

THE EUROPEAN SYNCHROTRON RADIATION FACILITY HYDROSTATIC LEVELING SYSTEM –TWELVE YEARS EXPERIENCE WITH A LARGE SCALE HYDROSTATIC LEVELING SYSTEM

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1. INTRODUCTION

This paper will discuss the European Synchrotron Radiation Facility (ESRF) Hydrostatic Leveling Systems (HLS) composed over 500 sensors. Note that in this discussion an HLS instrument will generally be referred to as a captor or sensor. This generic term refers to the capacitive sensor, the vessel and the temperature sensor ensemble. Refer to figure 1 for a schematic of the ESRF HLS instrument as well as its situation in the Storage Ring. We will dwell principally on the performance of the two main systems, the so-called first generation and second generation HLS, The main effort will be made to discuss how to qualify a large scale HLS.

The ESRF HLS systems as any HLS are based on a water (or liquid) equipotential surface common to all measuring points. The ESRF instruments are composed of three parts. The captor vessel which holds the liquid, a capacitive sensor measuring the capacitance (proportional to distance) between its electrode and the water surface and a temperature sensor used to correct the dilation of water as a function of temperature between the different vessels in the system

1.1 FIRST GENERATION STORAGE RING HLS

Note that in this discussion First Generation and SR HLS will be used interchangeably. This original system was conceived and installed to minimize the number of leveling surveys by providing a reliable real time height difference measure over a long (several month) time period, to control the vertical movements made by the Steinsvik Maskinindustri jacks during a machine realignment, and finally to follow machine and ground motion events in real time. As will be shown, these objectives have met with a varying degree of success

The first generation HLS is composed of 288 sensors three each installed on the 96 quadrupole girders in the Storage Ring (SR). The system has a precision of ~ 1 to $3 \mu\text{m}$ over short time spans (less than 24 to 48 hours). It is robust and relatively trouble free. The captors have been gathering data 24 hours per day over the last 12 years with only a handful of breakdowns.

1.2 SECOND GENERATION STORAGE RING HLS

This system was conceived and installed to follow the evolution of the beam line front ends and to provide a real time level reference in the beam line optical hutches. For a number of reasons, these objectives were abandoned and ultimately the system was installed on the

SR tunnel roof to provide a real time monitoring of site evolution in the vertical direction. It was also installed to provide large scale HLS qualification test system.

The second generation HLS is presently installed on the SR tunnel roof above the centers of the quadrupole girders. All sensors are installed on the interior wall with the exception of the injection zone area where they are installed on the exterior wall. Note that in this discussion Second Generation and Roof HLS will be used interchangeably. This installation is shown in figure 2.

2. HLS QUALIFICATION INTERNAL AND EXTERNAL COHERENCE

An HLS system's coherence can be qualified in two ways. The first, internal coherence refers how the system reacts with respect to known events such as a variation in the fluid level. Three examples are filling/purging of the system, electrical cut test (for SR) and most importantly the long-term stability followed in a controlled environment such as on a metrological marble. External coherence refers how well the HLS results agree with an independent control that has a well-established incertitude. Three examples are once again long term stability on a marble, machine alignment with the motorized jacks and control with the SR beam, and level and tilt surveys.

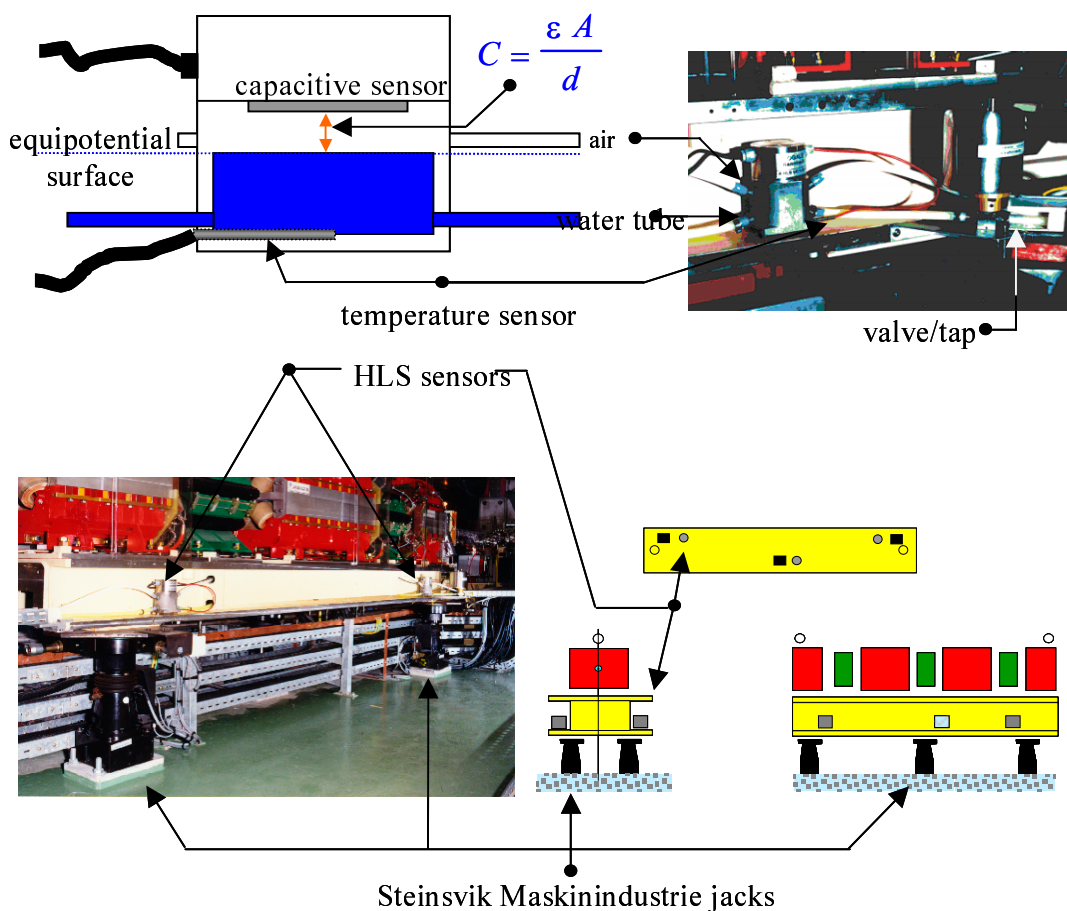


Fig. 1 Schematic of the ESRF HLS and its situation in the storage ring

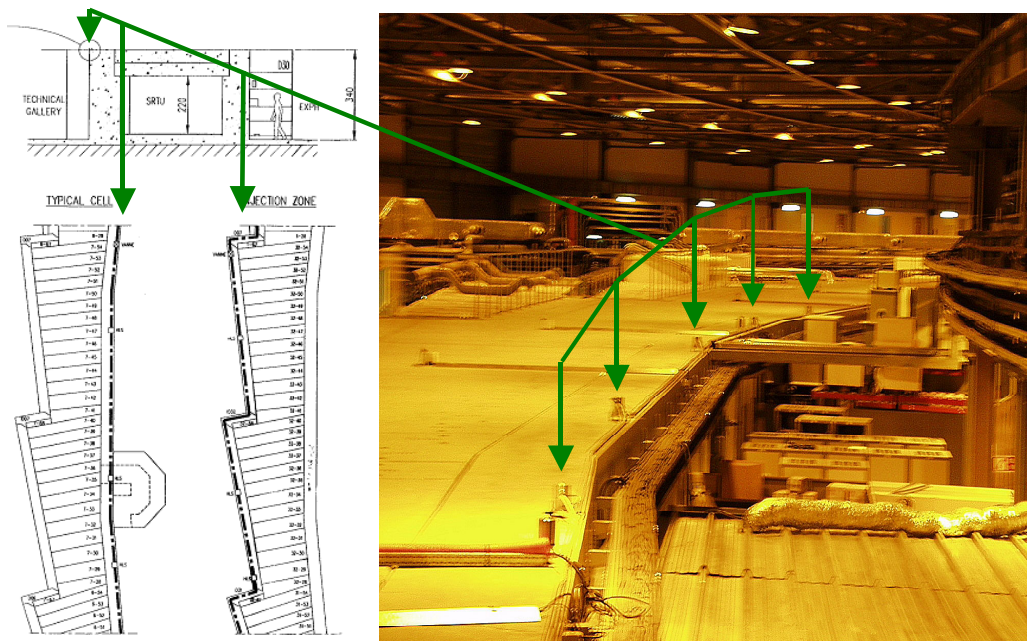


Fig. 2 Installation of the so-called roof HLS second generation HLS

2.1 HLS QUALIFICATION INTERNAL COHERENCE

The variation of the fluid level by either filling and/or purging has long been used at the ESRF to qualify the system coherence of an HLS. It provides two key controls: first that there is fluid communication between all of the vessels ensuring proper operation and a true equipotential reference surface; and secondly it verifies the sensor linearity over its full measurement range. Figure 3 shows the purging of the system over the period December 23 to 26, 1993. In the upper left corner we see the mean level of the system over this period. The upper right graph shows how the full system evolved over the period. The bottom graph shows the stability of the system with a standard deviation of 1 μm over the four hours prior to the operation.

