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Research in Astronomy and Astrophysics

The Coude Echelle Spectrograph for the Lijiang 1.8 m telescope

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Abstract The Coude Echelle Spectrograph (CES) was originally mounted on Xinglong 2.16 m telescope in 1994. When the High Resolution Fiber-fed Spectrograph (HRS) was commissioned at Xinglong 2.16 m telescope, the red path of CES was moved to Lijiang 1.8 m telescope, following some redesign and reinstallation. The CES of Lijiang 1.8 m telescope has the spectral resolution ($R = \lambda/\Delta\lambda$) ranging from 20000 to 50000 corresponding to different slit widths. With a 2k×2k PI CCD, CES has a wavelength coverage between 570 nm to 1030 nm. In particular, the resolution of 37000 at 0.5 mm slit corresponds to 1.3$''$ on the sky. The limiting magnitude is $V = 11.5$ with the use of the tip-tilt feedback system, and the S/N is about 40 for 1 hour exposure at 600 nm ($R = 37000$). During the installation of CES, the tip-tilt mirror technology had successfully fulfilled high precision guiding and tracking for high resolution spectral observation and significantly improved the observation efficiency.

Key words: Instrumentation: spectrographs — methods: observational — techniques: spectroscopic

1 INTRODUCTION

The Coude Echelle Spectrograph (CES) was designed by Nanjing Institute of Astronomical Optics & Technology (NIAOT) and was mounted on the coude focus of Xinglong 2.16 m telescope in 1994. The CES has worked for nearly 20 years, and it has satisfied the requirements of high resolution spectral observation for many scientists. The spectral range is from 330 nm to 1100 nm including 80 orders through two light paths. For different focal length, the spectral resolution of $R = 16000$, 44000, 170000 in the blue path and $R = 13000$, 37000, 170000 in the red path could be provided by CES. With 1 hour exposure, the limiting magnitude is $V = 9.5$ in the red path and $V = 7.2$ in the blue path for the S/N of 100. Zhao & Li (2001) have introduced CES used on 2.16 m telescope in detail.

When the High Resolution Fiber-fed Spectrograph (HRS) was commissioned at Xinglong 2.16 m telescope, the plan of moving CES to Lijiang 1.8 m telescope was lunched for making full use of astronomical instrument. At that time, only Xinglong 2.16 m and Weihai 1m telescope were equipped with high resolution spectrograph, which is far from satisfying the increasing requirements of high resolution spectral observation. Since the focal length of CES for the blue path is too short and no proper CCD camera has been found, only the red path of CES and the corresponding optical components were moved to Lijiang 1.8 m telescope.

The reform work of CES itself mainly includes recoating all optical components and changing a new echelle grating designed and bought from Newport Corporation by NIAOT. Xinglong 2.16 m telescope is equatorial type, while Lijiang 1.8 m telescope is altazimuth one with the aim to follow the fast moving objects. Hence, we need to test if the tracing system of the telescope is proper for high resolution spectral observation. With the use of the slit monitor system alone, engineers found that the high precision tracking cannot be realized. The target position is needed to be manually put back into the slit all the time. Besides, the system cannot feed back the target fainter than 9 magnitude in V band. Since astronomical observations cannot tolerant of much light loss and have frequent needs to track fainter targets, a fine tracking system was designed with tip-tilt mirror by Institute of Optics and Electronics (IOE). In addition, a focal reducer is needed for the alteration of focal ratio from f/45 (2.16 m telescope) to f/89 (1.8 m telescope). This was designed by Yunnan Observatories to realize the alteration of the focal ratio. A new calibration system and slit monitor system have also been redesigned by Yunnan Observatories.

In September 2014, reconstruct and reinstallation of CES were completed. With a 2k$\times$2k PI CCD, the measured wavelength coverage is from 570 nm to 1030 nm. The spectral resolution of CES ranges from 20000 to 50000, and the corresponding slit width is from 0.925 to 0.37 mm adjustable. In particular, the resolution is 37000 at 0.5 mm slit width corresponding 1.3$''$ on the sky which is tested at the installation process of CES and used for about 1 year as default mode. CES is proper to study stellar physics and radial velocity measurement with a precision of 100 m s^{-1} order of magnitude.

