

Absolute Accuracy Improvement of Ring Particle Accelerator Control Network Based on Micron-Level Backbone Network

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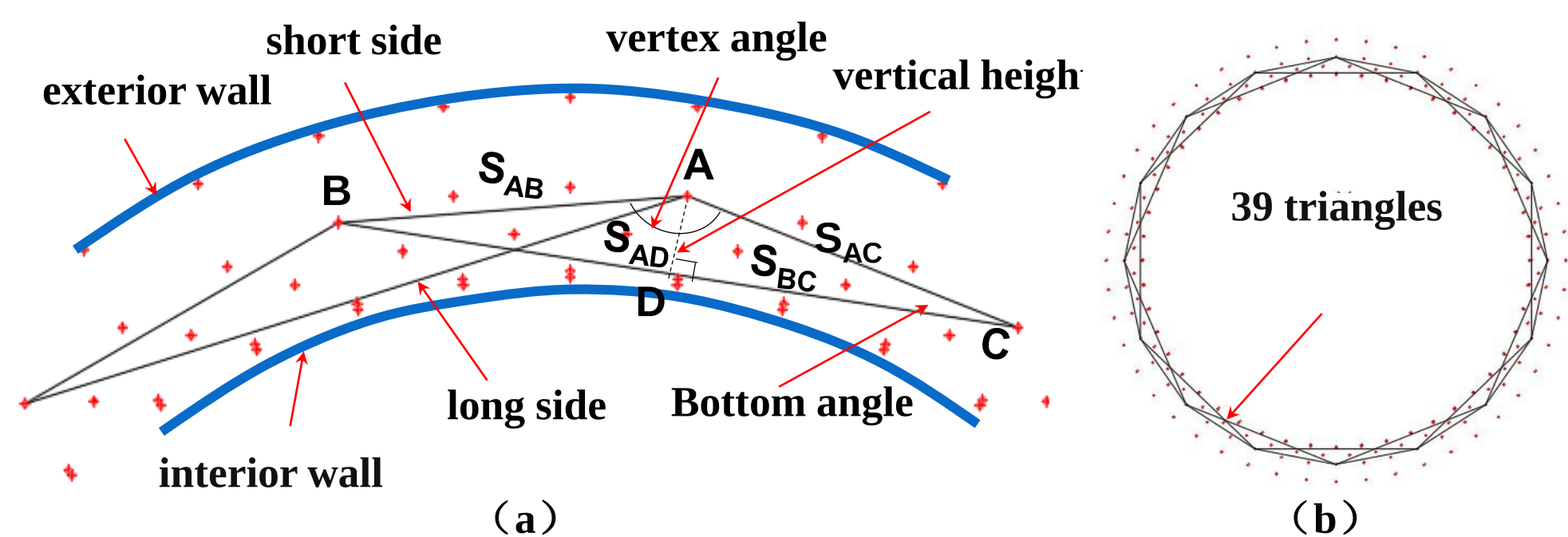
Introduction

This paper proposes a scheme for constructing a high-precision straight-overlapping triangular backbone control network. For measuring the height of long sides in large-scale obtuse triangles, an indirect measurement method based on taut wire offset measurement and additional vertex equilateral triangle side length measurement is introduced. Utilizing a self-developed telecentric optical coaxial image offset instrument and its data processing system. For side length measurement, a high-precision concentric measurement scheme based on the μ -base rangefinder is designed. The measurement accuracy of offset distance, long-side height and side length has reached 10 μ m. This scheme has been deployed and implemented across the entire HEPS storage ring, successfully improving the planar absolute accuracy from 0.13mm to approximately 0.06 mm without compromising the smoothness of the control network, with significant results.

