

Article

A Range-Extension Method for an Indoor Standard Device for Large-Scale Length Measurement

Chang'an Hu ^{1,2,*} , Liang Xue ², Jiangang Li ² and Fei Lv ³

¹ Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu 610054, China

² National Institute of Measurement and Testing Technology, Chengdu 610021, China; xueliang@nimtt.com (L.X.); lijiangang@nimtt.com (J.L.)

³ School of Computer Science, Chengdu Normal University, Chengdu 611130, China; lvfeichengdu@163.com

* Correspondence: jixiedcd@nimtt.com

Abstract: The Laser interferometer plays an important role in the field of geometrics for large-size measuring applications. Its linear displacement error can be traced from indoor large-scale standard devices. However, the measuring range of the indoor large-scale standard device is too limited to meet the full range measurement of the laser interferometer. So, the lack of accuracy of the results is one of the key issues of laser interferometers. To solve this problem, the corner reflector is used to extend the range of indoor large-scale standard devices, which meet the indication errors in the effective measuring range of the laser interferometer. The range-extension method not only doubles the effective measuring range, but also provides a way to trace the source of other large-size measuring instruments. This work proposes a significant solution to the field of length measurement.

Keywords: indoor standard device for large-scale length measurement; range extension; traceability of measurement; transfer of the value of a quantity; laser interferometer



Citation: Hu, C.; Xue, L.; Li, J.; Lv, F. A Range-Extension Method for an Indoor Standard Device for Large-Scale Length Measurement. *Appl. Sci.* **2023**, *13*, 9154. <https://doi.org/10.3390/app13169154>

Academic Editors: Humberto Cabrera and Takeo Minamikawa

Received: 26 June 2023

Revised: 6 August 2023

Accepted: 9 August 2023

Published: 11 August 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

A wide range of measurement methods and techniques have seen upgrades in the continuous development of industrial manufacturing. Large-scale metrology techniques refer to geometric measurement, with an effective range of tens of meters and an accuracy of micrometers. They are intertwined with modern manufacturing, with multiple applications, including assembling aircraft, reinstalling systems, developing large particle accelerators, and measuring antennas and automobile production lines. The large-size measuring instrument is the core of large-size measurement. To meet production needs, there is an increasing demand for large-size measuring instruments. The linear indication error of the large-size measuring instrument is traced back to the indoor large-scale standard device. Main large-size measuring instruments include long-range laser interferometers, laser trackers, laser radars, laser alignment instruments, laser rangefinders, indoor GPS, frequency-modulated laser rangefinders, etc. The measuring range of these instruments exceeds 50 m, and that of laser interferometers can be up to 80 m.

Standard devices for large-scale length measurement can be classified into indoor and outdoor variants. Indoor standard devices for large-scale length measurement are known for their exceptional measurement accuracy and ease of controlling environmental factors, albeit with a limited measuring range. Conversely, their outdoor equivalents boast a longer range of measurement, but exhibit lower accuracy and difficulties in regulating the measurement environment. Globally, indoor standard devices for large-scale length measurement measure distances less than 100 m, with the figure for the National Metrology Institute of Japan at 96 m, the National Institute of Standards and Technology of the US at 60 m, the Korea Research Institute of Standards and Science and the Physikalisch-Technische Bundesanstalt of Germany at 50 m, and that for our institute at 56 m.

Given the problems related to large-scale measurement, many studies have been conducted around the world. While Zhou formulated measurement standards for a range of 35 m [1], Peggs et al. introduced a variety of large-scale measuring instruments and the development trend of large-scale measurement [2]. Li et al. established an 80 m indoor large-scale standard device [3]. From the perspectives of the curved-surface evaluation and a united spatial measurement network, Ma carried out in-depth research on large coordinate metrology techniques [4]. Based on folding optics, Chen calibrated a total station using plane mirrors and an indoor fixed-length baseline [5]. With multiple rectangular prisms, Yang researched how a geodimeter can be calibrated at a distance of 40 m within a structure [6]. Qiao et al. used a plane reflector to reproduce a standard length of 50 m on a 16-m-long indoor guide rail [7]. Wang et al. proposed establishing a virtual length baseline field through successive rectangular prism reflections [8]. Moreover, Huang and Pan et al. raised a hypothesis about creating a virtual indoor baseline field through multiple reflections of two plane mirrors [9,10]. Yang et al. conducted a theoretical analysis of the straightness of a 26 m-long linear guide rail [11]. Zheng et al. investigated the measurement accuracy of a multi-beam laser tracking interferometer [12]. Li et al. explored how temperature can influence the accuracy of large-scale metrology instruments [13]. Haitjema studied the calibration methods of laser frequency, counting system, and other parameters of displacement laser interferometer system [14]. Voluminous studies have been undertaken on large-size metrology, some of which focus on the indoor standard device for large-scale length measurement. This suggests that it is of significant scientific value to extend the measuring range of these indoor standard devices. We think that there are two problems when using a plane reflector as a reflecting medium. Firstly, different measuring distances will cause different measurement errors. Secondly, experimenters using plane reflectors are only at the theoretical stage, and there are no suitable measurement data to support them. However, the pyramid prism used for the geodimeter is not necessarily suitable for the laser interferometer, because the measurement accuracy of the laser interferometer is higher than that of the geodimeter. Notably, laser interferometers are essential for transferring large-scale measurements, and their qualification depends largely on indication errors of linear measurement. In this paper, we proposed an effective method to extend the range of the laser interferometer, in which an indoor standard device for large-scale length measurement and corner reflectors with an accuracy of 0.2'' are major components. The experimental data validates the range extension with the high accuracy of the laser interferometer.

