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Precise alignment method of time-delayed integration charge-coupled device charge shifting direction in aerial panoramic camera

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Abstract. A time-delayed integration charge-coupled device (TDI CCD) in an aerial panoramic camera compensates the sweep image motion correctly on the premise that the TDI charge shifting direction is coincident with that of the sweep image motion. The coordinate transformation method is used to find out how the included angle between the two directions originated. Then the precise alignment method of the TDI charge shifting direction is proposed to eliminate the included angle. TDI CCD is operated in area mode, nodding the scan mirror, the trajectory of the image point is derived to be a hyperbola, which could be equivalent to an obliquely straight line. The tilt angle of the line is exactly the included angle between the two directions. Meanwhile, the tilt angle can be calculated by the least square method. Then the scan head or the focal plane assembly is precisely rotated to eliminate the included angle between the two directions. The assembling error after precise alignment is calculated at −16.4 s, which could hardly influence the MTF of TDI CCD. The panoramic imaging experiment and the flight test show that the precise alignment method is feasible and completely satisfies the operating requirement of the aerial panoramic camera. [DOI: 10.1117/1.OE.55.12.125101]

Keywords: aerial panoramic camera; time-delayed integration charge-coupled devices; coordinates transformation; image motion; precise alignment.

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1 Introduction

An aerial panoramic camera is used in a significant optical remote sensing system to acquire and process ground information. It is widely used in resource exploration, topographical surveys, and military reconnaissance, covering a larger ground area and having a simpler mechanical device.[1–3] Generally, the image sensor of aerial panoramic camera is the time-delayed integration charge-coupled devices (TDI CCD) to acquire high-quality, low noise, and high-contrast image even in low-illumination conditions.[4–6] The camera moves forward together with the aircraft and sweeps perpendicularly to flight track. Image motion generated is attributed to the forward translation movement and the mechanical sweep of the camera. The sweep image motion is compensated by a TDI CCD, which moves the charge row by row in the same direction and the same velocity as the sweep image motion.[6–8] Either magnitude mismatching or angle mismatching would severely affect the imaging quality.[9–11]

In order to synchronize the charge transport and the sweep image motion, several methods are proposed to generate the TDI CCD line transfer synchronization signal.[12–14] These methods can compensate the sweep image motion correctly on the premise that the TDI charge shifting and the image motion are in the same direction. However, in the assembly procedure of an aerial panoramic camera, assembling error is inevitable for a TDI CCD, which leads to an included angle between the directions of the TDI charge shifting and the sweep image motion. It is a problem to realize the precise alignment of the TDI charge shifting direction to reduce and even minimize the assembling error in the assembly procedure.

2 Direction of Sweep Image Motion for Aerial Panoramic Camera

2.1 *Mechanical Principles of Aerial Panoramic Camera*

An aerial panoramic camera mainly contains a scan head, lens assembly, focus mirror assembly, focal plane assembly, and camera housing as shown in Fig. 1. The major component of the scan head is the scan mirror, which is used to compensate for forward image motion. The focal plane assembly contains two groups of TDI CCDs, which are optically butted by a beam-splitter prism. The aerial panoramic camera sweeps perpendicular to the flight direction and obtains the ground scene by rotation of the camera housing around the primary optical axis.[15,16]

In the assembling procedure, every assembly is precisely assembled and aligned, then they are fitted together by the screws. Next, the focal plane assembly is adjusted to make the TDI CCD be coplane with the image plane of the lens. However, the positions of the focal plane assembly and the scan head are not confirmed and they can rotate in small angles around the primary optical axis. That leads to the angle mismatching between the directions of the TDI charge shifting and the sweep image motion. Consequently, precise alignment of the focal plane assembly (TDI CCD) and the scan head is required to ensure the uniformity in both

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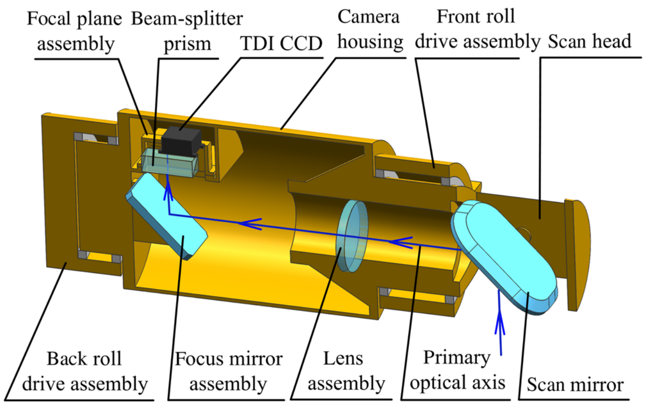

Fig. 1 Structural diagram of aerial panoramic camera.

directions. This is an important step in the assembling procedure of an aerial panoramic camera.

