SOME REFLECTIONS ON THE VALIDATION AND ANALYSIS OF HLS DATA

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1. INTRODUCTION

A Hydrostatic Levelling System (HLS) is a powerful tool that can be used effectively in the precise monitoring of vertical motion in sensitive applications. At the European Synchrotron Radiation Facility (ESRF) a high quality hydrostatic levelling system (HLS) was conceived and installed on the principal accelerator –the Storage Ring- at the inception of the facility. This system is composed of 288 devices (HLS pots and captors) installed on 96 magnet supports evenly distributed around the ring. It has a precision in the order of the micron (over the period of several hours). A second similar large scale system composed of 96 devices is installed on the Storage Ring (SR) tunnel roof. This paper will present some reflections and discussion concerning the validation and analysis of a Hydrostatic Levelling System (HLS) using long term data collected from these systems.

The coherence of an HLS can be qualified in two ways; internal and external coherence. The first, internal coherence refers how the system reacts with respect to known events such as a variation in the fluid level and monitoring long term behaviour on a marble. The second, external coherence refers how well the HLS results agree with an independent control that has a well-established incertitude. Examples of external coherence are monitoring long term stability on a marble, and level and tilt surveys. A detailed discussion of internal and external coherence in HLS systems was made in *The European Synchrotron Radiation Facility Hydrostatic Levelling System –Twelve Years Experience with a Large Scale Hydrostatic Levelling System* [13]. In that paper several examples were given of both internal and external coherence. This paper will develop and extend upon the work presented there.

2. THE ESRF HLS

The ESRF HLS based on a water (or liquid) equi-potential 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

2.1. The First Generation System – The 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 levelling 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 Maskinindustrie jacks during a machine realignment, and finally to follow machine and ground motion events in real time. 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 µm 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 since 1991 with only very occasional breakdowns.

2.2. Second Generation 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. This HLS is presently installed on the SR tunnel roof above the centres of the quadrupole girders. Note that in this discussion Second Generation and (SR) Roof HLS will be used interchangeably.

3. EXTERNAL COHERENCE – THE PROBLEM STATEMENT

It can be stated unambiguously that a high precision HLS is generally installed in order to give accurate height displacement information. At the ESRF, this statement can be extended to include high accuracy height displacement over time. Once again, at the ESRF, an appropriate time interval is considered to be 6 months which is the period between successive vertical alignment campaigns of the SR machine. The question of course is what precision should we consider as reasonably attainable? In addressing this question, we must not neglect the temporal stability of a sensor; in other words, its drift behaviour over time? Secondly, how can we verify that the system is performing reliably?

Addressing these questions in order, clearly, we would like for the system to measure as precisely as possible. If we take levelling as a standard, we can expect a precision in height differences between adjacent sensors of 20 to 30µm over periods of six months or even one year. This precision is the attainable limit of the best levelling instruments available on the market today. Thus we expect any HLS to be at least this precise. We can hope and expect for much better performance.

An HLS such as the one installed on the ESRF machine and SR tunnel roof is an instrument nominally capable of measuring vertical displacements in the order of the micron. Furthermore, the ESRF HLS can be considered to measure vertical displacements more or less independently of separation distance. In fact it is difficult to quantify the effect of separation distance. As soon as a movement is made, there is a system perturbation and a *wave* is induced. This wave in general must be modelled out to appreciate a displacement. Simultaneously, the system is subject to continual random movements with magnitudes in the order of the micron. Nonetheless, when a movement is deliberately induced on the ESRF SR HLS at two different points with the Steinsvik Maskinindustrie jacks, we see them very clearly.

It has been shown on a marble, that an 8 sensor sample of the second generation HLS is stable with a standard deviation of 1.7 µm over a three month period [12][13]. More recently, long term tests on 16 other sensors from the second generation HLS indicate a sensor drift between 7 and 11 µm over a six month period. (Refer to Figure 8) However, it is extremely difficult to demonstrate this temporal stability on a large scale system subject to both systematic and random movements. In fact, the ESRF first generation HLS, although very accurate over the short term (24 to 48 hours), is not particularly coherent over the long term (6 months). The sensors are subject to drift. This drift has been acknowledged by the manufacturer. Nonetheless, it is worth noting that it was only recognized after extensive study of the temporal behaviour of the system. Sensor drifts tend to be small and extremely difficult or at a very minimum tedious to detect.

Clearly, it is very important to verify the correct functioning of the HLS. This brings us to the second question of how to verify the system reliability. The simplest way to validate an HLS is to level the height differences between sensors and compare them with those measured by the HLS. The primary difficulty with this type of comparison is the relative inequality of error between the two methods. On the one hand, with a correctly functioning HLS one can theoretically expect incertitude between two sensors, independent of separation distance, of less than 5 µm over three months. On the other hand, the incertitude in a closed levelling survey of the SR Roof HLS network is estimated to be 160 µm. Secondly, although HLS errors are in principle independent of separation distance, they have a temporal dependence. This is attributable to sensor drift. Levelling errors, on the other hand, are independent in time but have a strong spatial dependence. The challenge is to qualify the HLS using levelling with its inherent relative imprecision.