2. Indoor Standard Device for Large-Scale Length Measurement

The indoor standard device for large-scale length measurement was fitted with a laser interferometer measuring system, a long-scale guide rail system, an automatic control system, and a regulated environment [15]. A diagram of the major components of an indoor standard device for large-scale length measurement is shown in Figure 1.

2.1. Laser Interferometer Measuring System

The laser interferometer measuring system comprised three standardized laser interferometers. The final measurement uncertainty needed to satisfy: $U \leq 1/2$ of the maximum permissible error (MPE). If the measurement uncertainty U is less than half of the MPE, the quantity transmission of instruments will be meaningless. Since the MPE between the tested sample and calibrator is too close, there is no transfer chain between them. This system is mainly used to calibrate the laser tracker, with an MPE of $15 \mu\text{m} + 6 \mu\text{m} \times L$. Then, the MPE at a distance of 50 m is $315 \mu\text{m}$, meaning when $U = 7.5 \mu\text{m} + 3 \mu\text{m} \times L$, then $U = 150 \mu\text{m}$ at a distance of 50 m. The system consisted of three independent commercial dual-frequency laser interferometers for linear measurement with a measuring range of up to 80 m to enable laser triangulation to eliminate Abbe error.

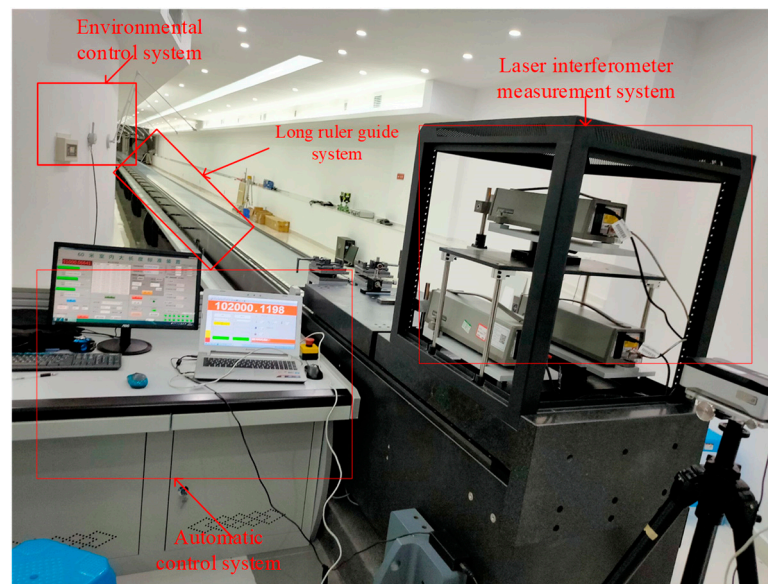


Figure 1. Major components of an indoor standard device for large-scale length measurement.

2.2. Long-Scale Guide Rail System

The guide rail spanned a length of 57 m, boasting an operational noise level of below 40 dB. The guide rail system should be easily expandable and accommodate additional mobile platforms, and the positioning accuracy of each of these platforms stood at 50 μm . A fixed instrument platform was in place at both ends of the rail, while the starting end was fitted with four pre-set manual sliding tables (two with four sliders and two with two sliders). Furthermore, a pre-set automated mobile platform complemented the system's capabilities.

To ensure accurate control of the long-scale moving target, specific control error thresholds were set. The straightness error should not exceed 0.03 mm/m, 0.05 mm/4 m, 0.10 mm/20 m, and 0.25 mm/57 m. Similarly, the flatness error must stay within 0.03 mm/m, 0.08 mm/4 m, 0.12 mm/20 m, and 0.30 mm/57 m. Operating at noise levels below 40 dB, the guide rail boasted a robust load-bearing capacity of at least 150 kg. Its foundation, spanning 57 m, required careful pouring based on stable rock layers, taking into account necessary allowances. The granite-made guide rail was supported by adjustable frames on a concrete foundation, enabling adjustments in six directions. Quality standards dictated that the guide rail's foundation surface remained free from any scratches, cracks, delamination, or rust. Overall, the guide rail system was assembled by no more than 14 pieces of granite rail, each measuring at least 600 mm $\times$ 500 mm. To overcome the limitations of the friction-driven air-floating platform, characterized by low operational speed and insufficient stability, we incorporated linear guides and transmission racks into the granite guide rail system.

2.3. Automatic Control System

The automatic control system encompassed electric power distribution, a human-machine interface and operator console, a logic control center, motion control and positioning, and data communication. It ensured automated control of motion and closed-loop feedback control of interferometer data within the measuring range, thereby facilitating high-accuracy positioning. The driving mechanism featured a continuously variable transmission, endowing the motion platform with swift and agile mobility.

2.4. Regulated Environment

Control of temperature, pressure, and humidity: the pressure remained unregulated, while the humidity was automatically controlled through a dehumidification system, and the temperature was regulated via an air conditioning system.

