Systematic Geolocation Errors of FengYun-3D MERSI2

Hongbo Pan, Member, IEEE, Zehua Cui, Xiuqing Hu and Xiaoyong Zhu

Abstract—Geolocation accuracy is a critical issue for remote sensing applications. To achieve sub-pixel accuracy, geolocation errors need to be systematically identified and corrected. In this study, we propose a geometric sensor model for FengYun-3D MERSI2, a second-generation VIS/IR spectroradiometer, to generate the Geolocation Lookup Table (GLT). The geometric sensor model retrieves the imaging rays from the focal plane to the K-Mirrors, 45° scanning mirrors, the platform, and the earth’s surface. After refining the attitude errors with ground control points (GCPs), the rigorous sensor model can achieve sub-pixel geolocation accuracy. However, significant systematic geolocation errors were identified from the residuals, especially for the area with large view angles. To study the errors of MERSI2, we proposed a homogenous coordinate in the focal plane. As proven by both theory and experiments, the attitudes were adjusted to a wrong value and introduced systematic errors when there were principal point errors. The pitch angle error of K-Mirrors caused the oscillation in the flight direction. The principal distance error introduced line coordinate-related error in the flight direction. Meanwhile, the initial phase angle error between the K-Mirror and 45° scanning mirrors caused the line coordinate-related errors in the scanning direction. After correcting all the above-mentioned errors, the systematic geolocation errors of MERSI2 were removed. With twenty-three independent datasets, the root mean square errors of 250 m bands were approximately 0.4 pixels, 100 m at nadir.

Index Terms—Geometric sensor model, MERSI2, Geolocation

I. INTRODUCTION

The Medium Resolution Spectrum Imager-II (MERSI2) is the new generation payload of Chinese polar-orbiting meteorological satellites, which was adopted in FengYun-3D (also referred as FY-3D). The follow-up mission, FengYun-3E, was launched in Jul 05 2021 on an early-morning orbit.

MERSI2 is a 25-channel VIS/IR spectroradiometer, replacing and merging MERSI-I [1] and VIRR (Visible and Infra-Red Radiometer) of FY-3A/3B/3C [2]. The ground distance of instant field of view (IFOV) of six channels is 250 m at nadir, while the ground distance of the rest of the nineteen channels is 1000 m [3]. The MERSI2 captures the image of approximately 2900 km swath with a single scan from an 830 km orbit height. And 23 types of global information products daily were generated by ground application system [3].

The geolocation procedure is a fundamental pre-processing step. It generates the Level 1B product from the Geolocation Lookup Table (GLT). This geolocation information can additionally be used to combine the multi-sensor, multi-temporal remote sensing data, as well as analyze quantitative physical and chemical information about land, ocean, and atmosphere [4, 5].

Much effort was devoted to developing sub-pixel geolocation methods for whiskbroom cameras, like AVHRR (Advanced Very High Resolution Radiometer) [6, 7], MODIS (Moderate-resolution Imaging Spectroradiometer) [8, 9] and VIIRS (Visible Infrared Imaging Radiometer Suite) of SNPP and JPSS [10–12]. In the early era of development of these methods, both ephemeris and attitude should be estimated for satellite navigation. With the improvement of ephemeris accuracy, only attitude needs to be refined for AVHRR [6, 13]. Recently, several studies also reported the compensation for attitude can achieve sub-pixels geolocation accuracy for FY-3D’s Microwave Radiation Imager (MWRI), whose spatial resolution is approximately 5-6 km [14, 15]. For MERSI of FY-3A, the geolocation accuracy can achieve approximately 2 pixels for 250 m bands, after compensating for the boresight bias via several ground control points (GCPs) at the coastline [16]. The MERSI2 of FY-3D achieved similar geolocation accuracy in the object space for 1000 m bands, when the images of Landsat-8 OLI are used as reference images [17].

In general, there are two ways to analyze the geolocation errors for whiskbroom cameras: in the object space and the image space. In the first case, the whiskbroom image would be rectified in a specific projection, and the image correlation would be used to extract high-precision GCPs from higher accurate reference images [9, 18]. The absolute geolocation accuracy is determined in the specified projection. However, the ground sample distance (GSD) of the whiskbroom camera changes with the distance between the satellite and the object. Therefore, the geolocation errors in the object space depend on the view angles. Additionally, map projection on an area of over 2900 km is prone to distortion owing to the difficulty of
choosing an appropriate map projection. Past research has tried to reproject the object coordinate to the image space to determine the errors in the image space [13, 19], because the geolocation errors introduced by sensors or platform depend on the imaging geometry. Schmidt, King and McVicar [19] found that there were view zenith angle (VZA) related geolocation errors. And the geolocation errors increased with view angle for MERSI2 1000 m bands [17].

To improve the geolocation accuracy, a more comprehensive investigation on the error sources is required, similar to the MODIS [9, 20]. Due to the very small Filed of View (FoV), these errors were correlated. More than that, there is a unique equipment, K-Mirror, in MERSI2 to correct the image rotations [21]. In this manuscript, a rigorous sensor model was developed for geolocation of MERSI2. To analyze systematic errors, a homogenous coordinate in the focal plane was proposed.

Section II presents the geometric sensor model for MERSI2, including detailed MERSI2 design, the transformation of imaging rays and geolocation. Section III proposed a new homogenous coordinate in the focal plane to analyze geolocation errors related to sensors, platforms, and targets. A dataset was used to explore the properties of geolocation errors for FY-3D MERSI2. A summary appears in the final section.

II. GEOMETRIC SENSOR MODEL FOR MERSI2

The geometric sensor model describes the relationship between the image coordinate and spatial coordinate of target, which is used to calculate the GLT. In general, the geolocation can be described as the line of sight (LoS), retrieved from image coordinate, which intersects with the earth’s surface for the geodetic coordinate.

