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REAL TIME ALTIMETRIC CONTROL BY A HYDROSTATIC LEVELLING SYSTEM

By

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1. Introduction

Accelerators and Synchrotron Radiation Storage Rings require higher and higher standards of alignment quality in order to guarantee maximum beam longevity. It is with this objective in mind that the ESRF Alignment and Geodesy Group (ALGE) have applied two fundamental concepts. The first of these concepts is the continual real time monitoring of sensitive elements (Quadrapoles) of the ESRF storage ring by a Hydrostatic Levelling System (HLS). The instrumental resolution of this monitoring system is greater than 1 um and its accuracy is greater than 5um. The second concept applied by the ALGE group is the remote control adjustment of sensitive elements by servo controlled jacks based on information gathered by the HLS. The subject of this paper is the presentation of the general principle of the HIS, and of the results of tests performed on the system to date.

2. General Principle Of The Hydrostatic Levelling System

The HLS is based on the principle of communicating vessels. Fluid, which will always seek a level of equal potential, is allowed to flow freely between adjacent vessels. It is in this way relative differences in level (dh) between neighboring vessels may be determined. Figure 1 shows this principle and figure 2 shows the preserial HLS vessel.

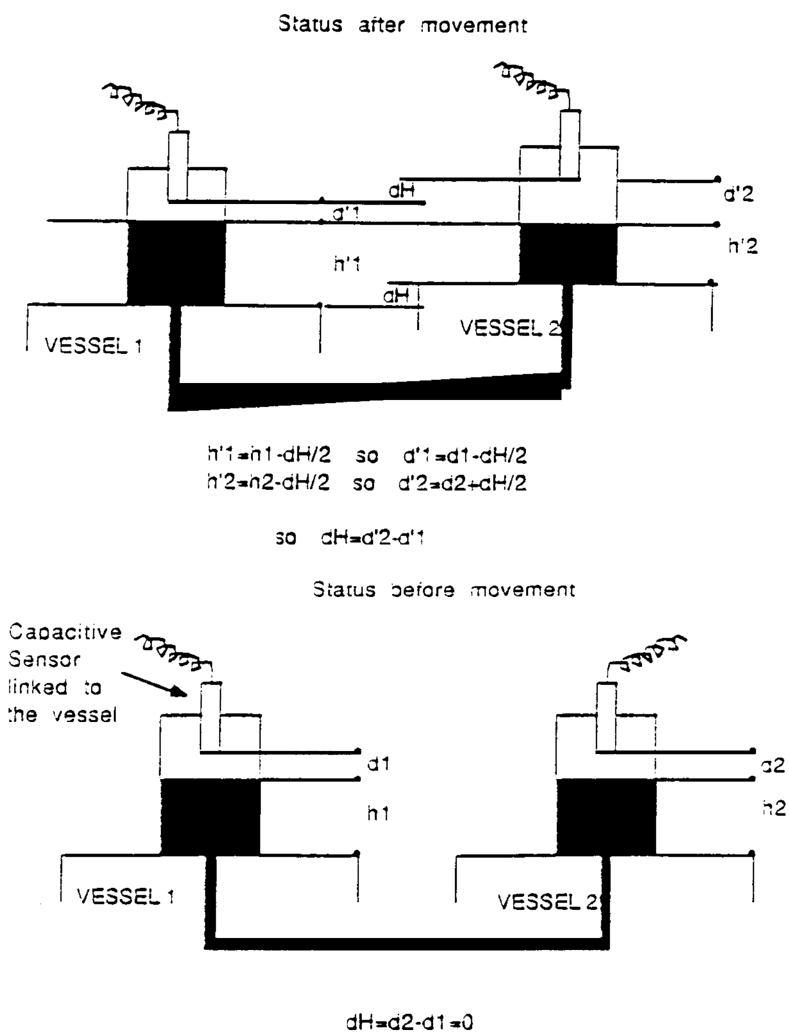

Figure 1 General scheme showing the principal of communicating vessels and the determination of relative difference in level (dh).

2.1 Materials

The HLS vessel is made of stainless steel to avoid chemical corrosion resulting from mildly chlorinated water.