Compensation of temperature, pressure, and humidity: A measuring and compensation system was implemented to measure the real-time environmental readings of atmospheric pressure (p), air temperature (t), and air humidity (f) along the laser path, which were then used to calibrate the laser interferometer values based on the Edlen equation. Specifically, a comprehensive temperature measurement system consisting of 30 temperature sensors was employed to enable consistent temperature distribution. Along the laser path, 28 sensors were precisely placed at two-meter intervals along the Z1 wall, while the remaining two were installed on the Z3 wall, two meters and four meters above the ground, respectively. Furthermore, a dedicated temperature detection system utilizing 12 sensors was set up to monitor the temperature of materials under test. These sensors included two near the arc corridor on the Z1 wall, four on the long-scale moving target platform, two placed flexibly, and four at the shorter scale on the Z3 wall. An overhead view of the laboratory that houses the indoor standard device for large-scale length measurement is illustrated in Figure 2.

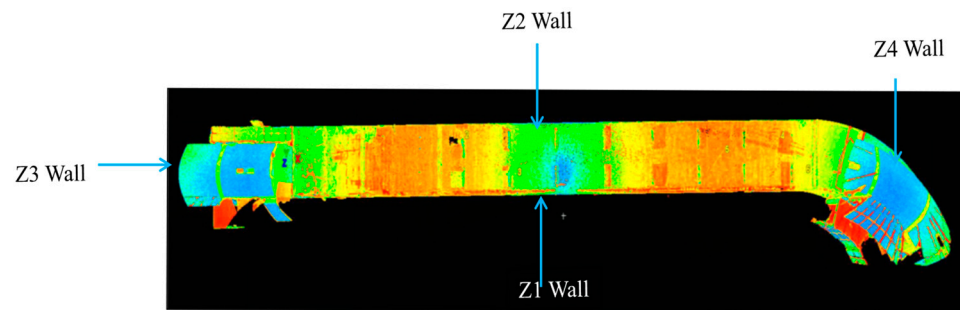


Figure 2. The top view of an indoor standard device for large-scale length measurement.

To measure air pressure and humidity, we utilized sensors for monitoring air pressure, temperature, and humidity. The accessories for these sensors were customized based on the specific laboratory requirements. Also, they should facilitate the adjustment of sensor positions to ensure stable and accurate length measurement and the measurement and compensation of precise environmental parameter inputs.

3. Range Extension of the Indoor Standard Device for Large-Scale Length Measurement

In our research, corner reflectors were employed to extend the measuring range of the indoor standard device for large-scale length measurement. A comparative analysis of the data obtained from the laser interferometer upon the range extension demonstrated the significance of extending the range of an indoor standard device for large-scale length measurement, whose primary reference instrument is represented by the laser interferometer due to its exceptional linear measurement accuracy. Beyond a major lab-based standard device for length measurement, the laser interferometer is typically used for the field test of such high-accuracy surveying systems as machine tools. The Renishaw XL-80 laser interferometer is capable of measuring linear distances of up to 80 m, and by leveraging its strengths, we managed to double the measuring distance within a range of 52 m by equipping it with special corner reflectors.

3.1. Design and Performance Analysis of Corner Reflectors

As an optical range-extension component in this paper, the hollow corner reflector is composed of a group of glass prisms with three perpendicular faces, as shown in Figure 3.

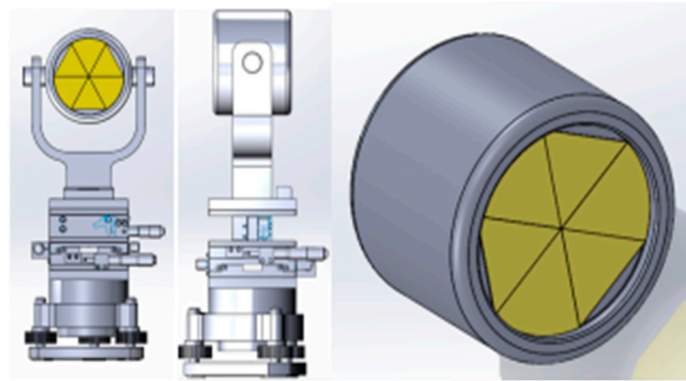


Figure 3. Structure of the hollow corner reflector.

Compared to solid corner cubes, hollow corner reflectors offer three distinct advantages. First, the hollow corner reflector uses air as the transmission medium and will not cause transmission optical path differences. Second, the hollow corner reflector can achieve ultra-precise return light parallelism (i.e., the angle between the outgoing beam and the return beam) by precision setting. Last, the manufacturing of hollow corner reflectors with large apertures is relatively effortless. In contrast, solid corner cubes, typically produced through conventional machining, usually have diameters no greater than 50 mm, and their retroreflection parallelism is typically limited to around $3''$. The hollow corner reflector required for this work has a diameter of $\Phi 100$ mm and a return light parallelism of $0.2''$. We set up a measuring system, as shown in Figure 4, which is mainly composed of an autocollimator, a reading display platform, and a lifting mechanism. We adjusted the corner reflector and measuring system to ensure levelness, recorded the readings of the corner reflector, and took the maximum value of the measurement result as the measurement result.

