Thesis for the Degree of Master of Science

Auto Guiding System
for CQUEAN(Camera for Quasars in Early uNiverse)

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Graduate School

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February, 2011

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Submitted to the School of Space Science

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Master of Science

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ABSTRACT

The Center for the Exploration of the Origin of the Universe (CEOU) recently developed an optical CCD camera, Camera for QUasars in EArly uNiverse (CQUEAN), which is sensitive at 0.7-1.1 μm to observe high redshift quasars. To enable observations with long exposures, we developed an auto-guiding system for CQUEAN. This system consists of an off-axis mirror, a baffle, a CCD camera, a motor and a differential decelerator. To increase the number of available guiding stars, we designed a rotating mechanism for the off-axis guiding camera. The guiding field can be scanned along the 10 arcmin ring off from the optical axis of the telescope. Combined with the auto-guiding software of the McDonald Observatory, we confirmed that a stable image can be obtained with an exposure time as long as 1200 seconds.

Keywords: ground-based optical telescope, imaging instrument, auto-guiding

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1. INTRODUCTION

1.1 Auto-guiding system

Every star moves in the sky due to the Earth's rotation, so the telescope should track the target with exact speed and direction during an exposure to make a long and sharp exposure of an astronomical source. The polar axis of a telescope must be exactly aligned to the Earth's rotation axis, and correct Right Ascension motor speed is needed to achieve the good tracking performance of the telescope. However a perfect telescope alignment is practically impossible, so that guiding of the telescope is needed to track the target more accurately.

Historically, guiding of a telescope was first done by astrophotographers, by staring a guide star through an eyepiece to produce an image of deep sky objects. They operated telescopes manually to track a guide star. Introduction of CCD as a guiding camera revolutionized the astrophotography because it can automatically guide a telescope without any human interventions for a very long duration with better accuracy (Birney et al. 2006).

In the auto-guiding system, the camera takes a series of exposures and passes them on to the computer. Software detects small changes in the exact positions of the guide stars in each image, and commands Telescope Control System (TCS) to make compensating corrections to keep the position of guide star fixed. Auto-guiding is essential to reduce following errors elaborately: (1) a poor polar alignment and periodic errors in the telescope tracking; and (2) Random environmental errors like scatter of atmosphere (Lee 2007), and dirt or dents in the gears.

In Korea, auto-guiding systems with CCD have been developed to improve the tracking efficiency (Jeong et al. 1999, Yoon et al. 2006), and Mun (2006) developed a telescope control program which has auto-guiding capability for the telescope in Kyung Hee University. Various efforts have been made to improve guiding accuracy (Iseki 2008) and pointing accuracy (Kanzawa 2006). Commercial auto-guiding program is getting popular among amateur astronomers these days.

1.2 CQUEAN

CQUEAN (Fig.1) is an optical camera system for the survey of high redshift ($z>5$) quasars in the early universe, which is developed by the Center for the Exploration of the Origin of the Universe (CEOU). It is composed of a science CCD camera, a focal reducer, seven broad-band filters (g’, r’, I’, z’, Y, Iz and Is) and an auto-guiding system. The science camera has a deep-depletion CCD chip whose sensitivity at 1 um is better than conventional ones. It is attached to the 2.1m Otto Struve Telescope in McDonald Observatory, Texas, USA. The overall description of CQUEAN will be presented in Park et al. (2011).

1.3 The 2.1m Otto Struve Telescope

At an altitude of 2,070 m and with clear sky, the McDonald Observatory boasts very good weather conditions for astronomical observations[1]. The 2.1m Otto Struve Telescope (Fig. 2) is a classical cassegrain telescope built in 1939[2]. The focal ratio at cassegrain focus is f/13.65. Unlike the most of modern telescope, it is mounted on German equatorial mount. An auto guider of the telescope had been developed in the past (Abbott 1990), but it is not used anymore. Thus we developed an auto-guiding system for CQUEAN and the telescope in order to observe faint targets with long exposures.

In this paper, we describe the development of the CQUEAN auto-guiding system and the result of its guiding performance analysis. In section 2, we show the tracking status of the 2.1m Otto Struve Telescope without auto-guiding, the sensitivity of the guide CCD camera, and the expected number of guiding stars for the estimated sensitivity. In section 3, the system design and the components of the auto-guiding system are described. In section 4, we present the analysis results of the first observation. Section 5 is a conclusion.

[1.] <http://cleardarksky.com/clmt/c/McDonaldObTXct.html>

[2] <http://mcdonaldobservatory.org/>

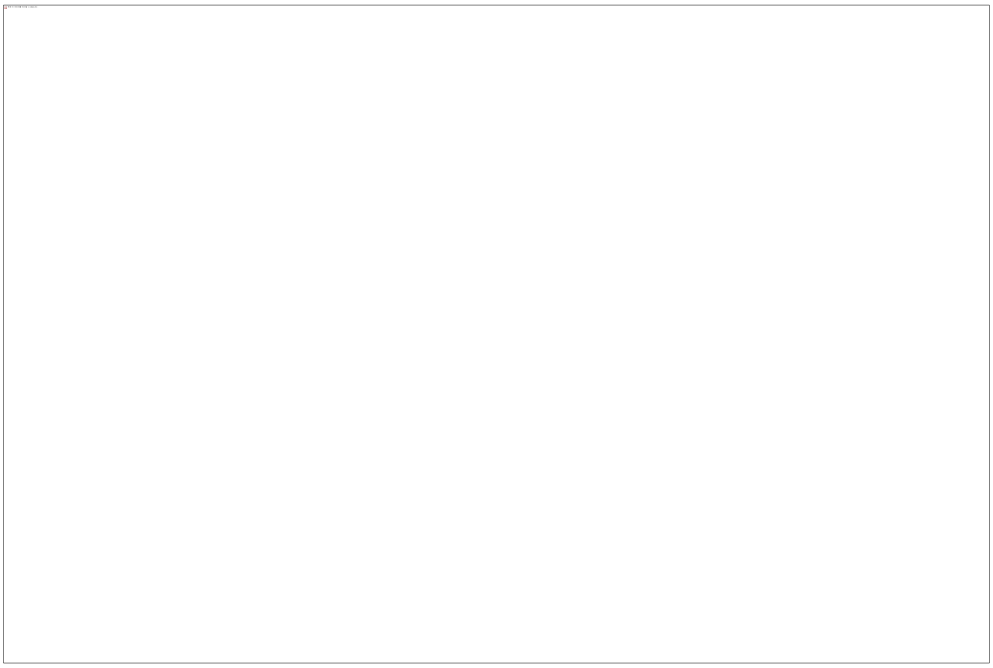


Fig. 1. CQUEAN installed on 2.1m Otto Struve Telescope.

Fig. 2. The 2.1m Otto Struve Telescope at McDonald Observatory.

2. SYSTEM REQUIREMENT

2.1 Tracking Errors

The telescope moves with two separate gear sets for quick and slow motions. The slow motion is accomplished through a cascade of three worm gears. Kuehne (2009) studied the tracking performance of the 2.1 m telescope system, and they discovered that there are some noticeable tracking errors, which are caused by incorrect motor speed in RA direction. The error is roughly roughly 7"/1200 sec or 0.006"/sec (Fig. 3). This implies that the RA tracking can cause about 0.1" drift in the pointing for 25 sec exposure frames. Since the telescope is not perfectly aligned to the polar axis, the displacement in Dec is about 2.25"/3000 sec, 0.00075"/sec, which is negligible in most long exposure observations (Fig. 4). Also a periodic jump in the RA direction of about 1" in every 120 seconds is caused by imperfections, damage, or wear of the slow motion gear which rotates every 2 minutes (Fig. 3). This periodic spike rises at the rate of 0.05" per second to the maximum value of ~1".

Therefore, in order to keep the telescope within 0.1" accuracy, we require the correction of the pointing at least every 2 seconds using a suitable guide star.

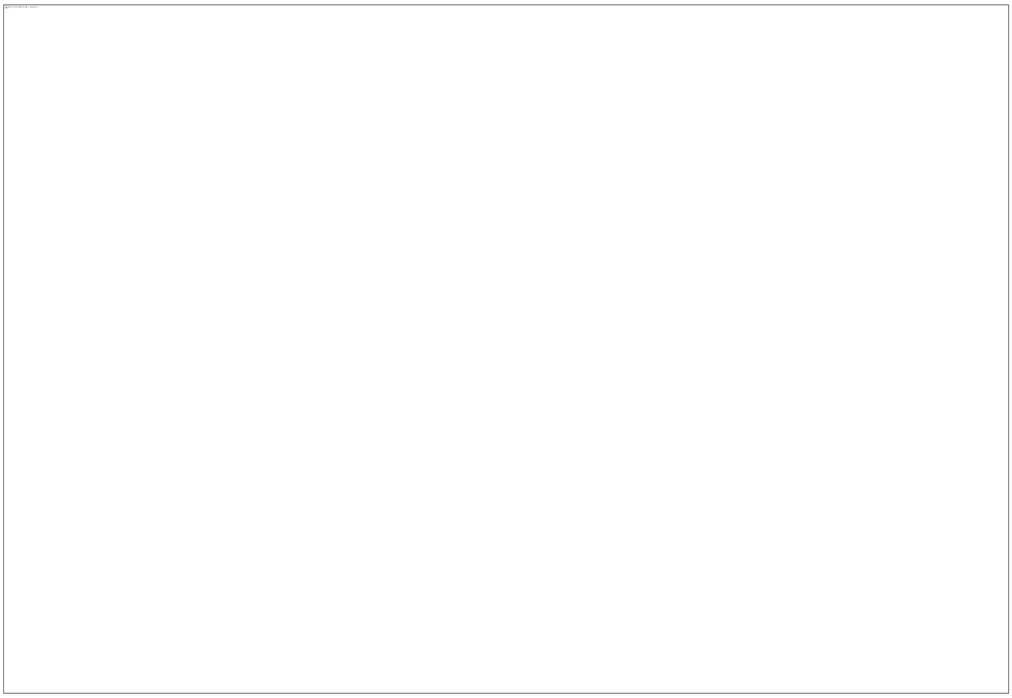


Fig. 3. Displacement of a point source in RA direction on the 2.1m telescope field of view without auto-guiding. Note the two minute periodic errors (Kuehne 2009).

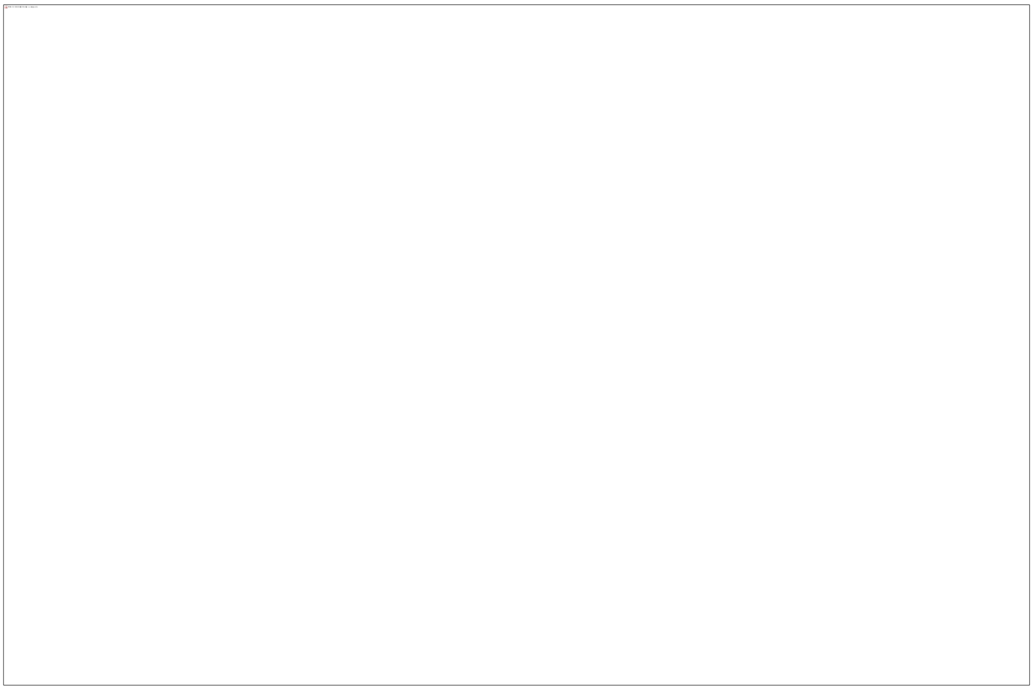
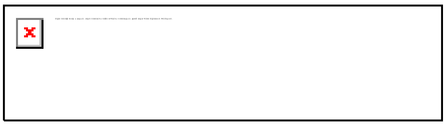


Fig. 4. Displacement of the telescope in Dec direction without auto-guidng (Kuehne 2009).

