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# Calibration and precise orientation determination of a gun barrel for agriculture and forestry work using a high-precision total station

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ABSTRACT

To meet the agricultural and forestry needs of humans, the introduction and use of modern technologies with high precision and applicability in the field of agro-forestry is inevitable. Moreover, the accuracy of currently used instruments and techniques is undergoing constant improvement to yield better results. The effectiveness of the gun barrel for agro-forestry has been compromised by its low precision and high cost for many decades. This study aimed to develop a new method to increase the accuracy of the gun barrel by integrating the absolute fixed-point orientation and adjustable gun barrel calibration profile using a total station for precise determination. For this purpose, the reunification of the measurement of an absolute coordinate system by total station resection with the aid of two or more known control points was carried out. Then, through barrel calibration, a fixed measurement target was set on the barrel and a fixed spatial position relationship between the measurement target and the axis of the barrel was established. After that, the orientation of the barrel was adjusted, and the three-dimensional coordinates of the fixed target were measured using a total station instrument. The barrel simulation test results showed that the total station has a good accuracy in the calculation of azimuth angle and elevation angle, while the measurement error could be guaranteed within 0.2 mil. Our newly proposed method has satisfied the accuracy test requirements and shown higher accuracy than other related conventional methods. It will make the gun barrel more useful and will enhance its applicability in the field of agro-forestry.

## 1. Introduction

With the introduction of applied electronic equipment, an exponential and a rapid growth has been observed in the field of agro-forestry [1,2]. In addition to many newly introduced advanced technologies, the gun barrel is still used as an important tool in a variety of agro-forestry activities. It is important in combating drought in dry seasons using dry ice to provoke artificial rainfall, as well as for seed sowing [3] and propelling fire extinguishing balls to fight forest fires [4]. It can also be used for the control of pests and diseases in agro-forestry [5]. Moreover, the gun barrel is also useful in dust removal and environmental protection by firing water spray shells to distant areas [6]. However, the precision and accuracy of firing projectiles from the gun barrel is still unsatisfactory for all these applications to maximize its efficiency and applicability. Elevation and azimuth angles are the key indexes that affect the gun barrel adjustment, real-time accuracy and launch efficiency [7,8].

The traditional methods of barrel inspection developed in 1950s and 1960s were mainly “distant point methods” or “inspection plate methods”. These methods are largely manual and insufficiently precise. Moreover, the manual measurement methods have low accuracy and complicated, time-consuming and laborious operational mechanisms, which eventually reduce the efficiency of these methods, thus not meeting the modern needs of agriculture and forestry [9,10]. With the extensive use of precision measurement, precise and information-based instruments have gradually been applied to enhance the accuracy and performance of gun barrels. Presently, the most commonly used gun barrel accuracy detection method is the “Two Theodolites Method” [11,12], which uses two theodolites to measure the azimuth angle and angular altitude of the target point. The measurement results of the

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**Fig. 1.** Measuring instrument (NTS-391R total station).

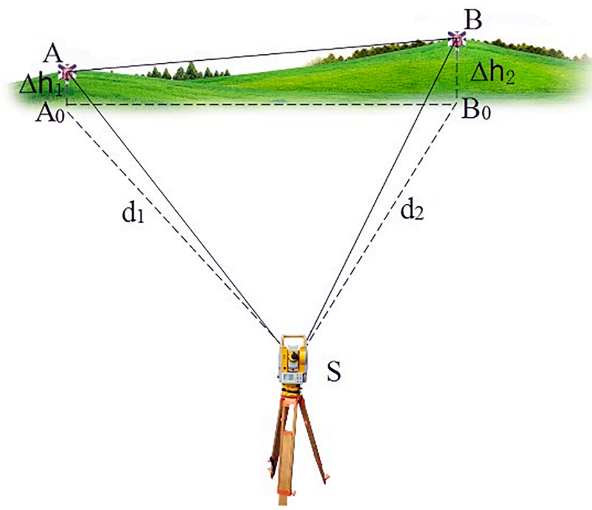


**Fig. 2. Resection principle diagram.** S is the installation position of the total station, $A_0$ and $B_0$ are the points projected onto the horizontal plane by A and B, respectively; $\Delta h_1$ and $\Delta h_2$ represent the elevation difference between A and B and the horizontal plane, respectively; $d_1$ and $d_2$ represent the horizontal distance from S to target points A and B, respectively.

simultaneous theodolite measurements determine the height and azimuth posture of the barrel. Subsequently, various angular transducer and navigation positioning systems were also introduced to adjust the gun barrel position and orientation [13–15]. Furthermore, photogrammetry has also been applied to the orientation measurement process [16–18]. In addition, as a common instrument for precision measurement, the total station has also been applied to gun barrel positioning [19,20]. These measurement patterns were improved and promoted by improving the traditional methods of barrel measurement, and they have also completed the relevant detections and measurement missions and requirements up to a certain extent. However, these methods still have some limitations, including complicated operation, low efficiency and low precision, as well as the inconsistency of the actual axis of the barrel with the axis of measurement.