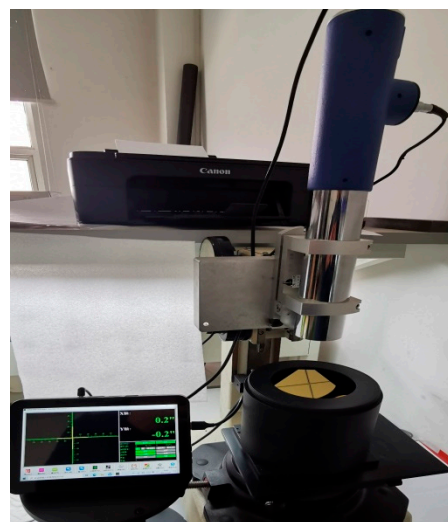


Figure 4. The optical path tests the corner reflector's retroreflection parallelism.

3.2. Optical Path Setup in the Range-Extension Measuring System

Figure 5 demonstrates how the measuring optical path is created by the laser interferometer measuring system. Upon traversing a corner reflector, the incident light fell on the reflector of the laser interferometer. After being refracted by the interferometer's reflector, the light was reflected by another corner reflector before entering the main unit of the laser interferometer. Overall, the incident light underwent two reflections to achieve the range-extension experiment of the laser interferometer.

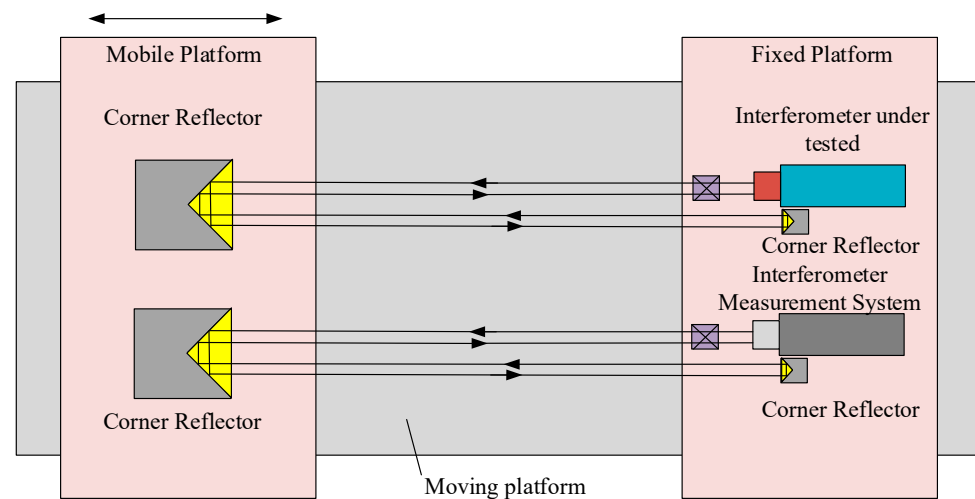


Figure 5. A diagram of the simulated optical path for the range-extension measurement of a laser interferometer.

The range-extension experiment of the laser interferometer, as depicted in Figure 6, involved large-size corner reflectors with a diameter of 100 mm each, which served as the primary measuring device. By adjusting the positions of the corner reflectors and the reflector of the laser interferometer, we managed to extend the measuring range. The original reflectors were replaced by large-size corner reflectors, which allowed for the reception of more laser beams when reflecting over long distances. It can receive more laser beams when reflecting over long distances. In addition, the light reflectivity of mirror reflection is higher than that of transmission reflection.

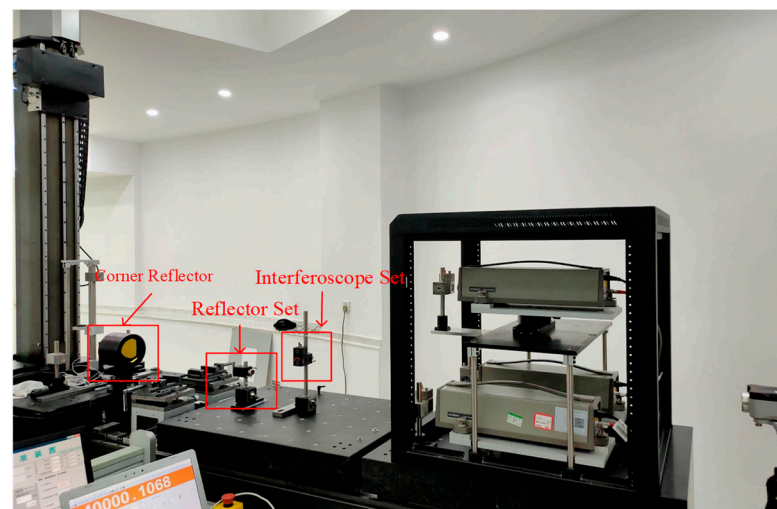


Figure 6. A diagram of the optical path in a laser interferometer's range-extension experiment.

