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Rapid instrument exchanging system for the Cassegrain focus of the Lijiang 2.4-m Telescope *

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Abstract As a facility used for astronomical research, the Lijiang 2.4-m telescope of Yunnan Astronomical Observatories, requires the ability to change one auxiliary instrument with another in as short a time as possible. This arises from the need to quickly respond to scientific programs (e.g. transient observation, time domain studies) and changes in observation conditions (e.g. seeing and weather conditions). In this paper, we describe the design, construction and test of hardware and software in the rapid instrument exchange system (RIES) for the Cassegrain focal station of this telescope, which enables instruments to be quickly changed at night without much loss of observing time. Tests in the laboratory and at the telescope show that the image quality and pointing accuracy of RIES are satisfactory. With RIES, we observed the same Landolt standard stars almost at the same time with the Princeton Instruments VersArray 1300B Camera (PICCD) and the Yunnan Faint Object Spectrograph and Camera (YFOSC), while both were mounted at the Cassegrain focus. A quasi-simultaneous comparison shows that the image quality of the optical system inside the YFOSC is comparable with that provided by the PICCD.

Key words: telescopes: Lijiang 2.4-m Telescope — instrumentation: photometers — instrumentation: spectrographs — telescopes: automation

1 INTRODUCTION

The Lijiang 2.4-m telescope (IAU observatory code O44) was installed at Lijiang Observatory, which is administered by Yunnan Observatories, Chinese Academy of Sciences, in 2007, and was available for astronomers the next year. Lijiang Observatory is at $100°2'$(E), $26°42'$(N), about 35 km from the city of Lijiang, Yunnan province, China[1]. It is a general-use optical telescope which can observe fast moving natural objects and artificial satellites in the solar system, Galactic stars and

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[1] *http://www.gmg.org.cn*

clusters, and distant extragalactic objects including active galactic nuclei (AGNs), gamma-ray bursts (GRBs), supernovae, etc. In order to satisfy different scientific demands, it is equipped with several instruments. These are the Yunnan Faint Object Spectrograph and Camera (YFOSC), a Princeton Instruments VersArray 1300B CCD Camera (PICCD), the LiJiang Exoplanet Tracker (LiJET), and the Fast Optical Camera (EMCCD). A fiber-fed high-resolution Echelle spectrograph (HiRES) and a two-dimensional spectrograph named the China Lijiang Integrated Field Unit (CHILI) are being built and will be installed on the telescope in 2014 and 2015, respectively. All these instruments are designed to be mounted on the Cassegrain focus of the telescope. The YFOSC can work as a direct imaging camera and a low resolution spectrograph. The LiJET is a combination of a thermally controlled monolithic Michelson interferometer and a cross-dispersed Echelle spectrograph for high precision Doppler measurements of bright stars. The EMCCD is a fast optical camera with an E2V L3CCD (EMCCD) chip, and the image can be read out at 15 MHz with a gain as high as 5000. It is thus usually used to monitor very fast variability and to carry out high spatial resolution observations with the Lucky Imaging technique (Mackay 2013).

Usually the direct imaging of celestial objects can only be performed when seeing is good enough; photometry needs very dark and clear nights, while spectroscopy can be done on grey nights or when there are some thin clouds in the sky. The weather and seeing may change from time to time at night, especially at Lijiang Observatory which is effected by the Bangladeshi monsoon. In order to optimize the observation program accordingly, general-use telescopes should thus have the capability to quickly change different instruments or observing modes at night. For example, when thin clouds appear or the seeing gets worse during photometric or direct imaging observations, the observing mode should be changed to spectroscopic observation. On the other hand, an observation of a Target of Opportunity (ToO) for transient objects, such as GRBs and supernovae, also requires a quick change of the instrument at night to acquire both photometric and spectrographic observations of the object. In addition, observational programs that focus on studies of long period variability, e.g. AGN black hole mass measurement, the search for exoplanets, etc. need a continuous and reasonably dense data sampling from night to night. These require many of the observation nights be shared by at least two observation programs, which implies the instruments should be quickly changed at night.