![Fig. 1 The sketch of MERSI2.](image-url)

A. MERSI2

The MERSI2 utilizes a 45° scanning mirror to capture ground images in the across-track direction. However, the mirror would introduce misalignment of image rotation for those sensors with multi-detectors, like MERSI2. To correct this image rotation, a K-mirror with three reflectors was adopted since FY-3A [21]. After many reflections, the light would be focused by telescope and projected to the focal plane, as illustrated in Fig. 1. To analyze the imaging geometry, an instrument frame system was introduced, whose X-axis is the rotation axis of 45° scanning mirror, Z-axis points to the center of earth view angle and Y-axis is determined by right-hand rule.

The 45° scanning mirror was named by the 45° angle between rotation axis and normal vector of reflective mirror. To scan the across-track direction, the rotation axis parallels the flight direction. The mirror makes a round in 1.5 s, capturing a frame about 10 km in the nadir. The center of the earth view angle points to the nadir.

The K-mirror is composed of three reflectors. The normal vector of the second mirror is perpendicular to the rotation axis, while angles of first and the third mirrors between the normal vector and rotation axis are equal to $\beta$. The rotation axis of the K-Mirror is designed the same as 45° scanning mirror. The rotation velocity of the K-mirror is half as 45° scanning mirror, 20 rounds per minute. The normal vector of the second mirror points to -Z direction of the instrument frame, when the 45° scanning mirror points to the nadir.
After being separated by four dichromic beam splitters, the collected radiation was projected to five focal plane assemblies (FPAs) for five spectral intervals, including visible (VIS), visible and near-infrared (VNIR), short-wave infrared (SWIR), mid and long-wave infrared (MLWIR), and long-wave infrared (LWIR), as illustrated in Fig. 2. There were two types of linear multi detectors, 40 detectors with 0.3 mrad for 250 m bands and 10 detectors with 1.2 mrad for 1000 m bands. The linear detectors are perpendicular to the scanning direction in the FPAs. In the focal plane frame, the $x$-axis is opposite to the flight direction, while the $y$-axis is determined by right hand rule. After correcting the image rotation by K-mirror, all bands were co-registered to the reference band by a simple shift in the scanning direction. Therefore, the geolocation of MERSI2 is carried out for the reference band.

**B. Geometric Sensor Model**

For the dynamic imaging system, both the imaging ray and the imaging time are important. With the rows in the image coordinate and the number of detectors $M$, the pixels $(r, c)$ can determine the corresponding frame $N$ and the corresponding detector $r_N$ in the frame. Then, the coordinate $(x, y)$ in the focal plane frame is

$$
\begin{align*}
x &= r_N - \frac{M}{2} \cdot \mu + x_0 \\
y &= y_0
\end{align*}
$$

(1)

where $\mu$ indicates the pixel spacing of detectors and $(x_0, y_0)$ is the central point of the linear CCD (Charge Coupled Device) in the focal plane.

Getting the imaging ray in the telescope requires two steps: retrieving three-dimensional imaging rays in the camera

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_c =
\begin{bmatrix}
x \\
y \\
-f
\end{bmatrix},
$$

(2)

and changing the coordinate to the instrument frame with transformation matrix $R_{c}^{\text{tel}}$.

$$
R_{c}^{\text{tel}} =
\begin{bmatrix}
0 & 0 & 1 \\
0 & 1 & 0 \\
-1 & 0 & 0
\end{bmatrix}
$$

(3)

Because of the rotation of K-mirror and 45° scanning mirror, the scan angle $\theta$ depends on the time $t$. The detectors of 1000 m bands sample at an interval of $t_0$ which is 224 µs, while the sample frequency of 250 m bands is four times that of the 1000 m bands. Within 0.4587 seconds, the 45° scanning mirrors scan the earth view from -55.04° to 55.04° with velocity $\dot{\theta}$ which is 4.189 rad per second. For a 1000 m band, the angle interval of adjacent columns is 0.94 mrad, smaller than the instant field of view (IFOV). Let $\theta$ equal 0, when the sample $c$ is at the center of the image. Then scan angle is defined as

$$
\theta = \left\{ c - \frac{W}{2} \right\} \cdot t_0 \cdot \dot{\theta}
$$

(4)

where $W$ is the width of the image, and $t_0$ is the dwell time, which is different for 1000 m bands and 250 m bands.

According to equation (19), the reflection matrix of K-mirror is independent of the angle $\beta$. More details about the reflection matrix of 45° scanning mirror and K-Mirror can be found in the appendix. Using equation (18), the rotated reflection matrix of K-Mirror is

$$
R_{k}^{\theta/2} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & \sin \theta \\
0 & \sin \theta & -\cos \theta
\end{bmatrix}
$$

(5)

In the nadir view, the normal vector of 45° scanning mirror is $\vec{n} = [-1/\sqrt{2}, 0, 1/\sqrt{2}]^T$ in the instrument frame. And the reflection matrix of 45° scanning mirror is

$$
R_{m}^{\theta} =
\begin{bmatrix}
0 & -\sin \theta & \cos \theta \\
-\sin \theta & \cos^2 \theta & \sin \theta \cdot \cos \theta \\
\cos \theta & \sin \theta \cdot \cos \theta & \sin^2 \theta
\end{bmatrix}
$$

(6)

Combine the K-Mirror and 45° scanning mirror, the transformation matrix of scan assemblies is...
\[
R_{\text{mld}} = R_x(\theta) \cdot R_y(\theta/2) \cdot R^e_{x'}
\]
\[
= \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & -\sin \theta \\
0 & \sin \theta & \cos \theta
\end{bmatrix}
\]  \hspace{1cm} (7)

And the LoS in the body system is
\[
\begin{bmatrix}
X \\
Y \\
Z_{ECEF}
\end{bmatrix} = R_{\text{mld}} \cdot \begin{bmatrix}
X \\
Y \\
Z_{ECEF}
\end{bmatrix}
\]
\[
= \begin{bmatrix}
x \\
y \cdot \cos \theta + f \cdot \sin \theta \\
y \cdot \sin \theta - f \cdot \cos \theta
\end{bmatrix}
\]  \hspace{1cm} (8)

According to the equation (7), the K-Mirror compensates for the image rotation with its multi-detectors, because the transformed ray in X direction is independent from scan angle \( \theta \).

