CCD Image Stitching Experiment Postprint

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Abstract

To obtain high-precision astronomical images with a large field of view, a mosaicking method for telescope CCD images was implemented. The coordinate transformation from the original images to the final mosaic image employed a six-constant model combined with the UCAC4 star catalog. Unlike hardware-level mosaicking, a pixel-by-pixel grayscale value redistribution scheme was used for image fusion. Furthermore, CCD images captured by the 2.4m telescope at Yunnan Observatories were used for testing. The results demonstrate that this algorithm can produce high-quality large-field CCD images, enable intuitive detection of moving objects, and significantly improve the signal-to-noise ratio of faint stars. High-precision image mosaicking is also inseparable from the preprocessing of distortion correction for raw data. Compared with those without distortion correction, the positional accuracy of image mosaicking improved by approximately a factor of two (about 0. 02 pixel).

Full Text

An Experiment on CCD Image Mosaicking

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Abstract

To obtain high-precision astronomical images with a wide field of view, we have implemented a method for mosaicking telescope images. Coordinate transformation from original images to the final combined frame employs a six-parameter model together with the UCAC4 catalog. Unlike hardware-level mosaicking, our approach uses a pixel-by-pixel redistribution scheme for image fusion. The algorithm has been tested extensively on CCD frames obtained with the 2.4 m telescope at Yunnan Observatories. Results demonstrate that this method can

produce high-quality wide-field CCD frames, enabling straightforward detection of moving objects and yielding significant improvements in the signal-to-noise ratio (SNR) of faint stars. High-precision image mosaicking is inseparable from preprocessing that corrects geometric distortions in the raw data; compared with uncorrected frames, distortion correction improves the positional accuracy of the mosaicked images by approximately a factor of two (to about 0.02 pixel).

1. Introduction

Long-focus telescopes typically produce small field-of-view images that often suffer from insufficient reference stars in the target region [1], a problem caused by either excessively faint reference stars or too few available stars. While overlapping exposure observations can address this issue for small-field astrometric calibration [2–3], the reduction process remains complex. This paper presents a direct approach to obtain wide-field images through image mosaicking that can be used for high-precision positional measurements.

Our method draws inspiration from the "Drizzle" algorithm originally developed for mosaicking dithered Hubble Space Telescope (HST) images [6], which has also been applied to other telescopes including the Spitzer Space Telescope. The Drizzle method ensures high resolution and preserves optical statistics through linear reconstruction of undersampled images [7]. However, ground-based telescopes are affected by atmospheric seeing and do not require sub-pixel dithering; simple translation and intensity summation suffice. For high-fidelity imaging, geometric distortion correction is essential because optical systems—such as lenses affected by gravity—introduce distortions that cause pixel values to deviate from their true positions. We employ Peng et al.' s geometric distortion solution method [12] to obtain distortion-free images, which has proven successful for planetary satellites and near-Earth asteroids like Phoebe and Apophis [13–14].

Mosaicking offers several advantages: it enables detection of faint stars by effectively increasing cumulative exposure time through overlapping frames, thereby improving SNR proportionally with the number of overlaps. Multiple short-exposure frames can overcome limitations of long exposures, preventing saturation of bright stars [15] and facilitating visual identification of moving objects [16]. For high-precision astrometry, distortion correction is crucial, as demonstrated by its significant impact on position measurements [13–14].

2. Algorithm Description

We have developed software in a Windows/Visual C++ environment to implement the mosaicking algorithm. The input consists of multiple CCD frames and the positions of primary reference stars in each frame from the UCAC4 catalog [17]. Star matching between images and catalog stars employs the method described in [19]. If sufficient reference stars are available, a distortion matrix is derived and applied to correct the input images. Notably, a distortion model obtained from dense star fields can be directly applied to sparse star images, as the model remains stable [12].

The mosaicking procedure is illustrated in Figure 1. Input images may be raw or distortion-corrected frames. The six-parameter plate model establishes the relationship between standard coordinates and pixel coordinates, accounting for translation, rotation, scaling, and shear effects, as well as small differential atmospheric refraction and aberration corrections corresponding to pointing inaccuracies.