In this paper, we describe different components of CES. The tip-tilt tracking system is introduced in Section 2. The optical system and calibration system are described in Section 3. Section 4 shows the characters of the 2k$\times$2k PI CCD. In addition, Section 5 describes the main characteristics of CES.

2 THE TIP-TILT TRACKING SYSTEM

When the alignment of CES was completed, we found that the existing tracking system using the slit monitoring technique does not satisfy the tracking accuracy required by the CES. On the one hand, the target position is needed to be manually put back into the slit repeatedly in the exposure process. The position information is fed by the slit monitoring system. Unknown light loss could be caused due to the target-position feedback time and the manual adjustment time. On the other hand, the slit monitoring system cannot provide feedback on the target position for objects fainter than $V = 9$ magnitude, while the users usually need to observe fainter targets.

Thus, a fine tracking system using tip-tilt mirror technology was developed for CES. Please refer to Wei et al. (2010) for more detailed descriptions. In November 2014, IOE completed the adjustments and preliminary tests of the tip-tilt guiding system, and later detail tests for the system was made by astronomers which indicated that the system works very well. If the close-up tracking is on, the fine tracking system can realize fine tracking of target brighter than 11.5 magnitude in V band with a sampling frequency of 1000 Hz. The optical layout of the fine tracking system designed for CES is shown in Figure 1. Here, we summarize the main characters of the tip-tilt system. The full-width at half-maximum (FMHM) of the point spread function (PSF) of stars after tip-tilt mirror correction is 0.1$''$ near the diffraction limit of 1.8 m telescope between 700 and 900 nm, and the field of the guiding FOV is 4$''$, while the average seeing of Lijiang Observation is about 1.0$''$ from 2015 to 2017 (Wang et al. 2019). In this work, the tip-tilt mirror technology successfully realized high precision guiding and tracking for the high resolution spectral observation.

3 THE OPTICAL SYSTEM AND CALIBRATION SYSTEM

The focus ratio for the 1.8 m telescope at coude focus is f/89, while it is f/45 for the 2.16 m telescope. Therefore, a focal reducer is needed for the installation of CES , and the optical layout of the focal reducer designed by Yunnan Observatories is shown in Figure 2. The beam splitter in front of the focal reducer in the light path shares 80% light from the telescope to CES, and the other 20% light is to the tip-tilt feedback system for guiding.

Since the focal length of the blue path of CES is too short and no proper CCD has been found, only the red path of CES and the corresponding optical components were moved to Lijiang 1.8 m telescope. The reform work is mainly focused on changing a new echelle grating and recoating all optical components. The new echelle grating was designed and purchased from Newport Corporation by NIAOT, and the main characteristics of the new echelle grating given by the manufacturer as well as the old one are listed in Table 1. After recoating all optical components and changing the new echelle grating of the main body of CES by NIAOT in 2012, the total optical efficiency of the

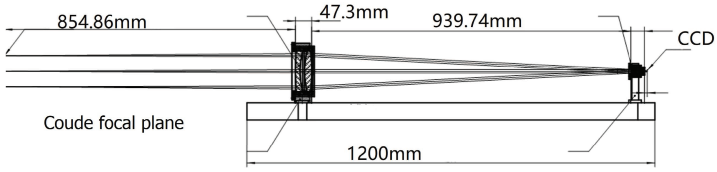

Fig. 1 The optical layout of the fine tracking feedback system for CES.

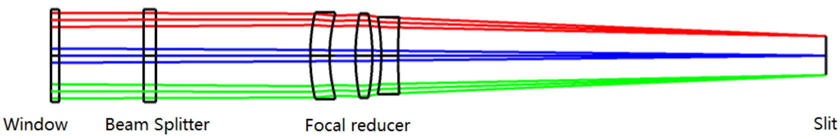

Fig. 2 The optical layout of the focal reducer designed for CES.

