A Fast High-Precision Measurement Method for Antenna Elevation Axis Deformation Based on Virtual Camera (Postprint)

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Abstract

Rapid and high-precision measurement of small-scale structural deformations in antenna elevation axes caused by wear and torsion is of significant value for correcting the pointing accuracy of large-aperture fully-steerable radio telescope antennas and for active health monitoring of elevation axes. This paper proposes a virtual camera-based method for measuring elevation axis deformation, which constructs a single-camera measurement system for data acquisition, establishes a mathematical model of the measurement system, and utilizes virtual cameras to convert structural deformations into spatial transformations in virtual camera space. Experimental results demonstrate that the method achieves a comprehensive accuracy of 0.2825 mm for translation components and a minimum accuracy of 0.2918° for rotation components, enabling rapid measurement of elevation axis deformations at the 1 mm scale. The system and method offer advantages including non-contact operation, high precision, and rapidity, satisfying the requirements for long-term rapid measurement of elevation axes in large-aperture, high-frequency, high-precision radio telescopes, and are also applicable to measurement of other large-structure, small-deformation scenarios.

Full Text

Research on Rapid and High-Precision Measurement Method for Antenna Pitch Axis Deformation Based on Virtual Camera

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Abstract: The rapid and high-precision measurement of small-scale deformation in antenna pitch axis structures caused by wear and torsion is of significant value for correcting the pointing accuracy of large-aperture fully steerable radio telescope antennas and for active health monitoring of the pitch axis. This paper proposes a virtual camera-based method for measuring pitch axis deformation. By constructing a single-camera measurement system for data acquisition and establishing a mathematical model of the measurement system, structural deformation is converted into virtual camera spatial transformation. Experimental results demonstrate that the method achieves a combined accuracy of 0.2825 mm (RMS) for translational components and 0.2918° for rotational components, enabling rapid measurement of 1 mm-scale deformation of the pitch axis. The system and method offer advantages of non-contact operation, high precision, and rapid measurement, meeting the demands for long-term, rapid, high-accuracy measurement of the pitch axis in large-aperture, high-frequency radio telescopes, and are also applicable to small deformation measurement in other large structures.

Keywords: virtual camera; large-aperture radio telescope; antenna pitch axis; small-scale deformation; target space transformation
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0 Introduction

Long-term operation of radio telescope antenna pitch axes leads to wear and torsional deformation. Although the magnitude of change is small, its impact on high-precision pointing cannot be neglected, becoming more pronounced with increasing antenna aperture, higher observation frequencies, and enhanced comprehensive performance requirements. Research on the positional variation of the pitch axis is therefore crucial for improving telescope pointing accuracy [1][2].

Current research on performance impacts caused by key structural changes in large-aperture, high-precision antennas both domestically and internationally primarily focuses on measurement and compensation of medium- and large-scale deformations. For instance, the American GBT 100-meter telescope [3] installed temperature sensors on the antenna mount and subreflector support legs to measure temperature-induced structural effects. Qian Hongliang, Fan Feng, and colleagues [4,5,6] considered antenna structural shadowing effects, conducted thermodynamic simulations for the 500-meter Aperture Spherical radio Telescope (FAST) and Shanghai Tianma 65-meter radio telescope (TM), and analyzed temperature distribution characteristics of various antenna types.

The Italian SRT 64-meter telescope employed Position Sensing Devices (PSD) to measure subreflector pose, correcting positional deviations caused by self-weight and environmental loads [7,8]. Shanghai TM applied PSD to measure three-dimensional subreflector displacement and analyze pose variations in large radio telescope subreflectors due to various factors [9,10]. Ukita et al. [11] utilized inclinometers, thermocouples, and anemometers to establish empirical formulas correlating azimuth axis errors with temperature gradients, wind-induced overturning moments, and azimuth axis deflection. Xinjiang Nanshan 26-meter telescope measured track elevation differences and analyzed their impact on pointing accuracy [12].

Research on small-scale deformation measurement of critical antenna components remains limited. Igor A. Konyakhin et al. designed an autocollimation-based angular deformation measurement system for the RT-70 Suffa radio telescope pitch axis, achieving a system error of 15 arcminutes at a 22-meter measurement distance and 16 arcminute measurement range [13]. An improved autocollimation system achieved a measurement accuracy of 11 arcseconds (Root Mean Square, RMS) at an 8-meter distance [14]; however, autocollimation methods suffer from complex system structure, high installation requirements, and difficult maintenance.

As a critical antenna structural component, the pitch axis experiences wear and torsion during long-term operation, causing small-scale positional changes that create deviations between the elevation angle acquired by the axis angle encoder and the actual elevation angle, thereby affecting pointing accuracy. Moreover, the evolution of internal organizational properties caused by these minute changes can accelerate pitch axis fatigue at specific stages. Precise measurement of pitch axis deformation provides essential support for antenna pointing accuracy correction, active pitch axis system maintenance, and the formulation and dynamic adjustment of reasonable telescope observation polarization schemes.