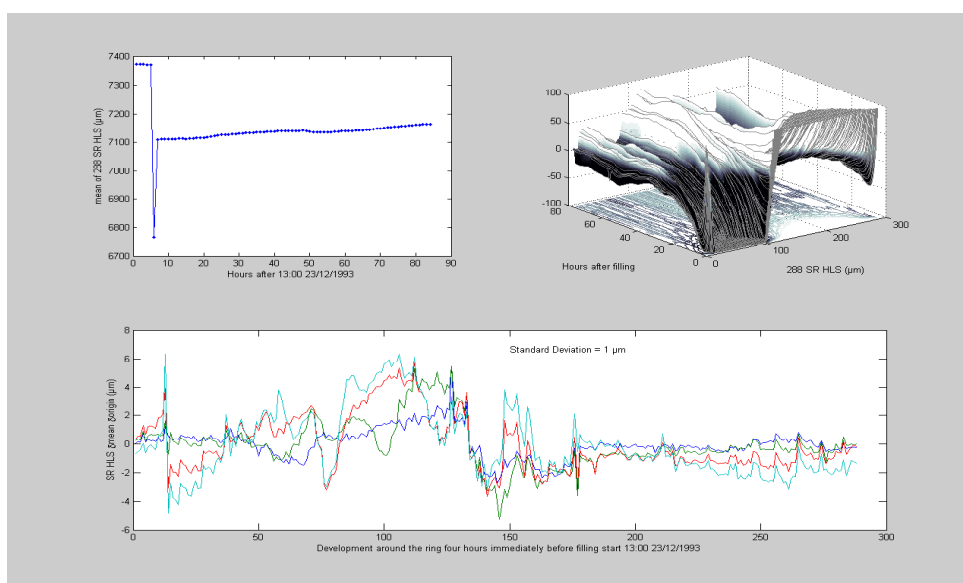


Fig. 3 Purging of the Storage Ring HLS 23 to 26 December 1993

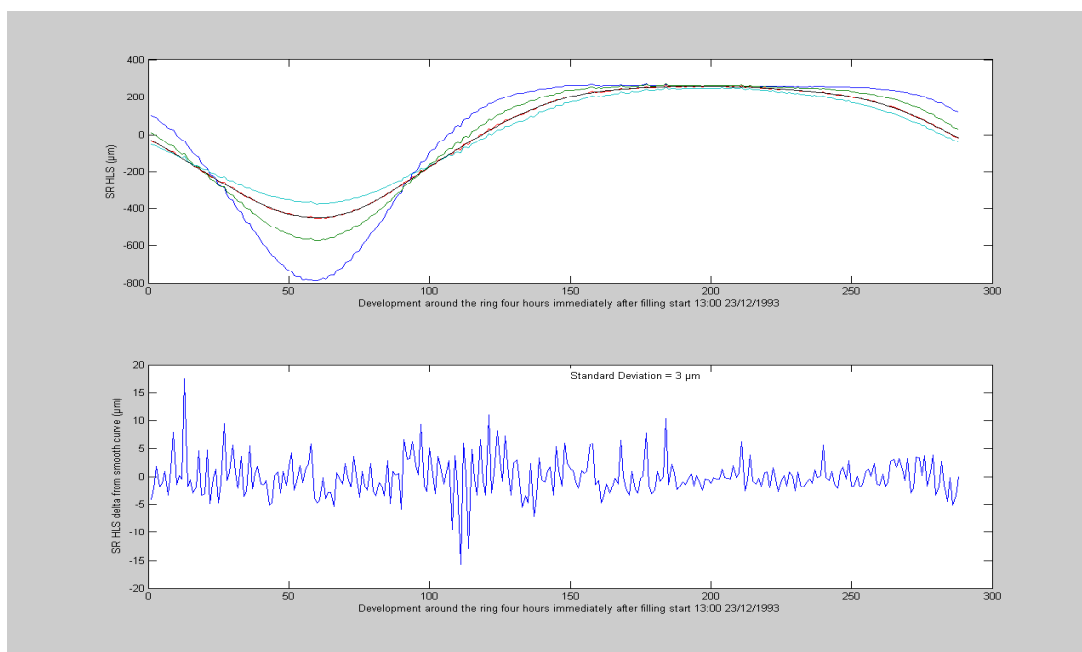


Fig. 4 Purging of the Storage Ring HLS 23 to 26 December 1993 2 to 6 hours after the purging start.

The subsequent figures 4, 5 and 6 show the evolution of the system immediately after, and 12 and 24 hours after the purging start. As one can see, although the system is seriously perturbed, it forms a smooth wave. A Fourier series (for example) can be used to model this smooth wave. Theoretically, if the system is functioning correctly, residuals from the smooth curve should be zero. However, in reality, small movements will occur and residuals with respect to the smooth curve represent a combination of these movements and departures from linearity over the measurement range for the system. For this reason it is extremely important to conduct this test during a calm period. These residuals are shown in the graphs at the bottom of figures 3 through 6. A resume of the situation for this test is given in table 1. The system is operating correctly in this instance. For comparison, figure 7 shows the system performance over a calm five-day period in September 2000. This figure gives an indication of the natural temporal change in the system under calm conditions. On the left of this figure is the development around the ring with respect to the origin for each hour over the five-day period. On the right is the standard deviation of all of the captors with respect to their initial position as a function of time. There is *degradation* in the standard deviation of 2.5 μm in 48 hours.

Generally, sensor linearity should only be an issue if there are large variations over time. At the ESRF this is not the case. Typical real peak-to-peak movements are in the order of $\pm 300 \mu\text{m}$ per six months. Furthermore the water level doesn't vary significantly over time. When there is a blockage in the system, a discontinuity in the wave is formed.

<i>Time after purge start</i>	<i>"Wave" peak to peak (μm)</i>	<i>standard deviation of residuals with respect to the "Wave" (μm)</i>
-2	± 4	1
2	± 1000	3
12	± 250	6
24	± 80	9
48	± 40	13

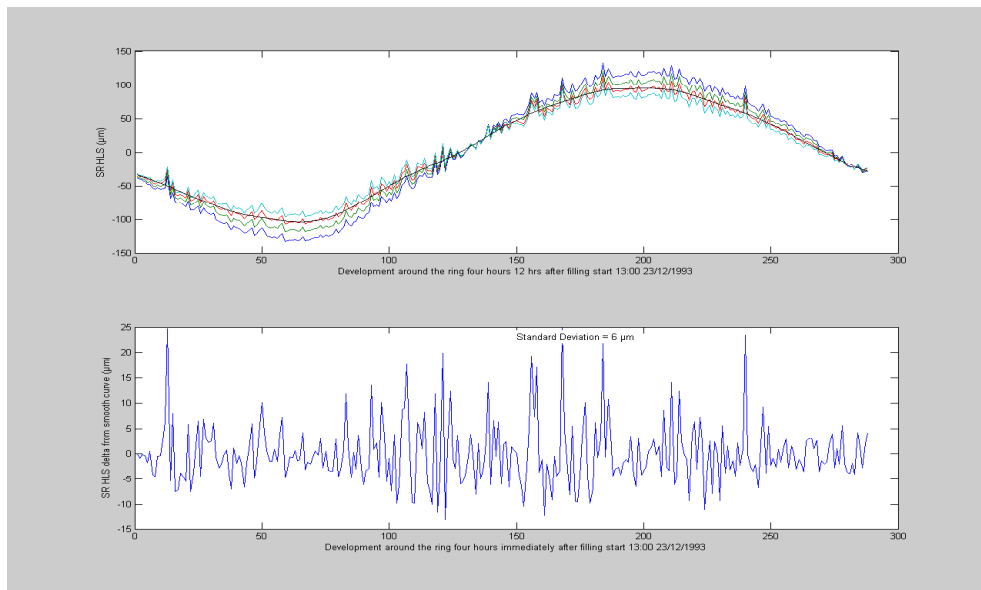


Fig. 5 Purging of the Storage Ring HLS 23 to 26 December 1993 10 to 14 hours after the purging start.

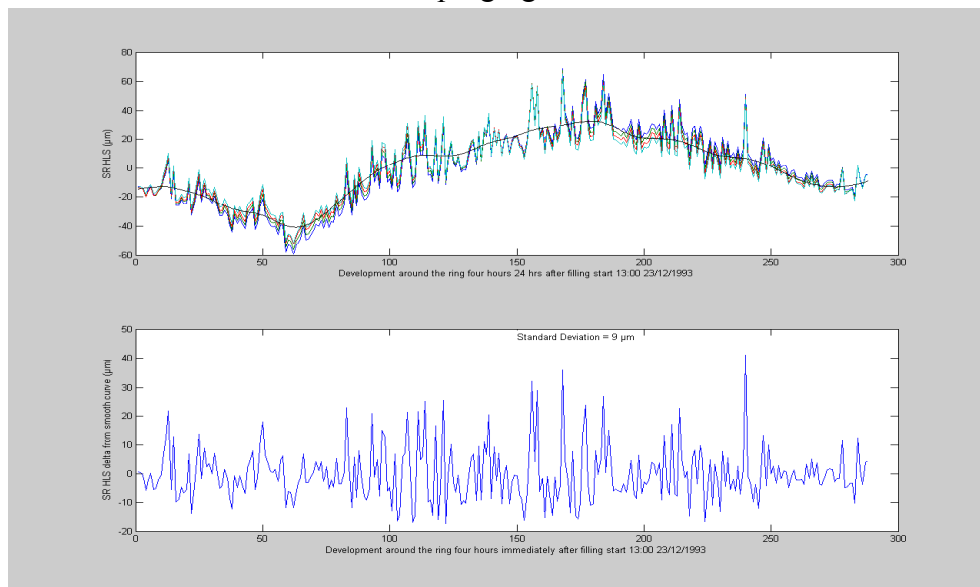


Figure 6 Purging of the Storage Ring HLS 23 to 26 December 1993 22 to 26 hours after the purging start.

