High Precision Alignment Design for Swissmetro Rig

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Key words: Swissmetro, high precise alignment, metrological train, offset measurement

SUMMARY

This paper presents a metrological method for rail alignment of high precision about HISTAR (High Speed Train Aerodynamic Rig of Swissmetro). Based on the support system model of one-third real size, theoretical research and analysis are carried out on its alignment technique and procedure based on the offset measurements. Some mathematical models about the alignment are established following the geometrical features of the support system.

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1. INTRODUCTION

The Swissmetro SA company has the goal to develop a new and revolutionary high-speed transport system, able to carry passengers in full safety at speeds exceeding 400 and even 500 km/h. This transport system, called *Swissmetro*[1] (Figure 1), consists in an underground Maglev traveling through a tunnel network of small diameter in which, to diminish the energetic consumption, the air pressure is reduced to approximately 10% of the atmospheric value. The system is presently under design by using several numerical and experimental simulations, and the operational start up of a first pilot line could occur before 2015.

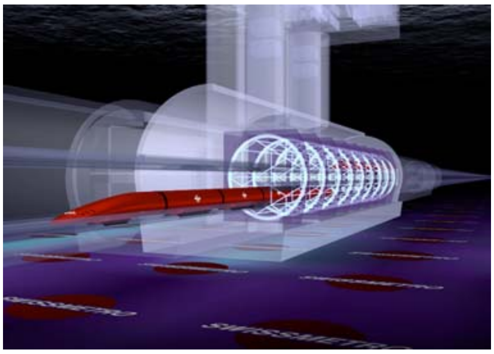


Figure 1: Swissmetro

HISTAR (High Speed Train Aerodynamic Rig of Swissmetro) project is a reduced-scale rig under construction in Lausanne with the purpose to analyze the aerodynamic effects generated by the high-speed transport system in general and the SWISSMETRO system in particular. The HISTAR rig is basically a 250-meter long track on which a vehicle model at scale 1/10 will be towed at speeds over 500km/h by two high performance hydraulic units, the power of which exceeds 1.2 MW. The rig has been developed with the cooperation of various laboratories of EPFL, the University of Lausanne and the company Swissmetro SA and its industrial partners. The project is financed by the Swiss Authority for the Promotion of Innovation and Technology (CTI-KTI) and the company Swissmetro SA.

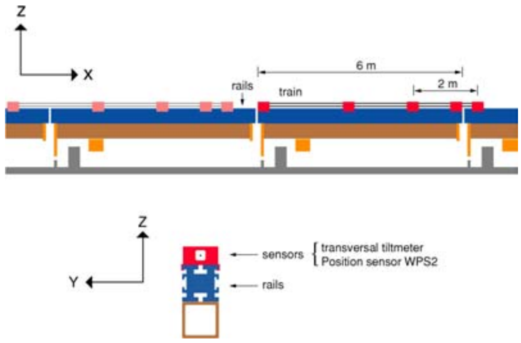


Figure 2: Metrological Train

The guiding system is based on air lubricated skids sliding on rails mounted on the beams; this solution has been chosen because of the reduced negative impact on the air flow and the

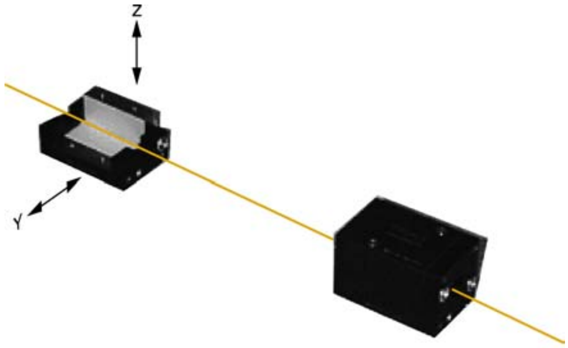


Figure 3: Sensor

small resistance to motion at high speeds. The skids are designed to withstand the efforts due to the aerodynamic loads and the inertial loads due to the action of the propulsion units. When the vehicle is in motion, addition traverse loads appear as the vehicle follows the non-straight trajectory due to the differences between the track guiding surfaces and ideal straight planes. The minimal requirements for the allowed difference between the track geometry and an ideal straight line are 1 mm over 7 m. 0.1 mm over 2 m and 0.002 mm over 1 m.