In this study, we developed a method that combines a gun barrel calibration and real-time orientation determination based on the high-precision three-dimensional coordinate measuring function of the total station to achieve a higher precision and an accurate projectile launching of the gun barrel. Our gun barrel adjustment, operation and accuracy measurement system are based on our patented methodology [21]. By using the total station measurement system to achieve high-precision calibration and measurement of the gun barrel, we can improve the shortcomings and defects of the existing measurement methods.

## 2. Materials and methods

### 2.1. Structural design and operation of the measurement system

The measurement system (Fig. 1) is composed of an NTS-391R total station instrument (measuring accuracy: ±1 mm + 1 ppm; Tracking time: 0.15 s), a notebook computer (supporting Visual Studio 2013 integrated development environment, NET Framework 4.5 framework using C # language to write solver software), measuring targets, measuring mirrors, and a special fountainpen line. The total station instrument was used for data collection, the notebook was used to process and analyze data, while the measuring targets and reflectors were used for calibration and point measurement.

The main research object of this study was the artillery firing commonly used in agriculture and forestry. A stepwise description of our system's operation in the field is given below.

(1) We used two or more known fixed control points in the launching region, or used the Beidou high-precision static baseline measurement of more than two coordinate control points). Using the angle and distance measurement function of the total station and the method of resection, the three-dimensional coordinates of the set station were determined to determine the fixed-point orientation of the set station.

(2) After that, the gun barrel was transferred to an absolute horizontal state using the total station instrument. At the end of the gun barrel, the joint spider was set to determine the axis of the gun and the horizontal position of the outer part of the gun barrel. The black markline determined the "contour line" on the outside of the barrel based on two target points at the outer side of the barrel and the barrel axis. In addition to these two selected points, two more points were chosen at the "contour line" near the end of the gun barrel. The target was fixed at the four target points (the two points chosen in the middle were permanent and rigid).

(3) We used the high-precision 3D coordinate measuring function of the total station, and the four target points of the outer tube were determined at the absolute level. Through modeling, the offset relation between the straight line determined by the target point at the outer edge of the barrel and the axis of the bullet line of the gun barrel was established.

(4) In the case of any adjustment of the gun barrel orientation, the three-dimensional coordinates of two fixed target points on the outer side of the gun barrel were measured using the total station instrument. After automatic storage, the data were transmitted to the workstation (Personal Computer end) through the data line. After the data were converted into excel format, they were directly imported into the computer end-program for solution. According to the offset relationship between the target line outside the barrel and the trajectory of the gun barrel established in step (3), the azimuth and the elevation angle corresponding to the trajectory axis of the barrel were finally determined to realize the accurate and rapid determination of the barrel at any corresponding orientation.

### 2.2. Mathematical modeling and spatial solution

#### 2.2.1. Fixed point and orientation

We selected two control points named A and B inside the visual range of the launching area. The three-dimensional coordinates of the two points A and B were accurately measured using two BeiDou RTKs (Real - Time Kinematics) as known control points, and then converted into three-dimensional geodetic coordinates A ($X_A, Y_A, Z_A$) and B ($X_B, Y_B, Z_B$).

According to the positions of known control points A and B and the

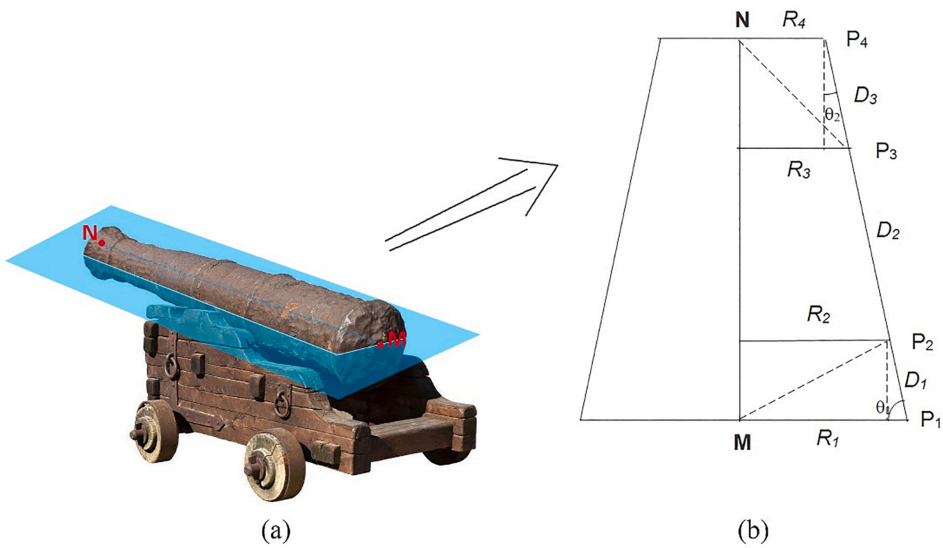


**Fig. 3. Cross section diagram corresponding to the gun barrel (a), and principle of gun barrel calibration (b).** $P_i$ (i = 1,2,3,4) represent the position of the fixed measurement targets on the outside of the gun barrel. $R_i$ (i = 1,2,3,4) represent the radius of the regular cross section of the gun barrel at 4 measuring targets. The real lengths of $P_1P_2$, $P_2P_3$, $P_3P_4$ in the cross-section position are described by $D_i$ (i = 1,2,3). $\theta_1$ and $\theta_2$ stand for two angles.

erection position of the gun barrel, we selected the total station erection position point S (Fig. 2).

