CHES: A RAPID ALL-SKY TIME DOMAIN SURVEY

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ABSTRACT

Dynamic sky is a recent focus of observational astronomy. Thanks to the popularization of large field telescopes and large format sensors, it is possible to build array to survey the whole visible sky in a short period. To do that, we start Changing Events Survey (CHES) project. It is a general survey program for different kinds of transient events, from high energy bursts to periodic variable stars, NEOs to space debris. With specific observation strategies, the observation resource can be shared by both time domain astronomy and space surveillance societies. To implement these goals, we built a prime CHES telescope array, and its first light was in March 2018. The array consists of 12 individual large field refractors whose aperture is 280mm to cover 600 sq. deg in total, and two 800mm prime focus telescopes to do the following up and some deep survey. The rapid survey telescope will detect sources brighter than 18th magnitude within 1-minute exposure, and the array could survey all the local sky above 25 degree in 20 minutes. Thanks to the combination of long and short exposures, all the sources between 7th magnitude and 15th magnitude will have significant S/N to form credible light curves with photometry precision better than 1% magnitude. From the 650GB raw image per night (10 hours), we can extract the events whose cadence is lower than 20 minutes, including fast moving NEOs and space debris streaks. By stacking, deeper static sky will be reached. Considering the response timeliness of the transient event and the scalability of the sensor network, CHES has its own flexible hardware infrastructure, management software system, and data reduction pipeline, they have worked for several months as trial run and are still in evolving. The success of this prime model will encourage the following development of CHES program greatly.

Keywords: telescope, survey.

1. INTRODUCTION

Humans recognized that the sky is not static for a long history, such as the supernova in 1054 observed by Chinese, Japanese and Arab astronomers, but so obvious transient event is too rare to study, so studying the change of the sky is not so popular for some time. Recent years, as the observation technology developing, the presision, the coverage and the cost of large field sensors make it possible to detect the variation of the sky intentionally, this bring up a new branch, time domain astronomy.

Time domain astronomy is a broad concept which focus on the variation of different kinds of celestial bodies, in position or luminosity. Obviously, the discovery of unpredictable events relies on the spatial, time and detection depth coverage, so the efficient of the observation affetcs the time domain discovering capability. On the other hand, the large field sensor means we will get much more signals other than what we expert every detection, so a joint purpose facility which can meet the demand of several scientific goals is more efficient.

Small size robotic optical telescope array is widely used in rapid large field survey, for different kinds of research, basically two faction, transient searching and space situational awareness. The former one considers the events with dramatic change in luminosity, while the latter one follows the fastest moving objects in the sky, but both of them need to watch all the sky. So, combine them together can increase the utilization of the observation resource.

Based on this consideration, we introduce a new general ground based large field optical survey program called CHanging Event Survey (CHES) which aimed at several objective surveys, specially at objects whose has rapid variation in position or luminosity. This paper describes the design and operations of the first CHES facility, also the preliminary performance and SSA result, future work is discussed at last.

2. DESIGN CONSIDERATIONS

The complete survey is full coverage in time and space with as deep as possible detection and as short as possible cadence, but all these are mutual restraints under limited funding. So we build up a multiplex survey architecture, with different level surveys under one uniform coordination. The network links up all the facilities, including all sky monitor, wide field survey system, deep survey system, follow up system or so. Using the operation and data reduction feed back mechanism to optimise the survey processes and doing follow ups dynamically, can maximize the observation efficient and flexibility for different goals.

For the first implementation, we planned a small size large field telescope array to do the main all sky survey at 16th mag in tens of minutes; a medium size and medium field telesope for follow ups and deep survey at region of interest down to 20th mag; and an all sky lens for condition monitor and extreme bright events down to 12th mag. The field coverage is maximized by the telescope design.

3. FACILITIES

This premier implementation of CHES program consists of several telescopes in a single site of Yunnan, China, some of them are modified from other projects. The main part of the observation network is a telescope array of 12 large field telescopes which undertake the general survey, short for GSS (General Survey Subsystem); and there are 2 larger telescopes to do the deep survey and follow ups called DSS (Deep Survey Subsystem); ASS (All Sky Subsystem) a customized fisheye lens will monitor all the sky continuously.

3.1. General Survey Subsystem

GSS consists of 12 refractors each of which has 50 square degrees FOV, to achieve 600 square degrees in total for one exposure. Each lens is individually operated with a German equatorial mount instead of bundling several lenses together, to meet the flexibility for different goals, such as objects searching with position uncertainty in different direction. The whole system is installed in a roll off roof (ROR) observatory.

