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Research on Guide Star Distribution of Sub-Arcsecond Attitude Determination for Microsatellites Reusing Scientific Cameras

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Abstract: Onboard scientific cameras are reused in attitude determination to meet the sub-arcsecond attitude determination accuracy requirements of microsatellites. This approach does not require an additional payload for microsatellites. It involves reusing high-quality optical lenses from the scientific camera and utilizing the peripheral high-quality imaging areas of its square-shaped detector. Separate detectors are placed within these areas as attitude determination detectors to obtain star patterns for closed-loop attitude determination, thereby achieving high-precision attitude determination for microsatellites. The star patterns obtained using this method may pose specific issues due to the relative positions of stars. Through an analysis of the theoretical model that examines the relationship between attitude determination accuracy and the main influencing factors, it is indicated that guide star distribution is one of the main, complex factors determining attitude determination accuracy. A further simulation analysis was conducted on the specific impact of two guide star distribution characteristics—namely, the coverage of guide stars in the attitude determination areas and the proportion of the average field of view occupied by the guide star triangles to the total field of view of the attitude determination areas—on attitude determination accuracy. This study concludes that when the measurement error of the guide stars is bigger than the attitude determination accuracy requirement for its area configuration, four attitude determination areas should be configured. Four attitude determination areas should be prioritized when the measurement error is equal to or smaller than the attitude determination accuracy requirement, followed by the option to configure three attitude determination areas or two symmetric attitude determination areas. When selecting guide stars for star pattern recognition, the guide stars should cover the attitude determination areas as much as possible, and guide stars with a higher proportion of the average field of view occupied by the guide star triangles to the total field of view should be chosen. Finally, experimental validation was conducted using star patterns from dense star fields and sparse star fields. The research results provide an important reference for the optimization of attitude determination area configuration, navigation star catalog construction, and star pattern recognition algorithm research for microsatellites equipped with scientific cameras.

Keywords: microsatellite; attitude determination; sub-arcsecond; guide star distribution

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1. Introduction

According to satellite mass classifications, satellites weighing between 10 and 100 kg are generally referred to as microsatellites [1,2]. Currently, microsatellites are actively utilized for important scientific research in the field of space science on both the domestic and international scales. The Air Force Research Laboratory (AFRL) in the United States has proposed six key technologies for microsatellites, one of which is a high-precision attitude determination and control technology [1]. With the continuous advancement of microsatellite applications, complex application scenarios have placed higher demands on this technology. In addition to simplicity, reliability, ease of implementation, long lifespan, low cost, and easy maintenance, high-precision attitude determination is another critical basic requirement. The need for attitude determination accuracy has specifically reached the sub-arcsecond level [2–9].

The Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) is a 6U CubeSat. A pointing stability of 0.5 arcsecond RMS over 20 min is needed to achieve the goal of the mission, which is to image and perform photometry on bright, nearby stars and possibly detect transiting exoplanets orbiting these stars [3]. In the feasibility study report on small satellites participating in the "NASA Astrophysics Eyes Big Science with Small Satellites" competition announced by NASA in 2019, a significant requirement for some of these small satellites is the ability to achieve high-precision attitude determination [5]. For example, the Miniature Distributed Occulter Telescope (mDOT) needs to achieve 0.2-arcsecond image stabilization for diffraction-limited imagery [6,7,10], and the primary mission objective of MicroArcsecond Small Satellite (MASS) is to measure the positions of stars brighter than 6 mag accurate to 4 μas in 1 h of integration [8,11].

For missions with sub-arcsecond-level or higher attitude accuracy, special hardware and software are needed for spacecraft attitude determination and control [12,13]. For example, the Hubble Space Telescope (HST), the Spitzer Space Telescope (SST), the James Webb Space Telescope (JWST), and the Euclid Telescope (Euclid) each utilize Fine Guidance Sensors (FGSs) in the hundred-kilogram range to provide high-precision attitude determination for the spacecraft [14–18].

Due to strict constraints on mass and volume for microsatellites, it is impossible to equip them with Fine Guidance Sensors (FGSs). Many microsatellites are equipped with scientific cameras [2–9], so a viable technical approach for such microsatellites is to reuse onboard scientific cameras for sub-arcsecond attitude determination without the need for additional payload.

However, the observation strategy of scientific cameras is designed to serve scientific objectives and cannot be used for continuous satellite attitude determination. Additionally, the larger aperture and smaller field of view (FOV) of scientific cameras (compared to traditional star sensors) can lead to problems such as dimmer guide stars. Therefore, this paper proposes a high-precision attitude determination method for microsatellites that utilizes the peripheral areas of the square focal plane of a scientific camera without affecting its regular operation.

This work is carried out in the following five parts. Firstly, the star pattern features for attitude determination are introduced. Then, the theoretical model that describes the relationship between attitude determination accuracy and its main influencing factors is presented. Next, a comprehensive simulation analysis is conducted. Experimental verification is performed using typically observed star patterns. Finally, a summary and our outlook are provided.