The attitude and orbit determination system also provides crucial attitudes for geolocation. GPS receiver was adopted to determine the position \([X_S \ Y_S \ Z_S]^T\) of FY-3D satellite. There are two types of attitudes for FY-3D. The first describes the satellite body coordinate and orbit coordinate. With the position and velocity in the earth-centered inertial (ECI) coordinate, the transformation matrix \(R^{o}_{ECEF}\) from orbit coordinate to the ECI coordinate can be calculated. The second are the quaternions, indicating the transformation matrix between navigation system and ECI. In this case, the boresight alignment of the navigation system would need to be considered. Both attitudes can calculate the transformation matrix \(R^{ECEF}_{body}\). The LoS in the ECI can be transformed to earth-centered earth-fixed (ECEF) coordinate by IERS conventions [22].

With above transformation, the LoS of each pixel in the ECEF is
\[
\begin{bmatrix}
X \\
Y \\
Z_{ECEF}
\end{bmatrix} = \begin{bmatrix}
X_S \\
Y_S \\
Z_S
\end{bmatrix} + m \cdot R^{ECEF}_{ECEF} \cdot R^{ECEF}_{body} \cdot R_{mld} \cdot \begin{bmatrix}
x \\
y \\
-f
\end{bmatrix}
\]  \hspace{1cm} (9)

where \( m \) is scale factor.

C. Geolocation

The retrieved ray would intersect with the earth’s surface to determine the scale factor \( m \) and calculate the Cartesian coordinate in the ECEF. Due to the varying view angle, the topographic relief introduces disparity in the image. Therefore, a 7.5-arc-second spatial resolution global digital elevation model (DEM), GMTED2010 [23], was used to determine topographic surface. To avoid divergence as well as any occlusion-induced problem, the ray-tracing method is preferred as it determines the intersection in a fixed elevation interval.

Transforming the Cartesian coordinate to the geodetic coordinate can be expressed as the solution of a quartic equation [24]. To achieve a better computation efficiency and accuracy, the iterative method is applied [25]. After intersection and coordinate transformation, a GLT for each pixel could be built for MERSI2.

III. THE SYSTEMATIC ERRORS IN FOCAL PLANE

The sources of geolocation errors common with the MERSI2 can be classified into three categories: the sensors, the platforms and the targets [26]. Ideally, the geometric sensor model can be described by equation (9). However, due to the imperfect assemblies and the varieties of space environments, these errors need to be taken into consideration. Some past studies have preferred to categorize the geolocation errors according to frequency [20]. Certainly, the frequency of geolocation errors is an important indicator because different error sources would introduce geolocation errors with different frequencies.

Due to the very small FoV and highly dynamic imaging system, the errors of MERSI2 are correlated. For example, the roll angle error of a platform cannot be distinguished from the principal point errors \( y_0 \) in the focal plane. Time errors and scan errors introduce the similar geolocation errors. It is difficult to calculate the image coordinate \((r, c)\) from the object coordinate with geometric sensor model.

According to the above section, each pixel defines the LoS, which has one freedom. To analyze the systematic errors of MERSI2, the homogenous coordinate \([p_x \ p_y \ f/\mu]\) in the focal plane is introduced, which is defined as
\[
\begin{bmatrix}
p_x \\
p_y \\
f/\mu
\end{bmatrix} \equiv \begin{bmatrix}
X_c/Z_c \\
Y_c/Z_c \\
1
\end{bmatrix}
\]  \hspace{1cm} (10)

The units of \((p_x, p_y)\) are pixels, and 1 pixel equal to one IFOV. Considering the smaller dwell angle in the scanning direction, the spatial resolution of \( p_x \) is lower than the real image space. Nevertheless, the \( p_y \) is in the flight direction and the \( p_x \) in the scanning direction, which were counterintuitive.

A. Errors of MERSI2

According to the Figure 1, the errors of MERSI2 can be further divided into three different assemblies, including the telescope with focal plane, the K-Mirror and the 45° scanning mirror.

The principal distance \( f \) and principal points are interior orientation parameters. However, the principal point error can be absorbed by the deployment parameters \((x_0, y_0)\) of equation (1). According to equation (8), the \( y = y_0 \) is correlated to the scanning angle \( \theta \), which relies on the sample coordinate \( c \). In most cases, the \( y_0 \) is calibrated by band-to-band registration. For the sake of simplicity, let \( y_0 = 0 \), then the \( \Delta x_0 \) cause the errors in \( \Delta p_x \) as \( \Delta p_x = \Delta x_0/\mu \). And the
errors of principal distance $f$ would introduce normalized line coordinate $r_x$ related errors in $\Delta p_x$, which is

$$\Delta p_x = \frac{\Delta f}{f + \Delta f} \cdot \frac{x}{\mu}. \quad (11)$$

The major error of K-Mirror is boresight misalignment. The misalignment of K-Mirror can be represented with three angles the $\phi$ with X-axis, the $\alpha$ with Y-axis and $\gamma$ with Z-axis. As shown in Appendix B, $\gamma$ has no impact on the geolocation. $\alpha$ indicates the pitch angle of K-Mirror. $\phi$ represents the initial phase angle between the K-Mirror and 45° scanning mirror, and can be directly summed with scanning angle $\theta/2$. Given the boresight misalignment, the reflection matrix of K-Mirror is derived as Equation (22).

