Thesis for the Degree of Master of Science

New Auto-Guiding System for CQUEAN

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Advised by

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Submitted to the School of Space Research
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Abstract

We developed a new auto-guiding system for Camera for QUasars in EArly uNiverse (CQUEAN). CQUEAN is an optical CCD camera system attached to the 2.1m telescope at McDonald Observatory, USA. The new auto-guiding system differs from the original one in followings: Instead of cassegrain focus of the 2.1m telescope, it is attached to the finder scope; It has its own filter system for observation of bright targets; It is controlled with CQUEAN Auto-guiding Package (CAP), a newly developed auto-guiding program. Finder scope commands very wide field of view at the expense of poorer light gathering power than that of 2.1m telescope. Based on the star count data and the limiting magnitude of the system, we estimated there are more than 5.9 observable stars in all sky using the new auto-guiding CCD camera. An adapter was made to attach the system to the finder scope. The new auto-guiding system successfully guided 2.1m telescope to obtain the science data with CQUEAN during the test run on 2014 February. The analysis of FWHM, ellipticity, and position angle of the stellar profiles on the CQUEAN image guided with new auto-guiding system revealed that it has similar guiding performance with the original auto-guiding system for CQUEAN. The new auto-guiding system will be used for second generation CQUEAN, but it can be used for other cassegrain instruments of 2.1m telescope.

Thesis Supervisor: Sami Khan Solanki
Title: Professor

국문초록

우리는 맥도널드 천문대 2.1m 망원경에 부착된 광학 CCD 카메라 시스템인 CQUEAN의 새로운 자동 추적 시스템을 연구 개발하였다. 이 새로운 자동 추적 시스템은 기존의 것과 달리 2.1m 망원경 대신 독립적인 파인더 망원경에 부착된다. 이 시스템은 새로 개발한 CAP (CQUEAN Auto-guiding Package)라는 자동 추적 프로그램을 사용하여 제어하며, 자체 필터 시스템을 가지고 있어서 밝은 천체를 관측 및 연구할 수 있다. 파인더 망원경은 2.1m 망원경 보다 낮은 집광력을 가지지만 매우 넓은 시야를 제공하며, 천체 산출 데이터와 시스템 한계등급에 근거하여, 파인더 망원경에 새로운 자동 추적 CCD 카메라를 부착하여 사용하였을 때 시야상에서 5.9개 이상의 천체를 관측할 수 있다고 추정되었다. 또한 우리는 파인더 망원경에 새로운 시스템을 부착할 수 있도록 어댑터를 제작하였다. 새로운 자동 추적 시스템은 2014년 2월 시험 관측에서 2.1m 망원경이 CQUEAN으로 연구 데이터를 얻는 동안 성공적으로 추적을 수행하였고, 새로운 시스템을 사용하여 자동 추적을 시행한 CQUEAN 이미지에서 각 천체의 반치폭, 이심률, 위치각을 분석한 결과 기존의 자동 추적 시스템과 동등한 추적 성능을 보였다. 새로운 자동 추적 시스템은 2세대 CQUEAN에 사용될 예정이지만, 이 외에도 다른 망원경의 파인더에 부착하여 사용이 가능하도록 개발하였다.

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Chapter 1

INTRODUCTION

When a telescope tracks a star during an astronomical observation, usually the star would drift out of the field unless the telescope tracking system is accurately calibrated. The auto-guiding system continually calculates the offset of the guide star and feeds back the amount of offset to the Telescope Control System (TCS), which results in reducing the error of tracking (Chen et al. , 2012). As a result, more perfect image can be obtained than without additional auto-guiding system or with manual guiding method (Birney et al. , 2006).

The auto-guiding system thus became popular by many professional telescopes, as well as many amateur astrophotograhers. For example, Mun et al. (2006) developed a telescope control software which includes auto-guiding system for the telescope in Kyung Hee University (KHU) observatory. Jeong et al. (1999) and Yoon et al. (2006) developed an auto-guiding systems for improvement of tracking accuracy of telescope in Seoul National University observatory and Chungbuk National University observatory respectively. Sung et al. (2012) suggested a new TCS to improve the tracking accuracy of the 1.8m telescope at Bohyunsan Optical Astronomy Observatory. As well, Kanzawa et al. (2006) and Iseki et al. (2008) made an effort to improve the accuracy of pointing and guiding of Subaru Telescope.

Camera for QUasars in EArly uNiverse (CQUEAN) is an optical charge coupled device

(CCD) camera developed by Center for the Exploration of the Origin of the Universe (CEOU). CQUEAN is more sensitive in the longer part of the optical wavelength and thus it is quite efficient to search for high redshift quasars in the early universe (Park et al. , 2012). Since 2010, it has been attached to the 2.1m Otto Struve Telescope at McDonald observatory, Texas, USA and performed several missions. Because CQUEAN is installed at Cassegrain focus (f/13.65) which has a characteristic of high magnification and small field of view (FOV), a focal reducer was developed in order to reduce the focal length and result in larger FOV (Lim et al. , 2013). In addition, Kim et al. (2011) made an auto-guiding system specifically for CQUEAN, because other existing auto-guiding systems for 2.1m telescope could not be adapted for CQUEAN. The auto-guiding system made by Abbott (1990) was not suitable for long time exposure, and the one for Sandiford Echelle Spectrograph, a spectrograph for 2.1m telescope, cannot be used for other instrument.

The CQUEAN system has used the PL1001E CCD camera from Finger Lakes Instrumentation (FLI) as the guide CCD camera. The pixel size of guide CCD camera is 24μm $\times$ 24μm, and its pixel scale is $0.174''$/pixel and FOV $2.97' \times 2.97'$ at the Cassegrain focus of the 2.1m telescope. Guide camera is held by an arm that can rotate around the optical axis of the telescope to find a guide star in the off-axis fields (Kim et al. , 2011). The auto-guiding software, *agdr*, originally developed for 2.7m telescope by McDonald Observatory, was modified to be used for CQUEAN and 2.1m telescope.

After about three years of operation, however, the mechanical shutter of the guide CCD camera got worn out and it needs to be replaced. Meanwhile, CQUEAN system is planned to be equipped with a new filter system. It turned out that the filter wheel for the new filter system would interfere with the existing guide CCD camera. Therefore, we decided to make a new auto-guiding system. The new system is attached to the back of the finder scope. The finder scope reduces the number of observable star significantly due to much smaller diameter, but it offers very wide FOV which should compensate for the small diameter of the telescope. A new auto-guiding software, CQUEAN Auto-guiding Package (CAP), was also developed. Based on the same auto-guiding method used in the Slit Camera Package (Kwon et al. 2012; Lee et al. in preparation) for Immersion GRating INfrared Spectrograph (IGRINS) (Park et al. , 2014), it detects the position of a selected source on the reference image and tracks continually the position shifts on subsequent images. The software is written in python which will make it easy to customize the auto-guiding system if needed.

In this paper, we describe the new auto-guiding system in detail. We examined the system requirements, such as the required exposure time of guide CCD camera to reduce the tracking errors, and the number of observable stars with the guide CCD camera under the usual observation condition. The development of the system, installation and test results are described, and the performance of the new auto-guiding system is compared with the original auto-guiding system.

Chapter 2

AUTO-GUIDING SYSTEM REQUIREMENTS

2.1 Exposure Time Requirement

Auto-guiding system continually calculates the system offset during an observation. The more frequently, the better the auto-guiding. The frequency of the auto-guiding depends on many factors, such as exposure time of the scientific observation, and/or the performance of the telescope tracking. To calculate the auto-guiding feedback frequency, we first examined the performance of the 2.1m telescope tracking system. We analyzed observation data of CQUEAN science camera. The observation was conducted with 0.5 seconds exposure time and about 1.81 seconds cycle time for 5 minutes without auto-guiding. The cycle time here is defined as total time that includes exposure time, data readout time and image display time.

The position of a star center would be fixed to a single pixel among a series of consecutive exposure images under the perfect guiding condition. In reality, usually it is not due to imperfect guiding of the telescope. Figure 1 shows the drift of target center on the CQUEAN images along the RA, aligned with X axis of the CCD chip, and Dec, Y axis of the chip, without auto-guiding system. Kim et al. (2011) showed that there is a misalignment of the worm gear in the 2.1m telescope mount which causes a periodic error of about 2 minutes. The different direction of tracking offset labeled as sections 2 and 4 are caused by this misalignment of the gear. The tracking error along Dec turned out to be very small: $0.0001''$/sec. Meanwhile, the values along RA are about $0.03''$/sec for sections 1, 3, and 5, and $0.02''$/sec for rest sections. Thus we estimate the average tracking error along RA is about $0.03''$/sec.

The science camera of CQUEAN has pixel scale about $0.3''$/pixel with 2.1m telescope. Therefore, the tracking error would not be detected if the offset amount is less than $0.3''$, i.e., one pixel. From this condition, we can estimate the cycle time of guide camera which will make tracking error less than $0.3''$. Figure 1 indicates that the the drift along declination direction will be about $0.3''$ for 3000 seconds cycle time and along RA direction about $0.3''$ for 10 seconds cycle time. Therefore, we deduced that the cycle time of guide camera should be less than 10 seconds, which is quite longer than the shortest exposure time of the guide CCD camera.