2.2 *Calculation of the Sweep Image Motion Direction*

The coordinate transformation method is used in this section to calculate the sweep image motion, which can relate the object in a ground coordinate system to the image in a focal plane coordinate system.[17,18]

In order to calculate the direction of the sweep image motion for an aerial panoramic camera, the forward movement of the camera is not considered here. The two groups of TDI CCDs, optically butted by the beam-splitter prism, are treated as a whole.

In an ideal assembling status, the relative positions of the scan mirror, lens, focus mirror, and the focal plane are given as shown in Fig. 2. Five important right-handed Cartesian coordinate systems are built along the light ray travel direction. The corresponding axes of these coordinate systems are parallel to each other and their directions are just as shown. The ground coordinate system is O_0-$x_0y_0z_0$, and its z-axis is vertical. The scan mirror coordinate system and the focus mirror coordinate system are, respectively, O_1-$x_1y_1z_1$ and O_3-$x_3y_3z_3$, and their x-axes are both parallel to the primary optical axis. The lens coordinate system is O_2-$x_2y_2z_2$, and its origin is the rear nodal point of the lens. The focal plane coordinate system is O_4-x_4y_4, which is a two-dimensional

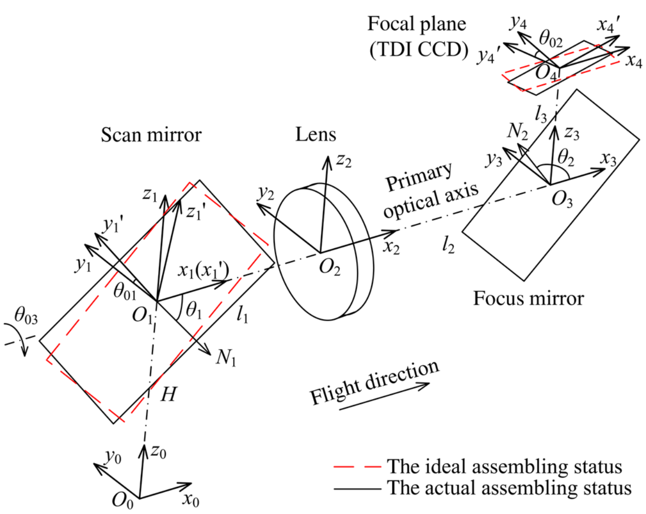

Fig. 2 Schematic diagram of aerial panoramic camera.

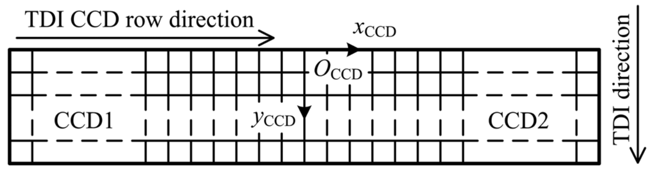

Fig. 3 Fixed coordinate system of TDI CCD.

plane coordinate system. A new plane coordinate system O_{CCD}-$x_{\mathrm{CCD}}y_{\mathrm{CCD}}$ is established on the TDI CCD in pixels, as shown in Fig. 3. The origin is located at the center of the TDI CCD and the x-axis is parallel to the row direction of the TDI CCD, while the y-axis is along the direction of the TDI charge shifting. H, l_1, l_2, and l_3 are, respectively, the distances between the five coordinate systems along the primary optical axis. The unit normal vectors of the scanning mirror and the focus mirror are $\mathbf{N}_1$ and $\mathbf{N}_2$, respectively, and their included angles from the positive x-axis are, respectively, θ_1 and θ_2. Then $\mathbf{N}_1$ and $\mathbf{N}_2$ can be written as

$$N_1 = [\cos\theta_1 \quad 0 \quad -\sin\theta_1]^{\mathrm{T}}, \tag{1}$$

$$N_2 = [\cos\theta_2 \quad 0 \quad \sin\theta_2]^{\mathrm{T}}. \tag{2}$$

These two angles are initialized to be $\theta_1 = 45$ deg and $\theta_2 = 135$ deg.

However, in the actual assembling procedure of the camera, the relative positions of the scan mirror and the focal plane cannot be as perfect as that of an ideal assembling status. The scan head can rotate by a small angle (within ± 1 deg) around the x-axis of O_1-$x_1y_1z_1$, and the focal plane assembly can rotate a small angle (within ± 0.5 deg) around the z-axis of O_3-$x_3y_3z_3$, as shown in Fig. 2. Therefore, the new coordinate systems O_1-$x_1'y_1'z_1'$ and O_4-$x_4'y_4'$ are built by rotating the scan head and the focal plane assembly, and the rotation angles are θ_{01} and θ_{02}, respectively (right-handed screw). The values of θ_{01} and θ_{02} are defined as positive in Fig. 2. At present, the TDI charge shifting direction is along the positive y-axis of O_4-$x_4'y_4'$.