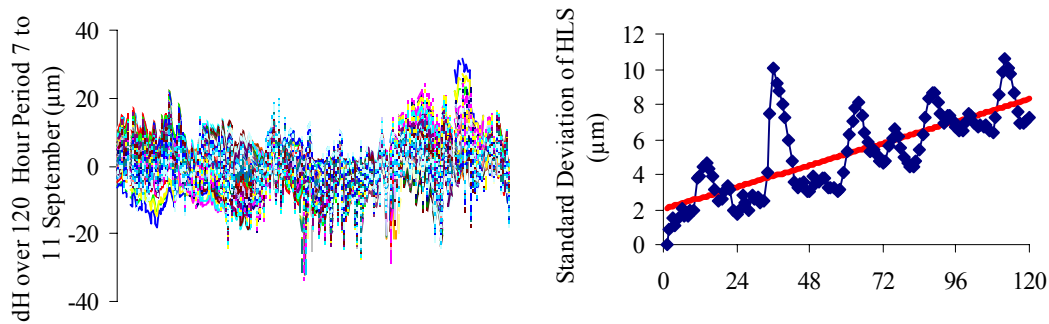


Fig. 7 Perturbations to the SR HLS system over a calm five-day period in September 2000.

The most important internal coherence test is the captor long-term stability. Captor long-term stability refers to coherence between real height difference and those reported by the HLS. This test should be performed on every HLS captor over a sufficiently long time period so as to demonstrate its temporal stability. At the ESRF this is conducted in a temperature controlled laboratory on a metrological marble. The marble is massive and no flexion is to be expected. All HLS are fixed to the marble and can only move as an ensemble in a plane. Theoretically after the planar movements have been modeled and removed from the captor readings we should see no movement between the different sensors.

Figure 8 shows the results of tests made on the first generation SR HLS over the three-month period April to July 1997. As can be seen, the overall standard deviation is $16.3\ \mu\text{m}$. These results show very clearly that this particular sensor has a long term drift associated with it. The manufacturer of the ESRF HLS, FOGALE Nanotech has since confirmed this drift and proposed a solution.

In parallel to the tests on the first generation system, the so-called second-generation system was also tested. This system proved to be significantly more stable with an overall standard deviation over the 3-month period of $1.7\ \mu\text{m}$. These results are shown in figure 9.

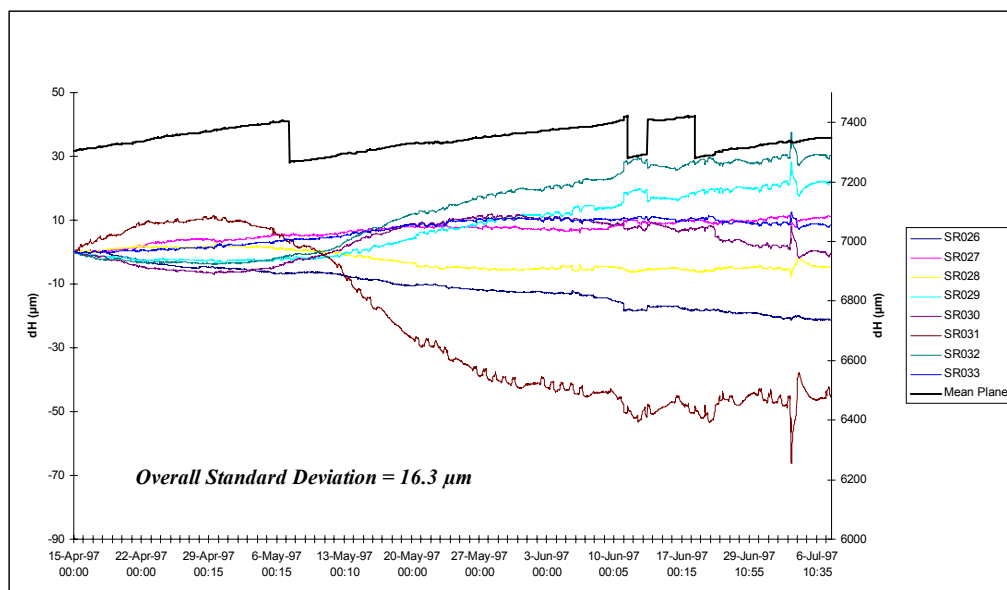


Fig. 8 Laboratory tests showing the performance of the ESRF first generation HLS

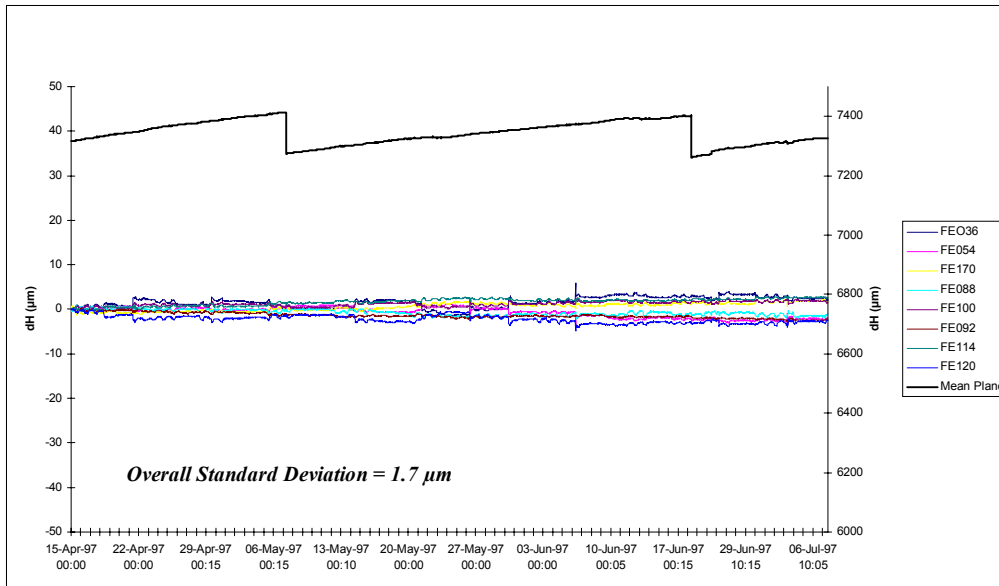


Figure 9 Laboratory tests showing the performance of the ESRF second generation HLS system

These results demonstrate the absolute imperative to make long-term tests to validate the temporal behavior of an HLS system. This is of critical importance considering that one of the main incentives of using an HLS is to have real-time reliable data. If the instrument itself demonstrates a temporal drift, it is impossible to later separate real movements from drifts.

2.2 HLS QUALIFICATION EXTERNAL COHERENCE

As was mentioned earlier, external coherence refers how well the HLS results agree with an independent control that has a well-established incertitude. The captor long-term stability test can be considered both an internal and external coherence test.

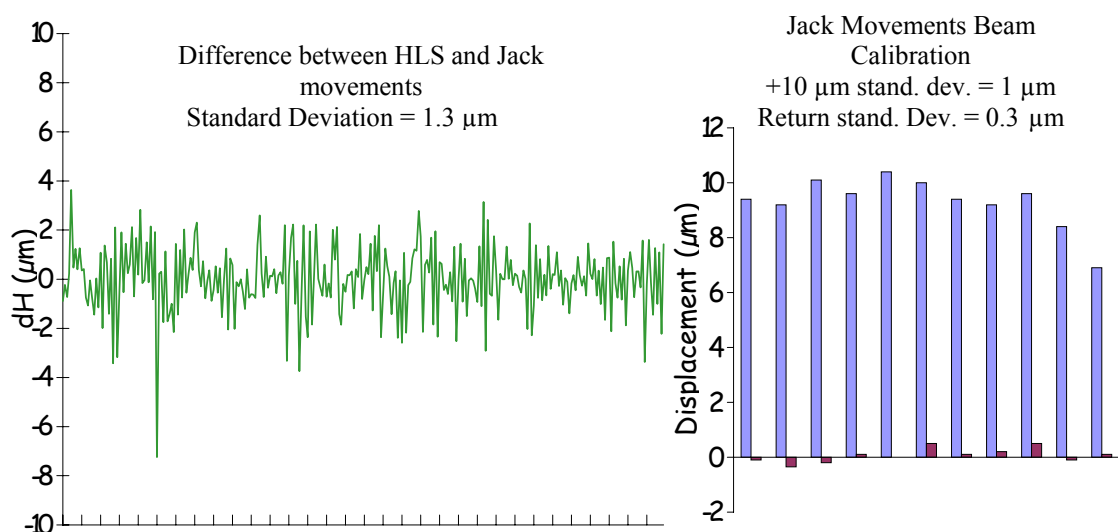


Figure 10 Correlation between the first generation SR HLS, the Steinsvik Maskinindustrie jacks and the ESRF electron beam.

