Antenna Parameter Calibration for Mobile Communication Base Station via Laser Tracker

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Abstract: In the field of antenna engineering parameter calibration for indoor communication base stations, traditional methods suffer from issues such as low efficiency, poor accuracy, and limited applicability to indoor scenarios. To address these problems, a high-precision and high-efficiency indoor base station parameter calibration method based on laser measurement is proposed. We use a high-precision laser tracker to measure and determine the coordinate system transformation relationship, and further obtain the coordinates and attitude of the base station. In addition, we propose a simple calibration method based on point cloud fitting for specific scenes. Simulation results show that using common commercial laser trackers, we can achieve a coordinate correction accuracy of 1 cm and an angle correction accuracy of 0.25°, which is sufficient to meet the needs of wireless positioning.

Keywords: antenna parameter; parameter measurement; coordinate transformation; point cloud; laser track; angle correction

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1 Introduction

Locating a terminal in a cellular communication system usually requires the time difference of arrival (TDOA) and the angle of arrival (AOA)[1], combined with the engineering parameters of base station antennas. The engineering parameters of indoor base station antennas, including antenna coordinates and orientation, have a significant impact on the accuracy of terminal positioning results. However, inevitable engineering errors in the installation of base station antennas, as well as factors such as lax acceptance standards and routine optimization adjustments, can also change the antenna engineering parameters. Such parameter changes can result in significant discrepancies between the actual and recorded parameters of the antenna, thereby reducing positioning accuracy. How to measure and calibrate these errors is one of the key issues in cellular communication positioning.

Traditional mobile communication base station detection requires maintenance staff to carry measuring instruments such as tape measures, inclinometers, compasses, GPS locators, mobile phones, and cameras for measurement. All engineering parameter information must be collected and recorded manually, resulting in long operation time and high workload. In addition, these traditional methods lack precision, and GPS measurements are only applicable to outdoor scenarios. For indoor base stations, it is necessary to explore new high-precision antenna parameter calibration methods.

In recent years, a number of new technologies for antenna parameter measurement have been proposed. High-precision sensors can replace manual measurement. They can measure the antenna's directional angle, downtilt angle, and displacement via gravity, sunlight, and geomagnetism. However, the orientation of the gravity field and Earth's magnetic field tends to produce large errors, which is difficult to meet the needs of high-precision positioning.

Simultaneous localization and mapping (SLAM) achieves

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the goal of simultaneous positioning and mapping construction based on self-perception[2] and can be used in antenna parameter measurement. There are two types of SLAM: visual SLAM and Lidar SLAM. Visual SLAM processes antenna photographs to measure antenna parameters[3–4], yet it has limited accuracy, particularly in complex environments. Lidar SLAM uses laser radar to collect point cloud data to measure the antenna parameters with high accuracy, but the measurement equipment is expensive and algorithms are complex.

The laser tracker is a new type of measuring instrument developed in the past twenty years. It can track the real-time target, and the spatial coordinates of the target point can be easily calculated. This method is simple to operate and has low equipment costs, so it has been widely used in industrial measurement and robotics[5–6].

This paper introduces an indoor antenna measurement method based on the laser tracker to efficiently and accurately measure antenna engineering parameters.

2 Measure Model

The indoor antenna of a cellular mobile communication system is usually installed in an enclosure, mounted on a ceiling or wall. Assume the antenna to be calibrated is a rectangular cuboid installed indoors, and we use a laser tracker to scan and measure it. A laser tracker comprises a laser ranging module and an encoder angle measurement module, which can measure the spherical coordinates of any point in space relative to the instrument itself, and then convert them into Cartesian coordinates. To enable measurement, it is first necessary to establish a coordinate system. The coordinate system established in the simulation is shown in Fig. 1.

• World Coordinate System (WCS) O_w: It is used for calibration in measurement, and other coordinate systems are located based on it. WCS is fixed to buildings.

• Laser tracker coordinate system O_1: It is fixed on the laser tracker, and the measured result of the laser tracker is generated based on it.