The two points A and B were observed in turn, and the trajectory position of point S was calculated using the resection method using three-dimensional coordinates of control points A and B, respectively. Finally, their average was taken to obtain the three-dimensional coordinates of station S.

Eq. (1) represents the solution model of the resection method.

$$\begin{cases} X_S = \dfrac{X_{S1}+X_{S2}}{2} = \dfrac{X_A+X_B+d_1\cos\alpha_{AS}+d_2\cos\alpha_{BS}}{2} \\ Y_S = \dfrac{Y_{S1}+Y_{S2}}{2} = \dfrac{Y_A+Y_B+d_1\sin\alpha_{AS}+d_2\sin\alpha_{BS}}{2} \\ Z_S = \dfrac{Z_{S1}+Z_{S2}}{2} = \dfrac{Z_A+Z_B-\Delta h_1-\Delta h_2}{2} \end{cases} \tag{1}$$

whereas $(X_S, Y_S, Z_S)$ stands for object coordinates of site S estimated from point A and point B.

The object space coordinates of position S were calculated from point A and B represented by $(X_{S1}, Y_{S1}, Z_{S1})$ and $(X_{S2}, Y_{S2}, Z_{S2})$; the horizontal distance from S to A and B is represented by $d_1$ and $d_2$; and the height difference from point S to A and B is represented by $\Delta h_1$ and $\Delta h_2$, respectively.

$$\begin{cases} \alpha_{AS} = \alpha_{AB} + \alpha_1 \\ \alpha_{BS} = -\alpha_{AB} - \alpha_2 \end{cases}, \alpha_{AB} = \tan^{-1}\frac{Y_B - Y_A}{X_B - X_A}$$

### 2.2.2. *Calibration of the gun barrel*

The barrel calibration was conducted by calculating the three-dimensional coordinates of the two points M and N selected at both ends of the barrel. Then, the fixed space orientation difference of the straight line of the gun barrel outside the target and trail axis was measured using the point M and N by the method of coordinate calculation (via the azimuth angle $\Delta\alpha$ and the angular angle $\Delta\beta$). The calculations were done keeping the barrel in a horizontal position, assuming it as a plane structure having a smaller front and a larger rear end (Fig. 3).

After calibrating of the gun barrel, the three-dimensional coordinates $P_1$, $P_2$, $P_3$ and $P_4$ in the external area of the barrel were measured by the total station, described by $(X_1, Y_1, Z_1)$, $(X_2, Y_2, Z_2)$, $(X_3, Y_3, Z_3)$ and $(X_4, Y_4, Z_4)$, respectively. The three-dimensional coordinates at the end points M and N were calculated from $(X_M, Y_M, Z_M)$ and $(X_N, Y_N, Z_N)$, respectively.

For the larger point M on the gun barrel axis, the feature points $P_1$ and $P_2$ were used to obtain the 3D coordinates of M, which were described by $(X_M, Y_M, Z_M)$ via the joint solution method (formula (2)).

$$\begin{cases} (X_M - X_1)^2 + (Y_M - Y_1)^2 + (Z_M - Z_1)^2 = R_1^2 \\ (X_M - X_2)^2 + (Y_M - Y_2)^2 + (Z_M - Z_2)^2 = R_1^2 + (D_1 \cdot \sin\theta_1)^2 \\ Z_M = Z_1 = Z_2 \end{cases} \tag{2}$$

In the formula, $\theta_1 = \cos^{-1}\frac{R_2 - R_1}{D_1}$.

For the small end-point N on the gun barrel axis, the feature points $P_3$ and $P_4$ were used to obtain the 3D coordinates of N, which were described by $(X_N, Y_N, Z_N)$ via the joint solution method (formula (3)).

$$\begin{cases} (X_N - X_4)^2 + (Y_N - Y_4)^2 + (Z_N - Z_4)^2 = R_4^2 \\ (X_N - X_3)^2 + (Y_N - Y_3)^2 + (Z_N - Z_3)^2 = R_4^2 + D_3^2 - 2D_3R_4\cos\theta_2 \\ Z_N = Z_3 = Z_4 \end{cases} \tag{3}$$

In the formula, $\theta_2 = \cos^{-1}\frac{R_4 - R_4}{D_3}$.

After calculating the coordinates of M and N, the direction of the barre axis in space was determined using the space vector relation described by formula (4).

$$\vec{a} \cdot \vec{b} = |\vec{a}| \cdot \left|\vec{b}\right| \cdot \cos\Delta\alpha \tag{4}$$

In the formula, $\vec{a} = (X_M - X_M, Y_M - Y_N)$, and $\vec{b} = (X_2 - X_3, Y_2 - Y_3)$.

Based on formula (4), the difference of the azimuth angle, described by $\Delta\alpha$ between the axis of the barrel and its outer contour was determined.

$$\Delta\beta = \beta_2 - \beta_1 \tag{5}$$

In the formula, $\beta_1 = \tan^{-1}\frac{Z_M - Z_N}{|\vec{a}|}$, and $\beta_2 = \tan^{-1}\frac{Z_2 - Z_3}{|\vec{b}|}$.