The camera sweeps around the primary optical axis to image the ground scene. In other words, the ground coordinate system is fixed, whereas the other coordinate systems rotate all together at an angle (named sweep angle, right-handed screw) from the positions in Fig. 2 around the primary optical axis. Suppose the sweep angle of the camera is θ_{03}.

Then at the actual assembling procedure, the imaging mathematical model of the camera is established based on the imaging matrices of the plane mirror and the lens. In consideration of the sweep angle θ_{03}, if the object point in the ground coordinate system is $A(x_0, y_0, 0)$, the coordinates of the image point A' in O_4-$x_4'y_4'$ can be calculated as

$$\begin{bmatrix} x_{4a}' \\ y_{4a}' \\ 0 \end{bmatrix} = \mathbf{M}_3\mathbf{R}_2\mathbf{T}_c\mathbf{M}_2^{-1}\mathbf{R}_1\mathbf{M}_2\mathbf{M}_1 \begin{bmatrix} x_0 \\ y_0 \\ -H \end{bmatrix} - \mathbf{M}_3\mathbf{R}_2\mathbf{T}_c \begin{bmatrix} l_1 \\ 0 \\ 0 \end{bmatrix} - \mathbf{M}_3\mathbf{R}_2 \begin{bmatrix} l_2 \\ 0 \\ 0 \end{bmatrix} - \mathbf{M}_3 \begin{bmatrix} 0 \\ 0 \\ l_3 \end{bmatrix}, \tag{3}$$

where $\mathbf{R}_i = \mathbf{E} - 2\mathbf{N}_i\mathbf{N}_i^T$ $(i = 1, 2)$, $\mathbf{R}_i$ is the imaging matrix of the plane mirror,[19] and $\mathbf{E}$ is the unit matrix

$$T_c = \frac{f'}{f' - x_0 \cos 2\theta_1 - H' \sin 2\theta_1 - l_1} E,$$

$\mathbf{T}_c$ is the imaging matrix of the lens,[20] and f' is the image-space focal length of the lens

$$H' = H \cos(\theta_{01} + \theta_{03}) + y_0 \sin(\theta_{01} + \theta_{03}),$$

$$M_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{03} & \sin\theta_{03} \\ 0 & -\sin\theta_{03} & \cos\theta_{03} \end{bmatrix},$$

$$M_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{01} & \sin\theta_{01} \\ 0 & -\sin\theta_{01} & \cos\theta_{01} \end{bmatrix},$$

$$M_3 = \begin{bmatrix} \cos\theta_{02} & \sin\theta_{02} & 0 \\ -\sin\theta_{02} & \cos\theta_{02} & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Substituting $\theta_1 = 45$ deg and $\theta_2 = 135$ deg, then

$$\begin{bmatrix} x'_{4a} \\ y'_{4a} \\ 0 \end{bmatrix} = \frac{f'}{f' - H' - l_1} \times \begin{bmatrix} x_0 \cos(\theta_{01}+\theta_{02}) + B \sin(\theta_{01}+\theta_{02}) \\ x_0 \sin(\theta_{01}+\theta_{02}) + B \cos(\theta_{01}+\theta_{02}) \\ 0 \end{bmatrix}, \tag{4}$$

where $B = y_0 \cos(\theta_{01} + \theta_{03}) - H \sin(\theta_{01} + \theta_{03})$.

When the object point $A(0,0,0)$ in the ground coordinate system is substituted into Eq. (4), one obtains

$$\begin{cases} \Delta x'_{4a} = x'_{4a}|_{\theta_{03}>0} - x''_{4a}|_{\theta_{03}=0} = C \sin(\theta_{01}+\theta_{02}) \\ \Delta y'_{4a} = y'_{4a}|_{\theta_{03}>0} - y''_{4a}|_{\theta_{03}=0} = C \cos(\theta_{01}+\theta_{02}) \end{cases}, \tag{5}$$

where

$$C = -\frac{f' H \sin(\theta_{01}+\theta_{03})}{f' - H\cos(\theta_{01}+\theta_{03}) - l_1} + \frac{f' H \sin\theta_{01}}{f' - H\cos\theta_{01} - l_1} (\theta_{03} > 0).$$

The result shows that there is an included angle $\theta_{01} + \theta_{02}$ between the positive y-axis of O_4-$x'_4y'_4$ (the direction of the TDI charge shifting) and the sweep image motion direction, and the included angle is called θ, $\theta = \theta_{01} + \theta_{02}$. If and only if $\theta = 0$ deg, the two directions will be the same, and this is the principle for precise alignment of the direction of the TDI charge shifting.

For an ideal assembling status $\theta_{01} = \theta_{02} = 0$ deg, the directions of the sweep image motion and the TDI charge shifting are the same. However, at the actual assembling status, θ is usually unequal to zero. Although the measurement of θ_{01} and θ_{02} is almost impossible according to their definitions in a practical assembling process, the sum of θ_{01} and θ_{02}, i.e., θ represents the relative positions between the scan head and TDI CCD. Thus, it has become an urgent problem of how to accurately measure and eliminate the included angle θ.

