# A Method to Establish Height Datum Online Based on Absolute Hydrostatic Leveling System

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**Abstract:** The fourth generation light source HEPS under construction in China demands higher alignment accuracy. However, it is difficult to improve height accuracy based on the overlap method of geometric and tracker leveling. Based on the study of hydrostatic leveling systems for ground settlement monitoring, this paper proposes a new method, Absolute Hydrostatic Leveling System (AHLS), for establishing height datum. The principle of establishing height datum for AHLS is described in detail, and it is emphasized that absolute calibration of the level is crucial for implementing this plan. A set of absolute calibration methods for non-contact absolute hydrostatic level is proposed, including measuring key dimensions of the level and precise measurement of liquid depth. The absolute calibration accuracy reaches 0.031mm. The height accuracy of validating an AHLS between two points within 10 meters using a laser tracker is more than 0.05mm. The results demonstrate the feasibility of using AHLS to establish absolute height datum with high precision. With this method, the absolute height of each point can be obtained independently without any accumulated errors, allowing the establishment of height datum with high precision on a large scale. This approach can be used in the next generation of accelerator devices and also represents a novel method for achieving high-precision vertical monitoring.

**Keyword: absolute hydrostatic leveling system, height datum, absolute calibration, liquid depth measurement**

## 1. Introduction

The development of scientific research has promoted continuous improvements in the energy and scale of accelerator facilities, leading to a higher demand for accurate and reliable device alignment, especially for the alignment accuracy of 4th generation synchrotron radiation light source devices [1]. For instance, China's High Energy Photon Source (HEPS) [2], under construction, is the largest facility in China (with a storage ring circumference of 1,360 meters) and has the highest precision for alignment. Therefore, the establishment of large-scale, high-precision alignment datum is an urgent problem.

At present, the alignment stage of accelerator devices mainly relie on the leveling method [3-4] to establish the height datum, while the hydrostatic leveling system (HLS) is used for high-precision settlement monitoring during the operation stage [5-6] (HLS), with the two methods being independent of each other. Establishing unified datum based solely on geometric leveling through overlapping measurements is the main method for establishing tunnel height datum and adjusting the device height of the initial accelerator, as adopted by the LEP and LHC at CERN [4], BEPC in China [7], and NuMI/MINOS in the United States [8]. In practice, the actual leveling accuracy of the 200-meter straight line at BEPC is about 0.2mm [9-10], but the disadvantage of this method is the scarcity of points, difficulty in increasing accuracy, and low alignment efficiency.

In the early 20th century, laser trackers were widely used in accelerator alignment due to their high efficiency, intuitive and intelligent measurement modes. The alignment method relied on station overlaps of vertical angles and slope distances [11]. The alignment experts from CERN [12], Hefei Light Source [13], and BEPCII [10,14] conducted in-depth research on the accuracy of geometric and tracker leveling, and found that tracker leveling can achieve more accurate results in a small range, but the deviation between tracker leveling and geometric leveling can reach millimeter-level in a large range. Accelerator devices currently constrain tracker leveling using geometric leveling to establish large-scale, high-density height datum. This approach is adopted by facilities such as BEPCII [15] and Shanghai Synchrotron Radiation Facility [16]. Geometric leveling provides global height accuracy, while tracker leveling provides local accuracy. Improving geometric leveling accuracy is critical to improving height accuracy of overall facility. However, both methods rely on height transfer through station overlap, resulting in cumulative errors with increasing distance, making it difficult to increase accuracy.

Based on research on the HEPS settlement monitoring method called HLS, the research team innovatively proposed an absolute hydrostatic leveling system (AHLS) with no cumulative error. This paper provides a detailed introduction to the establishment of high precision height datum based on AHLS, including the principle of establishment, absolute calibration of the hydrostatic level, absolute height acquisition of an AHLS between two points within 10 meters with an accuracy of 0.05mm, and the process of establishing absolute height datum using AHLS.

This method uses the actual level surface within the HLS as a datum, with no accumulation of errors in the system, allow for obtaining high-precision absolute height of leveling points, online and in real-time. The height can be used not only to establish a high-precision height datum for the overall device in combination with leveling, but also as a high-precision height datum point in the tunnel to align critical devices (as shown in Figure 1). This is a new method for creating high-precision absolute height datum.