4. THE SR ROOF HLS LEVELLING CAMPAIGNS

Since September 2001 when the SR roof HLS was considered to be operational, 27 levelling campaigns have been made on the system. This classical levelling consists of measuring height differences between adjacent sensors. Three sensors are levelled from each station. Each HLS sensor is levelled from two different level stations. This scheme is illustrated in Figure 2. There are four points in the network where the HLS sensors cannot be levelled. Furthermore, there are two points in the RF zone where it is only possible to level from one station. This breaks the network regularity.

The levelling survey is generally made over a two day period during, or at the very end of the machine run. This is because there are two radio frequency (RF) zones which are inaccessible when the machine is in operation. Typically on the first day, the full network with the exception of RF zones is levelled with the DINI 12 electronic level. The RF zones are levelled the next day during either the scheduled *Machine Dedicated Shift* (MDT) intervention times or the first day of the shutdown period[1]. For reasons of encumbrance, the RF zones are levelled with a NA2.

[1] A word on the terms used: a machine run concerns the time when electrons are stored (being accelerated) in ESRF Storage Ring. This is the time when experiments may be made on the beam lines. Typically a machine run lasts six weeks. During the machine shutdowns, of which there are two types: short shutdowns lasting 10 days in March, May and October , and long shutdowns lasting approximately 4 weeks in January and August; the machine is

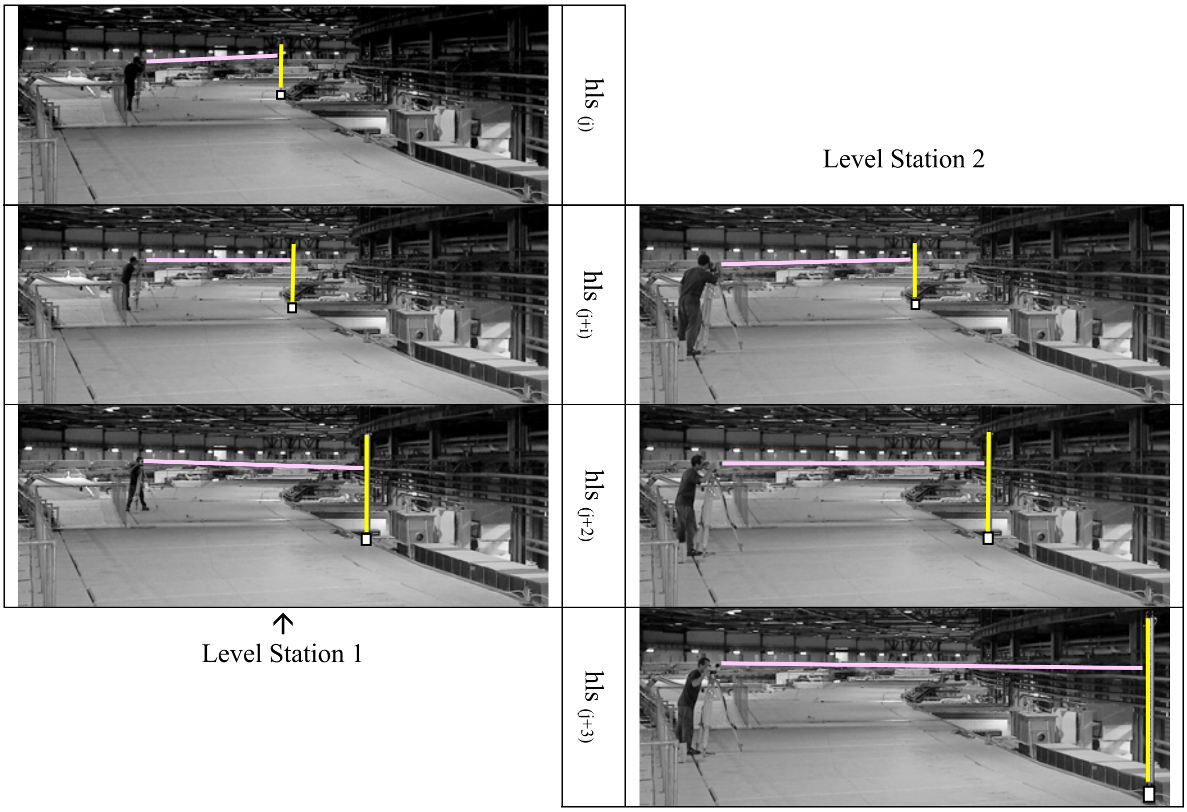

Figure 1 SR Roof levelling method. Each HLS sensor is levelled from two level stations. Two instrument heights are used at each station.

Of the 27 levelling campaigns, five have been rejected – three because of noisy measurements perhaps due to a poorly adjusted level and one because there were very poor results in the RF zone. Another survey has been removed from the study because not all of the points were measured. Similarly, two sensors have been eliminated because they were *shocked* during the study period. Thus we have 22 level surveys consisting of 90 points. Summary results from the 22 level surveys are shown in Figure 2. We see clearly that the point height incertitude for the surveys at one standard deviation (σ) are in good agreement with the simulated incertitude's and are a maximum of approximately 180 µm.

5. THE SR ROOF HLS MEASUREMENTS

Hourly measurements for the study period (September 2001 to August 2004) exist for 96 HLS sensors installed in the network. Only 92 of these sensors were levelled while two others were shocked and did not have a constant origin. Therefore, hourly data 90 sensors can be exploited. However, data during the machine shutdown periods[1] (approximately 13 weeks in the year) are unreliable.

stopped for maintenance work. Each week, there is one day (normally Tuesday) dedicated to machine specific activities. During this day (shift) there is a short time when the machine is stopped for brief interventions.

