Development and laboratory performance of a Multi-Mode Near-Infrared spectrograph for LAMOST

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ABSTRACT

We present a novel near-infrared (NIR) spectrograph for the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), enhancing its capabilities beyond the optical band (370–900nm). Designed for high-precision observations of bright NIR targets (e.g., late-type stars, red supergiants), the instrument integrates a VPH grating, refractive camera, and cryogenic Dewar on a rotary stage, enabling three observing modes via coordinated rotations. Each mode acquires simultaneous NIR spectra for 100 targets. Laboratory verification confirms: complete 900~1400nm wavelength coverage with spectral resolution R=900–1600 (via NeAr/HgCd lamps); throughputs of 51.5% (980nm) and 55.5% (1064nm), consistent with coating simulations; and exceptional stability (0.05 Å/hour drift over 4 hours). These results demonstrate full compliance with LAMOST's NIR survey requirements. The system opens new avenues for large-scale NIR studies, complementing optical data to deliver complete spectral distributions for millions of objects. Future work focuses on observational mode optimization.

Keywords: LAMOST; Near-Infrared; Spectrograph; Multi-Mode; Laboratory Performance; Mechanical Design;

1. INTRODUCTION

Modern large-scale spectroscopic surveys, particularly those operating in the NIR band, have revolutionized our understanding of galactic structure and cosmic evolution by penetrating dust-obscured regions inaccessible to optical observations. Key international projects exemplify this progress: The James Webb Space Telescope's NIRSpec enables simultaneous multi-object spectroscopy for 100 targets, probing early-universe galaxy formation and exoplanet atmospheres at unprecedented depths[1]. The APOGEE survey — part of the Sloan Digital Sky Survey — pioneered

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high-resolution NIR stellar spectroscopy, directly enabling the reconstruction of the Milky Way's radial density profile and revealing its true scale[2]. Meanwhile, the Dark Energy Spectroscopic Instrument (DESI) leverages 5,000 robotic fiber positioners to acquire millions of galaxy spectra, mapping cosmic expansion dynamics and providing critical spectral templates for cross-survey calibration[3]. These projects collectively address fundamental limitations of optical surveys, advancing studies of stellar populations, galactic kinematics, and dark energy[4].

The LAMOST is currently one of the telescopes with the highest spectral acquisition rate in the world. Its low-resolution spectroscopic survey primarily operates in the optical band (370~900nm)[5]. The current status of LAMOST and medium-to-low resolution spectrographs is shown in subfigures (a) and (b) of Figure 1, respectively. Due to the large number of Galactic late-type stars present in the released data from the LAMOST low-resolution survey, the measurement accuracy of parameters for such stars obtained solely through optical spectral features is insufficient. Additionally, it is currently difficult to effectively measure objects with strong NIR radiation within the Galaxy, such as red supergiants[6].

Driven by the above scientific motivations, we have developed a (multi-mode switchable) near-infrared spectrograph for LAMOST (LAMOST NIRS). This instrument extends the operational band of the low-resolution spectroscopic survey into the near-infrared for observing NIR targets in the J-band. The complete development framework - including scientific drivers, optical architecture, and performance simulations - is documented in a companion study under review at The Astronomical Journal (Zhang et al. 2025). The NIR spectrograph has now been integrated onto one of LAMOST's spectrographs and is in the test observation phase. This paper will focus on the mechanical design implementation of the spectrograph and laboratory performance testing.

(a) (b)

Fig.1 (a) shows the LAMOST, (b) shows the current status of the medium-to-low resolution spectrographs.

2. PERFORMANCE REQUIREMENTS

The performance requirements of the LAMOST NIRS primarily include three metrics: wavelength coverage, spectral resolution, and throughput. The specific requirements for these metrics are given in Table 1. Additionally, we have tested the stability performance of the spectrograph to ensure its reliability during observational operations; these results will be presented in detail later.

Table1 Instrument performance requirements of LAMOST NIRS

Parameters	Requirements
wavelength coverage	900~1400nm
spectral resolution	R=1500 (at central wavelength 1135 nm)
throughput	>35% (without fiber & CCD).