2.2 Hydraulic Pipework

The hydraulic pipework system used with the HLS is semi-transparent to aid in the elimination of air bubbles that form during the initial filling of the system. Standard 8/10 mm internal/external diameter pipes are used to minimize excessive fluid play and inertia in the system. In the case of the ESRF, the pipework must also be resistant to long term exposure to ionizing radiation (alpha and neutron radiation of minimum lifetime exposure of 10 MegaRad)

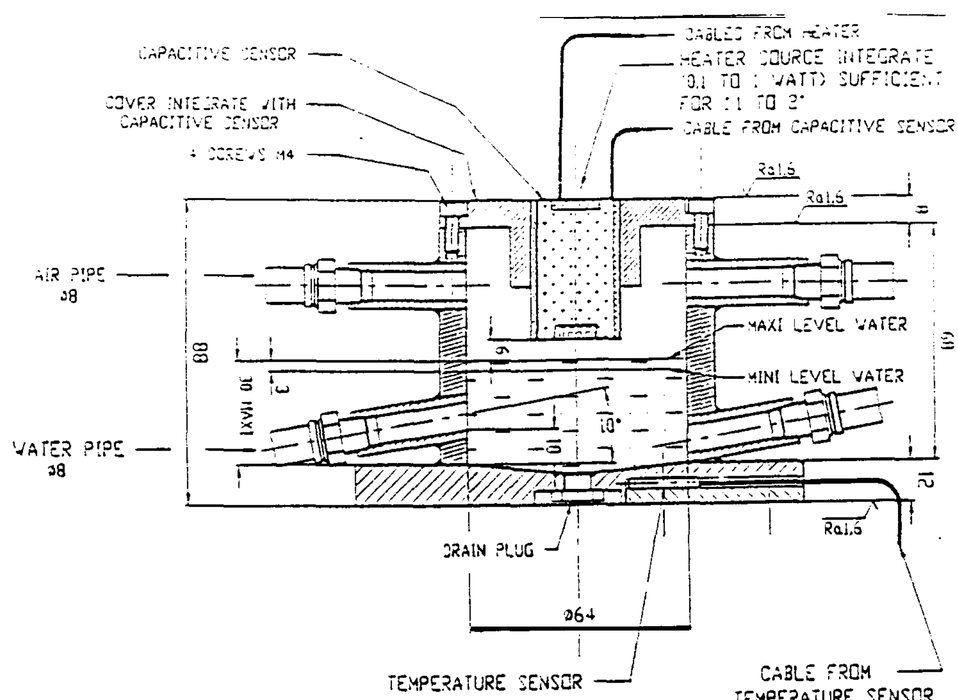

Figure 2 The preserial HIS vessel and sensors.

2.3 Valves And Vessel Connectors

Valves and vessel connectors must be completely watertight and resistant to the same long term exposure to ionizing radiation as the pipework. In addition, the interior diameter of the connectors and valves must not be less than 7 mm to permit the free passage of fluid

2.4 Reference Fluid

Water has been selected as the HLS fluid because it is safe, inexpensive, and is a good conductor of electricity. Chlorine is added to the water as an anti-bacterial agent. However, water has a relatively important coefficient of dilation (2 um/degree C/cm). Consequently, the temperature difference between vessels and the height of the column of water must be considered in dh measures. After a perturbation to the system, a period of fluid stabilization must be respected. This period is dependent upon the overall length of the pipework The period of fluid stabilization is approximately 2 minutes for a cumulative length of 40 meters of pipe between four prototype HLS vessels. As a result of slow evaporative losses to the system (approximately 24 um per day with the preserial vessels), an electromechanical valve system will be employed for periodic re-filling.

2.5 The Use Of Non-Contact Sensors

The use of non-contact capacitive sensors checks several problems that were common with traditional contact type sensors. These problems included:

- The wetting of the touch point of the sensor which reduces the precision of the measurement.
- Corrosion and mineral salt deposition on the sensor after prolonged contact with fluid changing a measurement value over time.
- Dust on the surface of the water. A dust particle of 20 um diameter on the water surface and in contact with the sensor will result in an error of 20um. (With a non-contact capacitive sensor of 10 mm diameter, the error is 0.00000001 um.)
- Vibrations on the waters surface. (With a non-contact sensor, the integrated capacity is constant if the sensor is properly centered.)
-Problems associated with the meniscus on the waters surface. (With the non-contact sensor, experience has shown that a vessel with a diameter approximately three times larger than the sensor surface eliminates the first order effects. The capacitive sensor can measure a pseudo-distance of integration even if the water surface is slightly spheric. This sphericity is constant in the case where all of the vessels are the same size, and the fluid is homogeneous. The calculated level differences between vessels (dh) is an exact solution.)

