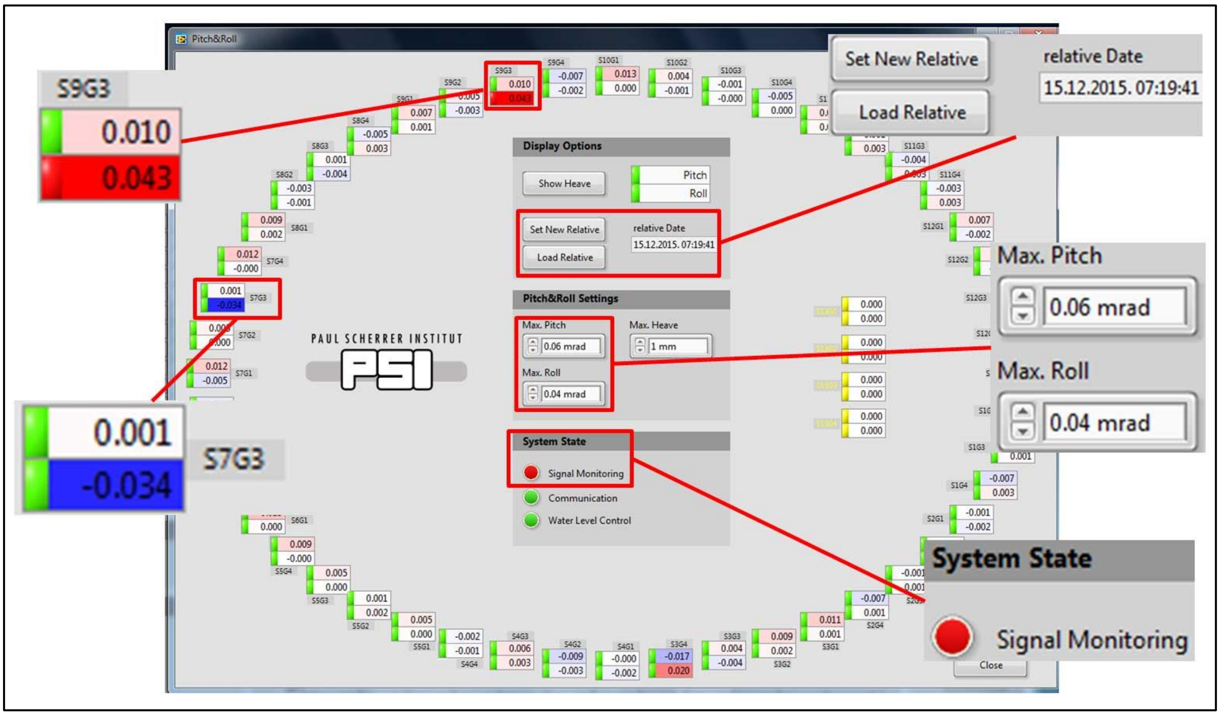
● Signal Monitoring
● Communication
● Water Level Control

Fig. 3): Overview screen showing heave values for all 48 girders in mm. Each square represents one girder (average value of 4 HLS sensors). In the ‘Settings’ field (center) the displayed colors can be changed by adjusting the heave value. The colors differ in the western (red) and eastern section (blue) of the ring, stating a tilting of the concrete base plate of the SLS during the last 10 year (since 2005). The ‘System State’ field (center bottom) allows a quick overview of the overall state of the tree state groups (green > function OK!).

In the pitch & roll view (Fig. 4) two squares per girder are displayed, the upper square showing pitch, the lower roll value. Pitch is the most important value, as this motion axis determines predominantly how well the girders are adjusted with respect to each other which as it turns out most important for the alignment.

In the 'Settings'-field (center) maximum pitch & roll values can be changed. If these values are exceeded, the 'System State' field shows a warning (red light) and the affected girders are highlighted (red).