The formula given in Eq. (5) was used to find the difference of the angle in the vertical direction described by $\Delta\beta$ between the axis of the gun barrel and its outer contour.

### 2.2.3. *Orientation determination of gun barrel*

The fixed offset of a barrel was determined by its calibration. This relationship was measured via the fixed point outside the barrel to calculate the azimuth angle and projection angle of the barrel.

The 3D coordinates of $P_2$ and $P_3$ in the external area of the gun barrel

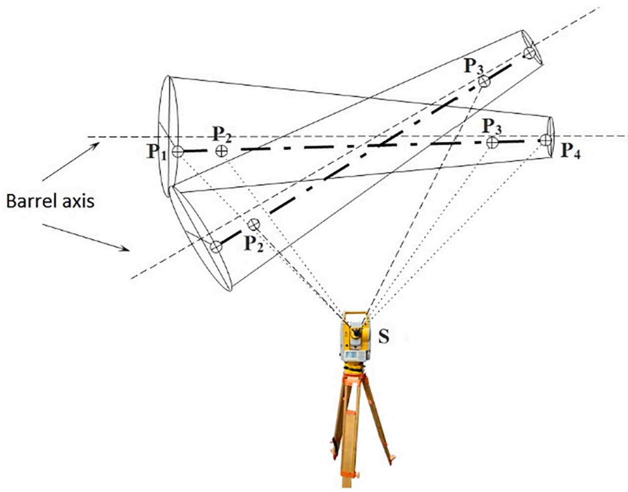


**Fig. 4.** Sketch of gun barrel orientation measurement.

were calculated by rotating the calibrated gun barrel and using the total station instrument set up in site S described by $(X_2, Y_2, Z_2)$, and $(X_3, Y_3, Z_3)$, respectively (see Fig. 4). Formulas (6) and (7) were used to obtain the azimuth angle and projectile angle of the outer contour line of the barrel.

$$\alpha_{23} = \left(\cos^{-1}\frac{X_3 - X_2}{S_{23}}\right) \cdot sgn(Y_3 - Y_2) + 2\pi \tag{6}$$

$$\beta_{23} = \tan^{-1}\frac{Z_3 - Z_2}{\sqrt{(X_3 - X_2)^2 + (Y_3 - Y_2)^2}} \tag{7}$$

In the formula, ①$S_{23} = \sqrt{(X_3 - X_2)^2 + (Y_3 - Y_2)^2}$.

②$sgn(Y_3 - Y_2)$ is a function used to obtain a symbol, if the value in the bracket is positive, it becomes "+", if it is negative, it becomes "−".

③if $\alpha_{23} \geq 2\pi$, $2\pi$ is removed from the whole.

When the elevation angles of the horizontal fixed space variables in gun barrel calibration were changed, the corresponding azimuth angular variables changed accordingly. For the conversion of calibration data, we used the formula (8) to correct the quantitative transformation for the orientation angle in the horizontal direction.

$$\Delta\alpha^{'} = 2\tan^{-1}\frac{\tan\frac{\alpha}{2}}{\cos\beta_{23}} \tag{8}$$

After obtaining the instantaneous posture of the outer contour line, the fixed spatial offset relation and the horizontal projection correction of the marked axis of the gun barrel were determined using formulas (4), (5), and (8), respectively. Then, the real-time orientation corresponding to the marking line of the outer contour of the gun barrel was corrected to the true azimuth A and elevation B corresponding to the trajectory axis of the gun barrel using formula (9).

$$\begin{cases} \alpha = \alpha_{23} + \Delta\alpha^{'} \\ \beta = \beta_{23} - \Delta\beta \end{cases} \tag{9}$$

### 2.3. Experimental design

To verify the feasibility of the research scheme and the error effect caused by the external conditions in the actual observation, we designed a test scheme to measure and verify the accuracy of the gun barrel using the total station. However, considering the objective conditions and testing difficulty, a verification test conducted in the laboratory was used to simulate barrel adjustment and testing.

To directly verify the feasibility of the research method, we made a barrel simulator (referred to as the "gun barrel" in further text) since the two ends of the barrel were not visible to each other and the true value of the orientation of the central axis cannot be determined. This verification test assumed that the gun calibration is $\Delta\alpha = 0$, $\Delta\beta = 0$. Therefore, two fixed measurement targets $P_2$ and $P_3$ in the outer diameter of the gun barrel were arbitrarily selected to represent the real gun barrel calibration, and the line determined by $P_2$ and $P_3$ was the axis of the gun barrel. This is the spatial orientation line $P_2P_3$ measured on behalf of the gun barrel axis orientation. The double theodolite intersection observation method (double theodolite method) was widely recognized and used in the field of gun barrel measurement [12,22], and its measurement accuracy can meet the accuracy requirements of standard gun barrel measurement (the error within 0.2 mil) [22]. Therefore, in this test the double theodolite intersection measurement values were used as standard values to verify the total station measurement error in the gun barrel measurement process.