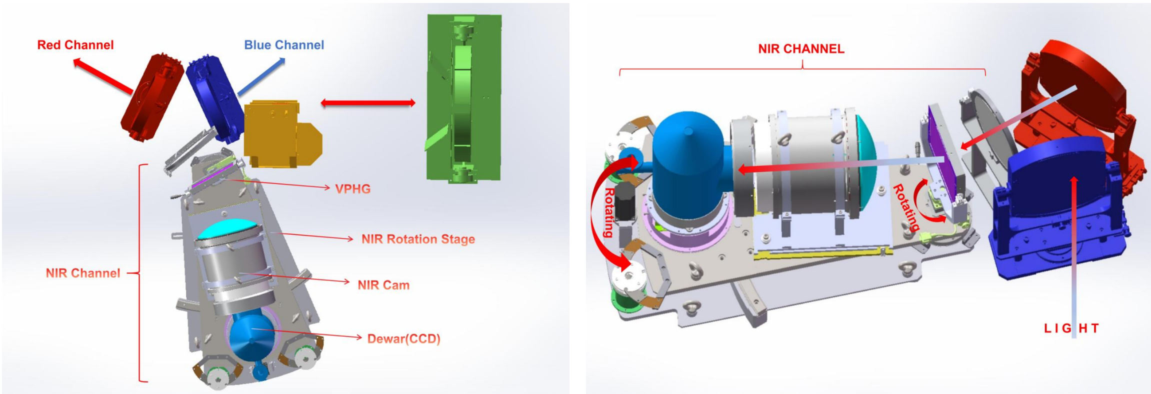
3. METHODS

Limited by the size of the near-infrared detector focal plane array (single CCD size: 640×512 pixels, pixel size: 20μm, a 2×2 tiling scheme is employed in actual operation), we adopted a multi-operation-mode alternating exposure approach to achieve the required wide-band wavelength coverage. Switching operation modes is accomplished by rotating the grating and the near-infrared (NIR) rotation stage.

The 3D schematic model of the LAMOST NIRS is shown in Figure 2(a). The VPH grating, transmissive camera, and Dewar assembly are integrated onto the NIR rotation stage serving as the substrate, as illustrated in Figure 2(b).

The VPH grating is connected to the rotational axis of the stage via a rotary motor, ensuring coincidence between the rotation centers of the stage and grating during rotation. The transmissive camera is mounted on an adjustable base fixed at the center of the stage, equipped with a focusing motor to enable active focusing of the spectrograph. The Dewar assembly is secured at the rear end of the stage through an attitude-adjustable base, allowing for alignment of the detector focal plane. Additionally, electromagnetic friction pads are installed on both left and right sides of the stage's rear end. During operation, these pads are energized to apply pressure against the stage, enhancing stability through increased static friction force.

During operation, the diffraction angle corresponding to the central wavelength of the current operation mode coincides with the central axis of the transmissive camera and Dewar assembly, ensuring the high diffraction efficiency of the VPHG. When changing the operation mode, the grating is rotated individually to alter the incidence angle. Simultaneously, the entire NIR rotation stage is rotated to realign the central axis of the camera and Dewar assembly with the diffraction angle of the central wavelength for the new operation mode. This achieves spectral band matching under the new operation mode, adjusting the wavelength coverage range while maintaining the high efficiency of the VPHG.



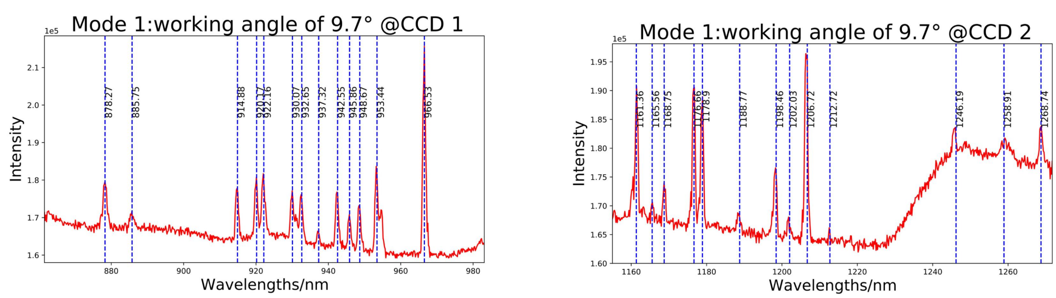
(a) (b)

Fig.2 (a) shows the 3D schematic model of the LAMOST NIRS, (b) shows the NIR rotation stage.