Fig. 3 The optical layout of CES mounted on 1.8 m telescope.

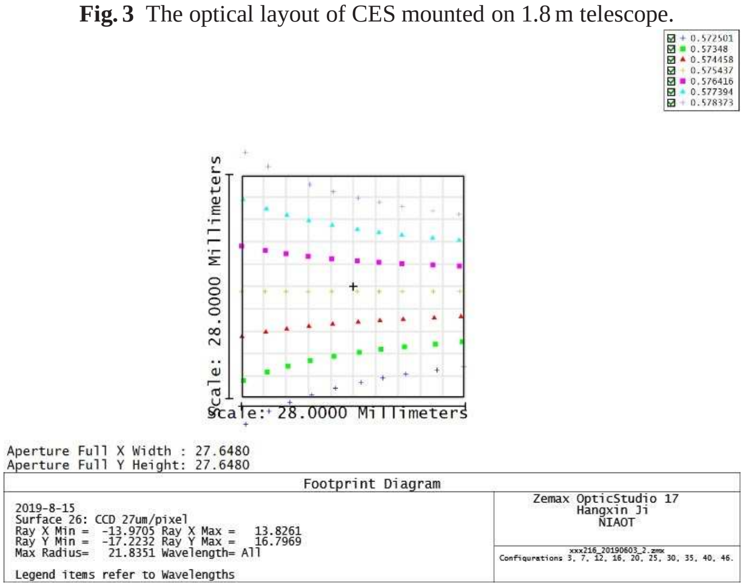

Fig. 4 The footprint diagram of CES.

Table 1 The Main Characteristics of the New Echelle Grating as well as the Old One

	Grove frequency	Blaze angle	Substrate Size	Efficiency at 580 nm
The new echelle grating	79 g mm^{-1}	63 degree	135mm×265mm	55 %
The old echelle grating	31.6 g mm^{-1}	63.43 degree	128mm×256mm	

instrument tested by a red laser at 6328 Å in the laboratory is about 35 %. The schematic layout of CES is shown in Figure 3. When the light passes through the focal reducer and the slit of CES, the light is dispersed by the new echelle grating and then cross-dispersed by the old 60 degree ZF3 prism. The footprint diagram of CES is shown in Figure 4. Because the present CCD detector is not large enough to cover the whole spectral range of CES, only part of the spectral range in the red path is available on the CCD as

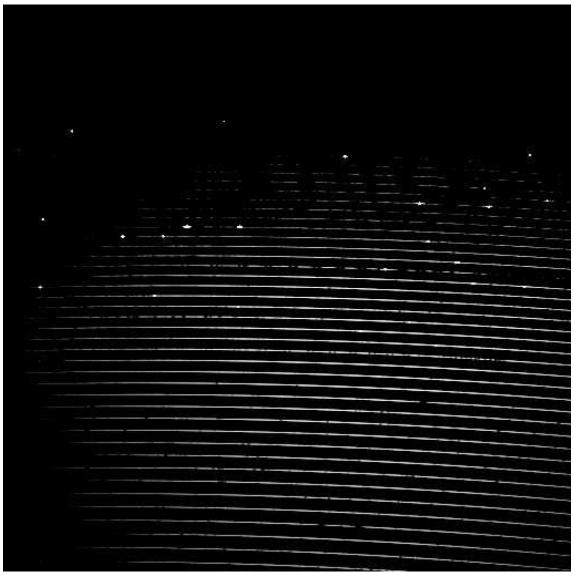

Fig. 5 The measured spectral format on CCD of CES mounted on 1.8 m telescope. In the figure ThAr spectrum is superimposed on the stellar spectrum.