In addition, the non-contact sensors provide other advantages over the contact type sensors. In particular, the capacitive sensor provides a continuous series of integrated measures over a long time period. This is ideal for a monitoring system. Only a periodic single measure can taken with the touch type sensor. Experience has shown that a measure taken with a sensor that has been properly calibrated has a resolution better that 0.1 um. Only the absence of a nanometric standard has limited an even more precise calibration.

The concept of the non-contact capacitive sensor developed at the ESRF for the monitoring of level differences in the ESRF storage ring has been considerably improved upon by the company FOGALE-NANOTECH. This company, which is responsible for the production of the preserial HIS, has used advanced aerospace components in their product. One of the major improvements on the prototype system is the relative independence of the distance between the sensor and the system controlling device (easily as much as 200 meters). Another important improvement over the prototype system is the provision of calibration curves with each sensor. (In the past each sensor had to be calibrated individually at the ESRF.)

3. Corrections And Solutions To Problems Associated With HLS Measures

To achieve a resolution of better than 0.1 um in dh between vessels, three elements must be considered.

3.1 The Variation Of Pressure Between Measurement Pots

It is clear that if differences in pressure between HLS vessels can not be avoided, a first order theoretical correction, based on pressure observations taken at each point, must be applied to the measures. However, the solution adopted by the ESRF, where it is expected that there will only be accidental, isolated and periodic pressure changes resulting from open doors etc..., is to maintain the system under an equal pressure by connecting each vessel with its neighbors by a closed air system. Experience has shown that variations in pressure between vessels separated by a cumulative 40 meters of pipe are not detectable.

3.2 The Variation Of Temperature Between Measurement Pots

Laboratory tests have shown that a global temperature change has no effect on dh. However, a difference of temperature of 1 C between two vessels with a water column height of 5.5 cm (prototype vessel) results in a measured difference in dh of 11 um. With the preserial vessel, the water column height is 3 cm which translates to an error of 6 um per degree of temperature difference. The presence of a sensor capable of measuring temperature to ± 0.1 C reduces this error by a factor of ten. The error in dh as a function of temperature differences and water column height is illustrated in figure 3. Other steps taken to reduce errors as a result of temperature variations are the maximization of the thermal inertia of the system by using low thermal conducting pipework, and the insurance of the best correlation possible between temperature measures and the temperature of the capacitive sensor itself by using a thermally conductive material (stainless steel) for the vessel.

3.2 The Solution To The Problem Of Condensation On The Captor Face

Periodic wetting of, or condensation on the surface of the capacitive sensor makes reliable measures impossible. Consequently, a system that ensures the sensor surface is free of fluid is imperative to the proper functioning of the HLS. Furthermore, the capacitive surface must be resistant to corrosion, and dimensionally stable with respect to humidity changes resulting from periodic submersion in mildly chlorinated water. The solution to corrosion and dimensional stability is to use a stainless steel captor encased in ceramic.

