Development of automated small telescopes as Dome A Site testing DIMM

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ABSTRACT

The extreme environment of Antarctic greatly benefits astronomical observations. Site testing works already show the excellent seeing and transmission on Dome C. And the higher, colder inland plateau Dome A is widely predicted as even better astronomical site than Dome C. Preliminary site testing carried out since the beginning of 2008 shows that Dome A has lower boundary layer and lower precipitable water vapour. Now the automated seeing monitor is urgently needed to quantify the site's optical character which is necessary for the telescope design and deployment. We modify the commercial telescopes with diameter of 35cm to function as site testing DIMM and make it monitor both seeing and isoplanatic angle at the same time automatically on Dome A at different height. Part of the processed data will be transferred back by Iridium satellite network every day. The first DIMM will be deployed on Dome A in early 2011.

Keywords: Dome A, automated seeing monitor, DIMM, seeing, isoplanatic angle.

1. INTRODUCTION

It is now well known that the dry, cold and clean air as well as the absence of aerosols and light pollution is the characteristic of Antarctic, and the average seeing at a median height of between 23 m and 27 m above the top of the surface layer has been measured about 0.36 arcsec at the Dome C [1]. In addition, long nights and days are well suited for long term monitoring programs. So according to the similarity of terrain and environment, it is possible that Dome A with higher altitude would be better observatory site than Dome C. The existing measurement data has initially identified the advantages of Dome A as an observatory site. However, we urgently need to measure seeing, which is a reliable estimation of observatory site performance. The DIMM (differential image motion monitor) principle is to produce twin images of a star, with the same telescope via two sub-pupils separated by a distance [2]. Now DIMMs have been widely used for measuring seeing at astronomical site testing, such as Thirty Meter Telescope (TMT) project [3], ESO VLT, Dome C and so on. With an annular mask which is placed at the entrance pupil at the same time, our modified DIMM can also monitor the isoplanatic angle, like what used in Dome C [8], but we needn't change the mask manually.

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In terms of hardware, the main consideration is how to overcome the potential operation-failure of instrument at the extremely low temperature at Dome A. A series of low-temperature experiments (from 20°C to -80°C) are carried out to ensure feasibility of this project, such as performance of motor and CCD camera, optical surface defrosting, replacement with low-temperature lubricant and grease. For those components which can't survive the winterization tests must be temp-controlled to a suitable temperature. While in terms of software and algorithms, the improved algorithm, minimize the errors from centroid calculation, centroid noise and finite exposure time. It is possible to get better result with the discussion about calibration constant which is used to calculate isoplanatic angle from scintillation index, and de-bias finite exposure time of scintillation index. The modular design consisted of instrument system operations and data processing is realized in the software frame.

In this paper, sect.2 briefly reviews the theory of seeing and isoplanatic angle. Sect.3 presents the main components of our site testing instrument, including small telescope, CCD camera, industrial control computer and software frame, as well as the modification and low temperature testing of some components. Section 4 describes various calibration procedures and data processing and the last part is the conclusion.

2. THEORY

2.1 Seeing

Atmospheric turbulence is responsible for the degradation of image resolution when observing astronomical objects. Fried (1966) introduced a parameter of atmospheric coherence length r_0 [4], which can be regarded as the diameter of a telescope whose Airy disc has the same size as the seeing disc. He derived the relation of $\varepsilon_{FWHM} = 0.98\lambda / r_0$ [2], generally expressed in units of arcsecond.

DIMM measures the differential motion of two stellar images at the image plane. The variance of differential image motion σ_d^2 (in square radians) is related to wavelength λ, telescope diameter D and Fried parameter r_0 as [5]:

$$\sigma_d^2 = K\lambda^2 r_0^{-5/3} D^{-1/3} \tag{1}$$

So

$$\varepsilon_0 = 0.98(\sigma_d^2)^{3/5} (D/\lambda)^{1/5} K^{-3/5} \tag{2}$$

Where all lengths are in the same units (meters). The constant K depends on the ratio of aperture separation to their diameter, $x = r / D$, and the direction of image motion.

2.2 Isoplanatic angle

Born and Wolf addressed the definition of isoplanatic region with a vigorous and complete mathematical approach. They showed that it was the area in which a system point spread function could be considered translation invariant and the corresponding angle was isoplanatic angle [6] [7]. So the isoplanatic angle can be estimated from the fluctuations of stellar flux received by an annular sub-aperture of this site testing instrument as [8] $\theta_0^{-5/3} = A\sigma_I^{\,2} (\cos z)^{-8/3}$. Again, because of the too long exposure time of current instrument, the scintillation index is generally reduced by time averaging. However, a practical method to eliminate the bias is proposed and further supported by the scintillation data from the GSM instrument [9].