The 250 m long track consists of 40 beams (sections) is about 6 m long and several variants of profiles are still investigated. The alignment of the beams will be done in two steps. The beam surface is cut-off straight by heavy machinery. Its alignment is realized by adjusting the five struts. A non-contact position sensor WPS2 based on the principle of capacitance can observe the relative displacement up to 10 mm of a wire with a resolution of 1um, in two directions[2] [3].

Based on the study on the first prototype of the support system[4], a new bigger one has been made during the year of 2002 (Figure 4). Its size is 1/3 times of the real one to be installed in experiment tunnel. Based on the experience during last two years, some new ideas come to the structure and positions of the struts. New type of strut is presented in Figure 5. Their positions are illustrated in Figure 4. The new system has 5 struts of each section, two of them are in the back and the other three are in the front.

Figure 4: Guiding and Support **System**

Figure 5: Strut

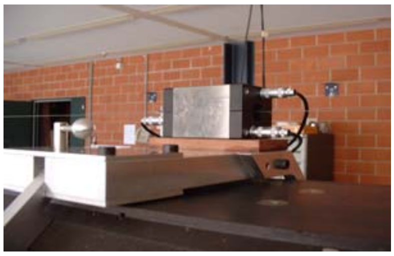


Figure 6: Alignment System

The main purposes of this research work to establish a method for the highly precise alignment of rails by using "fogale" system and other possible instruments and to find, by mathematical analytical approach, the mathematical relation between the struts' lengths and offsets measured. So a practical movable carriage (Figure 6) has been developed for implementing the rail alignment.

2. RAIL ALIGNMENT

For some description reasons, it is graphically presented for the section i in Figure 7 ~ 9. The struts have been pointed with $B_{1(ih)}$, $B_{2(ih)}$, $B_{3(i)}$, $B_{4(i)}$ and $B_{5(i)}$. Where i and h are the order of two successive section.

A special design is made for some purposes. They are could be described as follows:

– In order to keep its smoothness (even if any movement or deformation appear in one section), the struts are adopted for the supporting system. They connect successively the struts one and another.

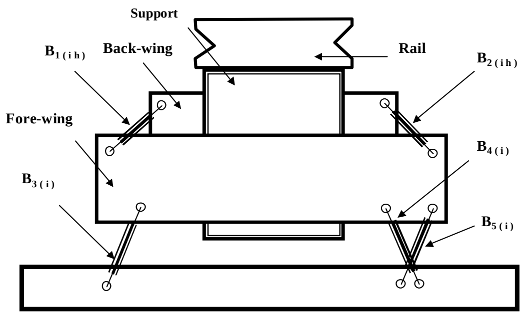


Figure 7: i - Section of HISTAR

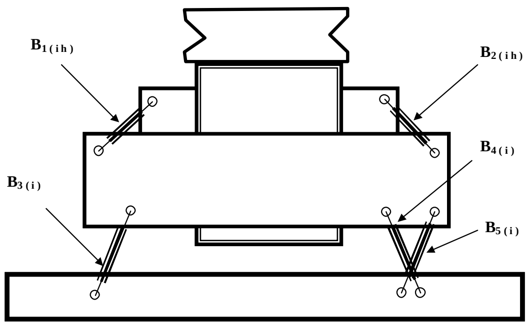


Figure 8: Fore-end of i - Section

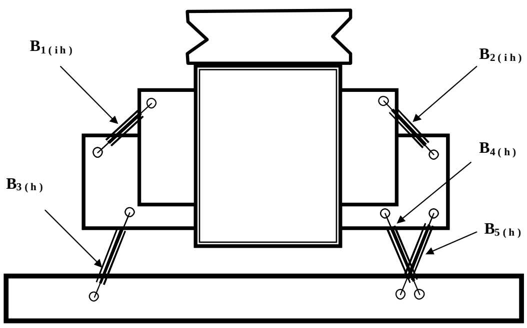


Figure 9: Back-end of i - Section

– The struts B_1, B_2, B_3 and B_4 get the weight of the upper part of the system. For the reason of stability, they are not symmetrical, so their intersection points are not in the symmetrical axe of the upper part.