INFLUENCE OF TEMPERATURE VARIATION BETWEEN TWO VESSELS

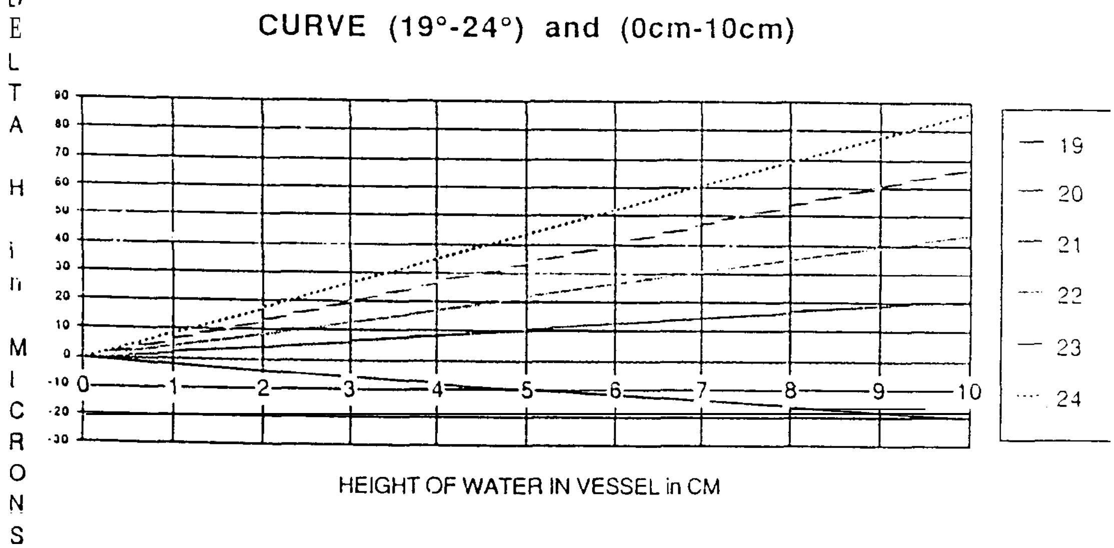

Figure 3 The error in dh as a function of temperature differences between vessels and the water column height.

4. Real Time Analysis Of Information Provided By The HLS Capacitive Sensors

4.1 Analogic/Digital Interface

The precision and reliability of the system is possible by the connection of the HLS output signal (0-10 V) to a high resolution analog/digital card. The precision and speed of acquisition is determined by the type of card that is used.

12 bit card	1 bit = 2.5 um
16 bit card	1 bit = 0.625 um
16 bit card	1 bit = 0.15 um

4.2 Real Time Error Detection

Real time calculations provided by intelligent software permit the detection of anomalous behavior of the system. For example, a local heating or cooling, or small leak in the system can easily be detected and repaired or corrected for. The use of a differential output signal avoids errors resulting from electrical parasites on the signal line.

4.3 Data Integration And Analysis By Computer

The signal or measurement output by the HLS sensor is in fact the mean of 100 measures taken over 3 seconds. (The time required per measure depends on the number of sensors connected to the system) At present, the HLS is connected to an IBM PC via a Nautal 12 bit analog/digital card. Software exists to receive and process data from HLS temperature and capacitive sensors. A subprogram permits the elimination of all accidents (electrical, electronic, hydraulic etc...) by imposing a threshold of confidence on the measures. If desired, an adjustment of the servo-controlled jacks based on HLS dh information may be made at this point. Eventually, the HLS and servo controlled jack network will be connected to the ESRF main frame computer via VME crates to comply with the ESRF standard. However, it is not inconceivable that the whole HIS network (288 HLS vessels and jacks) could be run from a PC.

4.4 Real Time Corrections

Corrections to the non-linearity of the sensor output over the range of 2.5 mm (0 - 10 V) and the error in dh as a result of temperature differences between vessels must be made. These corrections, although not complex (normally a third degree polynomial curve), can only be provided in real time by a computer.

4.5 Servo-Controlled Adjustment Scenario

The difference in level between vessels may be derived in two ways. Level differences can be calculated with respect to a reference vessel fixed to a wall. The other possibility is to determine dh with respect to a reference plane calculated from the mean of all HLS measures. There are two servo controlled adjustment scenarios based on the dh derived in the above.

-The first scenariois the adjustment of one or more elements by the direct intervention of an operator.
- The second scenario, which is only considered a possibility after the software that runs the HLS system has been thoroughly tested, is the automatic adjustment of elements when a variation of level is detected. At this point the HLS may be considered a dynamic alignment system.

5. Description And Results Of Experiments And Tests Performed On The System To Date

Several experiments have been made on the prototype HLS. Unfortunately, at the time of the writing of this paper, tests have not yet been made on the preserial HLS. It is hoped that comparative results between the prototype and preserial HLS will be available in September 1990.

5.1 Long Term Measurement (4 days)

Figures 4a and 4b show the results of a long term measurement using the HLS. The standard error of the cumulated displacement of three jacks as registered on their counters (figure 4a) is 2.5 um. This figure may be considered an absolute measure of ground movement. Figure 4b shows the stability of the difference of level between the three vessels on the marble and the reference on the wall. The maximum standard error is less than 0.5um.