Layout and Accuracy Study of the Straight-Overlapping Backbone Network

1. Backbone Network Layout

The straight triangular backbone network of the HEPS storage ring consists of 39 points, forming a closed backbone network composed of 39 obtuse straight triangles. Each triangle spans approximately 14 segments of the tracker control network. The entire backbone network comprises 78 sides, including 39 long sides and 39 short sides. Constrained by on-site equipment and tunnel structure, the short side lengths range from 30m to 39m, while the long side lengths range from 64m to 72m. The vertex angle corresponding to the long sides is approximately 160°, and the vertical height of the long sides ranges from 2.4m to 3.1m.



2. Accuracy Simulation Calculation

Based on the triangular backbone network, the functional models for distance observations (Equation 1) and long side height (Equation 2) are established:

$$L_{ik} = \sqrt{(X_i - X_k)^2 + (Y_i - Y_k)^2} \quad (1)$$

$$H_i = \frac{|Ax_i + By_i + C|}{\sqrt{A^2 + B^2}} = \frac{|(y_1 - y_2)x_i + (x_2 - x_1)y_i + x_1y_2 - x_2y_1|}{\sqrt{(y_1 - y_2)^2 + (x_2 - x_1)^2}} \quad (2)$$

Using the adjustment results of 240 station actual observations from the HEPS storage ring as theoretical coordinates, a 240-station tracker observation network was regenerated. The angular observation error σ_{angle} is 0.64" arcseconds, and the distance observation error σ_{dis} is 0.023mm. Five simulation adjustments were performed by applying different errors to the backbone network side length error σ_L and long side height error σ_H , as detailed in Table 1.

From the radial accuracy σ_r and tangential accuracy σ_t of the adjusted control network, it is evident that merely adding high-precision backbone network side lengths has limited impact on improving control network accuracy. Significant improvement in the ring control network accuracy only occurs when the observation accuracy of the long side height exceeds 0.02 mm.

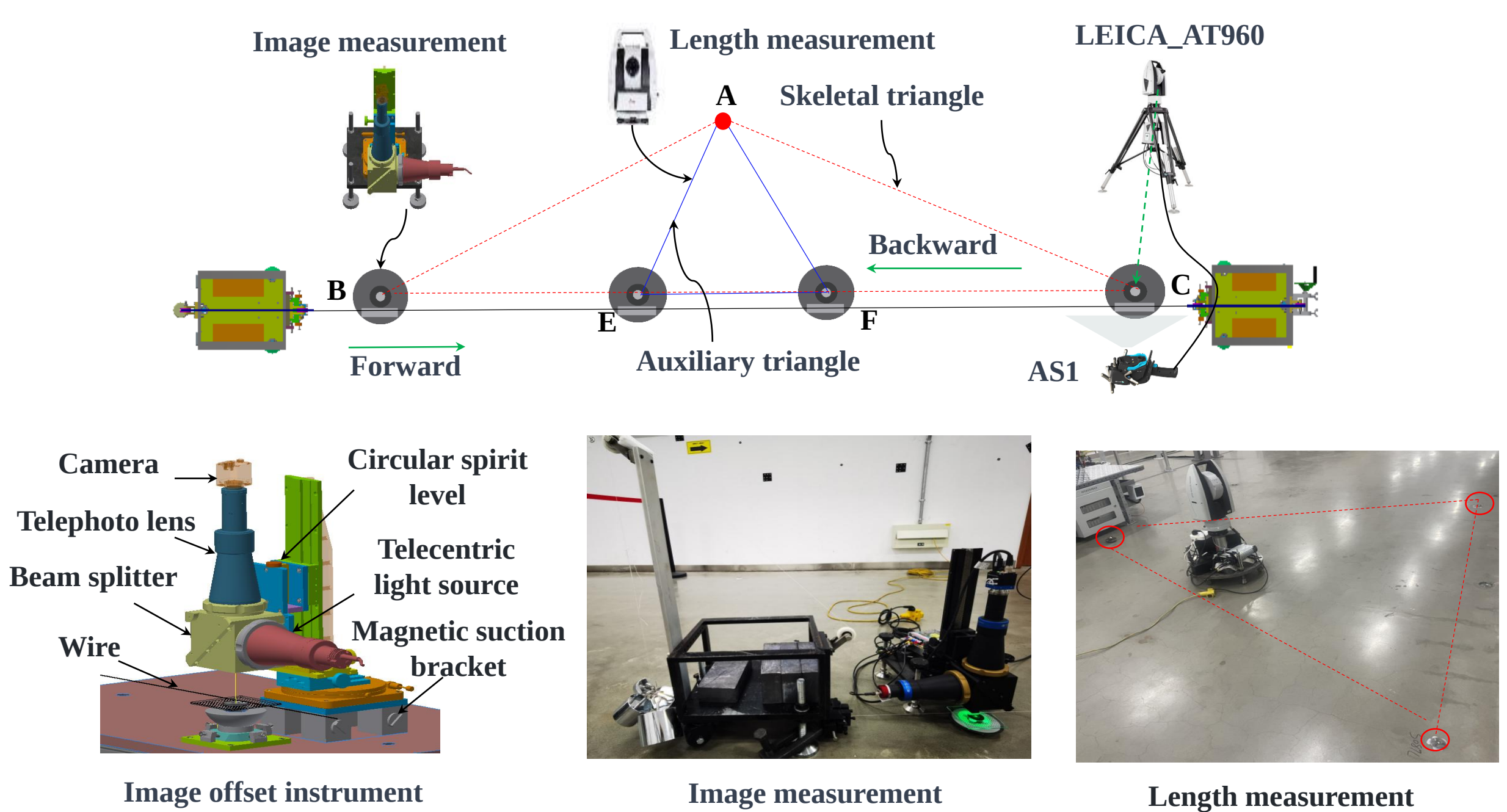
Table 1 Standard deviation of observations used in simulation adjustments