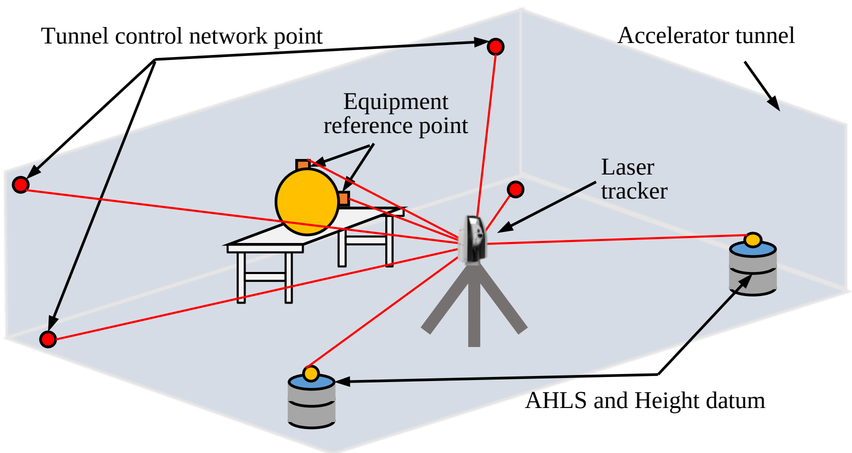



Figure 1 Height datum based on absolute hydrostatic leveling system (AHLS)

## 2. Principle of the Absolute Hydrostatic Leveling System

HLS is a real-time, large-scale deformation monitoring system with an accuracy of sub-millimetres or even microns, and is widely used in major engineering monitoring applications. The method determines the relative change in height between observation points based on the principle of a connector. In the late 1980s, it was gradually applied in the field of accelerator alignment [17-18].

As shown in Figure 2, an HLS is formed by connecting the liquid and air tubes of three hydrostatic levels.

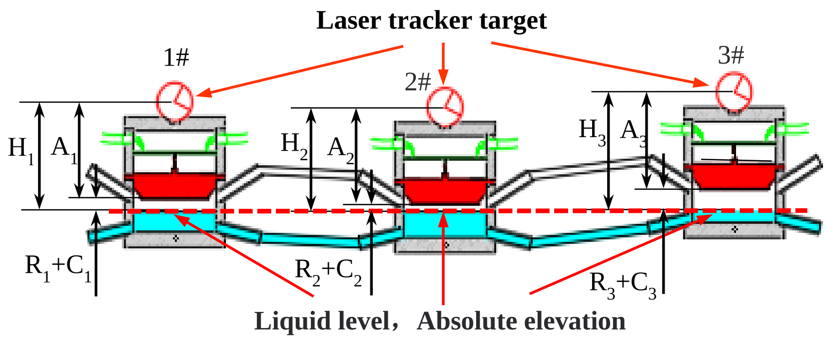



Figure 2 Schematic diagram of AHLS

The blue section indicates the liquid in the system, and the red dotted line represents stabilized liquid surface in the HLS, which is the actual level surface and can be used as the starting surface of absolute height in geodetic surveying. The top centre of all the levels in the figure are set with a datum base for a tracker's target ball. Using the liquid level in the system as the height datum, the absolute height ($H_{i\_k}$) of the level is the distance from the centre of the ball to the liquid surface, and can be calculated as

$$H_{i\_k} = A_k + (R_{i\_k} + C_k), k = 1, 2, \dots, K \tag{1}$$

Where, $R_{i\_k}$ is the distance from the zero point of the sensor at the $k$th level at time $i$ to the liquid surface, which can be read from the level. Because monitoring the liquid level using the level is based on relative calibration, there is a constant deviation $C_k$ between the obtained reading distance and the absolute distance. $A_k$ represents the distance from the zero point to the centre at the top datum point of the sensor, which is the absolute calibration value of the sensor.

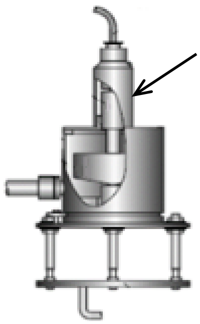
When $K$ levels are arranged and connected in accelerator devices, an actual level surface is formed in the devices. If the values of $A_k$ and $C_k$ are obtained, $H_{i\_k}$ transmitted by the $k$th level without error at time $i$ can be determined.

This type of system is called AHLS, which consists of several absolute hydrostatic levels and obtains the absolute height. AHLS can obtain the absolute height for each level without station overlap and cumulative errors, and its accuracy mainly depends on the relative monitoring accuracy of the level and the accuracy of the absolute calibration value $A_k$. Compared to traditional leveling methods such as geometric and tracker leveling, AHLS represents a new approach to obtaining height with high accuracy.

## 3. Structural Features of the Absolute Hydrostatic Level

According to the monitoring mode, the hydrostatic level is generally divided into contact and non-contact types [19]. The contact type level cannot be used in AHLS (as shown in Figure 3a) due to the following reasons. First, for the height survey, the external datum point of the level must be located at the top of the centre of the level; however, most of the contact levels use a differential survey, and its devices such as signal and power supply are located at the top of the level, with no suitable design position for the external datum point. Second, Absolute calibration of the level involves separating its upper and lower bowls; however, separating the float from the liquid may alter the liquid level in the bowl, making absolute calibration difficult to achieve.