Figure 1. GSS telescope array overview.

3.1.1. Optics of GSS

The customized refractors are 280mm clear aperture with 300mm focal length, f/1.07, 52mm usable field of view. Because for small size (below 300mm) telescope, the refractive design can get a better performance on FOV and optical efficient. The only problem is that effective wavelength range is narrower because of the chromatic aberration. With the great efforts of the optical designer, these lenses have apochromatic wavelength range of 500nm-800nm, considering that normal CCD chip is more sensitive at red end and the some glasses have a cutoff in transmission at blue end (about 400nm).

3.1.2. Sensors of GSS

The use of sensor is Finger Lakes Instrumentation (FLI) PL09000 CCD camera with 63.5mm shutter. It's a 3056 x 3056 full frame front illuminated CCD sensor with $12\mu m$ pixel size from On Semi, usable area is 36.7mm x 36.7mm. On this lens, the pixel size is $8.25''$ and the total FOV is $7^\circ \times 7^\circ$. The quantum efficiency of the camera is above 50% within the APO range and the peak is 70%. The digilization speeds are 2MHz and 8MHz, especially low noise $(15e^-)$ under 8MHz. This help us to save a lot of readout time during the survey and raise the efficiency. The $110,000e^-$ full well capacity and 100X anti blooming is useful in this kind of dense field survey to minimize the contamination of bright stars. These advantages with reasonable price makes it the first choice in our planning. Also, the 21mm back focus makes it possible to install a FLI CFW-9-5 filter wheel which has five $65mm \times 65mm$ filter positions. Currently, we have 4 filters, SDSS g' r' i' and a customized L band of 500nm-800nm to fit the APO design, the left one is reserved for future.

3.1.3. Mechanics of GSS

All the equipments are riding on a German equatorial mount DDM85 Premium with absolute encoder from Astro Systeme Austria (ASA). The mount is installed on a fixed pier that matching the geographical latitude of the site. The loading capacity is 100kg, enough for this system including a 75kg lens. According to the manufacturers specification the corrected pointing RMS should be better than $12''$ and the tracking precision should be better than $0.35''$ RMS during 5 minutes. The maximum slewing speed is $13^\circ/s$. Considering the potential unstability of USB interface chip, we connect the serial port direct to the control computer. With the help of Autoslew and Sequence software along with the mount, we can adjust the balancing, PID and polar alignment under GUI. The pointing model guarantee the all sky pointing presision and the automated pointing modeling workflow makes it easy to calibrated all 12 telescopes at the same time.

3.2. Deep Survey Subsystem

The DSS consists of two customized AZ800 prime focus reflector from ASA. This is a 800mm clear aperture telescope with 1760mm focal length, f/2.2, 100mm usable field of view. The designed spots of full FOV enclose 80% energy into $2''$, from 400nm to 900nm. The optical efficiency is 60% considering the reflectance, refraction and corrector obstruction.The telescope tube with customized derotator and $100mm \times 100mm$ four position filter wheel are riding on a alt-azimuth mount. The corrected pointing RMS should be better than $5''$ and the tracking precision should be better than $1''$ RMS during 60 minutes. The maximum slewing speed is $6°/s$ and maximum slewing acceleration is $1°/s^2$. All the devices including main mirror cover are controlled by Autoslew in a mini computer inside the telescope mount and communicate to host computer via network.

Both of them are equipped with Andor iKon-XL 231 CCD cameras that are based on e2v CCD231-84 'astro' back-illuminated sensor. This camera offering a very large $61.4 \times 61.4mm$ imaging area from a 4096 x 4112 array format and $15\mu m$ pixel size. The combining exceptionally low read noise of $2.1e^-$ with a very large well depth of $350,000e^-$, 90% peak QE, and optional 18bit digilization, 4 port 3MHz readout guarantee a high level performance, and flexibility to take care of depth, precision or efficiency. With the help of water cooling system, the temperature of chip can be cooled down to $-100°C$, and the temperature around camera can be stable to guarantee the seeing not be affect by the camera heating at prime focus position.

The practical FOV of DSS is $2° \times 2°$ and pixel size is $1.76''$. Also, there are 4 filters, SDSS g' r' i' but a customized L band of 400nm-900nm. These makes these two telescopes have the abilities of deep survey and deep following up for GSS.