One of the primary uses of the first generation SR HLS is to control the vertical movements made by the Steinsvik Maskinindustrie jacks during machine realignment. The system has been used extensively and very successfully to control the 6-month vertical realignment operations of the SR with well as a number of experiments. This has provided a unique opportunity to control the system with the ESRF electron beam and to a smaller extent the high precision jacks installed under the ESRF magnet girders. Figure 10 shows the excellent correlation first between the HLS and the jacks and then the jacks and the beam. These tests show that the short-term reliability of the first generation system is excellent. The obvious question is: what is short term? In the case of this particular system we consider the results to be of excellent quality over a 48-hour period.

The most important external qualification of an HLS is to compare it with leveling and tilt data. This type of qualification has been used extensively at the ESRF over the last twelve years. The HLS and Level/ Tilt data will be considered in two different ways. First, it is analyzed as the evolution of a system by the difference in the development around the ring at two different times, and secondly as the evolution of a single or girder triplet of sensors in time. This is illustrated in the graph shown in figure 11.

The SR HLS is not registered in any way, all calculations are referenced with respect to an origin. To eliminate the effect of evaporation the mean sensor reading is subtracted from all readings. For consistency, these calculations are systematically applied to the Roof HLS and the Level and Tilt (LT) data. All Level /Tilt data for the SR are transformed to equivalent motion at the HLS positions. The Roof HLS vessels are equipped with a survey reference and are leveled directly. Calculations are made and referred to in the following way at time $t=x$ with respect to an origin at time $t=0$ for:

$$\begin{aligned}
\text{HLS sensor}_i \text{ reading } H_{i,t=x} &= \left(hls_i - n^{-1} \sum_{j=1}^n hls_j \right)_{t=x} - \left(hls_i - n^{-1} \sum_{j=1}^n hls_j \right)_{t=0} \\
\text{Level/Tilt}_i \text{ reading } LT_{i,t=x} &= \left(lt_i - m^{-1} \sum_{k=1}^m lt_k \right)_{t=x} - \left(lt_i - m^{-1} \sum_{k=1}^m lt_k \right)_{t=0} \\
\text{HLS}_{i+1} \text{ wrt HLS}_i \text{ reading } ddH_{p,t=x} &= (H_{i+1} - H_i)_{t=x} \\
\text{Level/Tilt}_{i+1} \text{ wrt Level/Tilt}_i \text{ reading } ddLT_{p,t=x} &= (LT_{i+1} - LT_i)_{t=x} \\
\text{Height difference between HLS}_i \text{ and Level/Tilt}_i & dZ_{i,t=x} = (H_i - LT_i)_{t=x} \\
\text{Double difference between HLS and Level/Tilt } ddZ_{p,t=x} &= (ddH_p - ddLT_p)_{t=x}
\end{aligned}$$

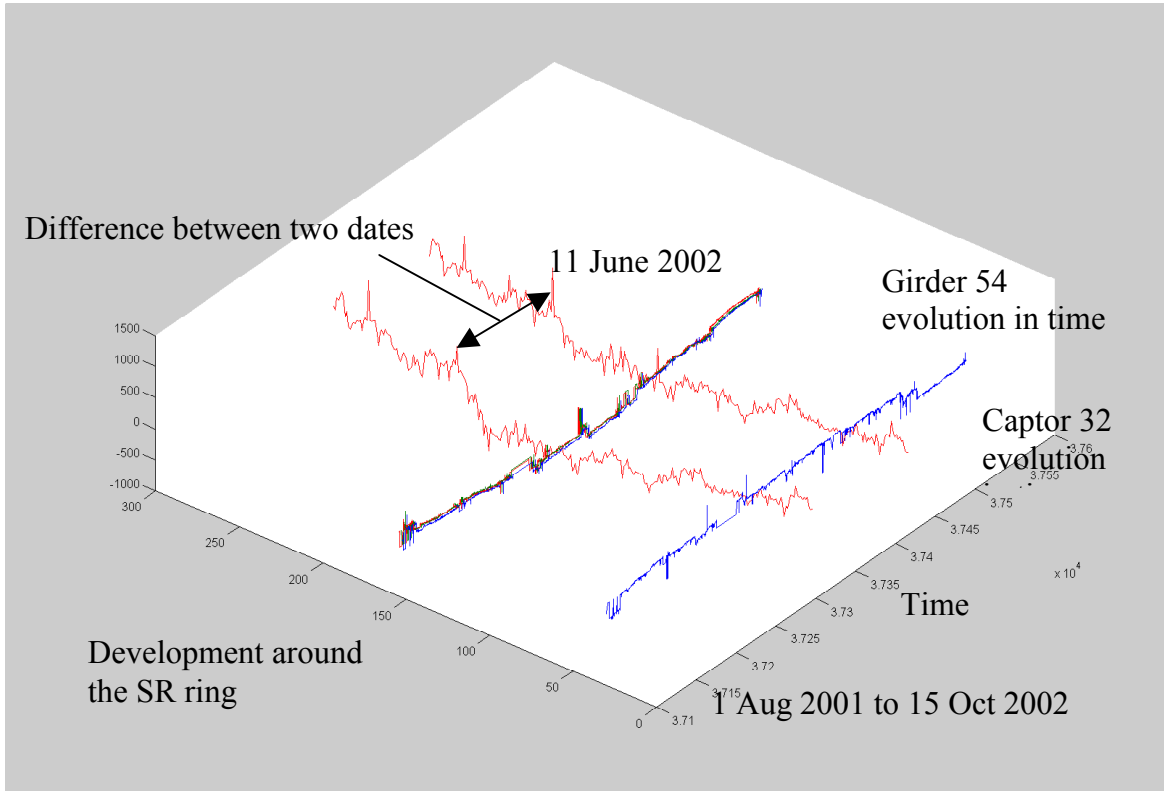


Figure 11 The manner in which the HLS and Level/Tilt data are compared.

Calculations of interest are the difference in the evolution of height at the HLS captor positions measured by the HLS and Level/Tilt surveys ($dZ_{p,t=x}$); and the double differences of these values between adjacent HLS ($ddZ_{p,t=x}$). In particular we will consider the standard deviations of the full system $SDdZ_{p,t=x}$ and $SDddZ_{p,t=x}$

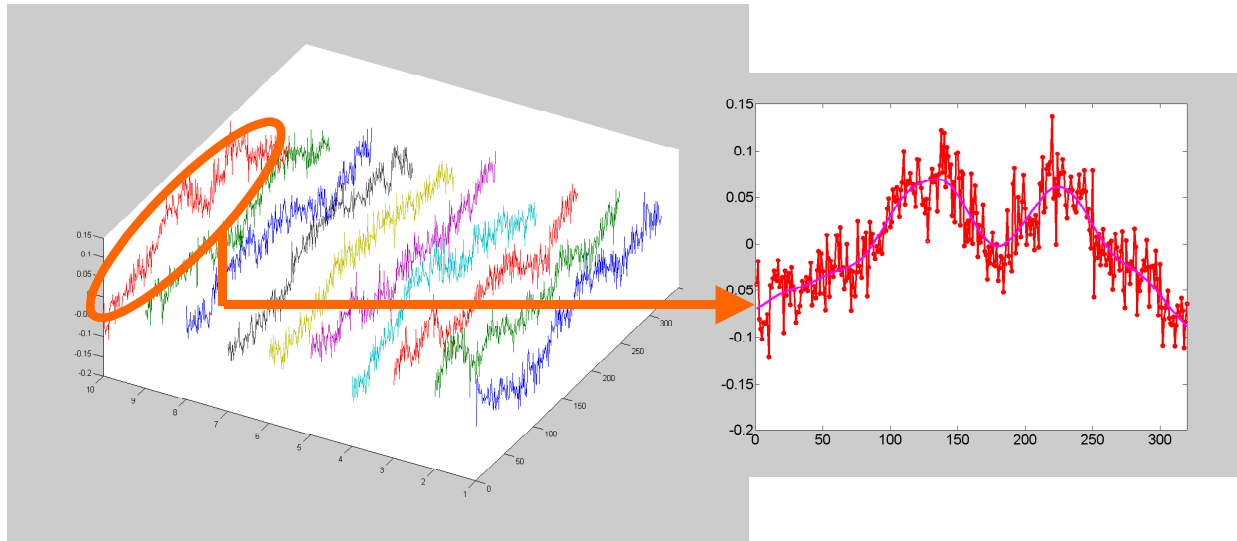


Figure 12 To the left is a series of 10 simulations of the ESRF SR level network while to the right is one of these simulations showing the error envelope and consequent incertitude associated with this level net.