3.3. Analysis of Range-Extension Measurements

The data obtained after the range extension within a range of 52 m are presented in Table 1. The nominal values are measured by a laser interferometer (model: HP 5519B, factory number: US52140378) fixed in the laboratory. The laser interferometer shows that the stability of its laser frequency is 2.5×10^{-10} at 1000 s during the 10,000 s time interval after frequency stabilization. Its average wavelength in the vacuum is $\lambda = 0.632991374 \mu\text{m}$, and the uncertainty of the average wavelength in the vacuum is $U = 2 \times 10^{-8}$ ($k = 2$). The laser interferometer for stationary use is featured by stable data and superior performance. The measured values are measured by an interferometer (model: XL-80, number: 747X57), and the stability of its laser frequency is 2.8×10^{-9} at 1000 s. The measured data of these

two laser interferometers are both from the secondary standard device with a 633 nm wavelength. The reflectors of the two laser interferometers are more than 1 m away from the laser interferometer. Therefore, the maximum allowable error at a nominal 1 m position is 0.5 μm , the maximum allowable error at a nominal 2 m position is 1.5 μm , and the maximum allowable error at a nominal 3 m position is 2.0 μm , and so on. As shown in the table, it is evident that the maximum measurement error was $-13.02 \mu\text{m}$, occurring at a distance of 102 m. At specific distances (of four meters, six meters, and eight meters), the data slightly deviated from the specified limits. Overall, the maximum indication error upon the range extension satisfied the standards for calibrating the laser interferometer as it fell within the required indication error range of $\pm 0.5 \mu\text{m}/\text{m}$. This experimental measurement requires repeated debugging of the optical path. Due to the large amount of measured data, only one measurement result can be presented in this paper. After several experiments, it was found that the proposed measuring method has strong repeatability.

Table 1. Measurements upon the range extension at a measuring range of 52 m.

Nominal Value (mm)	Measured Value (mm)	Measurement Error (μm)	Nominal Value (mm)	Measured Value (mm)	Measurement Error (μm)
1999.9866	1999.9880	1.42	54,000.3242	54,000.3191	-5.12
3999.9797	3999.9823	2.56	56,000.3477	56,000.3443	-3.36
6000.0039	5999.9952	-8.70	58,000.4102	58,000.4067	-3.46
8000.0005	7999.9942	-6.28	60,000.3867	60,000.3888	2.08
9999.9678	9999.9656	-2.18	62,000.4648	62,000.4525	-12.34
11,999.9609	11,999.9622	1.26	64,000.4609	64,000.4489	-12.04
13,999.9727	13,999.9681	-4.56	66,000.4688	66,000.4589	-9.86
15,999.9492	15,999.9444	-4.82	68,000.4688	68,000.4636	-5.16
17,999.9629	17,999.9566	-6.30	70,000.4609	70,000.4635	2.56
19,999.9609	19,999.9560	-4.94	72,000.4688	72,000.4702	1.44
21,999.9746	21,999.9703	-4.30	74,000.4531	74,000.4548	1.68
23,999.9570	23,999.9556	-1.44	76,000.4375	76,000.4430	5.50
25,999.9512	25,999.9503	-0.88	78,000.4609	78,000.4625	1.56
27,999.9609	27,999.9627	1.76	80,000.4688	80,000.4706	1.84
29,999.9805	29,999.9786	-1.86	82,000.4375	82,000.4419	4.40
32,000.0039	32,000.0028	-1.10	84,000.4531	84,000.4530	-0.12
34,000.0195	34,000.0180	-1.54	86,000.4609	86,000.4523	-8.64
36,000.0703	36,000.0695	-0.82	88,000.4297	88,000.4228	-6.88
38,000.0703	38,000.0737	3.38	90,000.3984	90,000.3960	-2.44
40,000.1094	40,000.1085	-0.88	92,000.3828	92,000.3812	-1.62
42,000.1406	42,000.1421	1.48	94,000.3125	94,000.3120	-0.50
44,000.1680	44,000.1656	-2.36	96,000.2813	96,000.2830	1.74
46,000.2227	46,000.2160	-6.66	98,000.2266	98,000.2312	4.64
48,000.2383	48,000.2339	-4.38	100,000.1875	100,000.1904	2.90
50,000.2656	50,000.2614	-4.22	102,000.1328	102,000.1198	-13.02
52,000.2891	52,000.2876	-1.46	104,000.0781	104,000.0688	-9.32

The measurement error in the range extension at a measuring range of 52 m is presented in Figure 7, which visualizes measurements. The measurement error resulted in a sawtooth pattern and oscillated as the measuring length increased.

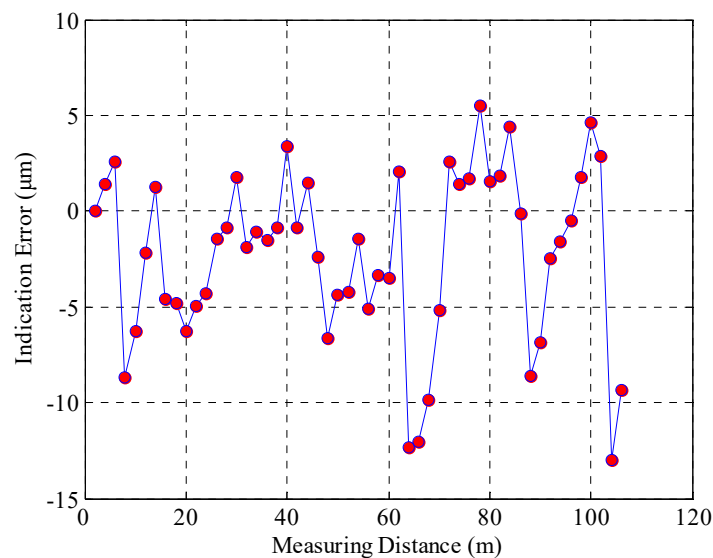


Figure 7. A diagram of measurement indication error in the range extension at a measuring range of 52 m.