The boresight misalignment of the 45° scanning mirror can be absorbed by attitude errors, which will be discussed in the following section. However, two other error sources should be considered: the scanning angle $45^\circ + \tau$ and the scanning errors. The former would introduce the similar errors as principal distance $f$, as demonstrated in Appendix C. The latter is caused by variation of rotation velocity of the scanning mirrors and causes the scanning angle $\theta/2$ to not be linearly correlated with time $t$. It can be modeled by a sum of the sinusoidal functions

$$\theta(t) = \sum_{i=1}^n a_i \sin(\omega_i \cdot t + \phi_i). \quad (12)$$

where $a_i$, $\omega_i$ and $\phi_i$ ($i=1, 2, \ldots, n$) are the amplitude, angular frequency and phase, respectively.

**B. Errors of platform**

The errors of platform are consisted of position error and attitude error. Since the Global Positioning System (GPS) receivers were used to determine the ephemeris of meteorological satellites, the position accuracy of satellites can achieve meters even without precise orbit, which can meet the requirement of geolocation. The attitude error is the major error source causing geolocation errors.

Two types of errors can be modeled by attitude errors, including the errors of attitude determination and the misalignment between navigation system and the whiskbroom cameras. Generally, the former is regarded as stable and can be compensated by a rotation matrix between $R_{\text{body}}^O$ and $R_{\text{mim}}$, whereas the latter changes with time and can be modeled by attitudes of $R_{\text{body}}^O$. In practice, there is no significant difference between above two errors.

The attitude errors can be modeled by three Euler angles, the roll angle $\Delta \omega$, the pitch angle $\Delta \varphi$, and yaw angle $\Delta \gamma$. These errors would introduce geolocation errors in focal plane, as shown in appendix D.

$$\left\{ \begin{array}{l}
\Delta p_x = \left( \frac{f}{\mu} + \frac{x^2}{\mu^2 \cdot f} \right) \cos \theta \cdot \Delta \varphi - \left( \frac{f}{\mu} + \frac{x^2}{\mu^2 \cdot f} \right) \sin \theta \cdot \Delta \gamma \\
\Delta p_y = \frac{x}{\mu} \sin \theta \cdot \Delta \varphi + \frac{f}{\mu} \sin \theta \cdot \Delta \omega + \frac{x}{\mu} \cos \theta \cdot \Delta \gamma
\end{array} \right. \quad (13)$$

For MERSI2, the maximum of $x/f$ is the half FoV, about 5/830, and the maximum of $x/\mu$ is 20 for 250 m bands. Therefore, the errors with coefficients $f/\mu$ are the major errors. The pitch angle error $\Delta \varphi$ introduce the cosine curves error in the flight direction $\Delta p_x$ and small sine curves error in the scan direction $\Delta p_y$. The roll angle error $\Delta \omega$ causes the shift in the scan direction, as same as initial scanning angle. And the yaw angle error $\Delta \gamma$ causes the geolocation errors in the flight direction as sinusoids about scanning angle, and cosine curves in the scanning direction. It is worth noting that $x/\mu$ is related to the line number, that is, the errors with coefficients $x/\mu$ would change with $r_x$ and view angle $\theta$, and are not negligible as AVHRR [27].

**C. Errors of targets**

The errors of targets are atmospheric refraction, light aberration, and elevation errors. The atmospheric refraction would cause the departure of view angle about 11 mrad at the 70° apparent zenith distance. This error can be ignored, because the minimum instant field of view (IFOV) is 236 mrad. Due to the lower resolution, the light aberration is also not significant. The elevation errors of target come from the elevation error of DEM and the planimetric error of geolocation. The GMTED2010 root mean square errors (RMSEs) at 7.5 arc-seconds resolution range between 26 and 30 m, which is sufficient for MERSI2 geolocation [23].

**IV. EXPERIMENTS AND DISCUSSIONS**

**A. Datasets**

The MERSI2 data of FY-3D is freely available from National Satellite Meteorological Center. The Level 1 250 m resolution data contain six 250 m bands earth view data after co-registration and a GLT with 20 pixels interval. Each file is partitioned with 5 minutes interval and in HDF5 (Hierarchical Data Format) format, resulting the image size with 8 192 pixels in columns and 8 000 pixels in rows. Nevertheless, a separated GLT file (named as GEOQK) is also provided, which include latitude and longitude for each pixel. During the geolocation processing, the ephemeris, attitudes, and time information are required, which are stored in the OBC (Onboard Calibrator) file.

To evaluate the geolocation accuracy, the datasets capturing the lands without cloud are preferred. Therefore, the dataset, FY3D_MERSI_GBAL_L1_20200517_0505_0250M_MS, was adopted, as shown in Fig. 4. The denoted the imaging time for 20200517_0505 was May 17, 2020 5:05, which was unique and used to indicate the dataset. Given the high signal-to-noise ratio (SNR), the reflective solar band 4 (named as RefSB4 with 0.865 $\mu$m center wavelength) was used to extract...
GCPs.

Fig. 3 The MERSI2 dataset covering Australia with few clouds.