• Antenna coordinate system O_b: It is fixed to the antenna, with its origin at an arbitrary corner of the antenna shell and its axes parallel to the three edges of the shell.

Antennas can be regarded as rigid bodies with six degrees of freedom, and their engineering parameters are represented by six parameters:

$$B = (x, y, z, \theta, \phi, \gamma) \tag{1},$$

where x, y, and z represent the 3D coordinates of the antenna and θ, ϕ, and γ represent the azimuth, pitch, and roll angles, also called the Euler angles.

WCS can be transformed into the antenna coordinate system through translation and rotation, where translation corresponds to the 3D coordinates of the antenna and rotation corresponds to the Euler angles. We split the rotation into three steps, and the Euler angles of the antenna parameters are defined as follows (see also Fig. 2).

• Azimuth angle: First, rotate the WCS around the z-axis;

• Pitch angle: Second, rotate the newly generated coordinate system around the y-axis;

• Roll angle: Perform the final rotation around the newly generated x-axis.

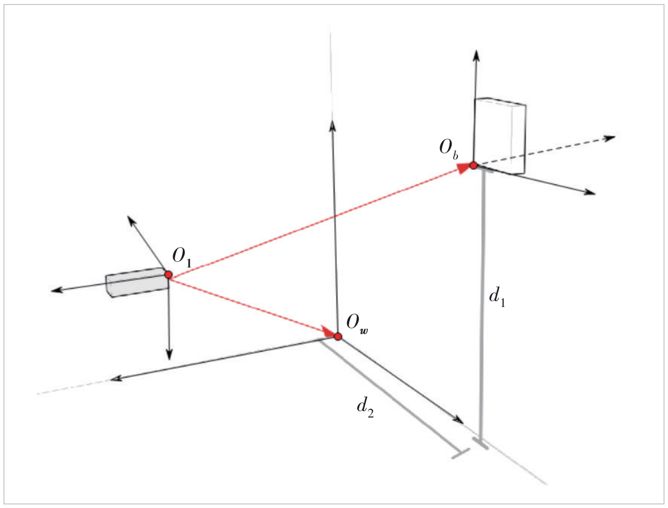


Figure 1. Measurement scene and three coordinates

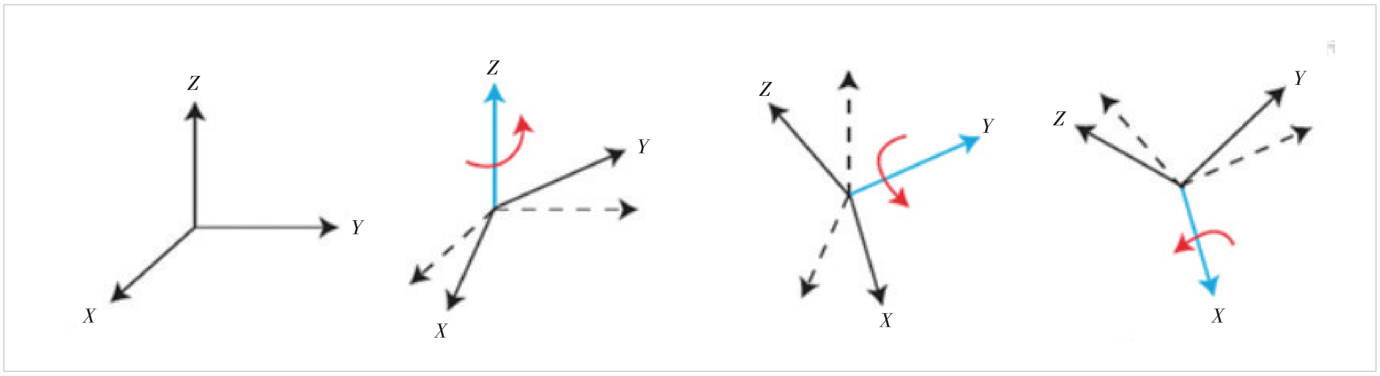


Figure 2. Definition of Euler angles

3 Proposed Antenna Parameter Calibration Method

3.1 Coordinate Transformation Method

The essence of antenna parameter measurement is to get the transformation between the WCS and the antenna coordinate system, and the laser tracker plays an intermediary role in it. The whole process is divided into two steps. First, determining the transformation from the WCS to the laser tracker coordinate system, which is the calibration of the instrument; second, determining the transformation between the laser tracker coordinate system and the antenna coordinate system, which is called the measurement step.

