Combine the space domain awareness and time domain astronomy with massive optical survey

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ABSTRACT

Space domain awareness is a kind of observation resource dependent task, it relies on time and space coverage, geometric distribution, observation depth of the sensors, to guarantee the completeness and rapid responding. Meanwhile, as the time domain astronomy developed, more and more large field survey telescopes have been put into use. Telescopes located on these different astronomy sites can scan the visible sky over and over during clear nights. So, it should be a great opportunity to extend the SDA ability with these sensors. Many efforts have been paid to share astronomy telescopes for certain tasks of SDA in time division mode, but this is not so efficient for both communities especially in survey. Here, we propose another observation and data reduction strategy for large field survey to take care of both space domain awareness and time domain astronomy at the same time. This will benefit both communities by improving the efficiency of the instruments. The strategy is based on exposure split and image differential, to isolate the fast-moving streaks. With the combination of long and short exposures, the orbital plane, position along the track and other information can be inferred from the position and length of the streaks and points. Afterwards, we have applied this strategy to an optical survey system CHES from Purple Mountain Observatory which consists of 12 large field refractors, whose goal is to cover the local sky every 30 minutes. With the four 10s exposures and one 1s exposure, we can make local template of static sky quickly and subtract the fast-moving objects brighter than 16 mag as dotted lines. All the objects whose transit time longer than 30min will be covered. These tracklets will be crossmatched with catalogues ASAP and any kind of unusual events will be reported to the SDA network for further follow-up.

1 INTRODUCTION

Space domain awareness is important for the safety of space activities, and it relies on the surveillance ability of space debris, especially the event discovery ability. With the help of large field optical telescope, it’s a feasible way to deploy telescope array to achieve sky coverage for optical surveillance7. For example, the Optical Telescope Array of Purple Mountain Observatory **错误!未找到引用源。** is a fixed array to cover low altitude sky fully for LEO survey. And the ISON debris survey for GEO and HEO [3]. But the conflict of field coverage, detection depth and observation cadence make it more complex.

However, in most cases, these survey programs can only keep a basic catalogue for its targets. The resource is far from reaching a well responding for space events, considering the more and more complex space environment. So, introducing any resource can be useful for SDA purpose. On the other hand, many time domain survey telescope arrays have good field coverage, such as ASAS-SN [4], GWAC [5], so they could be valuable for supplement.

For different types of objects, the obvious difference is moving velocity on local sky, makes different cadence and requirement of observation. So different kind of observation schemes and image reduction methods are used for different purpose. Tracking method, exposure length is the most important difference. The OTA uses very short exposure with fixed pointing for LEO cataloguing. ISON use longer exposure with starring at earth shadow boundary for GEO and HEO survey. But if we want to use the astronomy images to search space debris, the only scenario is longer exposure with sidereal tracking. Under this circumstance, we must figure out some other tricks for observation. Based on this consideration, we put the scheme into practice with a newly designed telescope array CHES.

2 SENSORS

2.1 Overview

CHES is a general survey telescope array with extreme large field coverage, for different scientific goals, the idea is for data multiplexing as much as possible, not only the time division strategy. It consists of 12 independent telescope units, each of which has a 280mm telescope, a German equatorial mount, a full frame CCD camera, a filter wheel with 4 filters and corresponding control system. Besides there are also a central database for observation management and a cluster for data processing.