3 Precise Alignment Method of TDI Charge Shifting Direction

The area mode of the TDI CCD is especially developed for assembly, and in the area mode, an aerial panoramic camera can image the object when the camera housing is static. When nodding the scan mirror, θ_1 is changing and the image point will move on the TDI CCD. By analyzing the trajectory of the image point, the precise alignment method of the TDI charge shifting direction is obtained.

3.1 *Trajectory of the Image Point Varying with* θ_1

The TDI CCD is operated in the area mode, and the object point $A(x_0, y_0, 0)$ can image on the TDI CCD without rotation of the camera housing. θ_{03} is set to be zero. $\theta_2 = 135$ deg and $\theta_{03} = 0$ deg are substituted into Eq. (3), and the coordinates of the image point A' are obtained as

$$\begin{bmatrix} x'_{4a} \\ y'_{4a} \\ 0 \end{bmatrix} = \frac{f'}{f' - x_0 \cos 2\theta_1 - H_1 \sin 2\theta_1 - l_1} M_4 \times \begin{bmatrix} x_0 \sin 2\theta_1 - H_1 \cos 2\theta_1 \\ y_1 \\ 0 \end{bmatrix}, \tag{6}$$

where

$$M_4 = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$H_1 = H \cos\theta_{01} + y_0 \sin\theta_{01},$$

$$y_1 = y_0 \cos\theta_{01} - H \sin\theta_{01}.$$

At an ideal assembling status, the coordinates of the image point are denoted by (x_{4i}, y_{4i}). Substituting with $\theta_{01} = \theta_{02} = 0$ deg into Eq. (6), one obtains

$$\begin{bmatrix} x_{4i} \\ y_{4i} \\ 0 \end{bmatrix} = \frac{f'}{f' - x_0 \cos 2\theta_1 - H \sin 2\theta_1 - l_1} \times \begin{bmatrix} x_0 \sin 2\theta_1 - H \cos 2\theta_1 \\ y_0 \\ 0 \end{bmatrix}. \tag{7}$$

A coordinate transformation, multiplied leftward by the matrix M_4^{-1}, is introduced into Eq. (6). Then a new coordinate system O_4-$x''_4y''_4$ is built by rotating O_4-$x'_4y'_4$ through an angle θ around the negative z-axis of O_3-$x_3y_3z_3$ (right handed screw). The coordinates of the image point A' in O_4-$x_4''y_4''$ can be written as

$$\begin{bmatrix} x''_{4a} \\ y''_{4a} \\ 0 \end{bmatrix} = \frac{f'}{f' - x_0 \cos 2\theta_1 - H_1 \sin 2\theta_1 - l_1} \times \begin{bmatrix} x_0 \sin 2\theta_1 - H_1 \cos 2\theta_1 \\ y_1 \\ 0 \end{bmatrix}. \tag{8}$$

The coordinates of the image point vary with θ_1. Eliminating the variable θ_1 in Eq. (7) and Eq. (8), the trajectories of the image point are obtained as

$$\frac{\left[y_{4\mathrm{i}} + \frac{f' y_0 (f'-l_1)}{H^2 + x_0^2 - (f'-l_1)^2}\right]^2}{\frac{f'^2 y_0^2 (H^2+x_0^2)}{[H^2+x_0^2-(f'-l_1)^2]^2}} - \frac{(x_{4\mathrm{i}})^2}{\frac{f'^2 (H^2+x_0^2)}{H^2+x_0^2-(f'-l_1)^2}} = 1, \tag{9}$$

$$\frac{\left[y''_{4\mathrm{a}} + \frac{f' y_1 (f'-l_1)}{H_1^2 + x_0^2 - (f'-l_1)^2}\right]^2}{\frac{f'^2 y_1^2 (H_1^2+x_0^2)}{[H_1^2+x_0^2-(f'-l_1)^2]^2}} - \frac{(x''_{4\mathrm{a}})^2}{\frac{f'^2 (H_1^2+x_0^2)}{H_1^2+x_0^2-(f'-l_1)^2}} = 1. \tag{10}$$

It can be concluded from Eq. (9) that the trajectory of the image point A' varying with θ_1 is a hyperbola in the focal plane coordinate system O_4-x_4y_4. The symmetry axis is the y-axis of O_4-x_4y_4.

Similarly, the trajectory for the image point A' in O_4-$x''_4y''_4$ is also a hyperbola for Eq. (10) [i.e., Eq. (8)], and the symmetry axis of the hyperbola is the y-axis of O_4-$x''_4y''_4$. According to the principle of coordinate transformation, the trajectory of the image point A' for Eq. (6) in the coordinate system O_4-$x'_4y'_4$ is also a hyperbola whose symmetry axis is still the axis O_4-y''_4, as shown in Fig. 4.