The 'Set New Relative' button in the 'Display Options' field is only visible if pitch & roll is selected. This applies new offset values for all pitch & roll values. The offset value results from the actual sensor value. All offset values are stored in a file and can be loaded at a later time ('Load Relative'-button).



relative Date: 15.12.2015. 07:19:41

Max. Pitch: 0.06 mrad

Max. Roll: 0.04 mrad

Max. Heave: 1 mm

Fig. 4): Overview screen showing pitch & roll values for all 48 girders in mrad (two squares per girder -> upper: pitch, lower: roll). In the 'Settings' field (center) maximum pitch & roll values can be changed. If these values are exceeded, the 'System State' field shows a warning (red light) and the affected girders are highlighted (red).

3.2 Historic data handling

With the new software 'History data' of each sector can be displayed, which are stored every second. This gives a whole new insight into the movements in the ring. It is possible to choose between absolute values and relative display with selectable offset in the 'Display Options'-dialog. The 'Relative Display'-function is used to display all signals relative to each other. This allows comparing the signals from the 12 sectors with each other very easily. With this option it is possible to note for example drifts between sensors.

In Figure 5 a data sample of a 12 h time interval from 24th August 2015 is displayed. The data sample from sector 1 is showing an earthquake between 3 and 4 o'clock in the morning, seen by all HLS sensors in this sector. In the diagram also the earth tides (influence of the Moon) are visible by the synchronously curved signals of all sensors over the whole time period.

