Digital zenith camera accuracy analysis scheme based on digital image processing

Deguo Yang 1a, Li Cui 2* and Congxia Liang 3

1School of Computer Science and Engineering, Northwest Normal University, Lanzhou, Gansu, 730070, China
2School of Computer Science and Engineering, Northwest Normal University, Lanzhou, Gansu, 730070, China
3Gansu Jinchang Sales Office, China National Petroleum Corporation (CNPC), Jinchang, Gansu, 737100, China

*yangdeguo@nwnu.edu.cn  *Li Cui’s e-mail:1635962765@qq.com

Abstract. This article uses a digital zenith camera to perform field measurements to obtain high-precision astronomical longitude and latitude data. To identify the photographed stellar markers, we utilize FFT and digital image processing methods to do CCD star image matching, the establishment of a numerical fit model for star matching, and then the astronomical coordinates of the station against the table decomposition, and finally the use of astronomical geodesy to calculate the vertical deviation of the station and the error in cyclic observation, to test the instrument in the Sensitivity in both directions, astronomical longitude and astronomical latitude.

1. Introduction
Digital zenith camera (DZC) is an important instrument for the analysis and research of vertical deflection, design, and implementation of the experimental scheme in this paper, the use of fast Fourier transform and astronomical geodetic processing to analyze astronomical observation data images, and according to the results of the analysis of digital zenith camera observation accuracy, cyclic observation errors, etc.

The experimental scheme of this paper is as follows: first obtain measurement data, before the instrument accuracy analysis we first process CCD imaging map, through the fast Fourier transform to eliminate and reduce the impact of edge information and noise in the captured image; then the stellar pixels for gray value quantization sorting, to filter out the higher quality of the captured pixels; using numerical fit model comparison stellar star matching table for star matching positioning; then, using the astronomical coordinates of the measuring station are decomposed from the celestial sphere coordinates of the stars in the catalog, and the vertical deviation is calculated according to astronomical geometry; finally, according to the extracted measurement data of the selected stars, we perform textual data analysis to calculate the error value in the cyclic observation, thus analyzing the accuracy of the instrument measurement.
2. Theory Analysis

2.1. Digital zenith camera principle
The astronomical coordinates of point \((\Phi, \Lambda)\) give the direction of the plumb line over point P. According to the principle of astronomy, the relationship between the astronomical coordinates of point P and the equatorial coordinates of the zeniths \((\delta, \alpha)\) as follows [1].

\[
\Phi = \delta_0, \Lambda = \alpha_0 - GAST
\] (1)

Given the geodetic coordinates \((\phi, \lambda)\), the Helmert vertical deflection of point P can be determined as follows [2].

\[
\xi_h = \Phi - \phi, \eta_h = (\Lambda - \lambda) \cos \phi
\] (2)

From the equation \(\Lambda = \alpha - GAST\), when calculating astronomical longitude, the GAST of the observing ephemeris needs to be calculated using the GPS timing function. GPS time is consistent with Coordinated Universal Time (UTC) and can also be expressed using the difference dUT1 between UTC and Earth Rotation Time UT1, as in the following equation.

\[
UT1 = GPST + (19 - n)s + dUT1
\] (3)

\(n\) is the leap second parameter announced by IERS.

UT1 is based on the time of the Earth's rotation, the effect of correcting the Earth's rotation based on UT1 to obtain GMST, and the effect of correcting the chapter motion of the Earth's rotation based on GMST to obtain GAST [3].

\[
\begin{align*}
GMST & = 24110.54841 + 864018.8640184 + 8128668T + 0.0931043T^2 - 6.2s \times 10^{-6} T^3 + \\
& UT1(1.002737909350795 + 5.9006 \times 10^{-11} T - 5.9 \times 10^{-15} T^2)
\end{align*}
\] (4)

In the formula, the number of Julian centuries corresponding to J000.0 when \(T\) is 0 of UT1 is used as the standard period. According to the dichotomous equation, from the GMST calculation GAST.

\[
GAST = GMST + \Delta, \psi \cos \varepsilon + 0.002644 \sin \Omega + 0.000063 \sin 2\Omega
\] (5)

\(\Delta, \psi\) indicates warp motion, \(\varepsilon\) is the yellow-red angle, \(\psi\) is the ascending node longitude.

In practice, GPS is used as a time receiver in practical applications. If the equatorial coordinates are measured again, the direction of the plumb-line is determined by calculating the astronomical coordinates among the equations. The GPS coordinates are then measured and the Helmert vertical deflection is calculated.