3.2 *Analysis of the Trajectory of the Image Point*

As mentioned before, Eqs. (7) and (6) are the coordinates of the image point, respectively, of the ideal assembling status and the actual assembling status (Fig. 2) for the aerial panoramic camera, and the trajectories are both hyperbolas. However, it is more convenient to process if the trajectory of the image point could be simplified as a straight line. So, the trajectory within the photosensitive area of the TDI CCD is analyzed.

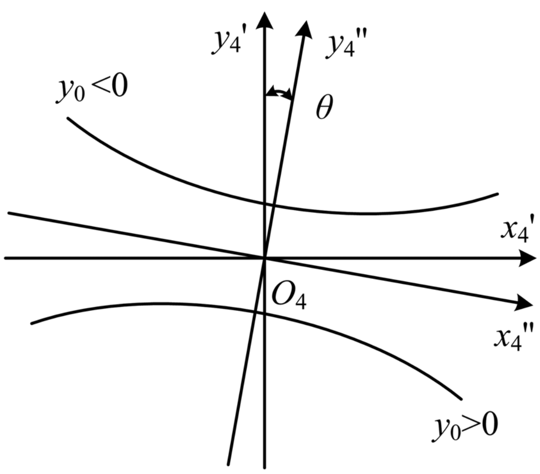

Fig. 4 Trajectory of the image point corresponding to Eq. (6).

For the camera, the total effective length of the optically butted TDI CCDs is $2a$. The pixel sizes are $b \times b$, and there are M stages of the TDI. In the area mode, when the scan mirror nods around the position for $\theta_1 = 45$ deg, the image point can reciprocate within the photosensitive area of the TDI CCD. According to Eq. (7), if the image point can appear within the photosensitive area of the TDI CCD, the coordinates of the image point should satisfy

$$-a \leqslant x_{4i} \leqslant a, \quad 0 \leqslant y_{4i} \leqslant Mb.$$

Substituting with $\theta_1 = 45$ deg and the above inequations into Eq. (7), one obtains

$$|x_0| \le \frac{a(H + l_1 - f')}{f'}, \tag{11}$$

$$-\frac{Mb(H + l_1 - f')}{f'} \le y_0 \le 0. \tag{12}$$

The hyperbola could be equivalent to a straight line if the image point moves within one row of the TDI CCD when the scan mirror nods. In other words, the difference Δ between the maximum value and the minimum value of the hyperbola should be less than or equal to nb, when $x_{4i} \in [-a, a]$, as shown in Fig. 5, and

$$|y_{4i}(0) - y_{4i}(\pm a)| \le nb \qquad (0 < n \le 1). \tag{13}$$

Considering $H^2 + x_0^2 \gg (f' - l_1)^2$, one obtains

$$-\frac{f' y_0 \sqrt{H^2 + x_0^2}}{H^2 + x_0^2 - (f' - l_1)^2} \left[\sqrt{1 + \left(\frac{a}{f'}\right)^2} - 1\right] \le nb. \tag{14}$$

Define the function

$$f(H, x_0, y_0) = -\frac{f' y_0 \sqrt{H^2 + x_0^2}}{H^2 + x_0^2 - (f' - l_1)^2} \left[\sqrt{1 + \left(\frac{a}{f'}\right)^2} - 1\right].$$

The function is an even function about x_0 and opens downward; it decreases with the rising of y_0. According to Eqs. (11) and (12), substituting with $x_0 = 0$ and $y_0 = -\frac{Mb(H+l_1-f')}{f'}$ into Eq. (14), one arrives at

$$\frac{MH(H + l_1 - f')}{H^2 - (f' - l_1)^2} \left[\sqrt{1 + \left(\frac{a}{f'}\right)^2} - 1\right] \le n. \tag{15}$$

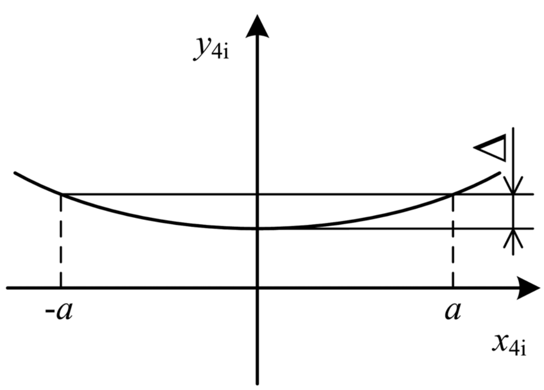

Fig. 5 The trajectory of image point on TDI CCD.