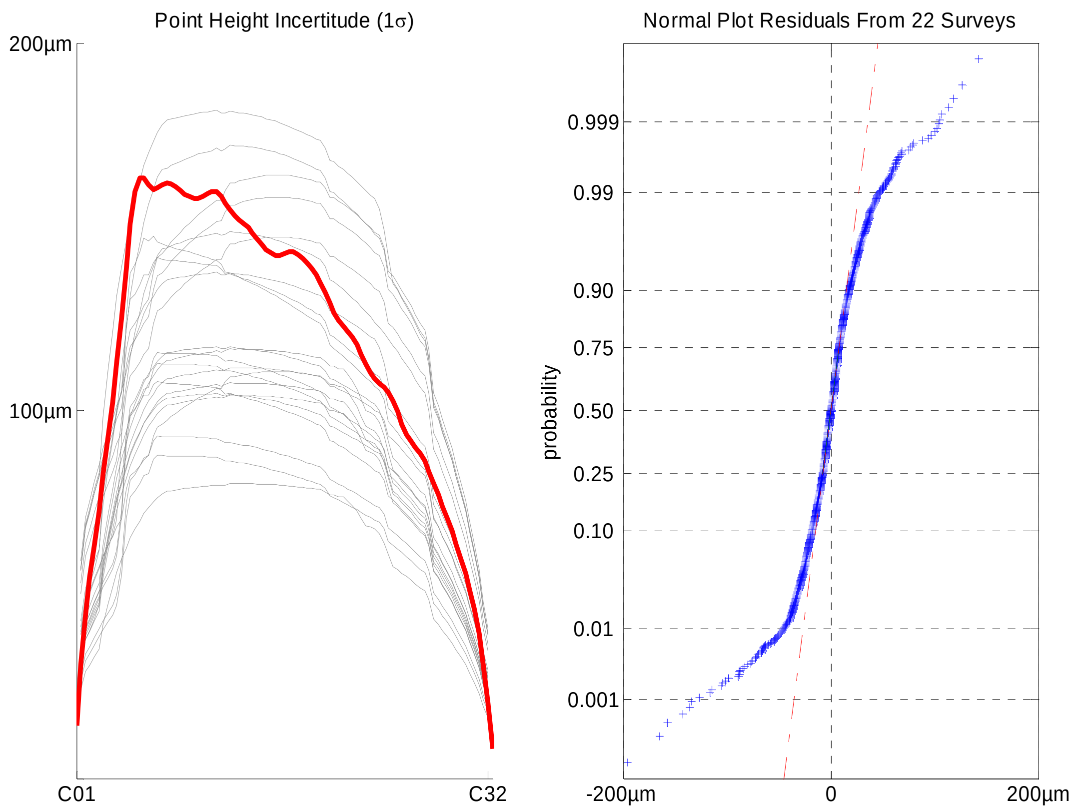

Figure 2 Results of SR Tunnel Roof levelling survey. The left panel shows the point height incertitude (one standard deviation) of the 22 closed levelling surveys issued from the least squares calculations. The heavy line shows the incertitude issued from simulations of the network. The right panel shows a normal probability plot of the combined residuals of ~5900 observations issued from the 22 level surveys. The non-symmetric shape of the incertitude plot and the heavy tailed distribution in the normal probability plot are due to the two different levels used in the survey.

For each hour, HLS readings are *normalized* by subtracting the mean value of the 96 sensors. This eliminates the effect of evaporation. To compare the HLS with the levelling, an HLS value for each of the 96 points and each of the 27 survey dates was estimated by passing a best fit line through the data over a period preceding and following the target date. Data was processed in this way because the levelling is generally made over a two day period. There is not an instant when one can consider that the height of a point was determined. An example of one HLS height estimate (of the approximately 2600 determinations) is shown in Figure 3.

To determine an estimate of the incertitude in the determination of the HLS sensor height ($Z_{hls(i)}$), we use the median values of the standard deviations for the best fit height determinations for the 22 levelling dates (Figure 4). A smoothing spline is then passed through these median values for the 96 HLS sensors in the network.