2.2 Expected Limiting Magnitude and Number of Guiding Star in Guide FOV

The feasibility of the auto-guiding system also depends on the number of observable stars. We calculated the number of observable stars, i.e., brighter than the limiting magnitude of the new auto-guiding system.

The expected limiting magnitude is estimated with the formula below (McLean , 2008):

$$m = m_{zp} - 2.5log\left(\frac{1}{g}\cdot\frac{S}{N}\cdot\frac{R}{T}\cdot\sqrt{\frac{N_{pix}}{n_0}}\right) \tag{2.1}$$

where m_{zp} is zero point, g is gain in unit of electron/ADU, S/N is signal to noise ratio,

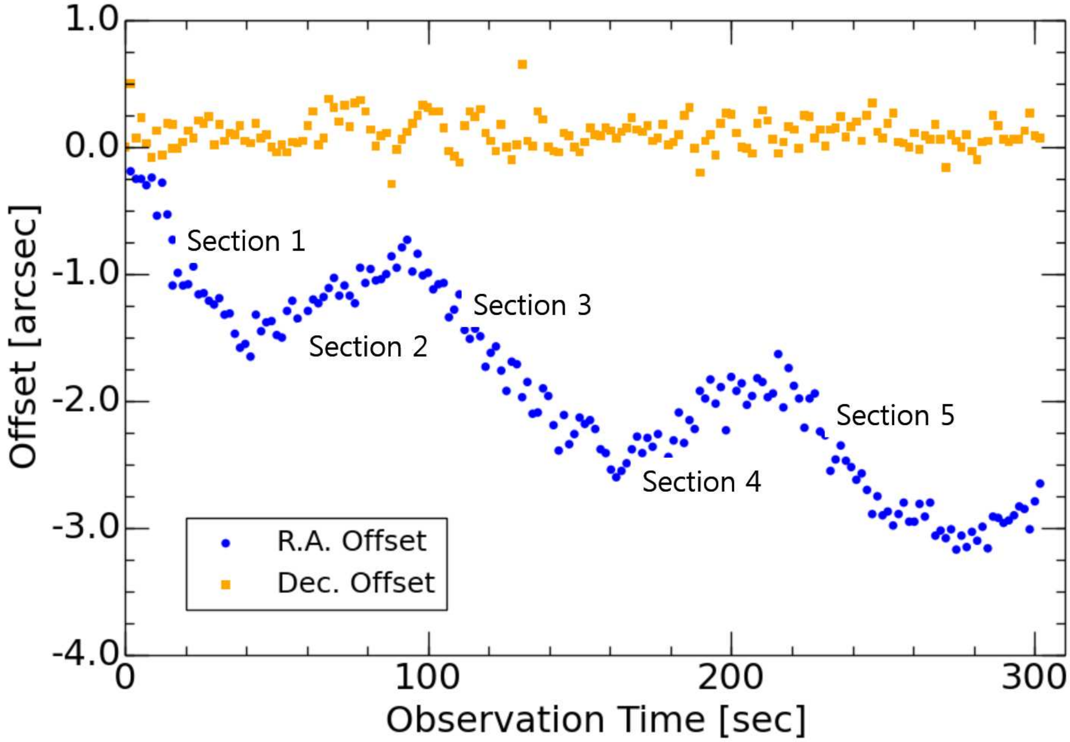

Fig. 1: The drifts of the center of star along RA and dec, on the image obtained with 2.1m telescope without auto-guiding. Yellow squares denote Dec drift and blue circles drift along RA. While the drift along Dec is very small over 300 seconds duration, the offset along RA gets as large as about 3 arcseconds, i.e. about 10 CCD pixels, over the duration. Note RA offset repeatedly shows a reverse pattern with about 100 seconds period, which is the backlash caused by the worm gear misalignment in the 2.1m telescope.

N_{pix} is the number of pixels that cover a stellar profile, n_0 is number of exposures, T is exposure time in unit of second, and R is readout noise in unit of electrons. The zeropoint of the system is estimated from the images obtained during the test runs. It turned out to be 18.7, with the CCD gain of 0.7 from the camera manufacturer's report. With the zeropoint estimated, the limiting magnitude of the system is calculated to be 11.7 in V for the case of S/N ratio of 10 with 1 second exposure, with readout noise of 12 electrons, N_{pix} of 12.2 pixels based on the pixel scale of the guide camera and average seeing of $1.2''$ at McDonald observatory (Kim et al. , 2011).

Figure 2 shows the expected number of stars in galactic pole regions that would fall in the FOV of our guide CCD camera, using the star count data (Allen , 2000). It can be seen from the plot that there are about 5.9 stars that are brighter than the limiting magnitude of the system. Note that the number of observable star will get larger in the lower galactic latitude region. Therefore, we conclude that our auto-guiding system is feasible because it can have enough number of stars at all sky regions.

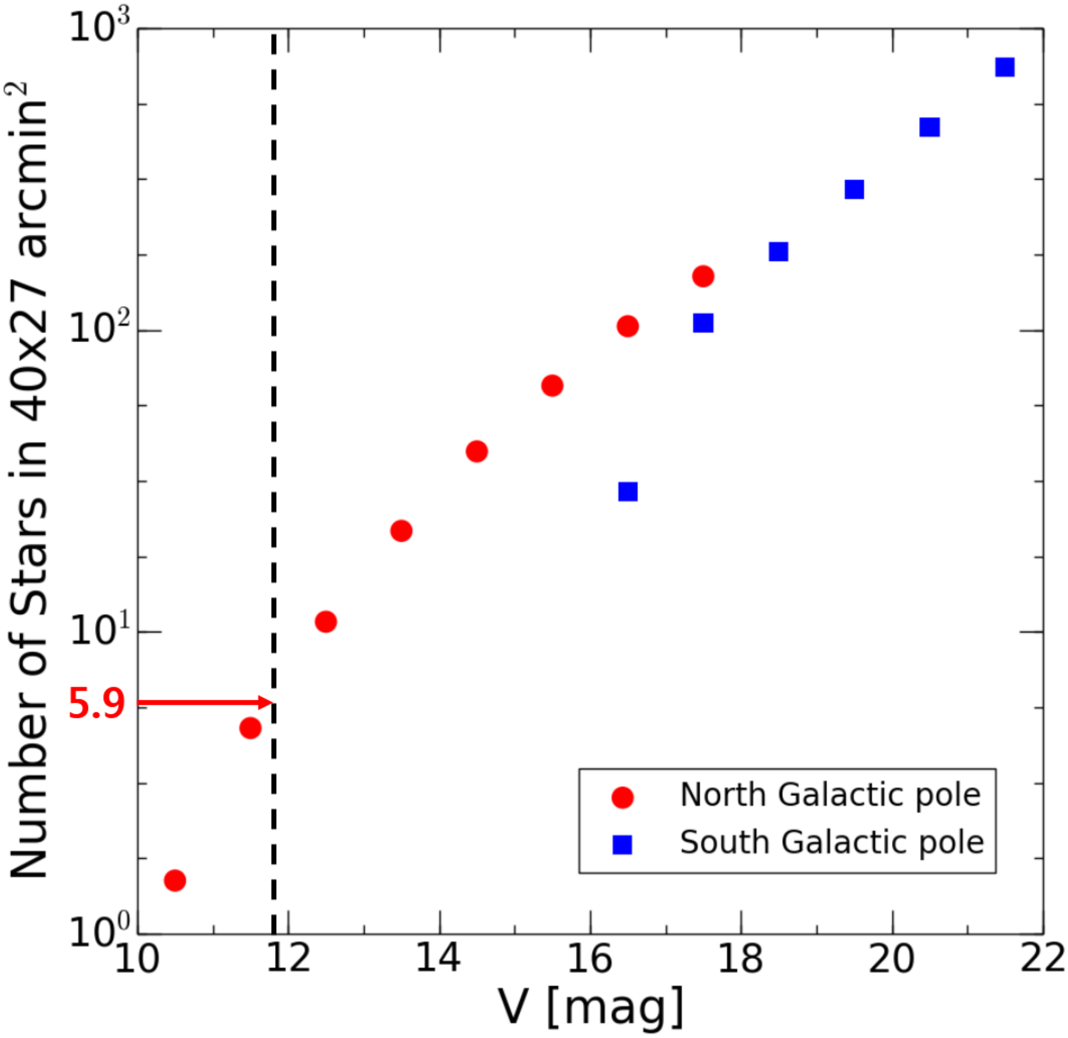

Fig. 2: The number of observable guiding stars in $40' \times 27'$ field with S/N ratio of 10 with 1 second exposure. The red circles represent the number of stars in the north galactic pole and the blue squares the stars in the south galactic pole. Black dashed line indicates the observed limiting magnitude for new auto-guide system.

Chapter 3

SYSTEM CONFIGURATION

The new auto-guiding system is attached to the finder scope of the 2.1m telescope. The finder scope is a refractor whose diameter is 255mm. Although an eyepiece was installed for visual viewing as seen in Figure 3, it has been left unused for many years since computer controlled TCS was introduced for 2.1m telescope. The complete optical configuration of the finder scope is not known but its focal length of 3037mm. Figure 4 shows the auto-guiding system on the finder scope. The new auto-guiding system consists of a optical CCD camera and a filter wheel. An adapter to attach the camera and the filter wheel to the telescope was made by us. By adjusting the the adapter, the camera position along the light path can be adjusted for correct focus. In addition to hardware, we also wrote a new software to control the new auto-guiding system. The whole configuration of second generation CQUEAN including the new auto-guiding system is described as a block diagram in Figure 5. Since the guide CCD camera is now attached to the finder scope, the new auto-guiding system is physically separate from the CQUEAN system. Therefore, the new auto-guidng system can be used not only with CQUEAN, but also with other instruments attached to the 2.1m telescope. With a little further modification in TCS interface part in the software, which is quite easy since the software is written in python, we expect the auto-guiding system can be used in other telescope system as well. In this section, each component of the new auto-guiding system is described in detail.