3. INSTRUMENT

A small telescope matched with a pupil mask, CCD camera and industrial control computer are the main components of this site testing instrument. We made some modification for them, in order to match with each other and suitable for work at very low temperature at Dome A.

3.1 Telescope

We bought a Celestron commercial telescope with diameter of 35cm for our purpose. Telescope tube, equatorial mount, CCD and tripod will be placed in the open air. Considering the very low working temperature at Dome A, some modifications have been made, see Fig.1. For the equatorial mount, low-temperature grease is used to replace the normal grease in bearings and gears, the motor will be heated to around -20℃ by PTC. And the CCD is also temperature controlled to about -25℃ by PTC. INVAR rods and rings will be used in the original aluminum optical tube. The Schmidt plate is fixed parallel to the structure and coated with ITO film to keep the frost and ice away from the surface in winter, shown in Fig.2. The tracking control box which is about 30m far from the telescope will be placed in the temperature controlled instrument house above -20℃.

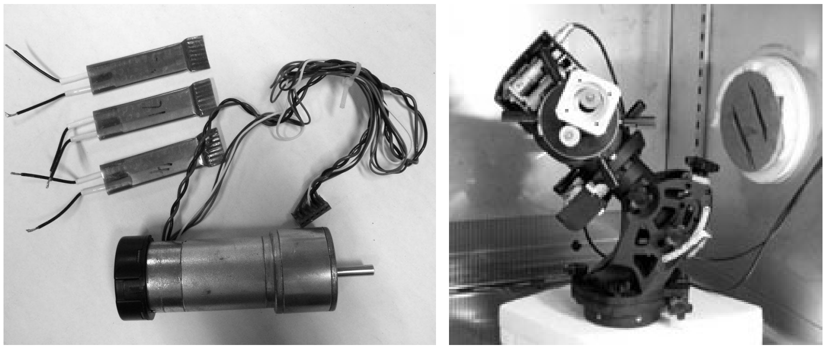

Fig1. PTC used for motor heating (left), equatorial mount in low-temperature test (right).

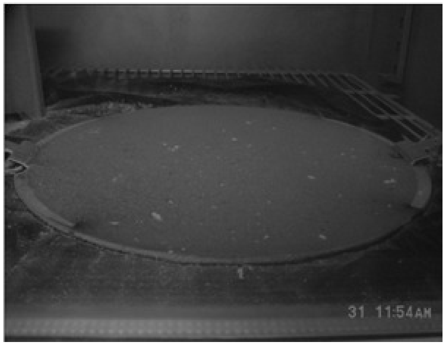

Fig2. ITO coating for defrosting

Because there is a distance of 30 meters the signal-transmission cable between controller and telescope, the output signals of photoelectric encoder and PWM signals which control rotation speed of motor will be weaken. The consequences are that: the attenuation of photoelectric encoder output signals leads to the failure of returning its feedback signals, and PWM signals attenuation would impact on the motor running. One possible solution is: PWM signal is turned into ideal square-wave signal with regulated duty ratio by reversing PWM twice with no gate. Signals are transmitted by differential transmission through linking signal output terminal of photoelectric encoder with middle-distance controller, to reduce attenuation. In the same time, a receiver placed on one end of telescope controller, restores original signal from differential signals.

Fig.3 shows the optics used for the pupil mask. Lenslet is placed at the exit pupil and a mask in front of the lenslet makes three subapertures on the pupil in which two with diameter of 60mm used for seeing measurement and one with diameter 100mm for isoplanatic angle measurement.

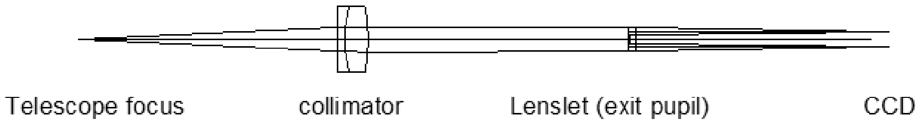

Fig3. Layout of the optics used for the pupil mask

3.2 Camera

We select MVC CCD camera, which has 659×494 pixels, 10bits bit depth, and could provide 4ms and 8ms exposure time. This CCD camera would be placed into a thermally controlled box, so it can work well around 0 ℃, and would communicate with industrial control computer via gigabit network.

Because the CCD camera will keep working for a long time at low temperature, so it needs to be heated. Specific measure is as follows: PTC warmer could automatically regulate its resistance and thermal power according to the change of its temperature, so as to control the change of controlled object’s temperature. So the temperature-control testing with PTC warmer is carried out on the CCD. The results show that the PTC heater can control the CCD temperature in the ideal range, thereby improving its working environment. Furthermore putting CCD camera into insulation box, and filling void space with insulation material, keep temperature of camera above -10 ℃.