Based on these factors, we designed a non-contact absolute hydrostatic level, which uses a capacitive sensor with monopole plate to monitor changes in liquid level, with a relative monitoring accuracy of 5 μm. The structure and components are shown in Figure 3b. Compared with traditional level, this level is designed with a 1.5-inch datum base for tracker's target ball at the top centre, allowing for absolute calibration of liquid level extraction. This level can not only use the absolute height obtained by monitoring the ground settlement as height datum for height adjustment, improving the absolute accuracy of the overall device's height, but also serve as a datum point for high-precision adjustment of the nearby device's height, achieving high-precision alignment of critical devices. Therefore, it is called an Absolute Hydrostatic Level(AHL)



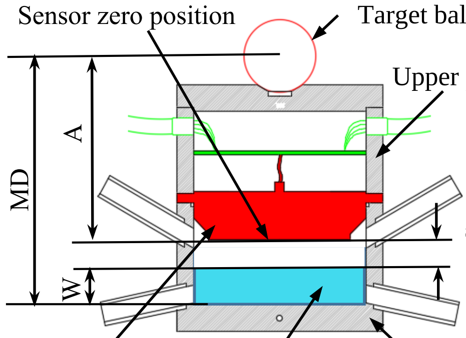




Figure 3 (a)Contact-type capacitive level (NAR in China),(b)Non-contact capacitive level

## 4. Absolute Calibration of the Level

Based on the principle of AHLS and the structure of AHL, the accuracy of the height obtained by AHLS depends on the precise determination of the constant $C_k$ and absolute calibration value $A_k$ of each level. Figure 3b shows the three key parameters of absolute calibration for AHL, including the distance $MD_k$ from the bottom of the lower bowl to the centre of the target ball, the liquid depth $W_k$, and the absolute distance $R_k + C_k$ from the zero position of the sensor to the liquid surface. If these three parameters are known, the value $A_k$ of the level *K* can be determined as

$$A_k = MD_k - W_k - (R_k + C_k) \tag{2}$$

Where $R_k$ is the monitoring reading of the level and $C_k$ is the deviation constant.

The absolute height of level *K* at time *i* is calculated as:

$$\begin{aligned} H_{i_k} &= A_k + (R_{i_k} + C_k) \\ &= MD_k - W_k - (R_k + C_k) + (R_{i_k} + C_k) \\ &= MD_k - W_k - R_k + R_{i_k} \end{aligned} \tag{3}$$

The deviation constant $C_k$ can be eliminated when calculating $H_{i_k}$, and $R_{i_k}$ can be obtained during monitoring. If the key parameters (such as $MD_k$, $W_k$, and $R_k$) of absolute calibration $A_k$ are known, $H_{i_k}$ can be obtained. Therefore, determining the above key parameters is the essential part of the method.

(1) *MD* of the bowl

As shown in Figure 4, the key dimension *MD* of the bowl was measured by the three-coordinate measuring machine (CMM). The lower bowl of the level was fixed on the coordinate machine platform. The inner bottom of the lower bowl was first measured, and then the target ball at the top was measured after the upper and lower bowls of the level were installed. Then the inner bottom of the level's lower bowl was fit to the plane to establish a horizontal coordinate system based on the measuring points to determine the distance between the inner bottom of the bowl and the centre of the ball at the top. The two levels were measured, and the deviation was found to be within 5 $\mu m$ based on measurement deviation analysis of target ball diameter (standard ball with diameter of 38.1 mm) and *MD* (as shown in Table 1).

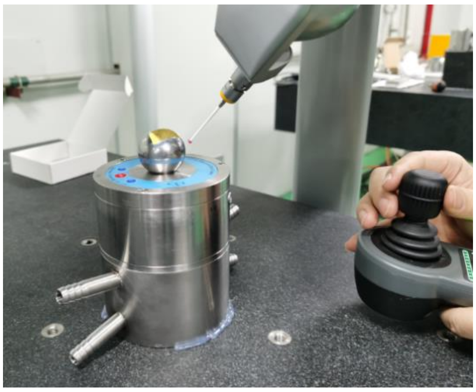


Figure 4 Calibration of the bowl's size using the three-coordinate measuring machine (CMM)

Table 1 Key dimension *MD* of the bowl and diameter deviation of the target ball

| Number of levels | *MD* deviation /μm | Diameter deviation of target ball /μm |
|---|---|---|
| 1# | 1 | 3 |
| 2# | 0 | 2 |

(2) Acquisition of the level readings $R_k$

The liquid was added to the lower bowl of the level within the range. After the liquid became stable, the level was fully preheated, and then the reading $R_k$ of the level was recorded directly. Based on the principle of obtaining absolute height using the AHLS, AHL should exhibit good repeatability in measuring the liquid level of the same height inside the bowl. This is primarily determined by the installation accuracy of the upper and lower bowls of the level (determined by its structure and machining accuracy) and the measurement stability of the sensor. To verify the measurement accuracy of AHL, liquid within the measuring range was injected into the lower bowl, and the initial measurement was taken. The power supply to the level was then turned off, and the upper and lower bowls were disassembled and reassembled. The liquid level in the bowls was then measured again for a total of eight times at equal intervals. The results of each liquid level measurement and their linear regression analysis are shown in Figure 5. The results indicate that the linear regression goodness-of-fit coefficient R is 0.8575, and the overall trend of the liquid level is decreasing, with a total change of 10 μm. This is likely due to the eight disassembly and assembly processes, which took a certain amount of time and exposed the liquid to air, resulting in evaporation and a slight change in the liquid level. However, the deviation between adjacent measurements is within 4 μm, and the deviation between six adjacent measurements is not more than 2 μm.

