A Fast Sharpness Evaluation Algorithm for Automatic Focusing of Wide-Angle Telescopes Based on Energy Concentration (Postprint)

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Abstract

The ground-based wide-field camera array comprises 36 tiled wide-field cameras, primarily targeting optical transients, and is characterized by an ultra-large field of view, high temporal sampling rate, and real-time data processing capabilities. Real-time automatic focusing is essential for automated system observations and enhanced scientific productivity. The core objective of automatic focusing is to improve image energy concentration; however, conventional evaluation metrics such as the 50% energy radius of stellar images and the full width at half maximum (FWHM) of the point spread function are computationally intensive. Leveraging the observation that during focusing of the ground-based wide-field camera array, the central region energy of stellar images varies significantly while the total flux and spatial distribution remain essentially constant, we propose a fast sharpness evaluation algorithm based on the percentage of central region flux relative to total stellar flux, and conduct a detailed investigation of two flux apertures. Additionally, we simplify the flux calculation method in the algorithm and refine critical parameters including background estimation, star selection criteria, and the number of selected stars, thereby establishing a comprehensive sharpness evaluation algorithm suitable for real-time automatic focusing of the ground-based wide-field camera array system. The algorithm delivers accurate results with a per-image processing time of approximately 0.1 seconds, satisfying the system' s requirements for rapid automatic focusing.

Full Text

Preamble

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Fast Clarity Evaluation Algorithm for Automatic Focusing of Wide-Angle Telescopes Based on Energy Concentration

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Abstract

The Ground Wide Angle Cameras (GWAC) consists of 36 wide-angle cameras for observing optical transients, featuring an ultra-large field of view, high temporal sampling rate, and real-time data processing. Real-time automatic focusing is essential for automated observations and maximizing scientific output. The core objective of auto-focusing is to improve the energy concentration of stellar images. Current evaluation metrics such as energy radius and the full width at half maximum (FWHM) of the point spread function are computationally expensive. Based on the observation that during focusing, the central region of star images changes dramatically while the total flux and overall distribution range remain essentially constant, this paper proposes a fast clarity evaluation algorithm that calculates the percentage of flux within a central region relative to the total flux. A detailed study of two aperture radii is presented. The flux calculation method is further simplified, and parameters affecting the algorithm—including background value selection, star selection criteria, and number of stars—are refined. The final algorithm is accurate, with a computation time of approximately 0.1 seconds per image, meeting the requirements for rapid automatic focusing in the GWAC system.

Keywords: Image clarity evaluation; Wide-angle telescope; Auto-focusing; Energy concentration

Introduction

The Ground Wide Angle Cameras (GWAC), a ground-based project for the Chinese-French astronomical satellite, primarily targets optical transients. The system comprises 36 wide-angle telescopes with 12 m pixels, 4k × 4k CCDs, individual fields of view, and a combined field of approximately . The system achieves a temporal sampling rate of 15 seconds with real-time data processing, representing a significant improvement over similar astronomical facilities.

For GWAC, detection capability is a core technical indicator. Increasing the detection depth by one magnitude increases the number of detectable sources by , substantially raising the probability of detecting transients. However, GWAC is a short focal ratio system, causing star image energy to disperse and reducing detection capability. The core objective of focusing is to maintain the system at the state of maximum energy concentration to enhance scientific output. Due to temperature effects, focal positions shift, making automatic focusing indispensable for efficient operation of all 36 telescopes.

Traditional metrics for evaluating star image energy concentration include the energy radius, which requires multiple aperture photometry measurements to obtain growth curves followed by interpolation—computationally prohibitive for GWAC’ s large field of view with numerous undersampled stars. The FWHM of the point spread function (PSF) is another common metric, related to the PSF parameter in a Gaussian model: $PSF = H \times e^{-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}}$ and $FWHM = 2\sqrt{2\ln 2}\sigma \approx 2.355\sigma$. While widely used and currently implemented in the GWAC prototype system via IRAF, this method is sensitive to model selection and fitting approaches, involves interpolation and non-linear fitting, and requires approximately 10 seconds per image—far exceeding the allocation of for clarity evaluation in GWAC’ s real-time processing pipeline.

Fast Algorithm Based on Energy Concentration

Principle of the Fast Algorithm

During focusing, defocusing causes star image profiles to become dispersed while the total energy remains constant. Analysis of GWAC focusing images confirms this pattern: energy in the central region diffuses outward. In a focus sequence moving the optical axis in 5 m steps from defocused to focused and back, approximately 50 stars were selected for aperture photometry with radii varying from 1 to 10 pixels. The flux variation differs dramatically across radii: smaller apertures show greater variation, while larger radii remain relatively stable.