2. Star Pattern Features for Attitude Determination

2.1. Geometric Features

The high-precision attitude determination method for microsatellites, without affecting its regular operation, utilizes the peripheral areas of the square focal plane of a scientific camera to obtain star patterns for attitude determination.

The optical lens of the scientific camera is optimized to achieve high imaging quality on the optical focal plane (usually circular), which is larger than the focal plane detector of the scientific camera (usually square). It is possible to achieve high-quality imaging with the flexible frame rate control used in high-precision attitude determination by placing attitude determination detectors in the surplus areas at the edges of the optical focal plane. Taking Figure 1 as an example, assuming the field of view of the scientific camera is a square, the attitude determination system independently controls the attitude determination areas 1, 2, 3, and 4 to acquire star patterns for attitude determination. This enables the completion of a closed-loop high-precision attitude determination task without affecting the regular operation of the scientific camera.

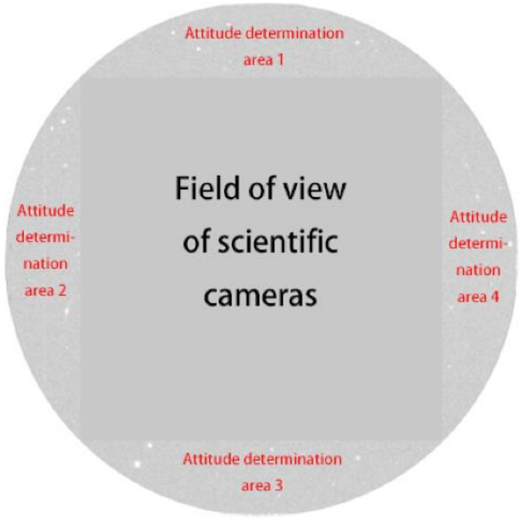

Figure 1. Candidate areas for attitude determination detectors of the scientific camera.

Assuming the camera has been calibrated, the degradation noise in star patterns, such as distortion and vignetting in the peripheral field, can be eliminated, resulting in a minor residual error equivalent to the measurement error of stars.

The star patterns for attitude determination, corresponding to our method, exhibit a certain specificity, primarily regarding their small field of view, irregular field shape, and scattered star distribution. These characteristics inevitably give rise to issues such as the special distribution of guide stars during star pattern recognition.

2.2. Features of the Number of Stars

As shown in Figure 1, the attitude determination system independently controls areas 1, 2, 3, and 4 to obtain the star patterns for attitude determination. Assuming the field of view of the scientific camera is a square with an angular size of V for each side, the field of view of the scientific camera is V^2. The total field of view of areas 1, 2, 3, and 4 is given via the following:

$$\pi\left(\frac{\sqrt{2}V}{2}\right)^2 - V^2 = 0.57V^2$$

The field of view of the star pattern for attitude determination is more than half of the field of view V^2 of the scientific camera, specifically $0.57V^2$. Therefore, a relatively large number of stars can be obtained from the attitude determination star pattern in most cases.

The typical astronomical microsatellite "Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA)" is referenced. It is equipped with a scientific camera with a field of view (Imager FOV) of approximately $8.5° \times 8.5°$. Although ASTERIA utilizes the scientific camera for attitude determination, the guide stars for attitude determination are selected from the field of view of the scientific camera. In Figure 2, the seven stars marked with "$\times$" symbols are the guide stars for attitude determination [3]. While this method of acquiring guide stars does not hinder certain scientific observations, it is not entirely independent of scientific observations and can potentially affect the efficient execution of some scientific observation tasks. This method is subject to certain limitations.

Taking the scientific camera of ASTERIA as an example, if the attitude determination method proposed in this paper is adopted, the field of view of the star pattern for attitude determination would be as follows:

$$0.57V^2 = 0.57 \times 8.5^2 = 41\left(\text{deg}^2\right)$$

Figure 2 shows that the field of view of the scientific camera of ASTERIA is not strictly inscribed within the circular field of view of the camera lens (Lens FOV). Therefore, it is evident that the field of view of the attitude determination star pattern, which has a high imaging quality, is generally greater than $0.57V^2$.

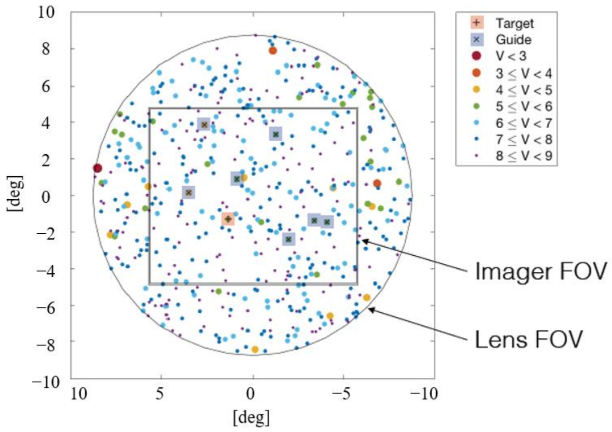

Figure 2. The imager FOV of the ASTERIA scientific camera, including target stars and guide stars for attitude determination.

