

Postprint: Research on Methods for Improving YFOSC Spectroscopic Observation Efficiency

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Abstract

The Lijiang 2.4-meter telescope, as the largest-aperture general-purpose optical telescope currently in China, plays a very important role in nighttime astronomical observations in China. According to the overall observation time allocation in recent years, spectroscopic observations with the Yunnan Faint Object Spectrograph and Camera (YFOSC) account for the largest proportion of the total observation time of the Lijiang 2.4-meter telescope. Therefore, improving its spectroscopic observation efficiency and data quality has become a critical factor for ensuring stable scientific productivity of the telescope. This paper will introduce methods for improving the efficiency and quality of YFOSC spectroscopic observations with the Lijiang 2.4-meter telescope, starting from two important factors that affect YFOSC spectroscopic observation efficiency—star image alignment with the slit and telescope closed-loop tracking.

Full Text

Research on Methods for Improving YFOSC Spectroscopic Observation Efficiency

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Abstract: The Lijiang 2.4-meter telescope, currently the largest general-purpose optical telescope in China, holds a pivotal position in the nation's nighttime astronomical observation landscape. Analysis of recent observation time allocations reveals that spectroscopic observations with the Yunnan Faint Object Spectrograph and Camera (YFOSC) constitute the largest share of the telescope's total observing time. Consequently, enhancing YFOSC's

spectroscopic observation efficiency and data quality has become critical for ensuring stable scientific output from the telescope. This paper addresses two key factors affecting YFOSC spectroscopic efficiency—star acquisition into the slit and telescope closed-loop guiding—and presents methods to improve the quality and efficiency of YFOSC spectroscopic observations at the Lijiang 2.4-meter telescope.

Keywords: spectroscopic observation; star acquisition into slit; telescope closed-loop guiding

Spectroscopic observation has consistently represented one of the most important operational modes for the Lijiang 2.4-meter telescope. The installation of a rapid instrument exchange system at the Cassegrain focus in 2012 enabled observers to select among five scientific instruments—including YFOSC, LiJET, HiRES, PICCD, and CHILI—according to observational requirements, with switching times of under half a minute. This configuration covers long-slit, fiber, and integral field unit spectroscopic observations, fulfilling scientific demands ranging from photometric to low-, medium-, and high-dispersion spectroscopic observations. Figure 1 illustrates the optical path of the Lijiang 2.4-meter telescope, with YFOSC positioned at the Cassegrain direct port. YFOSC's spectroscopic targets are typically faint and low-luminosity objects, resulting in relatively low signal-to-noise ratios in the observed data. Under given seeing conditions, telescope tracking precision significantly influences the coupling efficiency between stellar images and the YFOSC slit, which in turn determines the quality of spectroscopic data. Therefore, achieving high-quality and efficient spectroscopic observations requires meeting three criteria through coordinated operation of the telescope control system (TCS) and guide system hardware: (1) small pointing errors—currently less than 4 arcseconds after applying pointing model corrections, ensuring targets remain within the field of view; (2) high-precision slit acquisition—ensuring accurate and efficient coupling between stellar images and the YFOSC slit after pointing to the target; and (3) high-precision closed-loop tracking—necessitated by YFOSC's typical integration times exceeding 1000 seconds for faint targets, requiring sustained tracking precision throughout the exposure.

This paper focuses on the second and third technical challenges affecting YFOSC spectroscopic efficiency, elaborating on how to achieve high-precision slit acquisition and closed-loop tracking based on the existing software control and guide system hardware of the Lijiang 2.4-meter telescope. Section 1 introduces YFOSC spectroscopic observations and factors influencing its efficiency. Section 2 discusses the application of point pattern matching algorithms, using telescope closed-loop tracking as an example. Section 3 describes optimizations to the star acquisition algorithm. Section 4 presents performance tests after implementing these improvements. Section 5 provides a brief summary.

1.1 YFOSC Spectroscopic Observation Process

As shown in Figure 2, YFOSC spectroscopic observations are completed through the coordinated participation of various subsystems under the Observatory Control System (OCS), including TCS (Telescope Control System), ICS (Instrument Control System), and OAS (Observation Assistant System). The current spectroscopic observation workflow proceeds as follows: observers input target coordinates through the user interface provided by the observation control system; after the telescope points to the target, commands are issued through TCS to adjust the telescope pointing, moving the target within the field of view; the difference between the target's coordinates on the YFOSC camera focal plane and the slit center position is calculated, with values below threshold indicating correct positioning at or near the slit center; observers select appropriate slit sizes based on target type and seeing conditions, insert the slit and capture a verification image, then insert the grating and activate the guide camera for closed-loop tracking while selecting integration times according to scientific requirements; finally, after observation completion, data are inspected and archived.