As shown in Fig. 3, the transformation between two coordinate systems is linear, which can be expressed as:

$$\boldsymbol{P}_A = \boldsymbol{R}_B^A \times \boldsymbol{P}_B + \boldsymbol{T}_B^A = \begin{bmatrix} a_x & b_x & c_x \\ a_y & b_y & c_y \\ a_z & b_z & c_z \end{bmatrix} \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \tag{2}$$

where subscripts A and B represent the transformation from the coordinate system B to A. The rotation matrix $\boldsymbol{R}_B^A$ is determined by the Euler angles. The rotation matrix rotating around three coordinate axes is denoted as:

$$\boldsymbol{R}_Z(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$\boldsymbol{R}_Y(\phi) = \begin{bmatrix} \cos(\phi) & 0 & -\sin(\phi) \\ 0 & 1 & 0 \\ \sin(\phi) & 0 & \cos(\phi) \end{bmatrix} \tag{4}$$

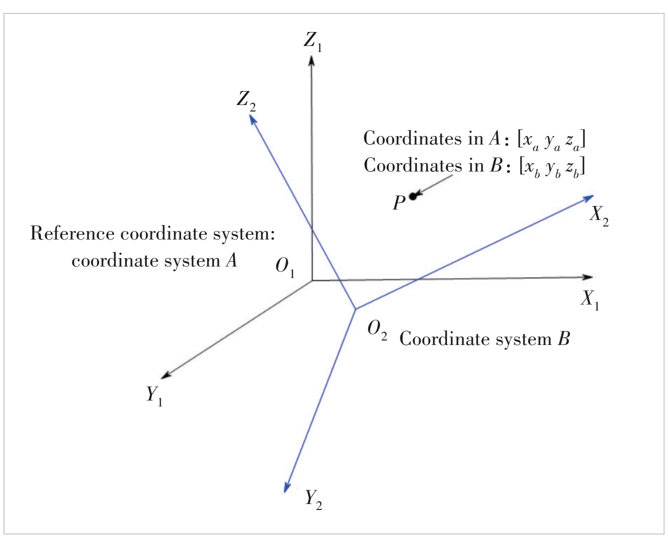


Figure 3. Coordinate transformation between two coordinate systems

$$\boldsymbol{R}_X(\gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi) & \cos(\phi) \end{bmatrix} \tag{5}$$

The complete rotation is a composite of three rotations, whose matrix can be represented as:

$$\boldsymbol{R}_B^A = \boldsymbol{R}_Z \boldsymbol{R}_Y \boldsymbol{R}_X \tag{6}$$

$\boldsymbol{T}_B^A$ represents the deviation of the origin of two coordinate systems, namely the vector $\boldsymbol{O}_1\boldsymbol{O}_2$. Given the transformation matrix $\boldsymbol{R}_B^A$ and $\boldsymbol{T}_B^A$, the coordinates of a point P in another coordinate system can be obtained. On the contrary, if the coordinates of the same points in two coordinate systems are known, the transformation matrix between coordinate systems can be inversely derived, and then the Euler angles can be obtained.