**Table 1**
Data collection characteristics of experimental design.

| Data characteristics | Near horizontal[1] | Small angle[2] | Medium angle[3] | Large angle[4] |
|---|---|---|---|---|
| Sample size | 10 | 10 | 10 | 10 |
| Range of azimuth adjustment difference (°) | 0–360 | 0–360 | 0–360 | 0–120 |

Note: The header indicates the different tilt state of the gun barrel due to adjustment of its elevation angle. Among them, 1 represents the state of inclination angle less than 10°, 2 represents the state of inclination angle between 10° and 30°, excluding 30°, 3 represents the state of inclination angle between 30° and 60°, excluding 60°, and 4 represents the state of inclination angle reaching or exceeding 60°.

In this experiment, two high-precision self-collimating electronic theodolites (TM5100A; Leica, Switzerland) were mounted on one end of the barrel and the side where the target was set. The two theodolites were oriented to establish a standard coordinate system. Then, the total station was erected at the barrel setting one side of the target, and a unified coordinate system was established by collimation and orientation with one of the theodolites. In order to better test the applicability and stability of the method proposed in this study, the gun barrel orientation was adjusted to make it in the state of near horizontal, small-angle, medium-angle and large-angle respectively, and the grouping experiment and independent observation were carried out with the statistical idea. Among them, each group was guaranteed to carry out more than 10 independent observation experiments. At the same time, the observation data (Table 1) were recorded according to the design specifications, so as to facilitate the later calculation and verification analysis.

## 3. Measurement error analysis

In order to better analyze the error sources of the proposed method for gun barrel positioning, we mainly analyzed the measurement error of the total station instrument itself, the leveling error of instrument observation, and the observation error of the human operator during aiming observation [23,24] which all may cause gun barrel positioning errors.

### 3.1. The angle measurement error of the total station

In this paper, the NTS-391R total station (SOUTH, China) was used to simulate the determination of the gun barrel azimuth and elevation angles. Through the instrument identification, the total station of this model adopted the absolute coding, four probe sampling angle measuring technique and new five coaxial ranging optical path design, the ranging accuracy reaches ±1 mm + 1 ppm. The measurement accuracy of horizontal and elevation angles reached 1". Although the calibration accuracy of the instrument itself can completely meet the

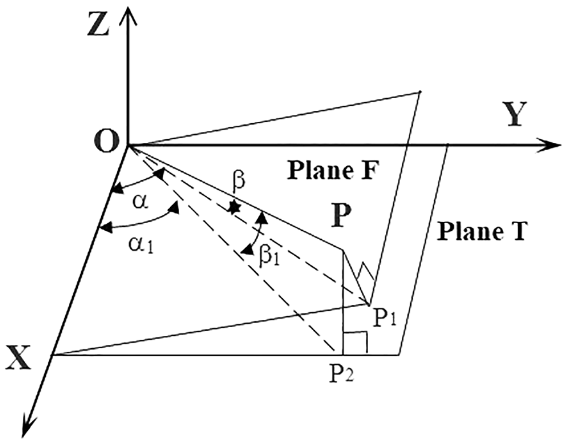


**Fig. 5.** Schematic diagram of angle error caused by leveling error of the instrument.

measurement requirements, with the progress of technology, the angle measurement accuracy of the total station itself will improve, which will eventually also improve the accuracy of gun barrel positioning [25].

### 3.2. Error caused by leveling of the instrument

The leveling accuracy of the precision measuring instrument plays an important role in obtaining accurate measurement results. The adjustment error of the instrument could inevitably lead to errors in the measurement results [26,27].

Fig. 5 shows the influence of measurement results on the azimuth and elevation angles of the total station in the leveling and non-leveling state, respectively. In the figure, the total station erection position was assumed to be in a three-dimensional coordinate system of O-XYZ space, in which plane T is the horizontal plane, plane F is the inclined plane, $P_1$ and $P_2$ are projection points on the inclined plane and the horizontal plane, α and $\alpha_1$ are azimuth angles of the inclined plane and the horizontal plane, while β and $\beta_1$ are the elevation angles of the inclined plane and the horizontal plane, respectively.

According to the geometric relation, the leveling accuracy of the total station instrument could directly affect the coordinate accuracy, and ultimately affect the determination of the azimuth and elevation angles. To overcome this problem, we used the CCD imaging function of the NTS-391R total station to accurately measure and compensate the error, which effectively alleviated the error of the measurement results caused by the instrument leveling error.

### 3.3. Observation errors

The observation errors are random errors, which are not only affected by the aiming observation error, but also by the external observation conditions [27,28]. An observation error can directly affect the accuracy of the measurement result.