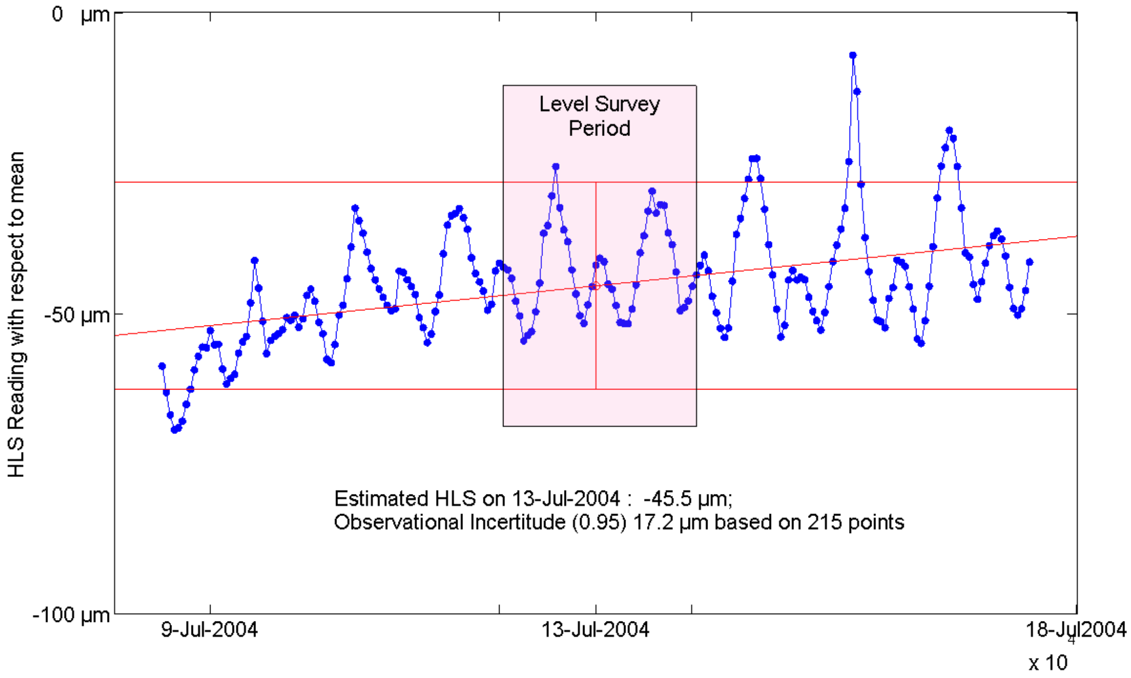

Figure 3 Example of the estimation of an HLS height value. In this example, the height of the sensor with respect to the mean HLS value is -45 µm and the incertitude (95%) in this height 17 µm.

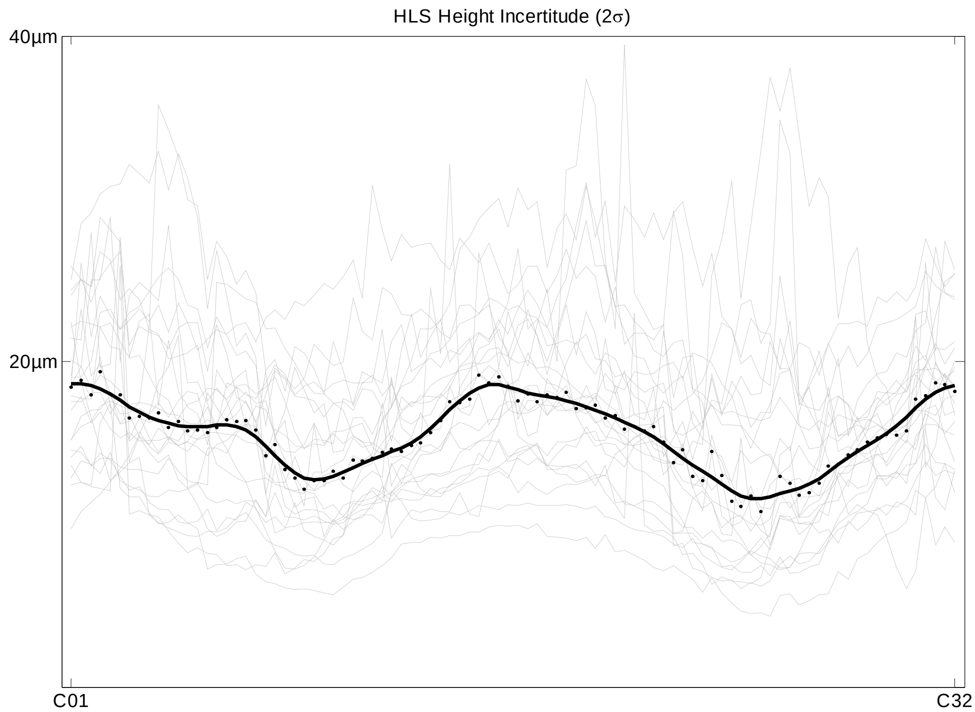

Figure 4 The HLS best estimate height incertitude's for the 27 levelling campaigns are shown by the light grey lines. The model incertitude for the determination of the height of an HLS sensor, shown by the heavy dark line, is derived by passing a smoothing spline through the median value of the each of the 96 HLS sensors in the network. There is no clear explanation for the wave shape.

6. COMPARISON BETWEEN THE SR ROOF LEVELLING AND HLS

In all of the discussions that follow, it is assumed the HLS has been qualified on a metrological marble as is considered to be coherent as discussed at length in [13]. If this is not the case, we cannot have full confidence that the HLS is functioning correctly. An example of two such tests is given in Figure 8.

Comparison between HLS and levelling is difficult because of the inequality of error between the two methods. It is further complicated by the fact that the HLS is temporally dependent but spatially independent. Levelling is the exactly contrary to the HLS with spatial error dependence and temporal error independence.

Levelling is a good example of a random walk process where the variance after N steps is given by $\sigma_N^2 = N\sigma_0^2$. In levelling the N is replaced by the distance L. In principal, the random walk process is rendered statistically stationary by differencing successive measures. Thus to avoid the complications associated with working with heights at point *i* ($Z_{hls(i)}$ or $Z_{lev(i)}$) directly we shall treat height differences between adjacent points *i* and *j* (i.e. $dH_{hls(ij)} = Z_{hls(j)} - Z_{hls(i)}$ and $dH_{lev(ij)} = Z_{lev(j)} - Z_{lev(i)}$).