Expanding

$$\begin{cases} \left\{n - M\left[\sqrt{1+\left(\frac{a}{f'}\right)^2}-1\right]\right\}H^2 + M\left[\sqrt{1+\left(\frac{a}{f'}\right)^2}-1\right](f'-l_1)H - n(f'-l_1)^2 \geq 0 \\ n - M\left[\sqrt{1+\left(\frac{a}{f'}\right)^2}-1\right] \geq 0 \end{cases}. \tag{16}$$

Substituting with $M = 200$, $a = 0.06$ m, $f' = 1.5$ m, $b = 8 \times 10^{-6}$ m, and $l_1 = 0.6$ m, one obtains

$$H > 0.9 \text{ m} \quad \text{and} \quad 0.16 \leq n \leq 1. \tag{17}$$

It is concluded that the image point can move within a $0.16b$ wide horizontal strip on the TDI CCD with the angle θ_1 changing, as long as H is >0.9 m. The practical flight altitude of the aerial panoramic camera is considerably larger than 0.9 m. Hence, the hyperbola can be simplified to be a straight line, as shown in Fig. 6(a). As mentioned before, $|\theta_{01}| \leq 1$ deg, so Eq. (10) is approximately the same as Eq. (9). The hyperbola for Eq. (10) could also be equivalent to a straight line [see Fig. 6(a)]. According to the coordinate transformation principle, the trajectory of the image point A' for Eq. (6) can be equivalent to an oblique line, and the included angle between the oblique line and the x-axis of O_{CCD}-$x_{CCD}y_{CCD}$ is $\theta(\theta = \theta_{01} + \theta_{02})$, as shown in Figs. 6(b) or 6(c).

In conclusion, for an aerial panoramic camera at the actual assembling status, there is an included angle θ between the directions of the TDI charge shifting and the sweep image motion. Thus, the TDI CCD is operated in the area mode, nodding the scan mirror, and the trajectory of the image point on the TDI CCD could be equivalent to an oblique line; the included angle between the oblique line and the x-axis of O_{CCD}-$x_{CCD}y_{CCD}$ is exactly θ. Thus, the value of θ can be calculated by the least square method, and the sign is determined according to Figs. 6(b) and 6(c). After precisely rotating the scan head or the focal plane assembly (TDI CCD) by the angle θ, the oblique line turns out to be parallel to the x-axis of O_{CCD}-$x_{CCD}y_{CCD}$, i.e., $\theta = 0$. Then the TDI charge shifting direction is the same as the sweep image motion direction.

4 Implementation of Precise Alignment for TDI CCD Charge Shifting Direction

Based on the method proposed in the previous section, the precise alignment process of the TDI charge shifting direction is described here in detail. During the precise alignment procedure, a collimator is used as the target (H is close to infinity). The collimator and the camera are laid on the vibration–isolation platform as shown in Fig. 7. Initially, the scan mirror is locked in the position for $\theta_1 = 45$ deg. Then the camera housing is rotated to face the scan mirror to the collimator, and the camera housing is locked by a pin to prevent it from rotating. The TDI CCD is operated in the area mode whose output images are collected and displayed on a computer in real time. A digimatic head is installed to precisely rotate the focal plane assembly. As shown in Fig. 8, when the focal plane assembly is required to rotate a tiny angle β around the fulcrum A, the adjustment values of the digimatic head are the product of the rotation radius L and the angle β (radian).

By adjusting the attitudes of the camera relative to the collimator, the image of the star point [see Fig. 7] is adjusted near the center of the TDI CCD ($x_{CCD} = 0$). Then unlocking and nodding the scan mirror, the image of the star point moves on the TDI CCD, and its central coordinates for different nodding angles of the scan mirror are collected. The coordinate data are processed by the least square method to acquire the included angle β (equal to θ) between the fitted straight line and the x-axis of O_{CCD}-$x_{CCD}y_{CCD}$.

Initially, the included angle β may be relatively large beyond the adjustment range of the focal plane assembly (>0.5 deg). At that time, the scan head needs to be slightly rotated around the x-axis of O_1-$x_1y_1z_1$ to diminish the value of β, until β is <0.5 deg. Then the focal plane assembly

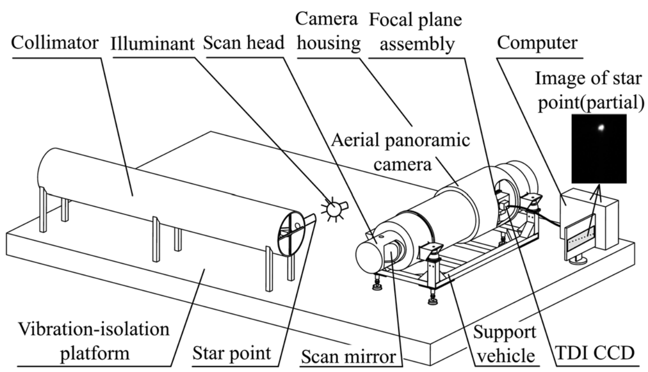

Fig. 7 Schematic diagram of precise alignment of TDI CCD in aerial panoramic camera.