3.1 Guide Camera and Filter Wheel

One of the requirements for the guide CCD camera is that it should be small and light enough to be attached to the back of the finder scope. The previous auto-guiding system consists of a guide CCD camera, an arm to hold the camera, and a motor drive which rotates the arm around the on-axis field of the 2.1m telescope. The 2.1m telescope itself is very large and heavy enough to hold all these auto-guiding hardware in stable condition. But the finder scope is much smaller and lighter that its weight balance might be affected easily although we do not need motor and arm in the new system. Another requirement of the guide CCD camera is that it does not have a mechanical shutter. Auto-guiding system usually takes enormous amount of short exposures in a night to track the guide star. According to the camera manufacturer, the Mean Time Between Failure (MTBF) of the shutter for PL1000E CCD camera in previous auto-guiding system is 1000000. While this number looks very long time, the shutter got worn out after about three years of operation. Therefore, we want the guide CCD camera to be free of mechanical shutter for long operation. Based on these requirements, we chose ML11002 model among MicroLine series from FLI as the new guide CCD camera. The MicroLine series comes with the smaller and lighter housing than the ProLine series. The model has an interline type Kodak KAI-11002 chip. Interline type CCD has separate readout channels between the light-sensitive pixels, and it can read the data out during exposures. Therefore, unlike a frame transfer type CCD, it does not require a shutter during readout. The low fill factor of the interline type CCD results in the poorer sensitivity than the frame transfer type, but auto-guiding application usually observes bright targets. The CCD chip in ML11002 camera has 4008×2672 pixels of 9μm $\times$ 9μm size. The pixel scale is 0.61 arcsec/pixel,

Fig. 3: The finder scope attached to 2.1m telescope. The picture shows the finder scope with an eyepiece. We removed the eyepiece and used an adapter to attach the auto-guiding camera and filter wheel.

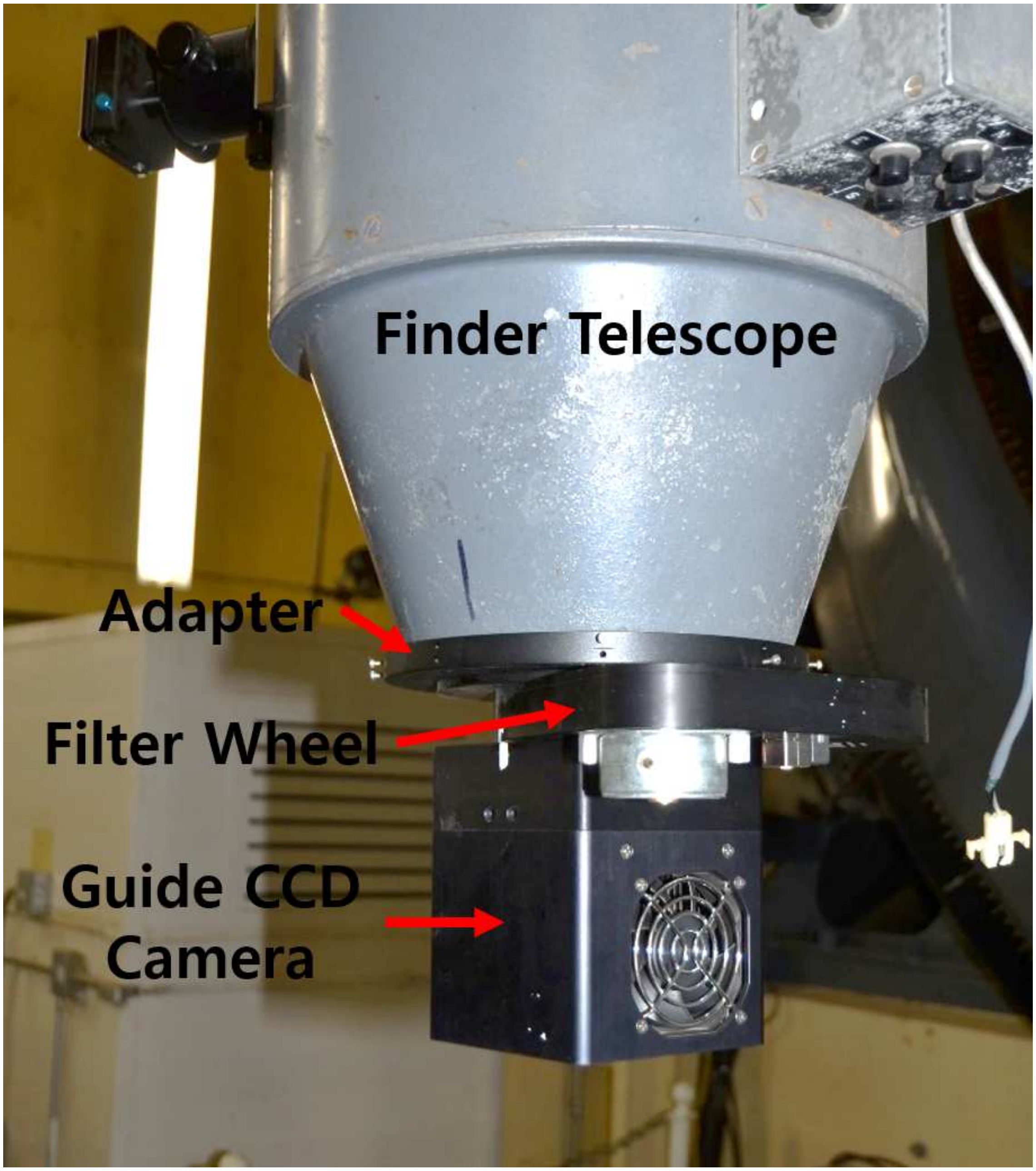

Fig. 4: Picture of the auto-guide system attached to the finder scope.

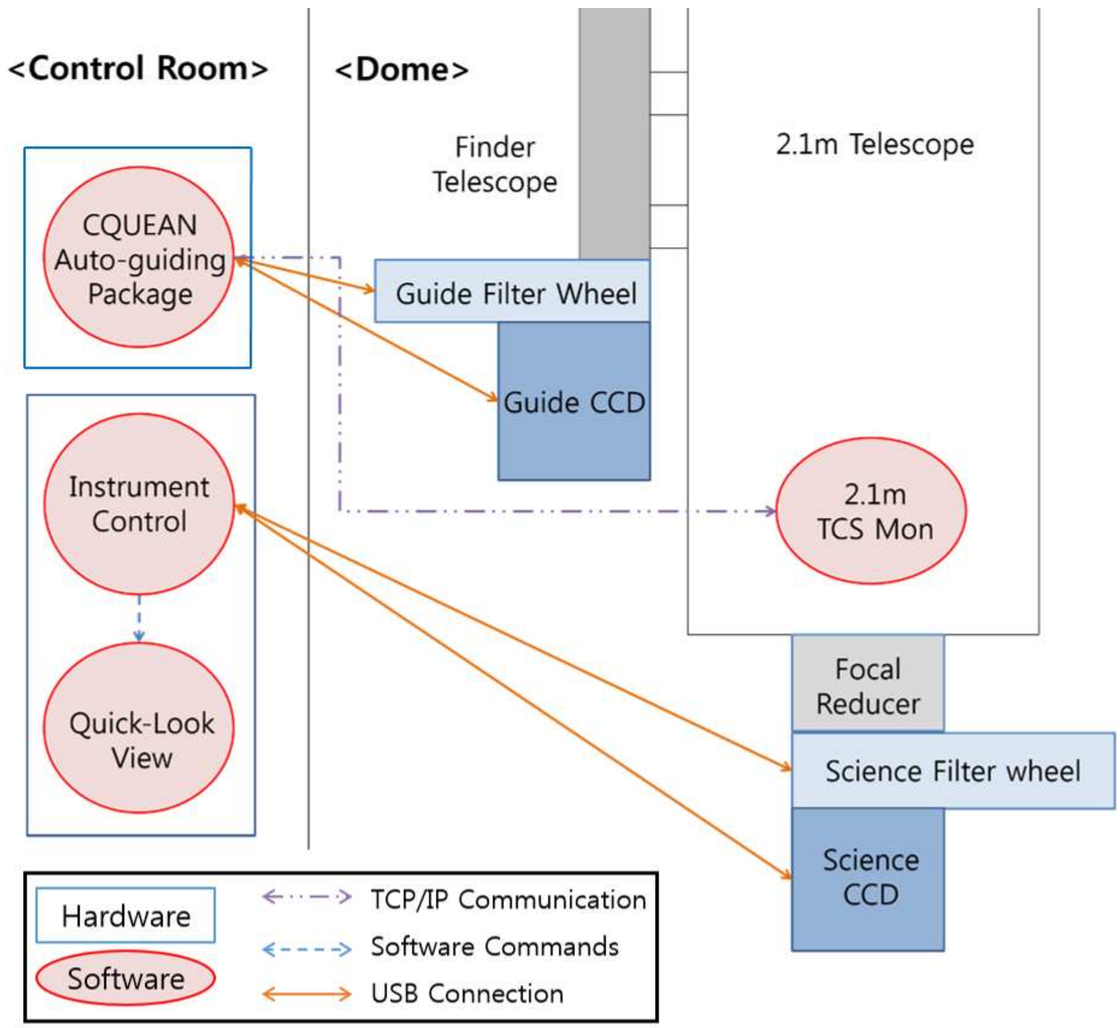

Fig. 5: Block diagram of new CQUEAN system.

and the FOV is $40' \times 27'$ at the finder scope. Table 1 shows the several characteristics of our guide CCD camera attached to the finder scope. The CCD is cooled down to -10°C during the operation by built-in fan cooling. It is connected to the computer via Universal Serial Bus (USB). An USB repeater is used to overcome the short distance limitation of the USB connection. Figure 6 shows an image obtained with guide CCD camera, along with a box indicating the FOV of CQUEAN science camera.