6.1. Registration Between the Levelling and HLS

Before continuing, we must address the problem of the registration of the HLS and levelling. There is an offset between height differences measured by the HLS and the level. This variation (ε) is due to mechanical differences between different sensors and pots. (Refer to Figure 5) Originally, ε was measured to be within a range of ±25 µm for the 180 second generation captors. Today we have measured on a small sample a standard deviation of 30 µm. This would tend to indicate a slow drift over time (10 years) of the HLS sensor zero. Under normal circumstances, the value of ε can and should be determined in the laboratory before the sensor is installed in situ. However, this step was unfortunately overlooked when the SR roof system was installed in 2001.

Nevertheless, we can get a good indication of the values of ε post priori by computing the difference between the HLS and levelling for all of the comparisons and then taking the median of these values. This is illustrated in Figure 6. The value issued from this is biased because it assumes there is no ground movement over the study period. There is also the problem of errors in the measurements which will talk about next. However, the median is a robust estimator of location and is used specifically to minimize these effects.

As an aside, the problem of registration can be eliminated by taking the difference between surveys at different epochs. This has been done on many occasions at the ESRF. However, this adds the complication of including errors from two levelling surveys in the calculated difference between the levelling and the HLS height determination. As shall be shown, these errors are difficult enough to manage with one survey without convoluting them in a mixture of two.

$$dH_{hls1} - dH_{hls2} = dH_{lev} + \varepsilon$$

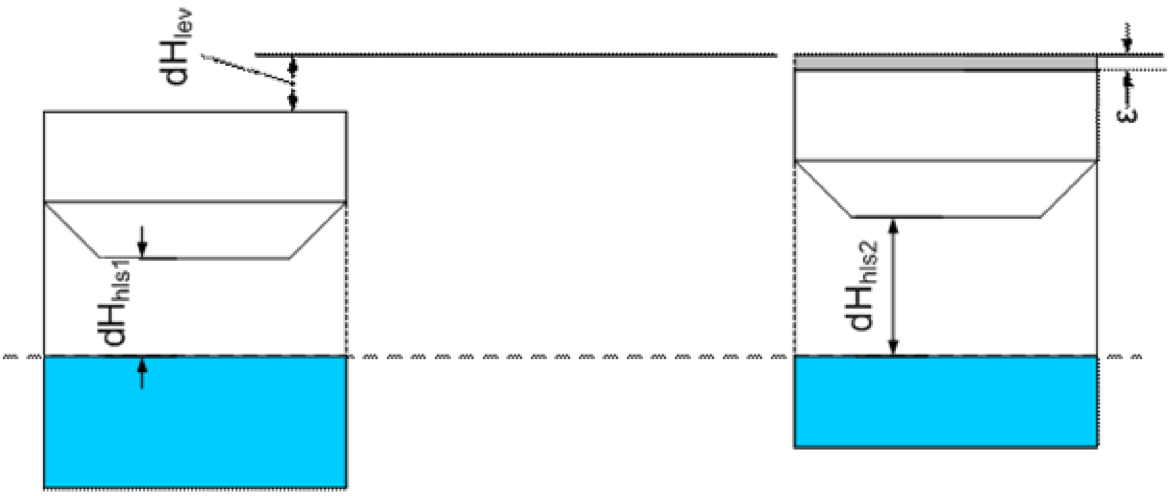

Figure 5 Difference between HLS height difference and level height difference. This discrepancy (ε) is introduced through mechanical variation between different HLS pots and sensor mounts. At the ESRF, we have found the standard deviation of this difference to be in the order of 30 µm. When the system was purchased in 1995, all values of ε were verified to be within a range of ±25 µm.

6.2. Brute Comparison Between the Levelling and the HLS Height Differences

The brute comparison between the levelling and the HLS gives a very useful comparison. In fact it is the most valid comparison. The problem when looking at the brute results is that one has the conviction that the relationship between the levelling and the HLS is better than what confronts the eye. This is clearly demonstrated in Figure 7. In this figure, the standard deviation of the difference between the levelling and the HLS is 60 µm. We get the impression there are zones where this is good agreement and other where there are peaks and sudden jumps.

Errors like this can come from both the levelling and from the HLS. A possible, if rare error with the ESRF type of HLS is a blockage of the fluid communication. It is evident with whole parts of the network displaced upwards or downwards with respect to other parts.

There are a good many possibilities for small but significant levelling errors. One common error is to not level exactly the same point in the fore and back sights. This type of error when it is small is difficult to detect. It shifts the level survey by a value dZ which when compensated by least squares adjustment or simply apportioning the closure error equally has a highly characteristic saw tooth shape. When there are several such errors of different magnitudes, the net result is a complex and indecipherable shape.

Another error common to the ESRF level network is level collimation error. Due to the configuration of our network it is unavoidable. (see Figure 2) If only one instrument is used for the full survey, this error manifests itself as an ever increasing or decreasing slope in the determined heights ($Z_{lev(i)}$). In the case of one instrument, this error is fully compensated by equally apportioning the closure error. If however, as is very often the case when this network is measured, two or more instruments are used, different parts of the network have different slopes due to the different levels used.