3.3 Industrial control computer

We have bought industrial control computer with wide temperature range operation，and carried out boot-shutdown and overload-testing under low temperature. The testing ensures that industrial control computer could work well around -30 ℃. However, actually it is placed in the instrument warehouse，where the temperature is kept above -20 ℃. And it has two gigabit networks, one for connection with CCD camera and other for signal communication with Iridium satellite through gigabit network. It also controls telescope via R232 protocol, and take real-time monitors for the temperature of thermally controlled box of CCD camera and actuating mechanism of telescope.

Fig. 4 Low temperature testing of Industrial control computer and CCD camera

3.4 Software frame [10] [11]

The DIMM software frame has these main functions as follows: Firstly, controlling startup and shutdown of the whole system and adjust working conditions of the telescope and CCD camera. Secondly, display running status of the system. Thirdly, communicating with database and saving results. It has graphic user interface, displaying real-time images, computed results and running status and long-distance control.

DIMM software is the core of the whole system. After system startup, the program firstly checks the work status of every component in this system, to ensure that industrial control computer communicates properly with the modified telescope with a mask and CCD camera. If this is the first time to start whole system, the Install Mode would be executed to make sure that there is no error in the connection of various components, and CCD could gain images meeting specific requirement. Later, the FindStar Mode would be used to adjust telescope to the target star, and judge whether telescope finds star successfully through analyze images, including the size, position and intensities of spots. After a success of finding star, the telescope maintains the automatic tracking and then program goes on the next step of seeing and Isoplanatic Angle Monitor Mode. A series of interlaced exposures of shorter and longer exposure time are taken, until to the end of accumulating time. Then parameters, calculated with large pool of data, are saved in the database, some of which are displayed on the Graphic User Interface. Long-distance control could also access the data in the database. Accumulating time is repeated in the same way until these cases happening: FindStar Mode repeats because of target star running out of the field, weather or other conditions causes working abnormally, or continuous time ends. During the time of this program running, GUI displays the work status of every part of this system and controls them directly, and long-distance control is implemented through transferring command and callback information and returns part of the processed data by Iridium satellite network every day.

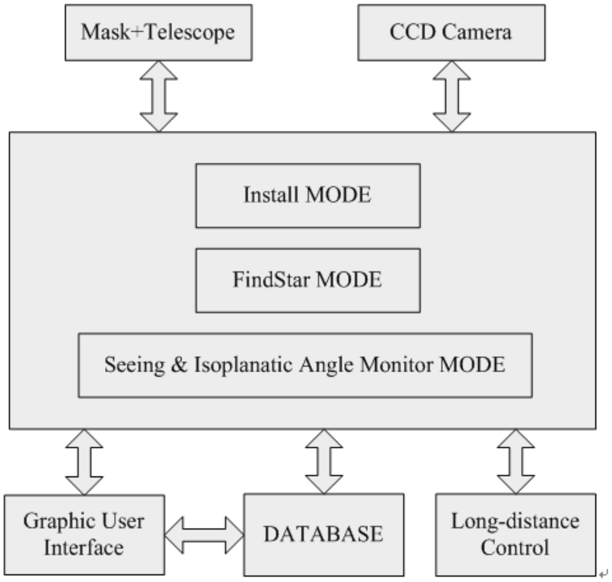

Fig.5 Software frame

4. DATA PROCESSING

The principles of seeing and isoplanatic angle measurement are known well simple, but their implementation are not because many additional small details intervene, such as minimum exposure time allowed by the hardware or by star brightness is not short enough to freeze the atmospheric image motion. Moreover, centroid algorithm and noise can cause a bias for the results much larger. How to increase the accuracy of the data processing is studied below.

4.1 Seeing calculation

Centroid algorithm: In this DIMM instrument, the image motion is estimated by calculating centroids of the spots. Setting a threshold well above the background noise and defining a window around the brightest pixel are used to reduce the influence of the noise. Threshold is set at the average+factor*stddev, where factor is about 3 and average and stddev are calculated with pixels in annular area around the spot. Centroid algorithm can be expressed by the formula:

$$c_x = \frac{\sum\limits_{window} x_{ij} I_{ij}}{\sum\limits_{window} I_{ij}} \;;\; c_y = \frac{\sum\limits_{window} y_{ij} I_{ij}}{\sum\limits_{window} I_{ij}} \tag{3}$$

Where c_x is the estimative centroid x-coordinate, I_{ij} is calculated by subtracting threshold from intensities, x_{ij} are their x-coordinates. Here we explore circular windows for pixels at a distance less than r_{window}, radius of the centroid window, from the spot centre.