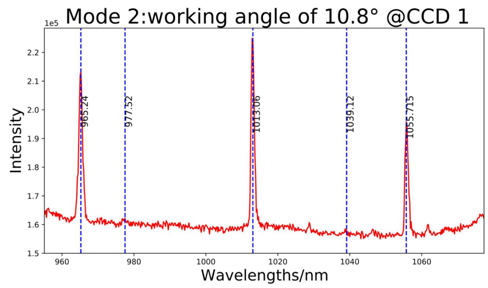
4. RESULTS

4.1 Wavelength coverage

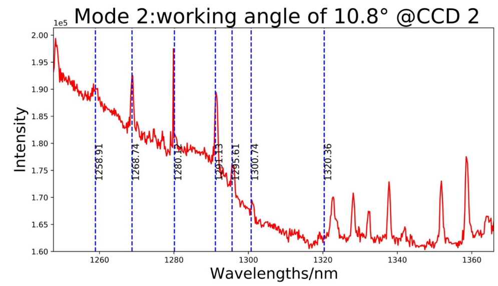
We used neon-argon and cadmium-mercury lamps as calibration sources to perform wavelength calibration for the LAMOST NIRS under multiple operating modes. As the NIR detector employs a tiled 2×2 array, there are two sub-CCDs along the dispersion direction. Due to the inter-chip gap, the wavelength coverage of these two sub-CCDs is discontinuous. Laboratory wavelength calibration tests were conducted for three operating modes, with results shown in Figure 3.



(a) (b)



(c)



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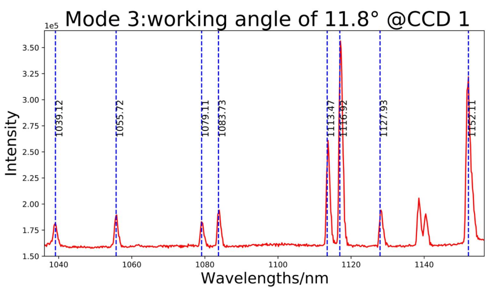
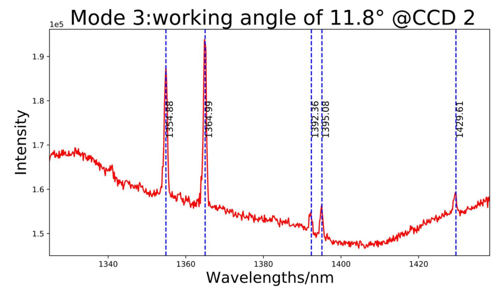


(e)



(f)

Fig.3 One-dimensional spectra and wavelength calibration results for both sub-CCDs in each mode: (a) and (b) for Mode 1, (c) and (d) for Mode 2, (e) and (f) for Mode 3.

The wavelength calibration results for the three operating modes are presented in Table 2. Through the combination of these three modes, the total wavelength coverage of the LAMOST NIRS spans 861~1440nm.

Table2 Instrument performance requirements of LAMOST NIRS

Mode	Working angle of VPHG	Wavelength coverage
1	9.7°	861~980nm, 1155~1270nm
2	10.8°	954~1073nm, 1244~1370nm
3	11.8°	1036~1156nm, 1325~1440nm

4.2 Spectral resolution

The spectral resolution was calculated for individual emission lines under each of the three operating modes, with outliers removed. Results are shown in Figure 4. Without slit constraints, the measured resolution at the central wavelength of 1135 nm is 1300. With slit constraints, the resolution at 1135 nm reaches 1550.

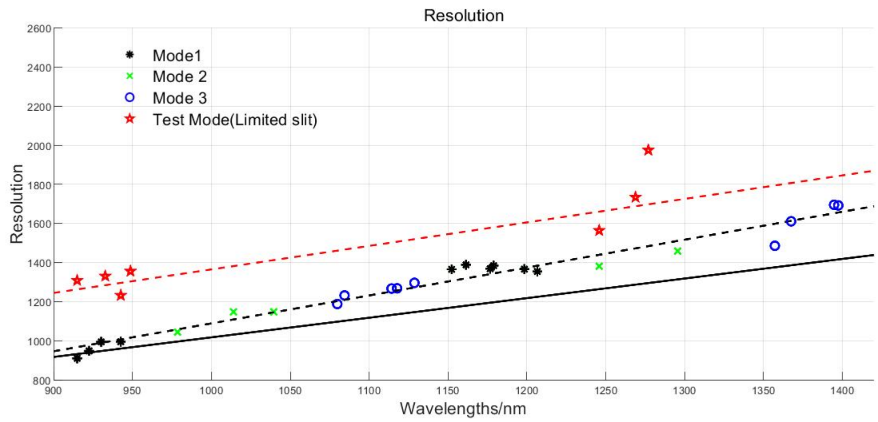


Fig.4 Spectral resolution of the LAMOST NIRS, the black solid line shows theoretically calculated resolution; discrete points (black for Mode 1, green for Mode 2, blue for Mode 3) represent slit-unconstrained resolution measured using calibration lamps; the red pentagram indicates actual slit-constrained observational results for Mode 1; the red dashed line fits the actual slit-constrained resolution.