This paper designs a single-camera deformation measurement system and proposes a virtual camera-based pitch axis deformation measurement method. By rapidly acquiring images of targets mounted on the pitch axis and analyzing deformation information at target locations, the system achieves high-precision, rapid measurement of small-scale structural deformation in the pitch axis, providing an alternative approach for pointing accuracy correction in large-aperture radio telescopes.

1 Single-Camera Deformation Measurement System

The design methodology of the single-camera deformation measurement system is illustrated in the left panel of Figure 1 [Figure 1: see original paper]. The system rapidly acquires images of targets placed on the pitch axis to analyze deformation information at target locations. Each target corresponds to the deformation condition at a specific pitch angle. Targets 1, 2, and 3 appear individually in the camera’ s field of view at pitch angles of 30°, 60°, and 90°, respectively. As shown in Figure 1, we define rotations following the right-hand rule along the positive X, Y, and Z axes as pitch, yaw, and roll angles, respectively.

The measurement procedure proceeds as follows. First, when the pitch axis is not in operation, a single frame of each of the three targets is acquired as an initial position reference. During normal operation, when the pitch angle reaches one of these designated angles, a single camera mounted at the end of the pitch axis rapidly acquires the corresponding target image. Image sets for the three targets are stored and processed separately. Finally, through image processing algorithms, multiple spatial transformations of the corresponding targets are obtained.

2.1 Virtual Camera

The virtual camera is a method that equivalently transforms real object spatial motion into real camera spatial motion, characterized by the fact that object motion observed in the real camera is identical to that observed in the virtual camera. The advantage of employing a virtual camera is that a fixed camera can monitor small-scale six-degree-of-freedom motion of an object, with a quantitative relationship existing between virtual camera spatial transformation and real object spatial transformation.

This study assumes that the real model consists of initial target A, deformed target B, and real camera O, as shown in Figure 2 Figure 2: see original paper; while the virtual model comprises initial target A, real camera O, and virtual camera P, as shown in Figure 2(b). A right-handed coordinate system is established: O O O_z is the real camera coordinate system and also the world coordinate system; A A A_z is the initial target coordinate system, with its axes parallel to those of the real camera coordinate system; B B B_z is the deformed target coordinate system; and P P P_z is the virtual camera coordinate system.

Assuming the existence of a virtual camera P, when target A on the pitch axis changes to B, the image of target A captured by the virtual camera is identical to the image of target B captured by real camera O, then equation (1) holds, where B_1 and B_2 are corresponding points on target B under different coordinate systems, as shown in Figure 2.

Based on the virtual camera concept and equations (1) and (2), target spatial transformation can be equivalently transformed into virtual camera spatial transformation relative to the real camera.

2.2 Spatial Equivalent Transformation

Due to the existence of the virtual camera, if target A undergoes translational transformation to B, this is equivalent to transformation from real camera O to P, as shown in Figure 3 Figure 3: see original paper. If target A undergoes rotational transformation to B, this is equivalent to transformation from real camera O to Q, as shown in Figure 3(b). A single spatial equivalent transformation is equivalent to the combined iteration of several translational and rotational transformations.

In Figure 3(a), the translational transformation relationship is given by equation (3).

In Figure 3(b), the rotational transformation relationship is given by equation (4).

2.3 Target Space Transformation

Based on Euclidean transformation of coordinate systems, the quantitative relationship of target spatial equivalent transformation can be derived. Let a vector be represented as a in the O O O_z coordinate system and as b in the A A A_z coordinate system. After a spatial transformation, the initial target coordinate system A A A_z (equivalent to the real camera coordinate system O O O_z) undergoes pose transformation, then the relationship in equation (5) holds.

From equation (5), equation (6) can be derived.

where AT is the system intrinsic matrix, related to the relative position between the real fixed camera and the initial target; OBT represents the target spatial transformation; and OPT represents the virtual camera transformation, which is the transformation from O to P. It can be easily concluded that OBT = OPT, thus the target spatial transformation relationship is given by equation (7).

where OAT can be obtained from equation (2).

3.1 Camera Model

An ideal camera can be regarded as a pinhole camera, as shown in Figure 4 [Figure 4: see original paper]. Let X_{cY}*{cZ}c be the camera coordinate system, X*{wY}_{wZ}w be the world coordinate system, and U-V be the image pixel coordinate system. Let point P have coordinates (X_w, Y_w, Z_w) in the world coordinate system and (X_c, Y_c, Z_c) in the camera coordinate system, with the imaging point P_0 having pixel coordinates (u, v). The camera imaging process is expressed by equation (8).

where K is the camera intrinsic parameter matrix and M is the extrinsic parameter matrix.