1.2.1 Optical Structure of the Cassegrain Guide System

The guide system serves as a critical component for closed-loop tracking and forms the foundation for improving telescope spectroscopic observation efficiency. To meet the high-precision photometric and spectroscopic observation requirements of Cassegrain instruments like YFOSC, the 2.4-meter telescope is equipped with an offset auto-guiding system. As illustrated in Figure 3, a 45-degree mirror positioned before the Cassegrain focal plane extracts a $4' \times 4'$ field from the telescope's main optical path for auto-guiding. To enhance the guide CCD's field coverage and limiting magnitude, a focal reducer was added to the guide camera and achieving a sky angle of 0.24 arcseconds per 13.5 μ m pixel. Testing demonstrated that under 1.5 arcsecond seeing conditions, the auto-guide camera could detect stars to approximately 17th magnitude with 2-second integration. Furthermore, the auto-guiding mechanism can utilize an annular region from 10' to 20' that does not obstruct the instrument's field of view, while operators can execute the ag-rad command to radially move the 45-degree mirror, addressing situations where bright guide stars are unavailable in the camera's field of view (Figure 4).

1.2.2 Cassegrain Guide Camera

With increasing operational time, the original guide camera CCD developed numerous bad pixels, degrading its limiting magnitude detection capability and severely affecting the success rate of star centroid extraction during closed-loop tracking. Consequently, the 2.4-meter telescope maintenance team replaced the auto-guide camera in 2013. Table 1 compares the performance of the new and former guide cameras. The new SBIG ST-3200ME camera reduced full-frame readout time from approximately 10 seconds to about 4 seconds, decreasing guide star acquisition time and increasing error sampling and feedback

frequency. Additionally, the new camera's peak quantum efficiency reached 87%, improving the guide system's limiting magnitude under equivalent conditions. However, due to budget constraints during the guide system upgrade, the selected CCD had a relatively small focal plane, corresponding to only $4' \times 2'$ on the sky, failing to fully utilize the expanded $10' \times 10'$ guide field. Future plans include configuring a guide camera with a larger imaging focal plane to further improve spectroscopic observation efficiency.

1.3 Factors Affecting YFOSC Spectroscopic Observation Efficiency

Optimizing star acquisition into the slit and telescope closed-loop tracking algorithms represents a crucial pathway for improving YFOSC spectroscopic observation efficiency. Through years of spectroscopic observation experience with YFOSC at the Lijiang 2.4-meter telescope, the maintenance team identified star-slit coupling efficiency and telescope closed-loop tracking precision as the primary factors affecting overall efficiency under given seeing conditions.

1.3.1 Star-Slit Coupling Efficiency and Precision For the original YFOSC long-slit spectroscopic observation algorithm, after telescope pointing to the target field, single-target observations required calculating the coordinate deviation between the target star's centroid and the slit center on the image plane. Operators then manually input this deviation into the telescope control system, which transformed the image-plane offset into telescope pointing corrections through matrix operations. Typically, a single adjustment could not guarantee correct star-slit coupling, requiring multiple iterations and consuming approximately 10 minutes. For simultaneous observation of a scientific target and a nearby constant-flux comparison star—enabling acquisition of spectra through identical atmospheric paths under identical conditions—the process required moving the telescope while rotating the field to align both targets in the slit, often exceeding 10 minutes. Using YFOSC's common 2.51 arcsecond slit as an example, the slit width corresponds to 8.9 pixels on the image plane. Target calibration precision requirements dictate positioning accuracy: for single-target spectrophotometric calibration (Figure 5), at least half the starlight must enter the slit, meaning the centroid deviation from the slit center must not exceed 4 pixels; for simultaneous target and comparison star observations (Figure 6), deviations of both centroids from the slit central axis should be minimized—typically less than 0.5 pixels—to avoid introducing additional dispersion into traditional flux calibration methods due to differential photon losses. Manual telescope adjustment demands extensive operator experience, suffers from low efficiency, wastes valuable observing time, and requires significant effort to achieve adequate precision.

1.3.2 Telescope Closed-Loop Tracking Precision The original telescope closed-loop tracking algorithm employed a “single brightest star” method. After moving the target to the slit center, the guide camera activated and extracted

the centroid of the “brightest” star in the guide field, comparing its coordinate offset between frames to achieve closed-loop tracking. However, interference from adjacent bright stars could cause the algorithm to input incorrect star coordinates into the telescope control system, degrading spectroscopic data quality. To maintain the star within the slit during integration, centroid offset from the slit center must remain below 1 arcsecond throughout the exposure.

Based on this analysis of the two critical factors affecting YFOSC spectroscopic efficiency, algorithmic optimization targeting these elements is necessary to improve overall observation efficiency.