The scientific camera of ASTERIA works in the visible light wavelength range, with a detection limit greater than magnitude 9. Figure 2 only displays targets brighter than magnitude 9. According to the Gaia database [19], the number of stars in the visible light wavelength range with magnitudes less than magnitude 9 is estimated to be no less than 100,000. Calculations indicate that the average number of stars within a 41-square-degree field of view is greater than 99. The guide star selection is necessary due to the relatively large number of stars in the star pattern for attitude determination.

3. Theoretical Model of Attitude Determination Accuracy and the Main Influencing Factors

It is known that the spatial geometric guide star distribution is the primary factor determining attitude accuracy [20,21]. Furthermore, there are significant differences between the attitude determination star patterns in this paper and ordinary star patterns. It consists of multiple irregular small star patterns combined into a synthetic star pattern, and there is a substantial uniformity issue in the distribution of stars. Therefore, it is essential to study the relationship between attitude determination accuracy and the main influencing factor of guide star distribution. The following section presents a theoretical modeling approach.

Attitude determination star patterns based on scientific cameras often have small stellar measurement errors. Assuming that the errors are uncorrelated and axisymmetric around the true direction of stars, according to Markley's book [22], the covariance matrix ($\boldsymbol{P_\varphi}$) of the attitude rotation vector error ($\boldsymbol{\delta\varphi}$) is the inverse of the Fisher information matrix F, as shown in Equation (1).

$$\boldsymbol{P_\varphi} = \boldsymbol{F}^{-1}, \tag{1}$$

in which $\boldsymbol{\delta\varphi} = \begin{bmatrix} \delta\varphi_1 & \delta\varphi_2 & \delta\varphi_3 \end{bmatrix}^T$,

$$\boldsymbol{P_\varphi} = \boldsymbol{\delta\varphi}(\boldsymbol{\delta\varphi})^T = \begin{bmatrix} (\delta\varphi_1)^2 & \delta\varphi_1\delta\varphi_2 & \delta\varphi_1\delta\varphi_3 \\ \delta\varphi_1\delta\varphi_2 & (\delta\varphi_2)^2 & \delta\varphi_2\delta\varphi_3 \\ \delta\varphi_1\delta\varphi_3 & \delta\varphi_2\delta\varphi_3 & (\delta\varphi_3)^2 \end{bmatrix} \tag{2}$$

$$\boldsymbol{F} = \sum_{i=1}^{N} \frac{1}{\sigma_i^2}\left[\boldsymbol{I_{3\times 3}} - \boldsymbol{r_i^{true}}\left(\boldsymbol{r_i^{true}}\right)^T\right] \tag{3}$$

σ_i^2 represents the measurement variance of star i. $\boldsymbol{I_{3\times3}}$ is a 3 × 3 identity matrix. $\boldsymbol{r_i^{true}}$ is the true direction of star i, represented as a 3 × 1 matrix of unit vectors. N is the number of identified stars used for attitude calculation.

The trace of the covariance matrix $\boldsymbol{P}_{\boldsymbol{\varphi}}$, $tr(\boldsymbol{P}_{\boldsymbol{\varphi}})$ provides the variance of the overall attitude error, which is the sum of the variances of attitude errors along the three axes of the reference frame.

$$tr\left(\boldsymbol{P}_{\boldsymbol{\varphi}}\right) = (\delta\varphi_1)^2 + (\delta\varphi_2)^2 + (\delta\varphi_3)^2 \quad (4)$$

From Equations (1)–(4), Equation (5) can be derived as follows, which more explicitly represents the relationship between the variance of the overall attitude error and the influencing factors.

$$tr\left(\boldsymbol{P}_{\boldsymbol{\varphi}}\right) = tr\left(\left\{\sum_{i=1}^{N} \frac{1}{\sigma_i^2}\left[\boldsymbol{I}_{\boldsymbol{3}\times\boldsymbol{3}} - \boldsymbol{r}_{\boldsymbol{i}}^{\boldsymbol{true}}\left(\boldsymbol{r}_{\boldsymbol{i}}^{\boldsymbol{true}}\right)^T\right]\right\}^{-1}\right) \quad (5)$$

As is shown in Equation (5), the astronomical attitude determination accuracy based on star pattern recognition is related to two factors:

(1) Guide star measurement errors.
(2) The distribution of guide stars.

In addition to measurement errors, attitude determination errors depend on the true directions of multiple guide stars, indicating an important connection between attitude determination accuracy and the guide star distribution. Furthermore, the guide star distribution can amplify the impact of guide star measurement errors on attitude determination accuracy.