2.2 Number of expected guiding stars and Guide camera field of view

Since auto-guiding requires fast processing in the positional measurement, a guiding star must be bright. We estimated the expected number of guiding stars with our guiding CCD camera to check the feasibility of the auto-guiding system. Since the guiding camera will make short exposures of bright stars, system noise would affect the sensitivity more than sky background. Thus we assumed that the sensitivity of guide CCD is limited by the system noise, and calculated the detection limit with S/N of 10 with 1 sec exposure time. The detection limit under high system noise (McLean 2008) is given as below.



(1)

m_{zp} : zeropoint

g : gain [electron/ADU]

S/N: Signal to noise ratio

N_{pix} : number of pixels that cover a stellar profile

n_0: number of exposures

T: exposure time [sec]

R : readout noise [electrons]

The zeropoint of the system is calculated to be 23.18 mag with the assumptions that total system throughput is 0.8 and CCD gain is 10. As for the readout noise, we use the value of 8 electron/pixel from the CCD manufacturer's test report. We assumed N_{pix} to be 149.42 pixels based on the f-ratio of the telescope and median value of 1.2″ for seeing condition in V at McDonald Observatory. With all assumptions, we obtained m_v = 18.17 for the assumed operational condition of the guide CCD camera.

Using the star count data at galactic poles (Allen 2000), we calculated the expected number of stars brighter than the limiting magnitude over a 2.97′ x 2.97′ field of view. Fig. 5 shows that at most 1.2 stars may fall on our guiding CCD field of view. The number will be higher than this value at the lower galactic regions. There will be nights with bad seeing and clouds, so we require that there should be at least 5 stars suitable for guiding (S/N > 10) in the guiding field. To satisfy such a requirement, we designed a moving mechanism to rotate the guiding camera around the optical axis to provide a wide guiding field, which increases the guiding field of view by about a factor of 5.

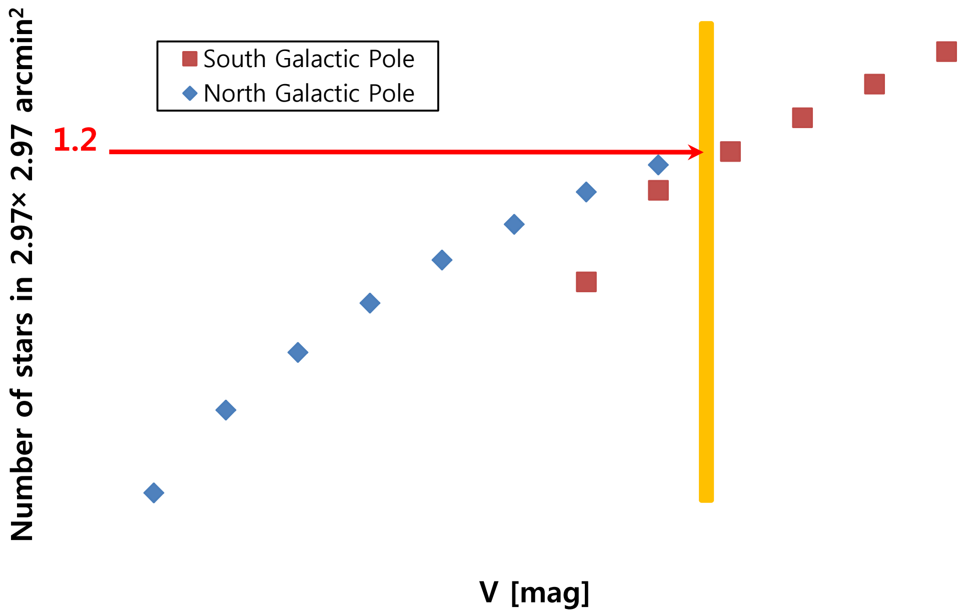


Fig. 5. Expected number of guiding stars in the guide CCD field (2.97′× 2.97′) that can be detected with 10-σ limit in 1 sec exposure. The blue diamonds in the graph represent the number of stars in the north galactic pole and the red squares the stars in the south galactic pole. Thick yellow line indicates the limiting magnitude for our guide CCD camera.

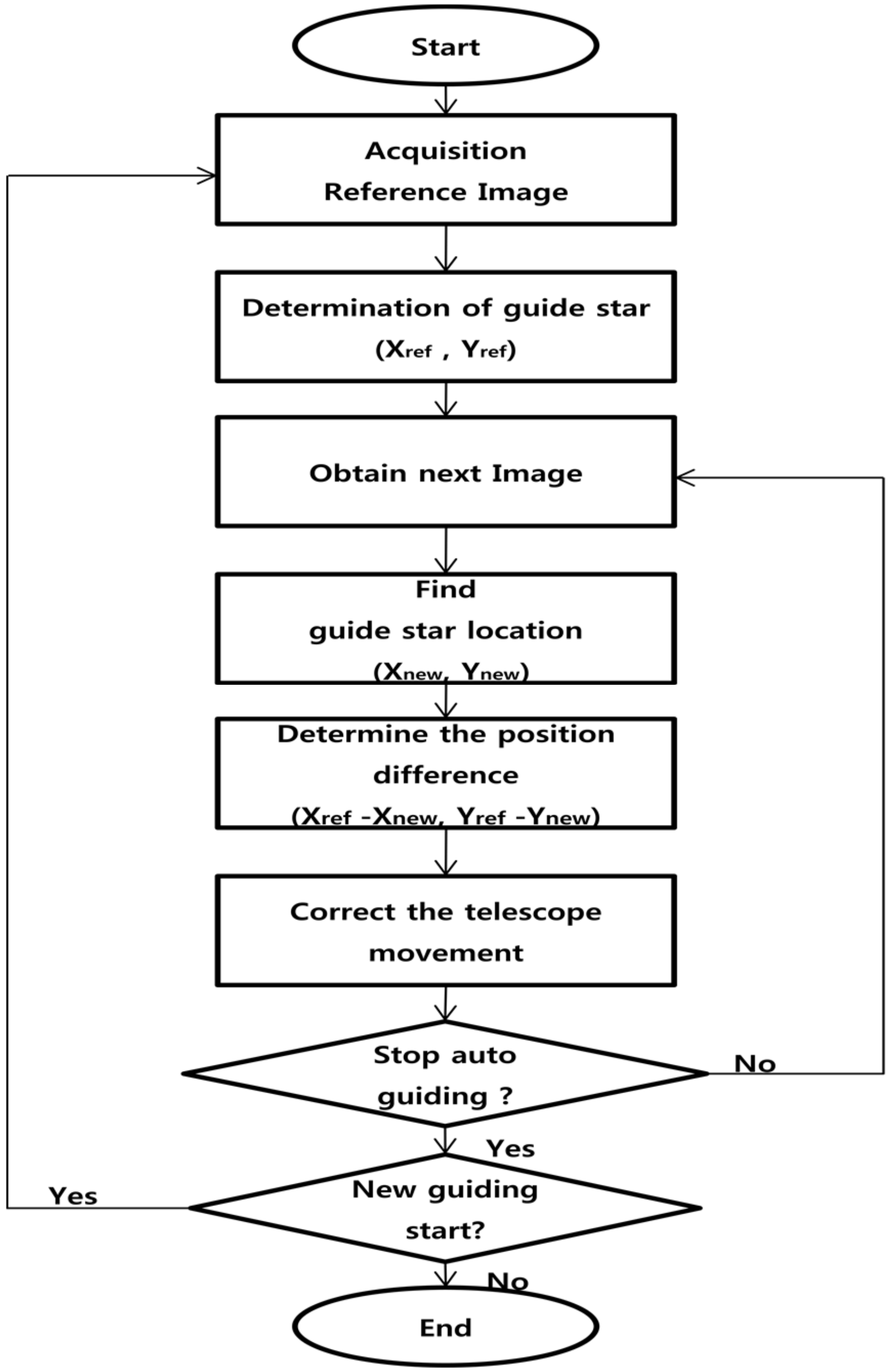


Fig. 6. Auto-guiding procedure of CQUEAN.

3. CQUEAN AUTO-GUIDING SYSTEM

With the requirements for the guiding at hand, we designed an auto-guiding system.

Fig. 6 shows the auto-guiding procedure. The auto-guiding system makes an exposure of a guiding field to find a guiding star (normally a bright star). Then, it registers the position of the star on the CCD, and compares it with the position of the same star in the next image. With the location and the time difference between the reference image and comparison image, it calculates the tracking errors of the telescope. The system interacts with TCS to offset the telescope movement to correct the tracking errors. The whole process is to be carried out continually in real time to control the telescope.

3.1 Overview of the guiding system

The overview of the opto-mechanical part in the auto-guiding system is given in Fig. 7. The telescope adapter holds all components of CQUEAN: a science CCD camera, a guide CCD camera, a filter wheel, and a control PC. The incoming light of the guide field is sent from the telescope secondary to the off-axis mirror and it is reflected into the guide CCD camera. If no suitable guide star is found, the guide camera and the off-axis mirror are rotated with the arm around the telescope axis. The guide camera is controlled with the control computer, and the information of the guiding field is sent to the control software, called "*agdr*", which interacts with the TCS. The image of the guide field is taken at a short interval (typically 1-5 sec, but a higher frequency is possible) to provide necessary data for auto-guiding (See also Fig. 8 and the contents in Section 3.3). In the following subsections, we describe key hardware components and software component of the auto-guider.

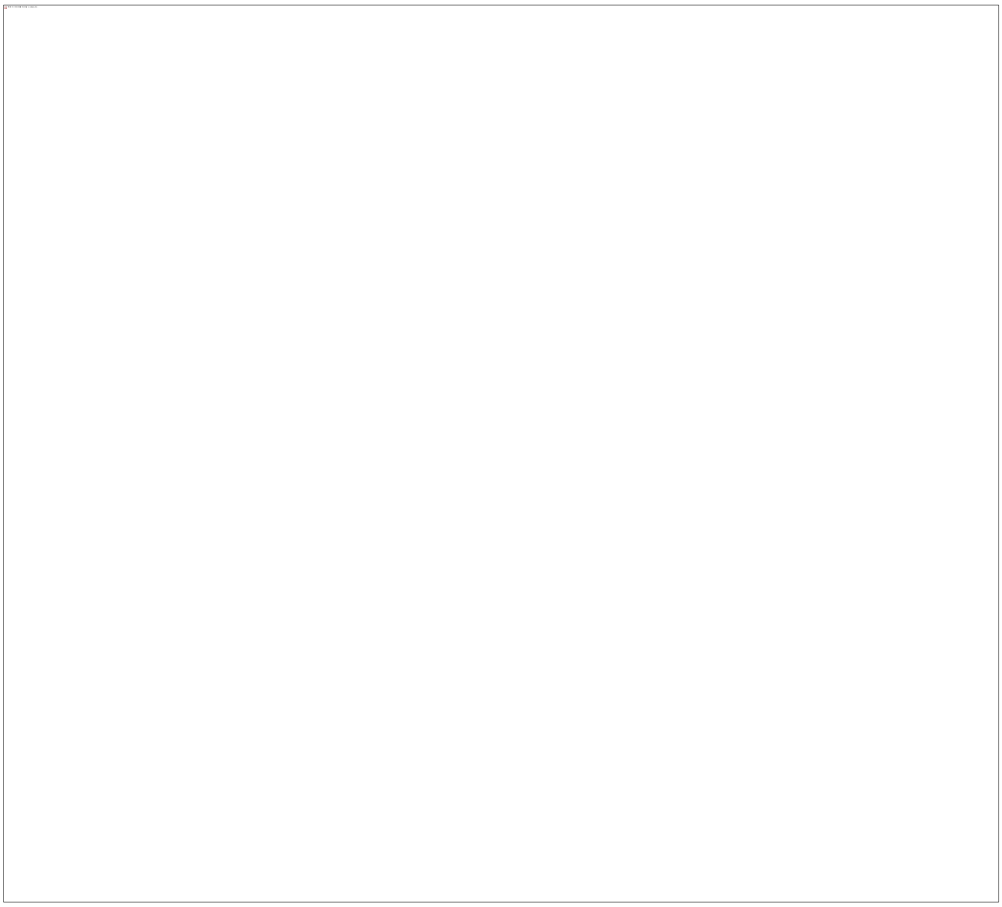


Fig. 7. 3D Design of CQUEAN structure (without the baffle and the cover).