Scheme	$\sigma_{angle}/''$	σ_{dis}/mm	σ_L/mm	σ_H/mm	σ_r/mm	σ_t/mm
1	0.64	0.023	—	—	0.13	0.12
2	0.64	0.023	0.02	—	0.13	0.12
3	0.64	0.023	0.01	—	0.13	0.12
4	0.64	0.023	0.02	0.02	0.10	0.09
5	0.64	0.023	0.01	0.01	0.07	0.06

Backbone Network Measurement Scheme

1. Long Side Height Measurement Using Tension Wire Offset Method

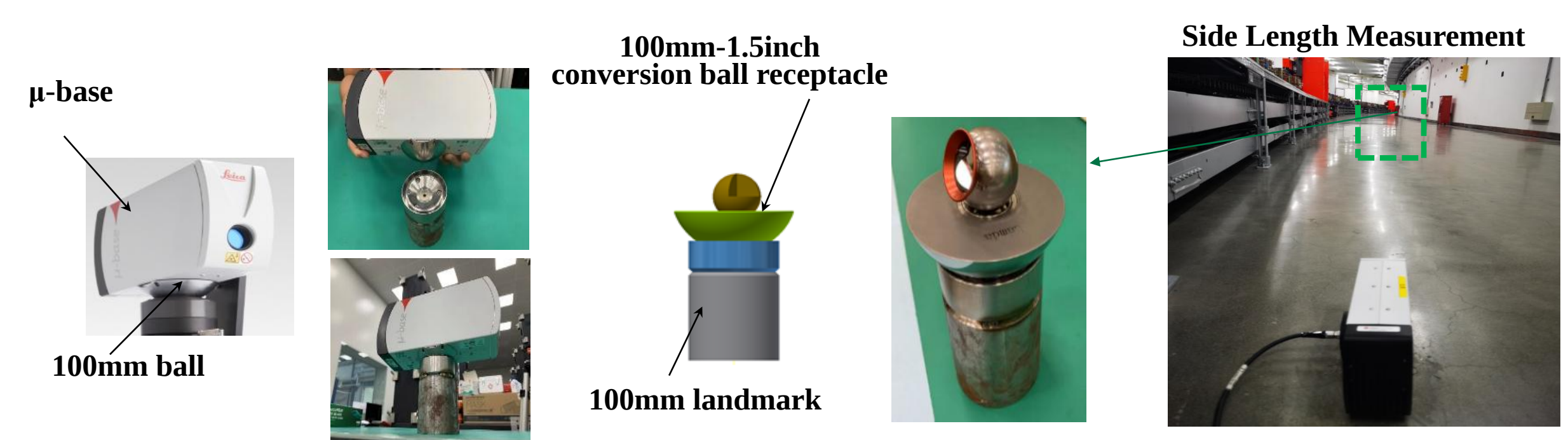
The long side height of the backbone network triangles is obtained indirectly through a scheme based on tension wire offset measurement and additional vertex equilateral triangle side length measurement. As shown in Figure for the measurement content of each triangle: a LEICA AT960 tracker positioned inside the additional vertex triangle $\triangle AEF$ for side length measurement; and a self-designed coaxial image offset instrument set up at base points A, B and additional base points E, F for offset measurement. The RMS for round-trip error of Class 3 measurement is 7 μ m.