The Lijiang 2.4-m telescope is a Ritchey-Chrétien reflector on an alt-azimuth mount, which makes it possible to automate instrument exchange at the telescope at night without much loss of observation time. In the past few years, we have built the rapid instrument exchange system (RIES), incorporating both hardware and software, for the Cassegrain focal station. After testing and upgrading for nearly one year, now the system works quite well. In this paper we report on work related to RIES. The design, manufacture, installation, and test of this system and of the interfaces for instruments are described in the next Section. In Section 3, we present an application of the system to illustrate its functionality. The summary is in Section 4.

2 AUTOMATING INSTRUMENT EXCHANGE

2.1 The Design

There are both Cassegrain and Nasmyth focal stations available at the Lijiang 2.4-m telescope (see Fig. 1), and a tertiary mirror may be manually installed to use either of the Nasmyth focal stations on both sides. However, automating the switching between Cassegrain and Nasmyth focal stations is very difficult and expensive due to the stringent requirements on mirror support, complicated mechanical structure and accurate motion that are required for the large and heavy tertiary mirror.

We have concentrated on automating the process of instrument exchange for the Cassegrain focus. There are two ways to realize fast exchange of instruments on the Cassegrain focus at night. The first way is to automate the manual operation of instrument exchange, like the Cassegrain Instrument

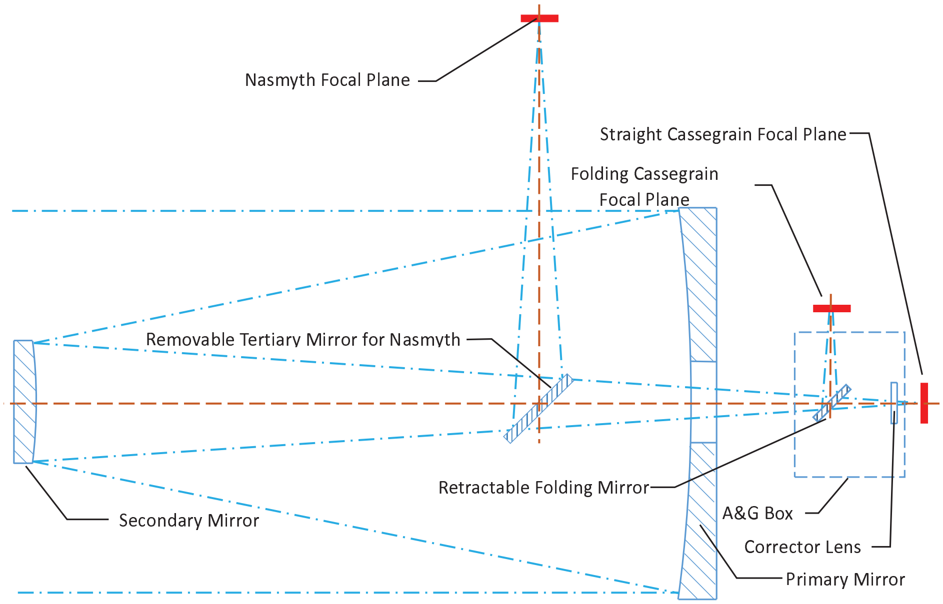

Fig. 1 The optical layout of the Lijiang 2.4-m telescope, together with the newly added folding mirror for side ports.

Automatic eXchanger (CIAX) system on the 8.2 m Subaru Telescope (Omata et al. 2002). CIAX incorporated a precision positioning system and an automatic connector system for electrical cables, optical fibers and fluid lines to robotize the removal and installation of instruments. Applying this approach to the our case is a bit complex and it is usually only used for extremely large instruments. The second approach is to automate instrument exchange by an additional mirror that folds the optical beam to any one of the permanently mounted instruments, e.g. like what is incorporated in the Gemini Telescopes and William Herschel Telescope[2]. The Lijiang 2.4-m telescope has an acquisition and guiding (A&G) unit on the Cassegrain focus, with eight instrument mounting flanges with proper flange-focal distance. The final design uses a flat mirror to rapidly and precisely position the telescope beam between the up-facing port and any of the horizontal-facing side ports on the Cassegrain focal station. High accuracy and repeatability of the system is the most important feature. The target should be maintained on either the central pixels of an imaging detector or in the small field of view (FOV) of the fiber coupling unit of a spectroscope each time an instrument is changed. The surface accuracy of the folding mirror and the stability of the mirror support should maintain the image quality on the folded focal plane. In addition, the whole assembly should not obstruct the optical beam and auto-guiding should be available for instruments mounted on all ports.