Table 2 The Parameters of the CCD for Low Noise

Gain type	Read-out mode	Gain (e ADU^{-1})	Read-noise (e)
g3	fast	1.35 ± 0.02	7.14 ± 0.10
g3	low	1.24 ± 0.02	2.73 ± 0.05
g2	fast	2.63 ± 0.04	7.58 ± 0.13
g2	low	2.41 ± 0.03	3.22 ± 0.05
g1	fast	4.93 ± 0.06	8.67 ± 0.12
g1	low	4.55 ± 0.11	4.44 ± 0.11

Table 3 The Parameters of the CCD for High Capacity

Gain type	Read-out mode	Gain (e ADU^{-1})	Read-noise (e)
g3	fast	6.04 ± 0.18	27.51 ± 0.84
g3	low	5.53 ± 0.24	9.82 ± 0.44
g2	fast	12.77 ± 0.98	32.33 ± 2.50
g2	low	10.45 ± 0.38	11.90 ± 0.44
g1	fast	22.06 ± 0.84	36.30 ± 1.41
g1	low	20.08 ± 0.88	18.44 ± 0.82

shown in Figure 4. The measured spectral format on CCD of CES can be seen in Figure 5.

As before, a ThAr hollow cathode lamp and a tungsten lamp are served as wavelength calibration lamp and flat field lamp respectively, and the two lamps are put on the optical table in the same room as CES. The optical layout of the calibration and slit monitor system is shown in Figure 6. The ThAr calibration spectrum superimposed on stellar spectrum can be seen from Figure 5, and only strong emission lines of ThAr spectrum can been seen in the Figure due to the contrast ratio of ThAr spectrum to the stellar spectrum. Differently as before, the calibration light is feed to CES by a optical fiber before the slit which is convenient for installation and adjustment.

4 THE CCD DETECTOR

The detector used for CES is a 2k$\times$2k PI CCD, and the pixel size is 13.5 μm$\times$13.5 μm. The gain and read out mode of the PI CCD is adjustable for several modes, and the parameters of PI CCD modes given by the manufacture can be seen in Table 2 for low noise and Table 3 for high capacity. At present, the default mode of gain type and read out mode of the PI CCD is the fast mode of g3. The corresponding gain and readout noise are 1.35$\pm$0.02e ADU^{-1} and 7.14$\pm$0.10e respectively. The relation between quantum efficiency of the PI CCD and the wavelength is shown in Figure 7. From the figure, we can see that the quantum efficiency drops with the increasing wavelength in the

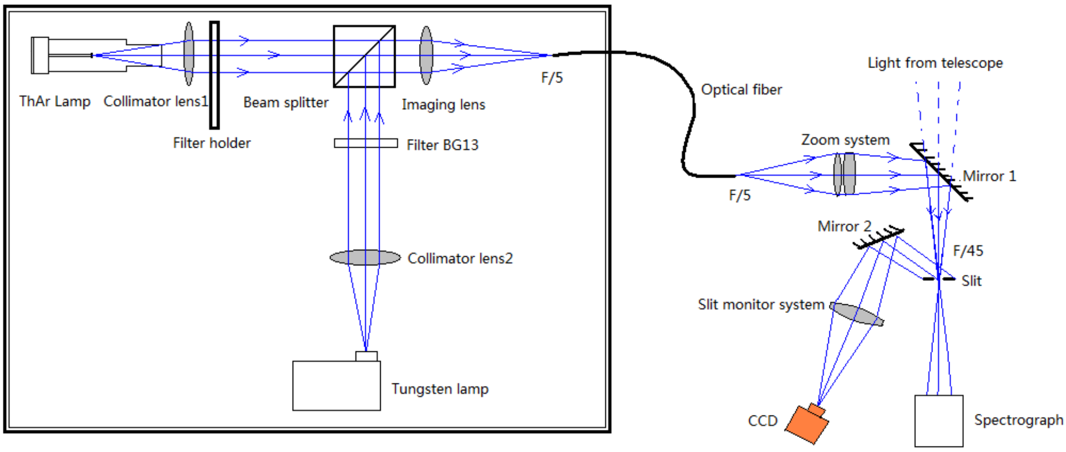

Fig. 6 The optical layout of the calibration and slit monitor system.