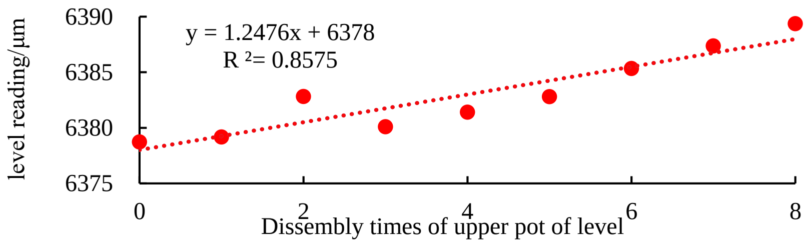



Figure 5 Repeatability test for the reading of level on disassembly and assembly

(3) Absolute measurement of the liquid depth $W_k$

During the repeatability test, we observed that the liquid in the level and reading took some time to stabilize, and there was slight evaporation of the liquid. To reduce the effects of liquid level changes on the calibration result, the measurement value of the level is read firstly, and then the liquid level is measured immediately. We used the displacement table and coaxial displacement meter, respectively, to measure the liquid level.

1) Measurement using the displacement table

This was achieved based on the liquid conductivity and precision displacement table. The needle of the multimetre was fixed on the precision displacement device, which shifted the needle from a datum plane to the liquid surface. When the needle contacted the liquid surface, the multimetre displayed a resistance value owing to the conductivity of the liquid. At this time, the distance $D_2$ along the height of the displacement device is from the liquid surface to the datum surface. In addition, the distance $D_1$ from the datum surface to the bottom of the bowl can be accurately obtained; therefore, the liquid depth can be obtained indirectly from the difference between the two distances. In this experiment, the needle of the multimetre were fixed with the probe of the CMM (as shown in Figure 6). The precise distance from the datum surface of the lower bowl to the liquid surface was obtained through the motion value of the CMM. However, the experiment revealed that with the surface tension of the liquid, although the needle of the multimetre touched the surface of the liquid, the multimetre did not display any value. Moreover, the probe of the CMM only moved when the displacement was greater than 0.01 mm. Therefore, the distance from the liquid level to the datum surface cannot be accurately obtained using this method.