To accurately measure a quantity, the repeated independent observation of the same measured object is needed. Generally, for 36 or more independent repeated observations of the same target point, the measurement results can indicate the systematic error (non-accidental error) of the observation [28]. In this study, we selected 36 independent repeated observations of the same target point, and recorded the data for each observation. We then used the formula (10) to calculate the standard deviation ($\delta_x = 1$ mm, $\delta_y = 1$ mm, $\delta_z = 1$ mm) of the sighting of each three-dimensional coordinate, respectively.

$$\delta = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1}} \tag{10}$$

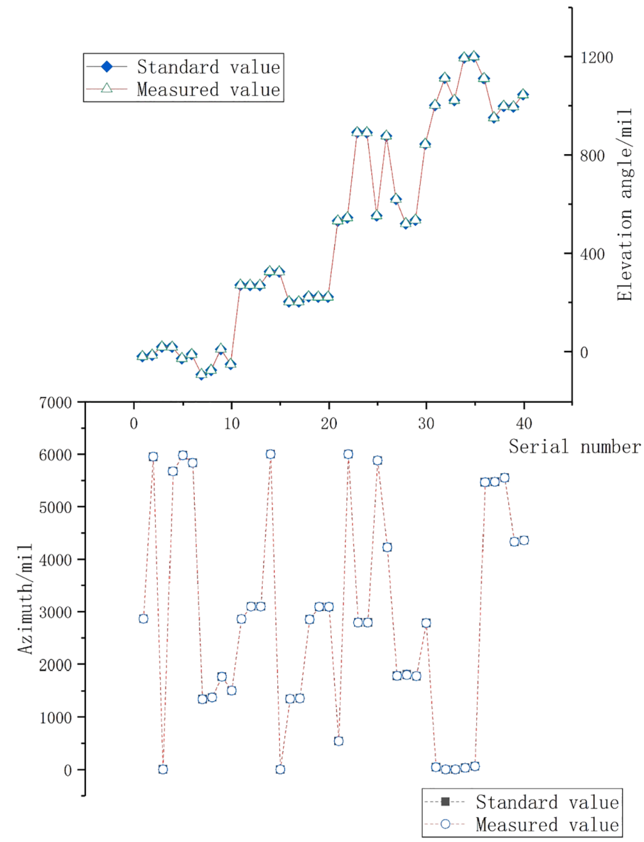


**Fig. 6.** Analysis chart of the observation accuracy of the total station method.

The formula, $\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$, $x_i$ represents each view measurement of the 3D coordinate values, whereby $\overline{x}$is its average value, n is the number of observations, and $\delta$ represents the standard deviation of observations.

In addition, the error caused by the external observation conditions is analyzed and discussed in detail in the experimental results.

### 3.4. Error analysis of gun barrel orientation measurement

According to the principle of synthesis error, it is considered that when the total station is used to calibrate and measure the gun barrel, the measurement accuracy could be affected by the measurement error of the instrument itself, the leveling error of the instrument during observation, the observation error of the human operator aiming the observation, and the error caused by the external conditions during observation [29].

## 4. Results

In order to verify the observation accuracy and applicability of the proposed method more comprehensively, the gun barrel orientation in the near horizontal, small angle, medium angle and large angle state was verified. Due to the assumption that the values of the azimuth angle and elevation angle for gun barrel calibration are zero, we used formulas (6) ~ (9) to respectively calculate the absolute azimuth angle and the elevation angle of the barrel axis under different conditions. Then, we compared the calculations with the measured values obtained using the double theodolite method (Appendix A).

As can be seen in Table A1, the overall accuracy of the total station measurement was excellent when compared to the values obtained using the double theodolite method as the reference standard. Among them, the accuracy of measurement results of azimuth and elevation angle was relatively close. In our results, under normal conditions, the

**Table 2**
Summary of the total station plan.

| Category | Test Conditions | Barrel condition (°) | | Error (mil) | Operability |
|---|---|---|---|---|---|
| Azimuth | Double theodolite intersection measurement value as the standard value | Small angle | 0–30 | 0.2 | Easy to repeat |
| | | Middle angle | 30–60 | 0.2 | Easy to repeat |
| | | Large angle | 60–90 | 0.8 | Repeatable |
| Elevation angle | | Small angle | −4–30 | 0.2 | Easy to repeat |
| | | Middle angle | 30–60 | 0.2 | Easy to repeat |
| | | Large angle | 60–75 | 0.8 | Easy to repeat |

measurement errors of azimuth and elevation angle could be guaranteed within 0.2 mil. However, when the pitch angle of the gun barrel was more than 60°, the measurement error was greater than 0.2 mil, which did not meet the relevant requirements of barrel positioning.

To demonstrate the measurement accuracy of the proposed method and the one-to-one correspondence between azimuth and elevation angle measurements involved in total station observation, we plotted a comparison diagram of measurement accuracy of the two observation methods (see Fig. 6). The comparison is based on the test data, in which the theodolite observation value was taken as the standard value and the total station observation value was taken as the measurement value. It can be clearly seen from the figure that in the process of gun barrel orientation adjustment, the azimuth and elevation angles of the gun barrel were considered under different orientation such as small angle, medium angle and large angle. Moreover, the observation times were reasonable, which indicated that the representativeness of the test samples was strong. In addition, the observed values overlapped with the standard values for both azimuth and elevation angles, which indicated that the total station method has a higher observation accuracy.

According to the calculation and comparative analysis, the total station instrument can be used to measure the gun barrel's orientation. It can meet the requirements of the precision of the gun for agriculture and forestry. For elevation observation, the corresponding measurement results of the gun barrel can be guaranteed within 0.2 mil under different angles, and the test was easy to conduct and repeat (see Table 2). For azimuth observation, the corresponding measurement results of the gun barrel can also ensure that the measurement results are within 0.2 mil under the small and medium angle orientation, while at the large orientation angle >60°, determination of azimuth error even reached more than 0.7 mil, and the values were very unstable, without good repeatability. Overall, the total station measurement of gun angular calibration and orientation determination was feasible and accurate.