Figure 2 shows the design of the folding mirror and its positioning system. Similar to the Liverpool Telescope[3], which has a 2-m telescope with a design that is similar to the Lijiang 2.4-m telescope, there is only one rotatable mirror for all instruments mounted perpendicular to the tube of the telescope. To use the instrument mounted at the straight-through port, the mirror is retracted off the beam by linearly moving to a stowed position. To use the instruments configured on the side

[2] *http://www.ing.iac.es/Astronomy/telescopes/wht/*
[3] *http://telescope.livjm.ac.uk/*

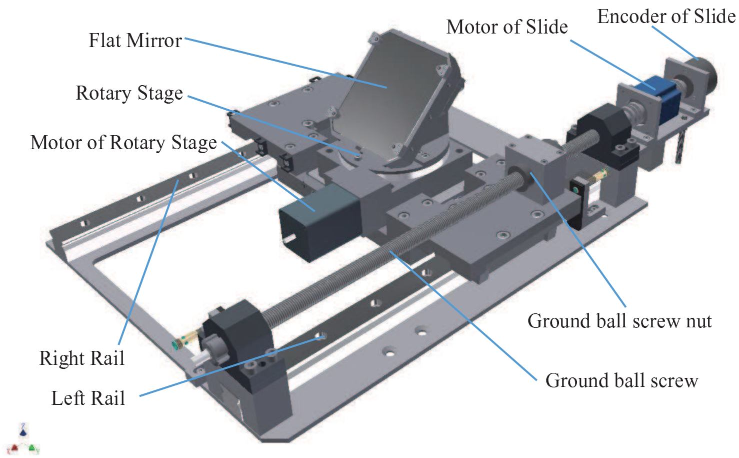

Fig. 2 The mechanics of the tertiary mirror rotating and retracting.

ports, the mirror is positioned in the optical axis, at the center of the A&G unit, and spun to face the instrument.

2.2 The Folding Mirror

The folding mirror and its mount were well designed to minimize image degradation. Maintaining the interferometric quality of the mirror surface is required when the telescope is positioned in an arbitrary orientation.

Due to limitations of space inside the A&G unit, the folding mirror assembly is a little bit smaller to cover the 10′ FOV. The FOV for the side ports is 8′ (vertical) by 10′ (horizontal). The folding mirror is close to the focal plane, so it is much smaller than the Nasmyth tertiary mirror. The mirror was fabricated from ultra-low-expansion glass ceramics, to avoid thermally induced deformations. The overall surface error was required to be lower than lambda/20 RMS over any ellipse with dimensions 105 mm (vertical) by 75 mm (horizontal). The mirror was manufactured by the Nanjing Institute of Astronomical Optics and Technology. The final figure of the coated surface was tested, and the result was better than the requirements, i.e. lambda/54 RMS. The mirror was installed on the mirror cell, against three teflon pads, with adjustable spring screws. With one set of kinematic Cone-Vee-Flat couplings, the mirror cell assembly is mounted on the rotary stage of the positioning system.

2.3 The Positioning System

There are two modes of motion for the folding mirror: linear and rotary. Adjusting the mirror's position uses a two-position linear mechanism. The mirror may be positioned in the optical path or retracted away by using spindle-driven linear rails. The action of folding the mirror requires it to be positioned on linear slides with an accuracy of 100 μm, as the plate scale of the Cassegrain focal plane is 93 μm per arcsecond. The high quality ground ball bearing lead screw and the guide rail, from SKF (Swedish Bearing Factory)[4] guarantee a high accuracy for the linear motion.