The 8th band of Sentinel-2 Multi-Spectral Instrument (MSI), central wavelength 832.8 nm, served as the cloud-free reference images via google earth engine. The geolocation accuracy of MSI non-refined L1C products is about 10 m at 94.45% confidence [28]. The spatial resolution of reference images was degraded to 240 m via averaging pixel values, slightly better than the spatial resolution of MERSI2 nadir images. However, the GSD of MERSI2 changes significantly with the view angle, resulting in panchromatic distortions of the original images. To reduce the impact of geometric distortions, the reference images were used to simulate a new reference image with GLT. After that, the RefSB4 of MERSI2 was matched with simulated images. The normalized cross-correlation algorithm is used to find the initial corresponding points, then the coordinates of conjunctive points were refined by the least square matching (LSM), which can achieve sub-pixel accuracy. The matching window is $11 \times 11$ pixels, keeping a balance between matching accuracy and details of errors. The outliers were removed by GLPM (Guided Locality Preserving Feature Matching) [29], and there were over 100,000 GCPs left.

B. Attitude Errors of FY3D MERSI2

The design parameters were adopted to retrieve the LoS of MERSI2. For dataset 20200517_0505, only Euler angles were available. Given that the attitudes of FY-3D are usually small and contain random Euler angle errors, the average attitude of the entire scene was adopted. Fifth-degree polynomials were used to build the orbit model. The GCPs were used to estimate the boresight misalignment to refine the geometric sensor model.

With equation (10), both object coordinate $(lat, lon, h)$ and image coordinate $(r, c)$ can be transformed to the focal plane to obtain two coordinates. The difference $\left( \Delta p_x, \Delta p_y \right)$ between two coordinates indicates the geolocation errors. The geolocation residuals are shown in Figure 4, in which the color indicates the magnitude of the errors, and the arrows show the direction. To make the geolocation errors consistent with the image coordinates, $p_x$ is plotted in the line direction and $p_y$ in the sample direction. The RMSEs of $(p_x, p_y)$ are 0.50 pixels, slightly better than the true RMSEs 0.52 pixels in the image space. This is mainly because the IFOV is slightly larger than the angle between adjoint pixels.

The GLT of view angles -27° to 40° can achieve sub-pixel accuracy. However, there were significant systematic errors pointing to right-up direction with larger view angles. To illustrate these systematic errors, the median residuals of every 8 columns were calculated and plotted with sample coordinate in Figure 5. The $\Delta p_x$ reduced from 0.2 to -1.0 pixels in the cosine curve way when the view angle increased with the sample coordinate. According to equation (13), such errors can be absorbed or introduced by $\Delta \varphi$. The $\Delta \varphi$ might be adjusted to an inaccurate value if there were other errors. Nevertheless, there were significant fringes in both sample and line directions, as illustrated in Figure 4. The fringes in the sample direction also can be identified from the figure 5. The $\Delta p_y$ was from -0.27 pixels to 0.75 pixels. To the best of our knowledge, the periodic fringes in the scan direction can be caused by the unsteady scanning of 45° scanning mirrors or K-Mirrors. The maximum magnitude of fringes was approximately 0.4 pixels, and reduced with the sample coordinate. The frequency of such periodic errors was approximately 20 Hz.

The fringes in the line direction are a unique phenomenon to the MERSI. To highlight the fringes, the median residuals of line 3000-3400 were zoomed in, as illustrated in Figure 6. The median of $\Delta p_x$ oscillated with line number. The frequency was 80 pixels, the same as K-Mirror. And the...
magnitude of such frame is about 0.2 pixels. Considering the scanning geometry of K-Mirrors, the misalignment in pitch angle might introduce such errors. In the first period of 45° scanning mirrors, the pitch angle of K-Mirrors would cause the LoS to point up as in figure 1. The K-Mirrors would point down, when the 45° scanning mirrors rotate to the same positions in the following rounds.

There were periodic skews in the $\Delta p_y$, whose frequency is equal to the $\Delta p_x$. As discussed in Section 3, such kind of errors can be introduced by attitude errors or the errors of MERSI2, such as the initial phase angle errors of K-Mirrors, principal distance errors.

C. Systematic Errors of MERSI2

To elaborate the properties of MERSI2 errors, different parameters were tested to illustrate the impact on the geolocation accuracy. Given the systematic errors, the central point error in the CCD direction $\Delta x_0$, the pitch angle error $\alpha$ of K-Mirror and the principal distance $f$ were further studied. The GCPs were used to verify the geolocation accuracy.

According to the errors of $\Delta p_x$, $\Delta x_0$ was set to $-\mu, -2\mu, -3\mu$, and the medians of $\Delta p_x$ were calculated with or without attitude compensation. The RMSEs increased from 0.50 pixels to 1.1, 2.0, and 3.0 pixels, when the same attitude compensation model was adopted. The median $\Delta p_x$ were almost synchronously increasing with $\Delta x_0$, as shown in Figure 7. However, the curvatures of the $\Delta p_x$ reduced with the $\Delta x_0$, when attitude compensation was adopted to correct attitude errors. After compensating for the attitude, the RMSEs were 0.50 pixels, 0.46 pixels, 0.43 pixels, and 0.42 pixels, at $0, -\mu, -2\mu, -3\mu$ respectively. The attitudes were adjusted to an incorrect value, introducing $\Delta p_x$ as cosine curves, if there were interior orientation parameters errors. After adjusting the $\Delta x_0$ to $-3\mu$, the median of $\Delta p_x$ was around 0 pixels, as shown in Figure 8.

The oscillation of $\Delta p_y$ can be modeled by rotation velocity of the scanning mirrors, as the equation (12). Considering the stabilization of machinery and electronics, the sum of sines with six sets of parameters were used to model the oscillation. And the scanning angle table with time is established for scanning angle interpolation. After compensating for the uneven scanning errors of 45° scanning mirrors, the median residuals were calculated with sample coordinate, as shown in figure 8. The noise of the first 1000 pixels was larger than the rest, because the GCPs were sparser and influenced by clouds.
Fig. 8 The median residuals of $\Delta p_x$ and $\Delta p_y$ after adjusting $\Delta x_0$ and scanning angles.