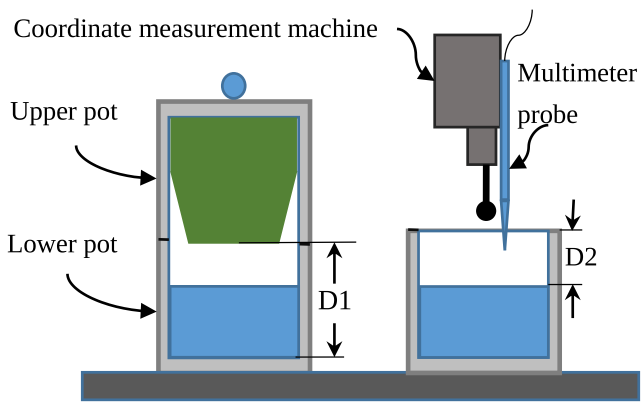


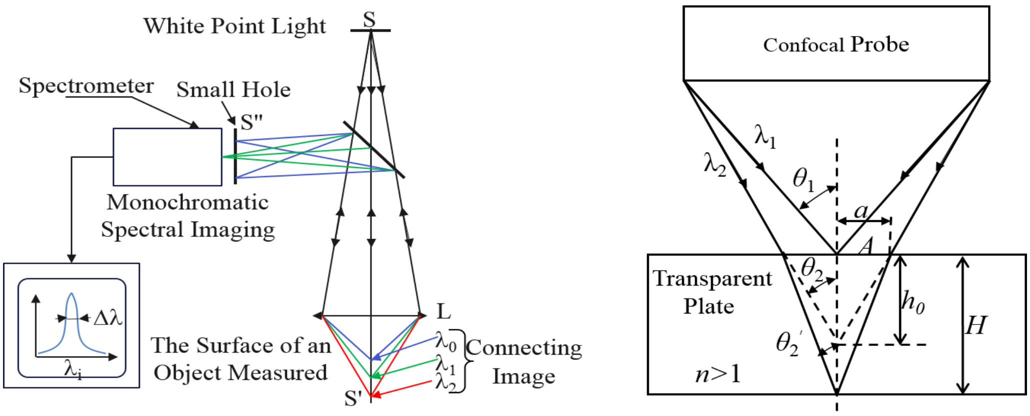

Figure 6 Liquid depth measurement using the displacement table

2) Measurement using a coaxial displacement meter

Based on the principle of spectral confocal measurement, a laser colour coaxial displacement meter (CL-L070, KEYENCE) can directly obtain the position and absolute thickness of transparent objects [20-21], as shown in Figure 7a. The spectral confocal measurement system is composed of a polychromatic light source, spectroscope, dispersive lens group, confocal pinhole, spectrometer, and other components. During measurement, the light source emits a beam of broad-spectrum polychromatic light (white light) through an aperture. After this beam is focused by the spectral confocal system, spectral dispersion occurs. A continuous monochromatic optical focus of different wavelengths is formed on the optical axis. After reflection from the surface of the object, the lights of different wavelengths pass through the spectral confocal system again. Only monochromatic light that meets the condition of confocality can enter the spectrometer through the aperture filter. Thus, the wavelength of light according to reflecting surface of the object is obtained through decoding, and finally the distance of the object is determined. As shown in Figure 7b, the top and bottom surfaces of the transparent object reflect light of different wavelengths, and the thickness of the measured transparent object can be calculated [22]. The thickness can be calculated as

$$H = \frac{h_0 \tan\theta_2}{\tan(\arcsin\frac{\sin\theta_2}{n})} \tag{4}$$

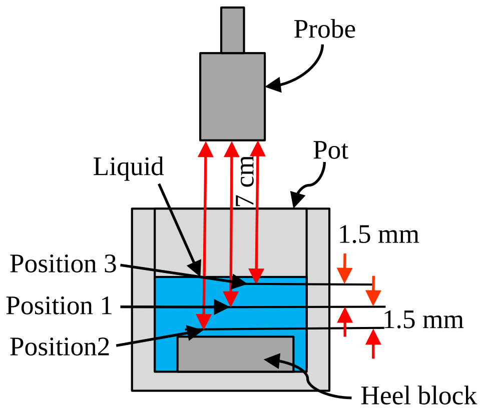
where $n$ is the refractivity of the measured object, $h_0$ is the thickness of the object when the refractivity of the measured object is one, and $\theta_2$ is the angle between the incident ray and vertical line at the top surface when the refractivity of the object is 1.




(a) (b)

Figure 7 (a)Principle of spectral confocal measurement,(b)Measurement of the depth of liquid level

The CL-L070 coaxial displacement meter was implemented to directly measure the liquid depth, with a nominal measuring range of 70 ± 10 mm and accuracy of ±2.2 μm. A nominal relative range of 20 mm is used for a substance with a refractive index of 1, while the refractive index of liquid used in the experiment is 1.3, and the relative range does not exceed 15 mm. The use of the instrument for the measurement revealed the following: 1) the thickness values of standard glass measured by the probe at different positions within the range were consistent; and 2) the liquid depth values measured by the probe at different positions in the range were inconsistent. Based on our analysis, these findings are attributed to two reasons. First, because of the large liquid depth, the top or bottom surface of the liquid was at the edge of the range or exceeded the range. Second, the small vibration of the liquid changed the intensity of reflected light, resulting in unstable measurement data and poor consistency. After several experiments and analysis, the measurement scheme of the liquid depth in the bowl using the coaxial displacement meter was optimised as follows (as shown in Figure 8). 1) The liquid depth is generally not more than 6 mm. Considering that the measurement exceeded the range of the level when the liquid level was extremely shallow, a standard height block was placed at the bottom of the bowl of the level to ensure accuracy of measurement by the coaxial displacement meter and the level. Thus, the liquid level in the bowl remained unchanged but the liquid volume decreased, which did not exceed the range of the level and coaxial displacement meter. 2) The probe of the instrument measured the liquid depth at three positions. The first position was approximately 70 mm from the probe to the mid-level of the liquid, the second position was 1.5 mm below the first position, and the third position was 1.5 mm above the first position. The top and bottom surfaces of the liquid at the three positions were within the measuring range of the instrument. The average liquid depth at these positions was used as the absolute value of the liquid depth.




(a)

(b)

Figure 8 (a)Direct measurement using the coaxial displacement meter,(b)Direct measurement of liquid depth in laboratory

Because we observed some errors in the refractive index of the measured object during direct measurement, we improved the indirect measurement (as shown in Figure 9). 1. A standard heel block was added to the bowl, and the coaxial displacement meter measured the distance between the probe and the top surface of the block, labeled as the first distance $h_1$. 2. Without moving the coaxial displacement meter, liquid was injected into the bowl, and the depth did not exceed the range of the level and coaxial displacement meter. The absolute distance between the probe and liquid level was measured, indicated as the second distance $h_2$. Thus, the liquid depth can be obtained from the difference between $h_1$ and $h_2$.