Furthermore, the mirror should be rotatable to direct the beam to each one of the side ports with an accuracy of 3″, equivalent to the telescope pointing accuracy. These positioning tolerances have

[4] *http://www.skf.com*

to be maintained for different temperatures and orientations of the telescope. The rotary mechanism is an accurate, heavy-duty rotary stage which allows precise and zero-backlash rotary positioning of the mirror cell assembly driven by a stepping motor. The distance between the center of the mirror and the focal plane is 575 mm. An accuracy of $2'$ and repeatability of $20''$ on the stage give a position error for a celestial target no greater than 0.335 mm, i.e. $3.6''$ of sky angle. All main parts of the mechanical assembly, except the mirror cell, are constructed with aluminium alloy that has good thermal stability, specified stiffness and quality manufacturing. These parts were manufactured by the Yunnan Optical Instrument Factory.

2.4 The Control System

The linear and rotary motions are both motorized with high-torque stepping motors driven and controlled by integrated motion controllers from Schneider MicroLynx-4 products[5]. The MicroLynx controllers provide the closed loop motion control on the deployment and rotation. The micro-step resolution is up to 51 200 steps per revolution of the motor.

Incremental encoders feedback the angular positions on both motions. On the axis of the rotary stage, a Heidenhain[6] RON275-18000 encoder feeds the orientation of the mirror to the controller. With the incorporated interpolation and digitizing electronics, the encoder produces 90 000 signals per revolution. This gives a resolution of $14''$ for the rotary motion of the mirror, which corresponds to $0.43''$ of sky angle in the focal plane. As the incremental encoder generates no absolute position, there is a Hall switch on the rotary stage to detect the "zero" position of the mirror. The procedure for finding the zero position is programmed in the MicroLynx controller, and will be executed once before the telescope is ready for observation. There is no limitation on the movement of the mirror rotary stage.

Since the accuracy of the SKF lead screw is high and the backlash is negligible, the linear position is measured by an angular encoder coupled to the shaft of the motor. The thread pitch of the lead screw is 5 mm. A Heidenhain ROD420 incremental encoder with a resolution of 5000 counts per revolution gives a resolution of 1 μm on the linear position. One proximity switch at the retracted end of the mirror is for finding the home position. Two more proximity switches are fixed to limit the furthest positions of linear movement in both directions. The functions of limitation and finding home are programmed into the MicroLynx controller.

There are two ways that can be used to integrate the control software at the telescope user level. One is to regard the switching system as an instrument. In this case, the user operates the switching system like an instrument, shown in the left panel of Figure 3. The other is to integrate the control from low level to the Telescope Control System (TCS), as shown in the right panel of Figure 3. The latter option was taken for the Lijiang 2.4-m telescope. The MicroLynx controllers are connected via the Controller Area Network (CAN) bus to one of the computers attached to the TCS. Control of the homing, moving and querying of the folding mirror is integrated into the telescope control system. The telescope operator can chose the instrument needed for observation by simply sending a TCS command or writing observation scripts.

2.5 The Installation

Before installing the system inside the A&G unit of the telescope, the repeatability of the positioning and reliability of the control software were thoroughly tested. As it takes several days to take the whole A&G assembly off and put it back on the telescope, the final installation was carried out during the first on-site re-aluminizing of the 2.4-m primary mirror in October 2012, to minimize loss of observation nights.