Let the coordinates of a set of points in each of the two coordinate systems be $\{\boldsymbol{A}_1, \boldsymbol{A}_2, \cdots, \boldsymbol{A}_n\}$ and $\{\boldsymbol{B}_1, \boldsymbol{B}_2, \cdots, \boldsymbol{B}_n\}$. We use the unit quaternions method to solve the rotation matrix between two coordinate systems[7–8]. First, center all point coordinates as:

$$\boldsymbol{a}_i = \boldsymbol{A}_i - \frac{\sum \boldsymbol{A}_i}{n} \tag{7}$$

$$\boldsymbol{b}_i = \boldsymbol{B}_i - \frac{\sum \boldsymbol{B}_i}{n} \tag{8}$$

Then, construct the following matrix:

$$\boldsymbol{N} = \frac{\sum \boldsymbol{a}_i \boldsymbol{b}_i^T}{n} \tag{9}$$

$$\boldsymbol{M} = \boldsymbol{N} - \boldsymbol{N}^T \tag{10}$$

$$\boldsymbol{\alpha} = [\boldsymbol{M}_{23} \quad \boldsymbol{M}_{31} \quad \boldsymbol{M}_{12}] \tag{11}$$

$$\boldsymbol{D} = \begin{bmatrix} Tr(\boldsymbol{N}) & \boldsymbol{\alpha} \\ \boldsymbol{\alpha}^T & \boldsymbol{N} + \boldsymbol{N}^T - Tr(N)\boldsymbol{I} \end{bmatrix} \tag{12}$$

where $\boldsymbol{D}$ is a real symmetric matrix, and the corresponding eigenvector $\boldsymbol{q}$ of its maximum eigenvalue is the quaternion representing the rotation transformation of two coordinate systems. Express $\boldsymbol{q}$ as:

$$\boldsymbol{q} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{13}$$

and then calculate the rotation matrix $\boldsymbol{R}$ from $\boldsymbol{q}$ as:

$$\boldsymbol{R}=\begin{bmatrix} 2q_1^2+2q_2^2-1 & 2(q_2q_3-q_1q_4) & 2(q_2q_4+q_1q_3) \\ 2(q_2q_3+q_1q_4) & 2q_1^2+2q_3^2-1 & 2(q_3q_4-q_1q_2) \\ 2(q_2q_4-q_1q_3) & 2(q_3q_4+q_1q_2) & 2q_1^2+2q_4^2-1 \end{bmatrix} \quad (14).$$

Further, according to Eq. (2), the displacement matrix $\boldsymbol{T}$ can be calculated as:

$$\boldsymbol{T}=\bar{\boldsymbol{A}}-\boldsymbol{R}\bar{\boldsymbol{B}} \quad (15),$$

where $\bar{\boldsymbol{A}}$ and $\bar{\boldsymbol{B}}$ represent the centers of all points.

Based on the above theories, four matrices need to be obtained to measure the antenna parameters: matrices $\boldsymbol{R}_w^1$ and $\boldsymbol{T}_w^1$ transforming WCS to the laser tracker coordinate system; matrices $\boldsymbol{R}_1^b$ and $\boldsymbol{T}_1^b$ transforming the laser tracker coordinate system to the antenna coordinate system.

In the instrument calibration step, a laser tracker is used to measure three or more reference points with known coordinates to obtain $\boldsymbol{R}_1^w$ and $\boldsymbol{T}_1^w$. In the measurement step, keeping the position of the laser tracker unchanged, we measure at least three corner points on the antenna shell to obtain $\boldsymbol{R}_1^b$ and $\boldsymbol{T}_1^b$. Finally, we calculate the joint transformation matrix $\boldsymbol{R}_b^w$ and $\boldsymbol{T}_b^w$ as:

$$\boldsymbol{R}_b^w=\boldsymbol{R}_1^w\boldsymbol{R}_b^1 \quad (16),$$

$$\boldsymbol{T}_b^w=\boldsymbol{R}_1^w\boldsymbol{T}_b^1-\boldsymbol{T}_1^w \quad (17),$$

where $\boldsymbol{T}_b^w$ is the 3D coordinate of the origin of the antenna coordinate system. According to Eqs. (3) – (6), the Euler angles are calculated from the rotation matrix as:

$$\begin{bmatrix}\theta\\ \phi\\ \gamma\end{bmatrix}=\begin{bmatrix}\operatorname{atan2}(\boldsymbol{R}_{32},\boldsymbol{R}_{33})\\ \operatorname{atan2}\left(-\boldsymbol{R}_{31},\sqrt{\boldsymbol{R}_{32}^2+\boldsymbol{R}_{33}^2}\right)\\ \operatorname{atan2}(\boldsymbol{R}_{21},\boldsymbol{R}_{11})\end{bmatrix} \quad (18),$$

where θ is the azimuth angle, φ is the pitch angle, γ is the roll angle, and $\boldsymbol{R}_{mn}$ is the element in row m and column n of the matrix $\boldsymbol{R}$.