There is an error envelope of incertitude associated with each level network. This envelope can be determined either by simulation or by a least squares adjustment calculation. Typically, for a level survey heights will oscillate about a smooth curve within this error envelope. It is the reference that will determine the precision with which a level survey can be used to control the HLS. This incertitude is demonstrated in the case of the ESRF SR level survey by the graphs shown in figure 12.

A priori it is assumed that the HLS gives significantly superior results to the Level/Tilt surveys. Consequently, the majority of any difference detected between them should be attributable to the level and tilt survey incertitude. For comparison, the incertitude in the Z determination issued from the least squares adjustment calculation of the level survey will be considered the reference. For the a priori assumption to be true, $SDdZ_{p,t=x}$ and $SDddZ_{p,t=x}$ must be statistically equivalent or at least very close to this reference incertitude. For example, given that the Level/Tilt incertitude for the Storage Ring survey is $57\mu\text{m}$, and assuming that the incertitude of the HLS is $10\mu\text{m}$ for this arguments sake, $SDdZ_{p,t=x}$ should be $58\mu\text{m}$ (i.e. $\sqrt{10^2 + 57^2}$). If $SDdZ_{p,t=x}$ is significantly larger, one can conclude that the HLS incertitude is not superior to the level and tilt survey results. Finally, more than one comparison should be considered.

In the early years of the ESRF a number of comparison tests between N3 leveling and the HLS were made. At the time (1993 to 1994) seven of these comparisons gave a mean standard deviation in the height difference $SDdZ$ of $100\mu\text{m}$. The mean double difference standard deviation $SDddZ$ was $79\mu\text{m}$. No comparisons between tilt measurements and the HLS were made at that time. Figure 11 shows one of these previously published comparisons.

The 1993 to 1994 data shown in figure 11 was revisited and the tilt measures included. We find values of SDdZ of 71 μm and SDddZ of 62 μm . These results are shown in figure 12. We can compare these results to a more recent period of August to October 2002. This gives results of 92 and 69 μm for SDdZ and SDddZ respectively shown in figure 13. These values show that for the double difference data at least, results are very similar today as those made ten years ago. Finally we can do the same for an equivalent period of time for the tunnel roof system (September to December 2001). These results give values of SDdZ of 73 μm and SDddZ of 41 μm .

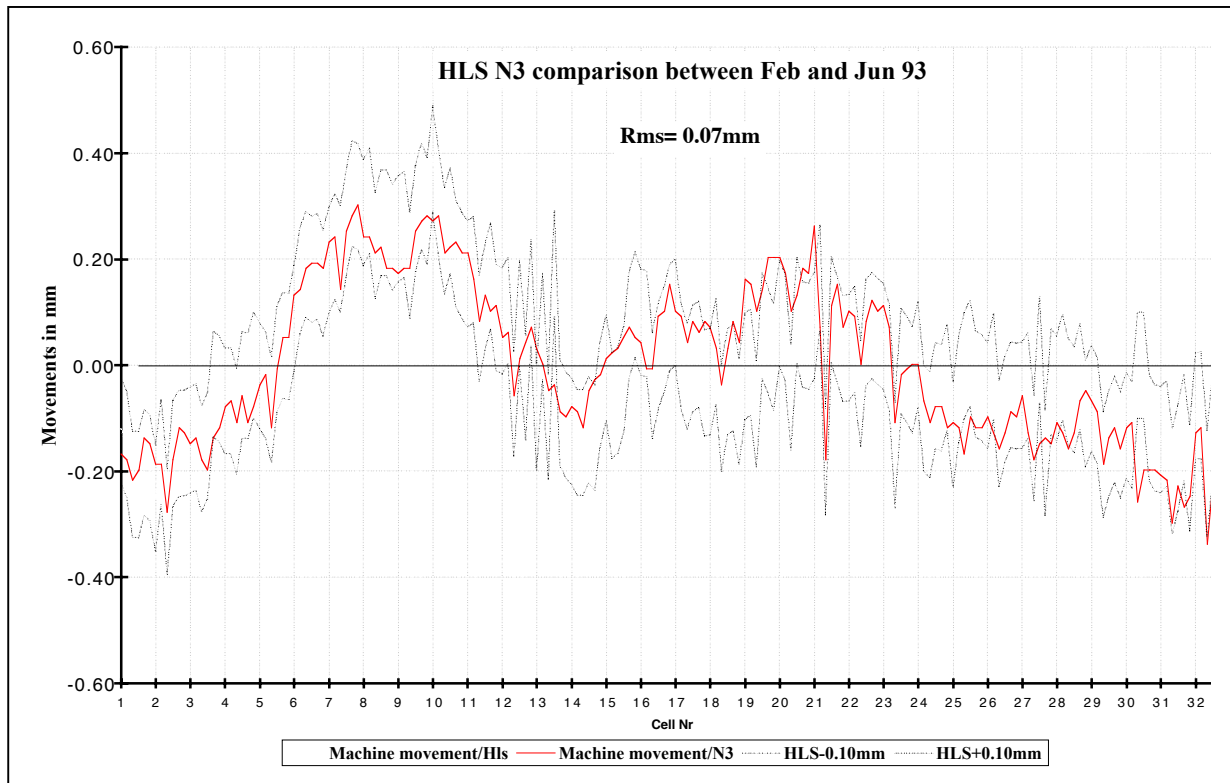


Figure 13 Comparison between HLS and leveling in 1993. Note that no tilt data was used at that time.

Calculating SDdZ and SDddZ for both the SR and Roof systems and for 28 combinations of surveys over the period August 2001 to October 2002 give the results summarized in table 2. Values for the absolute and relative errors issued from the least squares adjustment calculations (the so called reference) are also given.

For the first generation SR HLS, SDdZ is 120 μm for the period 2001 to 2003 (100 μm for the period 1993 to 1994). The reference value error envelope for this level survey is 57 μm . SDddZ is 87 μm for the period 2001 to 2003 (79 μm for the period 1993 to 1994). The reference value error envelope for this level survey is 38 μm . Both SDdZ and SDddZ are superior to the reference incertitude's and we can say that this system is not particularly coherent over the long term.

These results simply confirm those shown in figure 8. On the other hand, the second generation HLS installed on the roof of the SR tunnel fulfills the criteria for a system giving significantly superior results to those of the Level/Tilt survey data. In other words, we may consider this to be a reliable system.

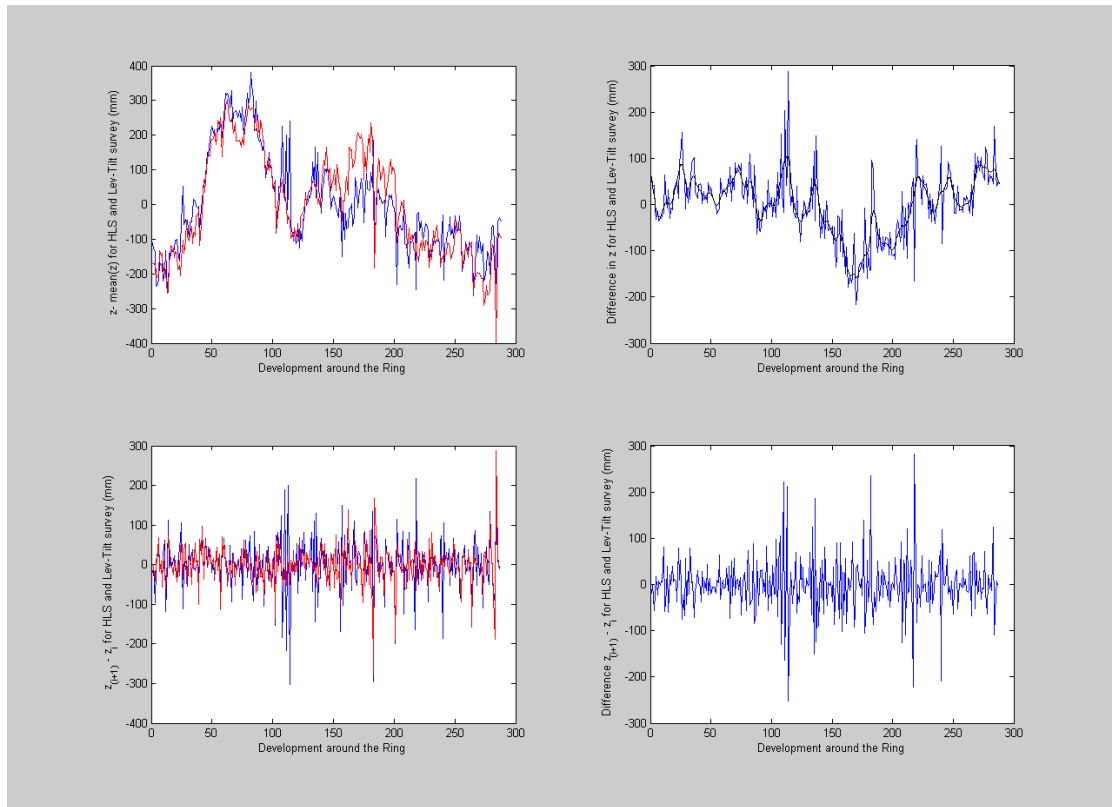


Figure 14 Data from the previous 1993 to 1994 revisited but this time including tilt data. SDdZ is 71 μm and SDddZ is 62 μm .