[5] *http://www.schneider-electric.com*
[6] *http://www.heidenhain.com*

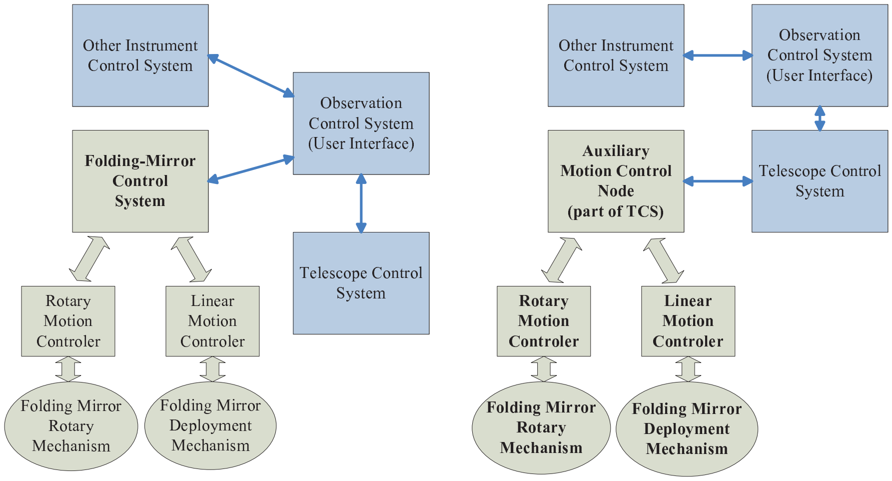

Fig. 3 Block diagrams of two optional control structures. On the left, the switching system functions in the same way as an instrument, which is controlled directly by the observer. On the right, the folding mirror control is integrated as part of the TCS.

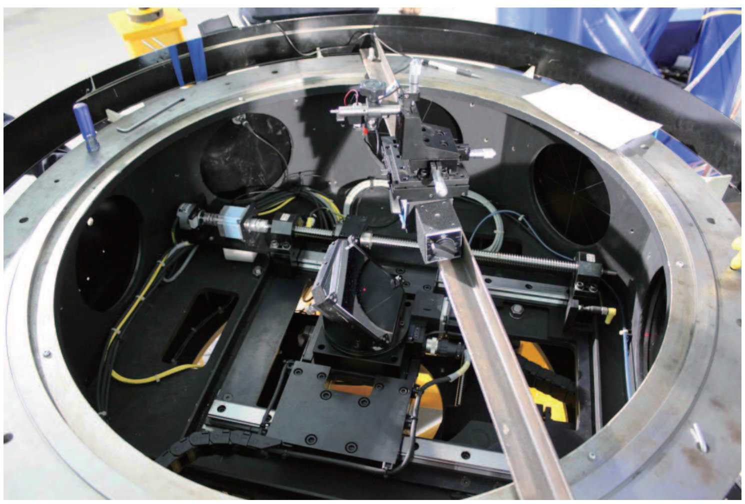

Fig. 4 The folding mirror installed inside the A&G unit. To center and align the mirror, a reference laser beam was pointed along the optical axis of the telescope.

By shimming the mount surface of the mechanical assembly and adjusting the three kinematic couplers attached to the mirror cell, the angle and rotary axis of the folding mirror were precisely aligned with the telescope's optical axis. Figure 4 shows the installation and alignment. Two limit switches for the linear mechanism were aligned to define the range of movement with respect to the edge and the center of the telescope beam. The final installation and alignment were finished over a couple of days in October 2012.