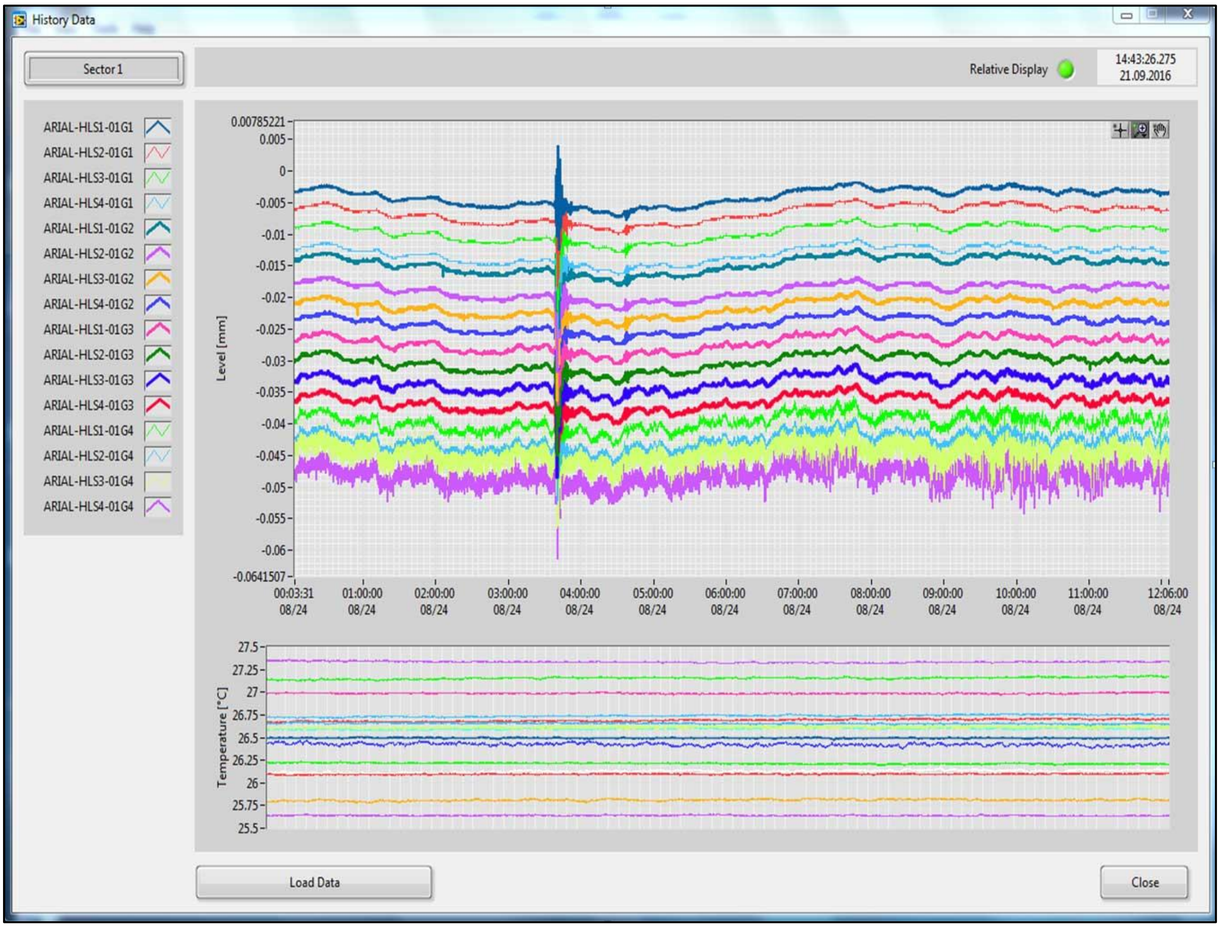


Fig. 5): History data example of a 12 h time interval. All signals for one sector are displayed as a line graph. It is possible to choose between absolute values and relative display with selectable offset, enabling detection of drifts between sensors. The data sample is showing a recorded earthquake. The curved signals of all sensors in this sector over the entire time period are due to the moon influence.

4. ACTIVE GIRDER DISPLACEMENTS – DYNAMIC HLS SIGNALS

4.1 Signals reloaded in historic data window

Figure 6 shows the history data for a girder displacement test at PSI, in order to find out how well the HLS system tracks the changes applied to the girder. The pitch axis of girder 12G4, which is the girder left of the injection straight as seen from the ring center, was deliberately changed by +20 µrad and back to the initial position as given by the encoders which control the girder motors. This change is at the lower end of deliberate changes which are typically applied to the machine in order to correct for misalignments. This deliberate change was applied twice during the measurement.

For a better visibility of the changes seen with the HLS software, only the HLS sensors of the moved girder where selected for display. The two pitch steps are clearly visible in the diagram. The 4 sensors display contrary signal characteristics, with 2 line graphs (2 sensors) deflecting up- and 2 downwards. The first pitch change is showing the expected correct signal sequence. However, in the second change shows differences in the amplitude value (different plateaus) compared to the first change, which were caused by tripping motor power supplies.

Fig. 6): HLS history data for a girder-displacement test. 2 x +20 µrad pitch steps were applied according the readout of the motor encoders. Only the HLS sensors of the moved girder are displayed (12G4), showing contrary signal characteristics (2 up, 2 down). The first displacement step is showing the correct signal sequence, whereas the second step suffered from intermittent motor power supply trips at the beginning of the change.

4.2 Disturbance of the reference water table

In Figure 7 the signals of the displaced (active) girder were suppressed to demonstrate the influence of the changes on the water surface seen by the HLS sensors of the neighboring girders. The water level displacement is visible at the next 2 girders located upstream of the displaced girder, with the maximum amplitude of 12 microns at the closest sensor (red). As this water is missing at the displaced girder, it will cause a small artefact in the 'heave' signals, which leads to lower values until the water surface is balanced again.