3.2 Point Cloud Fitting Method

When the environment around the antenna is relatively regular, the method of point cloud scanning and fitting can be used to obtain more accurate angle data. Drawing inspiration from Lidar SLAM, a laser tracker is used to scan the lower, side, and front surfaces of the antenna shell to generate a point cloud. By performing plane fitting on the scanned point cloud, the orientation information of the antenna coordinate system can be derived. Since the base station shell can be viewed as a plane, a simple plane fitting method can be used to obtain the orientation information of the antenna shell.

As shown in Fig. 4, when scanning a plane, the measured points will be randomly distributed near the plane due to the noise. The goal of fitting is to find the plane closest to all measured points. The normal vector of the fitting plane can be obtained through the principal component analysis (PCA)[9–10]. Set the measurement data obtained by scanning a certain plane as:

$$\boldsymbol{P}=[\boldsymbol{p}_1 \quad \dots \quad \boldsymbol{p}_n]^{\mathrm{T}}=\begin{bmatrix} x_1 & \dots & x_n\\ y_1 & \dots & y_n\\ z_1 & \dots & z_n\end{bmatrix} \quad (19).$$

Using a plane to fit all measurement points, we get:

$$\boldsymbol{n}^{\mathrm{T}}(\boldsymbol{p}-\boldsymbol{q})=0 \quad (20),$$

$$\boldsymbol{n}=[a \quad b \quad c]^{\mathrm{T}} \quad (21),$$

$$\boldsymbol{p}=[x \quad y \quad z]^{\mathrm{T}} \quad (22),$$

$$\boldsymbol{q}=[x_0 \quad y_0 \quad z_0]^{\mathrm{T}} \quad (23).$$

Plane fitting solves the following optimization problem:

$$\min_{\boldsymbol{n},\boldsymbol{q}}\sum_{i=1}^{n}[\boldsymbol{n}^T(\boldsymbol{p}_i-\boldsymbol{q})]^2, \quad \text{s.t. } \boldsymbol{n}^T\boldsymbol{n}=1 \quad (24).$$

By taking the partial derivative of $\boldsymbol{q}$ and making the derivative 0, the optimal solution for $\boldsymbol{q}$ can be obtained as:

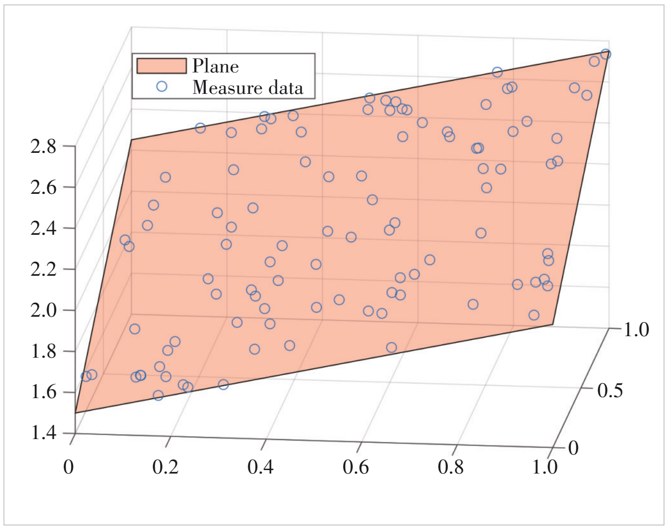


Figure 4. Scanning results of 100 points on the plane

$$\boldsymbol{q}^* = \frac{1}{n}\sum_{i=1}^{n}\boldsymbol{p}_i \tag{25}$$

which is the center of all measured points. Substituting Eq. (26) into Eq. (25) can transform the optimization problem to:

$$\min_{\boldsymbol{n}} \boldsymbol{n}^T\boldsymbol{B}\boldsymbol{n}, \quad \text{s.t. } \boldsymbol{n}^T\boldsymbol{n} = 1 \tag{26}$$

where

$$\boldsymbol{B} = \sum_{i=1}^{n}(\boldsymbol{p}_i - \boldsymbol{q}^*)(\boldsymbol{p}_i - \boldsymbol{q}^*)^T \tag{27}$$

which is the covariance matrix of $\boldsymbol{p}$. And this problem can be solved using PCA. When eigen-decomposition is performed on $\boldsymbol{B}$, the eigenvector corresponding to its minimum eigenvalue is the plane normal vector $\boldsymbol{n}$.

By scanning and fitting the three mutually perpendicular planes of the antenna shell, the normal vectors of the three planes can be obtained. At this time, the orientation information of the antenna coordinate system is also uniquely determined.

The same method is used to obtain orientation information for the WCS. Three mutually perpendicular reference planes are selected in the building whose orientations are known, and the laser tracker is employed to scan these reference planes to generate point cloud data. PCA plane fitting is then performed to derive the orientation information of WCS, and the three Euler angles of the antenna are calculated.

3.3 Error Analysis

Laser trackers can measure the 3D coordinates with noise of any point on an object. The error of the proposed algorithm is theoretically analyzed in the following part. For simplicity, the measurement error of the proposed method will be quantitatively analyzed using a 2D case as an example, and the conclusion is similar in a 3D case.

As shown in Fig. 5, the pitch angle θ is estimated by the coordinates (x_i, y_i) of N measurement points A_i. The Likelihood function of the measured value is

$$\ln P(X|\theta) = \frac{\sum\left[x_i - r_i\cos(\theta + \alpha_i)\right] + \sum\left[y_i - r_i\sin(\theta + \alpha_i)\right]}{2\sigma^2} + C \tag{28}$$

The Cramer-Rao lower bound (CRLB) can be denoted as:

$$\text{CRLB}_\theta = -E\left[\frac{\partial^2 \ln P}{\partial\theta^2}\right] = \frac{\sigma^2}{\sum r_i^2} \geqslant \frac{\sigma^2}{N r_{\max}^2} \tag{29}$$

The angle error is inversely proportional to the sum of the squares of distances between the measurement points and directly proportional to the coordinate measurement error.

To achieve the required angle accuracy of less than 1° for high-precision wireless positioning, if a coordinate system conversion method is used, the point coordinate measurement accuracy must reach at least the millimeter level. The point cloud fitting method improves the accuracy of angle estimation by increasing N, which can greatly reduce the requirement for the accuracy of the instrument itself and is more suitable for scenarios that require higher accuracy.

4 Simulation Results

Assuming the antenna is a rectangular cuboid with dimensions of 0.2×0.2×0.1 m^3, we establish a simulation scenario as shown in Fig. 6 and use Matlab to perform the simulation. The antenna is fixed at a specific location in the 3D scene and has a certain angle. Additionally, the coordinates of the laser tracker are known, and there are several reference points with predefined coordinates in the scene. Gaussian noise is added to simulate the angle and distance measurement errors in the laser tracker.

