# The HLS Used as an Absolute Reference for the Alignment of the SOLEIL Storage Ring

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The installation of the SOLEIL Storage Ring is being achieved, the commissioning with beam started in May 2006. An innovating strategy held at SOLEIL using a dedicated HLS network as an absolute reference for the vertical alignment of the girders. The principle consisted in mixing mechanics, magnetic measurement & HLS in order to minimize the error budget from the reference free water surface to the magnetic centers of the quadrupoles.

## 1. INTRODUCTION

The Hydrostatic Leveling System (HLS) is based on a displacement capacitive sensor fixed on a structure and in front of a free surface of water which is considered as a horizontal reference. A HLS network set on 56 storage ring girders of SOLEIL allows defining the reference plane of the machine and controlling the evolution of its vertical displacements.

## 2. THE SOLEIL HLS NETWORK

### 2.1. General Layout

The network had been presented at IWAA 2004 [2]. Three HLS sensors (fig.1) manufactured by Fogale company*, Nîmes, France*, are set on each of the 56 girers (fig.2) and connected together by firstly, a collecting stainless steel pipe ø40mm and secondly, connecting pipe ø20mm between sensors and collector. The collector covers the whole ring, going along girders and straight sections. It has to be noticed that the collector is equipped at both ends of each straight section with sectioning valves whose dimension reduces the diameter of the collector by ø20mm.

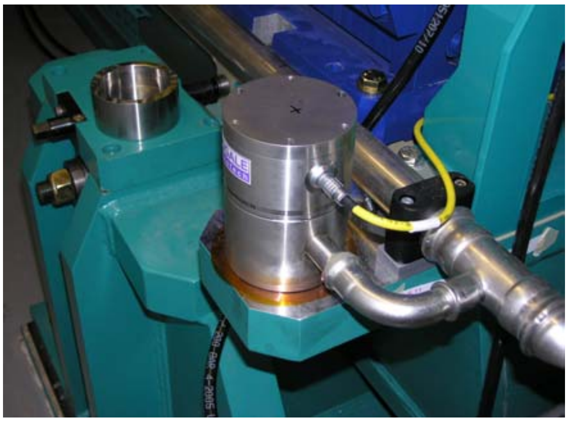

Fig. 1: Fogale HLS sensor

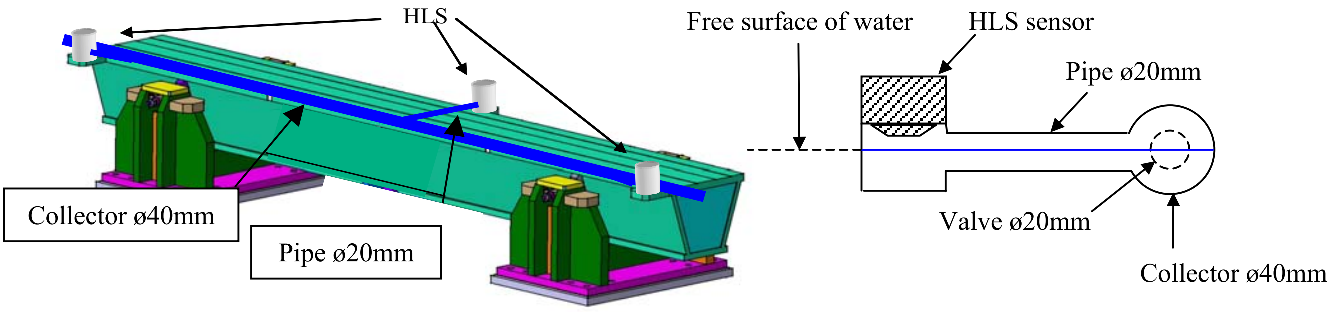


Fig. 2: HLS sensors on a girder

Since the system uses the same free surface of the water all along the storage ring in mono-tube configuration, there is no water expansion effect to be corrected. Therefore, any temperature sensor is set on the network. In the preliminary tests [2], a thermal dependence of the sensor electronics has been reported, but within a reasonable range (<1µm/°C). Since the tunnel has been stabilized in temperature at rougthly ±0.2°C, the use of such sensors has been canceled. A kapton sheet (50µm calibrated thickness.) is inserted between the girder and the vessel in order to isolate electrically the network. The stainless steel pipes are connected together by means of fixed and definitive crimping, or by means of movable and flexible silicon joints designed at SOLEIL (fig.1). Then, thanks to these flexible joints, the girders can move separately.