Various effective methods currently achieve high-precision stellar positioning to reduce guide star measurement errors [23]. However, due to the special relative positional relationships among stars in the attitude determination star pattern of this study, and the complex relationship between the guide star distribution and attitude determination accuracy indicated in the analysis of the aforementioned model, further research is required. This study will combine a simulation analysis with inductive summarization to analyze, in-depth, the influence of the multi-area distributions of guide stars on attitude determination accuracy.

4. Simulation Analysis

The sub-arcsecond attitude determination method reusing the onboard scientific camera requires star pattern recognition to achieve attitude calculation. The triangle algorithm is the most classic and widely used star pattern recognition algorithm [24] based on the principle of matching recognition using triangle congruence. In this study, the influence of guide star distribution on attitude determination accuracy is investigated via this algorithm by setting reasonable simulation input parameters.

When the number of guide stars is large, the triangle-based star pattern recognition algorithm may encounter redundant matches or mismatches [25]. Similarly, when the number of guide stars is too small, the recognition probability of the star pattern may be low or even unsuccessful. Therefore, in the simulation analysis, the number of guide stars is set to five, which is a low number threshold with a high recognition probability [26,27]. The measurement error range is the same for each guide star, and the reference star catalog does not include interfering stars.

The following simulation analysis examines the attitude determination accuracies and probabilities when five guide stars are differently distributed within attitude determination areas 1, 2, 3, or 4, as shown in Figure 1. The distribution is characterized by the coverage of guide stars in the attitude determination areas and the proportion of the average field of view occupied by the guide star triangles to the total field of view of the attitude determination areas.

Firstly, the reliability of the simulation system to investigate the impact of the guide star distribution on attitude determination accuracy is demonstrated and verified in the following two aspects. (1) When the guide star measurement error is set to zero, regardless of the distribution of the five guide stars within the attitude determination areas, the matching errors after successful star pattern recognition are in the order of magnitude of 10^{-6} arcseconds, which can be neglected. This demonstrates the reliability of the star pattern recognition algorithm itself without computational errors. (2) The method of traversing the attitude determination areas with a step size of 7% of the scientific camera's field of view is adopted to construct all possible combinations of five guide stars, making the simulation results more comprehensive and avoiding analysis result biases based on specific combinations.

Figure 3 shows the attitude determination accuracy for different distributions of the five guide stars when the guide star measurement error is 0.1″. Figure 4 presents the corresponding probabilities for different attitude determination accuracies in this scenario. Figure 5 shows the probabilities of achieving an attitude determination accuracy better than 0.1″ for different average coverage ratios of the triangles formed by the guide stars. Since attitude determination areas 1, 2, 3, and 4 are the same, only one case of each distribution type needs to be provided in the simulation. For example, the case where guide stars are only distributed in area 1 represents the scenario where guide stars are only distributed in area 2, 3, or 4. The case in which guide stars are distributed in areas 1 and 2 represents the scenario where adjacent areas have guide star distributions, for example. The case where guide stars are distributed in areas 1, 2, 3, and 4 represents the only scenario where all four areas have guide star distributions.

Figure 3 shows that as the average coverage ratio of the triangles formed by the five guide stars increases, the overall trend of attitude determination accuracy improves.

As shown in Figures 3 and 4, even when the guide star measurement accuracy reaches sub-arcsecond levels, a compact guide star distribution can still result in poor attitude determination accuracy. For example, when the guide stars are distributed in only one of the attitude determination areas, most attitude determinations have an accuracy bigger than 0.1″ and even bigger than 1″.