## 5. Discussion

In today's society, the continuous development of science and technology has brought technological progress, and further technological grade of agro-forestry has become a pressing the demand of social development [1,30]. However, considering the limitations imposed by the cost of technology, as well as regional differences in popularization and application, there is still a great demand for shell launching systems with the traditional gun barrel as the power tool, especially for applications in agriculture and forestry [4,5]. This paper presents a method of gun barrel calibration and measurement using a total station intersection measurement, and makes a thorough discussion and analysis.

In this test, the proposed total station method showed good observation ability in gun barrel calibration and orientation measurement. Except in the case of high elevation in which the measurement error of azimuth is too large, the measurement accuracy in all other cases meets the measurement requirements [31,32]. The most likely reason for the measurement error of azimuth angle of large elevations could be that the projection baseline of two targets on the gun barrel is too short under the conditions of large elevation, resulting in a slight deviation of the coordinate value of the observed target point. This in turn could affect the angle calculation in the later stage, leading to the error of orientation observation. Similarly, this is a common problem when measuring using optical instruments [33–35]. In addition, in the actual operation of the gun barrel for agriculture and forestry, it is rare to meet the situation of azimuth adjustment under the premise of a pitch angle >60°. Therefore, the proposed method can fully meet the needs of gun barrel application in the agriculture and forestry industry considering the measurement accuracy.

Convincing experimental results are sometime quite difficult to achieve without scientific and effective experimental design. Reasonable grouping experiment and repeated observation in a group are the precondition to ensure the robustness of experimental design [25,28]. Therefore, this paper set up four different cases including near horizontal, small-angle, medium-angle and large-angle to verify the robustness. At the same time, taking into account the relevant principles of statistics, this paper conducted more than 10 independent observations in each group of experiments to ensure the stability of each group of observations, and selected representative experimental results for discussion and analysis. Our results showed that the measurement error of gun barrel can be controlled within 0.2 mil, which indicate that the proposed method has a good application prospect in the field of agro-forestry gun barrel positioning. However, in practical operation, due to the cumulative influence of external forces such as gun barrel orientation adjustment and shell shooting, there may be some errors in measuring the stability of the central axis between the target and the barrel. In order to effectively alleviate this possible factor, we can try from the following two aspects. Firstly, we suggest that according to the actual use frequency of the gun barrel, a new calibration should be carried out every 6–12 months to reduce the calibration error of the equipment. Secondly, we can select materials with relatively stable performance to make measurement targets, such as materials with corrosion resistance, deformation resistance, easy identification, and easy fixation, so as to further ensure the stability of observation.

In addition to having higher accuracy and stronger stability, our proposed method is economical and user friendly in operation compared to other methods. For instance, the double theodolite method is considered the most recognized and widely used method in gun barrel angle measurement at present, but the cost of two high-precision theodolites plus auxiliary equipment is much higher than that of our proposed total station method [36,37]. Moreover, the operation process of the double theodolite method is also very complex [12,38]. Although other information-based observation methods, such as laser measurement [35,39,40], have produced great innovations, its observation cost is often ignored, and there are certain limitations in its promotion and application in the industry. Compared with the existing technical methods, our proposed total station method has higher measurement accuracy, excellent cost effectiveness and good applicability in field of agro-forestry and related industry.

## 6. Conclusions

In this paper, we present a new method for calibrating the gun barrel by means of known control points and its applicability in agriculture and forestry using a high-precision total station. The feasibility and accuracy of the method proposed in this paper were verified by comparison with the conventional double theodolite's intersection method.

Our proposed total station method can be used to calibrate a gun barrel with higher accuracy (within 0.2 mil) than other methods. In addition, this method is economical, simple and easy to implement. However, limited by objective conditions and financial resources, there are still some deficiencies in the test. Nevertheless, using the total station for agricultural and forestry gun calibration and orientation determination is a viable new measurement model, and it can provide good results in the development of agriculture and forestry information.

## 7. Patents

Zhongke Feng, Jincheng Liu, Zixuan Qiu. A method of automatic and rapid determination of azimuth angle of agricultural and forestry rocket with total station [P]. China, Patent CN 108088412A, 2016-11-23. http://epub.sipo.gov.cn/patentoutline.action.

## CRediT authorship contribution statement

**Jincheng Liu:** Conceptualization, Methodology, Software, Writing - original draft. **Tauheed Ullah Khan:** Formal analysis, Writing - review & editing. **Zhengang Nie:** Investigation, Resources, Data curation. **Qiang Yu:** Visualization, Supervision, Funding acquisition. **Zhongke Feng:** Validation, Supervision, Project administration.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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*Declaration of Competing Interest*

The authors declare no conflicts of interest.

*Data Accessibility*

The datasets supporting this article have been uploaded as part of the Supplementary Material. Relevant solution software can be obtained in the following links (https://pan.baidu.com/s/1KVMdYvcYO1iPXu2BIaoCFw).