3.3. All Sky Subsystem

ASS is a customized fisheye lens with FLI ML50100 CCD camera riding on a Sky-Watcher AZ-EQ5PRO Synscan German equatorial mount. The usable field is larger than $140°$ to cover all sky $20°$ above horizon. The $6\mu m$ pixel correspond to $1.23'$.

3.4. Electronics and Computing

Each camera has an individual GNSS clock which support GPS and Beidou signal to provide precise timing of exposure. The latch is trigged by fire signal from camera and then the timestamp of start and exposure length are recorded. After the exposure, the time can be read from serial port.

Each telescope of GSS and ASS is controlled by a Windows 10 computer with multiple serial ports, most of them are IEI Tank-720 fanless industrial computer containing 128GB SSD and 2TB HDD. Each DSS telescope is controlled by a Dell T3620 workstation running Debian 9, containing 128GB SSD and 6TB HDD, because another Lenovo mini PC acts as a central device controller inside the telescope fork.

Addtional data storage and database is provided by a Dell R710xd rack mount server, using NFS to export to compute nodes and FTP to export to control computer. There are two computer nodes Dell T630 and Dell T430, each of which has 128GB RECC memory and dual 8-core Intel Xeon E5 CPU. These compute nodes are managed by Slurm workload manager, so the computation capability can be easily extended if needed.

All the computers are connected by H3C gigabyte switch while servers connected to 10GbE ports. With the help of site to site L2TP/IPSec VPN provided by TP-Link router, the internal network connects to the institution as a subnet via internet, so all the sites and data center are always in a virtual secure intranet. But limited by the bandwidth, image data is not suitable for realtime transmission for now, so a Dell LTO7 tape recorder is used for image backup and transportation, each tape can write 6TB uncompressed data with 300MB/sec speed.

4. OPERATIONS AND SURVEY

4.1. Operations

All the CHES system is automated, but considering the safety of the facilities, currently, the dome and whole system switch are controlled by observation assistant from other programs, they check the weather and decide whether to start or stop the system, besides that all the work is unattended.

Each telescope is controlled by a python daemon program called PyAOS running on the control computer. The daemon startup with OS and wake up all the program need for each devices, something like Autoslew for mount, and maintain the whole system as standby status via different connection protocols such as ASCOM, INDI or RASCOM. During the observation, this program queries from the operation database and execute the operation using pre-defined action combination.

The dispatch scheduling for the telescope cluster is done by an operation database which is running in the data center and shadowed on site and query strategies in PyAOS. We didn't choose centralized controlling structure based on the considering of reducing software system complexity and observation network scalability, at the expense of a small amount of responding speed. The operation requirements can be imported to database in several ways, the most common one is a web based GUI for users to submit the operations, also, the pipeline can submit operations according to the data reduction results for follow-ups. Also, there is a survey table for each type of telescope to record the process of survey. In this table, the fields are pre-partitioned on equatorial celestial sphere, to match the fields during long term observation for image differencing.

4.2. Control Program

We tried several observatory control software at the beginning, but met some problems. Supporting different types of device in a uniform set of software is difficult; need more work to support different observation and data requirements; always need to make a centralized user interface for scheduling. So we develop a python program to do the high level control.

The PyAOS program does not always control device directly, instead, it accepts high level API, such as ASCOM, RASCOM, MaxIm DL COM, Indi from Autoslew, TheSky, MaxIm DL or wINDI program, and packages them into a specific class for each telescope. The daemon thread is alive during the whole lifecycle of program, polling the operation database and checking the status of telescope. The program is always running as normal state, and all the devices are powered up, connected and stay idle. When the running condition satisfied, the program will run the observation preparation such open cover, cooling camera, take bias frames and so on; when a suitable operation accquired, a new observation thread is initialized to do the actual observation. When meet to standby signal, it will do the cover closing, camera heating up and park actions.

The program code is well separated into several parts to maximize the code reuse rate. The device code for each telescope type is loaded based on the naming rules and config items, so it's easy to support new facilites without rewriting all the code. Operation code is a individual class for each kind of operation including all kinds of observation, start and ending procedures. This part of code is written as plugins for future extension. The daemon thread code is an infinite loop which is ensured unblocked, to take the charge of polling operation request, checking telescope status and feed the status back to database.