3.4. Verification of the Range-Extension Experiment

To further validate the reliability of the range-extension data within the 52 m measuring range and assess the feasibility of our proposed range-extension method, we conducted a separate experiment at a range of 50 m. A comparison was made between the measurement results obtained without using corner reflectors and those obtained with the corner reflectors.

Table 2 provides the verification results of the range-extension experiment. The three left columns represent the values directly measured at a range of 50 m, while the three right columns present the results upon the range extension at a measuring range of 25 m. The measurement results indicated that the maximum indication error in direct measurement was $-4.8 \mu\text{m}$ at a distance of 18 m. In contrast, the maximum indication error in range-extension measurement was $12.6 \mu\text{m}$ at the actual distance of 15 m. Both error results were within the required indication error range of $\pm 0.5 \mu\text{m}/\text{m}$.

Table 2. Verification results of the range-extension experiment.

Nominal Value (mm)	Measured Value (mm)	Measurement Error (μm)	Nominal Value (mm)	Measured Value (mm)	Measurement Error (μm)
1999.9648	1999.9645	−0.3	1999.9694	1999.9687	−0.7
3999.9551	3999.9548	−0.3	3999.9372	3999.9367	−0.5
5999.9102	5999.9106	0.4	5999.9484	5999.9497	1.3
7999.8794	7999.8760	−3.4	7999.9180	7999.9191	1.1
9999.8643	9999.8611	−3.2	9999.8594	9999.8620	2.6
11,999.8398	11,999.8363	−3.5	11,999.8272	11,999.8297	2.5
13,999.8272	13,999.8233	−3.9	13,999.8116	13,999.8053	−6.3
15,999.8291	15,999.8249	−4.2	15,999.7656	15,999.7609	−4.7
17,999.8457	17,999.8409	−4.8	17,999.7578	17,999.7535	−4.3
19,999.8496	19,999.8505	0.9	19,999.7344	19,999.7301	−4.3
21,999.8652	21,999.8660	0.8	21,999.7208	21,999.7181	−2.7
23,999.8926	23,999.8933	0.7	23,999.6856	23,999.6805	−5.1
25,999.9063	25,999.9074	1.1	25,999.6640	25,999.6577	−6.3
27,999.9180	27,999.9185	0.5	27,999.6602	27,999.6539	−6.3
29,999.9316	29,999.9311	−0.5	29,999.6640	29,999.6514	−12.6
31,999.9609	31,999.9600	−0.9	31,999.6660	31,999.6576	−8.4
33,999.9570	33,999.9560	−1.0	33,999.6640	33,999.6551	−8.9
35,999.9375	35,999.9363	−1.2	35,999.6992	35,999.6903	−8.9
37,999.9102	37,999.9081	−2.1	37,999.6876	37,999.6845	−3.1
39,999.9180	39,999.9180	0.0	39,999.7070	39,999.7087	1.7

Table 2. Cont.

Nominal Value (mm)	Measured Value (mm)	Measurement Error (μm)	Nominal Value (mm)	Measured Value (mm)	Measurement Error (μm)
41,999.8906	41,999.8913	0.7	41,999.7266	41,999.7270	0.4
43,999.8633	43,999.8659	2.6	43,999.7384	43,999.7396	1.2
45,999.8242	45,999.8207	−3.5	45,999.7852	45,999.7923	7.1
47,999.7500	47,999.7500	0.0	47,999.7930	47,999.7966	3.6
49,999.6797	49,999.6794	−0.3	49,999.8008	49,999.8087	7.9

Figure 8 describes the indication errors before and after the range extension. The green circles indicate the measurements obtained directly within the 50 m range, while the red squares represent the indication errors produced upon the range extension at the measuring range of 25 m. Both approaches enabled measurements within the 50 m range. The indication error of measurement based on the range extension still met the calibration requirements of the laser interferometer and, more importantly, justified the feasibility of the proposed range-extension method. To facilitate a deeper understanding of the measurements, we also carried out a data analysis of the measurement uncertainty following the range extension.

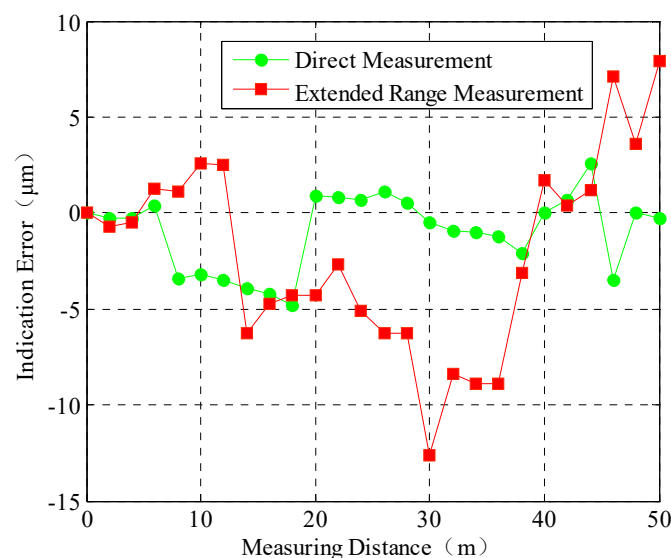


Figure 8. A diagram showing indication error before and after the range-extension experiment.