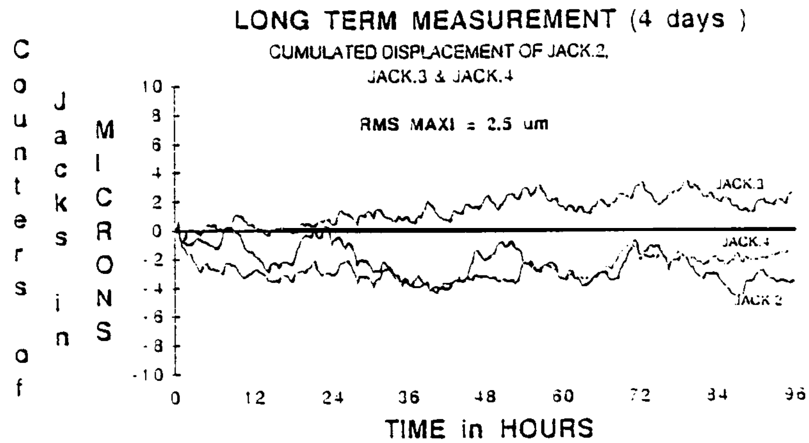

Figure 4a Long term measurement (4 days) showing the cumulated displacement of three jacks as illustrated by their counter readings.

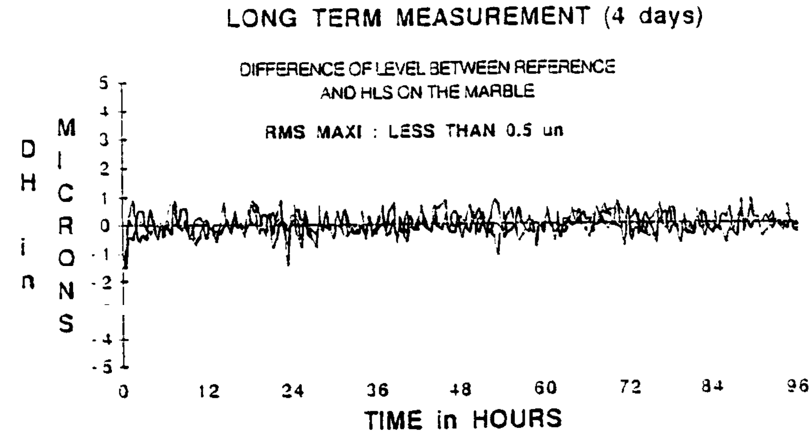

Figure 4b Long term measurement (4days) showing the difference of level between the reference HLS on the wall and the three HLS on the marble.

5.2 Simulations of a ground settlement.

A random movement of the jacks was made and the system relevelled each hour using the servo-controlled jacks. Figures 5a, and 5b show the results of this simulated ground settlement and adjustment. In both figures 5a and 5b, backlash elimination, the final upward movement of the jacks to eliminate play in the screw, was employed. The importance of backlash elimination is illustrated in figures 6a and 6b where it is shown that the jacks do not return to the same position if this correction is not used.

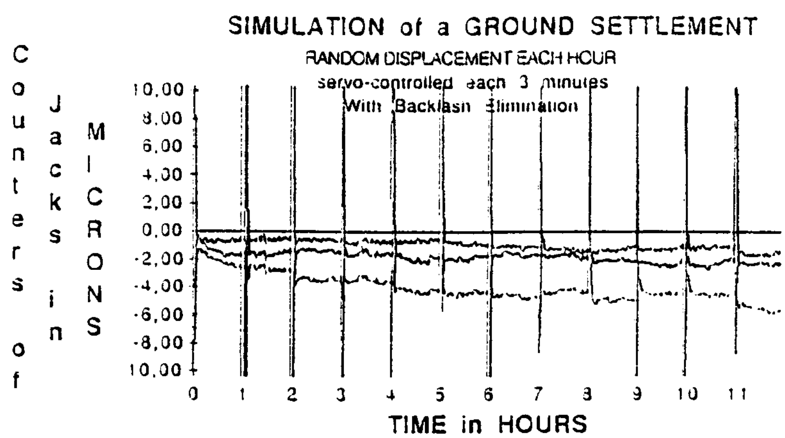

Figure 5a. Simulation of ground settlement with backlash elimination showing the cumulated displacement of the three jacks as illustrated by their counter readings.

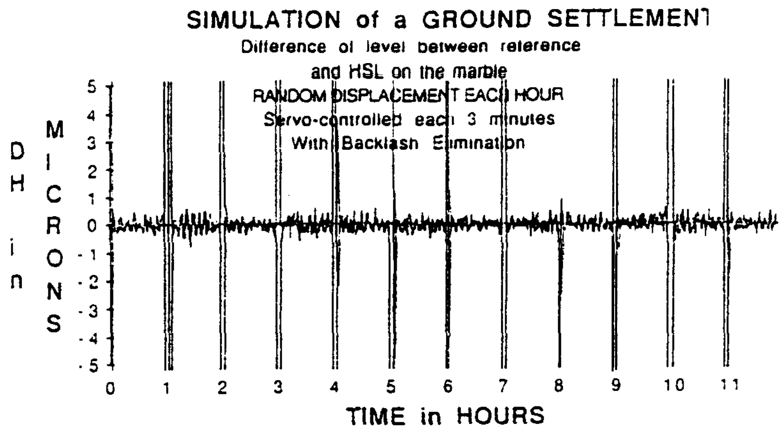

Figure 5b. Simulation of ground settlement with backlash elimination showing the stability of dh.