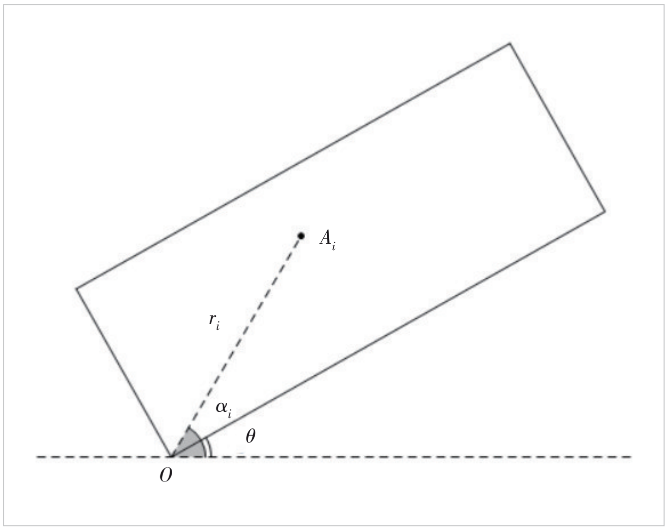


Figure 5. 2D antenna parameter measurement model

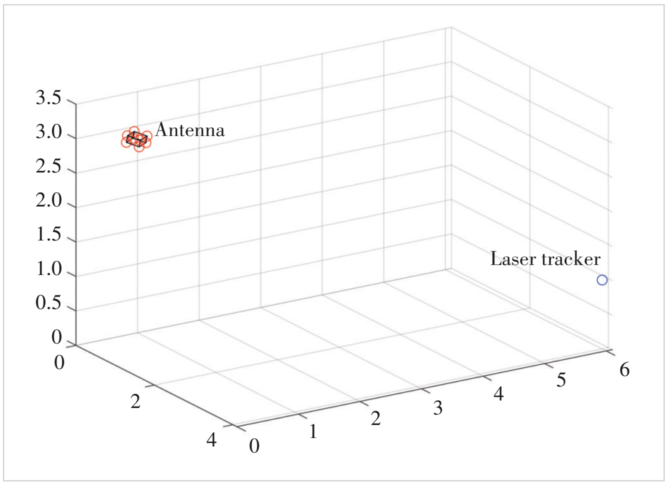


Figure 6. Simulation scene settings

In the simulation, the laser tracker first measures the calibration points of four known indoor coordinates to complete calibration. Then it measures several reference points on the antenna shell, calculates Euler angles of the antenna (i.e., the antenna's attitude), and computes the root-mean-square deviation of the measurements. The simulation results are shown in Figs. 7 and 8.

Fig. 7 shows that in the set scenario, the accuracy of 3D coordinate measurement is less than 1 cm and meets the centimeter level requirement for wireless positioning. Moreover, the error is basically independent of the number of measuring points; since the coordinate measurement error is mainly determined by the instrument calibration phase, increasing measurement points cannot reduce this error.

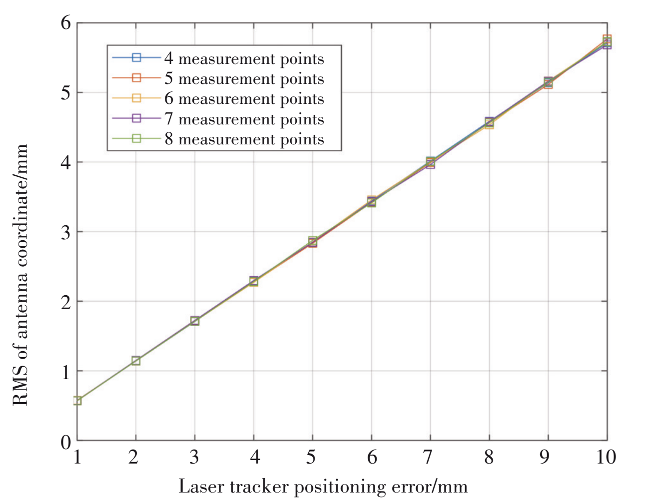
For attitude measurement accuracy, Fig. 8 shows that the more reference points measured on the base station, the smaller the attitude measurement error. This is because the distance between each reference point during the instrument calibration phase is very far, resulting in small angle errors during instrument calibration. The angle error mainly comes from the measurement phase, which is consistent with theoretical analysis. The attitude measurement accuracy using the coordinate system transformation method is relatively low, and it can achieve an accuracy of about 1° when the measuring instrument accuracy is 1 cm. However, it may introduce significant errors in long-distance wireless positioning.

The current laser trackers usually have a point cloud scanning function, which can form a point cloud through scanning measurement of the antenna. So the outer surface of the antenna shell can be restored through plane fitting, and then the attitude of the antenna can be measured. The simulation setup scenario is the same as above. We generate a noisy point cloud between the bottom of the antenna shell and the building wall for fitting, and then measure the posture of the base station relative to the wall. The results are shown in Fig. 9.