In the future, we will implement a GUI mainthread for telescope access. The GUI is powered by flexx web GUI framework, so anyone in the intranet could access each telescope using web browser. This work is still in progress.

4.3. General Survey

The strategy of the survey telescope is user request executed at priority, then if the telescope is idle, it will do a survey observation of one field. The program will find the earliest revisited field above pre-defin
elevation, a simple strategy for all sky uniform coverage.

The long exposure of survey will be split into several exposures, to take care of more goals, especially SSA. The telescope is sidereal trakcing during the survey, because the most and known objects are stars. One short frame is in the middle of four longer frames, base on several considerations. Using the median algorithm can easily remove all the moving objects from image and get a clean image for astronomy which avoid the mutual contamination of moving objects and stars as much as possible. Then every frame subtract the median frame can get a moving objects only frame, a local template differencing. Four possible streaks clearly more reliable than one streak for SSA, but considering the significant error along the tracklet of streak detection, the point like spot from short frame can play the role of reducing this error. Also, this mode can extent the dynamic range of the detection. Currently for GSS, the exposure time is 10s and 1s. Normally, for CCD chips, the dynamic range is about 7 magnitudes, this operation can extent several magnitudes to keep the bright sources. That's why readout time matters.

5. DATA

5.1. Pipeline

5.1.1. Astrometry Calibration

Because of some semi-realtime data reduction for followups feedback, the pipeline split into several parts located on different computers. After the image acquisition, a lightweight pipeline running on the control computer with Windows Subsystem for Linux (WSL) will do the preliminary source extraction, image astrometry, data organizing, data transferring to local storage and slurm submission. With the astrometry, we can also write image quality evaluation to database for monitoring. The astrometry is done by a customized semi blind astrometry package[1] of our own. Blind is for unknown position angle because when doing fast tracking, de-rotator will stay at any position for time saving. The optimised parts are using Gaia DR2[2] catalogue, iteration for stars at corners to describe the distortion of large field more precise, and exception handling for mismatch. The WCS is expressed with SIP[3] distortion model and the catalogues of source extraction, used reference and matching results are written back to the fits file as binary table of multi-extension FITS (MEF).

5.1.2. Photometry Calibration

After the transmission to the on site storage, a reduction job will be submit to the slurm queue to run a pipeline. The pipeline differs as different observation requests, the common one is photometry calibration. Because of the need of different catalogues for multiband photometry, this part of work is not done on control computer.

The deep source extraction is also done by SExtractor[4] with optimised parameter, using FLAGS to filter the 'good' point sources, and output several FLUX from different algorithm. With the pre-made WCS, we can crossmatch the source catalogue with reference catalogue. Thanks to the catsHTM[5] package, we can use different reference catalogues for crossmatching. Using G band and GBp GRp color index from GAIA2 to calibrate the L band image, using APASS[6] or SDSS[7] or PS1[8] for sloan g' r' i' band image calibration. The differencing photometry calibration of large field image is a little complex than the normal mean zero point. So we use the large catalogue to fit a more complex photometry model. The model contains the parameters who influence the calibration precision, including vignetting, atmospheric extinction, object's SNR, color index. We record the coefficient as photometry coordinate system

5.1.3. General Survey Reduction

For general survey image group, after the common reduction, the pipeline will do the local differencing. Pre-made WCS is adopted to do the image registration, and the resampling done by reproject python package. The align images then used for stacking and subtraction.

The median image of four long frames works as local template, then subtracted from four original frames to get residual images. Streak detection provided by ASTRiDE[9] python package is adopted to detection long streak of fast moving objects, tracklets are associated directly. With the extracted tracklet, we can easily find the corresponding point on short frame, then the tracklet is fully extracted[10].

The local template then treated as a normal longer frame to do the source detection and photometry calibration, and output the catalogue for further use. In addtion, a sum stacking image will also be produced, to be the comparison image of median image, because sometimes sum image keeps more signal than median image for extreamly faint objects. Global image differencing is still in progress because of the more complex image registration.

5.2. Performance

We have tested the telescopes in good condition for performance evaluation, good means photometry night without moon light, high elevation to minimize atmospheric extinction, lower readout speed to reduce the readout noise.

We test them with 30 seconds exposure in L band, and calibrated with GAIA DR2 G band.

The GSS photometry calibration results are shown with residuals plot Figure 2 and residuals statistics Figure 3. From the graph, the detection limit of 30s image is about 17.2 Gmag. The photometry calibration precisions are respectively 0.101 0.123 0.180 for the cases that stars brighter than 14 16 Gmag and all.