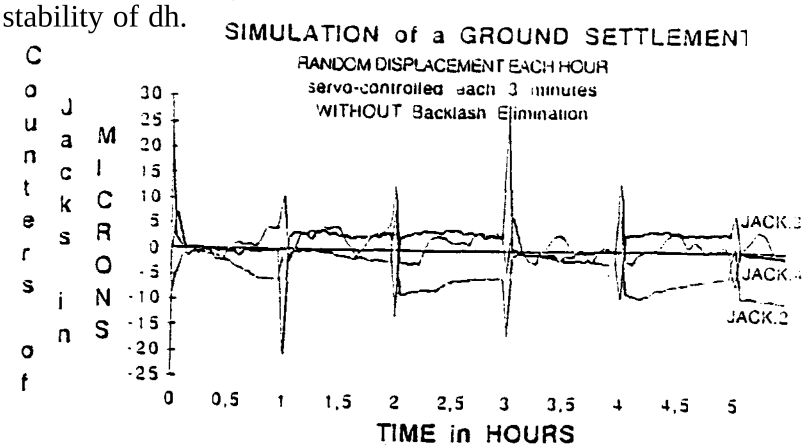

Figure 6a. Simulation of ground sedement without backlash elimination.

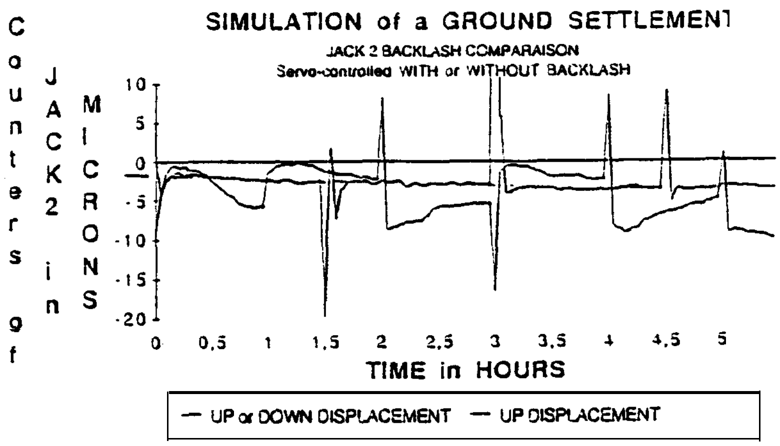

Figure 6b. Simulation of ground settlement with backlash elimination (without backlash eliminations superimposed).

6. Improvements On The Prototype System

6.1 Dilation Of Water

In an effort to minimize the effects of temperature difference between vessels on dh, the height of the water column in the preserial vessels has been lowered from 5.5 cm (prototype vessels) to 3 cm. (Preserial vessels)

6.1 Calibration Curves (prototype and preserial systems)

Figures 7a shows the mean third degree polynomial calibration curve and the signal output of HLS prototype vessel No.1 over the range of 2 Volts. The residuals between the actual signal output and the mean curve are shown in figure 7b. Figure 8 shows the residuals between the mean third degree polynomial curve developed for the preserial HLS system and the preserial vessel No.1 signal output over the range of 0 to 10 volts. As can be seen with figures 7b and 8, there is nearly an order of magnitude difference between the residuals of the preserial (maximum -0.2 um) and prototype systems (maximum -1.4 um). This result not only represents the superiority of the preserial sensor over the prototype sensor, but also the superiority of the calibration process used for the preserial system.