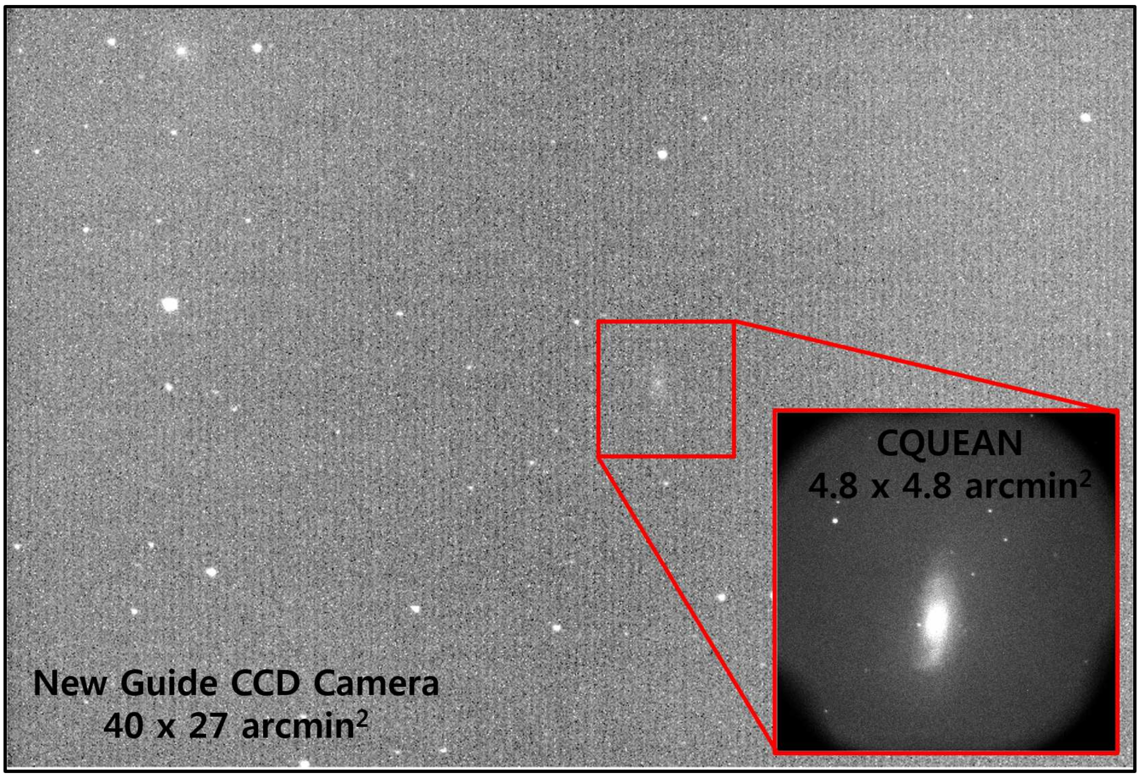

Fig. 6: An example image obtained with the guide CCD camera. The field of view of the guide CCD camera is $(40' \times 27')$. The $4.8'' \times 4.8''$ FOV of the science CCD camera is shown as red box in the image.

A filter wheel is installed in front of the guide CCD camera for possible science observation. A CFW-1-5 model, also made by the same company, is used in our system. The

Table 1: Specification of ML11002 CCD camera on the new guide system

Pixel Size	9μm $\times$ 9μm
Pixel Scale	$0.61''$/pixel *
Field of View	$40' \times 27'$ *
CCD Type	Interline Transfer
Cooling method	Air Cooling
Linear Full Well	40,000 e-
Gain	0.7 electrons/ADU
Readout noise	12 e-RMS @ 1 MHz
Readout Speed	1 MHz @ 16-bit data
Peak Quantum Efficiency	50 % @ 500 nm

* Measured by authors.

filter wheel is also connected to the control computer via USB. This filter wheel can house up to five circular shape filters of which diameter is 50mm and thickness less than 5mm. We installed only four filters: Johnson *B, V, R* and *I*, and left the remaining hole empty. During the normal auto-guiding operation mode, we do not use any filter for maximum transmission efficiency. But for bright targets such as supernova or variable stars in the Galaxy, guide CCD camera can carry out a science observation on its own, or along with CQUEAN science camera which has different filters. Although we do not present any detail about scientific aspect of the guide CCD camera system in this study, further test is planned to calibrate the system for scientific observation.

To attach the camera and the filter wheel to the finder scope, we designed and fabricated a custom adapter. Figure 7 shows the picture and the front view drawing of the adapter. The adapter is made of aluminum, and all parts of the adapter were anodized to prevent the reflection of light. The adapter basically consists of two plates and a ring. One plate holds the guide CCD camera system, and the other one is attached to the telescope. A large ring holds two plates securely to each other. By rotating the ring, the distance between two rings can be adjusted for fine focus adjustment of the guide CCD camera. Once the camera is in focus, the position is fixed by 8 bolts around the ring.

3.2 Guiding Software

CAP controls the guide CCD camera and the filter wheel to obtain the imaging data from the guide CCD camera system, and interacts with TCS for 2.1m telescope via TCP/IP protocol to control the 2.1m telescope movement. It is designed and made on the basis of the auto-guiding software for IGRINS slit viewing camera. However, user interface was designed to be similar to that of *agdr*, the original auto-guiding software, so that a experienced CQUEAN user has little difficulty in using the new software. CAP is written in python. The `Tkinter` library is used for its graphical user interface (GUI) design, and

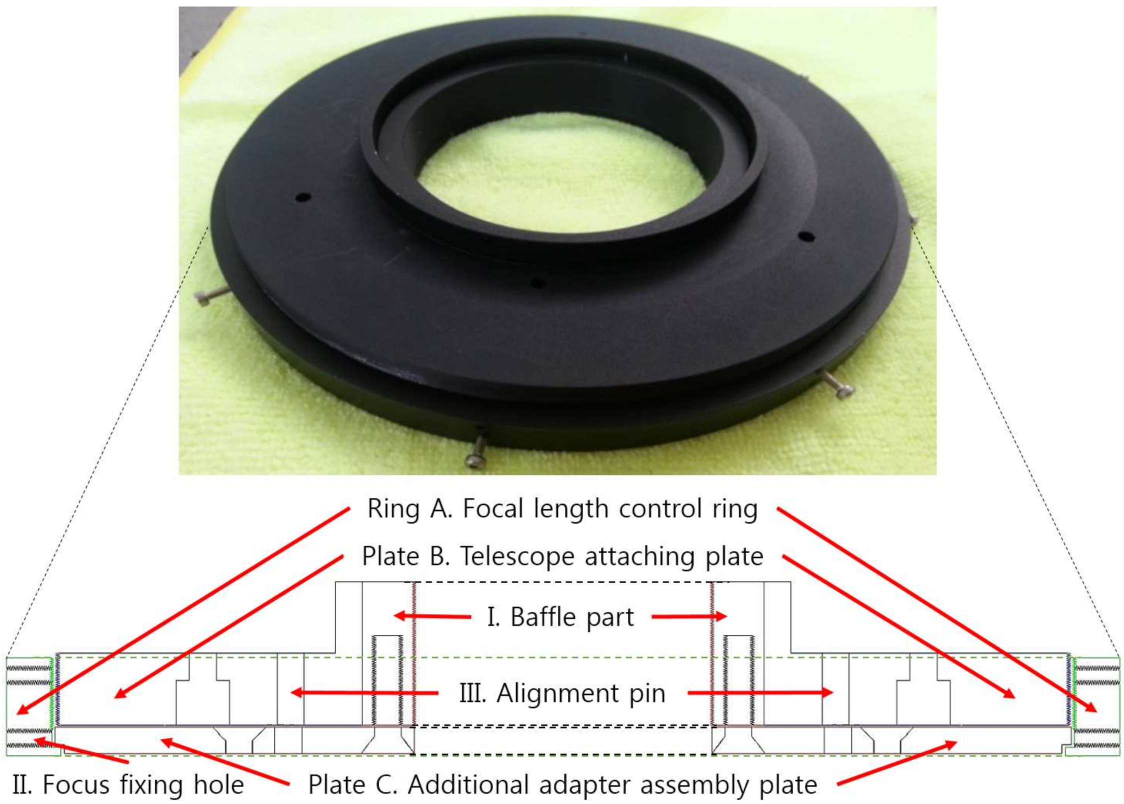

Fig. 7: Picture and front view drawing of the adapter. The adapter consists of three parts: two plates indicated by B and C, and a ring (marked as A) that holds the two plates. The baffle part, marked as I, in the plate B is inserted into the baffle of the finder scope. The plate C is holding the filter wheel. The alignment pin III aligns two plates B and C. By rotating the ring A, the distance between two rings can be adjusted for better focus of the camera system. 8 bolts were used in part II to fix the distance after the system is in focus.

mathematical library `numpy` for the data analysis code in the program. It is running on linux platform.