2.2. Vertical deflection measurement method
The method of astronomical geodesy in which the station has located a station at an astronomical mega-point so that both geodetic \((\phi, \lambda)\) and astronomical coordinate \((\Phi, \Lambda)\) can be obtained, and the data obtained can be analyzed and calculated to get the perpendicular deviation of the astronomical mega-point, which is also called the Helmert perpendicular deviation. This value is also known as the Helmert perpendicular deviation and is calculated using the following formula.

\[
\begin{align*}
\left(\phi, \lambda\right) & \Rightarrow \left(\xi, \eta\right) = \left\{\begin{array}{l}
\xi = \Phi - \phi \\
\eta = (\Lambda - \lambda) \cos \phi
\end{array}\right.
\end{align*}
\] (6)

The astronomical geodetic method is highly accurate, but because of its large operational volume, it is only suitable for use in a small number of astronomically large locations.

2.3. Fast Fourier transform (FFT)
The fast Fourier transformation (FFT) is a fast algorithm for the Fourier transform, which is mainly used to reduce the computational and storage overhead, and is beneficial for hardware implementation [5]. The FFT algorithm is based on a method called successive doubling, which converts the original Fourier into two recursive formulas by deduction.
\[ F(u) = \frac{1}{2} \left[ F_{\text{even}}(u) + F_{\text{odd}}(u)W_{2u}^{K} \right], \quad F(u + K) = \frac{1}{2} \left[ F_{\text{even}}(u) - F_{\text{odd}}(u)W_{2u}^{K} \right] \]

\[ u = 0, 1, 2, \ldots, M - 1; M = 2K; \quad F_{\text{odd}}(u) \text{ is the Fourier value of } K \text{ points.} \]

3. Data acquisition methods

On a clear night sky, choose a quiet flat place that can accommodate a 30-meter long-baseline in the east-west and north-south directions respectively. Use a compass oriented, in the east-west (longitude direction), north-south (latitude direction) at the intersection of the origin O, every 5 meters were set symmetrically A, B, A', B', C, D and the C', D' point. The GPS receiver is set up at the point B, B' for static observation for 2 periods (more than 1.5 hours), and then at the point D, D' for static observation, the total time for static GPS observation is about 3 hours. The static GPS observations took more than 3 hours in total. The zenith instrument started observing at point O, and observed the astronomical longitude and latitude in sequence O – A – A – B – B – C – C – D – D – O to obtain 10 sets of observations. The selected measurement points are the DDDYD station, the top of Qinling, and the Feng Yu Kou of Qinling (each point is observed for 30min, which takes about 300min in total, i.e. 5 hours). Among them: \( \delta A = \delta A' = 1 m, \delta B = \delta B' = 5 m, \delta C = \delta C' = 2 m, \delta D = \delta D' = 5 m. \)

In CCD imaging, due to the small value of vertical deflection, it is necessary to use GPS to measure the station's geodesic coordinates \((\lambda, \phi)\), and assumed that the geodesic coordinates equal to the initial astronomical coordinates of the station, which helps to determine the stellar field near the zenith of the station, according to the exposure period corresponding to the GAST, we can calculate the approximate equatorial coordinates of the zenith \((\delta_0, \alpha_0)\) [2].

\[ \delta_0 = \phi - \lambda + \text{GAST} \]  

4. Image processing

CCD stellar images taken by a digital zenith camera provide an intuitive understanding of stellar and noise identification through the feature styles of different selections, and the image processing steps in this paper include:

- Subdivision of subgraphs. If several stars fall in the same map at the same time, the same region will be searched repeatedly, and the overlapping parts of the subgraphs will be combined and re-divided.
- Fast Fourier transforms. The use of FT correlation transforms (FFT, IFFT) to eliminate or reduce background noise, improve the signal-to-noise ratio of CCD images, and remove the effect of noise on data results.
- Pixel field inspection. Detecting the neighborhood of each pixel, quantifying and ranking its rate of change in grayscale, with stars divided into basic and reference stars based on their brightness, with basic stars being brighter.
- Pixel correction. For a star point that has been found and confirmed, image correction is performed on the point, which is marked after the location is completed, after which the gray value of the point is set to zero. Reduces efficiency so that the next search of the area does not require repeated analysis and decomposition.
- Star image matching recognition (numerical fit). In the CCD image coordinate system, the equatorial coordinates of the star belonging to the spherical coordinate system, to establish the conversion relationship between the equatorial coordinates and the image plane coordinate system, the equatorial coordinates are projected to the tangent plane coordinates tangent to the zenith and the zenith, the tangent plane requires a close zenith and tangent to it, the zenith is an approximation of the zenith derived from the GPS measurement results.
4.1. Fast Fourier transform (FFT)

Fourier transform the CCD imaging map to obtain its grayscale histogram and the transformed spectral map, analyze the image stellar pixels and noise distribution, and use a reasonable method for noise reduction processing, FT correlation transformation diagram as follows.