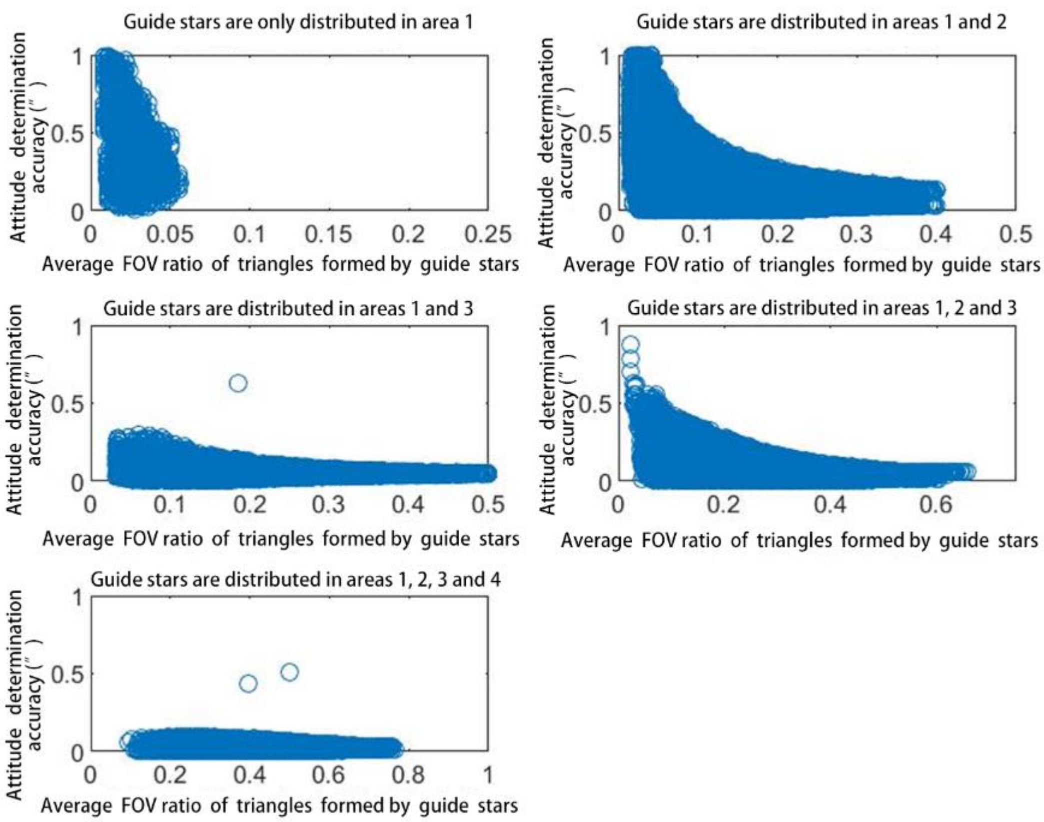

Figure 3. Attitude determination accuracy for different distributions of the guide stars when the guide star measurement error is 0.1″.

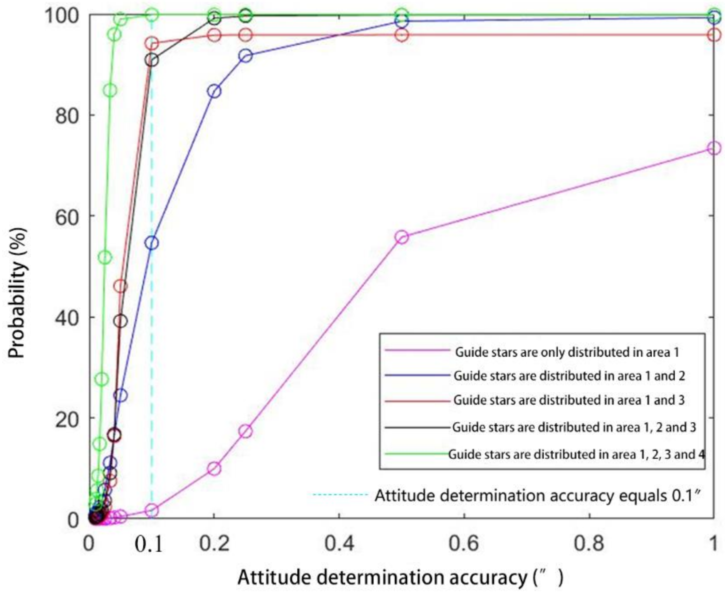

Figure 4. Probability of outperforming different attitude determination accuracy when the guide star measurement error is $0.1''$.