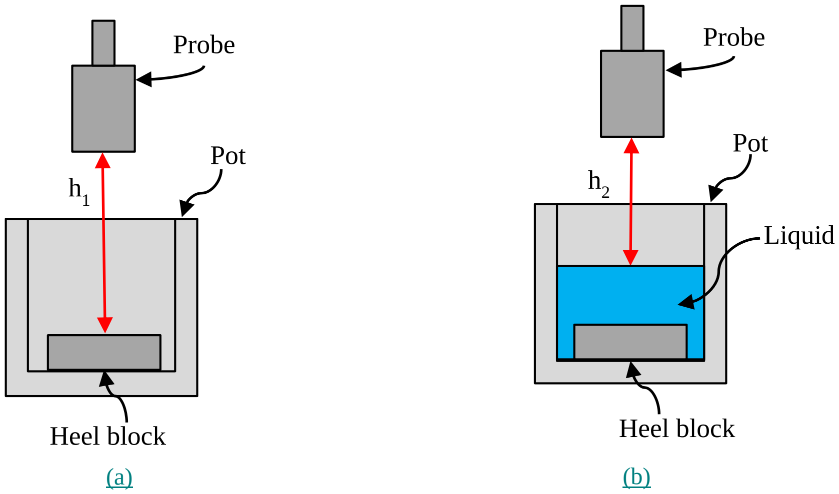



Figure 9 (a)Step 1 of indirect measurement using coaxial displacement meter,(b) Step 2

The liquid depth was measured four times through direct and indirect measurement using the coaxial displacement meter. The results are shown in Table 2. The measurement deviation of the two methods was within 0.025–0.029 mm, which may be caused by a system error. Through several tests, we confirmed that the measurement accuracy of the liquid depth based on the coaxial displacement meter is within 0.03 mm. In the calibration experiment of AHL, the repeatability deviation of the absolute calibration values of the level determined through several direct measurements using the coaxial displacement meter was found to be less than 8 μm; whereas, the repeatability deviation of the calibration values of the level with the indirect measurement was less than 2 μm. Therefore, the repeatability of the calibration value obtained through indirect measurement method was better than that obtained through direct measurement.

Table 2 Measurement of the liquid depth using the coaxial displacement meter

| Number | Direct measurement/mm | Indirect measurement/mm | Deviation between direct and indirect measurement values/mm |
|---|---|---|---|
| 1 | 3.248 | 3.275 | -0.027 |
| 2 | 3.496 | 3.521 | -0.025 |
| 3 | 3.716 | 3.745 | -0.029 |
| 4 | 3.613 | 3.642 | -0.029 |

By measuring the above mentioned three key parameters (namely *MD* of the bowl, $W_k$, and $R_k$), the $A_k$ value of each level can be determined. According to equation 2, the absolute calibration accuracy can be calculated as:

$$m_{\mathrm{A}} = \sqrt{{m_{MD}}^2 + {m_W}^2 + {m_R}^2} \tag{5}$$

The measurement accuracy $m_{MD}$ of the bowl structure was 5μm, the measurement accuracy $m_W$ of the liquid depth was 0.03 mm, and the reading accuracy $m_R$ of AHL was 5 μm. According to equation 5, the absolute calibration accuracy $m_{\mathrm{A}}$ of the level was within 0.031 mm.

According to Equation 1, the accuracy of the absolute height $H_{i\_k}$ of the level can be calculated as:

$$m_H = \sqrt{{m_A}^2 + {m_R}^2} \tag{6}$$

According to equation 6, the accuracy $m_{\mathrm{H}}$ is 0.0314mm. When factor k is 2, the expanded uncertainty of absolute height $H_{i\_k}$ is 0.063mm. Obviously, for micro-scale hydrostatic level, the measurement accuracy of liquid depth determines the acquisition accuracy of absolute height.

# 5. Accuracy Verification of the proposed AHLS

(1) Experimental methods

Based on the proposed scheme, the two levels after absolute calibration are connected in series to form a simple two-point monitoring system for the AHLS. Owing to the lack of a high-precision method to measure large-scale height, the principle and accuracy of the absolute height established by AHLS can only be verified using the micron-level displacement table and laser tracker with electronic level. During measurement, the laser tracker was first adjusted to an approximate level, and the in-built electronic level measured the level. Then the deviation between the vertical axis of instrument and the direction of the plumb was obtained. Establishing a horizontal coordinate system, the height between points can be determined. The accuracy of laser tracker's height measurement has been previously studied in China, indicating that a single laser tracker station can provide reliable leveling height measurement accuracy within a short range [10, 14].

The verification scheme of the AHLS is shown in Figure 10. Two levels were positioned on two micro-scale displacement table (the micron displacement table was developed in this study; it had a stroke of 120 mm, a repeat positioning accuracy of 3 μm, a resolution of 1μm, and a load-bearing capacity of 35 kg) 10 meters apart from each other. The liquid pipes, air pipes, and related collection equipment were connected to form a two-point monitoring system of AHLS. The accuracy was verified by comparing the absolute height difference of Level 1# (Level 2#) measured by the laser tracker and two-point AHLS. The specific methodology is as follows. After the laser tracker measured the target ball at the top of the level, the corresponding absolute height under the level coordinate system was obtained, and then the absolute height difference between Levels 2# and 1# were determined. The two-point monitoring system of the AHLS directly obtained the absolute height of the target ball under the current liquid level (geoid) according to Equation 1, and then derived the absolute height difference between Levels 2# and 1#.