Fig. 9 shows that using point cloud fitting methods can greatly improve the measurement accuracy of antenna attitude. When the number of scanning points reaches 1 000, as long as the positioning error is controlled less than 1 cm, the attitude error can be less than 0.25°. Common laser tracker products on the current market can scan hundreds of thousands of points, with scanning accuracy reaching the millimeter level, which is sufficient to meet the accuracy requirement for antenna calibration.

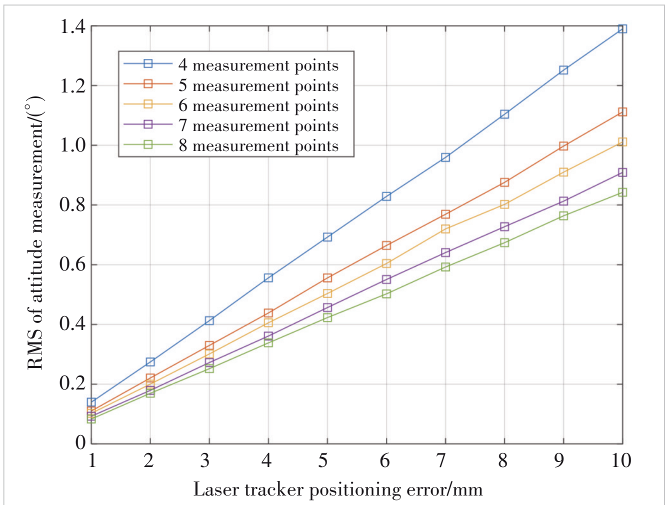
5 Conclusions

In this paper, we summarize the shortcomings of traditional base station antenna calibration methods and introduce several



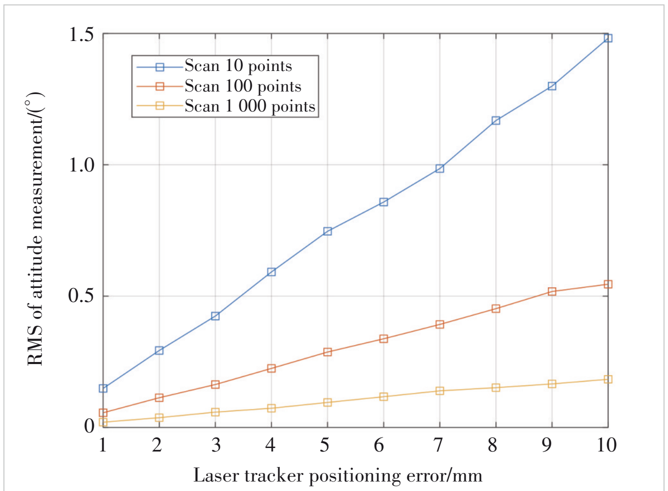
RMS: root-mean-square

Figure 7. RMS error of antenna coordinate measurement



RMS: root-mean-square

Figure 8. RMS error of antenna attitude measurement



RMS: root-mean-square

Figure 9. RMS error of antenna attitude measurement using point cloud fitting method

new methods. We propose an antenna calibration method using a laser measurement strategy. Based on the measurement results of the laser tracker, we use a coordinate system transformation algorithm or a plane fitting algorithm to calculate the 3D coordinates and Euler angles of the antenna. The simulation results show that this method can achieve high measurement accuracy and has certain practicality in engineering.

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Biographies

LI Junqiang works in ZTE Corporation as a standard pre-research algorithm engineer and he is the member of the National Key Laboratory of Mobile Network and Mobile Multimedia Technology. His main research area focuses on the pre-research and implementation of wireless positioning and device positioning algorithms, including indoor positioning networks, Beidou + 5G positioning, integrated sensing, and sensor fusion positioning. He supports prototype development and testing, patent layout, and participates in the formulation of national positioning standards and national key scientific research projects.

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