With the equation (22), the pitch angle errors $\Delta \alpha$ of K-Mirrors would cause the two times errors in the focal plane. After adjusting the $\Delta \alpha$ to -0.1 IFOV, the significant oscillation of $\Delta p_x$ between the adjacent frames were removed, as shown in Figure 9. Nevertheless, there were pulses for each 40 pixels, as the same as frame height. The bow tie phenomenon of whiskbroom cameras introduces such errors because the matching windows would contain the pixels of adjacent frame, which is suffering from geometric distortions. It is difficult to extract highly accurate GCPs for discontinuous images, which have large gradients at the edges of frames. Compared with Figure 6, the oscillation in the scanning direction was also reduced.

In each frame, there were skew in both flight and scanning direction. The principal distance error $\Delta f$ would cause the skews in the flight direction, as proved in equation (11). From Figure 9, approximately 0.1 to -0.1 pixels skew can be identified. Therefore, the principal distance error is about $f/200$. The skews in the scan direction are not very significant, approximately -0.1 to 0.1 pixels for the first six frames. With the frame size $M = 40$, the initial phase angle is about -0.1/40. After correcting the principal distance and initial phase angle, there were no systematic skews in Figure 10.

Fig. 9 The residuals with K-Mirror pitch angle correction.

After compensating for the systematic errors, the $\Delta p_x$ and $\Delta p_y$ were recalculated with GCPs. The RMSEs were reduced to 0.32 pixels. As shown in Figure 11, there were then no systematic errors but many gross errors, whose residuals were much larger than those of their neighbors.

Fig. 10 The residuals with principal distance and initial phase angle correction.

After compensating for the systematic errors, the $\Delta p_x$ and $\Delta p_y$ were recalculated with GCPs. The RMSEs were reduced to 0.32 pixels. As shown in Figure 11, there were then no systematic errors but many gross errors, whose residuals were much larger than those of their neighbors.

Fig. 11 The geolocation errors of MERSI2 after compensating for systematic errors.

D. Geolocations of MERSI2

Due to the limited accuracy of attitudes in the OBC file, the average attitudes need to be refined with GCPs. Meanwhile, the geometric parameters might change with time. To validate the geometric model, twenty-three datasets, covering Asia, Africa, Europe, and Australia over one year, were used in four
schemes experiments:
- Scheme 1 (S1): Geolocation with parameters of dataset 20200517_0505, not refining attitudes;
- Scheme 2 (S2): Geolocation with three different sets of parameters: 20200517_0505, 20210111_1315, and 20210620_1100, not refining attitudes;
- Scheme 3 (S3): Geolocation with parameters of dataset 20200517_0505, refining attitudes;
- Scheme 4 (S4): Geolocation with three different sets of parameters: 20200517_0505, 20210111_1315, and 20210620_1100, refining attitudes.

For the majority of datasets, the number of GCPs were over 80,000. And the rest were covered a lot of featureless area, oscillations than Fig. 6. After estimating the geometric calibration of dataset 20210111_1315 and dataset 20210620_1100, the RMSEs for S1 were within 2.0 pixels. The geolocation accuracy was not improved by the even in the whole scenes.

2.0 pixels. The geolocation accuracy was not improved by the such as deserts, clouds and oceans. The GCPs were distributed evenly in the whole scenes.

The RMSEs were calculated for each scheme. In spite of only one geometric calibration, the RMSEs for S1 were within 2.0 pixels. The geolocation accuracy was not improved by the geometric calibration of dataset 20210111_1315 and dataset 20210620_1100, since the attitude errors of OBC file were random. The RMSEs for S2 were within 1.0 km, achieving sub-pixels geolocation accuracy for 1000 m bands. After refining attitudes with GCPs, the RMSEs for S3 were time dependent. For the datasets of May 2020, the RMSEs were approximately 0.4 pixels. In the case of 20200513_1320, the RMSEs were 0.55 pixels, because the attitudes changed with time and the mean attitudes were not sufficient to guarantee the highly accurate geolocation. After six months or more time operation, the geometric parameters varied, especially the pitch angle of K-Mirrors, which introduced more significant oscillations than Fig. 6. After estimating the geometric parameters, the RMSEs for S4 were approximately 0.4 pixels.

| Datasets          | Number of GCPs | RMSE (pixels) |
|-------------------|----------------|---------------|
|                   |                | S1            | S2            | S3            | S4            |
| 20200504_1110     | 122827         | 1.10          | 1.10          | 0.36          | 0.36          |
| 20200504_1250     | 144129         | 0.89          | 0.89          | 0.46          | 0.46          |
| 20200508_1135     | 119000         | 1.20          | 1.20          | 0.38          | 0.38          |
| 20200509_1255     | 109911         | 1.48          | 1.48          | 0.42          | 0.42          |
| 20200512_1020     | 83356          | 0.57          | 0.57          | 0.40          | 0.40          |
| 20200513_0440     | 89187          | 0.75          | 0.75          | 0.41          | 0.41          |
| 20200513_1320     | 120552         | 1.46          | 1.46          | 0.55          | 0.55          |
| 20200514_1300     | 117080         | 1.28          | 1.28          | 0.39          | 0.39          |
| 20200517_1025     | 76730          | 0.89          | 0.89          | 0.38          | 0.38          |
| 20210105_1145     | 95261          | 0.96          | 2.04          | 0.54          | 0.34          |
| 20210110_0455     | 55329          | 1.91          | 3.33          | 0.58          | 0.40          |
| 20210110_1150     | 85402          | 0.88          | 1.64          | 0.57          | 0.40          |
| 20210112_0615     | 41136          | 0.79          | 1.99          | 0.61          | 0.44          |
| 20210112_0935     | 82254          | 0.79          | 1.50          | 0.64          | 0.48          |
| 20210113_1235     | 110113         | 1.85          | 0.47          | 0.56          | 0.36          |
| 20210517_1145     | 146941         | 0.72          | 1.48          | 0.66          | 0.51          |
| 20210617_1020     | 51520          | 1.00          | 1.88          | 0.56          | 0.38          |
| 20210617_1155     | 92144          | 1.17          | 2.15          | 0.61          | 0.45          |