## 2.2. Mechanical aspects of HLS vessels & sensors

The primary goal of the HLS network is to define a reference plane for the storage ring, i.e. to use it in an absolute way. Therefore, positioning and/or measuring paths from the Quadrupole magnetic centers (Qpole MC) to the zero of the HLS sensor measurement must be fully controlled. In that way, since the upper face of the girder is an accurate machined plane, it was necessary to also measure precisely the height of the vessel which supports the sensor. Three bosses were machined on both, upper and lower faces of the vessels in order to define accurate planes and therefore to improve mechanical contacts & metrology.

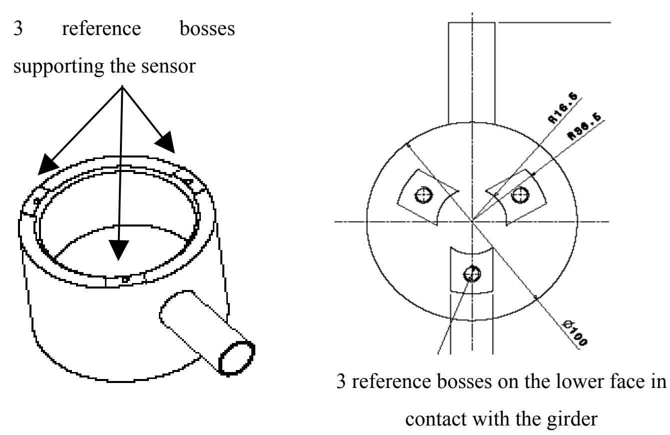


Fig. 3: SOLEIL HLS vessel

## 2.3. Data acquisition

A special rack has been designed for SOLEIL in order to use the Control-Command of the storage ring: we profited to the 16 bits analogic-digital conversion cards planned for other sensors or actuators. The SOLEIL rack is quite similar to the manufacturer one, except for the number of measurement channels: 12 single channels for distances instead of 8 double for distances & temperatures with the Fogale rack. The 16 racks are managed by the Tango Control System, designed with ESRF computing services. The HLS acquisition works with the max frequency equal to 1 Hz. up to now, we plan an "historical database" to store 168 HLS readings every 15mn (filtered by a simple average). In addition, an acquisition to the highest frequency (≈1Hz) is possible for delays of several days at most.

### 2.4. The HLS sensor

The used electrode on that sensor version is made of ceramics, without front glass as we noticed at IWAA2004 [2]. The measuring range is 5mm, from 5 to 10mm. Each sensor is used with its calibration curve coming from the manufacturer. Only few tenth mm of the range centered around zero should be used.

## 3. THE PRELIMINARY TESTS

### 3.1. Reminder of the tests until 2004

We presented a complete set of preliminary tests at IWAA 2004 [2]. The main goal was to define the frequency bandwidth upper & lower limits of the system. Significant differences have to be noticed between the test configuration held in 2004 (fig.4) and the storage ring network: the diameter of the collecting pipe has increased from 20 to 40mm, the length of the network from 110 to 354m.

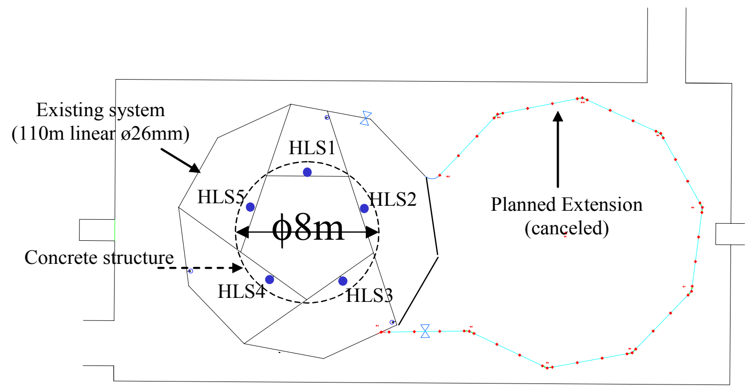


Fig. 4: Layout of the preliminary tests

The upper limit was estimated to T≈2h1/2 for a 354m circumference ring in ø20mm (without any estimation of acceptable amplitude). The lower limit was estimated in two different ways: an electronic stability test on a stainless steel calibration block showing a maximum of 7µm discrepancy on the HLS reading after having measured it again 10 months later, and a long term stability test held on a monolithic structure where 5 HLS sensors were fixed (fig.4). In that last case, the network of pipes was 110m long. The achieved accuracy defined by the residuals of the reading related to the least square plane was σ=5µm after 4 months. That last test seems to be the more representative since it is closer to the real measurement conditions in the storage ring.