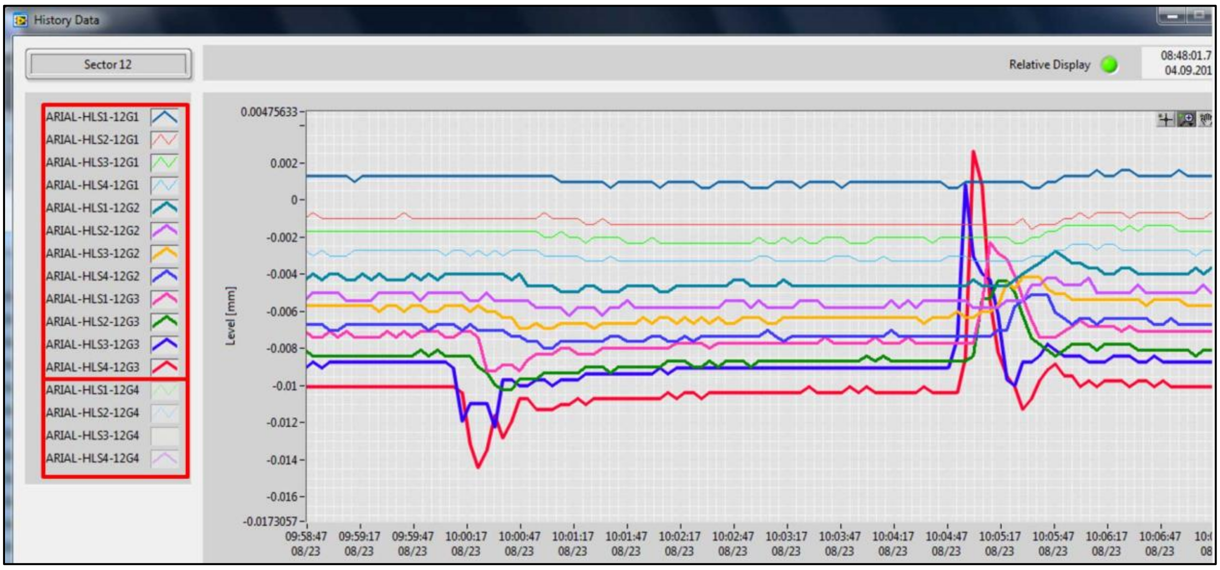


Fig. 7): HLS signals of neighboring girders (auto scale). The signals of the displaced girder are suppressed (not activated). A water level displacement is visible up to the next 2 girders upstream. As this water is missing at the displaced girder, it will cause an artefact in the 'heave' signals. The maximum amplitude is 12 microns at the closest sensor (red).

4.3 Measured HLS values versus motor encoder values

In order to compare the HLS signals with the motor encoder values, pitch, roll and heave were calculated from the HLS signals of the first displacement (Fig. 8). The diagram shows that the pitch value quite accurately corresponds with the +20 µrad change shown by the motor encoders. The roll value was not affected by the displacement step when compared with the starting value. Only the heave value shows a larger difference of a few micrometers to the initial data. The heave is following a settling curve in time which is not reaching its initial value by the end of the first displacement step, due to water flow to the neighboring girders as recorded by the HLS sensors, see Fig. 7.