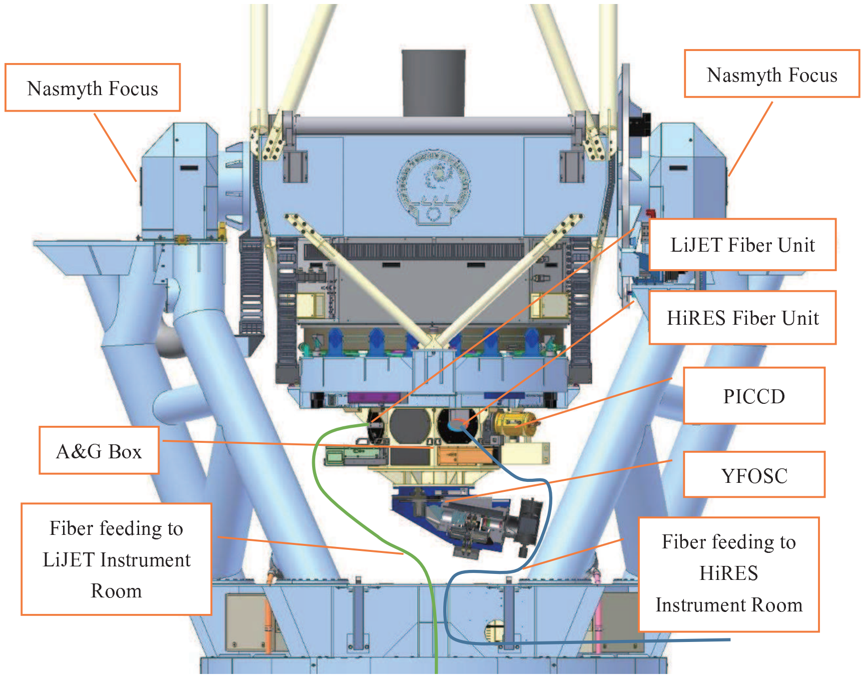

Fig. 5 The instruments mounted on the Cassegrain A&G box. YFOSC is mounted on the straight-through focal plane. The PICCD, and fiber coupling units of LiJET and HiRES are mounted on the side ports.

2.6 The Interfaces of Instruments at the Side Ports

Due to the limited space and payload capacity, very large and heavy instruments cannot be mounted on the side ports. Because of their small size and light weight, EMCCD and PICCD can be directly mounted on the side ports. However, LiJET, HiRES and CHILI are too large, so they are fiber-fed, and their fiber-feeding units can be mounted on the side ports. We designed and manufactured each interface for EMCCD, PICCD and LiJET. As shown in Figure 5, YFOSC is mounted on the straight-through port, while other instruments are mounted on the folding ports around the A&G box. For each instrument, parameters were measured and written in a configuration file, including the focal position, the telescope focus offset, the pointing offset caused by mount misalignment, the offset of the sky angle, etc. Once an instrument is installed, aligned and well defined, it is quite convenient to quickly switch for observations at any time.

As mentioned in the Introduction Section, the EMCCD is usually used to monitor very fast variability and to carry out high spatial resolution studies with the Lucky Imaging technique. We thus bought a filter wheel with filters, and made a flange plate for it. This filter wheel has standard broad band Johnson UBV (Johnson et al. 1966), Kron-Cousins RI (Cousins 1981) and SDSS $ugriz$ (Fukugita et al. 1996) filters. The filter wheel and these filters are shared by the PICCD, because the EMCCD is used less often than the PICCD and can be easily interchanged with the PICCD. Mounted at a side port, the PICCD is often used as a complement for YFOSC photometry and direct imaging, especially when rapid reaction is needed for a ToO observation. However, the YFOSC filter wheel contains narrow band filters, because the number of filters that can be mounted at the YFOSC is limited (see the next section for a comparison of these two instruments). The PICCD's FITS files are much smaller than those of the YFOSC, even for a sub-window with the same FOV. It takes a shorter time to transfer data acquired by PICCD to remote users than those acquired by YFOSC for the same target. The PICCD is thus necessary for fast reaction observations, such as GRBs and supernovae, so that the data can be processed remotely in real-time. In addition, the PICCD is also used as a seeing monitor for LiJET and the other fiber-fed spectrographs.

2.7 The Performance of the System

Since the side ports became available in October of 2012, the instrument switching system has performed quite well, and the image quality observed from the side port is as good as expected. The instruments may be changed with small overhead and as accurately as the observer demands. New interface plates were made for the PICCD camera and the LiJET fiber coupling unit to mount them on the side flanges. In addition to the existing public instruments mounted on the side ports, custom-made instruments brought by guest observers that are lightweight and have a small FOV should be mounted on the side ports.

The accuracy of the instrument switching was tested by observing with the PICCD over one night. First, the telescope was pointing and tracking a star with an appropriate magnitude. Then instrument switching was repeated between the straight-through port, the side port on which PICCD was mounted and the opposite side port. The centroid of the target on the image was acquired on the camera each time after the switching was performed. The dispersion of the centroid from data acquired in this way gives an indication of the repeatability of the switching system. Three sets of tests were performed with the telescope pointing to targets with different altitude angles of 80°, 60° and 40°to evaluate the influence of gravity on the mirror support and the positioning structure.