<i>HLS System</i>	<i>dZ Level/ Tilt Incertitude issued from Simulation and Calculation (μm)</i>	<i>Level/Tilt HLS comparison SDdZ (μm)</i>	<i>ddZ Level/ Tilt double difference Incertitude issued from Simulation and Calculation (μm)</i>	<i>Level/Tilt HLSdouble difference comparison SDddZ (μm)</i>
First Generation SR HLS	57	120	38	87
Second Generation Roof HLS	151	120	32	35

Table 2 Results of HLS Level/Tilt comparisons for the ESRF SR and Roof HLS.

This type of analysis is interesting, but it doesn't allow one to fully appreciate the system behavior. This is not a trivial problem given the enormous quantity of data. In one year we collect approximately 2.5 million data points for the SR HLS alone! This sheer quantity of makes it difficult to imagine an all-encompassing representation to this data. Looking at individual captors over this period is informative – however for the case of the ESRF SR HLS there are 288 of them! Nonetheless, several examples showing this type of data representation are given at the end of this document in annex 1.

Another way of looking at this data is to consider triplets of captors installed on the girders. Of particular interest in accelerators is the radial (across the girder) and longitudinal (along the girder) tilt. Once again several representative examples are given in annex 2.

Examples show in annexes 1 and 2 are interesting in so far as they show the captor behavior over a long time period. They also demonstrate the remarkable advantages of using this type of system when it is operation correctly.

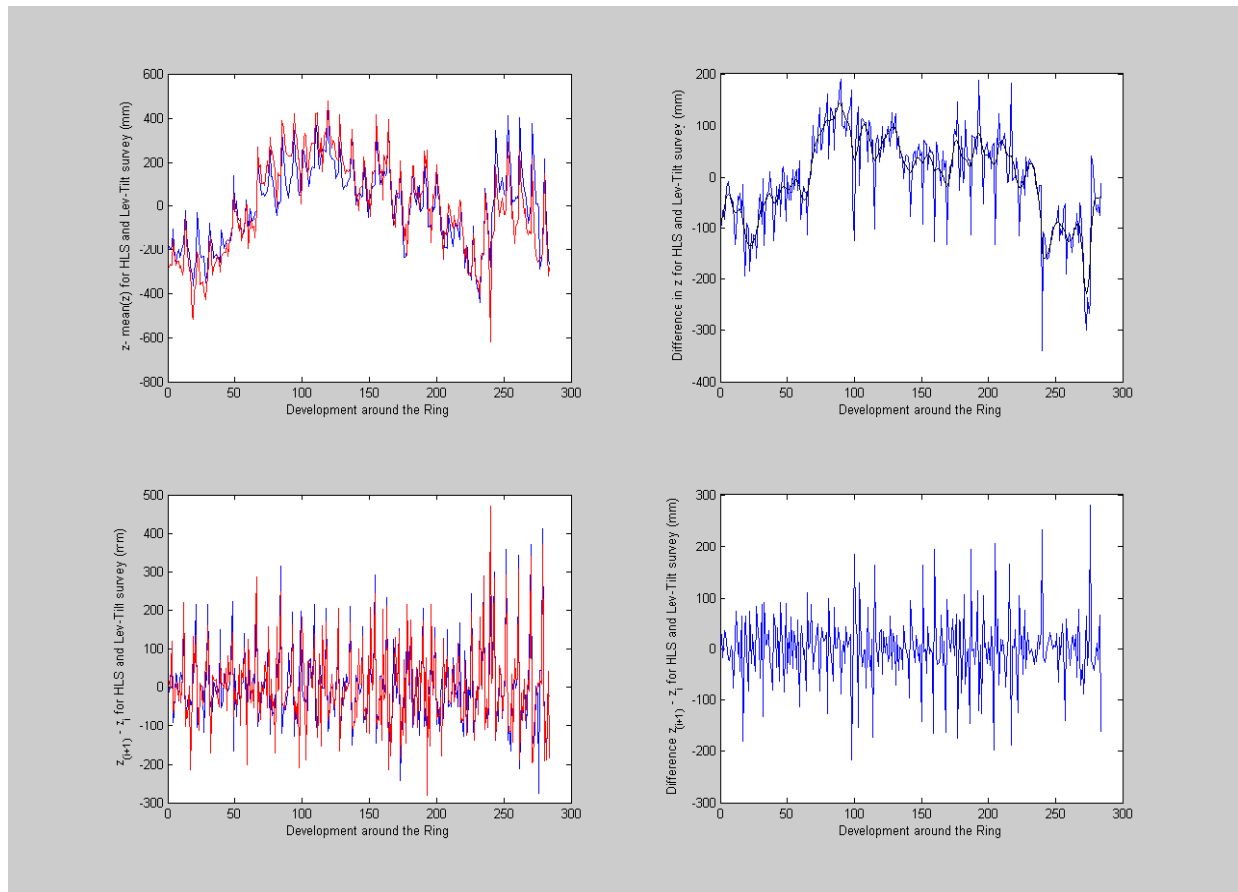


Figure 15 Data from 2002 with a SDdZ of 92 μm and SDddZ of 69 μm .

3. CONCLUSIONS

This paper has spent considerable time discussing and developing the methods used at the ESRF to qualify the proper operation and coherence of an HLS. In particular the importance of long term stability and independent control with an instrument that has a well-established incertitude, namely the level and tilt surveys made at the ESRF.

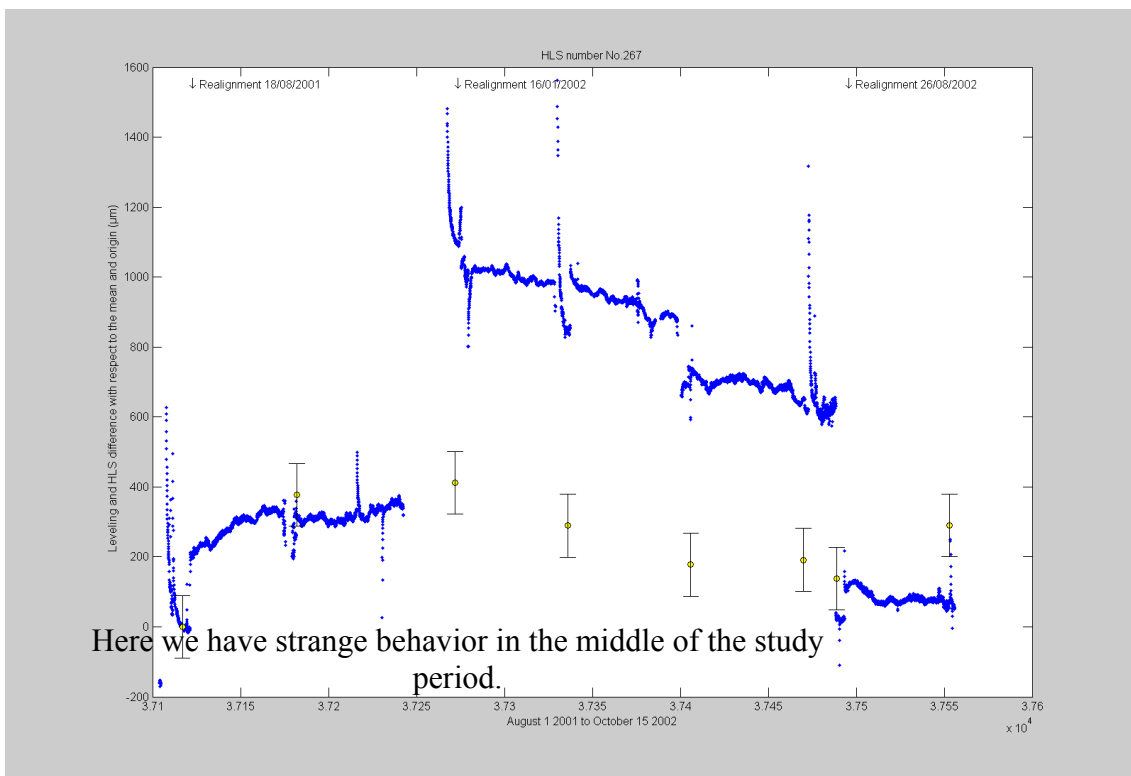
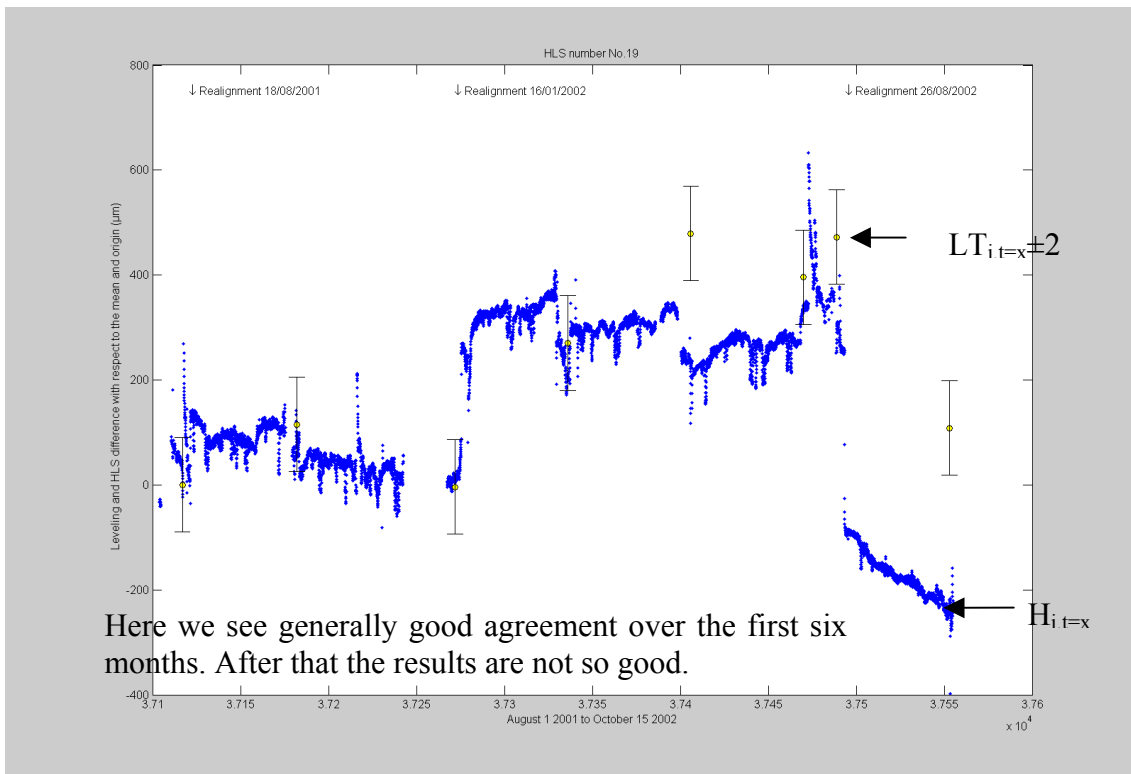
The so-called first generation HLS was conceived and installed to fulfill three main objectives. The first, to minimize the number of leveling surveys by providing a reliable real time height difference measure over a long (several month) time period, has not been particularly successful. The second, to control the vertical movements made by the Steinsvik Maskinindustri jacks during the machine realignment has been very successful. The HLS is regularly employed at the ESRF permitting the real time control of the machine realignment with beam in the machine. This provides a considerable savings in time at the startup for the machine as all pertinent parameters can be followed and corrected on line. Finally following machine and ground motion events in real time is generally reliable over short time spans typically in the order of 24 hours to two weeks.