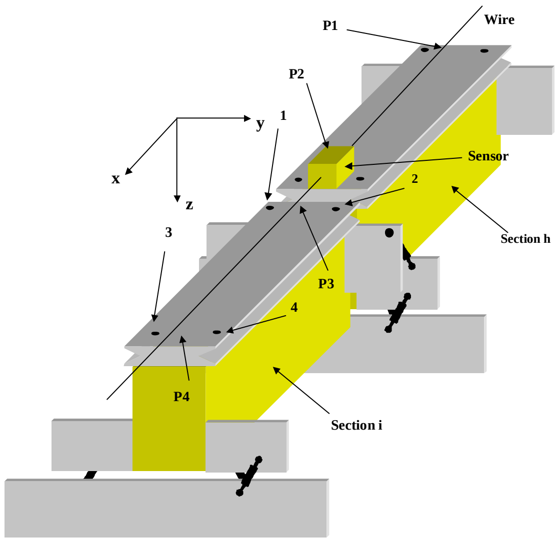


Figure 10: Geometrical Description

- The fifth strut B_5 is used to fix the posture of the upper part of the system, or to adjust the geometrical form.

2.1 Definitions

From Figure 10, $P1$ and $P2$ are the two positions of the sensor at the section h. $P3$ and $P4$ are the two positions of the sensor of the section i. 1, 2, 3 and 4 are the four points of each section, used to leveling. There is a local coordinate system as presented in Figure 10.

For the alignment of the section i with respect to the section h, 6 parameters (displacements and rotations) are usually used to describe this procedure. Three displacement parameters are Δx_0, Δy_0 and Δz_0 (Δx_0 is not considered for alignment). The rotation parameters are α, β and γ (Figure 11~13).
Where α being the rotation angle around the x-axe, β Being the rotation angle around the y-axe, γ Being the rotation angle around the z-axe.

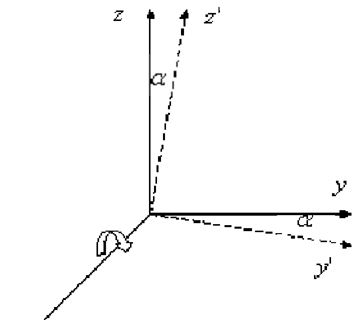


Figure 11: Rotation α

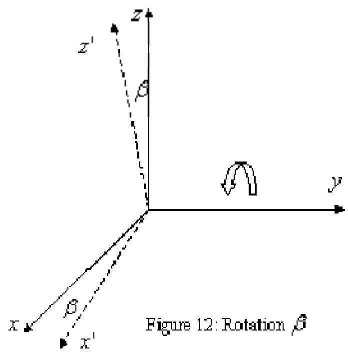


Figure 12: Rotation β

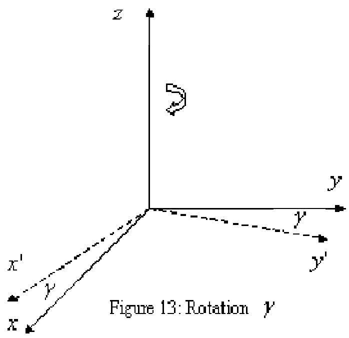


Figure 13: Rotation γ

2.2 Rail Alignment

The alignment procedure can be divided into four stages. The first is to put α being zero. The second is to get all measurements necessary (offsets, angles and lengths) and to calculate the alignment parameters: length corrections of the struts. The third is to calculate the alignment parameters. The fourth is to adjust the struts to align it.

2.2.1 Making $\alpha \approx 0$ (Leveling)

Following the design position and the initial installation of each section, it can be approximately put in its position. Then α should be made zero as possible as you can by struts' adjustment. This procedure is progressively realized for both ends of each section.