Figure 8 shows the GUI of the CAP. The main panel of CAP is the Image Window which shows a full image of the guide CCD camera. When a user selects a guide star by clicking a star on the Image Window, a yellow box appears to indicate that a guide star has been selected, and zoom-up image of the star appears in the Zoom-in Box panel. Full Width at Half Maximum (FWHM) of the guide star is obtained with Gaussian profile fitting on the selected guide star. In addition, observation field of CQUEAN science camera is indicated with purple box in the Image Window and CQUEAN panel. The camera panel has camera control functions: Initialization, setting CCD temperature, showing current temperature, exposure time, X-Y binning, filter, and observation start/stop buttons. X and Y in the guide panel represent current position of the guide star and dx and dy the position difference between the current image and the reference image. The reference image is the one that the user has selected the current guiding star. TCS panel displays the current pointing of the 2.1m telescope and its focus value. It also has four arrow buttons to move the 2.1m telescope by 10 arcseconds in the sky. Finally, CAP status window shows low level messages so that a user can check immediately the cause of problem in case of emergency.

Guide camera takes a image of the field and displays it in the Image window. After the user chooses a guide star with a click on the image, CAP automatically puts a yellow box around it. And CAP finds X and Y coordinate of the guide star center using 1-D Gaussian fitting. The auto-guiding starts when the user clicks the AG Start button, by continually making exposures with exposure time set in the program. It detects the guide star center coordinate in each frame and calculate offset with respect to those on the reference image. CAP converts the offset into celestial coordinate based on the current 2.1m telescope position obtained from TCS. Then the offset information is sent to TCS,

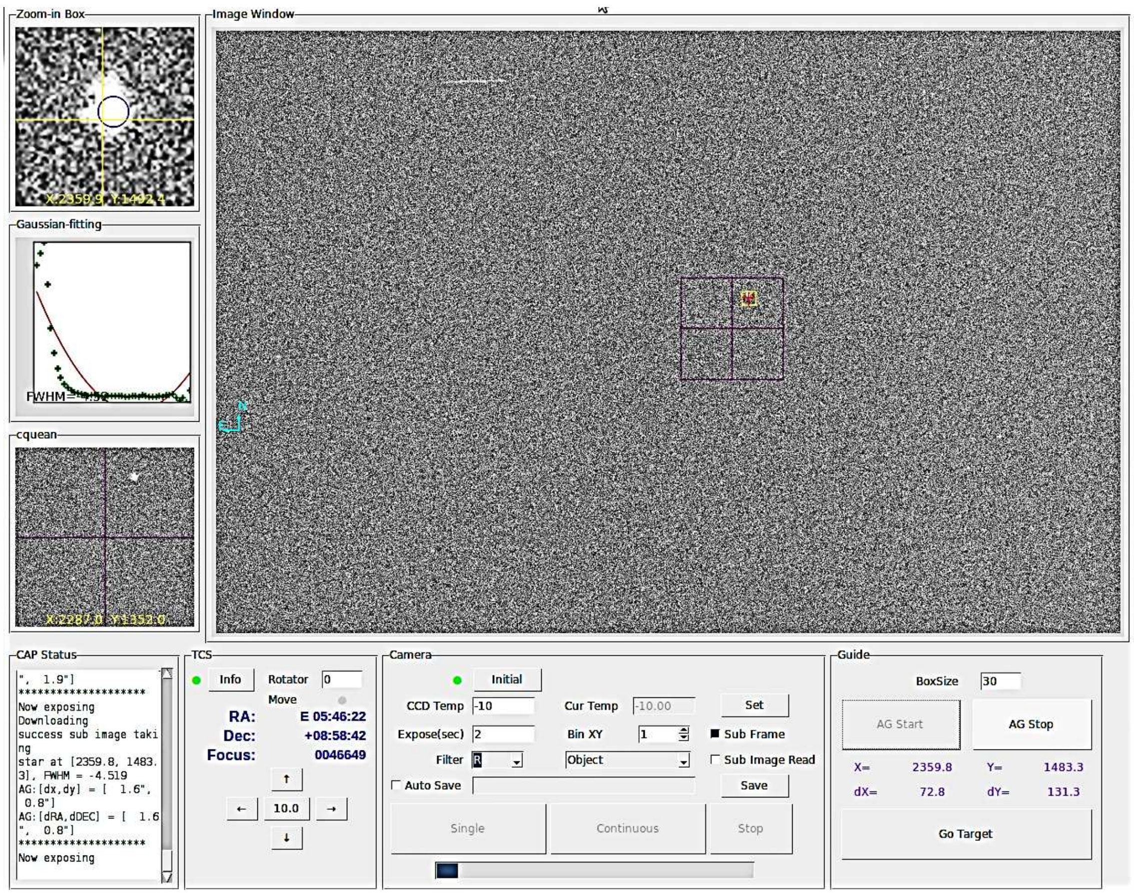

Fig. 8: The graphical user interface of CAP, auto-guiding software.

and TCS moves the telescope to correct the tracking error. This procedure is repeated until the user stops it.

Chapter 4

INSTALLATION AND TEST

The first hardware test of the new auto-guiding system occurred on 2013 June. The guide CCD camera was installed at the finder scope for the first time. This test was to verify all hardware components to be assembled as expected, and check the focus adjustment with the new adapter. The optimum focus positions depend on the filters, because of the chromatic aberration of the telescope.

Additional test observation was carried out to find the limiting magnitude of the system at the finder scope. We acquired 50 seconds exposure images of V1515 Cyg with B, V, R and I band filters. The limiting magnitude was estimated to be 11.7 in V. Note that the actual value will be higher (i.e., fainter) than this because the test observation was conducted in non-photometric night.

The pixel scale of the guide CCD camera with the finder scope was accurately calibrated with the imaging data obtained in the next test run in October 2010. The movement of the 2.1m telescope is controlled in celestial coordinate unit while the CAP obtains the tracking offset in pixel unit. Therefore the pixel scale of the guide CCD camera is very important for accurate auto-guiding. CAP code was revised with the measured pixel scale.

Instrument control and TCS communication part of the CAP were tested on subsequent nights in the same run. CAP successfully controlled the filter wheel and the camera to take the image data. User could set the camera exposure time, X and/or Y binning, CCD cooling, and so on. Communication between CAP and TCS, sending and receiving the information of RA and Dec was confirmed in this test run.

The real auto-guiding test with CAP was carried out on three test runs in 2013 November, 2014 February, and 2014 April. The full sequence of auto-guiding procedures was tested, and new auto-guiding system was confirmed to work without any problem. Auto-guiding test was done with various configurations such as with different guide CCD exposure times, different region in sky, and for different exposure times of science CCD camera. For comparison purpose, auto-guiding tests with new and original system were also carried out.

Chapter 5

DISCUSSIONS

5.1 Guiding Performance of CAP

The performance of the auto-guiding system can be estimated by examining the stellar profiles on the science camera image that are obtained with auto-guiding system. Figure 9 shows a section of a 300 seconds CQUEAN image where two stellar images are seen. Both two stellar images are of circular shape, indicating the guiding during the exposure was quite good. It would be better to compare with the same exposure image obtained without auto-guiding, but it could not be obtained during the test. Instead, we refer to the Figure 9 in Kim et al. (2011) for the performance of 2.1m telescope tracking without auto-guiding.