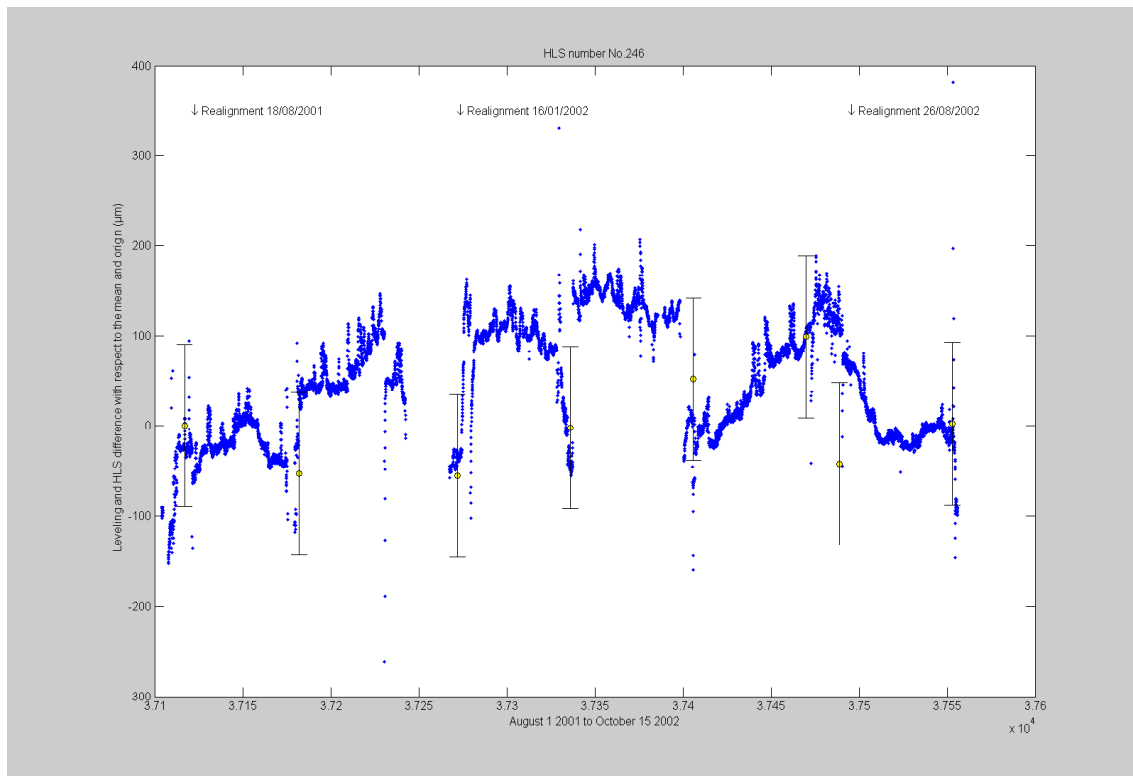
The second generation HLS presently installed on the Storage Ring tunnel roof on the other hand has unequivocally proved to be a reliable system. It demonstrates the usefulness of such a system when it is operating correctly.

4. REFERENCES

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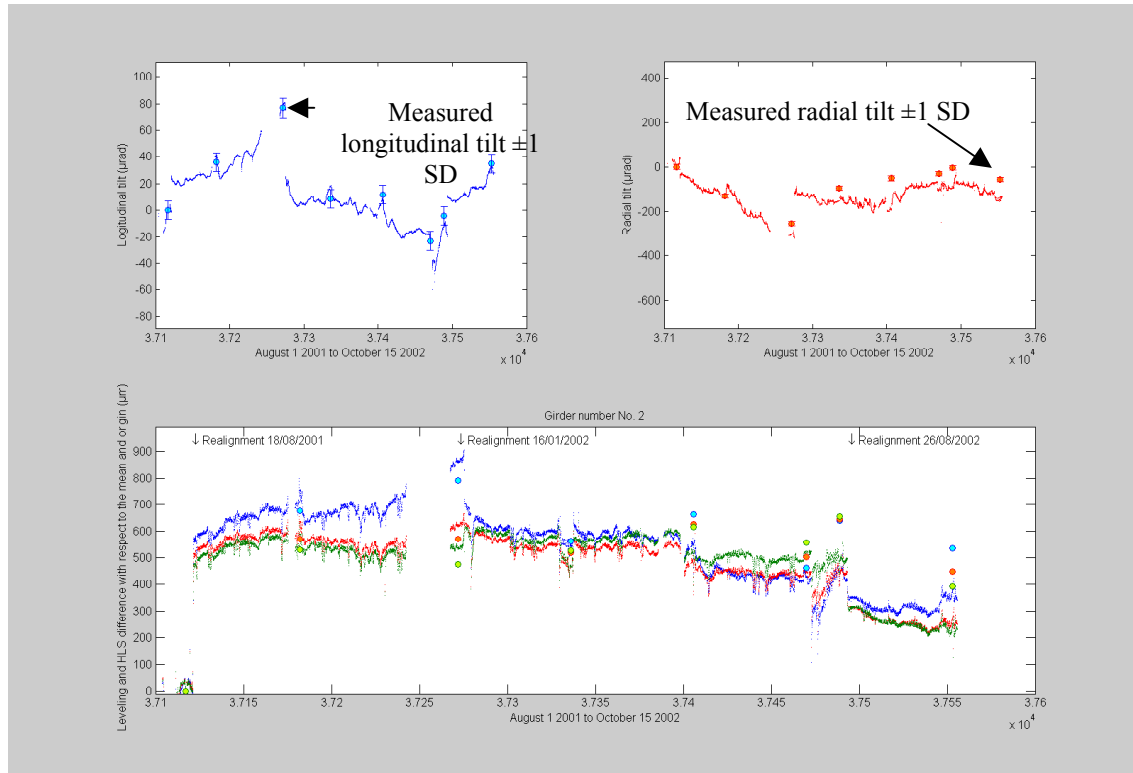
ANNEX 1 DEVELOPMENT OF INDIVIDUAL CAPTORS OVER TIME