### 3.2. Long term stability test:

The long term stability test went on until 2005 on the same network. As a result, we achieved a σ ≈ 10µm accuracy (fig.5) after a year of measurements in the same conditions. That achievement is already a good result, but it is not sure it can be extrapolated to more than a year. That is the reason why we decided to implement a checking method to verify periodically the validity of the sensor reading in terms of the electronics long term stability.

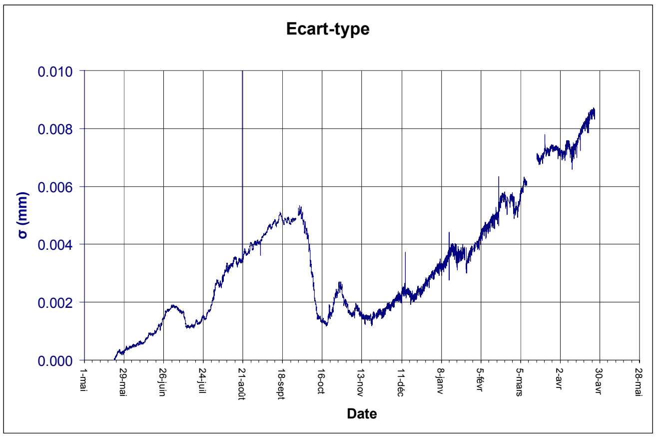


Fig. 5: Long term stability test with 5 sensors / least

## 4. FIRST TESTS HELD ON THE STORAGE RING

The accuracy of the HLS network for the alignment of the storage ring can be approximated by the bandwidth limits estimation. Conditions in the storage ring are slightly different from the ones during the preliminary tests since we cannot use a stable and monolithic structure. Therefore, any long term result is available by this means.

The spectral analyses are calculated by using a simple rectangular window on the temporal signal, the shown spectral density powers consider the true values (mm, rad instead of mm², rad²).

### 4.1. Filling test:

A filling of the network has been held in order to create a large wave inside the pipes. This test lies in estimating the delay for the water to come back at rest and the corresponding residual amplitude. Eight sensors roughly equidistant all along the ring have been selected, symmetrically located related to the point where the wave started. Fig.5, shows that the eight sensors came back 3h later within ±7µm, and 16h later within ±4µm. At the range of accuracy we really need for the storage ring alignment, we can consider that the practical upper limit is (±7µm, 3h).

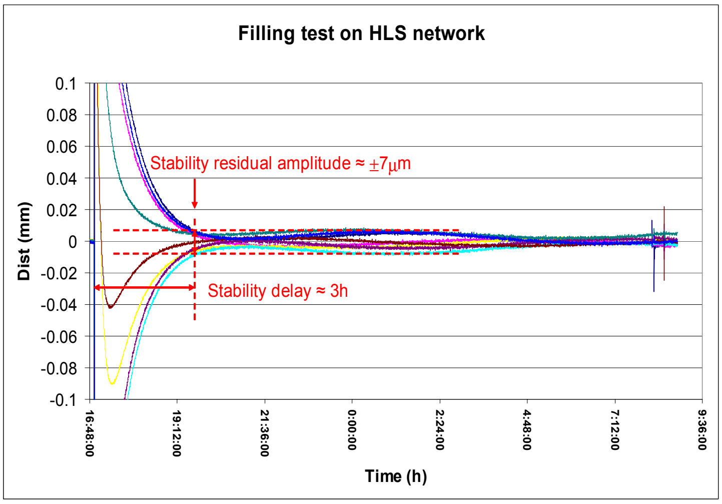


Fig. 5: Filling test on HLS network

Another approach is possible to interpret that test. The free surface of the water is essentially instable. As a consequence, the study of that system (water & pipes) needs the complete set of the hydrodynamics equations. But practically, we use the free surface as a fixed plane (the reference plane for position and/or displacement of the machine). Consequently, we have to study the stability of that approximation. We propose to consider the system whose definition is as follows "the slope of the mean plane calculated with n sensors". In that frame, the filling test can be seen by the system as an input pulse (Dirac function). We can then extract the transfer function of the system from the output signal. The transfer function in fig.6 shows that the frequency cut has around several hours as period. It means that the system can properly accept movements of the fluid (in amplitude & phase) whose period is greater that this cut. That last can be considered as the stability delay of the HLS system. A

