Structure Design and Analysis of the Special Mounting and Tracking System of the LAMOST

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ABSTRACT

The Large sky Area Multi-Object fiber Spectroscopic Telescope is a very special reflecting Schmidt telescope with a 40 m long optical axis between the reflecting Schmidt correcting plate and the spherical main mirror. In the middle is located the spherical focal plane of 1.75 m in diameter. The reflecting Schmidt correcting plate serves not only to correct wavefront by active optics but also to point and track celestial objects by normal tracking with collaboration of the focal plane to form a special mounting and tracking system. In this paper, the operational principle and technical specification of the tracking system is briefed. Design and test measurement as well as driving mode of both the Schmidt plate and the focal plane are investigated with structural calculations and analyses. The paper is closed with the conclusion that the mounting and tracking system is to meet global technical specifications of the LAMOST excellently.

Keywords: The LAMOST, Reflection Schmidt plate, Focal plane, Mounting and Tracking system, Structure analysis

1. INTRODUCTION

The Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST) is substantially an astronomical transit observing celestial objects in 1.5 h while they are passing through the meridian¹. Fig. 1 shows the overview of LAMOST. Its optical axis is lying on the meridian plane with a 25° inclination above the horizon. The reflecting Schmidt plate, M_A , is located at the curvature center of the spherical primary mirror, M_B , which is fixed on the foundation. M_A is to serve as Schmidt correcting plate with active optics and simultaneously to track the field with an Alt-Azimuth mounting, while field rotation during the tracking is compensated for by active rotation of the spherical focal plane of 1.75 m in diameter (parent sphere diameter 40 m). Thus, the tracking system of LAMOST is actually formed by the M_A system and focal plane with the relay of M_B . However, the tracking mode is, different from traditional telescopes, to track the normal of the reflecting Schmidt plate, M_A . Hence, the tracking and pointing accuracies are double.²

LAMOST is to be sited at Xinglong station where altitude is 40.4° and longitude 117.5° . Agreeing with the observed sky coverage of $-10^{\circ} \leq \delta \leq +90^{\circ}$, the normal of M_A should span the zenith distance from 7.7° to 57.7°. Being segmented with 24 hexagonal sub-mirrors, 1100 mm long tip to tip and 25 mm thick each (refer to Fig. 2), M_A exploits a combined technology of both thin-mirror active optics and segmented-mirror optics to fulfill the correcting task of the Schmidt plate. And carrying ~4000 optical fibers, the focal plane is to actively compensate for the consequent field rotation.

The special tracking configuration of the LAMOST involves in special consideration on structural design and mechanism of M_A supporting and mounting system and focal plane. A space truss support structure is adopted for the M_A cell, which turns to be lightweight with high stiffness. It is attached to the azimuth mounting yoke by two journals on both sides. Friction drives are employed for both axes motion. Spherical bearings are used for elevation axis while hydrostatic pads for azimuth. In view of minimizing blockage of light, the optical plane is mounted on a steel-plate-welded frame, which is mobile along two axes, along and transverse to optical axis. In the following sections, the structural design schemes of M_A cell, M_A mounting and focal plane system are respectively investigated and detailed with relevant finite element modeling.

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2. GENERAL SPECIFICATIONS

According to the global technical specification and configuration of the LAMOST, ^{3,4} during the observation of 1.5 h while celestial objects pass the meridian, the largest angle at which M_A rotates/tracks about the elevation axis is only 0.34°, so the gravitational deflection of M_A support structure in the tracking period can be very tiny and possible to be corrected for by open loop control system. Meanwhile, M_A azimuth mounting rotates a maximum range of $\pm 20^{\circ}$ across the meridian and, correspondingly, in addition to by focusing, the focal plane has to compensate for the field rotation, by tip-tilting within the angular range of 0′ to 6′ in the meridian plane.⁵

In order to observe exceptional celestial objects/phenomena, the tracking system should widen its coverage larger than generally required above. And from the structural design of view, all the mechanisms must be designed with the idea of easy maintenance and adjustment in mind.