To estimate the guiding performance of the new auto-guiding system in a more quantitative way, we measured with imexamine task in IRAF the quantitative stellar profile parameters in several science CCD images of different exposure times that were obtained with auto-guiding system. We also obtained the same exposure images auto-guided by *agdr*, the previous auto-guiding system, and measured same stellar profile parameters. To make similar test condition, we first obtained a science image auto-guided with *agdr*, then we repeated same target observation auto-guided with CAP. The images of CQUEAN sci-

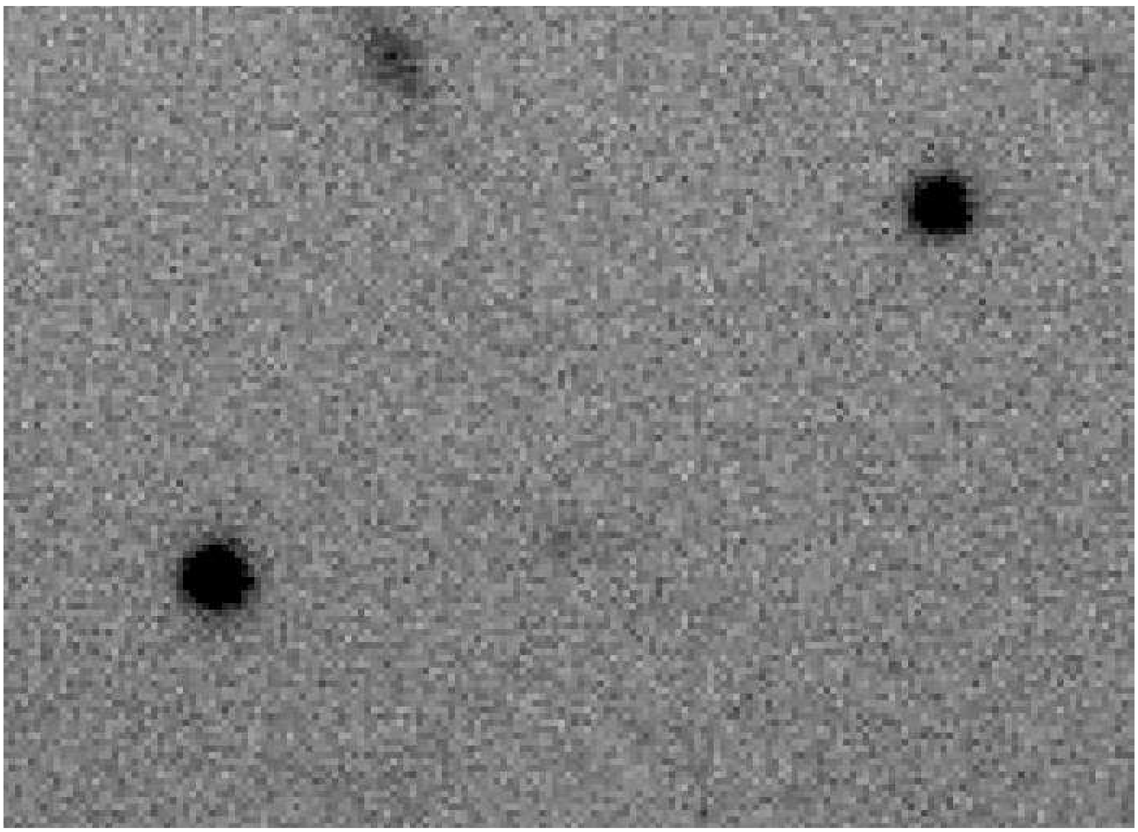

Fig. 9: A portion of 300 second CQUEAN science image obtained with CAP guiding. The seeing condition of the night was $1.4''$.

ence camera were obtained with 10, 20, 30, 60, and 300 seconds, and the exposure times of both guide CCD cameras were kept to 1 second during all test observation. Several bright point sources were selected in each individual frame, and their FWHM, ellipticity and position angle (PA) were obtained. The ellipticity is zero for perfect round profile, and becomes 1 for the line. The PA is angle between the major axis of a source profile of a star and X axis of the science camera image, and it ranges between -90° $\sim$ 90°. The stellar profile would be an ellipse rather than a circle on a poorly guided image, thus ellipticity of all stellar profiles would be close to 1, and the PA distribution of them would have a strong peak toward the star drifting direction which corresponds to X axis of the chip in our case. The results are summarized in Table 2, and plotted in Figures 10 and 11. As seen in figure 10, the median value of FWHM remains constant with respect to the exposure time for CAP case. As for the *agdr* case (Figure 11), similar trend was observed but with larger error. We note that the FWHM values are similar for longest exposures. Other factors such as wind, and atmospheric effect might affect the telescope guiding in the shorter exposures, but they would be smoothed out and only telescope mechanical effect would remain on longer exposures. That two median values of FWHM are similar to each other on 300 seconds images indicate that CAP performance is comparable to that of *agdr*. As for the ellipticity, the median values remain constant with respect to the exposure times in both cases. The median values of the ellipticity turn out to be around 0.1, indicating the stellar profiles are quite circular in most cases. Meanwhile, PA distribution shows large scatter for all exposure times in both cases. As mentioned before, the PA distribution would show a strong concentration at 0 degree if guiding was not perfect. But random distribution of PA indicates that both *agdr* and CAP did guide the CQUEAN as expected. Note the PA distribution for 300 seconds exposures is strongly peaked at 0, but we could not make any conclusion due to few number of data.

Table 2: Comparison of the guiding performance between new system (CAP) and original system (*agdr*).

Guiding Software	Exposure time [second]	FWHM		Ellipticity		Position angle	
		median	σ	median	σ	median	σ
CAP	10	6.25	0.72	0.19	0.26	-9.00	57.70
	20	5.98	0.73	0.10	0.09	-12.00	71.55
	30	5.78	0.39	0.08	0.06	19.00	31.47
	60	6.04	0.98	0.10	0.10	2.50	19.61
	300	5.34	0.30	0.22	0.25	4.02	3.61
agdr	10	5.09	0.50	0.08	0.09	-19.50	51.45
	20	5.45	1.33	0.06	0.05	-23.50	61.08
	30	5.36	0.40	0.06	0.13	9.00	53.38
	60	6.35	0.93	0.09	0.11	1.00	32.85
	300	4.85	0.44	0.19	0.31	3.59	1.26

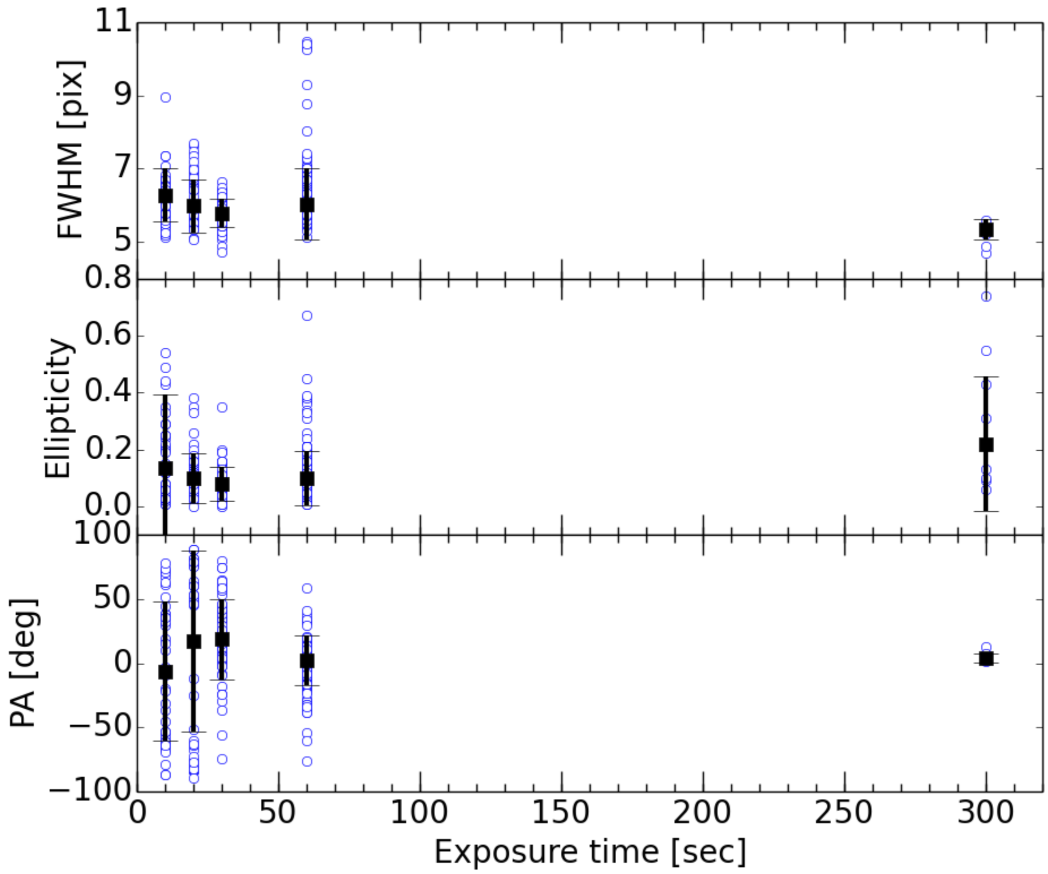

Fig. 10: FWHM (top), ellipticity (middle) and PA (bottom) of stellar image profiles on CQUEAN science image auto-guided with CAP. The x-axis is the exposure time of the CQUEAN image. Blue open circles represents the individual measured values, and black squares denote the median value of the data. Error bars indicate the 1 sigma level of the data.