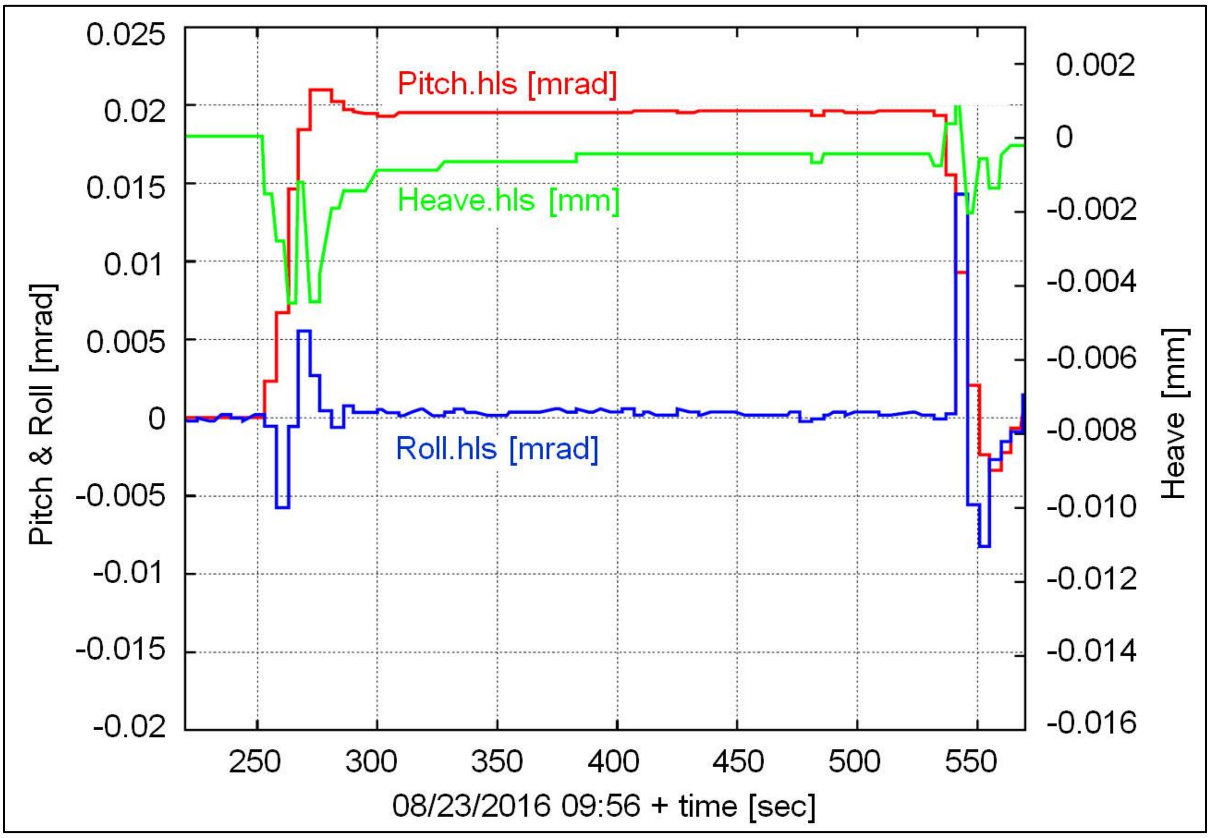


Fig. 8): Heave, pitch and roll calculated from the HLS signals for the first displacement step. The pitch value is in excellent agreement with the +20 µrad change applied with the motor encoders. The roll value was not affected by the change, whereas heave is not reaching its initial value.

Figure 9 shows the initial changes of pitch, roll and heave calculated from the motor encoders. The pitch value is exact within the error of the motor control algorithm which is used to establish the set value of +20 µrad. Heave and roll values are not significantly influenced compared with the initial values before the displacement step.