Fig. 1: Overview of LAMOST

3. STRUCTURE DESIGN OF M_A CELL

As indicated in Fig. 2, the reflecting Schmidt plate is segmented with 24 hexagonal sub-mirrors with seam of ~5 mm left in between. Each sub-mirror system, weighing about 150 kg, is positioned by three displacement actuators (layout seen in Fig.2 right) which are connected to the top of the M_A support structure, namely, M_A cell, thus, a 24-sub-mirror composed reflecting surface is formed, and therefore, the structural deflection between every two adjacent sub-mirror should be as small as possible.⁶

During the process of the M_A cell design, the following principles are kept in mind as rules:^{7,8}

- 1) The M_A cell is to be a space truss.
- 2) The flow of forces in the truss should be transferred as directly as possible, all concentrated loads should be applied onto joints.
- 3) Joints should be simple, actually a ball-styled joint has been investigated. And truss members converging at one joint should be kept at suitable number.
- 4) Industrial formed steel pipes are selected. Thinner walled pipes are preferable for small thermal constant.
- 5) By FEM calculation and optimization, efforts should be made to obtain a lightweight structure but with high stiffness to benefit servo control.

6) In addition, the structure should be simple and concise, and should be convenient for access and maintenance.



Fig. 2: Segmented Schmidt plate M_A and actuators layout (right)

The mirror cells of such as KECK and HET are studied,^{6,7} but different from traditional telescope mirror cell, the M_A cell of LAMOST is supported only by two journals without strong central section. Keeping this point in mind, a three-layered space truss is design for M_A cell, as shown in Fig. 3, with the three layers shrinking down, the cell turns to shape in a half ellipse.⁹ It is supported and driven about elevation axis by two journals at both sides on its top layer. The elevation axis is in the mirror plane of M_A .

Refer to Fig. 2, the sub-mirrors are thus arranged and attached to the top of the cell with three supporters (displacement actuators) each as indicated with an asterisk. Each supporter of the total 72 is set on corresponding joint of the top layer, thus, the top layer grid is patterned in Fig 4. The components on both sides will be connected with elevation journals. On the edge of the top layer, there stands a ring of "guardrail" truss for protecting the mirrors and for attaching mirror covers.

The middle layer is a plane truss with hexagonal grids that are patterned with the projection of the sub-mirrors. A plane middle layer would facilitate access and maintenance of the sensors and actuators. The connecting links between the top and middle layers are shown in Fig. 4, too.

The bottom of the cell is actually a concaved layer of truss patterned with triangles, as shown in Fig. 3, the projections are congruent equilateral triangles.



Fig. 3: M_A cell layout (left: front view, right: side view)





By modeling with finite element software, an optimized M_A cell has been achieved with weight of 2640 kg including journals, and the maximum gravitational deflection is about 0.25 mm when it points to zenith. The lowest eigenfrequency is as high as 27.2 Hz.⁹

4. DESIGN OF M_A MOUNTING SYSTEM

As the configuration of LAMOST requires, M_A uses an alt-azimuth mounting for tracking.¹⁰ Because of the special mode of normal tracking, technical requirements are twice stricter than those of ordinary telescopes. The design of the M_A mounting system follows the extra considerations below:¹¹

1) As the sky coverage demands, M_A elevation rotating range should correspondingly cover from zenith distance 7.7° to 57.7°, while azimuth rotation should span $\pm 19.31^\circ$ over the meridian. For possible observation of exceptional/ special celestial objects, the azimuth rotation range extends to cover up to $\pm 51^\circ$ and for convenient access, adjustment and maintenance of the mirrors. Elevating range covers 0° to 65° to include the extreme pointing positions of zenith and horizon.

2) Tracking accuracy is better than 0.34" with close loop of guiding.

3) Good thermal performance. The thermal capacity of the structure should be kept at a minimum level, cooling and ventilating system is to be equipped to maintain good mirror seeing.

Fig. 5 sees the outline of the M_A mounting with M_A cell illustrated. Mainly, nine sub-systems are indicated in it and selectively described in detail in the following sections.