## Appendix

See Table A1.

**Table A1**
Comparison and analysis of measured data obtained using the total station instrument and the double theodolite method.

| Adjust number | Measured value (mil) | | Standard value (mil) | | Absolute error (mil) | |
|---|---|---|---|---|---|---|
| | Azimuth | Elevation angle | Azimuth | Elevation angle | Azimuth | Elevation angle |
| 1 | 2864.7677 | −18.7325 | 2864.87 | −18.75 | −0.1023 | 0.0175 |
| 2 | 5950.9914 | −13.7431 | 5951.17 | −13.88 | −0.1746 | 0.1369 |
| 3 | 2.3198 | 20.0443 | 2.18 | 20.13 | 0.1398 | −0.0857 |
| 4 | 5674.2459 | 19.2136 | 5674.40 | 19.42 | −0.1541 | −0.2064 |
| 5 | 5978.8044 | −27.6967 | 5978.93 | −27.80 | −0.1256 | 0.1033 |
| 6 | 5835.3400 | −10.6052 | 5835.50 | −10.76 | −0.1602 | 0.1527 |
| 7 | 1340.0711 | −92.9010 | 1339.96 | −92.84 | 0.1071 | −0.0631 |
| 8 | 1373.8222 | −75.2578 | 1373.66 | −75.42 | 0.1644 | 0.1626 |
| 9 | 1769.6866 | 10.3985 | 1769.77 | 10.28 | −0.0849 | 0.1175 |
| 10 | 1503.8911 | −51.0062 | 1503.77 | −50.86 | 0.1243 | −0.1502 |
| 11 | 2856.6241 | 271.3157 | 2856.46 | 271.50 | 0.1641 | −0.1843 |
| 12 | 3097.1284 | 270.3995 | 3097.33 | 270.51 | −0.2016 | −0.1105 |
| 13 | 3097.2287 | 270.5435 | 3097.06 | 270.61 | 0.1687 | −0.0665 |
| 14 | 5999.8164 | 325.4657 | 5999.67 | 325.29 | 0.1464 | 0.1757 |
| 15 | 0.4774 | 325.2794 | 0.65 | 325.40 | −0.1726 | −0.1206 |
| 16 | 1347.2570 | 203.4551 | 1347.35 | 203.38 | −0.0943 | 0.0792 |
| 17 | 1357.2442 | 203.4463 | 1357.11 | 203.29 | 0.1387 | 0.1573 |
| 18 | 2851.2429 | 223.9812 | 2851.38 | 224.18 | −0.1337 | −0.2011 |
| 19 | 3090.6306 | 223.0296 | 3090.78 | 223.20 | −0.1520 | −0.1692 |
| 20 | 3091.3245 | 222.8444 | 3091.18 | 222.95 | 0.1398 | −0.1088 |
| 21 | 541.8059 | 531.9110 | 541.66 | 531.76 | 0.1459 | 0.1510 |
| 22 | 5999.8766 | 544.6699 | 5999.69 | 544.80 | 0.1866 | −0.1301 |
| 23 | 2791.0162 | 891.2086 | 2791.20 | 891.35 | −0.1838 | −0.1414 |
| 24 | 2791.5840 | 891.2277 | 2791.40 | 891.34 | 0.1840 | −0.1123 |
| 25 | 5879.7103 | 553.3327 | 5879.51 | 553.46 | 0.2003 | −0.1273 |
| 26 | 4226.9516 | 877.3396 | 4226.80 | 877.22 | 0.1522 | 0.1212 |
| 27 | 1785.2455 | 619.9442 | 1785.40 | 620.05 | −0.1497 | −0.1097 |
| 28 | 1802.5563 | 521.1396 | 1802.73 | 520.94 | −0.1725 | 0.2007 |
| 29 | 1778.5529 | 535.7698 | 1778.73 | 535.90 | −0.1800 | −0.1325 |
| 30 | 2782.4589 | 844.0826 | 2782.32 | 844.20 | 0.1398 | −0.1183 |
| 31 | 45.9442 | 1001.9707 | 45.51 | 1001.80 | 0.4342 | 0.1707 |
| 32 | 0.8770 | 1112.5158 | 1.15 | 1112.70 | −0.2730 | −0.1842 |
| 33 | 0.2164 | 1022.0843 | 0.60 | 1021.89 | −0.3836 | 0.1943 |
| 34 | 33.1814 | 1194.9107 | 33.69 | 1194.70 | −0.5086 | 0.2107 |
| 35 | 62.9794 | 1199.8923 | 63.74 | 1199.69 | −0.7606 | 0.2023 |
| 36 | 5464.8067 | 1110.7862 | 5464.63 | 1110.95 | 0.1727 | −0.1599 |
| 37 | 5474.3317 | 951.3597 | 5474.60 | 951.56 | −0.2659 | −0.2038 |
| 38 | 5550.6931 | 998.4174 | 5550.13 | 998.23 | 0.5609 | 0.1895 |
| 39 | 4329.5289 | 995.8366 | 4330.24 | 995.64 | −0.7144 | 0.2000 |
| 40 | 4356.8659 | 1045.2343 | 4357.49 | 1045.43 | −0.6238 | −0.1981 |

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