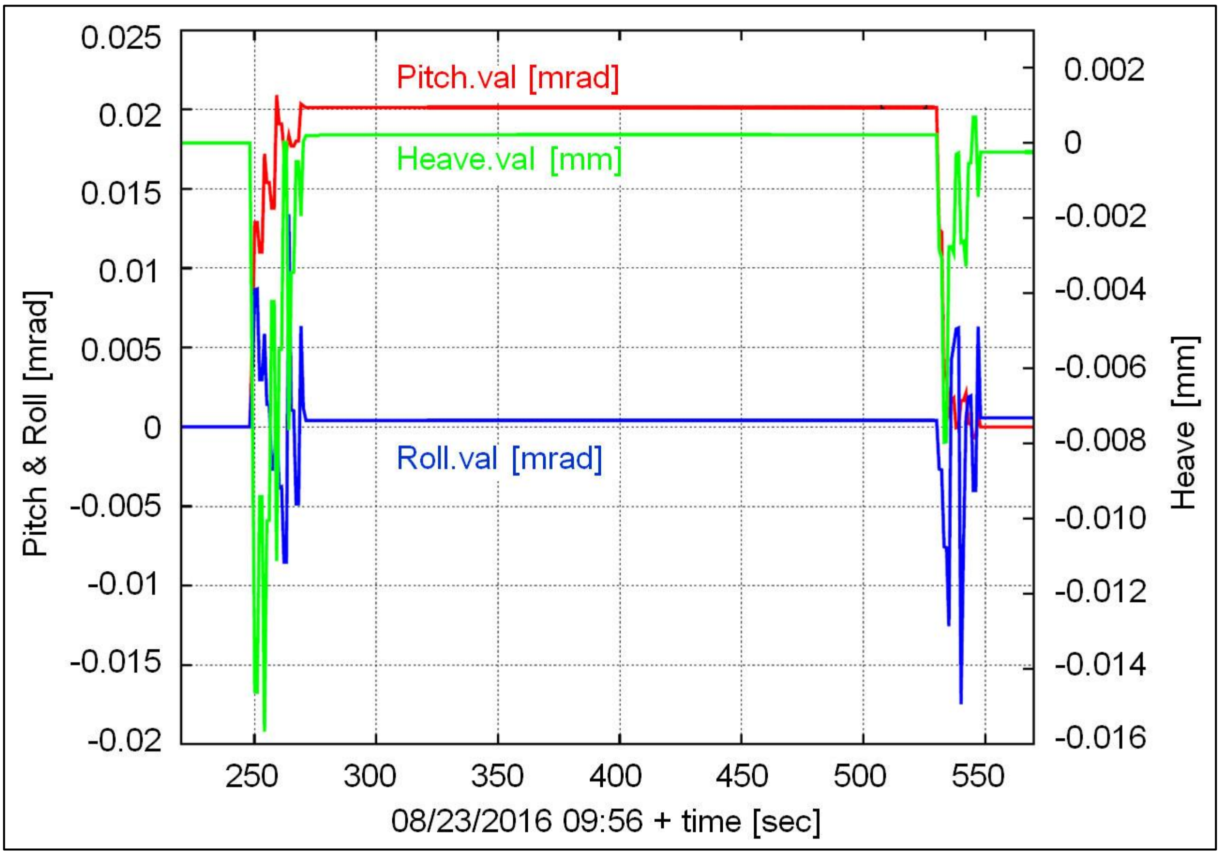


Fig. 9): Pitch, roll and heave calculated from motor encoder readings. The pitch value precisely reads back the desired +20 µrad. Heave and roll are not significantly influenced compared with the values before the changes were applied.

Figure 10 displays an exponential fit to the heave settlement of the HLS water level. The settlement of the water level is delayed compared to the fast girder changes applied with the girder motors. The process can be described by an exponential function. The time constant for the heave settlement is determined with tau = 22+-1 sec.