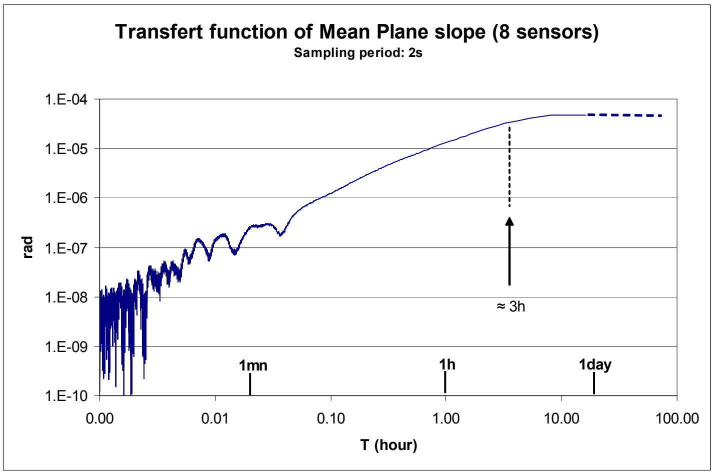


Fig. 6: Transfer function of Mean plane slope

similar analysis has been realized on a two sensor tiltmeter with, even an analytic study [5]. In the case of the SOLEIL HLS network, only measures can lead to the transfer function because of the too much complex topology.

## 4.2. Short term Spectral analysis

A spectral analysis has been calculated on time signal in a calm period namely during a machine run. The goal is to detect the potential eigen frequencies of the fluid depending partially on the pipe geometry [1], and the noise level due to eventual parasitic vibrations. These analyses must be seen as purely qualitative. We just try to approximate to horizontal reference definition.

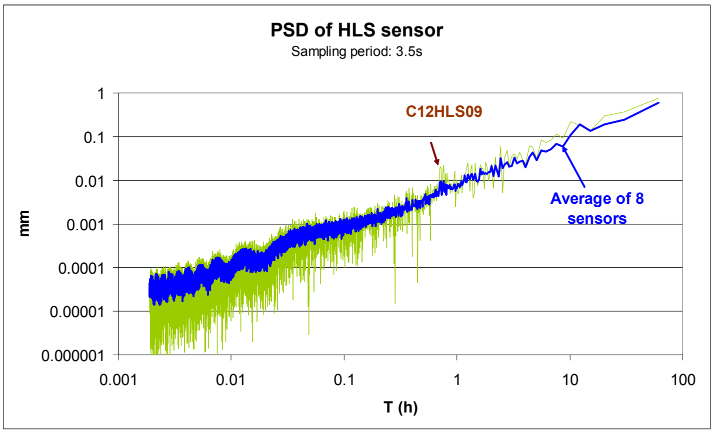


Fig. 7: Power Spectral Density of the HLS sensor

Fig.7 shows the average of 8 HLS sensors spectra obtained on a 3 day temporal window. The acquisition frequency is around 3.5s, the signal is slightly digitally filtered before the spectral analysis. Any disturbing free mod of the water can be seen, the noise level (lower periods) is correct and the main peak is around 12h, probably due to the tides. Nevertheless, we show one sensor that presents a distinct pick around T = 3/4h. It may be linked to the machine run or to the air conditioning system inside the tunnel. As a qualitative result, we can consider that the network topology is sufficiently complex to fear for critical oscillations (higher periods), and that the mechanical mounting is stable enough to limit the noise level.

## 4.3. 11 days Spectral analysis

The following configurations are to be considered: an analysis per sensor and the analysis of the beat of the mean plane. As a first step, we calculate the least square plane with the eight sensors regularly distributed all along the ring. The signal is strongly filtered (15mn integration duration); then we analyze the oscillations (in time) of that mean plane in terms of maximum slope line: amplitude and direction. As a result (fig.8, 9), any free mode of the hydraulic network exists, the tidal effects are well visible (T=6h, 8h, 12h, etc.).