3.5. Influence of the Measurement Uncertainty

The measurement uncertainty of the range-extension technique for the indoor standard device for large-scale length measurement rests primarily on the angular error θ of the hollow corner reflector, the straightness error S of the long guide rail, the laser interferometer error I , and the environmental error T . The analysis of measurement uncertainty in this section is mainly used to analyze the feasibility of the range-extension method described in this paper. The overall measurement uncertainty of the entire installation was determined as follows:

$$U = 2 \times \sqrt{u_{\theta}^2 + u_S^2 + u_I^2 + u_T^2} \quad (1)$$

Considering the current status and technological level of the indoor standard device for large-scale length measurement, and with the guide rail extended from 50 m to 100 m, we obtained the following analysis results:

(1) Measurement uncertainty caused by the angular error θ of the hollow corner reflector was:

$$u_{\theta} = \frac{100,000}{\cos(3\theta)} - 100,000 \quad (2)$$

In the above equation, θ is the angular error of the hollow corner reflector (up to $0.2''$). Since there were three reflections involved on two hollow corner reflectors, the overall angular error tripled, and upon the substitution of the parameter into the equation, was as follows:

$$u_{\theta} = \frac{100,000}{\cos(3 \times 0.2'')} - 100,000 \approx 0 \quad (3)$$

Measurement uncertainty associated with the angular error of the hollow corner reflector could be considered negligible.

(2) Measurement uncertainty influenced by the straightness error S of the long guide rail was:

$$u_S = \sqrt{100,000^2 + S^2} - 100,000 \quad (4)$$

The straightness error of the long guide rail was 0.42 mm. Substituting the parameter into the above equation, we obtained:

$$u_S \approx 0 \quad (5)$$

Measurement uncertainty arising from the straightness error S of the long guide rail could be ignored.

(3) According to the specifications of the laser interferometer, its measurement uncertainty stood at 0.2 ppm. And its measuring range was extended to 100 m.

$$u_I = 0.02 \text{ mm} \quad (6)$$

Given that the indoor standard device for large-scale length measurement was placed in a controlled temperature and humidity environment, measurement uncertainty resulting from the environmental error T could be overlooked.

$$u_T = 0 \quad (7)$$

(4) By putting the results from the above analyses into the underlying equation for the device's measurement uncertainty, we obtained the following:

$$U = 2\sqrt{0.00042^2 + 0 + 0.02^2 + 0} = 0.040 \text{ mm} \quad (8)$$

Upon calculation, it was determined that the measurement uncertainty of the indoor standard device for large-scale length measurement after the range extension satisfied the requirements for calibrating the laser interferometer.

3.6. Theoretical Extended Range

We assume that the hollow pyramid plating is total reflection, without any light loss. The reflectors' reflectance ranged from 0.95 to 0.98; its transmitting power was between 0.8 mW to 1.0 mW; the detection capability of the detector varied from 150 μ W to 200 μ W.

We assume the transmitting power is 1.4 mW, and the detection power is 150 μ W, then the system's transmittance was expressed as $T = 150 \mu\text{W}/1.0 \text{ mW} = 0.15$. Considering only the light loss due to corner reflectors, the number of times the light propagated within the prism was $n = \log(0.15)/\log 0.98 \approx 94$. The multiplication factor of the light range extension followed an arithmetic progression: starting with 2, doubling to 6, tripling to 10, and so on. With 23 iterations, the range could be extended from 50 m to 1150 m. Therefore, using hollow corner reflectors, the measuring range can theoretically be extended by a factor of 23.

4. Discussion

Laser interferometers play a pivotal role in the realm of geometric metrology, serving as a vital link between diverse quantity values. Through an extensive literature review, it is observed that a predominant focus has been on large-size metrology. There is currently an

absence of a range-extension methodology tailored specifically for assessing the indication errors of laser interferometers. As such, we in this paper took the lead in investigating the traceability technique for linear error measurement in laser interferometers. We also carried out preliminary verification and analysis of experimental results, which filled the research gap in this field. Moreover, the research can not only save the experimental site, manpower, material resources, and funds, but also achieve the same or even better measurement effect.

On top of transcending the confines of measuring instruments for calibrating laser interferometers, the range-extension approach employed in our study is also applicable to other similar laser measuring devices, such as range extenders for laser rangefinders. Figure 9 illustrates the simulated optical path for the range-extension measurement of a rangefinder. While the optical setup of a laser rangefinder was similar to that of a laser interferometer, the former's final reflected light was achieved using a gray reflective plate, and the sandwiched corner reflector was rectangular. The corner reflector we use is a rectangular prism.