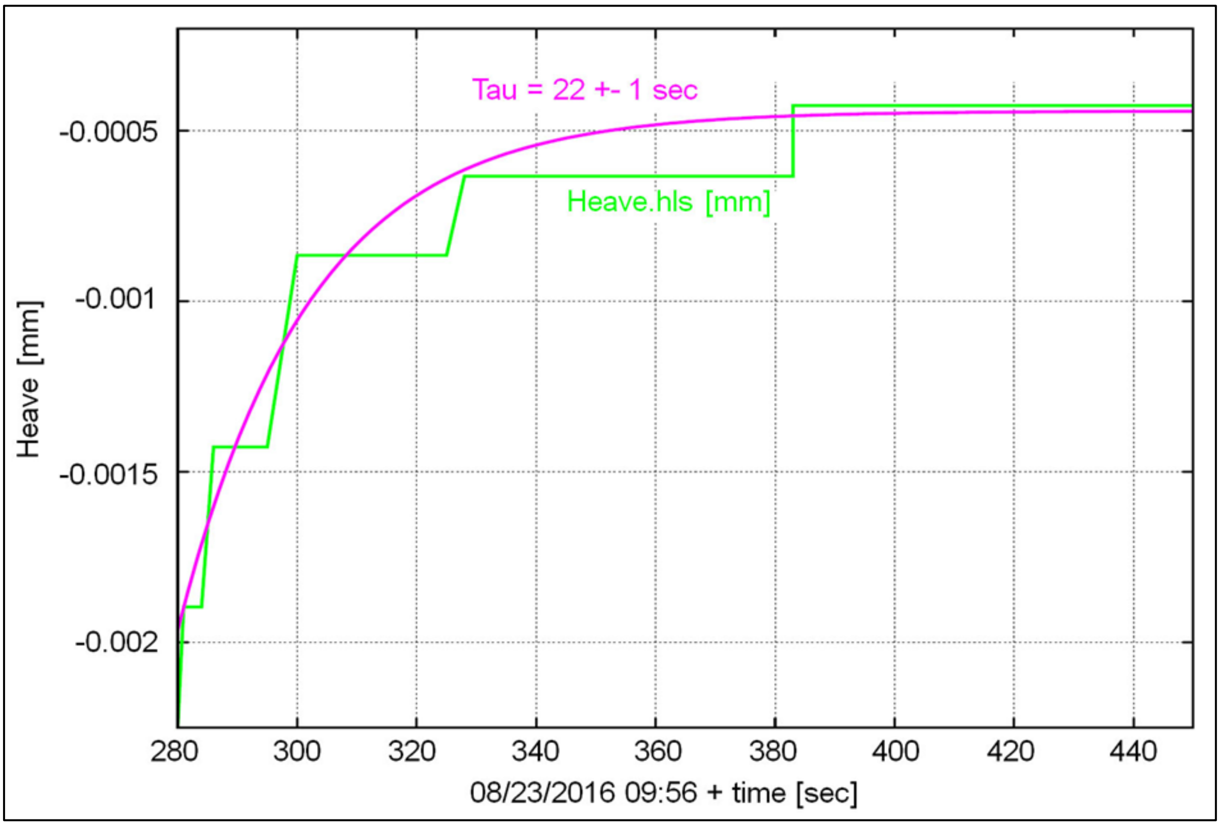


Fig. 10): Exponential fit of the heave settlement. The adjustment of the water level to the initial value is delayed compared to the fast changes applied with the motors due to the waterflow to adjacent girders. The time constant is fitted to be 22+-1 sec.

Figure 11 is depicting pitch, roll and heave both calculated from the encoder readings and the values measured by the HLS system in the same diagram.

The first observation is the systematic difference of pitch values. The encoders read back the desired +20 µrad (20.128 µrad). The HLS gives a systematically lower value of 19.53 +-0.1 µrad corresponding to a 3 % smaller value (factor 1.031). This can be explained by a calibration difference of both systems. The RMS error of 100 nrad can be considered to the measurement resolution of the HLS system. This is an extremely small value and corresponds to a movement of ~200 nm at both ends of girder. The pitch signal to noise ratio of 200/1 for the 20 µrad step is more than sufficient.

The second observation is the characteristic time constant of the settlement of the HLS reading. The heave settlement was fitted and a time constant of 22+-1 sec determined. This time constant can also be seen in the pitch and roll data, but it is less pronounced than for the heave.