The transformation from celestial coordinates (α, δ) to standard coordinates (,) is given by:

$$\xi = \frac{\cos\delta\sin(\alpha - A)}{\sin\delta\sin D + \cos\delta\cos D\cos(\alpha - A)}$$
$$\eta = \frac{\sin\delta\cos D - \cos\delta\sin D\cos(\alpha - A)}{\sin\delta\sin D + \cos\delta\cos D\cos(\alpha - A)}$$

where (A, D) are the celestial coordinates of the tangent point of the projection plane. The six-parameter model relates standard coordinates (,) to pixel coordinates (x, y) as:

$$\xi = ax + by + c$$
$$\eta = dx + ey + f$$

The six plate constants (a, b, c, d, e, f) are solved via least-squares fitting. We select the image nearest the field center as the reference frame and transform all other images to this plane. The coordinate transformation procedure (Figure 2) involves converting pixel positions to celestial coordinates through inverse operations, then transforming to the reference frame’ s pixel coordinates using the above equations.

For pixel intensity redistribution, when an input pixel is mapped to the reference frame, its coordinates are typically non-integer. The pixel’ s intensity is distributed among neighboring output pixels proportionally to the overlapping area. If the detector’ s fill factor is 100%, the intensity is allocated according to the area coverage in the reference frame. This process repeats for all pixels in all input frames, with intensities accumulating at each output pixel location. To normalize, the final intensity values are divided by the number of overlapping frames, bringing the entire output image to a uniform exposure level.

3. Observations and Preprocessing

The observational data were obtained with the 2.4 m telescope at Lijiang Station of Yunnan Observatories on January 12, 2015, using the Yunnan Faint Object

Spectrograph and Camera (YFOSC). A total of 16 frames were acquired with 30 s exposure each. YFOSC employs a back-illuminated CCD with extremely low-noise amplifiers. Its main technical parameters are listed in Table 1 .

Due to dithered observations, some stars appear in multiple frames (maximum 8 times). After flat-fielding and cropping, each image measures 1900 × 1900 pixels, covering 9 × 9 . Geometric distortion is corrected using the iterative method described in [12] to determine and remove distortions.

4. Results and Analysis

The left panel of Figure 3 shows the output mosaic combining all 16 distortion-corrected frames, with dimensions 4478 × 4478 pixels (blank regions correspond to unobserved areas). The right panel displays an enlarged view of the central region, clearly showing the trajectory of asteroid Apophis as a near-linear trail of multiple star images. Image mosaicking effectively increases exposure time by accumulating information from multiple frames, improving SNR according to Poisson statistics while avoiding saturation of bright stars.

Figure 4 compares a randomly selected region (4137 × 4137 pixels) between a single input frame and the mosaic. In the short-exposure input image (left), circled regions appear as noise with barely recognizable faint stars. In the mosaic (right), these stars become clearly visible, demonstrating how mosaicking enhances detection of faint objects.

Figure 5 plots intensity profiles of a faint star (estimated magnitude ~16) in mosaics created with different numbers of input frames. As overlap count increases, the intensity distribution approaches a Gaussian shape, with SNR improving proportionally. Similar behavior is observed along both X and Y axes.

5. Impact of Distortion Correction

To quantify distortion correction effects, we measured positional deviations in the final mosaic. Using the six-parameter model and UCAC4 catalog, each star’s measured coordinates in the input frames are transformed to the output frame and averaged to obtain theoretical positions. The deviations between searched positions and theoretical positions (Δx, Δy) are calculated.

For the central 1000 × 1000 pixel region, the mean deviation is $±$0.02 pixel with standard deviations of 0.027 pixel (Δx) and 0.029 pixel (Δy) when using distortion-corrected input frames—representing only the error introduced by the mosaicking process itself. In contrast, mosaics from uncorrected frames show standard deviations of 0.054 pixel (Δx) and 0.056 pixel (Δy). Thus, distortion correction reduces positional scatter by approximately half, to about 0.014–0.018 pixel (8 mas). Figure 6 shows these deviations, while Figure 7 displays the standard deviations for individual stars, with some elevated values caused by background differences in overlapping regions or moving objects crossing stellar images.

6. Conclusion

This experiment demonstrates that high-precision CCD image mosaicking is achievable. Distortion-corrected images produce superior mosaics with increased detection of faint stars and significantly improved SNR. However, computational efficiency requires optimization; mosaicking 16 frames on a high-memory computer takes considerable time due to the pixel-by-pixel interpolation and area calculations for millions of pixels per frame. Future work will focus on background matching and further precision improvements.

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Note: Figure translations are in progress. See original paper for figures.