Fig. 5: Overview of M_A mounting system



Fig. 6: Elevation drive system

4.1 Elevation drive system

Sketch of elevation driving and tracking system is referred in Fig. 6 above. Friction drive is selected. Compared with gear-driven drive system, Friction drive is predominant for excellent smoothness and lower cost. The driving ratio can be achieved by using relatively small drive rollers without the need of gearbox for speed reduction. Moreover, direct motor driving is possible to be used.

A set of friction driving system is installed on both sides of the elevation shaft. The big friction plate is actually a sector of a full circle. The small friction roller is located against the big plate beneath with a "floating" support system and its preload is exerted with spring and lever system.

The driving system features that each small roller is installed with two DC motor (axis to axis on each end of its shaft). One is used for pointing and the other for tracking so as to solve the difficulty facing the control of great velocity change from pointing to tracking. And the two motors are possible to collaborate to drive during the process of pointing or tracking.

A tape encoder from HEIDENHAIN Inc. with angular resolution of 0.04 arcseconds is used to measure elevation angle.

4.2 Elevation counterweight system

Because LMAOST has no mobile telescope tube, the total weight of elevating part of M_A is below the mirror surface, namely, offset to one side of the elevation axis, thus, greater counterweight/ countermoment is needed for balancing. In order not to block the light and not to introduce extra deflection of M_A cell, a scheme shown in Fig. 7 is



Fig. 7: Elevation counterweighing system

considered.

It is essentially two pairs of gear system with ratio of 1:1 attached to both journals of M_A cell by elevation axis flanges. During observation the counterweight ballast is always being rotated in counter direction of elevation of M_A , so, no light is to be blocked and unwanted deflection is to be introduced into M_A cell.

4.3 Azimuth positioning and bearing system

Refer to Fig. 5, the azimuth position and bearing system includes the base plates (upper and lower), oil pads system (hydrostatic bearings), azimuth central pintle bearing and the yoke.

The azimuth bearing is actually divided into two parts: the hydrostatic oil pads gliding in their track on the base plate, which are to carry vertical loads, and the relatively small central positioning pintle bearing, which is to carry side loads (wind load). The diameter of the oil pad track is 6.8 m. The four oil pads are evenly arrayed on the track cycle to carry a total weight of about 30 tons. A spherical bearing is selected for the azimuth positioning pintle bearing, which facilitate easier installation and adjustment. Its inner diameter is as big as 500 mm for the sake of easier cabling.

Compared with roller bearing, hydrostatic bearings have been selected thanks to their superior performance of super smoothness, high load carrying capacity, very low friction and very high stiffness. The difficulty lies in thermal problem in operation, so, cooling and ventilating measurements must be taken into consideration as well as use of dust protecting covers.⁶

Big parts as the azimuth bases and the yoke are welded with steel plates and pipes with heat treatment to relieve stress, for they are key members for carrying heavy loads with high precision.

4.4 Azimuth drive system



Fig. 8: Azimuth friction driving mechanism

Friction drive is also adopted for azimuth motion. There are three couples of friction driving systems polarly arrayed with interval of 60° and driven by six DC motors. The small rollers are attached on the upper base of the mounting and preloaded against the outer cylindrical rail of the lower base with hydrostatic pressure. Like the philosophy involved in elevation driving, two couples of the three are serving tracking, while the rest couple is serving pointing. Of course, the three are possible to collaborate whenever tracking or pointing.

An encoder same as that used for elevation angular measurement is selected for azimuth. It is to be installed onto the central pintle shaft.

The dust preventer is considered and to be integrated together with the oil pad protector at site.

5. FOCAL PLANE SYSTEM

The focal plane is situated in the middle of the optical axis with a declination angle of 25° to horizon. It is a spherical cap of 1.75 m in diameter, on which 4000 optical fibers are installed. The optical system of LAMOST results in the field rotation on the focal plane.^{1,2} In order to hold and keep all the fibers pointing to their objects precisely, the field rotation has to be compensated for by active motion of the focal plane. In other words, the focal plane is also to serve tracking task. Therefore, besides being able to focusing, the focal plane can rotate about its axis. And furthermore, optical calculations show that it is necessary for the focal plane to tip-tilt slightly in the meridian so as to achieve best image quality for observing the entire required sky coverage.