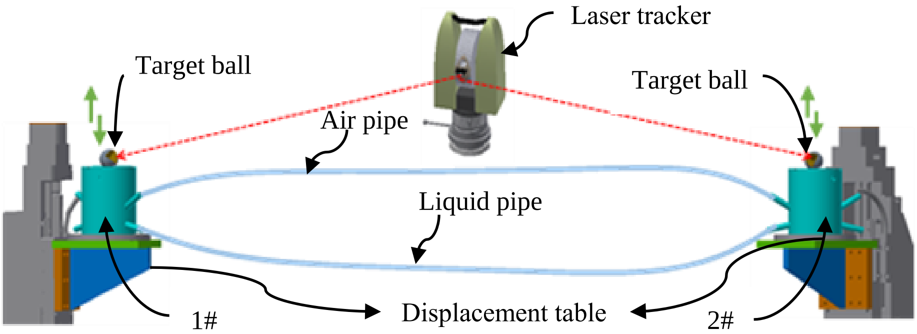



Figure 10 Schematic diagram presenting the accuracy verification of the absolute height determined using the proposed AHLS

In the test, Level 1# remained stationary, and the displacement table drove Level 2# to simulate the change in height between the two points. The displacement table moved upwards and downwards for 11 times each, with each displacement of 250 μm.

(2) Monitoring calculation of AHLS

According to the relative monitoring principle of HLS, after the *i*th movement of the displacement table, from time *i*-1 to *i*, the vertical displacement of Level 2# relative to Level 1# was determined as follows:

$$\triangle \mathrm{h}_{i\_i-1,\ 2\_1water} = \left(h_{i,2water} - h_{i,1water}\right) - \left(h_{i-1,2water} - h_{i-1,1water}\right) \quad (7)$$

Where $h_{i-1,1water}$ and $h_{i-1,2water}$ are the readings of the two levels after *i*-1 movements, $h_{i,1water}$ and $h_{i,2water}$ are the readings of the two levels after *i* movements.

According to the principle of the method for establishing the absolute height using the AHLS, the absolute heights of the target ball at the top of Levels 1# and 2# ($H_{1water}$ and $H_{2water}$) are calculated as follows:

$$H_{1water} = h_{i,1water} + A_1$$

$$H_{2water} = h_{i,2water} + A_2$$

After *i* movements, the difference in absolute height between Levels 2# and 1# obtained directly by the AHLS system is calculated as follows:

$$\triangle H_{i,2\_1water} = H_{2water} - H_{1water} = \left(h_{i,2water} - h_{i,1water}\right) + \left(A_2 - A_1\right) \quad (8)$$

Where $A_1$ and $A_2$ are the absolute calibration values of the levels, obtained through laboratory calibration.

(3) Height monitoring using the laser tracker

After *i* movements, the tracker measured the target ball at the top of the level, and then the absolute height difference between Levels 1# and 2# can be obtained as follows:

$$\triangle H_{i,2\_1\mathrm{tracker}} = h_{i,2\mathrm{tracker}} - h_{i,1\mathrm{tracker}} \quad (9)$$

where $h_{i,1\mathrm{track}}$ and $h_{i,2\mathrm{track}}$ are the heights of Levels 1# and 2# obtained by the tracker after *i* movements of the displacement table, respectively; and $\triangle H_{\mathrm{i},2\_1\mathrm{tracker}}$ is the height difference between Levels 1# and 2#.

Level 1# remained stationary, and between the *i*-1 and *i* movements, the relative displacement of Level 2# determined by the tracker was calculated as follows:

$$\triangle H_{i\_i-1,2\_1tracker} = \left(h_{i,2tracker} - h_{i,1tracker}\right) - \left(h_{i-1,2tracker} - h_{i-1,1tracker}\right) \quad (10)$$

Where $h_{i-1,1tracker}$ and $h_{i-1,2tracker}$ are the Level 1# and Level 2# heights based on the horizontal coordinate system obtained by the tracker after *i*-1 movements, respectively; and $h_{i,1tracker}$ and $h_{i,2tracker}$ are those after *i* movements, respectively.

(4) Analysis of validation results

Equation 7 represents the vertical displacement of level 2# relative to level 1# measured by the AHLS after a single movement of each level; whereas, Equation 10 describes the corresponding value measured by the tracker. The two results are then compared with the movements of the displacement table. Figure 11 shows the difference between the two results and the movements of the displacement table. The difference between the level and displacement table ranged from -3 μm to 7 μm. After eliminating the instrumental error of the displacement table itself, the relative monitoring accuracy of the level was found to be within 5 μm, which met the nominal accuracy of the level. The difference between the tracker and displacement table varied from -31 μm to 9 μm, which are consistent with the variation in nominal accuracy of the laser tracker. Thus, the measurement errors of the abovementioned methods is low and the measurement data can be considered reliable.