2.2.2 Taking measurements

Following the precision required and the possible instruments, a method more metrological is preferred. The horizontal and vertical offsets, the length and the inclined angle of struts are chosen as measurements.

Measurements of horizontal and vertical offsets are carried out through the Fogale sensor (Figure 6). A vernier caliper of precision 0.05mm is used for the measurement of strut length. And an automatic instrument of precision 0.01 degree, called "clinoBevel" (Figure 14), is used for the inclined angle measurements of struts.

Figure 14: ClinoBevel


Figure 15: Joint System

Among the system, there are some parts specially designed for convenience of practical measurements (Figure 15)

2.2.3 Calculating parameters

The alignment parameters mean the length corrections of the struts. The correcting procedure is realized by adjusting the struts' lengths, and also the rail alignment is carried out. There are two steps about the calculation of alignment parameters. The first is the horizontal and vertical displacements. The second is to calculate the alignment parameter by using the displacements Δy_0, Δz_0 and strut measurements. It is carried out as follows (Table 1).

- Offset measurements are listed in Column 1.
- Horizontal absolute offsets are put in Column 2.
- Distances from the starting point are in Column 3.
- Theoretical offset in Column 4 are calculated by using P_1 and P_2 as a reference line.
- Horizontal and vertical displacements Δy_0 and Δz_0 in Column 5 are graphically presented in Table 1.
-

For the second step, the whole procedure is carried out in Table 2 as follows:

- Measurements of strut lengths are listed in Column 1.
- Distances between the centers of two strut ends, b_0, are calculated from its measured length and listed in Column 4. Inclined angles measured, φ, are in Column 5.
- Distances between the centers of two strut ends of a strut after the correction Δz_0, b, are calculated through the following formula (Figure 16) and listed in Column 6.

$$b = \sqrt{b_0^2 + \Delta z_0^2 - 2 \times b_0 \times \Delta z_0 \cos(90^0 - \varphi)} \quad \Delta z_0 \le 0 \qquad (1)$$

$$b = \sqrt{b_0^2 + \Delta z_0^2 - 2 \times b_0 \times \Delta z_0 \cos(90^0 + \varphi)} \quad \Delta z_0 \ge 0 \qquad (2)$$

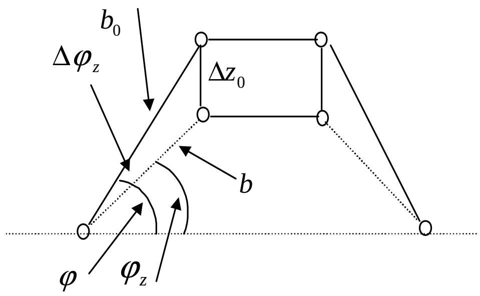


Figure 16: Change of φ_z with Δz_0

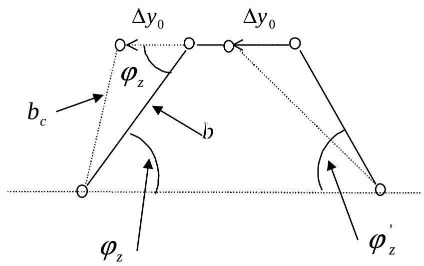
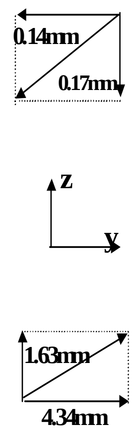


Figure 17: Change of b_c with Δy_0

Table 1: Offset Measurement

Horizontal Offsets (mm)					
	1	2	3	4	5
Point	Offset Measured	Offset Reduced	Distance	Theoretical Offset	Offset to Correct
*hh-1	40.0500	0.00	0.00		
*hh-2	31.5000	-8.55	1464.00		
ih-1	31.4500	-8.60	1496.00	-8.74	0.14
ih-2	18.6000	-21.45	2929.00	-17.11	-4.34
					(+Right - Left)