Exposure-time bias: Finite exposure time in a DIMM degrades the differential image motion, and biases the measured seeing to smaller values. In this case, a "modified exponential correction" has been developed [5]. If ε_1 and ε_2 are the seeing values calculated with 4ms and 8ms exposure time, the de-biased seeing ε_0 is estimated from

$\varepsilon_0 = 0.5(c_1\varepsilon_1 + c_1^{7/3}\varepsilon_2)$. The correction factor c_1 is averaged (smoothed) over time and its average value is then used to get the final seeing. Let $c_1^{current}$ be the current value of correction factor, and $c_1^{'}$ ($c_1^{'} = (\varepsilon_1/\varepsilon_2)^{0.75}$) be the new instantaneous correction factor computed from fresh seeing data. Then the updated factor c_1^{new} is $c_1^{new} = (1-g)c_1^{current} + gc_1^{'}$. The gain parameter g and the initial value of $c_1^{current}$ are used to start this recursive algorithm.

Centroid noise [5]: Even without atmospheric turbulence influence, the measured centroids fluctuate because of the errors caused by the photon noise and detector readout noise. The errors of intensities I_{ij} are independent in each pixel and equal to the sum of readout and Poisson noise, expressed in the signal as the following formula:

$$\sigma_{cx}^2 = \frac{1}{I_{tot}^2}\sum_{window}(x_{i,j} - c_x)^2(R^2 + I_{i.j}/G) \tag{4}$$

$$\sigma_{cy}^2 = \frac{1}{I_{tot}^2}\sum_{window}(x_{i,j} - c_y)^2(R^2 + I_{i.j}/G) \tag{5}$$

Here R is readout noise in ADU, and G is the CCD camera conversion factor (gain) in e^-/ADU. I_{tot} is the sum of intensities over pixels in the centroid window. Obviously, the noise variance of both centroids in the DIMM has to be evaluated and subtracted from the measured differential variance σ_l^2 and σ_t^2 by following formula before calculating the seeing.

$$\begin{cases} \sigma_{l-final}^2 = \sigma_l^2 - \sigma_{1x}^2 - \sigma_{2x}^2 \\ \sigma_{t-final}^2 = \sigma_t^2 - \sigma_{1y}^2 - \sigma_{2y}^2 \end{cases} \tag{6}$$

Data filter: The three spots in the image are detected and analyzed. Then images meeting the following conditions are rejected: The total numbers of pixels in each spot are computed. Too big spots are rejected. Spots with too large ellipicities, computed as the ratio of spot size in x and y, are rejected. The images which are too close to the ROI (region-of-interest) borders are rejected. Spots with too small Strehl ratio are rejected. The Strehl ratio is computed by the formula of $Strehl = \frac{I_{\max}}{I_{tot}}\frac{4}{\pi}(\frac{\lambda}{D\Delta x})^2$. Here $I_{\max}$ is the maximum intensities, Δx is the CCD pixel size, and D is the aperture diameter. Knowledge of Strehl is valuable in itself as a diagnostic of spot image quality.Using the preserved images to calculated seeing and isoplanatic angle will greatly improves the accuracy of calculation.

4.2 Isoplanatic angle calculation

The scintillation index σ_I^2 (intensity variance normalized by the square of the mean intensity) of the star at a zenithal angle z can be related to the isoplanatic angle by [1]

$$\theta_0^{-5/3} = A\sigma_I^2(\cos z)^{-8/3} \tag{7}$$

With A = 0.1963. A bias correction for the exposure time was applied by linear extrapolation on the scintillation indexes by $\sigma^2(0ms) = 2\sigma^2(4ms) - \sigma^2(8ms)$ [9]. Where $\sigma^2(4ms)$ and $\sigma^2(8ms)$ are the scintillation index values calculated with 4ms and 8ms exposure time.

5. CONCLUSION

Based on a commercial small telescope, we are developing an automated site testing DIMM for Dome A which is remote controlled and can measure the integrated seeing and isoplanatic angle as well without manually change the pupil mask. The optical tube and equatorial mount are modified to properly work under antarctic cold winter time. CCD is also temperature controlled to work right at very low temperature. The outside optical surface is coated with ITO film for defrosting which is already successfully used in our first antarctic telescope CSTAR[12]. Modular design of software has almost fully realized, especially image and data processing, controlling and communication. The software needs further optimization and testing measurements. The first DIMM is planned to be deployed at Dome A in the beginning of 2011.

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