In the actual camera model, various types of distortion exist, but generally considering radial and tangential distortion is sufficient.

3.2 First Frame Corresponding Virtual Camera Space Transformation

The spatial transformation of the virtual camera corresponding to the first frame is solved using two-dimensional projection [15], as shown in Figure 5 [Figure 5: see original paper]. Let P be a point in three-dimensional space, O_1 and O_2 be the optical centers of the real and virtual cameras, respectively, with spatial transformation R and t. Let p_1 and p_2 be the projections of spatial point P on the two imaging planes I_1 and I_2. Let l_1 and l_2 be epipolar lines, and e_1 and e_2 be epipoles. According to the pinhole camera model, equation (9) is obtained.

where K is the camera intrinsic parameter matrix and s_1, s_2 are feature point depths. If x_1 and x_2 are taken as the normalized plane coordinates of the two pixel points, equation (10) is obtained.

F is the fundamental matrix and E is the essential matrix. Decomposing E or F yields R and t. If multiple pairs of spatial points lie in the same plane, R and t can be obtained through the homography matrix H.

3.3 Remaining Frames Corresponding Virtual Camera Space Transformation

Using triangulation as in equation (11), depth information of spatial points is obtained. From the second frame onward, the relationship between adjacent frames is shown in Figure 6 Figure 6: see original paper, where O_{k-1} and I_{k-1} are the optical center and image of the previous frame' s corresponding virtual camera, O_k and I_k are the optical center and image of the current frame' s corresponding virtual camera, P_3 is a spatial point with projection points p_2 and p_3, and p_1 ‘, p_2’ , and p_3’ are additional projection points.

Based on three-dimensional information of multiple spatial points and the relationship between adjacent frames, the Perspective-3-Points (P3P) method [16] is employed to solve the spatial transformation of the virtual camera corresponding to the remaining frames, as shown in Figure 6(b). Spatial points A, B, and C correspond to image projection points a, b, and c, respectively, with geometric relationships expressed by equation (12).

4 Experiments and Results

This paper constructs an optical test platform to verify the spatial equivalent transformation in the measurement system mathematical model and to analyze experimental errors.

4.1 Optical Test Platform

The optical test system primarily consists of a high-precision spatial stage, fixed-focus lens, camera, and calibration plate, as shown in Figure 7 [Figure 7: see original paper], with parameters listed in Table 1 .

4.2 Results Analysis

In this analysis, spatial transformation data solved from images are taken as measured values, data from the high-precision four-degree-of-freedom stage as true values, and differences between measured and true values as errors, to analyze error conditions in each degree of freedom.

Given the small deformation magnitude, experimental conditions for translational components were: variation ranges of -4 to 5 mm, -2 to 2 mm, and -3 to 3 mm in the X, Y, and Z directions, respectively.

As shown in Figure 8 [Figure 8: see original paper] and Table 2 , for translational components, the maximum error in the X-axis direction is -0.3602 mm with a Root Mean Square Error (RMSE) of 0.1795 mm; the maximum error in the Y-axis direction is 0.3914 mm with an RMSE of 0.1355 mm; and the maximum error in the Z-axis direction is -0.3937 mm with an RMSE of 0.1710 mm.

For rotational components, experimental conditions were: pitch and roll directions set to zero, with yaw direction varying from -5° to 5°.

As shown in Figure 9 [Figure 9: see original paper] and Table 3 , for rotational components, the maximum error in the pitch direction is 0.0745° with an RMSE of 0.0376°; the maximum error in the yaw direction is 0.6138° with an RMSE of 0.2676°; and the maximum error in the roll direction is 0.6131° with an RMSE of 0.2918°.

Conclusion

This paper designs a single-camera pitch axis deformation measurement system, establishes a mathematical model, derives the quantitative relationship between virtual camera spatial transformation and target spatial transformation, and proposes a virtual camera-based pitch axis deformation measurement method. An optical test platform was constructed to verify the method’ s principle and analyze errors in each degree of freedom.

Experimental results demonstrate that: for translational components, the RMSE is 0.1795 mm within -4 to 5 mm in the X direction, 0.1355 mm within -2 to 2 mm in the Y direction, and 0.1710 mm within -3 to 3 mm in the Z direction; for rotational components, the RMSE is 0.2676° within -5° to 5° rotation in the yaw direction, and 0.0376° and 0.2918° at 0° for pitch and roll directions, respectively. Errors primarily arise from factors such as imperfect parallelism between camera coordinate axes and target coordinate axes, as well as image solution methods.

The system and method offer advantages of non-contact operation, high precision, and rapid measurement, satisfying the requirements for long-term, rapid, high-accuracy measurement of the pitch axis in large-aperture, high-frequency radio telescopes, and are also applicable to small deformation measurement in other large structures. The next step involves application to large-aperture radio telescopes.

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