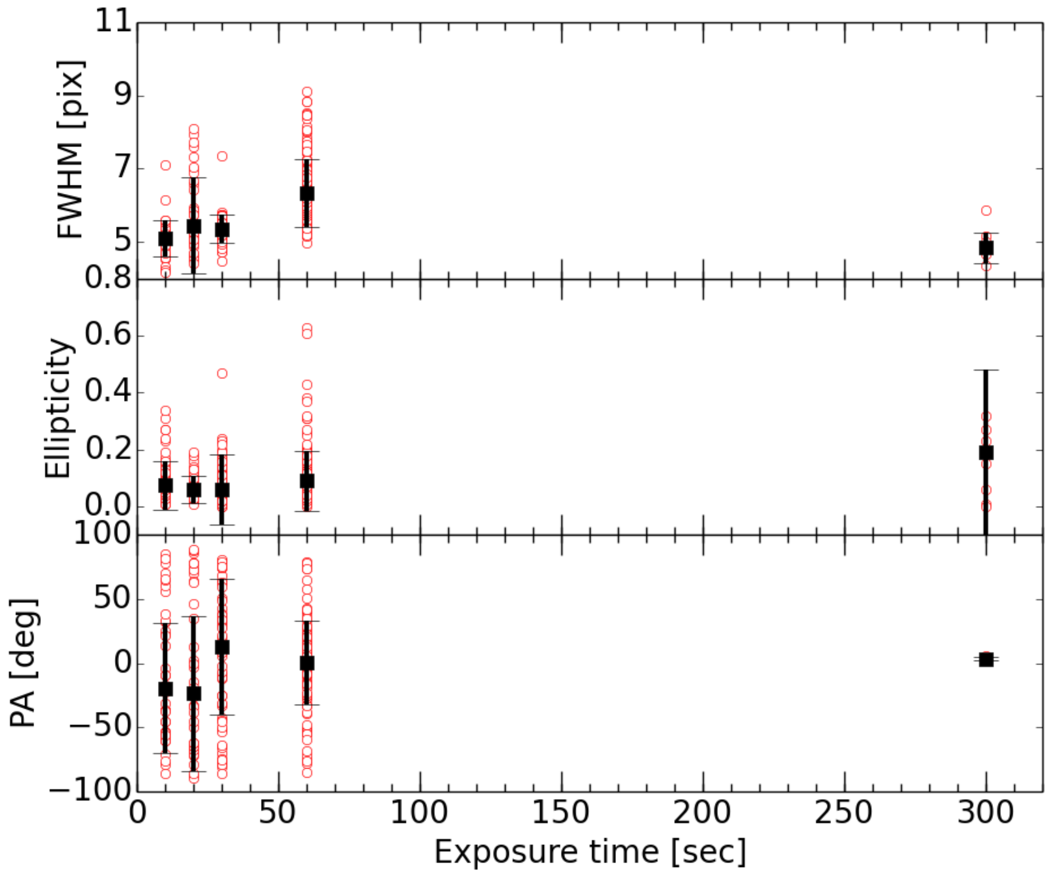

Fig. 11: FWHM (top), ellipticity (middle) and PA (bottom) of stellar image profiles on CQUEAN science image auto-guided with *agdr*. The x-axis is the exposure time of the CQUEAN image. Red open circles represents the individual measured values, and black squares denote the median value of the data. Error bars indicate the 1 sigma level of the data.

Table 3: Guiding performance with respect to the different cycle times.

Cycle time [second]	Exposure time [second]	Offset σ of RA	Offset σ of Dec
3.6	2	0.88	0.66
4.6	3	0.87	0.64
6.4	5	0.93	0.36
31.5	30	1.03	0.95

Note. – Offset unit is pixel.

Based on these results, we regard that new auto-guiding system with CAP has similar guiding performance to existing auto-guiding system with *agdr*. CQUEAN usually obtains science images of up to 10 minute exposures. Kim et al. (2011) showed *agdr* could guide the telescope up to 1200 seconds without introducing any error. We expect that CAP can guide the 2.1m telescope for longer exposures without any problem. We consider that CAP can meet the telescope tracking requirement of the second generation CQUEAN

5.2 The Effect Of Cycle Time

We confirm that the cycle time of guide camera affects the tracing center of the target. We use the CQUEAN science camera data on 2014 February 17, 18 and 19 and April 5 and 7 observed FU Ori field with CAP. This data shows center offset information of star, and the then guide CCD camera has four different exposure times with the different cycle time respectively (Table 3).

The offset data of the 2, 3 and 5 seconds exposure time have standard deviation value σ less than 1 pixel. But offset data of 30 seconds exposure time has σ bigger than 1 pixel along X direction (Figure 12) . In conclusion, when we use the new auto guiding system for observation, we should take data with short cycle time less than 10 seconds what we expected cycle time in Section **??**. When we use short exposure time of guide camera then only bright star can be guide star. Our FOV of new guide camera is wider than previous one, thus we have more bright star in FOV and it help to find the suitable guide star.

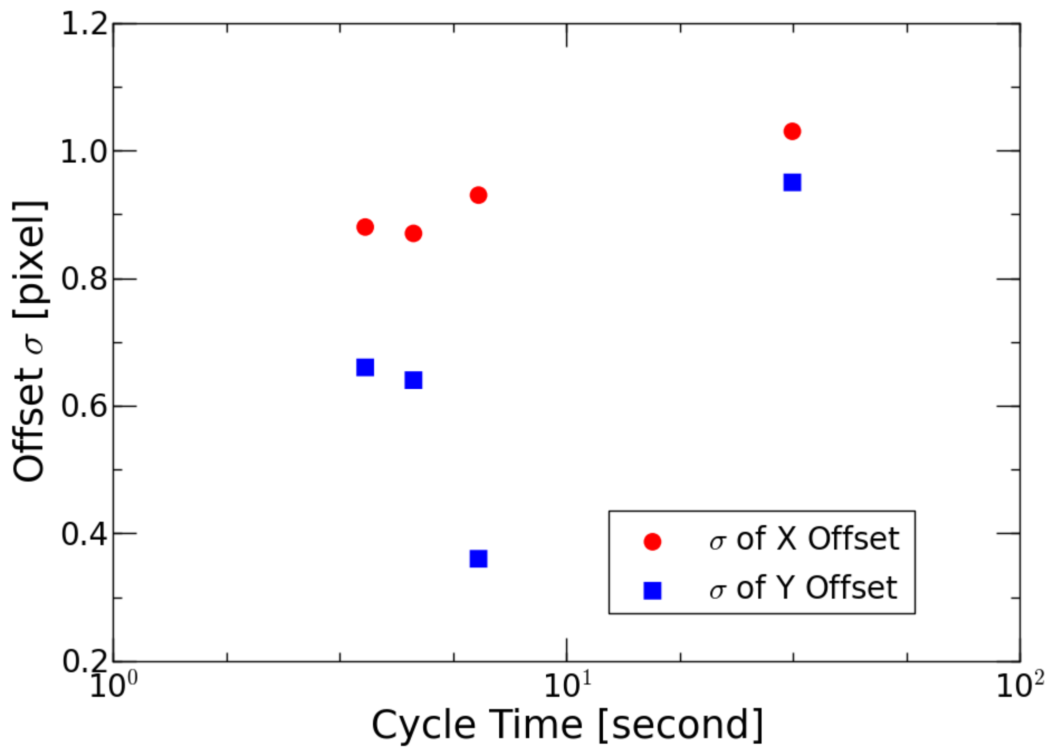

Fig. 12: The standard deviation of offsets along X-axis (red circle), and Y-axis (blue squares) of the science image, with respect to the cycle time of the guide CCD camera.

Chapter 6

SUMMARY AND CONCLUSION

We developed the new auto-guiding system for second generation CQUEAN. Analysis of the system requirements indicated that 2.1m telescope tracking can be corrected with an auto-guiding system with period shorter than 10 seconds, and that camera FOV with the finder scope is wide enough to find more than 5.9 stars that are brighter than the limiting magnitude of 1 second exposure case.

Hardware of the new auto-guiding system consists of an optical CCD camera, and a filter wheel. Johnson $BVRI$ filters were installed in the filter wheel for possible science observation with the guide CCD camera. This system is attached to the finder scope of 2.1m Otto-Struve Telescope at McDonald Observatory in Texas, USA. An adapter was made to attach the camera and the filter wheel to the finder scope. This adapter enables us to adjust the camera position for best focus. We also developed our own auto-guiding software, CAP, written in python.

The new auto-guiding system was put to first full auto-guiding test on 2014 February, after several stages of partial integration and operation tests. Resultant CQUEAN images were analyzed to obtain the image profile parameters such as FWHM, ellipticity and position angles for several point sources on the image. It turned out that the stellar profiles on the science images obtained with new auto-guiding system (CAP) shows very similar characteristics to those of stellar profiles on the images obtained with *agdr*, the previous auto-guiding system. This indicates that the performance of the new auto-guiding system is similar to that of the original auto-guiding system.

Based on the these results, we consider the new auto-guiding system meets the tracking requirement of the CQUEAN, and thus the second generation CQUEAN. Moreover, since the new system is physically separated from the CQUEAN science camera system, it can work with other instruments for 2.1m telescope. With a little further modification, we expect the new auto-guiding package can be used for other telescopes as well.

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Appendix – Guiding Adapter Drawing

All figures are guiding adapter components drawings using the AutoCAD. These are aluminum components, and partially anodized.