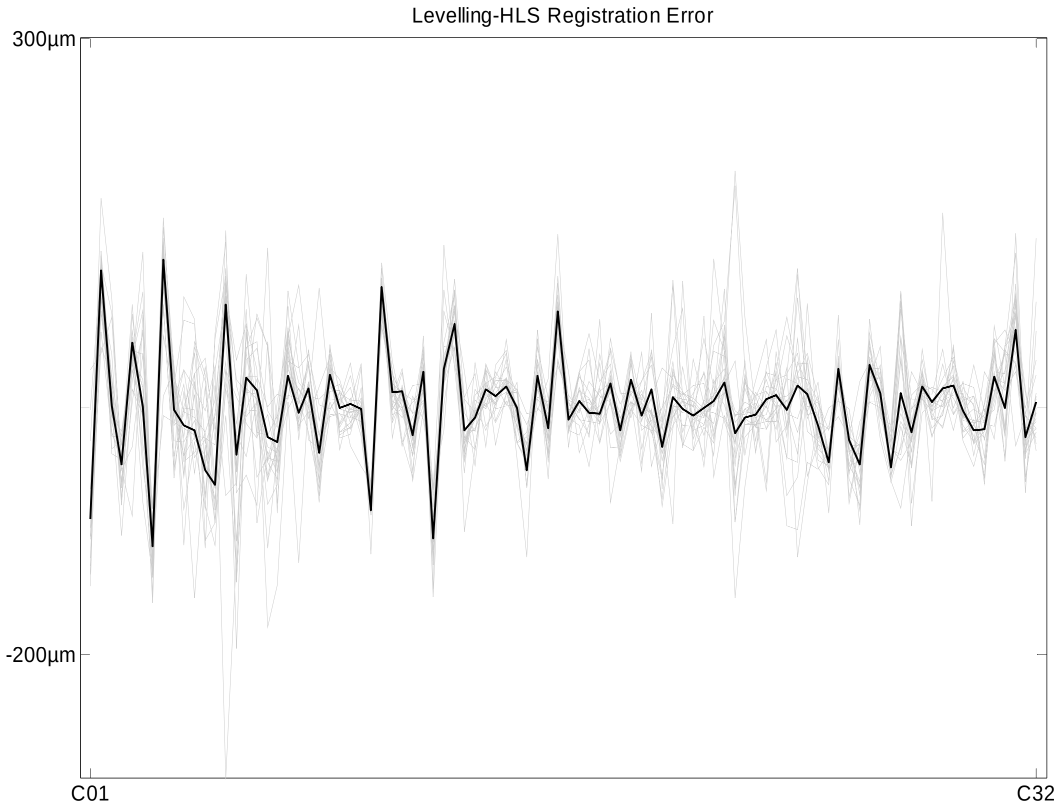

Figure 6 Registration error ε $dH_{lev} - dH_{hls}$. The thick black line shows the median value. One must be careful using this registration. Among other things, it assumes that there is no ground movement. This is clearly not the case. The dispersion about the mean line is partially due to movements between HLS.

6.3. Amelioration of the Brute Comparison Method

As has been mentioned, we cannot help but think that if the errors we mentioned in the previous section were corrected, then the overall agreement between the levelling and the HLS would be better. In fact this is generally the case. A method has been developed and will be elaborated below.

The first thing to do is to identify height differences between adjacent points that might be in error. This can be done by differencing the levelling and HLS height differences with a reference ($dH_{lev(ij)} - dH_{lev(ij)REF}$ and $dH_{hls(ij)} - dH_{hls(ij)REF}$). Values that are superior to a given threshold value can be corrected.

This has been successfully done with the SR Roof levelling and HLS data. The reference that is chosen is the median height difference value of the 22 level surveys mentioned previously. The threshold chosen for this study is 60 µm. This is the mean incertitude at 2σ of the relative errors between adjacent points issued from the least squares calculation for this network. The threshold value is nonetheless arbitrary.