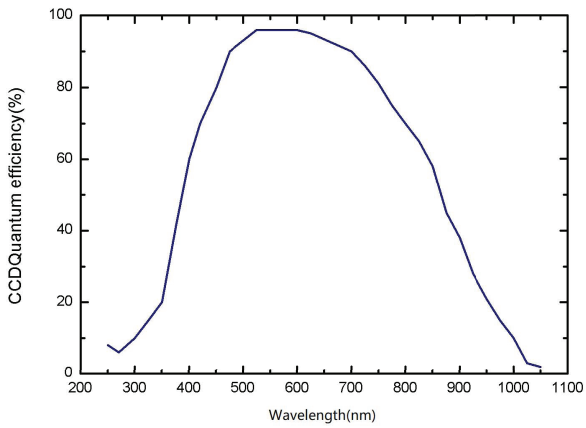

Fig. 7 The relation between the quantum efficiency of the PI CCD and the wavelength. In the wavelength coverage, the quantum efficiency begins to drop.

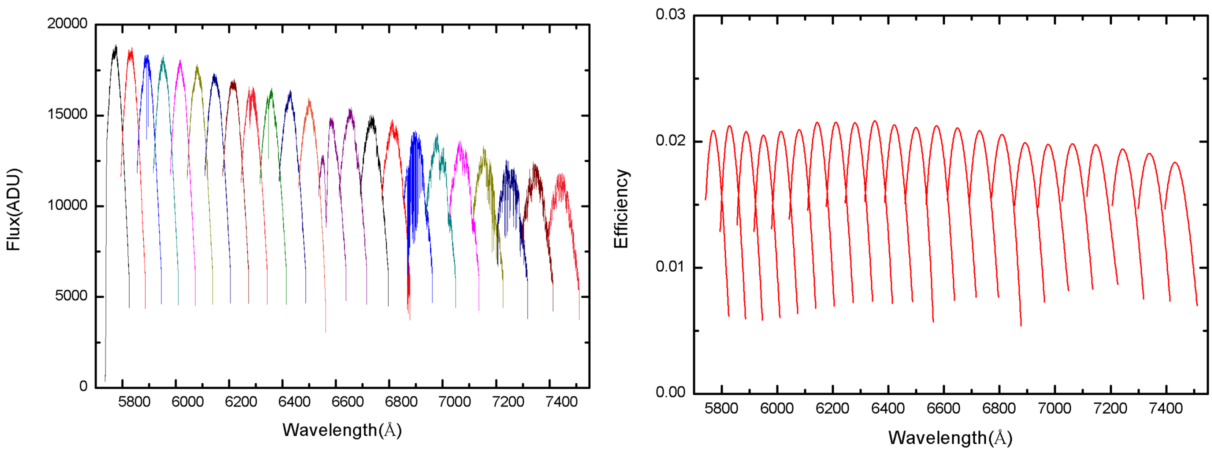

Fig. 8 The spectra of the standard star HD 23850 observed on 2016 January 18 and the derived total efficiency for CES based on the spectra at the spectral resolution of $R = 32000$.

wavelength coverage. The CCD saturation level is 64000 ADUs.

The CCD chip is cooled by a copper-braid that is connected to a liquid-nitrogen dewar. The desired cooling temperature is $-120°$C (temperature stable to within $0.05°$C)

Table 4 The Designed Spectral Resolution vs the Slit Width of CES, and the Corresponding Angle on the Sky