Vertical Offsets (mm)					
	1	2	3	4	5
Point	Offset Measured	Offset Reduced	Distance	Theoretical Offset	Offset to Correct
hv-1	5.2000	-0.14	0.00		
*hv-3	5.0600	0.00	1464.00		
iv-1	4.8900	0.17	1496.00	0.00	-0.17
iv-3	6.5500	-1.49	2929.00	0.14	1.63
					(+Up - Down)



- Corrections of inclined angle φ, $\Delta\varphi_z$, are calculated through the following formula (Figure 16) and listed in Column 7.

$$\Delta\varphi_z = Arc\cos((b^2 + b_0^2 - \Delta z_0^2)/(2bb_0)) \quad (+\text{ up and } -\text{ down}) \qquad (3)$$

- Inclined angles φ_z after correction Δz_0 are calculated through the following formula (Figure 16) and listed in Column 8.

$$\varphi_z = \varphi + \Delta\varphi_z \qquad (4)$$

- New lengths (between two centers) of a strut b_c after correction Δy_0 are calculated through the following formula (Figure 17) and listed in Column 9.

$$b_c = \sqrt{\Delta y_0^2 + b^2 - 2(\Delta y_0) b \times \cos(180 - \varphi_z)} \quad \text{(left)} \qquad (5)$$

- $$b_c = \sqrt{\Delta y_0^2 + b^2 - 2(\Delta y_0) b \times \cos(\varphi_z^{'})} \quad \text{(right)} \qquad (6)$$

Table 2: Measurement and Correction of Strut

	Mesurement of Strut (mm)					Correction of Strut (degree)					
	1	2	3	4	5	6	7	8	9	10	11
	Length	T-haute	T-bas	b0	Angle	b	Angle-Dz	Angle	bc	Nlongeur	DL
B-1(ih)	117.80	7.725	7.725	102.35	45.00	102.23	-0.07	44.93	102.14	117.59	-0.21
B-2(ih)	116.95	7.725	7.725	101.50	45.07	101.38	-0.07	45.00	101.48	116.93	-0.02
B-3(i)	114.30	7.725	7.725	98.85	60.62	100.27	0.46	61.08	102.45	117.90	3.60
B-4(i)	116.70	7.725	7.725	101.25	58.51	102.64	0.48	58.99	100.47	115.92	-0.78
B-5(i)	114.50	7.725	7.725	99.05	60.93	100.48	0.45	61.38	102.63	118.08	3.58

Angle---- φ ; Angle-Dz---- $\Delta\varphi_z$; Angle Corrige---- φ_z

- New lengths (between two ends) of a strut "Nlongeur" after correction Δy_0 are calculated through the following formula (Figure 17) and listed in Column 10.
- Corrections of strut lengths are in Column 11 (Figure 17). Sign "+" means that strut needs to be lengthened. Otherwise, strut needs to be shortened.

2.3 Leveling Aroud a Fixed Point

In some cases, leveling procedure should be realized by turning the section around a fixed point (for example, around the tensed wire). The advantage is not only to speed the leveling procedure, but also very good for the next step, precise alignment because it keeps the relative position between the wire and the sensor. In Figure 15, the section turns around the point 4. 1 and 2 are two extremities of a strut. As an example, it illustrates the mathematical relationship between its rotation and the change of a strut posture.

Suppose α be rotation angle, b_0 original length of strut, b_{14} the distance between 1 and 4, R_1 the distance between 2 and 4, φ_1 the inclined angle of strut. Measurements are α, b_0, b_{14}, R_1 and φ_1.

The rotation moves the point 2 to 3. The displacement can be decomposed into Δy_α and Δz_α. They can be calculated from the following formulas:

$$\Delta y_\alpha = 2R_1 \sin\frac{\alpha}{2}\cos\theta_1 \qquad (7)$$

$$\Delta z_\alpha = 2R_1 \sin\frac{\alpha}{2}\sin\theta_1 \qquad (8)$$

Where $\theta_1 = \angle 124 - \angle 324 - \varphi_1$

$$\angle 124 = Arc\cos\left(\frac{b_0^2 + R_1^2 - b_{14}^2}{2b_0 R_1}\right) \qquad (9)$$

$$\angle 324 = Arc\cos\left(\frac{R_1^2 + (R_1 \sin\frac{\alpha}{2})^2 - (R_1 \cos\frac{\alpha}{2})^2}{2R_1(R_1 \sin\frac{\alpha}{2})}\right) \tag{10}$$

$$\angle 324 = Arc\cos\left(\frac{1-\cos\alpha}{2\sin\frac{\alpha}{2}}\right) \tag{11}$$