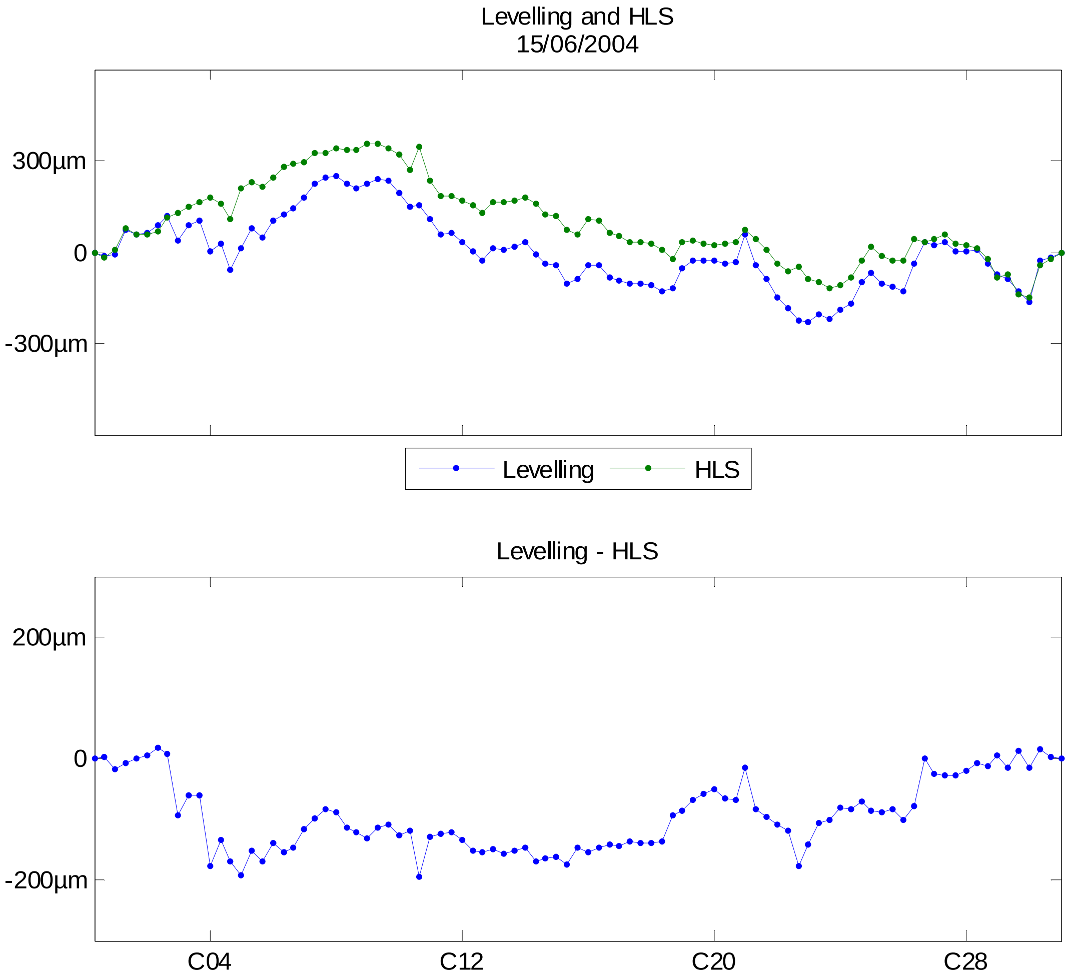

Figure 7 Typical levelling and HLS comparison. Here we see that the levelling follows more or less the HLS. Nevertheless, we feel convinced that the relationship could or should be better.

When height differences exceed the threshold value they are assigned either the reference value or as in the case of this study; the height difference for the HLS if the levelling height difference is in error (i.e. $dH_{lev(ij)} = dH_{hls(ij)}$) ; or the levelling height difference if the HLS height difference is in error (i.e. $dH_{hls(ij)} = dH_{lev(ij)}$). In this way, height differences will not be permitted to exceed the threshold value. It has been found that this gives sufficient leeway, and does not bias the network in an undue manner.

The height differences are summed around the network for both the levelling and the HLS to give the network heights ($Z_{hls(i)}$ and $Z_{lev(i)}$) around the network. The level network is finally corrected for the closure error.

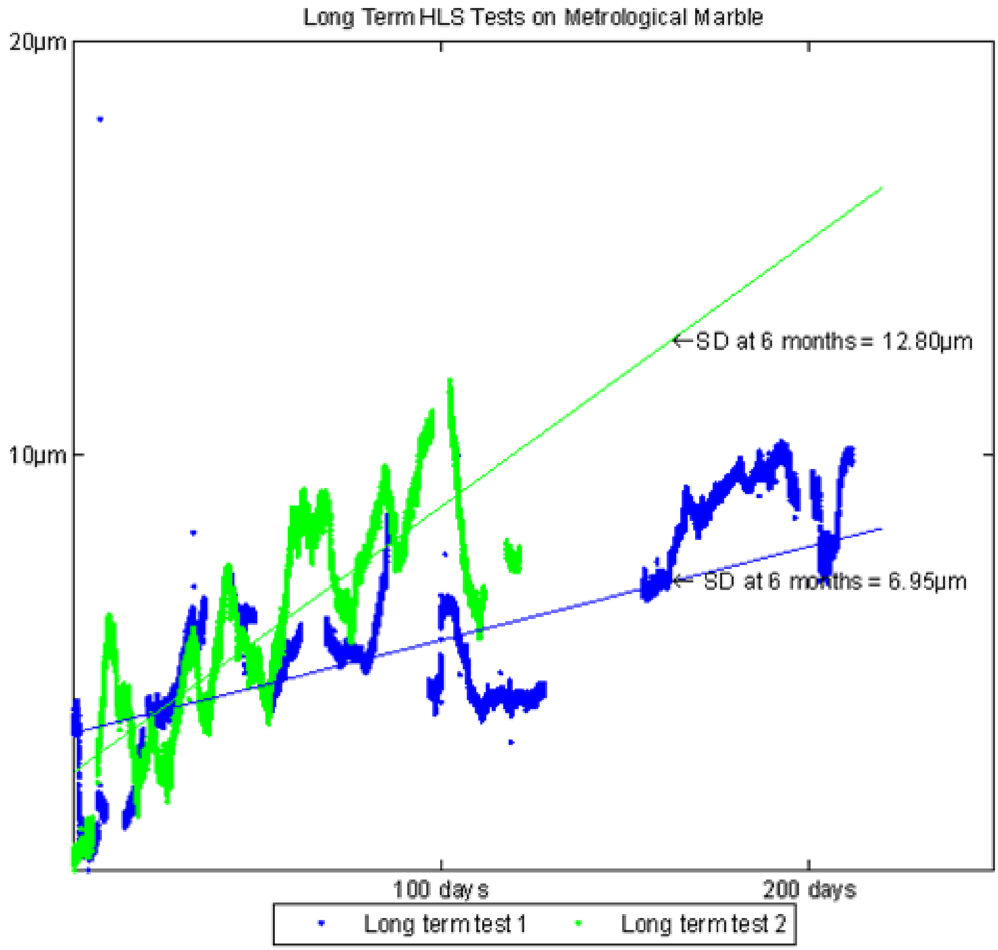

Figure 8 Standard deviations of two sets of 8 HLS captors at two different epochs on the ESRF metrological marble in our laboratory. This graph gives an idea of how much we expect the captors to drift over a given time period.