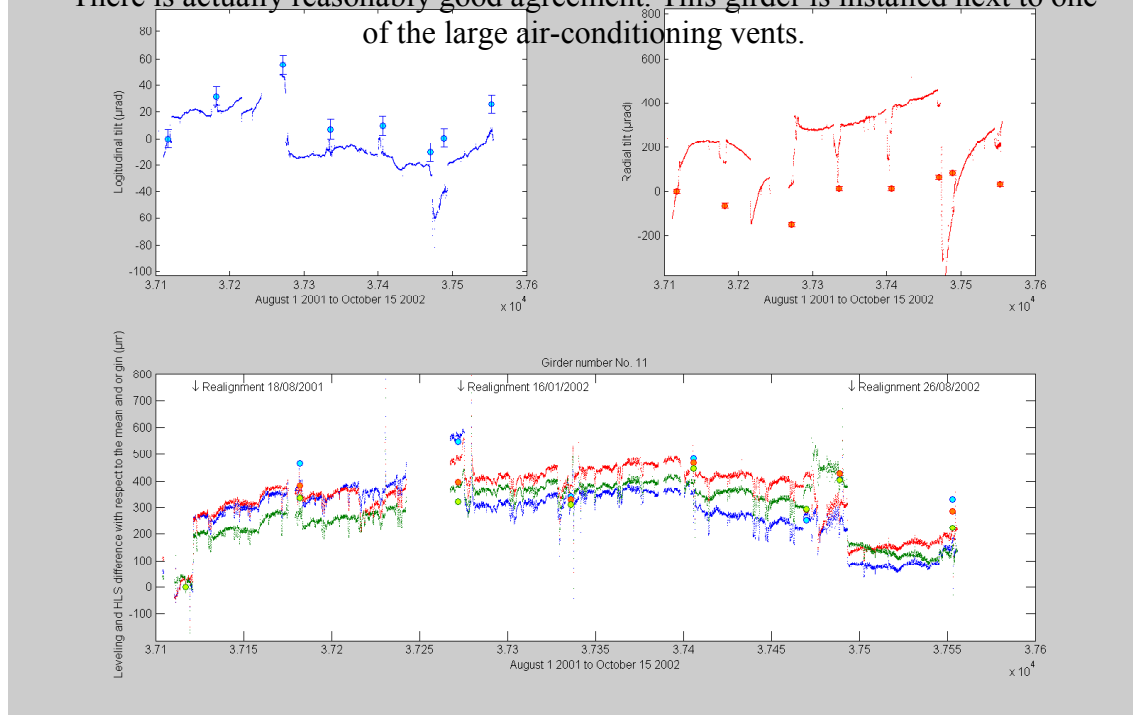


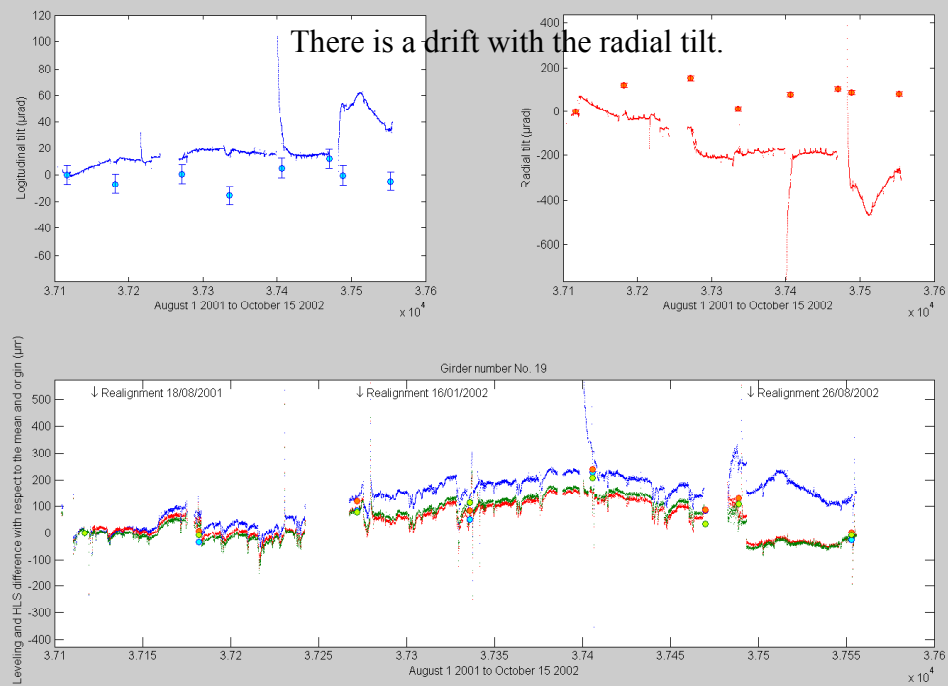
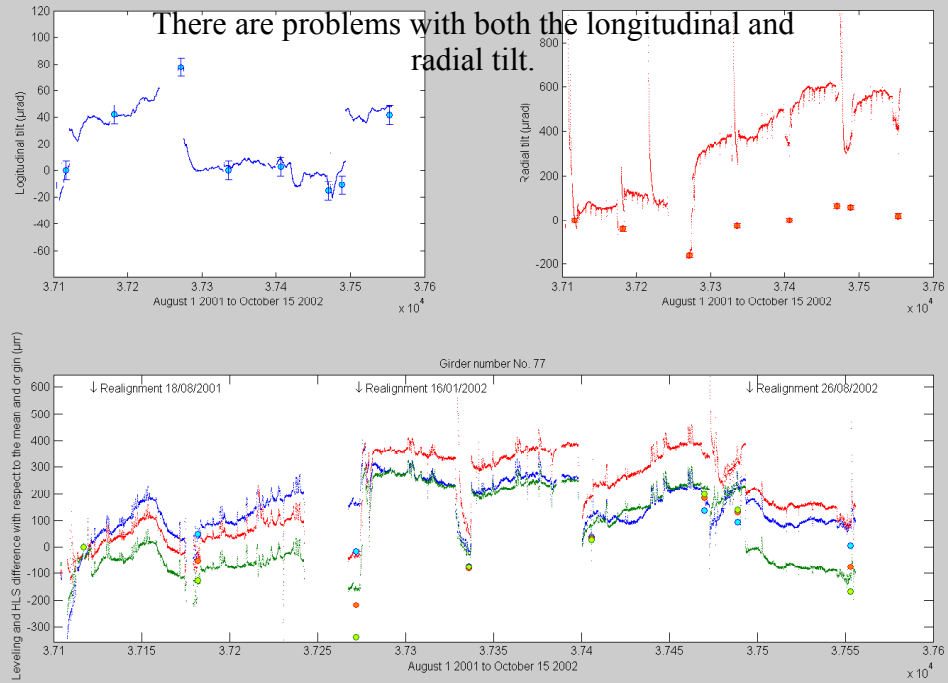
Here there is excellent agreement over the full study period

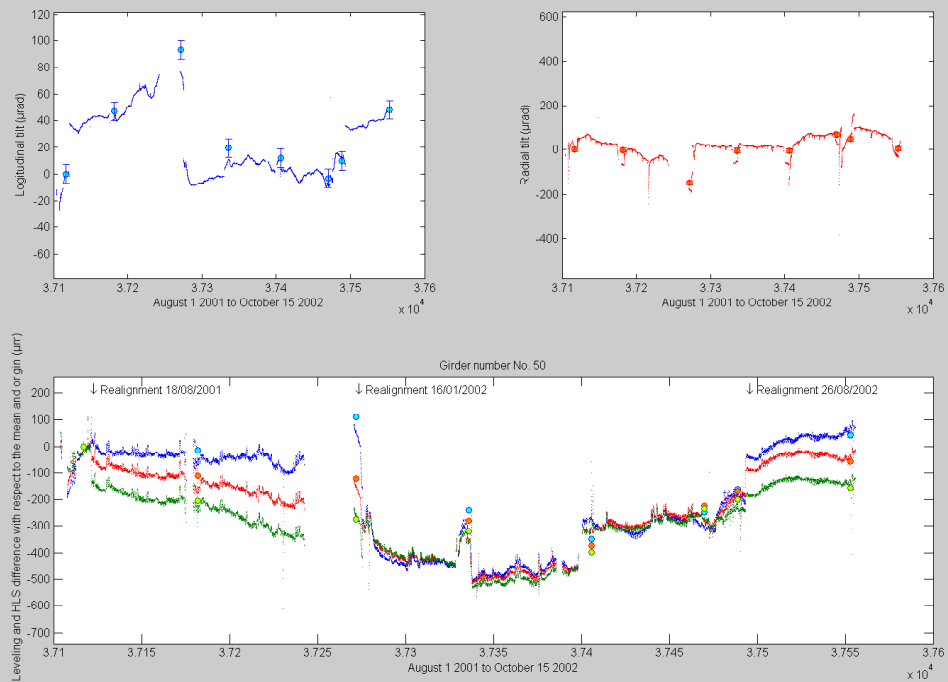
ANNEX 2 - DEVELOPMENT OF CAPTOR TRIPLETS INSTALLED ON GIRDERS



There is actually reasonably good agreement. This girder is installed next to one of the large air-conditioning vents.







Excellent agreement. This slide also illustrates the advantages of using the HLS when it is working well to follow long-term movements