Slit width (mm)	Resolution	Corresponding angle on the sky ($''$)	Slit width (mm)	Resolution	Corresponding angle on the sky ($''$)
0.370	50000	0.96	0.544	34000	1.41
0.378	49000	0.98	0.561	33000	1.46
0.385	48000	1.00	0.578	32000	1.50
0.394	47000	1.02	0.597	31000	1.55
0.402	46000	1.05	0.617	30000	1.60
0.411	45000	1.07	0.638	29000	1.66
0.420	44000	1.09	0.661	28000	1.72
0.430	43000	1.12	0.685	27000	1.78
0.440	42000	1.15	0.712	26000	1.85
0.451	41000	1.17	0.740	25000	1.92
0.463	40000	1.20	0.771	24000	2.00
0.474	39000	1.23	0.804	23000	2.09
0.487	38000	1.27	0.841	22000	2.19
0.500	37000	1.30	0.881	21000	2.29
0.514	36000	1.34	0.925	20000	2.41
0.529	35000	1.37			

Table 5 The Echelle Orders of CES and the Corresponding Wavelength Ranges

Order	Wavelength (Å)	Order	Wavelength (Å)	Order	Wavelength (Å)
98	5734–5824	85	6612–6715	72	7805–7928
97	5794–5884	84	6690–6795	71	7915–8039
96	5854–5946	83	6771–6877	70	8028–8154
95	5916–6008	82	6853–6961	69	8145–8272
94	5979–6072	81	6938–7047	68	8265–8394
93	6043–6137	80	7025–7135	67	8388–8519
92	6108–6204	79	7114–7224	66	8515–8648
91	6176–6272	78	7205–7318	65	8646–8781
90	6244–6342	77	7298–7413	64	8781–8919
89	6314–6413	76	7395–7510	63	8920–9060
88	6386–6486	75	7493–7610	62	9064–9206
87	6460–6561	74	7594–7713	61	9213–9357
86	6535–6637	73	7698–7819		

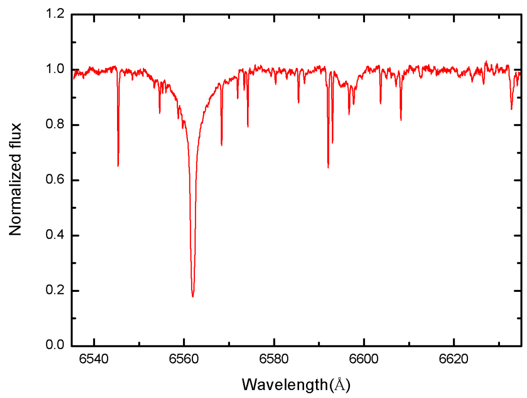

Fig. 9 Order 86 of the normalized spectra of radial velocity standard star HD 50692 observed on 2016 November 19.

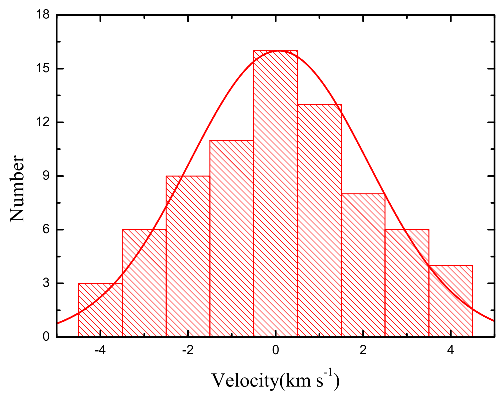

Fig. 10 The statistic distribution of the radial velocity zero point for CES measured by radial velocity standard stars.

to reduce the dark current to a negligible level for a short time exposure.

5 THE MAIN CHARACTERISTICS OF CES

With the 2k$\times$2k PI CCD, the measured wavelength coverage is from 570 to 1030 nm which is generally consistent with the designed value from 570 to 1100 nm for CES. The designed resolution of CES ranges from 20000 to 50000 by adjusting the slit width. The corresponding relationship between the designed resolution and the slit width as well as the corresponding angle on the sky is shown in Table 4. In

Table 6 The Radial Velocity Zero Point of CES Measured by the Radial Velocity Standard Stars