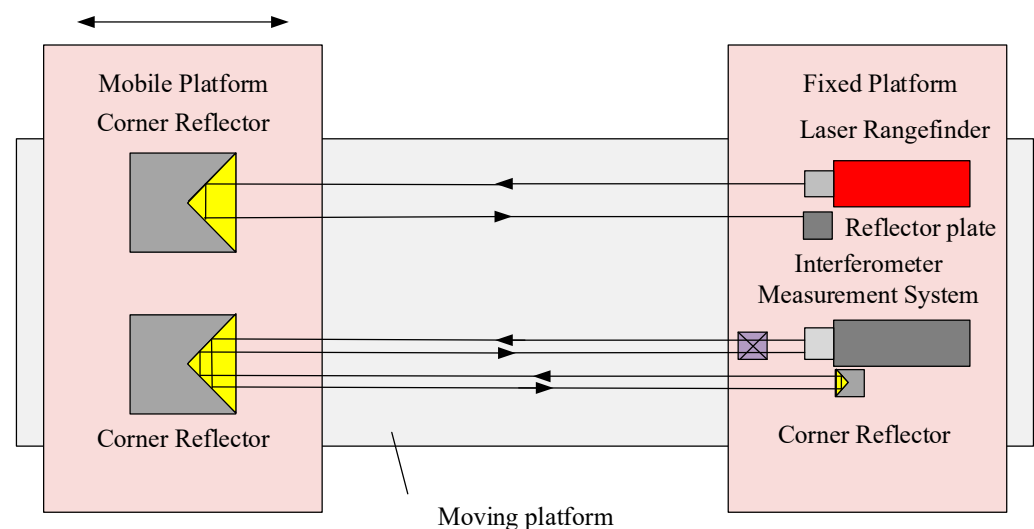


Figure 9. A diagram of the simulated optical path for the range-extension measurement of a rangefinder.

5. Conclusions

The work research proposed delved into the range-extension methodology applied to the indoor standard device for large-scale length measurement and established the measurement traceability of measurements in laser interferometers. Experimental findings revealed that the specific Renishaw XL-80 laser interferometer exhibited a maximum measurement error of $-13.02 \mu\text{m}$ within a 104 m range, at the 102 m distance to be exact. The measurement errors remained within the MPE range. Furthermore, a comparative analysis between measurements with and without the range extension was conducted within 50 m to assess their impact on measurement uncertainty, and the results substantiated the feasibility of the proposed approach. The range extension of the indoor standard device for large-scale length measurement can, to some extent, act as a viable alternative to its outdoor equivalents, facilitating the comparison of instruments with long measuring ranges within shorter distances. We first report the comparison measurement of laser interferometers in the world. Future research may explore range-extension traceability methods for other similar laser measuring instruments.

Author Contributions: C.H. and L.X. designed the experiments; J.L. helped to perform measurements; C.H. wrote the paper; F.L. revised the paper. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the National Key Research and Development Program of China (2021YFA1401100), the Innovation Group Project of Sichuan Province (20CXTD0090), and the National Natural Science Foundation of China (52202165).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhou, W. Research on the Precision Theory of Large-Scale Coordinate Measuring Systems. Ph.D. Thesis, Hefei University of Technology, Hefei, China, 2000.
2. Peggs, N.; Maropoulos, G.; Hughes, B.; Forbes, B.; Muralikrishnan, B. Recent developments in large-scale dimensional metrology. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2009**, *223*, 571–595. [[CrossRef](#)]
3. Li, J. Development of Indoor 80 m Large-Scale Laser Comparator National Standard. Ph.D. Thesis, Tianjin University, Tianjin, China, 2017.
4. Ma, L.; Cao, T.; Wang, J.; Sun, A. Discussion on Inspecting the Assembling Components by Using Large Volume Metrology Instruments. *Metrol. Meas. Technol.* **2013**, *33*, 7–11.
5. Chen, W. Total Station Calibration Test Based on Indoor Length Baseline Fields Simulation. Master's Thesis, South China University of Technology, Guangzhou, China, 2011.
6. Yang, W. Establishment Method of Longer Laboratory Baselines for Verification EDMs. Ph.D. Thesis, Institute of Geophysics China Earthquake Administration, Beijing, China, 2009.
7. Qiao, W.; Zhao, M.; Liu, K.; Li, Q.; Fang, J. Research on the Verification Method and System of Hand-held Laser Rangefinder. *Acta Metrol. Sin.* **2016**, *11*, 15–18.
8. Wang, J.; Yang, S.; Meng, X. The Research of the Feasibility to Establish Length Standard Inside a Laboratory. *Monarch. Minist. Maps* **2016**, *39*, 34–36.
9. Huang, S. The Research about the Feasibility to Establish Fictitious Length Standard inside a Laboratory. *Metrol. Meas. Technol.* **2006**, *26*, 22–25.
10. Pan, J.; Huang, S.; Zhang, Y. Research on Indoor Virtual Linear Baseline. *Acta Metrol. Sin.* **2015**, *36*, 19–21.
11. Yang, W.; Yan, H.; Yan, J.; Gao, P.; Guan, Z. Effect of the Straightness of Ultra-Long Guide Rail on Length Measurement Using Laser Interference Principle. *Acta Metrol. Sin.* **2018**, *39*, 45–48.
12. Zheng, J.; Miao, D.; Li, J.; Xu, Z.; He, M.; Li, L. Self-calibration Algorithm for Laser Multilateral Coordinate Measurement System Using Standard Length Method. *Acta Metrol. Sin.* **2019**, *40*, 64–70.
13. Li, T.; Li, J.; Miao, D.; Li, L.; Liu, X. Study of Temperature States Influence on the Accuracy of Large Size Measuring Devices. *Acta Metrol. Sin.* **2019**, *40*, 975–979.
14. Haitjema, H. Calibration of Displacement Laser Interferometer System for Industrial Metrology. *Sensors* **2019**, *19*, 4100. [[CrossRef](#)] [[PubMed](#)]
15. Hu, C.; Hu, S.; Sun, H.; Liu, J.; Li, J.; Yang, Z. Evaluation of the Large-Length Indoor Standard Installation Based on Single Point Scanning. *Appl. Sci.* **2021**, *11*, 8953. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.