Figure 6 shows the test results. With the telescope pointing at 80°, close to zenith, the measurement was repeated 21 times, and the RMS of the position error of the target was $0.35''$. With the telescope pointing to lower targets, the repeatability degraded down to $1''$. This accuracy still satisfies the requirements for all existing instruments mounted on the telescope, not only the camera used for imaging, but also the fiber coupling unit connected to the spectrograph.

The off-axis auto-guider works fine with the instruments on the side ports. When the folding mirror is in the deployed position, the beam to the pick-off mirror of the auto-guide camera, underneath the folding mirror structure, is not obstructed. When the guiding system is operating, the closed loop tracking is very accurate. This is very important for instruments that use the fiber-feed system.

3 EXAMPLES OF APPLYING RIES

The fast instrument exchange system makes it convenient to quasi-simultaneously observe the same targets with several instruments mounted at side ports and the straight-through port. As an example to illustrate the advantage of the system, it was applied to directly compare the full width at half maximum (FWHM) of star images between the YFOSC and PICCD through observing Landolt standard stars (Landolt 1992) to test the quality of the optical system in the YFOSC.

The YFOSC is a combination of a camera and a low resolution spectrograph that share the same optical system which includes a focal reducer, field lenses, etc. Altogether, there are 14 lenses and one flat mirror in this optical system. Due to scattering and loss of light, this optical system may, to some extent, affect the image quality of the telescope in the direct image mode. The whole optical system has not been tested in a laboratory, though every part, including the lenses and grism, has been tested by each separate manufacturer. Unlike YFOSC, there is not an optical system inside the PICCD. Mounted at a side port, the FWHM of PICCD images almost directly reflects the image quality of the telescope and the atmospheric seeing. Therefore, a comparison of YFOSC images with those of PICCD may serve as a test of image quality for the YFOSC.

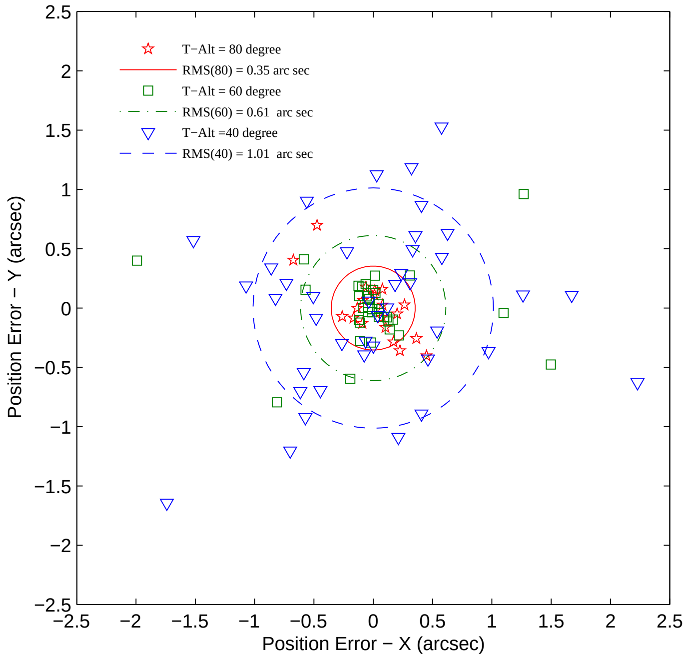

Fig. 6 The accuracy of RIES tested on PICCD. Each of the red stars, green squares and blue triangles represent the position error measured after one repetition of instrument switching with telescope altitude at 80°, 60° and 40°, respectively. The red solid, green dash-dotted and blue dashed circles show the RMS of the error with the telescope altitude at 80°, 60° and 40°, respectively.