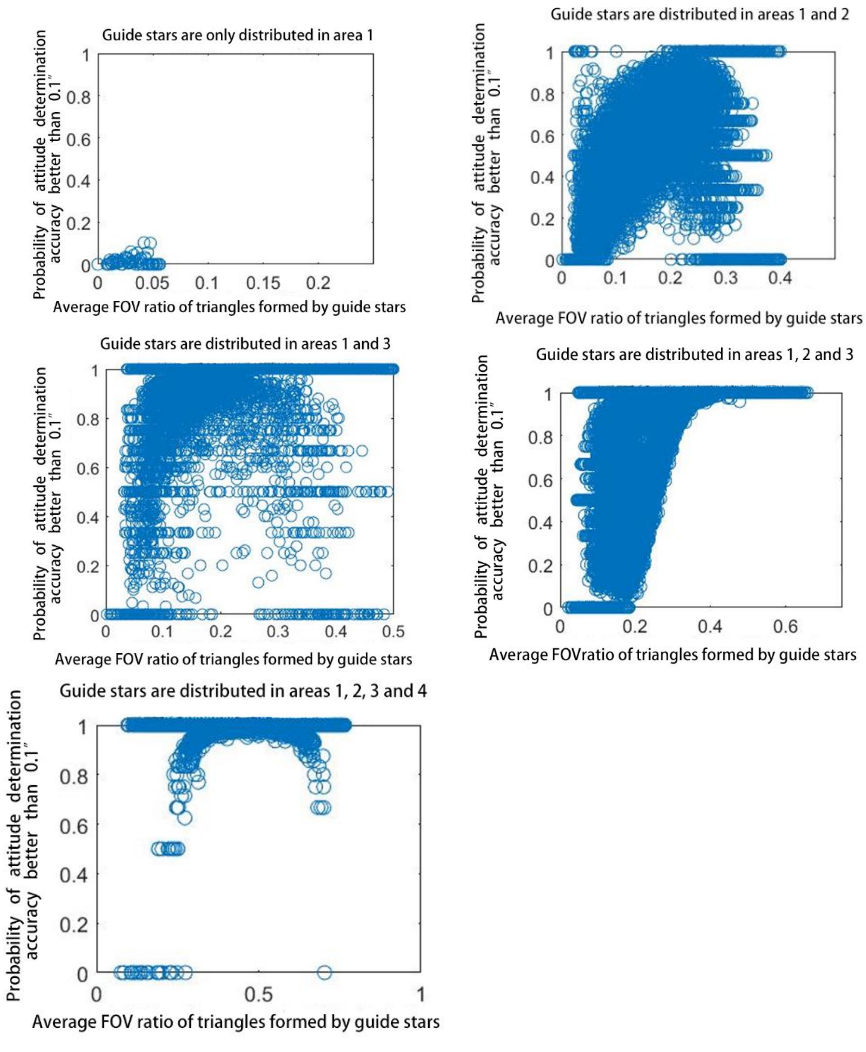

Figure 5. Probability statistics of the attitude determination accuracy better than $0.1''$ when the measurement error of the guide stars is $0.1''$.

Figure 4 shows that to achieve an attitude determination accuracy better than 0.1″, the case where the guide stars are distributed in all four areas is better than the case where the guide stars are distributed in two symmetric areas; which is better than the case where the guide stars are distributed in three areas; which is better than the case where the guide stars are distributed in adjacent areas; which is better than the case where the guide stars are distributed in only one area. Among these cases, the probability of achieving an attitude determination accuracy better than 0.1″ is over 90% when the guide stars are distributed in all four areas, two symmetric areas, and three areas.

Figure 5 presents the impact of the average coverage ratio of the triangles formed by the guide stars on the probability of attitude determination accuracy. When the guide stars are distributed in areas 1, 2, and 3 (i.e., distributed in three areas) and the average coverage ratio of the triangles formed by the guide stars is not less than 0.0567, the average probability of achieving attitude determination accuracy better than 0.1″ remains above 98.5%. When the guide stars are distributed in all four areas, the average probability of achieving attitude determination accuracy better than 0.1″ is consistently above 99%. When the guide stars are distributed in areas 1 and 3 (i.e., distributed in two symmetric areas), although the probability of attitude determination accuracy better than 0.1″ is not very stable, higher average coverage ratios of the triangles formed by the guide stars generally led to better overall probabilities. On the other hand, when the guide stars are distributed in only one area or two adjacent areas, the probability of an attitude determination accuracy better than 0.1″ is generally low or very unstable.

Table 1 provides the average probabilities of achieving attitude determination accuracy better than 0.1″ for different guide star distributions under different measurement errors.

Table 1. Average probability of attitude determination accuracy better than 0.1″ under different measurement errors and guide star distributions.

Average Probability of Attitude Determination Accuracy Better than 0.1″ (%)	Guide Stars Are Only Distributed in One Area	Guide Stars Are Distributed in Two Adjacent Areas	Guide Stars Are Distributed in Two Symmetrical Areas	Guide Stars Are Distributed in Three Areas	Guide Stars Are Distributed in Four Areas
Measurement error 0.3″	0.15	11.08	7.48	9.04	84.90
Measurement error 0.25″	0.24	16.46	16.38	16.75	95.97
Measurement error 0.2″	0.44	24.45	46.10	39.18	98.99
Measurement error 0.1″	1.65	54.67	94.21	90.94	99.87
Measurement error 0.05″	9.92	84.73	95.85	99.18	99.87
Measurement error 0.02″	55.82	98.60	95.89	99.84	99.87
Measurement error 0.01″	73.45	99.3	95.89	99.84	99.87

According to Table 1, when the guide star measurement error is bigger than the required attitude determination accuracy, to achieve a high success rate of 90% or above for an attitude determination accuracy of 0.1″, the measurement error should be smaller than 0.25″, and the guide stars should be distributed in all four areas. When the measurement error is equal to or smaller than the required attitude determination accuracy, the guide stars can be distributed in all four areas, three areas, or two symmetric areas to achieve a high success rate of 90% or above for an attitude determination accuracy of 0.1″. However, if the guide stars are distributed in only one area, even if the measurement error is 1/10 of the attitude determination accuracy, the success rate of achieving 0.1″ attitude determination accuracy is still not high, only 73.45%.