By analyzing the CCD grayscale histogram and the FFT spectral map found that the pixels in the image are mainly concentrated in the low-frequency region, and the noise and image edge information distribution is relatively uniform and wide, so image denoising is required. After spectral centering, the brightest point in the middle is the lowest frequency, which belongs to the DC component that is, the smooth part of the image, because the smooth part of the image accounts for a higher proportion of the image, so the energy is high; the further out, the higher the frequency. The use of low-pass filtering, suppressing the high-frequency component of the image, so that the low-frequency component through, you can reduce the impact of noise on the image, and then restore the image through the IFFT, you can get to remove the noise after the star map, the filtering process is as follows.

Low-pass filtering noise reduction, we Fourier transform the CCD image into the frequency domain to get the phase and amplitude values of each pixel of this image. The phase represents the image position shape information, in order to avoid the original image shape cannot be recovered, we do not process the phase. The amplitude value represents the amount of energy, that is, the amount of energy at each frequency, and this paper processes the amplitude value and then performs the IFFT transformation to recover the original distribution, after which we calculate the corresponding value for each pixel in combination with the phase, as shown in the following figure.
4.2. Astral matching recognition

The formula for projection transformation of stellar spherical projection to planar coordinates:

\[ l = \frac{\tan(\alpha - \alpha_0) \cos q}{\cos(q - \delta_0)}, \quad m = \tan(q - \delta_0) \tag{9} \]

\[ \cot q = \cot \delta \cos(\alpha - \alpha_0), \delta_0 = \varphi, \alpha_0 = \lambda + GAST \tag{10} \]

The numerical fit model of the stellar tangent plane and image point CCD image coordinates, the field of view angle of the telescope is about ten degrees, and due to the small vertical deviation, the image processing can be considered roughly parallel between the tangent plane and the CCD image plane. In the tangent plane, the basic star group is connected together, and in the CCD image plane, the basic satellite image group is also connected, and the comparative analysis of the two sets of images facilitates the alignment and identification between stars and images [6].

\[ \xi = \frac{\alpha_{11} + \alpha_{12} x_j + \alpha_{13} y_j}{1 + \alpha_{11} x_j + \alpha_{12} y_j}, \quad \eta = \frac{\alpha_{21} + \alpha_{22} x_j + \alpha_{23} y_j}{1 + \alpha_{21} x_j + \alpha_{22} y_j} \tag{11} \]

Assuming that the coordinate transformation coefficients in Eq. are invariant in single imaging, for the jth star, the constitutive observational equation is:

\[ \frac{\tan(\alpha_j - \alpha_0) \cos q_j}{\cos(q_j - \delta_0)} = \frac{\alpha_{11} + \alpha_{12} x_j + \alpha_{13} y_j}{1 + \alpha_{11} x_j + \alpha_{12} y_j} \tag{12} \]

\[ \tan(q_j - \delta_0) = \frac{\alpha_{21} + \alpha_{22} x_j + \alpha_{23} y_j}{1 + \alpha_{21} x_j + \alpha_{22} y_j}, \quad j = 1, 2, \ldots, n \tag{13} \]

\( n \) is the number of stars observed by the CCD.

\[ \cot q_j = \cot \delta_j \cos(\alpha_j - \alpha_0) \tag{14} \]

After the above series of steps, the measured coordinates of the stars can be obtained, and the geometric relationship between multiple stars can be used as the identification feature, which can be matched with the reference star chart to identify the photographed stars, and the astronomical
coordinates of the station can be solved by using the celestial sphere coordinates of the stars in the catalog to calculate the perpendicular deviation of the station.