3.2 Guiding CCD camera

ProLine1001E CCD camera (Fig. 8) from Finger Lakes Instrumentation Co. is used for the auto-guiding system. This camera employs a front illuminated KODAK KAF-1001E detector, which has 1024 × 1024 pixels of 24 × 24 μm size. The pixel scale is 0.174 arcsec/pixel, and the field of view is 2.97′× 2.97′ at the cassegrain focus of the 2.1m telescope. Table 1 summarizes the basic specifications of our guide CCD camera, and Fig. 9 shows the quantum efficiency of the guide camera.

The camera is cooled down to -30˚ during the normal operation via air cooling. The camera housing includes the CCD chip as well as the cooling unit and electronics for the chip. It is connected to the control computer via USB, and the readout speed is 1 MHz, which is more than enough for our auto-guiding application.

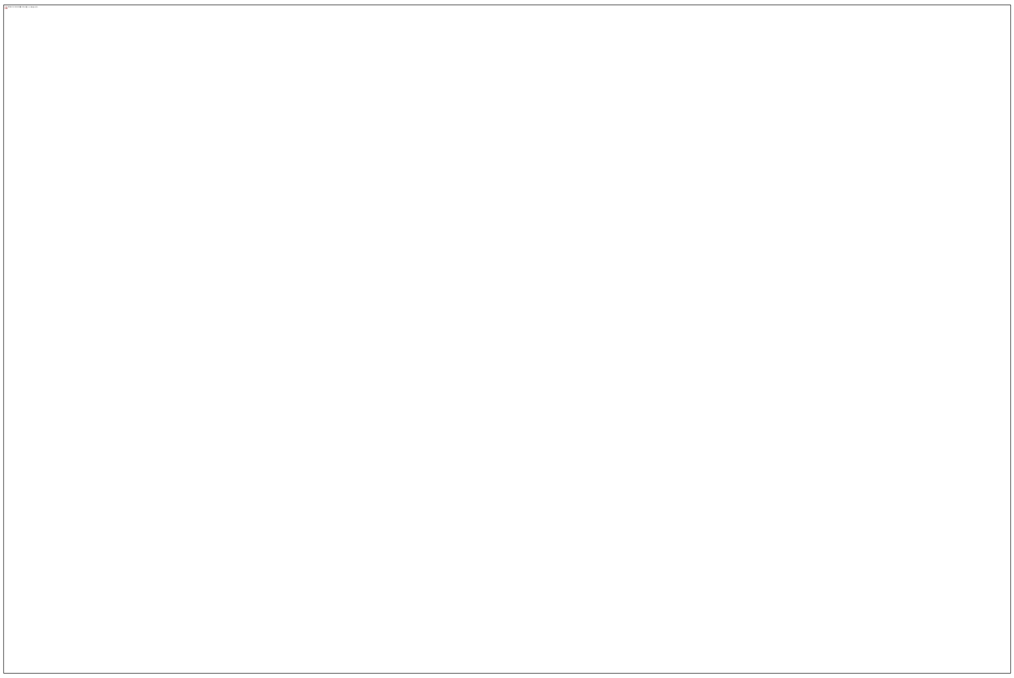


Fig. 8. ProLine1001E CCD camera from Finger Lake Instrumentation.

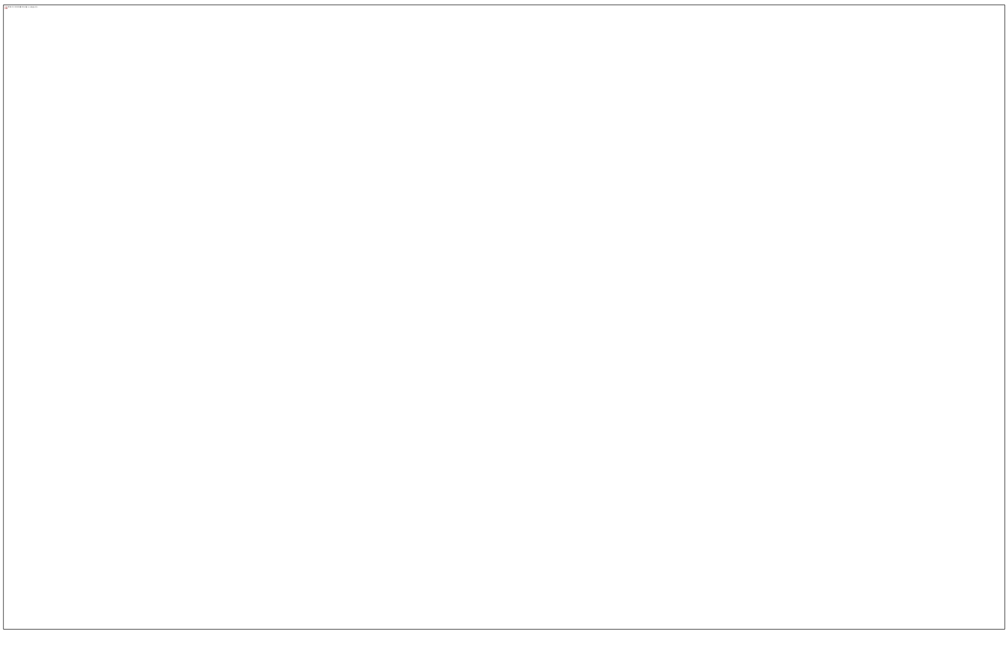


Fig. 9. Quantum efficiency of the guiding camera, FLI PL100E (FLI manual).

Table 1. Specification of FLI PL1001E on the 2.1m telescope

Pixel size	24µm×24µm
Pixel format	1024×1024
Pixel scale	0.174 arcsec/pixel
Field of view	2.97′×2.97′
CCD type	Front illuminated
Readout noise	8.70 e- RMS @ 1Mhz
Bias	1850 counts
Peak QE	72%
Cooling method	Air cooling
Dark current	Less than 0.2 e-/pixel/sec. @ -45º C
Linear full well	500,000 e-
Readout speed	1 MHz, 3.3 MHz
Gain	2.42 electrons/ADU

3.3 Guide camera system platform

As we described in previous section, the guide CCD camera system has to be movable to see different off-axis field. Therefore, the guiding camera and the off-axis mirror sit on one arm that rotates around the optical axis as a center. The guiding CCD camera is installed about 300 mm away from the optical axis, and it is 2.12 degree tilted forward to make the image plane be vertical to the central beam. The position of guide CCD camera can be adjusted for a focus adjustment.

A baffle and a cover are installed at later stage of design between the mirror and guide CCD camera to block the stray light from other directions. Fig. 10 shows the picture of the rotating arm, and the guide CCD camera system on it. The rotating arm is composed with three main pieces and two supporting pieces to prevent stress and flexure. The motor system consists of MDRIVE 34 motor from IMS and the differential decelerator, AD140-050-P1 from APEX. The motor is connected to the computer via USB port with serial-to-USB converter and controlled with pre-defined text commands that sent over USB port.

On the 2.1m telescope, the center of the guiding field is separated from the center of the science field of view by 10 arcmin. The arm is allowed to move from -20 deg to 70 deg which is the range that can avoid mechanical interference with other parts of the CQUEAN system. Therefore, the total available field of view is about 63 $arcmin^2$, satisfying the requirement for the number of available guiding stars.

Fig. 11 depicts how the guiding field is changed by the moving mechanism. Suppose simply that blue circle is the bottom, actually primary mirror, of the telescope and CQUEAN is on the telescope. The guiding camera is set to the south and the control PC is opposite side, the north. The guiding camera rotates from 20 degrees east to 70 degrees west, then the guiding camera takes pictures of from 20 degrees west sky to 70 degree east sky.

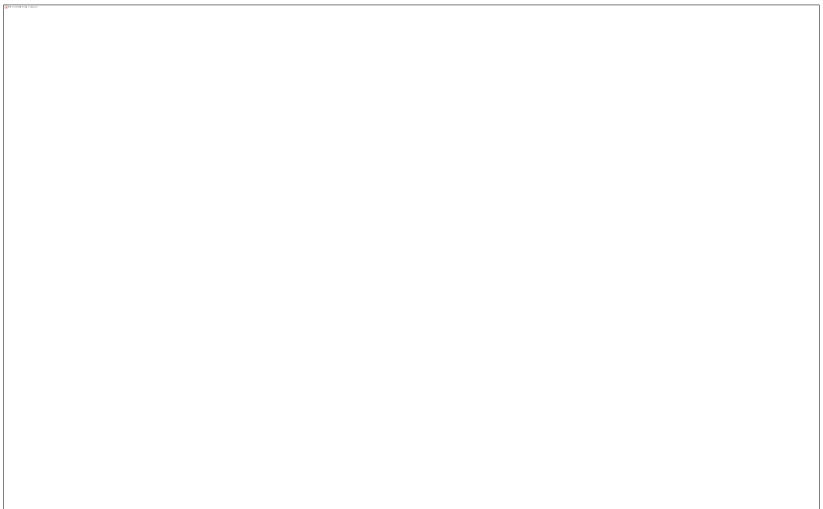


Fig.10. Guiding System of CQUEAN.

Fig. 11. Conceptual Design for enlarging guiding field by rotating guiding camera. Note that the distance between the science camera and the guiding field is exaggerated for better understanding.

3.4 Software

Two programs are used for auto-guiding of CQUEAN. The auto-guiding is controlled by the *agdr*, the guiding control program, and the arm motion is controlled by the *Data Taking Package*, which is the main control program of CQUEAN.

The *agdr* was originally developed for the 2.7m Harlan J. Smith Telescope of the McDonald Observatory and was newly modified for the 2.1m Otto Struve Telescope and CQUEAN by one of us (SO). Back-end routines and front–end GUI of the *agdr* are written in C and Tcl respectively. The main window of the a*gdr* displays the acquired images from the guide CCD camera. It has several buttons to control the auto-guiding action, and additional functions can be invoked by using menus in the upper part of the window. Fig. 12 displays the several windows of the *agdr* in running. In addition to auto-guiding, it continuously monitors the seeing condition of the guide star. The *agdr* calculates the amounts of telescope offsets in celestial coordinate system.Thus it has to know the guide CCD chip orientation, which varies with the rotation of guide CCD camera.

The *Data taking package* window (Fig. 13) developed by some of us (WKP, HJ) provides control panel to rotate the arm. The a*gdr* interacts with the *Data Tacking Package* to obtain the guide CCD chip orientation. The connections of two programs, as well as all hardware components of CQUEAN, are shown as a block diagrams in Fig. 14.