This method permits a net amelioration in the comparisons between the levelling and the HLS. Admittedly it is highly arbitrary and one can easily be led astray producing highly illusory results. Nonetheless, carefully applied, one feels comfortable with the results. (Refer to Table 1)

7. CONCLUSIONS

This paper has discussed how one can qualify the precision of an HLS. First and foremost, the system must be validated over a considerable period of time (minimum 3 months) on a metrological marble or in a similar manner. If the system drift is small then further tests can be made. If not, any further tests and results will be dubious.

Once the system has been fully qualified on a marble, and it is installed in a monitoring capacity, the only way, or at least the most economical way to confirm its validity is through high precision levelling. Alternatively, several sensors can be installed in close proximity on a common support giving redundant readings. This is a costly solution.

Table 1 Standard deviations of levelling and HLS comparisons for selected MDT days over the three year study period. Generally there is a clear improvement in the both the height difference $dH_{lev(ij)} - dH_{hls(ij)}$ and the height $Z_{lev(i)} - Z_{hls(i)}$ comparison results after making corrections to the levelling and HLS as outlined in this section.

Date	Before Correction		After Correction		No. Levelling Corrections	No. HLS Corrections
	Standard Deviation $Z_{lev(i)} - Z_{hls(i)}$ (µm)	Standard Deviation $dH_{lev(ij)} - dH_{hls(ij)}$ (µm)	Standard Deviation $Z_{lev(i)} - Z_{hls(i)}$ (µm)	Standard Deviation $dH_{lev(ij)} - dH_{hls(ij)}$ (µm)		
19/09/2001	125	43	63	21	5	4
31/10/2001	90	58	32	24	4	0
30/04/2002	73	45	41	20	8	3
22/05/2002	120	59	36	18	7	0
27/11/2002	137	59	33	21	7	2
29/04/2003	43	43	30	30	0	0
24/07/2003	97	37	121	20	4	0
23/09/2003	34	34	19	19	0	0
25/11/2003	73	40	26	16	4	2
15/06/2004	60	30	29	18	4	2
13/07/2004	55	49	27	20	6	1

The ESRF SR tunnel roof HLS consisting of 96 captors installed over a ~850 m loop has been studied and validated using levelling campaigns. However, levelling has its drawbacks and gives ambiguous results at the level of precision of the HLS. A method of auto-correction between the HLS and the levelling has been proposed. This method is admittedly somewhat arbitrary, but the results are nonetheless convincing. A possible next step in this process would be to try to apply some correction for the different level collimation errors. Results from these studies show there are clear sets of contiguous points that have the same slope which would indicate that a slope correction could be implemented further improving the Standard Deviation of the $dH_{lev(ij)} - dH_{hls(ij)}$ results.

References

[1] Roux D., Alignment and Geodesy for the ESRF project, Proceedings of the First International Workshop on Accelerator Alignment, July 31-August 2, 1989, Stanford Linear Accelerator Center, Stanford University (USA).

[2] Martin D, Roux D., Real Time Altimetric Control By A Hydrostatic Levelling System, Second International Workshop On Accelerator Alignment, September 10-12, 1990, Deutshes Elektronen Synchrotron (DESY, Germany).

[3] Martin D, Alignment at The ESRF, EPAC (Berlin, Germany, Mars 1992).

[4] Roux D., The Hydrostatic Levelling System (HLS)/Servo Controlled Precision Jacks. A New Generation Altimetric Alignment and Control System. PAC, Washington, USA, May 1993.

[8] Farvacque L., Martin D., Mechanically Induced Influences on The ESRF SR Beam. Proceedings of the Fifth International Workshop on Accelerator Alignment, APS Chicago Il USA, October 1997.

[10] Farvacque L., Martin D., Nagaoka R., Mechanical Alignment Based on Beam Diagnostics, Proceedings of the Sixth International Workshop on Accelerator Alignment 1999, Grenoble France.

[11] Gatta G., Levet N., Martin D., Alignment at the ESRF, Proceedings of the Sixth International Workshop on Accelerator Alignment 1999, Grenoble France.
[12] Martin D., Deformation Movements Observed at the European Synchrotron Radiation Facility, Proceedings of The 22nd Advanced ICFA Beam Dynamics Workshop on Ground Motion in Future Accelerators, November, 2000, SLAC, USA.
[13] Martin D., The European Synchrotron Radiation Facility Hydrostatic Levelling System –Twelve Years Experience with a Large Scale Hydrostatic Levelling System, Proceedings of The Seventh International Workshop on Accelerator Alignment 2002, November, 2002, SPRING-8, Japan.