5.2 Evaporation

Loss to the system as a result of evaporation is unavoidable. However, evaporative loss to the preserial system (24 um per day) is considerably less than to the prototype system (80 um per day). Considering the preserial HLS measurement range is 2.5 mm, refilling will be required once every 75 to 100 days in lieu of once every 30 days with the prototype system. This is important when considering the system cannot be used during the refilling process. (4 to 8 hours)

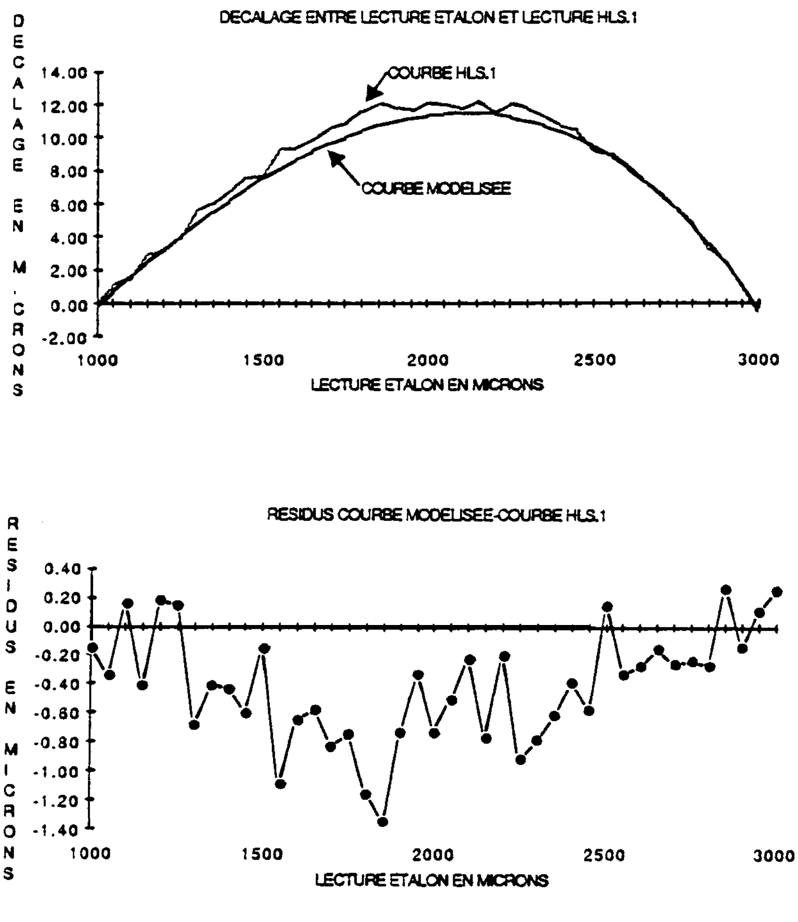

Figure 7 Calibrations and residual curves for prototype HLS vessel No. 1

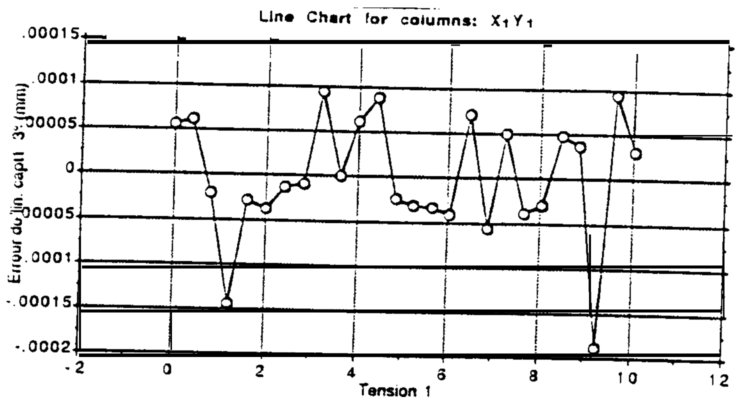

Figure 8 Residual curve for preserial HLS vessel No. 1

8. Conclusions

The high standard of alignment demanded by the ESRF storage ring to guarantee the maximum longevity of the beam has led to the development of the HLS system. After initial development at the ESRF, preserial sensors and vessels, with certain manufacturing improvements over the prototype version, have been developed industrially by FOGALE NANOTECH. Tests now being conducted at the ESRF give all indications that the HLS will easily meet and very likely greatly exceed its design responsibility in keeping the ESRF storage ring aligned vertically to within ± 0.1 mm. This system used in future accelerators and with other industrial users will provide a source of economy in the reduction of the number of people and time required for traditional realignment. It also will allow a realignment during a short machine shutdown. We believe that this system, coupled with the servo controlled jacks and the developments realized by CERN with respect to the CLIC project, marks the start of a new generation of automatically controlled accelerators.

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