5. Data processing results and analysis

After image processing, filter out stellar pixels and determine the stellar data needed for the experiment, this paper selects the station name DDYD, station number C003 of a set of data for the data processing in this paper. The first analysis of the inclinometer state parameter table, this set of data through the instrument to adjust and measure its internal state parameters, the table below is a zenith camera rotational axis of the calculation results, (part of the data in the table for the masking process).

| Table 1. Calculation results for the rotation axis of the dome camera |
|---------------------------------|---------------------------------|----------------|----------------|----------------|
| longitude | latitude | CCDX | CCDY | azimuth |
| Group1 | **9500479** | **5610781** | -36.693 | 64.152 | 3.89255 |
| Group2 | **9495522** | **5609412** | -35.563 | 63.031 | 4.67753 |
| Group3 | **9499266** | **5610549** | -33.621 | 64.350 | 5.46274 |
| Group4 | **9500955** | **5608964** | -33.975 | 65.517 | 6.24817 |
| Group5 | **9492645** | **5604034** | -34.589 | 66.288 | 3.10703 |
| Group6 | **9490678** | **5608438** | -34.681 | 65.957 | 0.75072 |
| Group7 | **9492499** | **5605915** | -36.984 | 65.378 | 1.53610 |
| Group8 | **9488011** | **5606214** | -36.200 | 64.633 | 2.32165 |

The instrument indicates that the angle directly in the form of a decimal point, analysis and processing has many inconveniences, the introduction of data into the angle format of the formula: = TEXT (MOD (A1/24, 7.5), "[h] °m’s") , after conversion of angle data can be more clearly and intuitively reflected, the following table.

| Table 2. Converted angular data |
|---------------------------------|---------------------------------|----------------|
| CCDX | CCDY | azimuth |
| 143°18′25" | 64°9′7" | 3°53′33" |
| 144°26′13" | 63°1′52" | 4°40′30" |
| 146°22′44" | 64°21′0" | 5°27′46" |
| 146°1′30" | 65°31′1" | 6°14′53" |
| 145°24′40" | 66°17′17" | 3°6′25" |
| 145°19′8" | 65°57′25" | 0°45′3" |
| 143°0′58" | 65°22′11" | 1°32′10" |
| 143°48′0" | 64°37′59" | 2°19′18" |
| 145°24′40" | 66°17′17" | 3°6′25" |

In calculations, where the resulting data is needed to represent an angle, the angle format can be used, which is more clear and intuitive, and the following is a set of inclinometer sensitive axis readings.

| Table 3. Inclinometer sensitive axis readings |
|---------------------------------|---------------------------------|----------------|----------------|
| X1 | Y1 | X2 | Y2 |
| Group1 | 81.918 | 72.853 | -91.908 | -70.062 |
| Group1 | 104.743 | -17.121 | -116.437 | 10.161 |
| Group1 | 58.26 | -92.802 | -83.254 | 87.571 |
| Group1 | -24.691 | -63.99 | -1.831 | 75.447 |
| Group1 | -1.12 | 115.028 | -23.984 | -106.8 |
| Group1 | -91.091 | 91.888 | 80.56 | -85.045 |
| Group1 | -114.591 | 15.911 | 102.382 | -10.699 |
| Group1 | -80.707 | -113.604 | 57.057 | 114.981 |
According to the data in the table, we can calculate the average of the results of the measurement of the state parameters of the cycle: directional angle of 325.147°, shear angle of 90.5229°, X scale coefficient of 1.01786, Y scale coefficient of 0.99842. We will calculate the positioning results of the three cycles of the calculation point with a graph, because of the high accuracy of the data, in order to make the icon fluctuations more obvious, the data from the decimal point. The third digit begins recording. Such as data 0.9216232, in the entire set of data in all the data of the third decimal point are 0.921, so that when plotted almost into a straight line, so the data of the group of charts in the plotting of the data collected from the third decimal point after the beginning of the calculation for the effective value. On the one hand, this can make the chart contrast obvious, on the other hand, so that the confidentiality of the data to be protected.

A comparative analysis of the three-cycle longitude and latitude variation line diagrams for eight points in Figure 7 and 8 reveals that the diagrams do not reflect significant coarse differences, indicating that the measurements are highly accurate. The undulating profile of the lines in the figure also indicates that the difference in the transformation of the longitude and latitude of each cycle is small. By analyzing the round-trip observation medians for latitude and longitude in Figure 9 and 10, it can be seen that the fold transformation magnitude is small and the observation medians for each cycle are more similar. After analyzing and calculating the data from the three cycles, the median observation error for each cycle and the average of the results of each cycle is shown in the table 4 (the confidential part of the data is masked).

| Table 4. Median observation error for each cycle |
|-----------------------------------------------|
| Longitude value (medium error) | Latitude value (medium error) |
|--------------------------------|--------------------------------|
| First cycle **.9216024°(0.047")** | **.5394038°(0.159")** |
| Second cycle **.9216333°(0.052")** | **.5394033°(0.199")** |
| Third cycle **.9216018°(0.083")** | **.5394248°(0.113")** |
| Average of the results of each cycle of observation positioning: |                              |
| Longitude value (medium error) | Latitude value (medium error) |
|--------------------------------|--------------------------------|
| **.9216125°(0.037")** | **.5394110°(0.025")** |
The astronomical longitude and latitude values (H=0.4km) attributed to the geoid: longitude** 55°17.805"", latitude** 32°21.879".