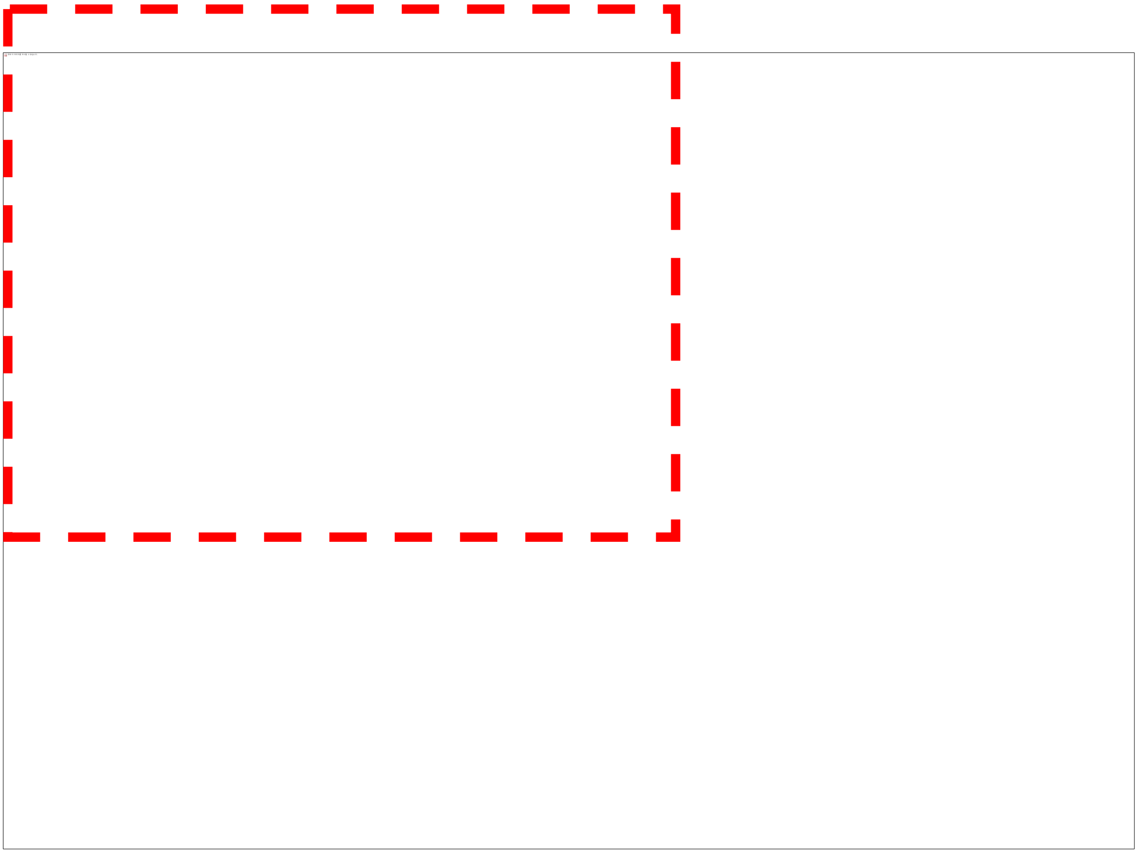


Fig. 12. *Agdr* – guiding control program. Red rectangle dashed line denotes main window.

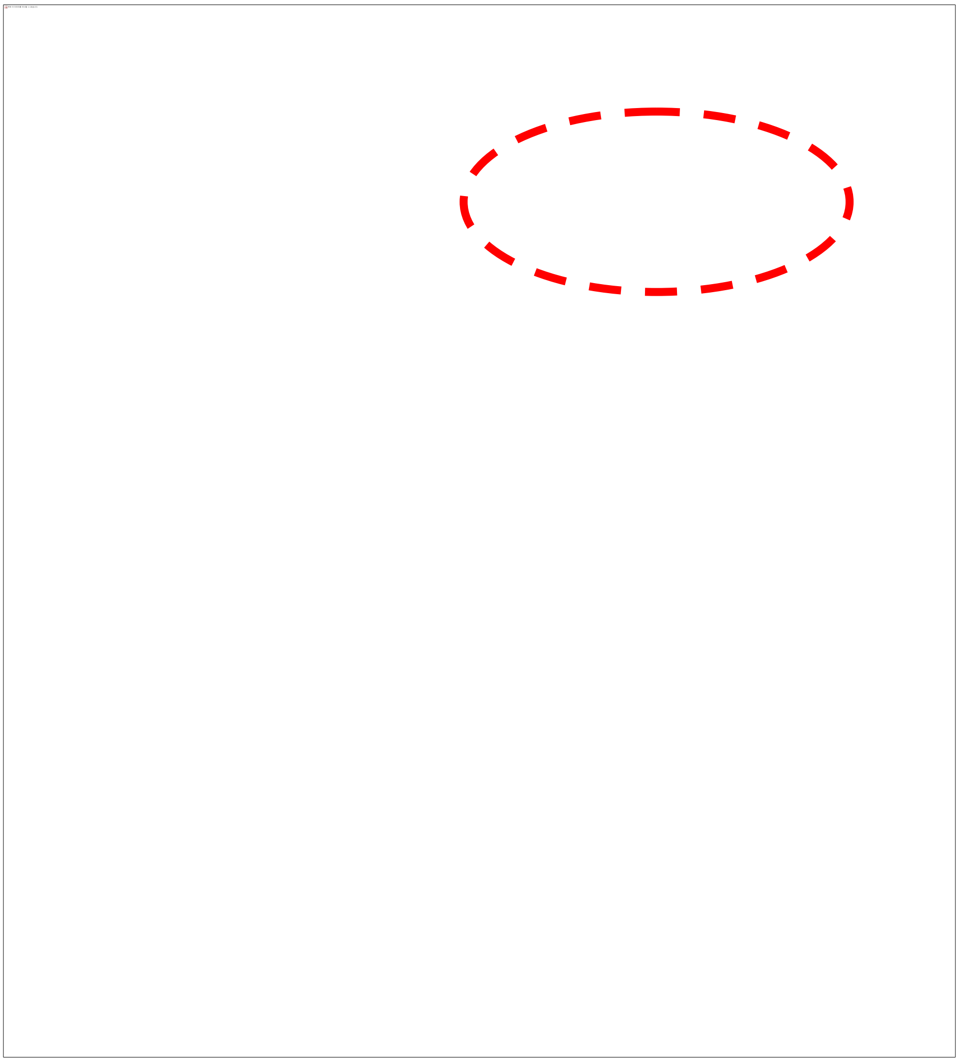


Fig. 13. Main window for CQUEAN data taking package. Red dashed circle indicates the auto-guiding field control part. It controls the rotation angle of the arm for the auto-guiding system.

Fig. 14. Block diagram of all CQUEAN components.

4. LAB TEST

Lab test was performed in order to check connection of FLI camera and control software, recognition of a guiding star and guiding accuracy (Fig. 15). Test processing is to make artificial stars first and see that the program could recognize slight movements of the artificial stars and work normally. Optical fiber's edge passing Neon-Helium laser source is a pointing source as an artificial star. Five optical fibers are stuck in the hole of the Input plate in front of the laser source and the other sides of the optical fibers are put in the random holes of the Output plate (7cm diameter) on the micro linear stage (Fig. 16). Figure 17 shows the artificial stars taken by FLI camera in the dark. We confirmed that Agdr recognized artificial stars' movements by fine-tuning 3-axis linear stage and guiding information was written in Guiding History.

Fig. 15. The entire experiment setup.

현재 이 이미지를 표시할 수 없습니다.

Fig. 16. The Input plate and Helium-Neon Laser source (Left) and the Output plate and the artificial stars (Right).

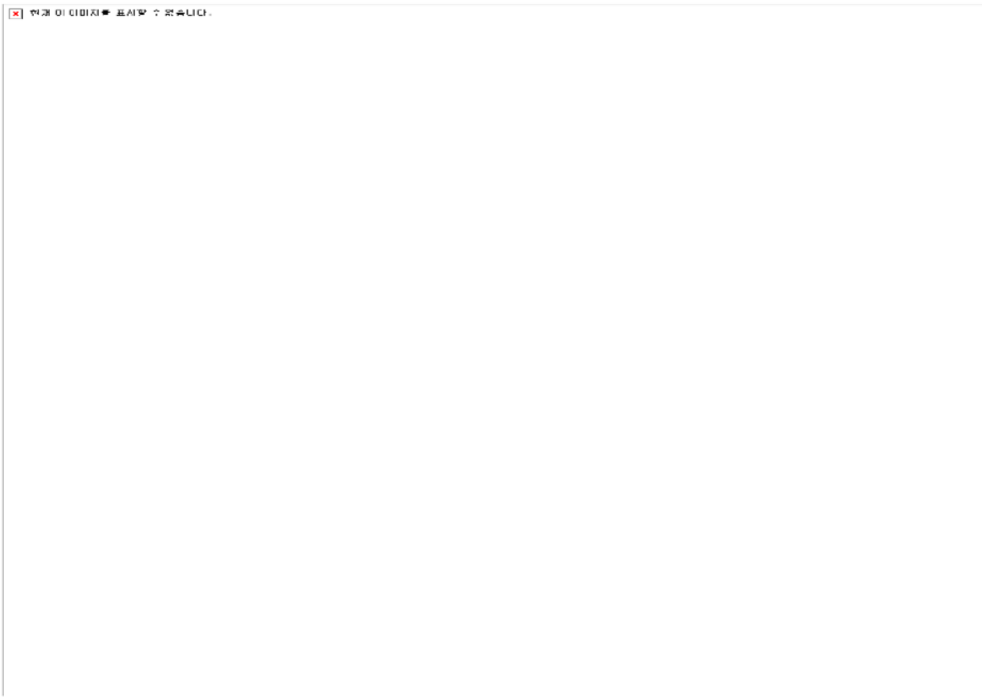


Fig. 17. Artificial stars Image of FLI guiding camera

5. TEST OBSERVATION AND ANALYSIS

5.1 Observation Log

During 2010 August 10-17, we installed CQUEAN to the 2.1m telescope and performed a commissioning observation. Operational test of all CQUEAN components including the auto-guiding system was carried out. Various targets such as standard stars, globular clusters, quasars, and gamma-ray bursts were observed with the science CCD camera to estimate its performance. Sky was clear except for one night and Table2 lists the average seeing obtained during the first observation. We varied the exposure times from 0.1 to 1200 seconds to test the performance of the auto-guiding system and the science camera. Additional test was carried out during the subsequent run on 2010 December 20-29.

We verified the hardware of the guiding system and observational performance. Also differences in guiding efficiency according to exposure time was investigated.

Table 2. Weather condition during the observation.

Date (UT)	FWHM of PSF[a,b]		Sky
	Science camera	Guiding camera	
	i'-filter	-	
2010 Aug 12	-	1.24	-
2010 Aug 13	0.96	1.22	-
2010 Aug 14	1.02	1.35	-
2010 Aug 15	1.07	1.44	thin cirus
2010 Aug 16	1.07	1.23	cloudy
2010 Aug 17	0.83	1.06	clear
2010 Aug 18	0.85	1.03	very clear

[a] Units in arcsec.

[b] average value during the night.

5.2 Operation Test

Fig. 18 shows an example of raw images obtained with the guide CCD camera when it is located at the south of science CCD camera, a reference image position denoted as W00 in Fig. 19. The east direction is down and the north is to the left of the image. We calibrated the Position Angle (PA) information in the *agdr* with correct value for accurate guiding.

To find out the exact location of the guide camera observation field with respect to that of the science CCD camera, and to investigate the orientation of guide CCD chip, we observed a region in NGC 6633 with both science and guide CCD camera on August 17, 2010. Different guiding fields were observed with the science CCD camera fixed to a position by rotating the arm by 20 deg in each step in order to check the performance of the moving mechanism. It turned out that the guide camera sees the field in opposite direction with respect to the optical axis of the telescope, i.e., it sees northwest field when the camera is at southeast position. Fig. 19 shows the locations of each guiding image with respect to the scientific field, and Table 3 lists the coordinates of the guiding field. Each field is named after the location of guide CCD camera. The RA and Dec of the science image center are 276.9260 deg and 6.56747 deg respectively. The separation between the science image and the guide-field images is about 10 arcmin - a more detailed analysis is given in the next section.