V. CONCLUSIONS

Geolocation accuracy plays a vital role in applications of MERSI2. In this study, we gave a brief view on the MERSI2, which adopted 45° scanning mirrors to scan the earth, and a K-Mirror to correct the image rotation. According to the optical design, a rigorous sensor model was developed to retrieve the imaging ray from the image coordinate to the ECEF coordinate. With exterior global DEM, the three-dimensional geodetic coordinate was determined to build the GLT. After compensating for attitude errors, the RMSEs of GLT which is built with design parameters, are approximately 0.52 pixels, achieving sub-pixel geolocation accuracy. However, there were systematic geolocation errors, relying on the view angles, frame numbers and line coordinates. The geolocation errors with large view angles were over 1 pixel, even with a larger GSD.

To further investigate the error properties, a homogenous coordinate frame in the focal plane was proposed. Errors caused by sensors, platforms, and targets were studied in such a frame. Despite the fact that as CCD position error in the flight direction introduces constant errors, the attitude compensation would cause the cosine curve errors when the pitch angle was adjusted to reduce the CCD position error. And there were scanning angle errors, perhaps introduced by mechanical scanning of 45° mirror. The alignment of the K-Mirror should be modeled by rigorous sensor model because the pitch angle of K-Mirrors introduces oscillation errors of approximately 0.2 pixels between adjacent frames. The initial phase angle caused the residuals in image rotations, which change linearly with the line coordinate in the flight direction. Principal distance correction was approximately f/200. After correcting all above errors, the systematic errors were removed and the RMSEs of twenty-three independent datasets achieved 0.4 pixels.

The systematic errors introduced by the initial phase angles and principal distance errors were rather small, approximately 0.1 pixels. This required highly accurate image matching. LSM can nevertheless achieve such accuracy in most cases. Many outliers were identified, which should be removed in future work. Limited by attitude accuracy of FY-3D OBC file, the geolocation accuracy can be further improved by other attitude records. The quaternion of FY-3D and FY-3E would be studied and integrated into automatic geometric calibration procedure for later.
APPENDIX

A. The reflection matrix

The reflected light ray $r'$ is determined by the normal vector $\tilde{n} = \begin{bmatrix} n_x & n_y & n_z \end{bmatrix}^T$ and incident ray $r$. According to the law of reflection, the $r'$ is

$$r' = r - 2n \cdot (n^T \cdot r) = (I - 2n \cdot n^T) \cdot r = R_m \cdot r$$

(14)

where the reflection matrix $R_m$ is

$$R_m = I - 2n \cdot n^T = \begin{bmatrix} 1 - 2n_x^2 & -2n_xn_y & -2n_xn_z \\ -2n_xn_y & 1 - 2n_y^2 & -2n_yn_z \\ -2n_xn_z & -2n_yn_z & 1 - 2n_z^2 \end{bmatrix}$$

(15)

The 45° scanning mirror rotate $\theta$ about axis X, then the rotated normal vector is

$$n_y = R(\theta) \cdot n = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \cdot n$$

(16)

The rotated reflection matrix $R_m(\theta)$ is

$$R_m(\theta) = R(\theta) \cdot R_m \cdot R^T(\theta)$$

(17)

In the case of K Mirror, the rotated reflected matrix $R_k(\theta/2)$ is composed by three rotated reflection matrices

$$R_k(\theta/2) = R(\theta/2) \cdot R_{k_y} \cdot R_{k_z} \cdot R_{k_y} \cdot R_{k_z}$$

(18)

$$= R(\theta/2) \cdot R_{k_y} \cdot R_{k_z} \cdot R^T(\theta/2)$$

When the 45° scanning mirror points to the nadir, the normal vectors of three reflectors are $\begin{bmatrix} \cos \beta & 0 & \sin \beta \end{bmatrix}^T$, $\begin{bmatrix} 0 & 0 & -1 \end{bmatrix}^T$, and $\begin{bmatrix} -\cos \beta & 0 & \sin \beta \end{bmatrix}^T$. According to equation (15) and (18), the reflection matrix of K-Mirror is

$$R_{k_0} = R_{k_y} \cdot R_{k_z} \cdot R_{k_y} \cdot R_{k_z} \cdot R_{k_y} \cdot R_{k_z}$$

(19)

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

B. The boresight misalignment of K-mirror

The misalignment of K-mirror can be represented with three angles $\phi - \alpha - \gamma$. Then the rotation matrix $R_m$ is defined as follows

$$R_m = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix} \cdot \begin{bmatrix} \cos \alpha & 0 & \sin \alpha \\ 0 & 1 & 0 \\ -\sin \alpha & 0 & \cos \alpha \end{bmatrix} \cdot \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(20)

According to equation (18), the three reflectors can be rotated as a unit. In this case, the reflection matrix of K-Mirror becomes

$$R_k = R_{k_y} \cdot R_{k_z} \cdot R_{k_y} \cdot R_{k_z} \cdot R_{k_y}$$

(21)

It is easy to prove that $R_{y_0} \cdot R_{z_0} = R_{y_0}$, and $R_{y_0} \cdot R_{z_0} = R_{y_0}$, Therefore, the reflection matrix of K-Mirror is

$$R_{k_0} = R_{k_y} \cdot R_{k_z} \cdot R_{k_y} \cdot R_{k_z}$$

(22)