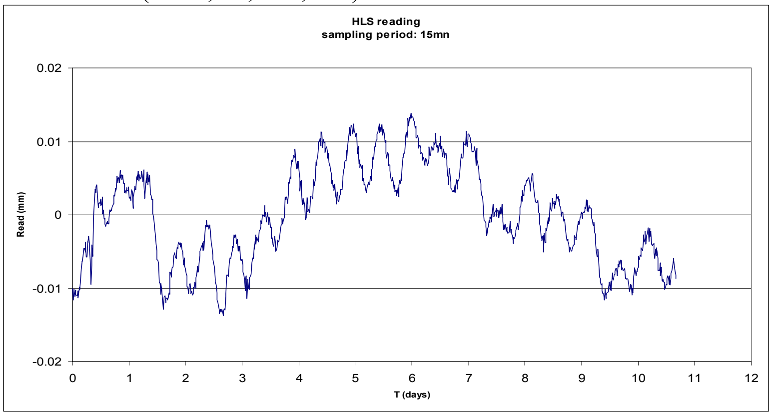


Fig. 8: HLS temporal signal

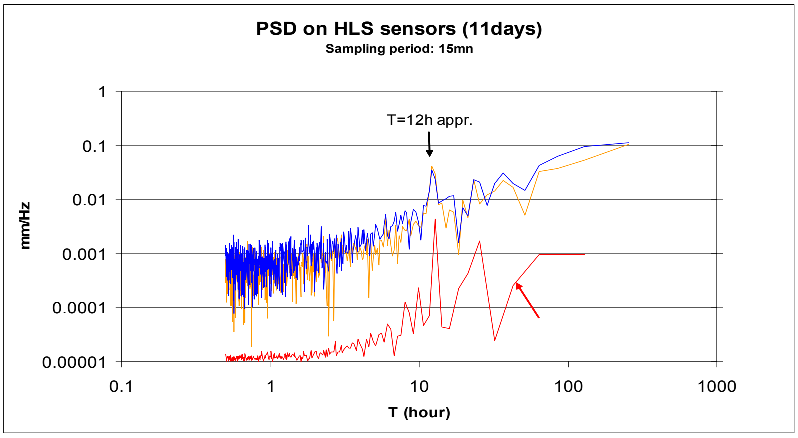


Fig. 9: HLS Power Spectral Density

### 4.4. Long term stability of the electronics sensors

The stability of the electronics is a fundamental question since its ideal Stability Time Constant (STC) [3] should be $STC_{elec} \approx$ (few µm, ∞) whatever the use of the HLS (relative or absolute). The electronics must not drift, even very slowly and it has to be proved. We held a long term stability test at Soleil from 2004 to 2005. It gave a STC roughly equal to (10µm, 1 year). These figures are encourageous. But that achievement cannot be extrapolated to many years. Consequently, we decided to apply the following strategy in order to use the HLS network in good conditions: every 6 months, we store each HLS reading when set on a fixed calibration block (fig.10). Since that calibration holds inside the tunnel, we integrate the whole real measurement channel of every sensor. With that method, we estimate that the STC is controlled to approximately (5µm, 6 months) for the position of the electronic zero of the sensor related to the mechanical machined reference surface of the sensor.

## 5. THE HLS NETWORK AS AN ABSOLUTE REFERENCE

The primary objective of the HLS system at SOLEIL is to define the reference plane for aligning the storage ring. Therefore, positioning and/or measuring paths from the Qpole MC to the zero of the HLS sensor measurement must be fully controlled. Initially, the link between both was planned by mechanical means: correction shims are determined to adjust the Qpole mechanical references according to the magnetic center (measures realized on a magnetic bench). Then, the Qpole with its shims are laid on the upper face of the girder; that face being a precise mechanical machined reference surface which also supports the HLS vessels.

### 5.1. Positioning & measuring paths of HLS on the girders

The initial analysis of the error budget led to an accuracy of about $\sigma \approx 20\mu m$ for the link between HLS and Qpole MC. Unfortunately, managing this positioning path is difficult with such a precision. A presentation of that positioning path is described in the horizontal direction instead of the vertical one in IWAA 2006 paper [3].

We propose another method, more direct and potentially better but not yet fully implemented. It is based on a measuring path instead of a positioning one and shown in Fig.10.