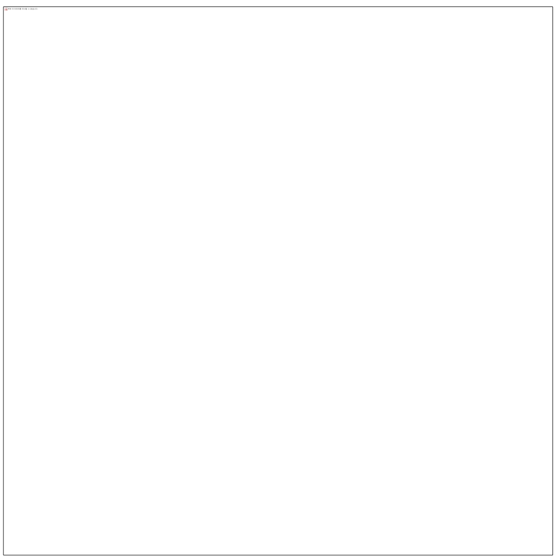


Fig. 18. Example of the guiding field image. The east is down and the north is to the left.

Table 3. Guiding image information.

Field	Angle[a]	RA[a]	Dec[a]	X axis rotation[a,b]	Y axis rotation[a,b]
e20	-20	276.86590	6.72022	68.894	248.836
w00	0	276.92226	6.73242	88.970	268.943
w20	20	276.97954	6.72482	108.801	288.867
w40	40	277.03124	6.69820	128.915	308.871
w60	60	277.06961	6.65577	148.927	328.924

[a] Units in degree.

[b] Angle between X-axis of the guiding image and RA axis direction.

[c] Angle between Y-axis of the guiding image and Dec axis direction.

Fig. 19. Locations of science CCD camera field and the guiding CCD camera fields. Note the guide field names are after the locations of guide CCD camera, not the locations of fields. See Section 4.2 for explanation.

5.2.1 Hardware Performance

We calculated the distance between the science image center and guiding image center, and the arm rotation angles to investigate a degree of flexure or hardware limitation for the auto-guiding system. With the celestial coordinates of each image centers, we calculated R, the distance between the science image center and a guide CCD image center, and θ, the angle between each successive positions of the rotating arm, as indicated in Fig. 19. We used following Eqs.(2,3) derived from spherical trigonometry.

$$R^2 \approx (\delta_g - \delta_s)^2 + \left\{(\alpha_g - \alpha_s) \cdot \cos\left(\frac{\delta_g + \delta_s}{2}\right)\right\}^2 \qquad (2)$$

$$\cos\theta = \frac{\cos\Delta\alpha - \cos\Delta\delta \cdot \cos R}{\sin\Delta\delta \cdot \sin R} \qquad (3)$$

where, $\Delta\alpha = (\alpha_g - \alpha_s) \cdot \cos\,\delta_g$

$\Delta\delta = \delta_g - \delta_s$

The results are listed in Table 4. Note that R is increasing as the arm rotates further into west direction. It may be due to that the arm rotation center does not exactly coincide with that of the science CCD. Therefore, we tried to find the science image center that minimizes the standard deviation of R values. The new center position was found to be located at $\Delta\alpha$ = 0.003 deg, $\Delta\delta$ = 0.00001 deg apart from the original center. The R′ and θ′ represent the values of R and θ on the re-centered data, and listed in the columns 6 to 8. Fig. 20 and Fig. 21 show θ - Φ and R with respect to each center.

Table 4. Angles and separations of the images.

Frame	Ideal rotation angle (Φ) [deg]	Original data			Re-centered data		
		Rotation angle (θ)[deg]	θ - Φ [deg]	Image separation (R) [arcmin]	Rotation angle (θ') [deg][a]	θ' -Φ [deg][a]	Image separation (R´) [arcmin][a]
E20	-20	-21.3520	-1.3520	9.841	-22.3162	-2.3162	9.907
W00	0	-1.3003	-1.3003	9.899	-2.3342	-2.3342	9.905
W20	20	18.6613	-1.3387	9.965	17.6831	-2.3169	9.909
W40	40	38.6322	-1.3678	10.042	37.8288	-2.1712	9.931
W60	60	58.2289	-1.7711	10.065	57.6880	-2.3120	9.913
Standard	-	-	**0.195**	**0.094**	**-**	***0.067***	***0.011***

deviation	

[a]After adjusting the science center by ($\Delta\alpha$=0.003deg, $\Delta\delta$=0.00001deg).

Fig. 20. Angle steps with respect to the original center and new center.

See section 4.2.1 for explanation.

Fig. 21. Image separation with respect to the original center and new center.

As for θ, we can see there is about -1.3 degree offset between the expected and the measured values. This is because the reference position of the guide CCD frame, W00, is not exactly aligned with the meridian with science CCD image. We also see there are scatters of about 0.195 deg and 0.067 deg for the current and new center respectively. The step size for the combined system of the motor and the decelerator can be calculated from the specifications of each device, i.e. $\Delta\theta_{step} = 0.0035$ deg. Also the backlash of the decelerator is 5′ (≈ 0.0083 deg). Considering these factors, we can expect that standard deviation of differences between re-centered and ideal rotation angle is affected by backlash of the decelerator.

In the case of R, there are still scatter, we regard this scatter is due to the mechanical flexure of rotating arm. Standard deviationof R at re-centered position is 0.011 arcmin (0.66 arcsec) for 80° rotation of the guiding system, and maximum of standard deviation is 0.094 arcmin. We estimate that 80° rotation of the guiding system corresponds to 80° tracking of the telescope, that is 5.3 hour continuous guiding situation. For 1200 sec exposure observation, we can expect the flexure of

$$\Delta R_{min}(t = 1200\,\mathrm{sec}) \approx \frac{0.66''}{80[\mathrm{deg}]} \cdot 15 \left[\frac{\mathrm{deg}}{\mathrm{h}}\right] \cdot 1200[\mathrm{sec}]$$

$$\Delta R_{max}(t = 1200\,\mathrm{sec}) \approx \frac{5.64''}{80[\mathrm{deg}]} \cdot 15 \left[\frac{\mathrm{deg}}{\mathrm{h}}\right] \cdot 1200[\mathrm{sec}]$$

The rotating arm flexure during 1200 sec observation would be 0.04 - 0.35 arcsec which is negligible for the size of the PSF.

5.2.2 Analysis of Guiding Performance

We examined profiles of astronomical sources in our science images to estimate guiding performance. Ideal auto-guiding would make stellar profiles in perfect circular shape, and would leave no trails in long exposures. To demonstrate how a bad guiding affects the image quality, we compare two 600 sec images with auto-guiding (left) and without auto-guiding (right) in Fig. 22. The stellar profiles on the auto-guided image are more round, while those in non-auto-guided image looks quite elongated to the RA direction as expected from the tracking error analysis as described in section 2.1. Also faint stars appear more vaguely on the non-auto-guided image, since the fluxes of stars were spread over larger area on the chip.

To analyze the guiding performance in a more quantitative way, we selected i-band images of various exposure times from 1 sec to 1200 sec in order to compare the PSF shapes with each other. This images were observed on August 10-17, 2010. For the analysis, the FWHMs and ellipticities were measured using the IMEXAME task in IRAF. We selected round and isolated sources in the images as many as possible, but stars near the edge of images were not included since their profiles might be affected from the aberration of the optics.

The medians and errors for FWHMs in different exposure times are plotted in Fig. 24 and same plot for ellipticies is shown in Fig. 25. The error bar indicates the 1-σ level of the data. FWHM seems to be increasing with exposure time but with large scatter. Note the plot includes data from various nights of different seeings to increase the number of points, thus FWHM may include the effect of different seeing condition. Therefore we cannot make clear conclusion with these data.

The ellipticity distribution also shows large scatters. However, we note that values are all smaller than 0.5, and median value shows little change over exposure time so we regard that auto-guiding work well. Indeed, we could not see any clear star trails in all of 1200 sec long exposures during the observation run, as shown with an example image in Fig. 23. We also could not observe any jitter in the image that would arise from the worm-gear (See section 2 for detailed explanation.). Therefore, with the available data, we concluded that auto-guiding system works well.

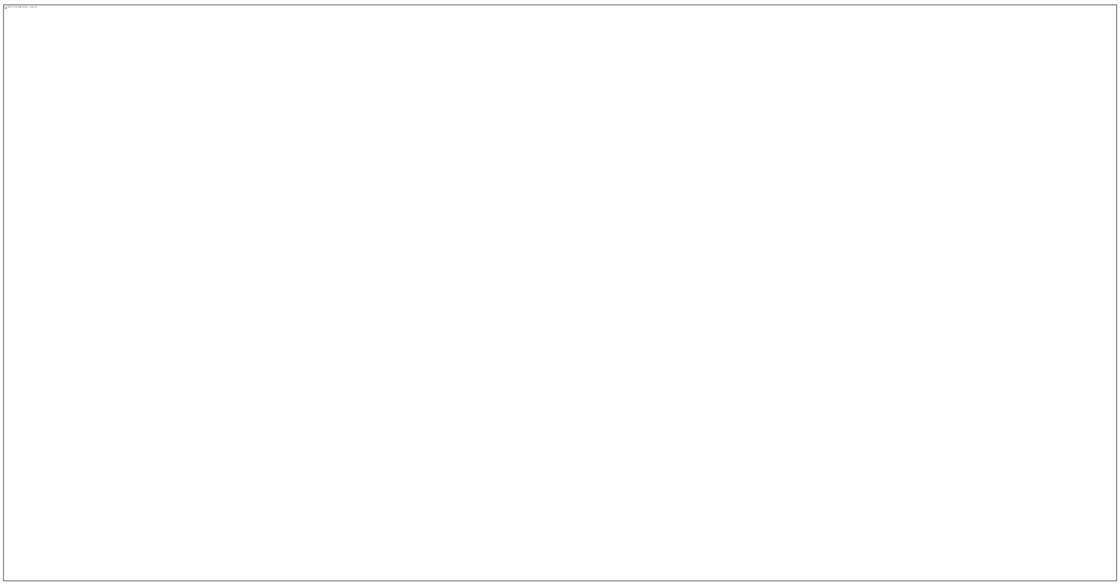


Fig. 22. Comparison of 600 sec images with auto-guiding (left) and without auto-guiding (right).

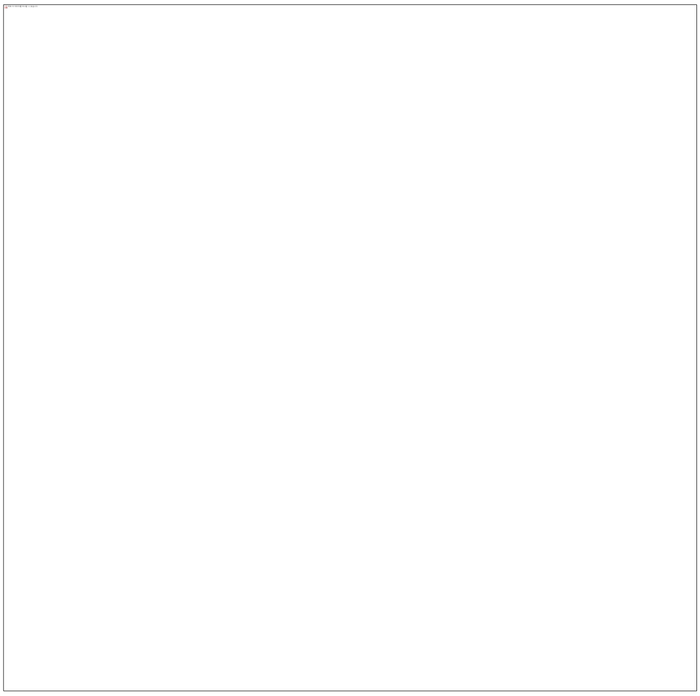


Fig. 23. The r´- filter image of GRB 100814A exposed with 1200 seconds. The stars in the image show no trails.