2 Point Pattern Matching Algorithm

Both the optimized star acquisition algorithm and telescope closed-loop tracking employ a point pattern matching algorithm adapted from F. Murtagh’s PPM (Point-Pattern Matching) algorithm. This section introduces the algorithm using its application in the Lijiang 2.4-meter telescope’s closed-loop tracking as an example. Murtagh’s algorithm proceeds as follows: first, construct feature vector sets based on stellar characteristics (magnitude, inter-star distances) in the image; then screen the reference and comparison frame feature vector sets for similarity and threshold compliance to complete matching.

2.1 Construction of Stellar Feature Vector Sets Two approaches exist for constructing stellar feature vector sets: (1) Using apparent magnitude ω and inter-star distance d_{ij} as parameters, which satisfy the property of being uncorrelated. For any star i in the reference frame, construct its feature vector where ω_j is the magnitude of neighboring star j , and d_{ij} is the squared two-dimensional distance between stars i and j . This creates a $1 \times N$ dimensional feature vector set for star i , where N represents all stars in the image. (2) When constructing feature vector P_{ij} for star i , ignore neighboring star j ’s magnitude, and calculate the angle θ_{ij} formed between star i and star j relative to the positive X-axis, counterclockwise. Then sort star i ’s feature vector set $\{P_{ij}\}$ in ascending order according to $\{\theta_{ij}\}$. This second approach is currently adopted for YFOSC spectroscopic observations because the guide camera’s brief integration time cannot achieve high-precision photometry, making the first approach potentially error-prone.

2.2 Extraction of Matching Star Pairs Based on Feature Vector Set Similarity The first frame captured by the guide camera is defined as the reference frame, with subsequent frames serving as comparison frames. After extracting stellar feature vectors, matching and similarity calculations are performed to obtain matched star pairs. For any star i ’ in the comparison frame, construct its feature vector set $P_{i'}$ and calculate the Euclidean Distance between P_{ij} and $P_{i'j}$. Euclidean Distance represents the actual distance between two points in n -dimensional space, expressed as:

Formula (2)

where x and y are n -dimensional vectors. The Euclidean distance d ranges from 0 to positive infinity. Typical similarity calculations require normalized ranges of $[0,1]$ or $[-1,1]$; therefore, the reciprocal of d is used to constrain results within $(0,1]$ as a similarity measure:

Formula (3)

The star pair i and i' with similarity closest to 1 represents the optimal match. The successfully matched star i' is designated i_{succ} . To enhance algorithm robustness and prevent guiding failure from mismatches, i_{succ} undergoes threshold screening:

Formula (4)

This equation calculates positional offset errors and magnitude differences for matched pair i'_{succ} and i . Here d_{off} represents the offset threshold, flux_{ref} and $\text{flux}_{\text{comp}}$ represent total flux in reference and comparison frames respectively, mag_{th} is the magnitude threshold, and k is an adjustable coefficient.

This describes the point pattern matching algorithm's application in the Lijiang 2.4-meter telescope's closed-loop tracking. The star catalog matching method in the next section follows a similar principle: the star catalog extracted for the target field corresponds to the reference frame in closed-loop tracking, while the field image captured by YFOSC corresponds to the comparison frame.

3 Optimization of Star Acquisition Algorithm

During YFOSC spectroscopic observations, after telescope pointing to the target, the stellar image must be moved to the slit center to ensure proper coupling, maximizing starlight reaching the camera and improving signal-to-noise ratio. Therefore, before spectroscopic integration, the target must be acquired into the slit using camera images. The acquisition algorithm proceeds in two chronological stages: "coarse adjustment" and "fine adjustment," as illustrated in Figure 8.

3.1 Coarse Adjustment Coarse adjustment aims to position the stellar image near the slit center. Two methods exist for calculating star coordinates during this phase: (1) **Astrometry.net astrometric solution**: After telescope pointing, YFOSC captures an image and uses Astrometry.net to solve for World Coordinate System (WCS) coordinates of stars in the field. Successful WCS solution enables directing the telescope to correct RA/DEC coordinates, bringing the target's centroid near the slit center. Though Astrometry.net typically requires detection of three or more stars for reliable solution, its high precision makes it the preferred method for coarse adjustment. Additionally, WCS data can monitor telescope pointing performance and improve pointing models. (2) **Star catalog pattern matching**: When too few visible stars exist in the target field for Astrometry.net to succeed, star catalog pattern matching is employed. Before observation, preprocessing of the target field's

FITS image is required: adding focal plane scale α , field rotation angle ROT, target star WCS coordinates, and their centroid image-plane coordinates (derived from star catalogs). The point pattern matching algorithm then matches star image-plane coordinates from the catalog with those from YFOSC images, passing the mean offset through coordinate transformation to TCS for coarse adjustment, achieving proper star-slit coupling.