2. Network Side Length Measurement

The LEICA μ -base absolute rangefinder achieves a measurement accuracy of 0.01 mm within a 160m range, serving as a long-distance, high-precision instrument. A concentric measurement scheme has been designed, achieving concentricity among the landmark, measuring instrument, and measurement target:

- (1) A 100mm tunnel ball seat landmark designed to ensure concentricity between the landmark center and the μ -base center, effectively avoiding projection errors.
- (2) A 100mm to 1.5-inch conversion ball receptacle designed to achieve precise concentricity between the tracker reflector and the 100mm landmark.



Adjustment Calculation and Results

In February 2025, the HEPS storage ring conducted tunnel control network measurements using a LEICA AT930, along with long side height and side length measurements of the backbone network. Three adjustment schemes were performed:

- (1) Independent adjustment of the laser tracker data.
- (2) Independent adjustment of the backbone network data.
- (3) Integrated adjustment of both laser tracker and backbone network data.

The posterior standard deviation from the three adjustments are shown in Table 2 and the tangential and radial accuracies of network points are presented in Table 3.

Table 2 The posterior standard deviation of observations for three types of adjustment (units: mm, ")

Laser Tracker		Backbone network		Laser Tracker + Backbone network			
σ_{dis}	σ_{angle}	σ_L	σ_H	σ_{dis}	σ_{angle}	σ_L	σ_H
0.031	0.879	0.011	0.009	0.031	0.878	0.011	0.009

Table 3 Point accuracies and correction values of backbone network observations from the three adjustments (unit: mm).

	Laser Tracker		Backbone network		Laser Tracker + Backbone network			
	σ_r	σ_t	σ_r	σ_t	σ_r	σ_t	V_L	V_H
Max	0.212	0.166	0.114	0.088	0.233	0.115	0.018	0.021
Min	0.000	0.000	0.000	0.000	0.000	0.000	-0.03	-0.027
RMS	0.132	0.122	0.072	0.066	0.065	0.059	0.013	0.012

The adjustment revealed that the backbone network, due to limited redundant observations, is highly sensitive to reliability—accuracy can drop sharply if individual observations contain large errors. From Tables 2 and 3:

(1) In the independent adjustment of the backbone network, the posterior standard deviations of both the side length and long-side height observations are approximately 10 μ m; the RMS values of the corrections V_L and V_H are also around 7 μ m. This indicates that the measurement accuracy of the obtuse triangles with a 70m span in the backbone network has reached 10 μ m;

(2) The radial accuracy σ_r of the storage ring control network improved from 0.132mm to 0.06mm, and the tangential accuracy σ_t from 0.122mm to 0.05mm, doubling the absolute accuracy of the storage ring control network, the effectiveness is remarkably significant.