Fig. 24.

FWHM of stars according to exposure time. Open red circles denote the individual measured values, and black diamonds denote the median value of the data.

Fig. 25.

Ellipticity of stars versus exposure time. Open red circles denote the individual measured values, and black diamonds denote the median value of the data.

We also examined how the guiding performance at different guiding rates (1 Hz and 0.2 Hz). The guiding performance according to the guide camera exposure time was tested. Figs. 18 and 19 show the changes of guide star positions on the guide CCD chip during the 1200 sec exposure. The offset values show the amount of correction for telescope tracking. We note the correction with 1 sec exposure auto-guiding have larger scatter than those from 5 sec exposure guiding. The auto-guiding with 1sec exposure was carried out on Aug. 15, a night with worse seeing condition than Aug. 17 when 5sec exposure auto-guiding was carried out (See Table 2). Therefore, large scatter may be partly due to the poor seeing condition. However, the correction for the periodic two minute spikes (see Section 2.1) in RA direction (y-direction here) are clearly seen in the 1 sec guiding, but not in 5 sec guiding. This indicates that guiding with a shorter exposure time is more effective in correcting short-term tracking errors as expected from the tracking performance analysis in Section 2.1. Another factor that needs to be considered is that the tracking errors are known to change with the telescope pointing direction. These considerations make it difficult to assess how much the guiding performance degrades with the guiding camera exposure time. Finally, we report that images taken with 5 sec guiding camera exposure do not show a serious degradation in the PSF shape by keeping its FWHM at ~1".

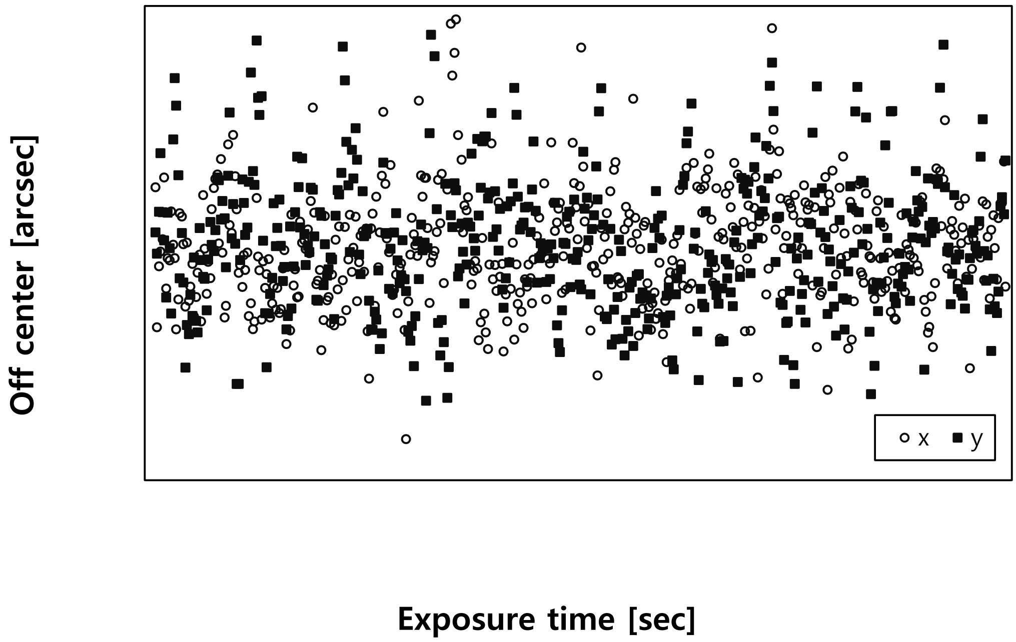


Figure 26. Guiding field X and Y off center exposed at 1 sec. Red dots are off center value on the X axis and blue dots are off center value on the Y axis.

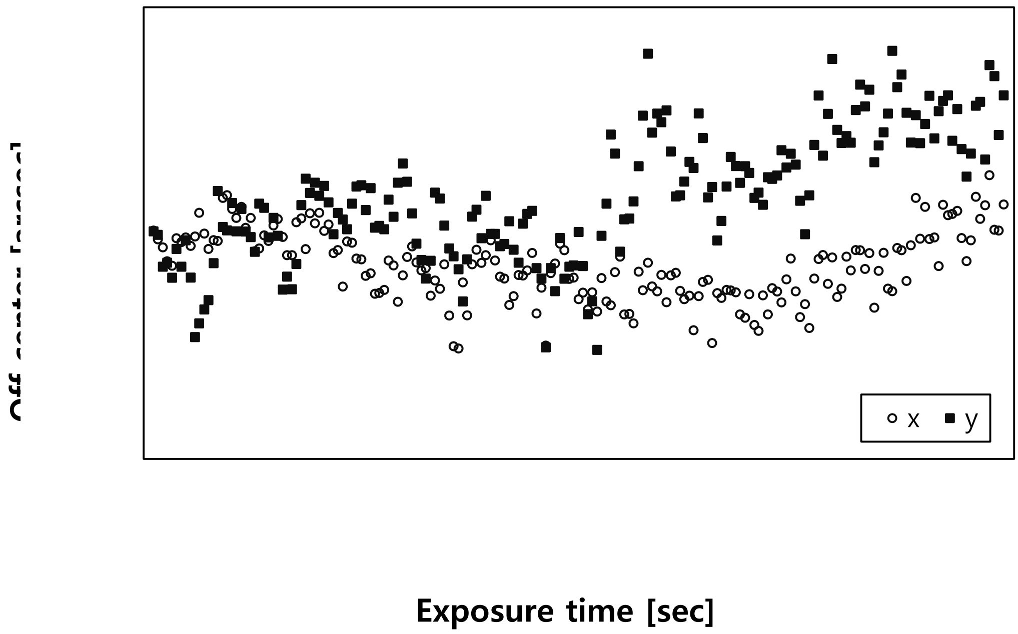


Figure 27. Guiding field X and Y off center exposed at 5 sec. Red dots are off center value on the X axis and blue dots are off center value on the Y axis.

6. CONCLUSION

We developed an auto-guiding system for CQUEAN. It consists of an optical CCD camera, ProLine 1001E model made by Finger Lake Instrumentation Co., an off-axis mirror, and an arm structure to hold all components. To increase the expected number of guide stars that are brighter than the limiting magnitude, a moving mechanism was developed to rotate the guide camera system for wider field of view.

Auto-guiding system was tested during the engineering run of CQUEAN at the 2.1 m telescope in McDonald Observatory, Texas, USA. We calibrated the guide CCD chip orientation (position angle) information in the *agdr*, the auto-guiding program. The astrometry to the guide CCD images showed that the center of the rotation arm does not coincide with the optical axis for the science CCD camera. After adjusting the science CCD image center, the analysis of R, the distance between the center of the science CCD image and the guide CCD image, revealed that there are still scatter of 0.011 deg, which might be caused by the flexure of mechanical arm. The scatter in the angles of rotation steps is mostly caused by the decelerator backlash. We estimated, however, that these factors do not affect guiding performance. It turned out that exposure time for guide CCD camera does not affect the guiding efficiency significantly. The comparison between two 600 sec exposures with/without auto-guiding indeed revealed auto-guider worked well. Exposures up to 1200 sec long were made with auto-guiding and the resultant images showed round stellar profiles, although seeing turned out to be larger than the ones from short exposure images.

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APPENDIX – CQUEAN Structure Drawing

All figures are CQUEAN Structure components drawings, and we used AutoCAD. These are aluminum components, and partially anodized.

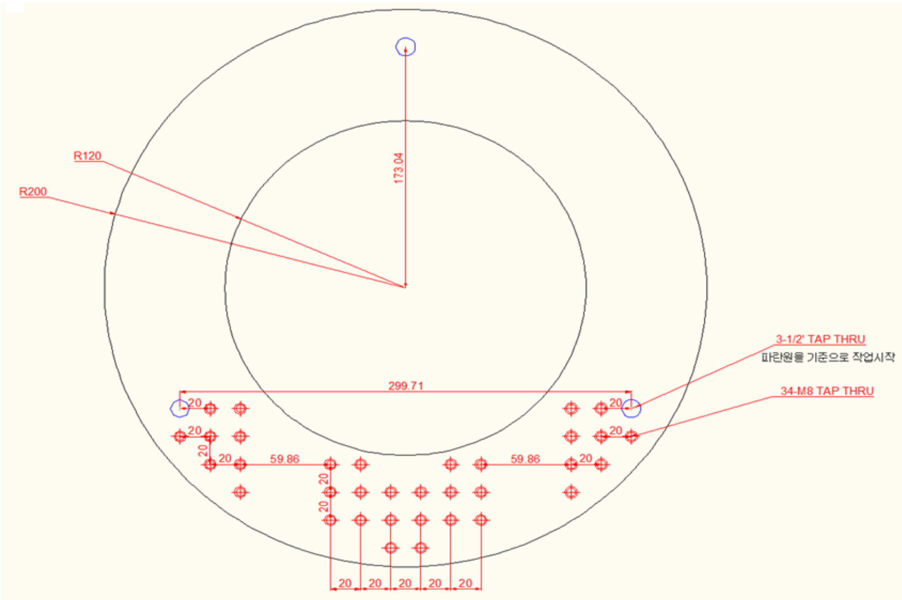

Fig. 1. T1

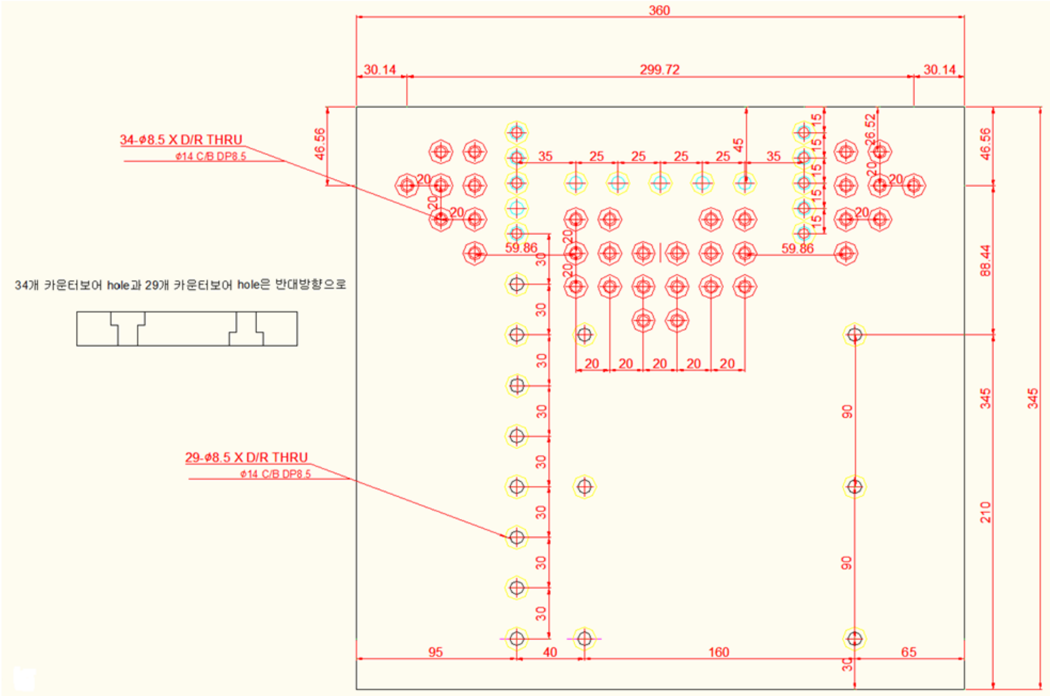
34-φ8.5 X D/R THRU
φ14 C/B DP8.5
34개 카운터보어 hole과 29개 카운터보어 hole은 반대방향으로
29-φ8.5 X D/R THRU
φ14 C/B DP8.5
360
30.14
299.72
30.14
345
345
210
95
40
160
65