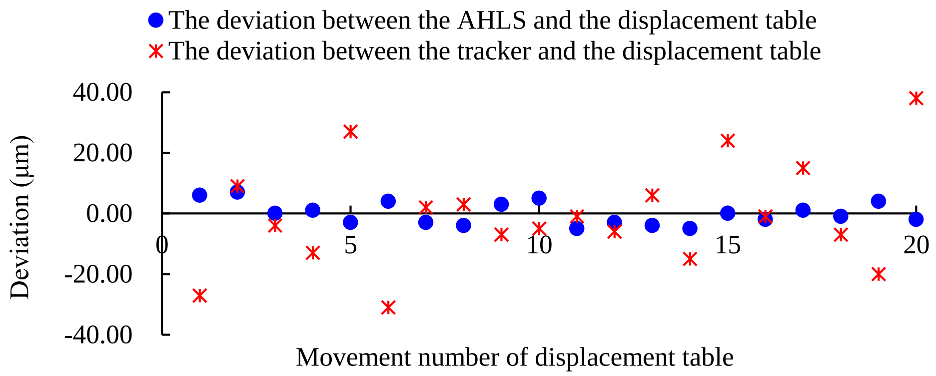



Figure 11 Comparison of deviation between the results obtained by the AHLS and laser tracker with respect to the displacement table

Equation 8 represents the absolute height difference between Levels 2# and 1# measured by the AHLS after single movements at the same moment; whereas, Equation 9 shows the corresponding value measured by the tracker. The deviation in the values obtained using the two methods is shown in Figure 12. Based on the measurement results from 22 upward and downward points, the RMS of all deviations is 0.031. Only two points have deviation values exceeding 0.05 mm, with the maximum deviation being 0.08 mm.  The remaining 20 points have deviation values within 0.05 mm. This deviation include the instrumental error of tracker itself. The experiment shows that AHLS can achieve absolute height with an accuracy of no less than 0.05mm within a 10m range, supporting the feasibility of the principle of absolute height acquisition of AHLS. Further experiments are needed to verify large-scale absolute height accuracy of AHLS.

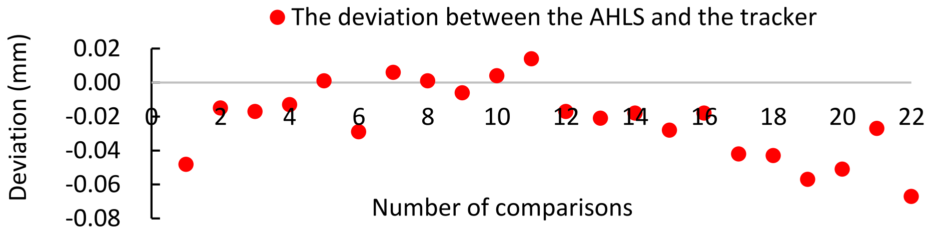



Fig 12 Comparison of the difference in height measured by the AHLS and laser tracker

## 6. Conclusion

This paper proposes a method for establishing absolute height datum based on the accelerator settlement monitoring method HLS, called AHLS, which addresses the current means and problems related to establishing height datum for accelerator alignment.

This method uses the actual level surface in the HLS as the datum, and by using absolute calibration, the liquid level is drawn out to directly obtain the absolute height of the external datum of the level. Since the height value is independently obtained at each point without error accumulation, high-precision height datum can be established.

The absolute calibration of the level is critical for obtaining the height from AHLS. In this study, the experiments were performed on a non-contact absolute hydrostatic level from three aspects: the level bowl's key dimension $MD_k$, level reading $R_k$, and the liquid depth $W_k$ inside the bowl, and the displacement table and coaxial displacement meter were used to conduct in-depth research on liquid depth measurement, achieving an absolute calibration accuracy of 0.031mm for a single level.

The laboratory established an AHLS between two points within 10 meters and used a laser tracker with an electronic level and a micrometer displacement table to verify and calibrate the principle and absolute height accuracy of the AHLS. The results showed that the absolute height accuracy within 10 meters is not less than 0.05mm.

AHLS not only provides relative monitoring, but can also provide absolute datum. By combining the accelerator tunnel network and operation settlement monitoring in the height direction, the two are no longer independent measurement methods. At present, the HEPS storage ring has been designed with a length of 1360 meters, including 60 absolute leveling devices based on AHLS. During the fine tuning stage of storage ring devices, it is desirable to integrate absolute height based on AHLS, geometric leveling, and tracker leveling to establish high-precision and high-density height datum, and to achieve accuracy verification and application of this method on a large scale.

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