Name	JD-240000	Velocity (km s^{-1})	S/N	Name	JD-240000	Velocity (km s^{-1})	S/N
HD3765	58081.12380	2.02±0.22	88	HD50692	57773.26671	0.15±0.28	211
HD10780	57702.18599	1.85±0.26	271	HD50692	57774.20596	–2.89±0.30	184
HD10780	57703.06360	–0.14±0.48	271	HD50692	57775.28519	–1.23±0.28	231
HD10780	58054.29016	–2.16±0.16	270	HD50692	57788.26573	0.03±0.25	206
HD10780	58055.25936	–1.9 ±0.17	241	HD50692	57789.27382	1.0 ±0.25	208
HD10780	58081.27182	–0.89±0.23	201	HD50692	57790.22177	0.21±0.31	216
HD10780	58082.16723	–2.15±0.22	206	HD50692	57791.27152	–3.15±0.31	185
HD10780	58083.07655	1.46±0.27	184	HD50692	58081.37118	2.75±0.35	159
HD10780	58084.06664	3.35±0.33	176	HD50692	58111.36622	3.08±0.44	142
HD10780	58111.06050	–0.81±0.31	150	HD50692	58113.22637	–0.12±0.44	128
HD10780	58112.02536	3.49±0.41	148	HD50692	58146.24558	0.08±0.46	36
HD10780	58113.02425	1.46±0.35	181	HD82885	57438.14837	–3.36±0.27	180
HD32923	57436.06912	1.52±0.29	412	HD82885	57728.40638	0.08±.32	240
HD32923	57438.10535	–0.7 ±0.30	263	HD82885	57730.42171	3.83±.23	282
HD32923	57702.30289	–2.45±0.27	356	HD82885	57773.33350	–0.11±.24	292
HD32923	57712.29548	1.38±0.41	253	HD82885	77774.34592	–1.64±.29	309
HD32923	57715.29166	2.58±0.25	306	HD82885	57775.43803	1.21±.24	256
HD32923	57716.29164	0.65±0.24	228	HD82885	57788.40403	1.05±.23	266
HD32923	57760.26683	–3.13±0.34	233	HD82885	57789.40411	1.42±.22	247
HD32923	57802.07524	1.52±0.26	284	HD82885	57790.31553	1.18±.24	253
HD32923	57804.07950	0.48±0.27	262	HD82885	57791.39527	–3.7 ±.23	290
HD32923	58083.16226	1.57±0.30	233	HD82885	57792.30131	–0.32±.23	225
HD32923	58084.18542	3.71±0.31	184	HD82885	57802.19028	2.0 ±.26	213
HD32923	58111.26624	2.94±0.43	230	HD82885	57803.64868	–3.64±.63	263
HD32923	58112.23188	1.36±0.41	230	HD82885	58148.28684	–3.21±.30	167
HD50692	57436.14308	4.04±0.30	258	HD82885	58149.27071	–0.89±.24	153
HD50692	57712.39903	4.61±0.47	176	HD109358	57773.42690	0.78±0.29	48
HD50692	57714.42293	0.34±0.22	218	HD109358	57774.40547	1.16±0.39	303
HD50692	57715.40400	4.85±0.37	170	HD109358	57802.34745	1.63±0.31	394
HD50692	57716.39880	2.38±0.31	181	HD109358	57856.27653	–2.43±0.27	352
HD50692	57728.26886	–0.58±0.35	191	HD109358	57857.29315	–2.26±0.29	319
HD50692	57729.27285	–0.67±0.32	174	HD109358	57858.25102	–0.85±0.30	290
HD50692	57730.29814	4.08±0.34	167	HD109358	58146.40030	–0.19±0.26	207
HD50692	57731.28902	3.78±0.34	173	HD109358	58147.40035	0.14±0.26	224
HD50692	57760.33623	–2.8 ±0.35	167	HD182572	58054.19883	–1.22±0.29	246
HD50692	57761.31396	–1.63±0.23	156	HD193664	57702.10269	0.62±0.29	223
HD50692	57762.29956	3.75±0.31	169	HD193664	57702.99063	–0.94±0.45	226
HD50692	57772.28513	–1.96±0.30	224	HD221354	58054.10577	–1.04±0.24	130

particular, when the slit width is set as 0.5 mm corresponding 1.3$''$ on the sky, the resolution $R = 37000$. 0.5 mm slit width was used by engineers and astronomers for the test of CES during the installation process, then it is used as the default slit width for observation during January to October 2015. The limiting magnitude is $V = 11.5$ limited by the tip-tilt feedback system of 1.8 m telescope, and the S/N is about 40 for 1 hour exposure at 600 nm ($R = 37000$) tested in January 2015.