When the 45° scanning mirror points to the nadir, the normal vectors of three reflectors are $\begin{bmatrix} \cos \beta & 0 & \sin \beta \end{bmatrix}^T$, $\begin{bmatrix} 0 & 0 & -1 \end{bmatrix}^T$, and $\begin{bmatrix} -\cos \beta & 0 & \sin \beta \end{bmatrix}^T$. According to equation (15) and (18), the reflection matrix of K-Mirror is

$$R_{k_0} = R_{k_y} \cdot R_{k_z} \cdot R_{k_y} \cdot R_{k_z}$$

(23)

$$\begin{bmatrix} -\sin \tau & 0 & \cos \tau \\ \cos \tau & 0 & \sin \tau \end{bmatrix}$$

C. The angle of 45° scanning mirror

If the scanning mirror is $45' + \tau$, the reflection matrix of 45° scanning mirror is

$$R_{m} = \begin{bmatrix} -\sin \tau & 0 & \cos \tau \\ \cos \tau & 0 & \sin \tau \end{bmatrix}$$

(24)

$$\begin{bmatrix} X & 1 & 0 & 0 \\ Y & 0 & \cos \theta & -\sin \theta \\ Z & 0 & \sin \theta & \cos \theta \end{bmatrix} = \begin{bmatrix} \cos \tau \cdot X + \sin \tau \cdot f \\ \sin \tau \cdot y + \cos \tau \cdot f \\ \sin \tau \cdot X - \cos \tau \cdot f \end{bmatrix}$$

D. The attitude errors

The attitudes of MERSI2 defined the transformation from the body system to orbit system. The three Euler angles $\phi, \omega, \kappa$, with Y-Z-X rotation order, were used to determine the rotation matrix

$$R_m = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix} \cdot \begin{bmatrix} \cos \omega & 0 & \sin \omega \\ 0 & 1 & 0 \\ -\sin \omega & 0 & \cos \omega \end{bmatrix} \cdot \begin{bmatrix} \cos \kappa & -\sin \kappa & 0 \\ \sin \kappa & \cos \kappa & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(25)
The LoS in the body system, as defined in equation (8), is transformed to the orbit system with

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
x \\
y \\
f
\end{bmatrix}
\]

(26)

Then the LoS of the object can be transformed to the focal plane with

\[
\begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix} = \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

(27)

The partial derivatives of \( [X', Y', Z']^T \) about \( \varphi, \omega, \kappa \) can be calculated. In general, the orbit and attitude control system of FY-3D would maintain the body system aligning with orbit system. That is, \( \varphi \approx 0, \omega \approx 0 \) and \( \kappa \approx 0 \). Then, the partial derivatives are

\[
\begin{align*}
\frac{\partial [X' Y' Z']}{\partial \varphi} &= \begin{bmatrix}
y \cdot \sin \theta - f \cdot \cos \theta \\
-x \cdot \sin \theta \\
-x \cdot \cos \theta
\end{bmatrix} \\
\frac{\partial [X' Y' Z']}{\partial \omega} &= \begin{bmatrix}
0 \\
-f \\
-y
\end{bmatrix} \\
\frac{\partial [X' Y' Z']}{\partial \kappa} &= \begin{bmatrix}
y \cdot \cos \theta + f \cdot \sin \theta \\
-x \cdot \cos \theta \\
x \cdot \sin \theta
\end{bmatrix}
\end{align*}
\]

According to the definition of homogenous coordinate \( (p_o, p_s) \), \( [\Delta p_o, \Delta p_s] \) is calculated with

\[
\begin{align*}
\Delta p_o &= \left( \frac{f}{\mu} + \frac{x^2}{\mu \cdot f} \right) \cos \theta \cdot \Delta \varphi - \left( \frac{f}{\mu} + \frac{x^2}{\mu \cdot f} \right) \sin \theta \cdot \Delta \kappa \\
\Delta p_s &= \frac{x}{\mu} \cdot \sin \theta \cdot \Delta \varphi + \frac{f}{\mu} \cdot \Delta \omega + \frac{x}{\mu} \cdot \cos \theta \cdot \Delta \kappa
\end{align*}
\]

(28)

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Hongbo Pan was born in 1987. He received the B.E., Ph.D. degree in photogrammetry and remote sensing from Wuhan University, China, in 2009 and 2014, respectively. He is currently an Associate Professor of School of Geosciences and Info-Physics, Central South University. His research interests include spaceborne photogrammetry, geometric processing of remote sensing imagery.

Zehua Cui was born in 1997. He is now a master candidate in the School of Geosciences and Info-Physics, Central South University. His research interests are photogrammetry and remote sensing.

Xiuqing Hu received the B.Sc. degree in atmospheric science from Nanjing University, Nanjing, China, in 1996, the M.Sc. degree in cartography and geographical information systems from Beijing Normal University, Beijing, China, in 2004, and the Ph.D. degree in quantitative remote sensing science from the Institute of Remote Sensing Application, Chinese Academy of Sciences, Beijing, in 2012. He is currently conducting research at the National Satellite Meteorological Center, China Meteorological Administration, Beijing. His research interests include calibration and validation for optical sensors, retrieval algorithms for aerosol/dust and water vapor, and climate data records from environment satellites.

Xiaoyong Zhu earned B.E. and master’s degrees in photogrammetry and remote sensing from the School of Remote Sensing and Information Engineering of Wuhan University in China. He is an associate researcher with the Land Satellite Remote Sensing Application Center, Ministry of Natural Resources, Beijing, China. His research interests include space photogrammetry and geometry processing of optical imagery.