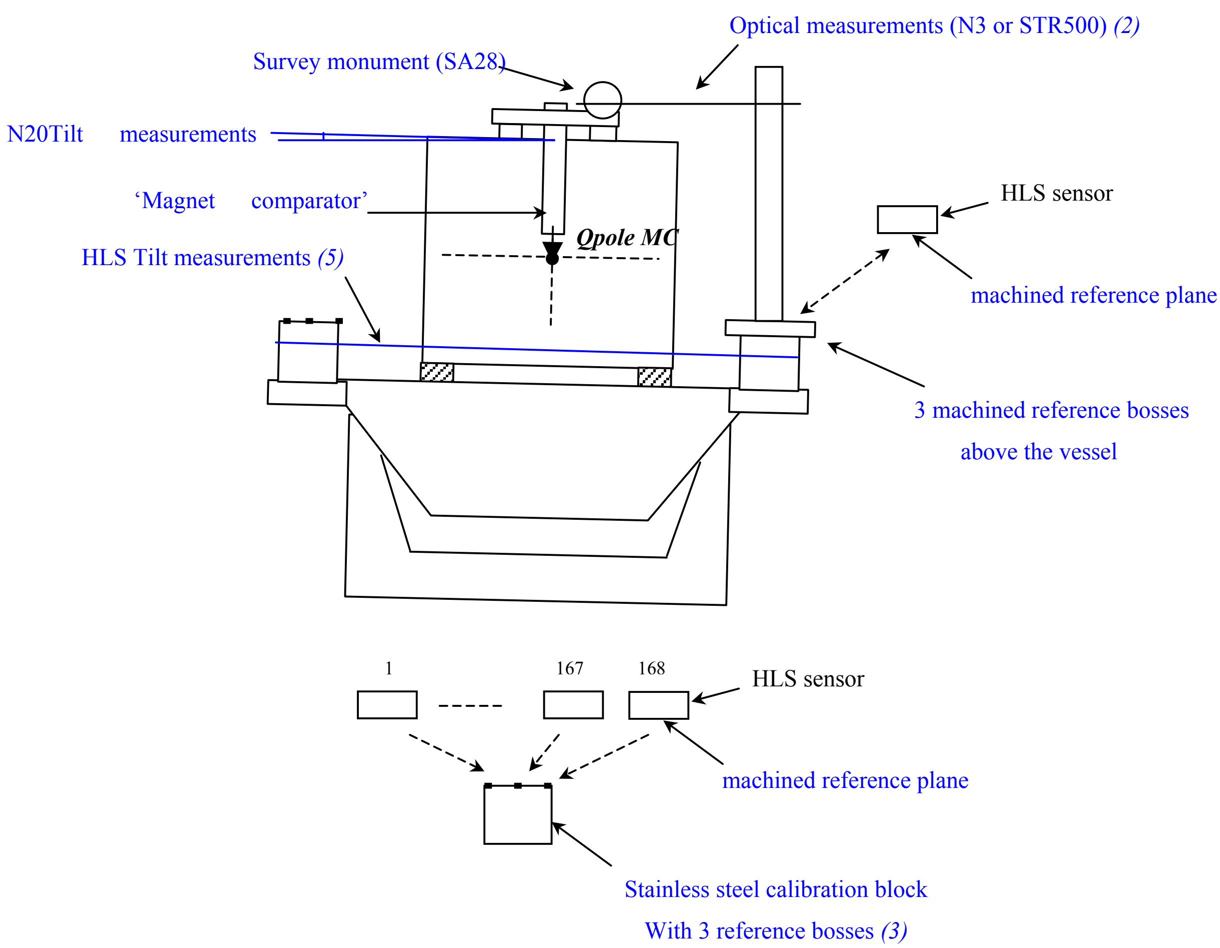


Fig. 10: Measuring path to determine the "HLS offsets"

*The following values in brackets & italics refer to the Fig.11.*

The magnet comparator measurements held on the Banc de Mesure Soleil (BMS) magnetic bench. More details are available on the magnet comparator and the BMS in [3]. The accuracy of these measurements between Qpole MC and SA28 are $\sigma$ = 11µm *(1).* The next term of the error budget is due to the dZ measurement between SA28 and the three reference bosses located above the HLS vessel. The proposed method is to measure as accurate as possible by means of a special mounting system including STR500 laser & Nivel20 clinometre. The expected accuracy should be around $\sigma \approx$ 10µm *(2)*. We could not yet implement that solution due to a lack of time, and we have been used the N3 leveling machine at very short distance in waiting for the definitive method. Then, the HLS sensor is laid on the three bosses. The next term concerns the position of the electronic zero of the sensor related to the machined reference surface of the sensor. Each of the 168 sensors are laid on a stainless steel calibration block in order to compare their whole readings, the corresponding accuracy is around $\sigma$<2µm *(3)*. Finally, since we use gravity reference, it is necessary to manage the tilt of the girder during the STR500/N3 measurements with a clinometer (Nivel20) that gives $\sigma \approx$ 5µm *(4)*.

Their quadratic sum leads to a global error of approximately $\sigma \approx$ 16µm for the STR500 version and $\sigma \approx$ 21µm for the N3 version. This set of measurements is called as "HLS offsets".

## 5.2. Comparison with N3/Nivel20 leveling

It is fundamental to notice that only three sensors per girder do not allow redundancy. As a consequence, the achieved results of a machine survey by HLS are given with an *a priori* standard deviation. Therefore, we carried out complete N3 optical level survey of the storage ring to compare the Z profile with the one calculated from HLS readings. These lasts should nevertheless, give better results (see previous chapter). Many tests already held at ESRF on an 857m circumference storage ring [4] as follows: the N3 leveling defines the reference plane and the machine vertical evolution is measured by means of HLS readings evolution and by another N3 leveling. The comparison between both methods always gave a standard deviation approximately around $\sigma \approx 70\mu m$. Since it depends on two N3 leveling, we can suppose that just one N3 leveling has:

$$\sigma_{N3} \approx \sigma / \sqrt{2} \approx 61\mu m$$

Fig.11 shows the storage ring Z profile determined by both HLS and N3 leveling at SOLEIL. The corresponding comparison is $\sigma$=57µm. That value is slightly better than the one from ESRF for a smaller circumference (354m at SOLEIL).