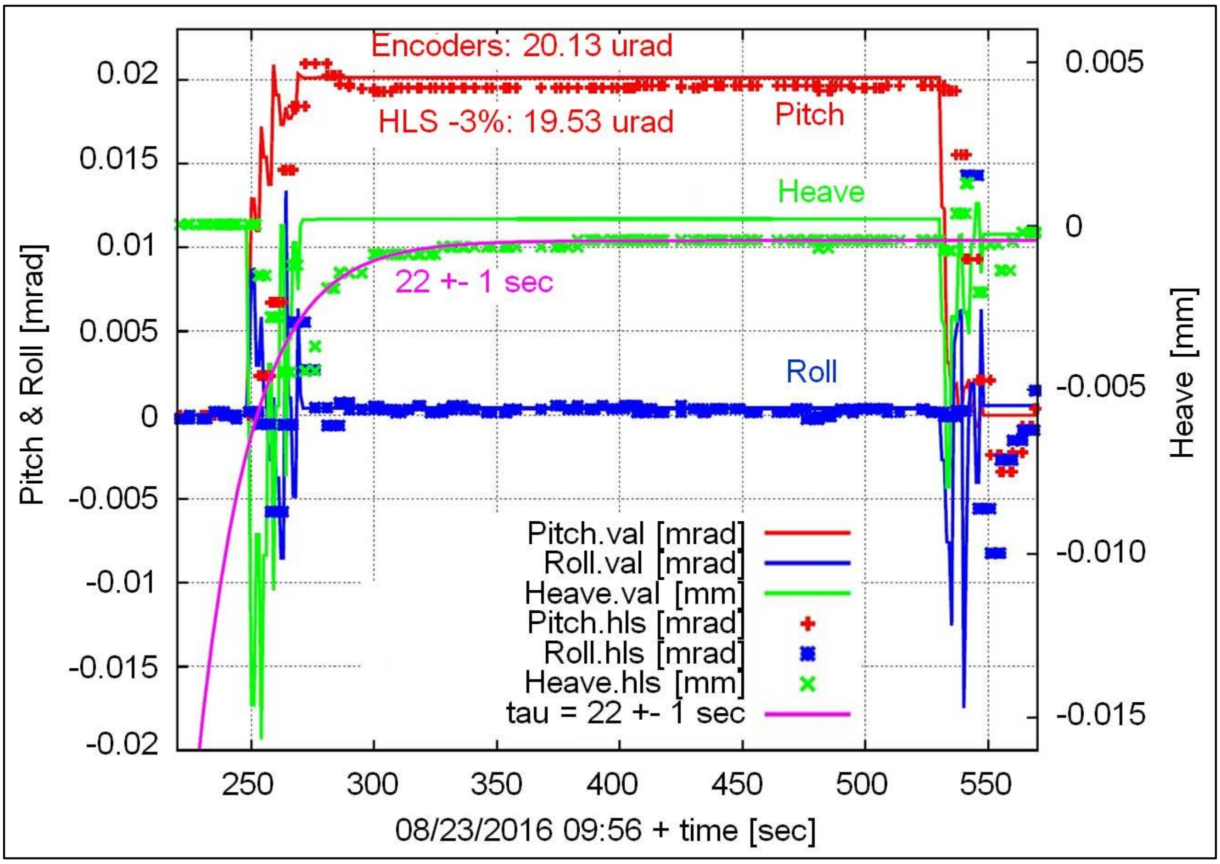


Fig. 11): Comparing motor encoder and HLS data. Pitch and Roll values correspond very well, although a small systematic difference of pitch values is visible (HLS -3 %). Heave data show a characteristic time constant of 22+-1 sec.

5. CONCLUSIONS AND OUTLOOK

Originally the HLS at SLS was developed for long term monitoring of the vertical machine alignment. One sample per 10 minutes and an accuracy of 10 microns was demanded. The continuous work with the system revealed a much better accuracy of the system on a much shorter time scale of seconds which allows its use for short term dynamic monitoring. With the new software the systematic effects due to liquid transport in the HLS tubes are easy to quantify. The good integration with the EPICS based SLS control system allows easy direct correlation of HLS data with other accelerator related data like the motor encoder read outs. The remotely controlled SLS girders together with the HLS system provide a precise control of the vertical machine alignment without having the need for an additional alignment survey which is very time consuming. For this reason PSI is considering to reuse the system for an upgrade of the present SLS named SLS-2 which will be even more demanding in terms of alignment tolerances and stability. Since SLS-2 will become operational >5 years from now with an envisaged time of operation of ~20 years the guarantee for future hardware compatibility of the HLS software is an important point.

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BIOGRAPHICAL NOTES

Edi Meier is managing director of the engineering company Edi Meier + Partner AG, Winterthur, Switzerland. He studied Geophysics at ETH Zurich. Subsequently he worked as a manufacturer of seismic instruments (Streckeisen Switzerland) for six years and founded his own engineering company in 1987. Since 1995 the company is collaborating in research and development of new instruments with the Institute of Geodesy and Photogrammetry of ETH Zurich.

Michael Böge is a senior accelerator physicist at the Paul Scherrer Institute (PSI), Villigen, Switzerland. He studied Physics at the Kiel and Hamburg University, Germany, where he got his PhD in 1994. After a fellowship at the European Organization for Nuclear Research CERN, Switzerland, he joined the Swiss Light Source Project at PSI.

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