The relative change in flux within an aperture during focusing, normalized by the mean flux, serves as an indicator of sensitivity. Table 1 shows this metric decreases from 1.33 at 1 pixel to 0.22 at 10 pixels, demonstrating that central regions are most sensitive to focusing changes.

**** The relative change of flux within different radii

Radius (pixel)	Relative Change
1	1.33
2	1.00
3	0.76
4	0.58
5	0.46
6	0.37
7	0.30
8	0.26
9	0.22

The algorithm uses the ratio of flux within a small central radius r to flux within a larger radius R as the clarity evaluation function. The radius R should contain a large percentage of total flux (70-100%) and remain relatively stable during focusing, allowing it to be fixed across images to simplify computation. Analysis shows the radius containing 70-100% energy varies only slightly (standard deviation < 1 pixel) during focusing, as shown in Figure 3 and Table 2.

**** The mean and variance of radii containing 70%-100% energy

Energy Percentage	Mean Radius (pixel)	Variance (pixel)
70%	3.527	0.925
80%	4.446	0.998
90%	5.937	1.016
100%	9.329	0.784

For GWAC, using 80-90% energy radius for R avoids crowded field effects while maintaining accuracy. The central radius r should be as small as possible for maximum sensitivity. Simulations with varying r values (1.0 to 3.0 pixels) on images with FWHM 2.8 pixels show that smaller r yields higher sensitivity and smoother curves, confirming that regions closer to the center are more sensitive to defocusing.

System Design and Implementation

Figure 6 shows the auto-focusing system flow. After star detection using SExtractor, the algorithm: 1. Determines fixed radii R and r 2. For each star, calculates total flux within radius R 3. Calculates flux within central radius r (pixel values minus background) 4. Computes the percentage ratio 5. Averages across N stars for the final clarity parameter

[**Figure 6: see original paper**] The auto-focusing system: (a) focusing flow; (b) clarity evaluation algorithm flow

Algorithm Design and Optimization

Flux Calculation Simplification

For auto-focusing, absolute photometric accuracy is unnecessary; relative changes near focus are paramount. The algorithm simplifies flux calculation by using direct summation within square regions instead of circular apertures. Near focus, the relative error between this simplified method and SExtractor’ s circular photometry is less than 2%, as shown in Figure 7. The square approach eliminates sub-pixel calculations, significantly reducing computation.

[**Figure 7: see original paper**] The relative error of simple method vs. SExtractor

Background Value Selection

For large-field telescopes, background distribution is non-uniform due to sky conditions. Traditional methods use annuli around each star, but given GWAC' s small calculation radii and abundant stars, the algorithm omits per-star background calculation and uses a fixed empirical value, which proves sufficient.

Star Selection

Single-star statistics are noisy. The algorithm uniformly selects N bright, non-saturated stars across the field. While larger N improves precision, it increases computation time. Tests with $N = 100$, 200, and 300 show that $N = 200$ provides smooth curves without excessive noise, balancing speed and accuracy (Figure 8).

[**Figure 8: see original paper**] Result of different star amounts

Star Center Precision

The algorithm uses SExtractor for star detection. Since it sums flux over a region around the center, precise centroiding is not critical. Tests using floor, round, and SExtractor centers yield consistent focus positions, though simplified centers produce noisier curves (Figure 9). For GWAC, using the brightest pixel coordinates as center is sufficient.

[**Figure 9: see original paper**] Result of different center calculations

Experimental Results

The algorithm was tested on two focus sequences (5 m and 10 m step sizes) from defocused to focused states. Results were compared with FWHM values computed by IRAF.

[**Figure 10: see original paper**] Final result on focusing images with 5 m gap
[**Figure 11: see original paper**] Final result on focusing images with 10 m gap

In both experiments, the algorithm' s identified focus position differed from the FWHM method by only one frame—a negligible difference given GWAC' s 28 m depth of field. The algorithm correctly locates the system focus with a unimodal focus curve.

Performance

For 1.1 gigapixel GWAC images, the Python implementation processes a single frame in approximately 0.1 seconds with $N = 5000$ stars—two orders of magnitude faster than the 10-second FWHM method. This meets GWAC' s real-time auto-focusing requirements.

Conclusion

The core objective of telescope auto-focusing is improving star image energy concentration. By analyzing GWAC' s image characteristics during focusing, this paper developed a fast clarity evaluation algorithm based on the ratio of central to total flux. Through systematic optimization of parameters and simplification of calculations, the algorithm achieves accurate focus determination with minimal computation. The method is directly aligned with the focusing objective, robust to tracking errors, and provides a valuable reference for similar telescope systems.

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