When the guide star measurement error is 0.1″, the probability of achieving attitude determination accuracy better than 0.1″ with guide star distribution in three areas is not ideal, being slightly higher than 90% at 90.94%. However, as shown in Figure 5, the probability of achieving 0.1″ attitude determination accuracy can be significantly improved by selecting guide stars with larger average coverage ratios of the triangles formed by them. If the average coverage ratio of the triangles formed by the guide stars is not less than 0.0567, the average probability of achieving attitude determination accuracy better than 0.1″ can be increased to 98.5%.

When the guide star measurement error is 0.3″, the average probability of achieving attitude determination accuracy better than 0.1″ is lower than 90%. In this case, selecting guide stars with higher average coverage ratios of the triangles formed by them can be used to achieve 0.1″ attitude determination accuracy. This is illustrated in Figure 6.

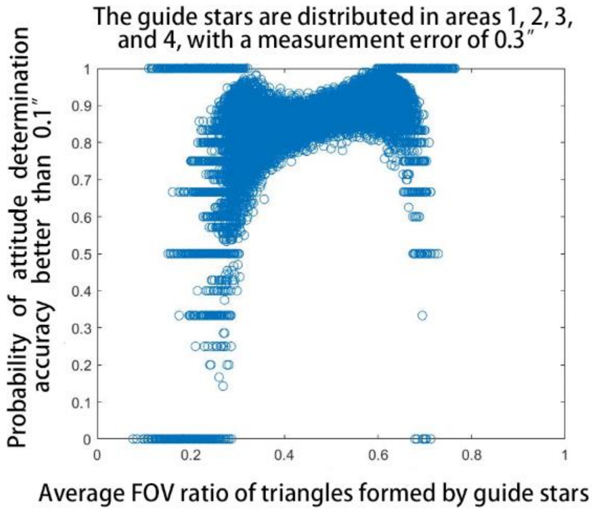

Figure 6. Probability statistics of the attitude determination accuracy better than 0.1″ when the measurement error of the guide stars is 0.3″.

As is depicted in Figure 6, when the average coverage ratio of the triangles formed by the guide stars is equal to or more than 0.3537, the average probability of achieving attitude determination accuracy better than 0.1″ consistently exceeds 90.0%. When the average coverage ratio is equal to or more than 0.5867, the average probability of an attitude determination accuracy better than 0.1″ consistently exceeds 95.0%. This indicates that in addition to improving attitude determination accuracy via the selection of guide star distribution, further improvement can be achieved by selecting guide stars with higher average coverage ratios of the triangles formed by them.

In summary, the attitude determination system detectors should be configured with four attitude determination areas, when the guide star measurement error is bigger than the required attitude determination accuracy. When the guide star measurement error is equal to or smaller than the required attitude determination accuracy, the configuration of four attitude determination areas should be prioritized, followed by three areas or two symmetric areas. When selecting guide stars for star pattern recognition, it is advisable to cover as many attitude determination areas as possible and choose guide stars with higher average coverage ratios of the triangles formed by them.

5. Experimental Verification with Observed Star Patterns

The observed star patterns with different resolutions were obtained from the DSS database on the SkyView website [28]. The Digitized Sky Survey (DSS), performed with Palomar and UK Schmidt telescopes, is a ground-based imaging survey of the entire sky in several colors [29]. A dense star field, i.e., an observing region centered at a right ascension of 150° and a declination of 0°, where there are many bright stars, was selected. Additionally, a sparse star field, i.e., an observing region centered at a right ascension of 240° and a declination of −80° located in the high-latitude region of the southern hemisphere with fewer bright stars, was also chosen.

A total of four observed star patterns with certain contrasts were obtained. To ensure that the number of effective pixels of the observed star patterns of the scientific camera is 2048 × 2048, the initial number of effective pixels of each obtained star pattern was 2896 × 2896, covering the peripheral high-quality imaging areas of the square-shaped detector of the scientific camera. The key parameters can be found in Table 2.

Table 2. Key parameters of astronomically observed star patterns.

	Equatorial Coordinates of the Central Point	Number of Effective Pixels	Pixel Scale	FOV
Star pattern 1	(150°, 0°)	2896 × 2896	2″	1.6° × 1.6°
Star pattern 2	(150°, 0°)	2896 × 2896	0.5″	0.4° × 0.4°
Star pattern 3	(240°, −80°)	2896 × 2896	2″	1.6° × 1.6°
Star pattern 4	(240°, −80°)	2896 × 2896	0.5″	0.4° × 0.4°

By conducting star pattern recognition with different attitude determination area configurations, the average attitude determination accuracy under different average guide star measurement errors was obtained, as shown in Tables 3 and 4. The attitude determination accuracy corresponding to three areas, two symmetric areas, two adjacent areas, and one area in the table represents the average value of all possible combinations since the geometric distribution of stars in the four optional attitude determination areas in the observed star pattern is different. For example, the combination of two symmetric areas includes two different cases, as shown in Figure 7.