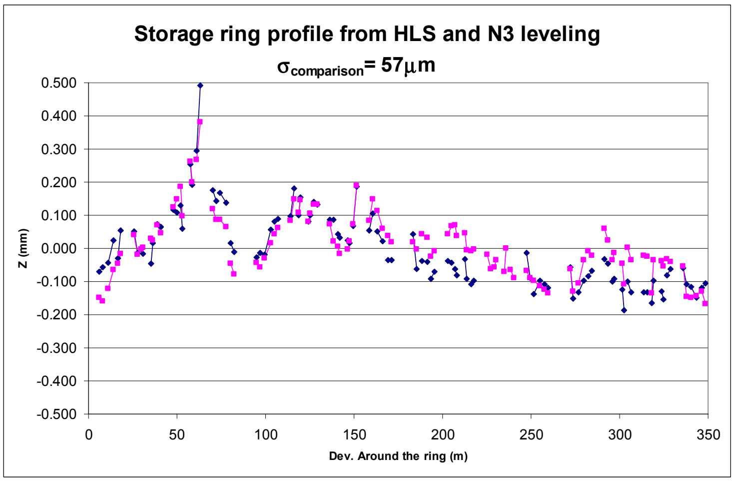


Fig. 11: Comparison of HSL & N3 leveling

In parallel, a similar study has been done for the tilt definition of the girder. Both, the Nivel20 clinometer and the HLS readings used with the HLS offset of the girder, can measure it *(4) & (5)*. Up to now, the comparison is not fully satisfactory since we achieved $\sigma$ = 25µrad instead of $\sigma \approx$ 17µrad expected. (with STR500/N20 method).

## 5.3. The storage ring alignment

Fig.12 resumes the iterative loop for positioning the girders and the fig.13 shows the achievement of the Qpole magnetic centers alignment on August 2006. It is important to notice that all SOLEIL results integrate the real Qpole magnetic center location and not only the girder. The state of the storage ring in the Z direction we present cannot be interpreted as the ultimate accuracy of the method. The HLS data acquisition was not ready at the date of storage ring alignment (March 2006), consequently we have used the N3 leveling for defining the reference plane. Then, we could partially optimize the machine adjustment due to a lack of time on essentially, the HLS offsets measurements. Nevertheless, Fig.13 shows the machine state in August, measured by the HLS.