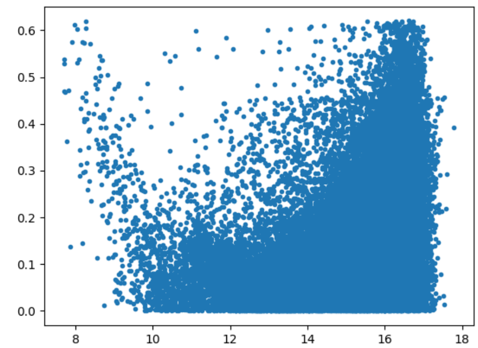

Figure 2. Photometry calibration residuals plot of GSS, X-axis is G magnitude from catalogue, Y-axis is residual after fitting.

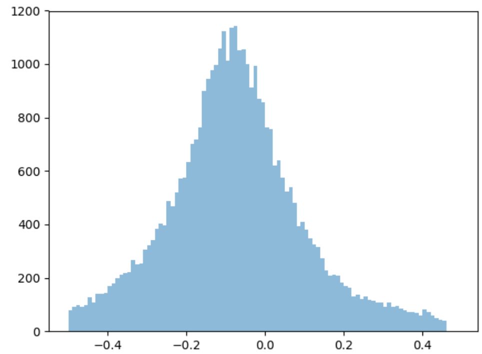

Figure 3. Photometry calibration residuals statistics of GSS, X-axis is residual, Y-axis is star counts in that residual bin.

The DSS photometry calibration results are shown with residuals plot Figure 4 and residuals statistics Figure 5. From the graph, the detection limit of 30s image is about 19.7 Gmag. The photometry calibration precisions are respectively 0.033 0.067 0.134 for the cases that stars brighter than 16 18 Gmag and all.

5.3. SSA Performance

We used the GSS to do the GEO region survey test for SSA purpose. The exposure is 4s per frame and 3min per field. The whole array will survey the belt in 20 minutes and cost 1 hour per night for 3 times survey, at dusk, midnight and dawn for as long time span as possible. In the test, 90% of the catalogued GEO objects were detected down to 16th magnitude[11].

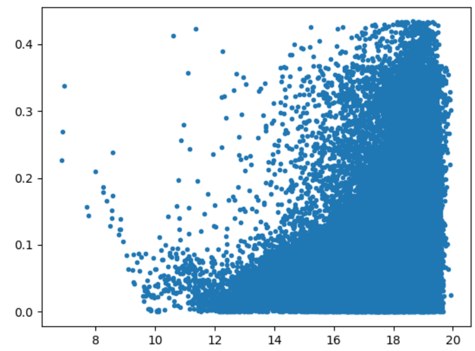

Figure 4. Photometry calibration residuals plot of DSS, X-axis is G magnitude from catalogue, Y-axis is residual after fitting.

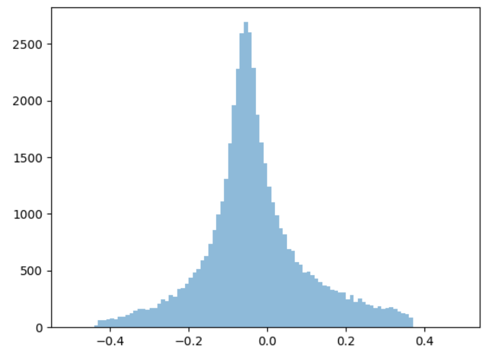

Figure 5. Photometry calibration residuals statistics of DSS, X-axis is residual, Y-axis is star counts in that residual bin.

6. DISCUSSION

Large field all sky survey is developing quickly, but the need of data is growing more quickly. This premier facility of CHES program is a trial of connecting two major communities (TDA and SSA) together to share the resource mutually. From the operation, the efficiency is clearly raised because the multiplexing of the image data. And more work need to be done to take care of more scientific goals. The dispatch strategy and observation method can be optimised. Also, the promotion of this architecture can extend the survey ability quickly.

On the other hand, as the explosive growth of CMOS, it maybe another great opportunity for time domain survey. We are trying to test some large format CMOS cameras to replace the CCD camera. Because of the electronic shutter and the fast readout, the observation and reduction method could be totally different. However, considering the defects of CMOS in precise measurement, careful test should to be made.

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