After we know Δy_α and Δz_α, the new lengths of struts can be worked out as illustrated

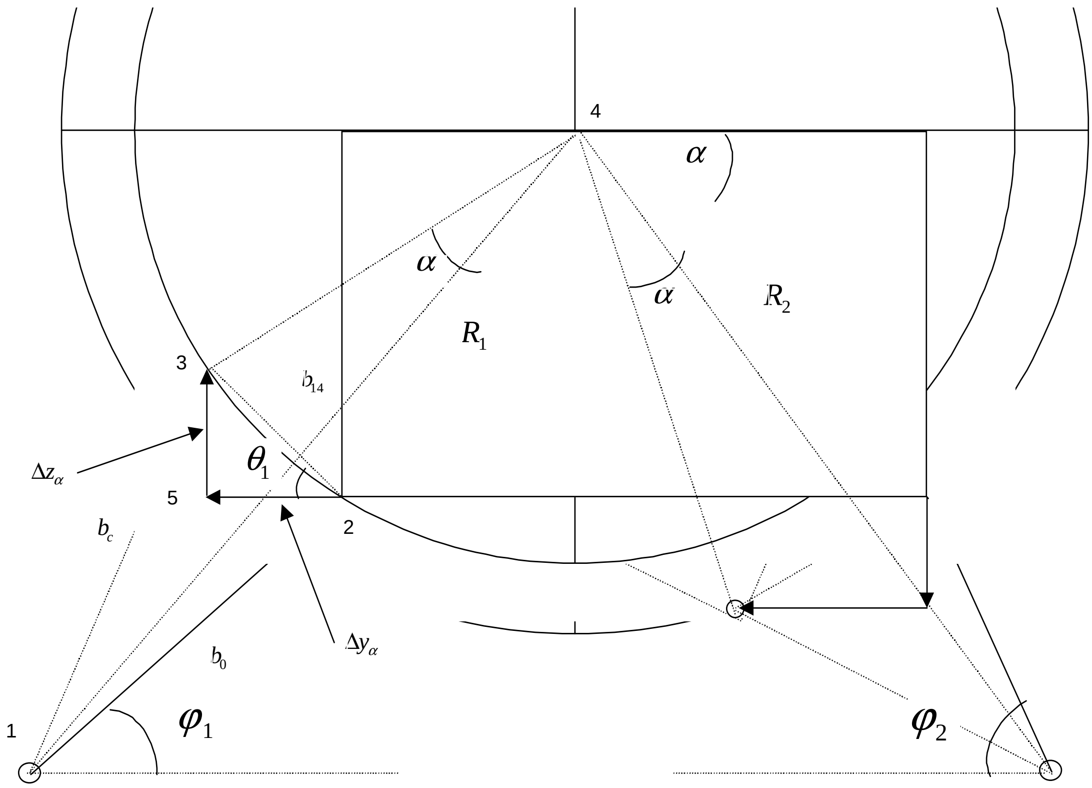


Figure 18: Leveling around a fixed point

in Table 1 and Table 2.

Namely, the other struts could be dealt with the same principle. So a leveling can be realized in one extremity of strut. Namely, another extremity can be managed too.