6. Conclusion

By calculating and analyzing the data obtained from instrument field measurements, it can be concluded that we use the Digital Zenith Camera Positioning System (D1017T01) model to perform a first-class astronomical survey on the known astronomical fundamental point C003 named DDYD, and compared the accuracy with its known astronomical point found that the latitude and longitude measurement error (RSM) are within the range of 0.2", indicating that the instrument's measurement accuracy is qualified, and the accuracy index of the digital zenith camera is up to standard. The statistics of the instrument's measurements at point C003 are shown in table 5

| Cycle | Instrument number: D1017T01 |
|-------|-----------------------------|
|       | astronomical longitude      | astronomical latitude |
|       | Alignment position results   | Median and internal accuracy |
|       | Alignment position results   | Median and internal accuracy |
| 1     | **.9216138                  | **.5394650              |
|       | ** 55 17.769                | ** 32 21.854            |
| 2     | **.9216118                  | **.5394760              |
| 3     | **.9215633                  | **.5393891              |
| 4     | **.9216206                  | **.5392850              |
| 1     | **.9216428                  | **.5394439              |
| 2     | **.9216055                  | **.5395099              |
| 3     | **.9216148                  | **.5394132              |
| 4     | **.9216700                  | **.5392799              |
| 1     | **.9216158                  | **.5394794              |
| 2     | **.9216395                  | **.5394673              |
| 3     | **.9215342                  | **.5394106              |
| 4     | **.9216176                  | **.5393419              |
| A mean and within-consistency error of observations for each cycle | ** 55 17.805         |
| Astronomical coordinates of survey sites known | ** 32 21.879         |
| Error result in one cycle of observations (RSM) | 0.078 0.088 |

The maximum value of the difference between the observed and known values

\[ m = \sqrt{\frac{\sum_{i=1}^{n} (x_i - x)^2}{n}} \]  

- \( x_i \) -- The results of the positioning of each cycle.
- \( x \) -- Known values at the survey site (astronomical latitude and longitude).
- \( n \) -- The total number of cycles of positioning measurement observations.

UCAC [7] and Tycho-2[8] provide more than two million stars with high catalog accuracy, high density, and outer character accuracy of 0.02"-0.1". In this experiment, the medium errors (RSM) of the one-cycle observation of astronomical longitude and latitude are 0.078" and 0.088" respectively, and the inner conforming medium errors of each cycle observation of astronomical longitude and
latitude are 0.025″ and 0.037″ respectively, and the maximum value of the difference between each cycle observation value and the known value is 0.132″. The measurement results show that the RSM of latitude and longitude is within 0.2″, which meets the requirement of accuracy and limit, therefore the positioning measurement accuracy of the instrument is judged to be qualified.

References

[1] Van der Geer, J., Hanraads, J.A.J., Lupton, R.A. (2010) The art of writing a scientific article. J. Sci. Commun., 16 HirtTC, Bürki B. Status of Geodetic Astronomy at the Beginning of the 21st Century[ R]. Wiss Arb Fach Geodäsie und Geoinformatik der Univ, Hannover, 2006

[2] Peter Clarke. GPS Satellite Surveying[J]. The Photogrammetric Record, 2007, 22(118).

[3] C. Jekeli. An analysis of vertical deflections derived from high-degree spherical harmonic models[J]. Journal of Geodesy, 1999, 73(1).

[4] Ansis Zariņš, Augusts Rubans, Gunārs Silabriedis. Digital zenith camera of the University of Latvia[J]. Geodesy and Cartography, 2016, 42(4).

[5] Glenn D. Bergland. Numerical Analysis: A fast fourier transform algorithm for real-valued series[J]. Communications of the ACM, 1968, 11(10).

[6] Yang S, Zhou Z, Liu X. Research on Data Fitting Model Based on Positioning of Digital Zenith Camera[C]// 2018 International Symposium on Communication Engineering & Computer Science (CECS 2018). 2018.

[7] Zacharias N, Urban S E, Zacharias M I , et al. The second US Naval Observatory CCD Astrograph Catalog (UCAC2)[J]. The Astronomical Journal, 2007, 120(4):2131.

[8] E. Hog, C. Fabricius, V. V. Makarov, etc. The Tycho-2 Catalogue (Hog+ 2000)[J]. Astronomical Journal, 2000, 1259(1):501-505.