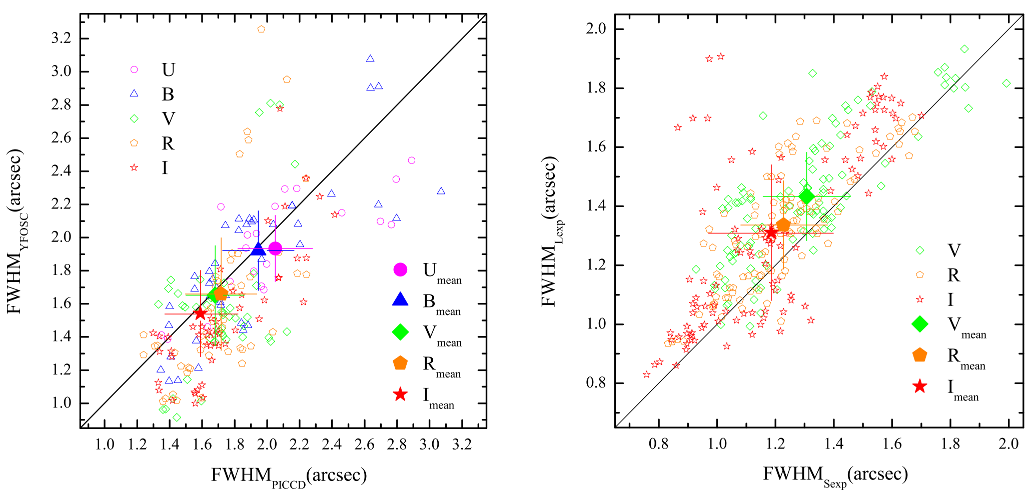

Fig. 7 FWHM comparisons. The left panel, observed on 2013 November 6 and 7, is a comparison between YFOSC and PICCD. The right panel, observed on 2013 December 2 and 3, is a comparison of YFOSC using two levels of exposure.

The left panel of Figure 7 shows a comparison of the FWHM between YFOSC and PICCD for the same targets with the same exposure at almost the same time. There is no obvious difference between YFOSC and PICCD with the same filters except in the U band. This indicates that the optical system in the YFOSC is good enough. The higher quantum efficiency of the YFOSC detector at the blue end might be related to the better FWHM in the U band. Notably, the FWHM decreases with the increase of wavelength in both systems.

Downing et al. (2006) pointed out that the PSF of the Deep Depletion CCD chip increases with the exposure level. So, we did some tests with YFOSC on 2013 December 2 and 3, shown on the right panel of Figure 7, where the short exposure (Sexp) is similar to that on 2013 November 6 and 7 and the long exposure (Lexp) is four times the former. Statistically, the FWHM on the Lexp model is 1.1 times that of Sexp.

4 SUMMARY

With the goal of achieving rapid switching of instruments, we have successfully automated instrument exchange at the Cassegrain focal station of the Lijiang 2.4-m telescope. The image quality and pointing accuracy of the system are good. After nearly one year's trial operation by various observers and upgrades, now the system works quite well. With this system, eight instruments can be mounted to the telescope at the same time with an FOV of $8'$ by $10'$, and can be switched with each other and with the instrument mounted on the straight-through port in less than half a minute. The control system is integrated with the TCS and allows the telescope operator to switch to any instrument that is used for observation. This approach not only saves a great deal of labor and working time, and reduces the risks of damage, e.g., on the electronics due to electrostatic discharge while connecting and disconnecting cables, but also enables running several observation programs over one single night, and observing the same targets quasi-simultaneously with different instruments. At present, there are three unoccupied side ports for more instruments that can be used at the telescope, and observers are welcome to bring and use their own instruments for scientific observation or technical testing at the telescope.

Quasi-simultaneous observational comparison between the PICCD and YFOSC shows that the optical system inside YFOSC is quite good. The quasi-simultaneous observation of the same targets by the PICCD and YFOSC makes the photometry of both cameras nearly equivalent to deferential photometry, which can also be used to directly compare the two photometric systems and to get more reliable transformation equations between the two photometric systems. We thus observed the same Landolt standard stars with the YFOSC and PICCD quasi-simultaneously to compare the two photometric systems and to get transformation equations between the two photometric systems (Fan et al. in preparation).

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