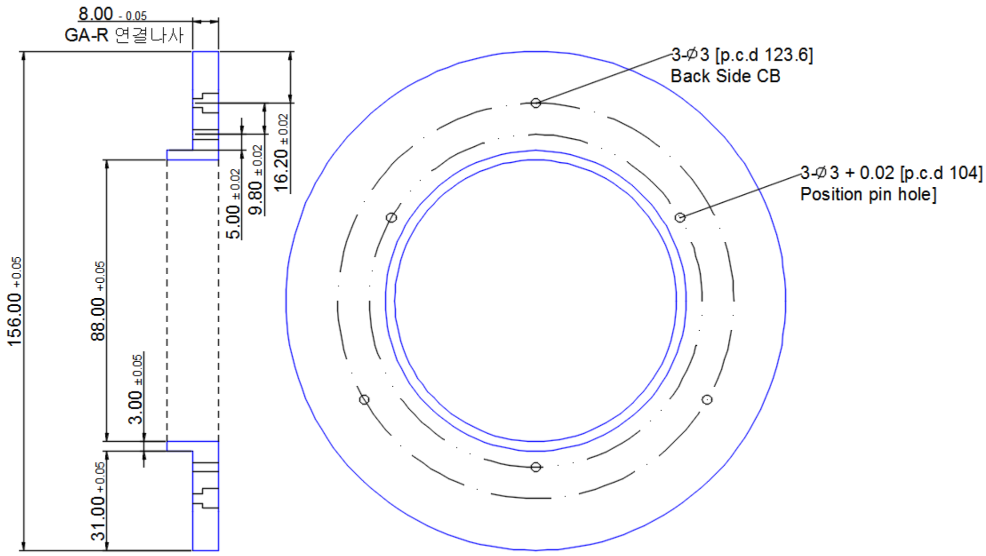

Fig. 1. GA−T

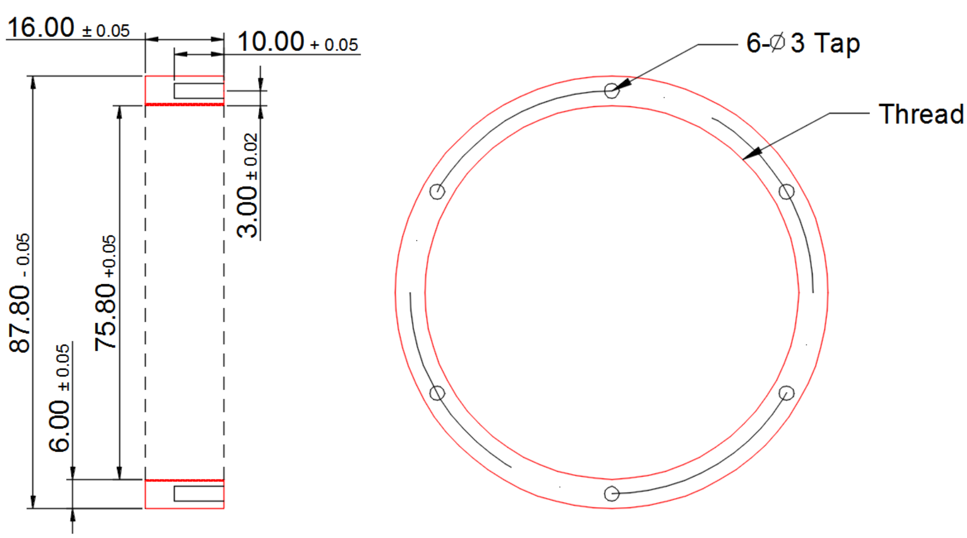

Fig. 2. GA−FC

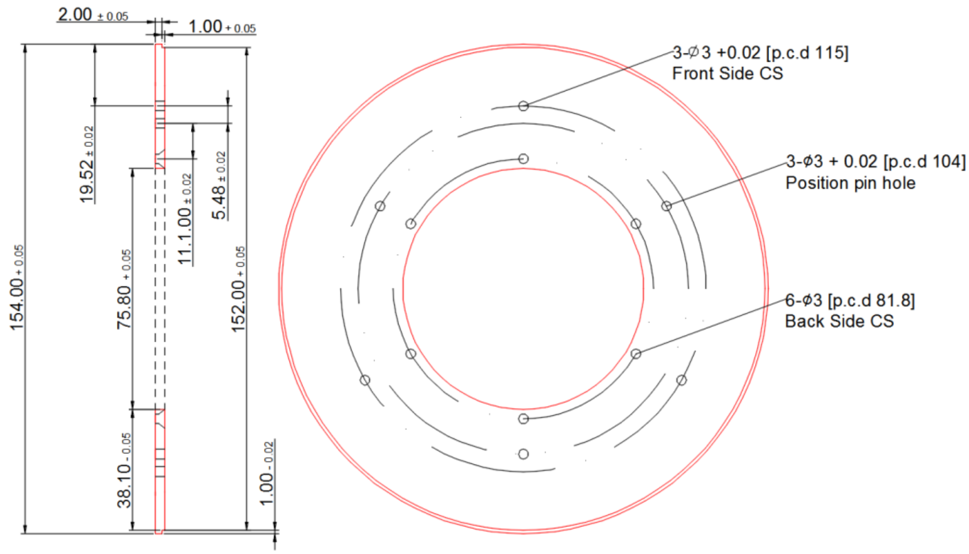

Fig. 3. GA−FD

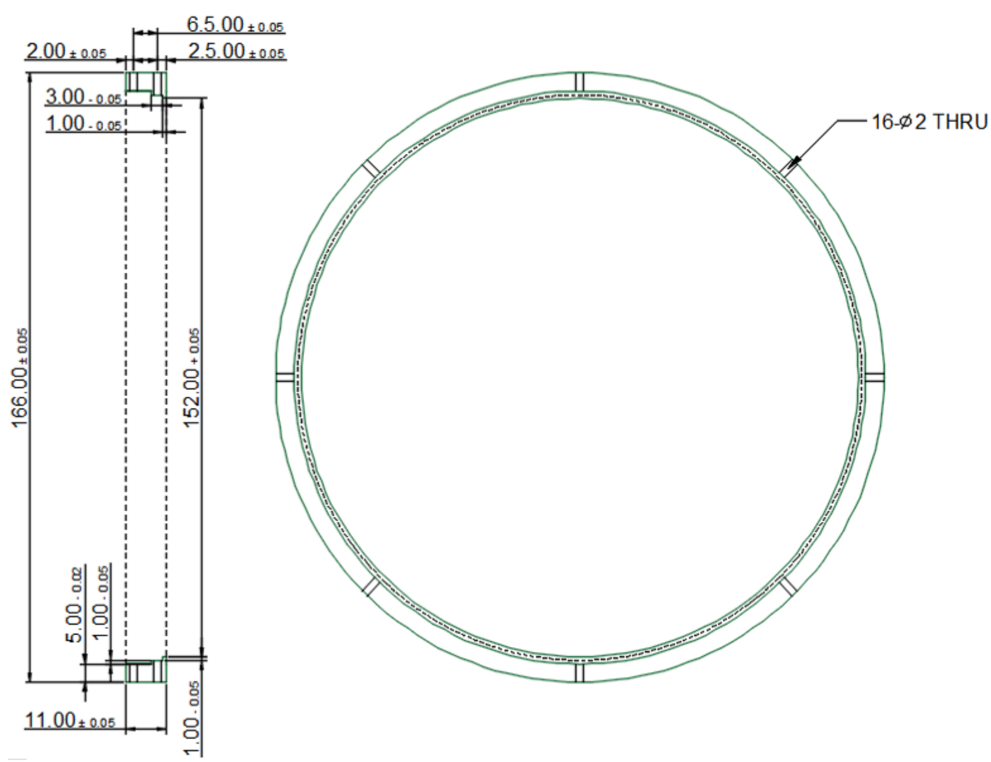

Fig. 4. GA−R

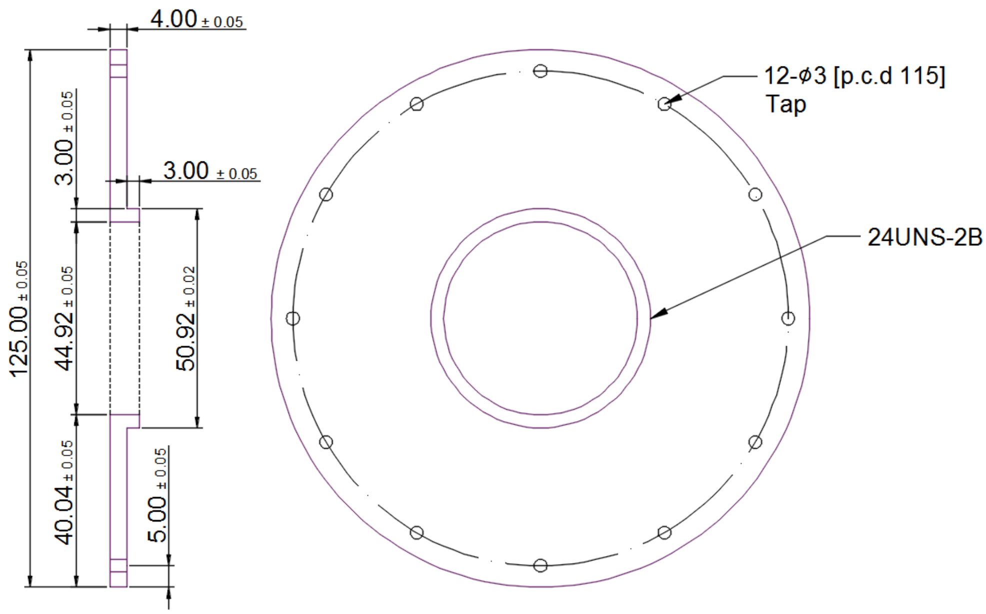
4.00 ± 0.05
3.00 ± 0.05
3.00 ± 0.05
125.00 ± 0.05
44.92 ± 0.05
50.92 ± 0.02
40.04 ± 0.05
5.00 ± 0.05
12-ϕ3 [p.c.d 115]
Tap
24UNS-2B

Fig. 5. GA−AD