Fig. 2. T2

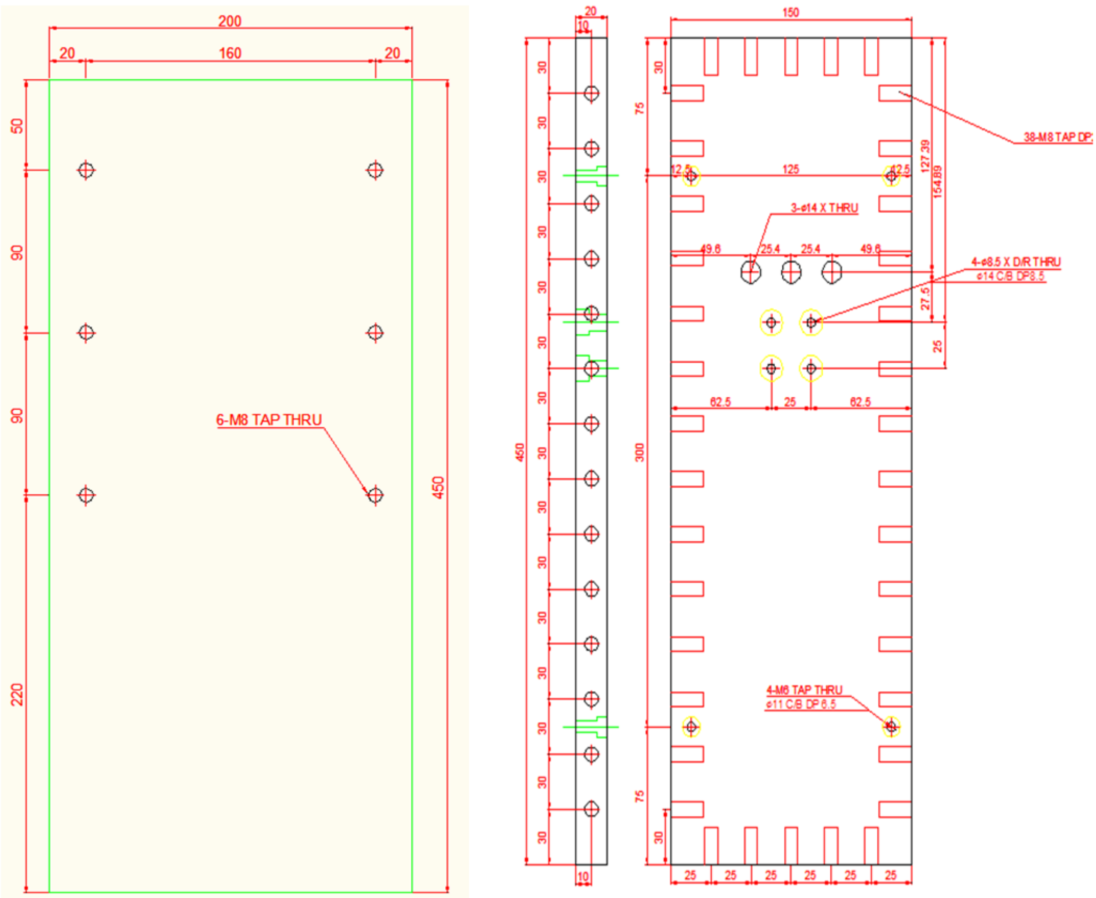
200
20
160
20
6-M8 TAP THRU
450
38-M8 TAP DP
3-φ14 X THRU
4-φ8.5 X D/R THRU
φ14 C/B DP8.5
4-M6 TAP THRU
φ11 C/B DP 6.5
150
125
300
450

Fig. 3. T3(Left) and S2(Right)