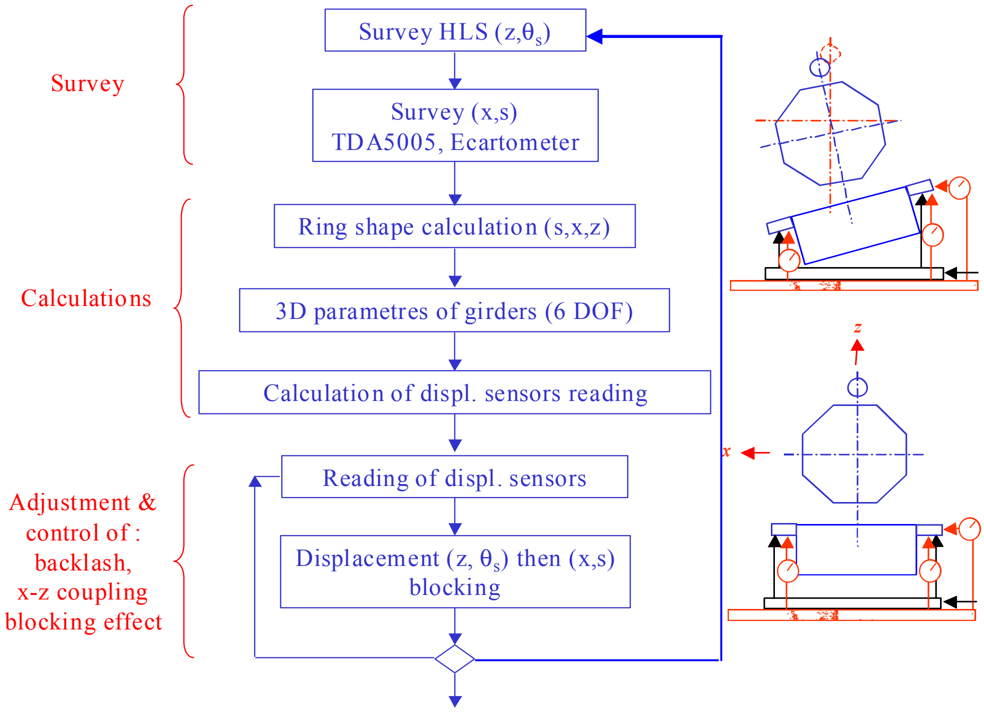


Fig. 12: Adjustment procedure of storage ring girders

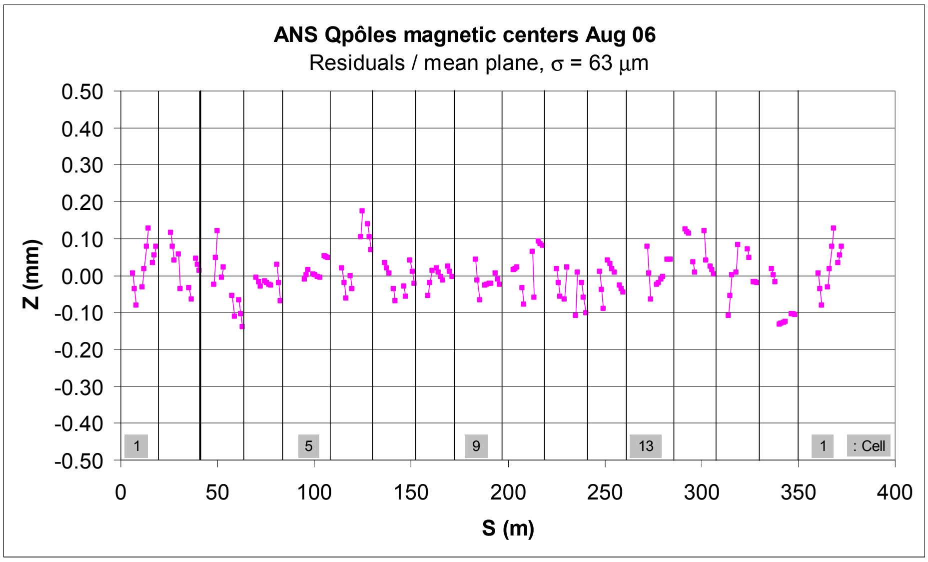


Fig. 13: Vertical profile of the storage ring achieved on August 2006

## 6. CONCLUSION

The HLS network is now fully operational. The tests we held since 2004 confirm that we can reach the primary use of the network, that is to say defining an accurate reference plane to adjust vertically the storage ring. The achieved values up to now, approximately $\sigma \approx 60$ µm including the adjustment operation, will be improved during next year because the link between HLS sensors and the Qpole magnetic centers could be better than $\sigma \approx 20$µm. However, the achieved results in terms of machine physics already confirm the high quality of the storage ring alignment since the physicists obtained several turns of the storage ring without any beam correction and without the use of the RF cavity or the sextupoles at the occasion of the very first tests. In addition, the estimation of the error budgets we present appear as being reliable since the beam natural vertical envelope without any corrector leads to an estimation of the alignment by means of the BETA model to 20µm for the Qpole magnetic center on the girders and to 50µm for the girders [6]. It has to be compared with respectively 11µm and 60µm noticed previously.

## Acknowledgments

That achievement shows the excellent work of both, girder machining and magnetic measurements directed by other SOLEIL teams (Conception/Iingénierie, Magnétisme/Insertion groups).

Such results could not be reached in so short delay regarding the size of the Alignment/Metrology Group (AMG), 5+1 persons, without the help of the SOLEIL mechanical team who has been pre-aligned the whole SR in the mm accuracy, thus favoring the fine alignment of the girders by the AMG.

## References

[1] C. Zhang, K. Fukami, S. Matsui "Primary hydrokinetics study and experiment on the Hydrostatic Leveling System", IWAA'07, Spring 8, November 2002.

[2] A. Lestrade, M. Ros "Qualification tests of the SOLEIL Storage Ring HLS", IWAA'08, CERN, November 2004.

[3] A. Lestrade C. Bourgoin, E. Guigné, M. Jagu (ATGT), M. Ros, M. Sebdaoui "Alignment Strategy Used for the Positioning of the Magnets and Girders of the SOLEIL Storage Ring", IWAA'09, SLAC, September 2006.

[4] D. Martin, "The European Synchrotron Radiation Facility Hydrostatic Leveling System –twelve years experience with a large scale Hydrostatic Leveling System", IWAA'07, Spring 8, November 2002.

[5] N. D'Oreye, W. Zuern " a very high resolution hls used in geophysics to record small signals in the frequency band ranging from earth free oscillations up to secular tilts",IWAA'08, CERN, November 2004.

[6] A. Nadji, communication privée, Synchrotron SOLEIL, September 2005.