4.3 Throughput

We measured the throughput of the spectrograph using 980 nm and 1064 nm lasers, comparing measured results with simulated efficiency curves based on coating performance (Figure 5). The overall trend between measured efficiencies at 980/1064 nm and simulated curves confirms the peak throughput is no lower than 55%.

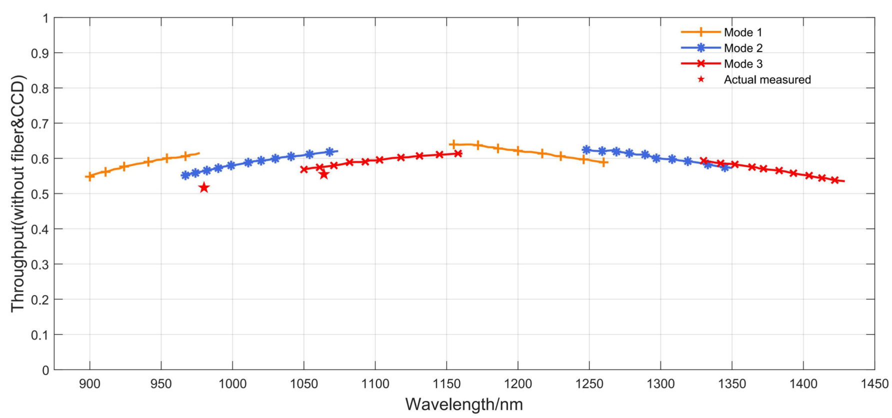


Fig.5 Efficiency curve of the LAMOST NIRS, red pentagrams denote measured efficiencies.

4.4 Stability

Calibration lamp spectra were obtained every 30 minutes over four continuous hours during one observing night to measure instrument stability. Three spectral lines were uniformly selected from each sub-CCD along the dispersion direction for analysis. Detailed results are shown in Figure 6. The maximum spectral drift is ~0.01 Å, with an average drift rate of -0.000038 Å/h, fully meeting the requirements for low-resolution near-infrared surveys.

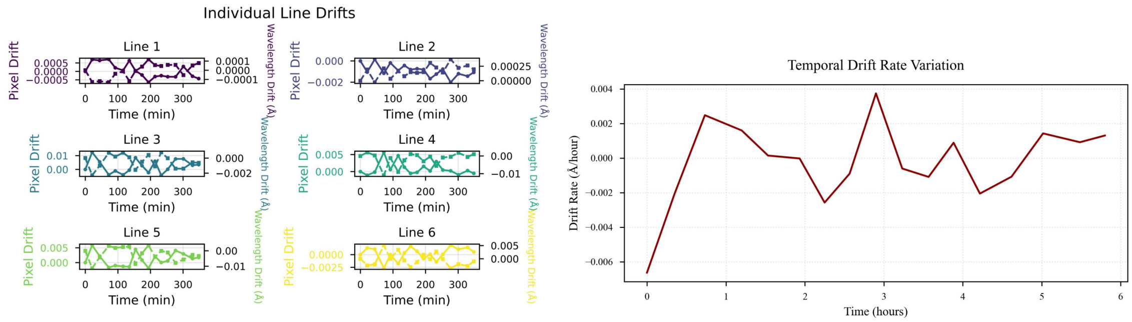


Fig.6 (a) shows the drift variation curves for six spectral lines, (b) shows the average drift rate variation for these six lines.

5. CONCLUSIONS

Laboratory tests of the LAMOST NIRS's performance parameters demonstrate that all metrics exceed the design requirements. The instrument is fully capable of conducting LAMOST NIR spectroscopic surveys. Currently, the spectrograph has commenced test observation operations. Beyond the regular scientific observation schedule, optimization of its operating modes will be considered in subsequent phases. Additionally, further testing will be conducted in the future to fully characterize the instrument's capabilities.

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The comprehensive instrument development framework presented in this work - including scientific drivers, design principles, optical implementation, and simulation results - is documented in detail in a companion paper currently under review at The Astronomical Journal (Zhang et al. 2025).

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