After October 2015, the frequently used slit width is 0.578 mm and the measured resolution is about 31700 in consistent with the designed value 32000, and it has the similar resolution to the high resolution spectrograph with 2$''$ optical fiber mounted on 2.4 m telescope. When the slit width is 0.578 mm, we test the total efficiency of CES (including the Earth's atmosphere, the telescope, the other optical components in the light path and the CCD quantum efficiency) by observing the flux standard star HD 23850 on 2016 January 18. The observed spectra as well as the relation between efficiency and wavelength are present in Figure 8. Besides, the echelle orders and corresponding wavelength ranges of CES are shown in Table 5.

In the spectrograph room, the temperature of the room maintains at about 25°C in case of moisture condensation with an industrial air conditioning. This reduces internal seeing and is helpful in the stability of spectrum including the calibration spectrum and target spectrum.

Through monitoring of the radial velocity standard stars for about two years, we found that the standard deviation of the radial velocity zero point for CES is about 2 km s^{-1}. The observed spectra are normalized to a continuum flux level of 1.0 with IRAF (Image Reduction and Analysis Facility), and order 86 of the normalized spectra of HD 50692 observed on 2016 November 19 is shown in Figure 9. The radial velocities are measured using the cross-correlation method (Simkin 1974; Gray & Corbally

1994) with synthetic spectral templates generated by the spectral synthesis package named as SPECTRUM (Gray & Corbally 1994). All of the 76 radial velocity zero point measurements derived from the radial velocity standard stars along with the star name, observation time, the S/N of the observed spectrum at 650 nm are listed in Table 6, and the statistic distribution of the radial velocity zero point measured by the radial velocity standard stars provided by IAU (Udry et al. 1999) is shown in Figure 10. Since the measured radial velocities for some late-type (F-M) stars can reach a precision of 100 m s^{-1} order of magnitude, much more precise than the stability of radial velocity zero point of CES its self. It is suggested that ThAr spectrum is necessary to be taken right after each target observation, and several radial velocity standard stars are suggested to be observed every night.

The overall performance of the wavelength coverage, the resolution and the environmental control of CES satisfy the scientific requirements such as the radial velocity measurements with a precision on the order of 100 m s^{-1}, studies of stellar abundance, and studies of stellar magnetic activities. Based on the high resolution observation by CES, the chromospheric activity study of late-type star DM UMa and V1355 Ori have been published (Zhang et al. 2016; Pi et al. 2016), and several Li-rich giant stars reported by Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) survey have been confirmed with atmospheric parameters and elemental abundances (Zhou et al. 2019).

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References

Gray, R. O., & Corbally, C. J. 1994, AJ, 107, 742
Pi, Q.-F., Zhang, L.-Y., Chang, L., et al. 2016, RAA, 16, 153
Simkin, S. M. 1974, A&A, 31, 129
Udry, S., Mayor, M., & Queloz, D. 1999, ASPC, 185, 367
Wang, C.-J., Bai, J.-M., Fan, Y.-F., et al. 2019, RAA (Research in Astronomy and Astrophysics), 19, 149
Wei, K., Zhang, X., Xian, H., et al. 2010, Chinese Optics Letters, 8, 1019
Zhang, L., Pi, Q., Han, X. L., Chang, L., & Wang, D. 2016, MNRAS, 459, 854
Zhao, G., & Li, H.-B. 2001, ChJAA (Chin. J. Astron. Astrophys.), 1, 555
Zhou, Y., Yan, H., Shi, J., et al. 2019, ApJ, 877, 104