Table 3. Attitude determination accuracy under different measurement errors and guide star distributions with an observation center at (150°, 0°).

Average Attitude Determination Accuracy (″)	Guide Stars Are Only Distributed in One Area	Guide Stars Are Distributed in Two Adjacent Areas	Guide Stars Are Distributed in Two Symmetrical Areas	Guide Stars Are Distributed in Three Areas	Guide Stars Are Distributed in Four Areas
Average measurement error 0.2″	6.51	0.34	0.21	0.21	0.08
Average measurement error 0.05″	18.02	0.13	0.06	0.10	0.04

Table 4. Attitude determination accuracy under different measurement errors and guide star distributions with an observation center at (240°, −80°).

Average Attitude Determination Accuracy (″)	Guide Stars Are Only Distributed in One Area	Guide Stars Are Distributed in Two Adjacent Areas	Guide Stars Are Distributed in Two Symmetrical Areas	Guide Stars Are Distributed in Three Areas	Guide Stars Are Distributed in Four Areas
Average measurement error 0.2″	34.04	0.42	0.21	0.26	0.07
Average measurement error 0.05″	1.17	0.21	0.03	0.07	0.03

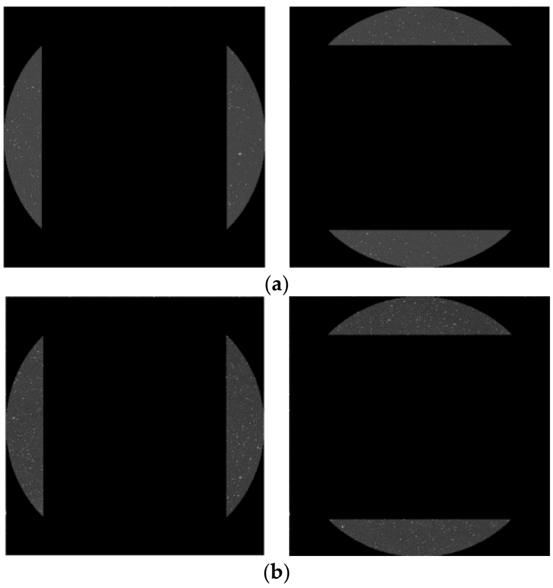

Figure 7. Two combinations of symmetrical two-attitude determination areas. (**a**) Observation center (150°, 0°), FOV 1.6° × 1.6°; (**b**) observation center (240°, −80°), FOV 1.6° × 1.6°.

According to Tables 3 and 4, when the guide star measurement error is bigger than $0.1''$, only the attitude determination accuracy achieved with the configuration of four attitude determination areas is better than $0.1''$, while other configurations do not meet the requirement. When the guide star measurement error is smaller than $0.1''$, the attitude determination accuracy achieved with the configurations of four attitude determination areas, three attitude determination areas, and two symmetric attitude determination areas is better than $0.1''$ for all. This is consistent with the simulation analysis results mentioned above.

6. Conclusions

By analyzing the sub-arcsecond attitude determination accuracy requirements for microsatellites, a high-precision attitude determination method was proposed. This method uses the on-board scientific camera's optical system and its high-quality imaging areas around the square detector's outer circumference as attitude determination areas, without affecting the normal operation of the scientific camera. Through an analysis of the geometric and star number features of the attitude determination star patterns obtained using this method, it was found that the attitude determination star patterns have special characteristics, such as a small field of view, irregular shape, and scattered distribution, which inevitably lead to issues, including peculiar star distribution. Additionally, the high limiting magnitude detection capability of the scientific camera requires the selection of guide stars.

The relationship between the attitude determination accuracy and the main influencing factors was analyzed using a theoretical model, and it was concluded that the guide star distribution was the main influencing factor. Further analysis of the impact of multi-area guide star distributions on attitude determination accuracy was carried out by combining simulation analysis and inductive summarization due to the complexity of the relationship.

The coverage impacts of guide stars in the attitude determination areas and the average coverage ratio of triangles formed by the guide stars on attitude determination accuracy were determined using the simulation analysis results. It was found that when the guide star measurement error is bigger than the required attitude determination accuracy, the attitude determination system detectors should be configured with four attitude determination areas. When the guide star measurement error is equal to or smaller than the required attitude determination accuracy, the configuration of four attitude determination areas should be prioritized, followed by three attitude determination areas or two symmetric attitude determination areas. When selecting guide stars for star pattern recognition, it is advisable to cover as many attitude determination areas as possible and to choose guide stars with higher average coverage ratios of the triangles formed by them.

The experimental verification results of the observed star patterns in dense and sparse star fields are consistent with the simulation analysis results.

The research results can provide an important reference for optimizing the attitude determination area configuration, constructing navigation star catalogs, and studying star pattern recognition algorithms for microsatellites equipped with scientific cameras. They also serve as crucial technical support for expanding the scientific application scope and improving the scientific output of microsatellites.

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