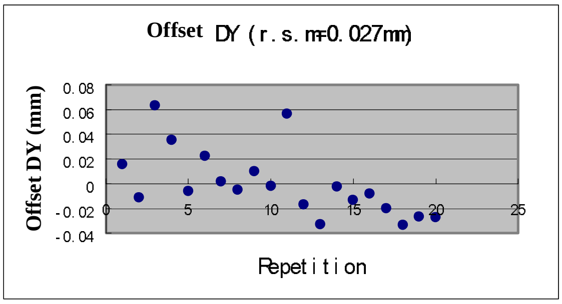


Figure 19: Repetition Precision on Y

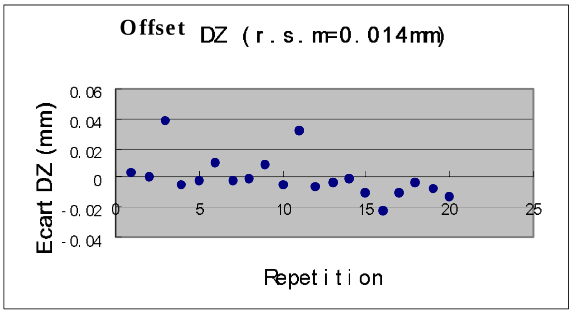


Figure 20: Repetition Precision on Z

2.4 Alignment Precision

In order to know the surveying precision of offsets with this surveying Carriage, some statistical tests have been carried out. Firstly, measurement repetitions were realized at the same position. The scatter of the measurement is illustrated in Figure 19 and 20, with the precision: $\sigma_y = 0.027mm$ and $\sigma_z = 0.014mm$. Secondly, 6 positions in one section are chosen for the surveying repetitions. The offsets reduced to means are presented in Figure 21

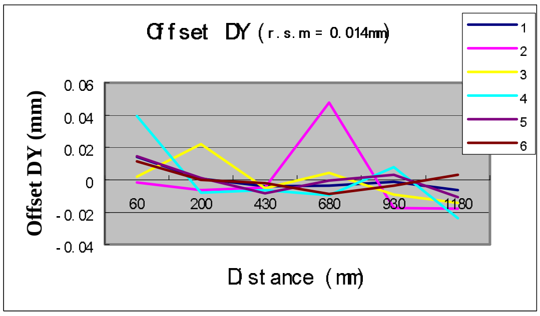


Figure 21: Repetition Precision on Y along Distance

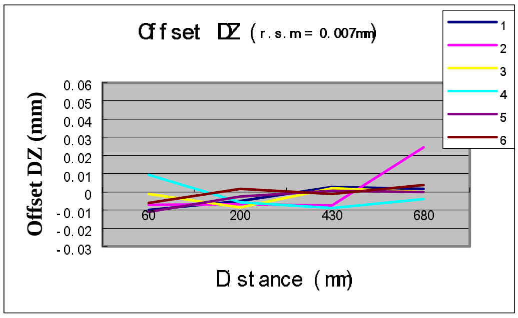


Figure 22: Repetition Precision on Z along Distance

and 22. The precisions are separately $\sigma_y = 0.014mm$ and $\sigma_z = 0.007mm$ but with some peak values about 0.05mm.

3 ALIGNMENT PROCEDURE

Following the experience and the required precision, the alignment procedure can be summarized up:

- Leveling precisely the two extremities of one section in y-direction, two methods can be considered:
  - Leveling with tilt instruments by adjusting the struts
  - Leveling with a rotation around one fixed point by adjusting the lengths of struts to the calculated values
- Measuring the offsets by sensor on carriage, two positions for each section. Measuring distances of the position w.r.p to the starting point.
- Measuring the lengths and inclined angles of the five struts

- Calculating the new lengths of struts
- Adjusting all struts to their new lengths
- Check measuring
- Repetition all above if alignment is not as good as desired

4 CONCLUSIONS

Following research and test, some experiences and conclusions can be presented as

- The method is verified to be available for the precise alignment of HISTAR system. Following the experiments, the alignment could be around ±0.05mm (Minimum reading of Length measurement is 0.05mm, the precision of inclined angle measurements is about ±0.02 degree, the precision of distances is about ±2mm). The precision of alignment is about 0.1 mm.
- Adjustable range of strut should be longer, 3mm. The difference should be smaller, 0.1-0.15mm.
- With respect the precision of sensor, the precision of carriage repetition should be improved by reducing its width and its contacting surfaces.
- A special measurement instrument of better precision (±0.005-0.01mm) for the lengths of struts is absolutely necessary for measuring and adjusting.

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