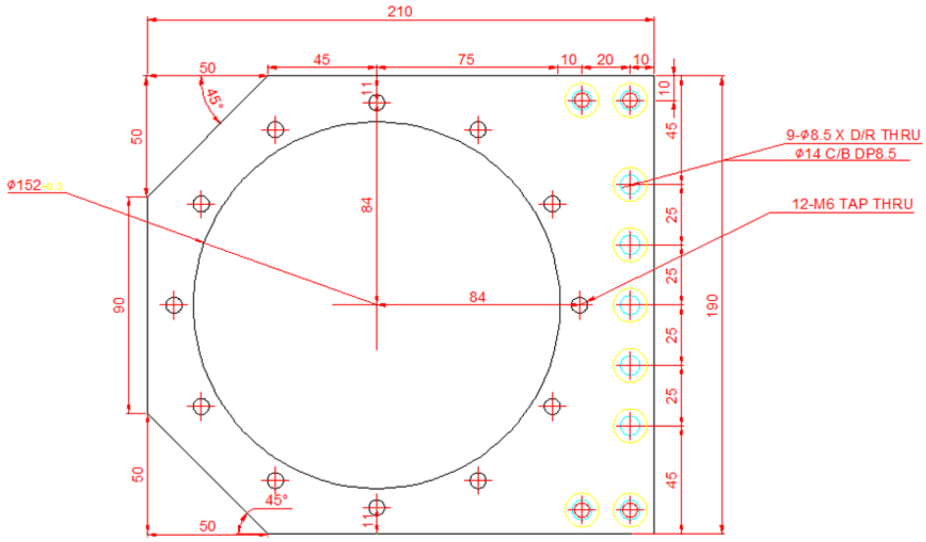

Fig. 4. S2

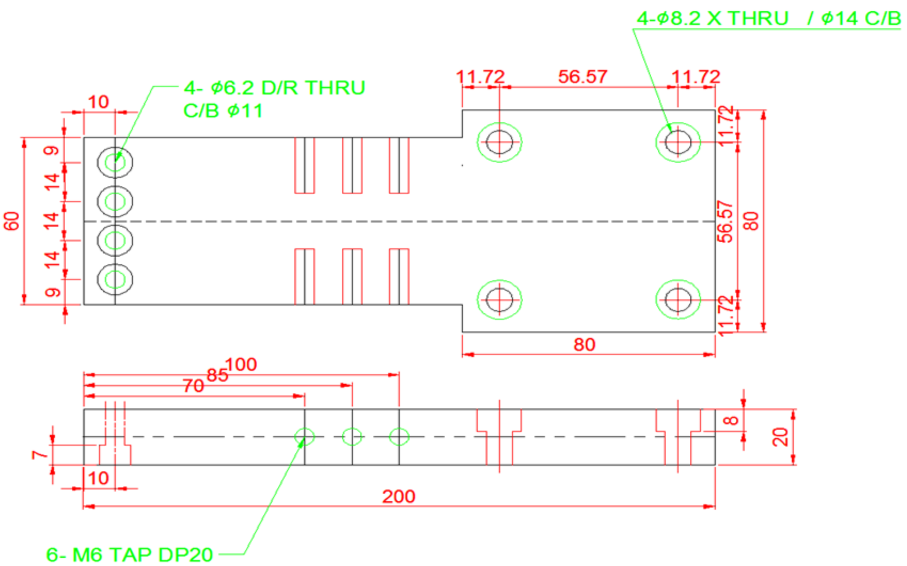

Fig. 5. G1

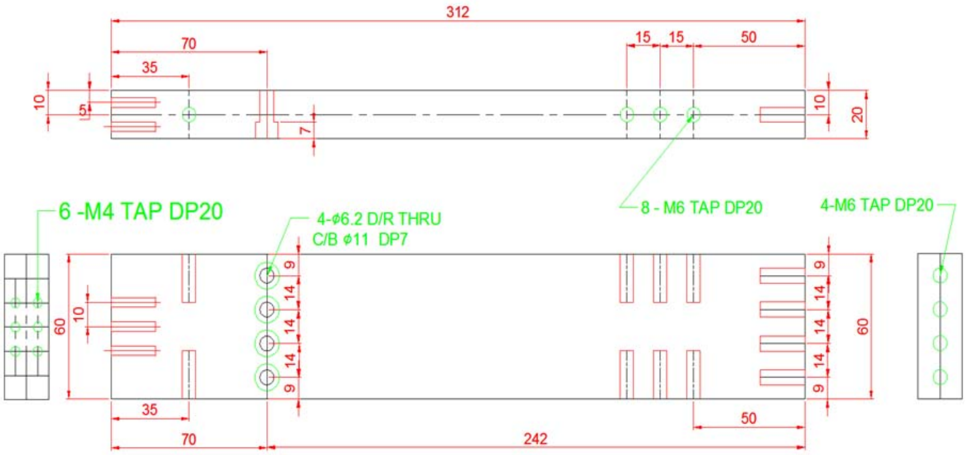

Fig. 6. G2

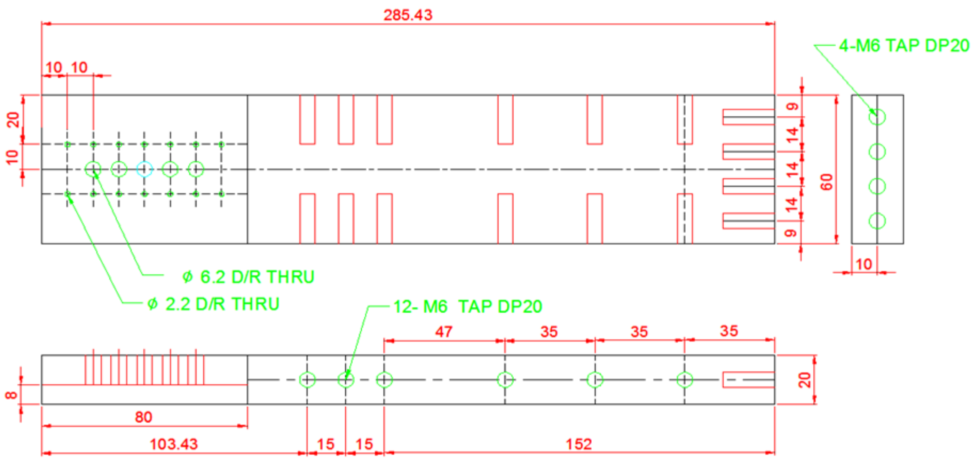

Fig.7. G3

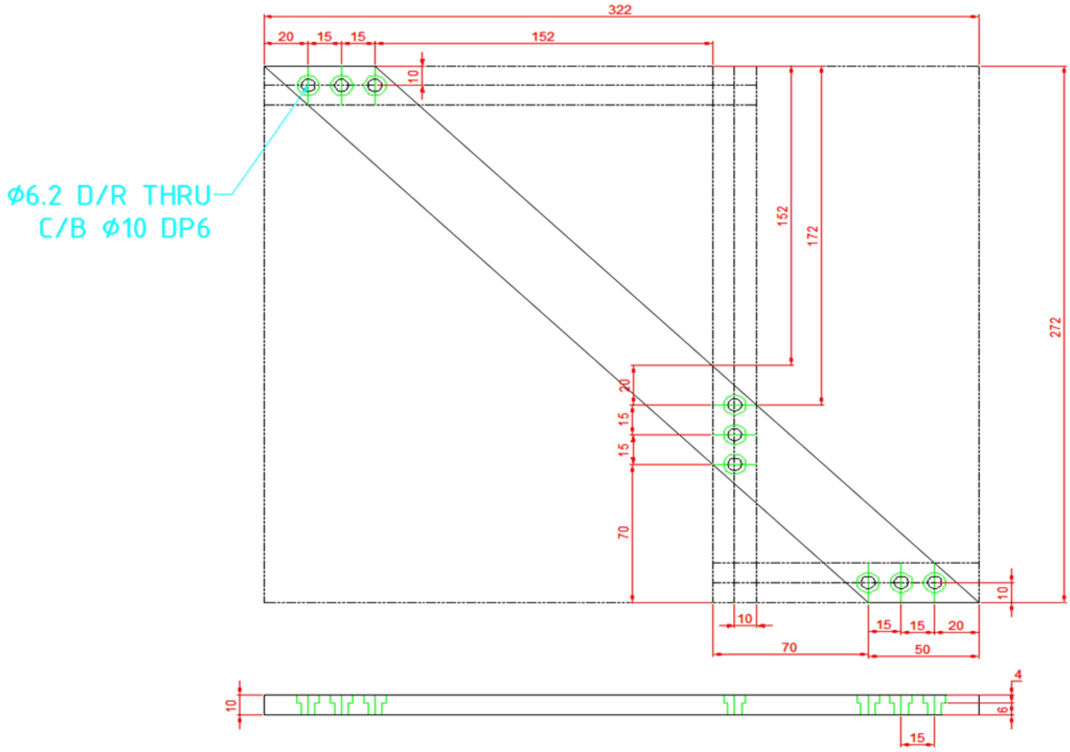

Fig. 8. G4

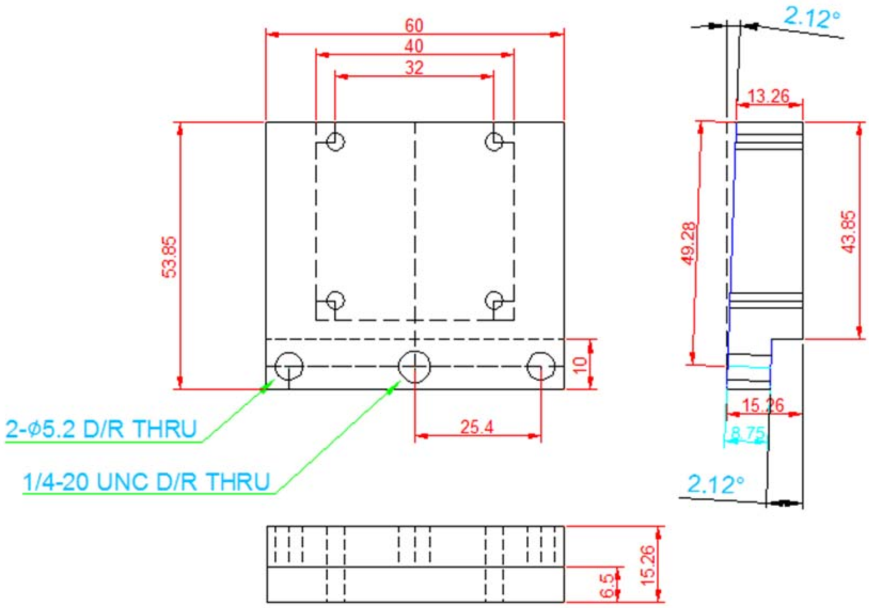

Fig. 9. G5

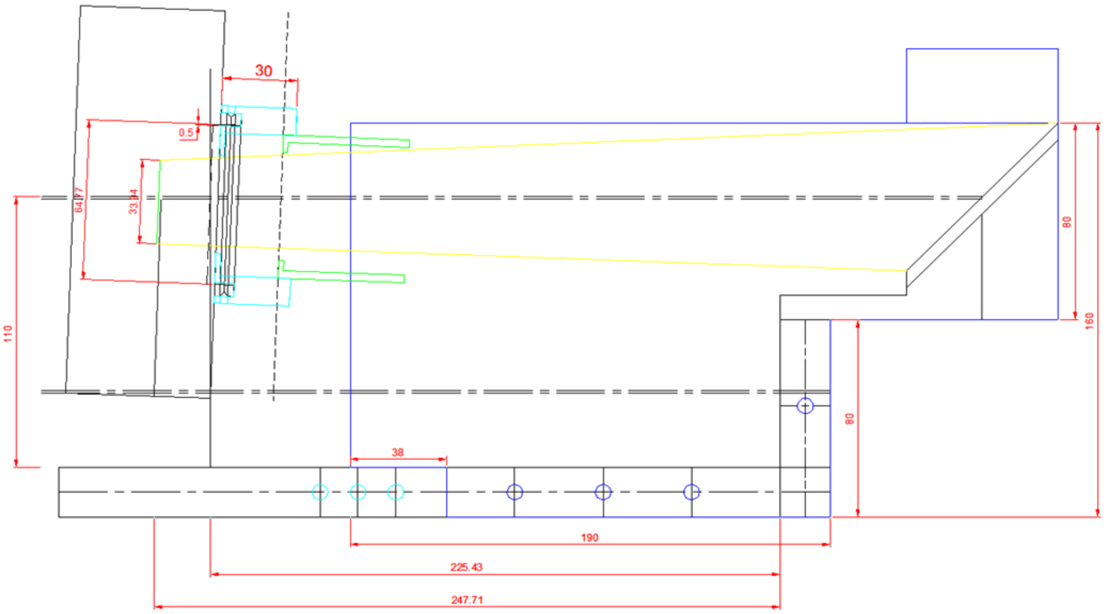

Fig. 10. Baffle and Cover

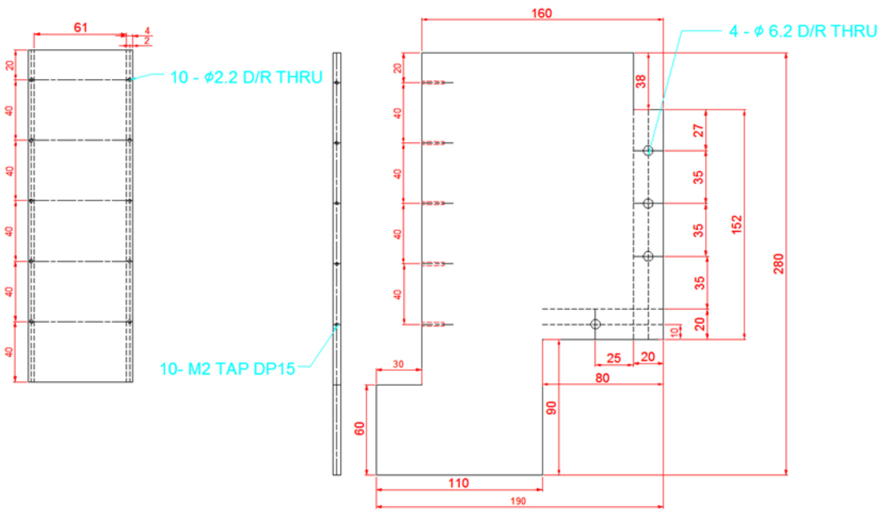

Fig. 11. Cover

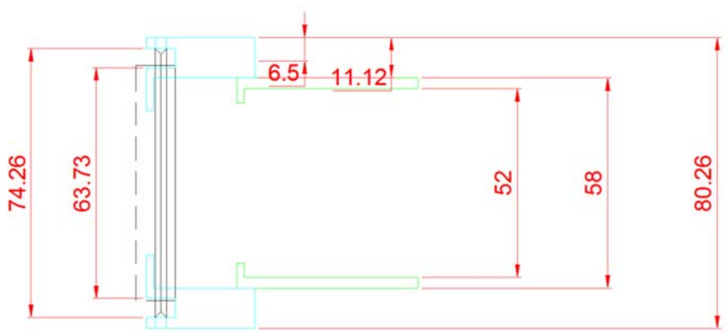

Fig. 12. Baffle

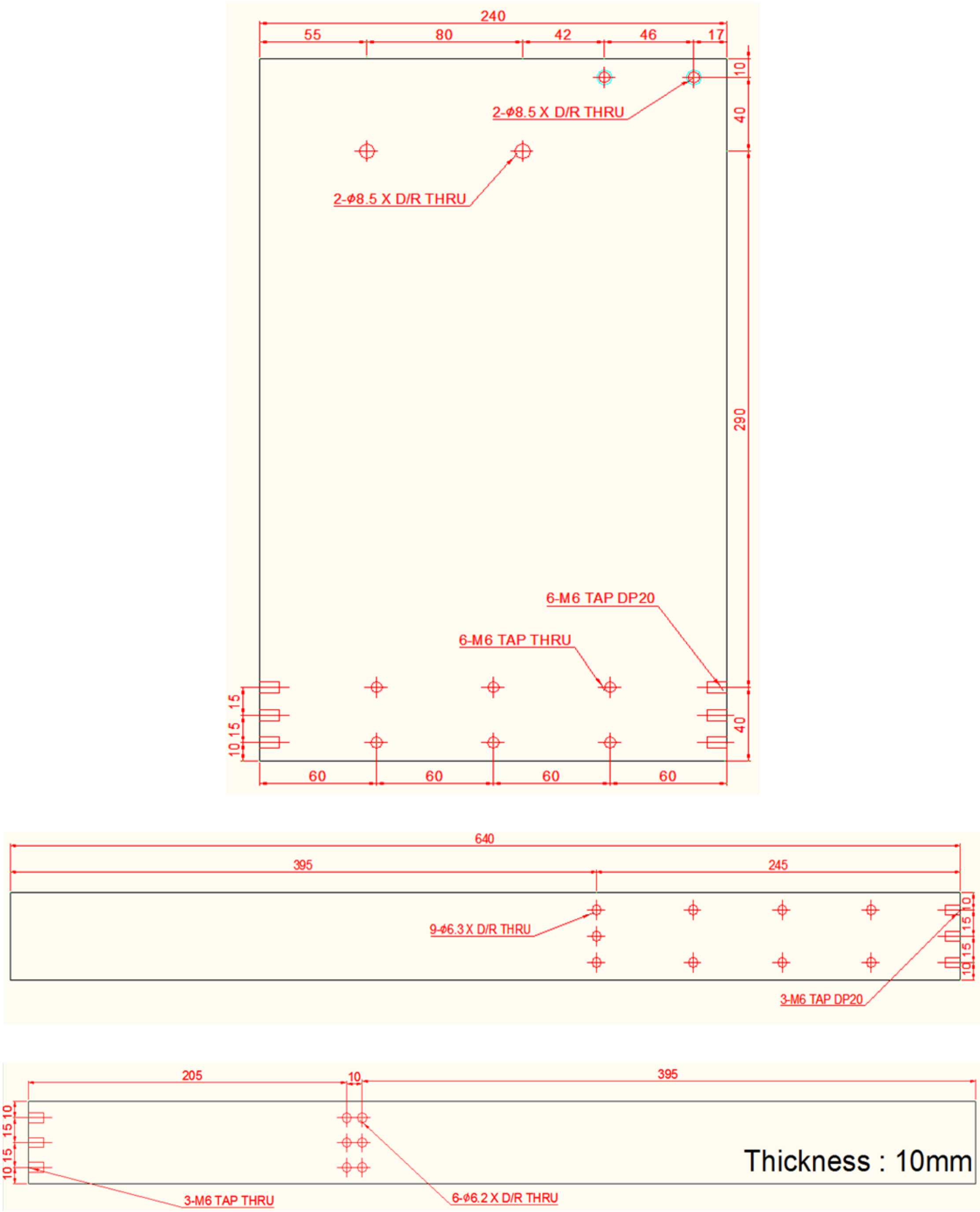

Fig. 13. B1,B2, and B3 (From the top)

국문 초록

초기 우주 연구센터(CEOU) 는 광학 CCD 카메라 시스템, CQUEAN(Camera for QUsars in Early uNiverse) 를 개발하였다. CQUEAN 은 0.7-11 μm 에서 감도가 높아 초기 우주에서의 적색편이가 높은 퀘이사를 관측하기에 적합하다. 장시간 노출로 관측하기 위해서 우리는 이 관측 기기와 2.1m 망원경에 적합한 자동 추적 장치를 개발하였다. 이 자동 추적 장치는 off-axis 거울, 베플, CCD 카메라, 모터 와 감속기로 이루어 진다. 추적별의 개수를 확보하기 위해서 추적카메라를 전체적으로 돌리면서 추적 영역을 확장시키는 메커니즘을 개발하였다. 미국 텍사스에 위치한 McDonald 천문대의 자동 추적 프로그램을 수정하여 적용한 후, 이 기기가 얼마나 안정적으로 작동하는지 확인, 분석하였다.