Based on the arguments above and global technical requirements of LAMOST, the focal plane has to fulfill the following specifications and tasks:

- 1) Tracking range of field rotation is $\pm 22.5^{\circ}$, with accuracy of ± 3 arcseconds, speed of 0 to 15 "/s and fine tracking speed of down to 1"/s.
- 2) Pointing accuracy ± 20 arcseconds.
- 3) Focusing distance range is ± 50 mm, with accuracy of ± 0.1 mm.
- 4) Tip-tilt range covers 0 to 6 arcminutes, with accuracy of ± 20 arcseconds.
- 5) Offset of the vertex of the focal plane from optical axis, ρ , is no greater than ± 0.2 mm.
- 6) Minimize light blockage and survive wind and seismic hazards.
- 7) Convenient access and maintenance.

As shown in Fig. 9, the focal plane system consists of five main components: the rotator, focal plane, supporting frame, base and base adjustor. The rotator is the connection between the focal plane and the support. It functions in driving and rotating to compensate for field rotation. Together with the focal plane and linking spar trusses, the rotator is actually a removable part for easy fabrication and installation, and therefore, the focal plane is possible to be replaced with other observing facilities, for example, some imager. Gradienter is used for detecting the inclination angle of the rotator, namely, that of the focal plane. Focusing and tip-tilting are fulfilled by movement of the base that is aligned with adjustors below during installation and maintenance. The support frame is welded with steel plates, with big holes cut through it, to minimize light blockage and weight.

Clearly, the rotator and the focal plane are crucial parts of the system, an optimized scheme of the them will benefit better performance of the whole focal plane system. As seen in Fig. 10, finite element model has been created for the integrated sub-system. It is optimized with three design variables as:

- 1) Wall thickness of the rotator
- 2) Outer radius, wall thickness and length of linking spar
- 3) Number of the spar.

And two main performance indicators are defined as bound variables:

- 1) Offset of focal plane, $\rho \leq \pm 0.2$ mm.
- 2) And angular declination of focal plane, $\alpha \leqslant 10''$

The optimization process is actually a trial-and-error method. Results are charted in Fig. 11, Fig 12 and listed in Table 1. Calculated with optimized dimensions after rounding, the offset of the vertex of the focal plane from optical axis, ρ , is only 0.03 mm, much less than specified requirement. And angular declination of the focal plane, α , is 9 arcseconds, which is within required specification.



Fig. 9: Overview of the focal plane system





Fig. 10: FEM of the rotator and focal plane sub-system





Fig. 12: Results vs length and number of spar

Table 11: Optimized result	Table1	1:	Optimized	results
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Number of spar	10	Value after rounding	
Wall thickness of rotator		15.842	16
Outer radius of spar		88.786	89
Wall thickness of spar		28.267	28
Length of spar	mm	300.82	300
Offset of focal plane, ρ		0.027417	0.0273198
Maximum deflection of focal plane	Maximum deflection of focal plane		0.027329
Declination angle of focal plane (")	9.0042	8.9781	

6. CONCLUSIONS AND PROSPECT

So far, this paper has described the special mounting and tracking system together with corresponding technical requirements. The mirror cell support structure of M_A is designed and a design with light weight and good stiffness is obtained. For the superior advantages of it, friction drive is employed for both elevation and azimuth axes. Hydrostatic oil pads are selected to support vertical loads on azimuth, while a spherical central pintle bearing is used to carry lateral load in addition to position the azimuth mounting. The structure of mounting system and driving systems are detailed in this paper. In order to compensate for the field rotation resulting from the normal tracking while celestial objects are passing the meridian. The focal plane system is thus designed and relevant optimization results in a focal rotator meeting technical requirements very well. Dynamical performance of the structures is to be evaluated for a thorough understanding of the mounting and tracking system.

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