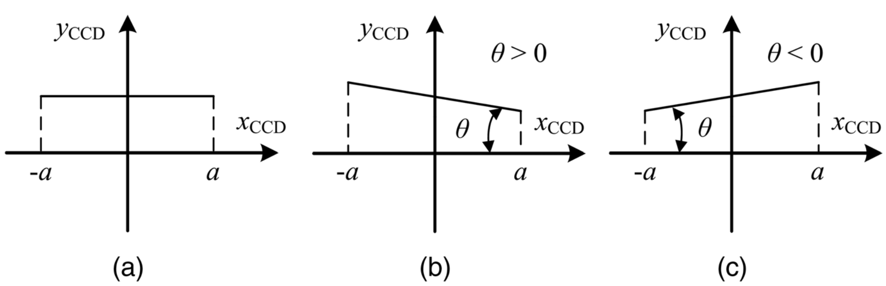

Fig. 6 Trajectory of the image point varying with θ_1: (a) Eq. (7) or Eq. (9), (b) Eq. (6) and (c) Eq. (6).

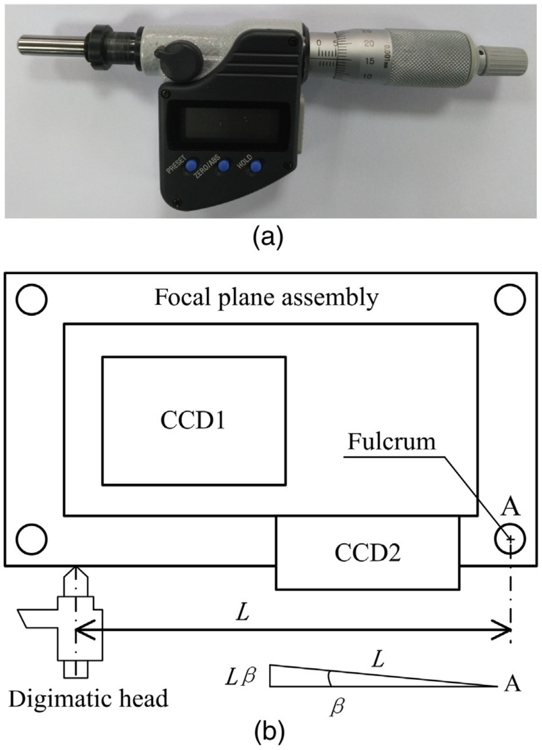

Fig. 8 Schematic diagram of rotation of focal plane assembly: (a) digimatic head and (b) detailed realization of precise rotation for focal plane assembly.

is rotated by adjusting the digimatic head to eliminate the included angle β. Finally, the central coordinates of the star point image for different nodding angles of the scan mirror are shown in Table 1. Processing the data in Table 1 by the least square method, the included angle β is obtained as

$$\gamma = \beta = -16.4\ \mathrm{s},$$

where γ is called the alignment error.

When the TDI CCD is operated in the TDI mode and the stage M is equal to 200, γ may further degrade the modulation transfer function (MTF) of the TDI CCD. The MTF at the Nyquist frequency f_N of the TDI CCD can be calculated as[21]

$$\mathrm{MTF}(f_N) = \frac{\sin\left[\frac{\pi M(1-\cos\gamma)}{2\cos\gamma}\right]}{\frac{\pi M(1-\cos\gamma)}{2\cos\gamma}} \frac{\sin\left(\frac{\pi M \tan\gamma}{2}\right)}{\frac{\pi M \tan\gamma}{2}} = 0.9999. \tag{18}$$

Consequently, the alignment error γ could hardly influence the MTF of the TDI CCD. It is demonstrated that the method proposed above can be used for the precise alignment of the TDI CCD charge shifting direction.

Before and after precise alignment of the TDI CCD, it is operated in the TDI mode, and the camera housing rotates around the primary optical axis to image a bar target through the collimator, respectively. The included angle β is equal to 1.48 deg before precise alignment of the TDI CCD. The target images for these two cases are shown in Fig. 9, and the bar images inside the white box correspond to the Nyquist frequency of the TDI CCD. Obviously, when $\beta = 1.48$ deg, the bar target images at the Nyquist frequency are smeared, and image distortion is produced in the images (from square to rhombus). But when precise alignment of the TDI CCD is finished ($\beta = -16.4$ s), the bar target images at the Nyquist frequency can be clearly distinguished, and there is no image distortion.