3.2 Fine Adjustment Fine adjustment aims to precisely align the stellar centroid with the slit center. After coarse adjustment, the target star's image-plane coordinates are typically nearest to the slit center position. Using the slit center as origin with a 5-10 pixel radius, SExtractor identifies the brightest source within this circular region and determines its centroid coordinates. Iterative calculations of the offset between the target star's centroid and the slit center progressively refine telescope pointing until the deviation falls within tolerance. For dual-target observations, after moving the brightest target into the slit center, the field is rotated based on the second target's image-plane coordinates determined during coarse adjustment, enabling correct coupling of both targets with the slit.

Figure 9 compares the field before and after rotation, with the red box showing the pre-rotation field and the background showing the post-rotation image (target star 17L08, captured 2022-02-03 18:57:36.945 UTC, 5s exposure). Blue and green arrows indicate target stars, with the green arrow marking the brightest source near the CCD center (slit center). Figure 10 shows the slit image after field rotation, with slit width corresponding to 17.67 pixels on the sky. For single-target observations where the bright star is the intended target, field rotation is unnecessary, as shown in Figure 11.

Testing demonstrated that the optimized YFOSC star acquisition algorithm significantly improved all coupling metrics, substantially enhancing spectroscopic observation efficiency. Table 2 compares manual and new algorithm performance. Manual acquisition tests (2021-01-08 15:50:22.621 to 21:59:15.340 UTC, targets J0309 and pg1012+008) versus new algorithm tests (2022-02-03 18:49:28.948 to 22:01:03.105 UTC, targets HD 105183 and 17L08) show dramatic improvements.

4 Optimization of Telescope Closed-Loop Tracking Algorithm

To ensure spectroscopic observation quality, auto-guiding must maintain the target star within the slit throughout the exposure. During actual observations, after obtaining slit images like Figure 10 or 11, the grating is inserted before YFOSC's camera, the guide camera activates for closed-loop tracking, and then exposure begins to ensure data quality during long integrations. This process is illustrated in Figure 15.

Closed-loop tracking corrects telescope tracking errors by comparing positional offsets of star i in the guide camera's reference frame with star i' in comparison

frames. The procedure is: (1) Calculate stellar offsets. Apply point pattern matching, similarity calculation, and screening to obtain successfully matched star i_{succ} , then compute mean offsets in x and y directions between coordinates $(x_{i_{\text{succ}}}, y_{i_{\text{succ}}})$ and (x_i, y_i) :

Formula (1)

Figure 16 shows reference frame (left) and overlay of successfully matched frame with reference frame (right), where Stars A, B, C in the reference frame match Stars A, B, C* in the comparison frame. Offsets ΔA , ΔB , ΔC are calculated and averaged to produce x_{Diff} and y_{Diff} .

While each guide camera integration yields offset values x_{Diff} and y_{Diff} , applying these corrections immediately would induce abnormal telescope jitter, particularly problematic for the Lijiang 2.4-meter telescope's large moment of inertia. Such jitter might even be detected as offset vectors and sent to TCS. To avoid this, multiple offset results are accumulated and averaged, designated as $x_{\text{Diff_avg}}$ and $y_{\text{Diff_avg}}$, to guide telescope tracking corrections. Coordinate transformation matrices establish relationships between guide camera offsets and telescope three-axis (ALT, AZ, ROT) corrections, achieving closed-loop tracking. Coordinate transformations are not the focus of this paper and are not detailed further.

Application of point pattern matching to the Lijiang 2.4-meter telescope's closed-loop tracking was tested on August 3, 2021. Results demonstrated one-hour closed-loop tracking precision better than 0.5 arcseconds, with stellar position offsets on the image plane not exceeding 1.8 pixels. The original "single brightest star" method achieved 0.5 arcsecond precision only when no bright star interference existed; with interference, "star jumping" could cause tracking failure. Point pattern matching utilizes all detectable stars in the field, improving long-term tracking precision and robustness. Guide camera image-plane stellar position offsets x_{Diff} and y_{Diff} are shown in Figure 17.

5 Summary and Outlook

In summary, improving spectroscopic observation efficiency of YFOSC—the primary instrument of the Lijiang 2.4-meter telescope—depends critically on star-slit coupling efficiency and high-precision telescope closed-loop tracking. The Lijiang station maintenance team has continuously optimized these aspects in recent years, with this paper presenting the optimized algorithms and their effectiveness. However, observational testing reveals further improvement potential, such as enhancing guide CCD field of view and detection capability to increase YFOSC spectroscopic efficiency. Additionally, the Lijiang 2.4-meter telescope's Nasmyth switching platform has been commissioned, enabling free switching between Nasmyth and Cassegrain foci. The algorithms described herein can be applied to guide system development at the Nasmyth focus, improving spectroscopic efficiency for Nasmyth instruments and thereby enhancing the comprehensive observational capabilities of the Lijiang 2.4-meter telescope for broader

astronomical research.

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