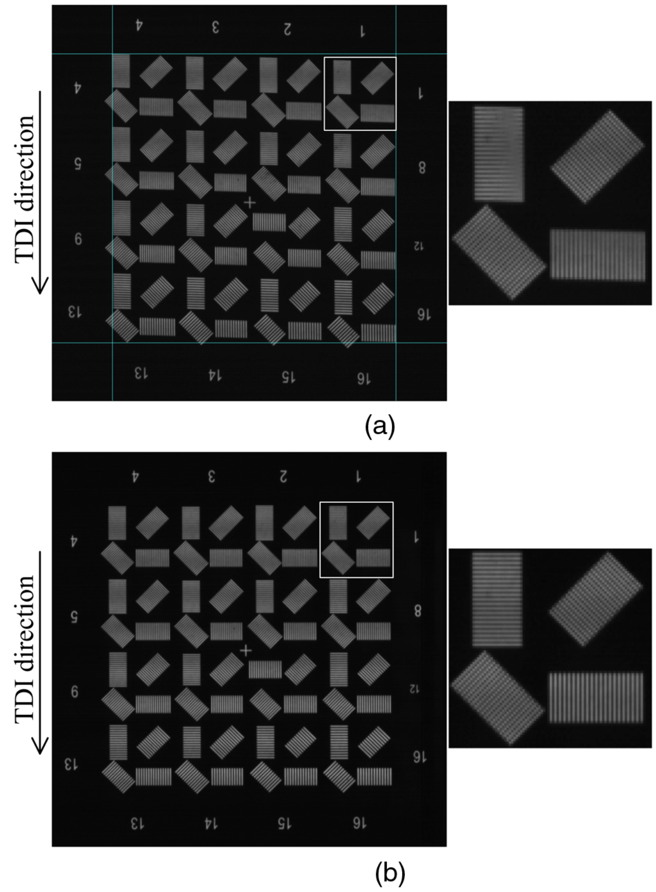

Fig. 9 The bar target images before and after precise alignment: (a) $\beta = 1.48$ deg (before precise alignment) and (b) $\beta = -16.4$ s (after precise alignment).

Furthermore, the aerial panoramic camera is installed on an aircraft to capture the panoramic images of the ground scene with tri-bar resolution targets in the oblique imaging mode, and one of the captured images is shown in Fig. 10. Five expert observers rate the flight test results, and they reach a consensus that the camera's ground resolved distance (GRD), which is equal to 0.6 m, has been achieved. It confirms that the proposed method is feasible and effective.

Table 1 The central coordinates of the image for different nodding angles of the scan mirror after precise alignment.

	1	2	3	4	5	6	7	8	9	10	11	12
x_{CCD}	−7498.6	−5799	−4469.7	−2971.2	−1487	−10.7	11.7	1484.8	3016.4	4459.2	5983.9	7524
y_{CCD}	10.8	10.0	10.5	10.2	10.6	11.1	11.1	11. 1	11.4	11.3	11.2	11.4

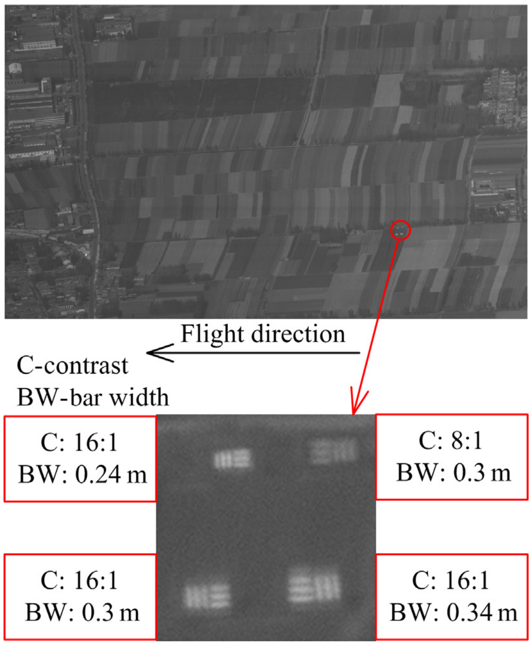

Fig. 10 The captured tri-bar resolution targets' images in the real-flight test.

5 Conclusions

In conclusion, a precise alignment method of a TDI CCD charge shifting direction for the aerial panoramic camera is proposed. During the actual assembling procedure, there is an included angle θ between the directions of the TDI charge shifting and the sweep image motion, which is attributed to the uncertain mounting positions for the scan head and the focal plane assembly. The TDI CCD is operated in the area mode, nodding the scan mirror, and the trajectory of the image point on the TDI CCD is derived to be a hyperbola, which can be equivalent to an obliquely straight line, where the included angle between the straight line and the TDI CCD row direction is exactly θ. Hence, the precise alignment of the TDI CCD is carried out, and the focal plane assembly is precisely adjusted to eliminate the included angle between the directions of the TDI charge shifting and the sweep image motion. The alignment error is -16.4 s, which could hardly influence the MTF of TDI CCD. This demonstrates the feasibility of the precise alignment method. The panoramic imaging experiment and the flight test further demonstrate that this method can completely satisfy the operating requirements of an aerial panoramic camera.

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