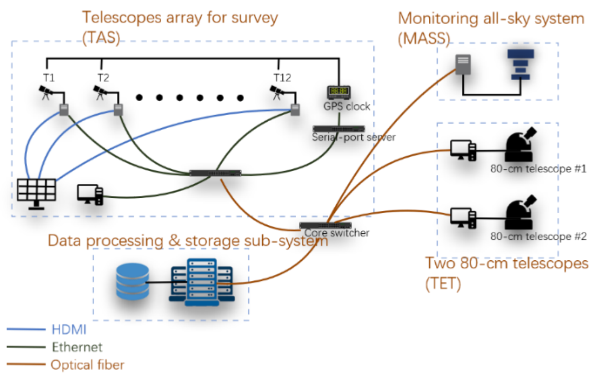

Fig. 1. Structure of CHES system

2.2 Hardware

The telescope is a custom APO refractor with 280mm effective aperture and 300mm focal length, and fully corrected and illuminated field is 55mm for the specific CCD chip. The designed APO optimized wavelength range is from 500nm to 800nm which covers nearly full bandpass of SDSS r' and i'.

The detector is FLI ProLine09000 whose sensor is ON Semi KAF-09000 front illuminated full frame CCD. The sensor has 3056 x 3056 12-micron pixels, makes it 51.9 mm in diagonal. With 8MHz digitization speed, the readout time is less than 1.8 sec for full frame read. On this telescope, the actual field of view is 7 x 7 degrees, and 8.25 arcsec per pixel. It means there will be nearly 600 square degrees coverage for one exposure with the whole array. The filters SDSS g' r' i' and a custom open filter for 500-800nm are installed in FLI CFW-9-5 5 position filter wheels, for general purpose, r' is the best choice. To take care of the space surveillance, all the camera has a precise clock server to record the real start and duration of exposure, the timing recorder is trigged by camera's exposure active indicator signal, the precision is higher than 1ns.

All the telescope components are loaded on an ASA DDM85 Premium German equatorial mount. With the help of direct drive motor, the 10 degrees per second high positioning speed can shorten the slew time significantly. The mount is controlled by ASA Autoslew for Windows and connected to control system via ASCOM.

Moreover, there are two 800mm prime focus telescopes for follow-ups. The telescope is a custom ASA AZ800 for large FOV with an Andor iKon-XL 231 camera. These telescopes can do any normal observation, waiting for the opportunity of different events.

Fig. 2. 280mm and 800mm telescopes of CHES

2.3 Software

Each unit's components are connected to a fan-less industrial computer running Windows. The unit's controller is written in Python. It communicates with mount camera and filter wheel via ASCOM, reads time from clock via serial port, acquires plans from central database, controls the whole observation procedure and reports the status of system and observation back to logging database. The observation plans are stored in plan database, and all the units acquire the next plan independently with a pre-defined strategy after finishing the current plan. This makes the whole observation plans can be adjust dynamically for transient observation and feedback response. For the purpose of fast check and response, there is a quasi-real time image reduction pipeline on each computer running under Linux subsystem for Windows. The pipeline is to do the preliminary image reduction, including general pre-reduction, source extraction and astrometry calibration, all the results are written back to the original image fits file as extended HDU.

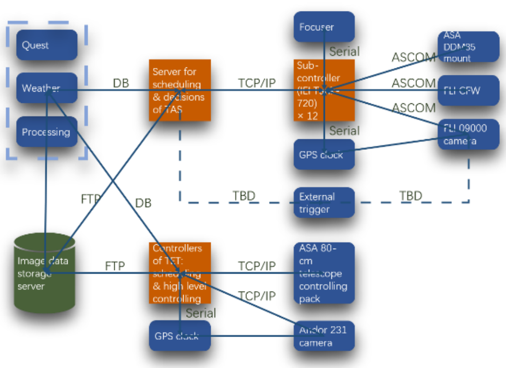

Fig. 3. Connectivity of CHES

After the pre-reduction for astrometry calibration, all the images will be transferred to a processing cluster for image processing. This cluster is managed by SLURM workload manager. Different pipeline can be chose based on the input task type. The delay of the processing is several minutes, depending on the duration of the task. So, this helps to accelerate the responding, all the interesting alarms can be used to trigger the follow-up telescopes. It is useful for transient events, and for space events. Now there are two 8 core nodes and 200TB storage for on-site data processing, and the cluster architecture can be enlarged quickly.

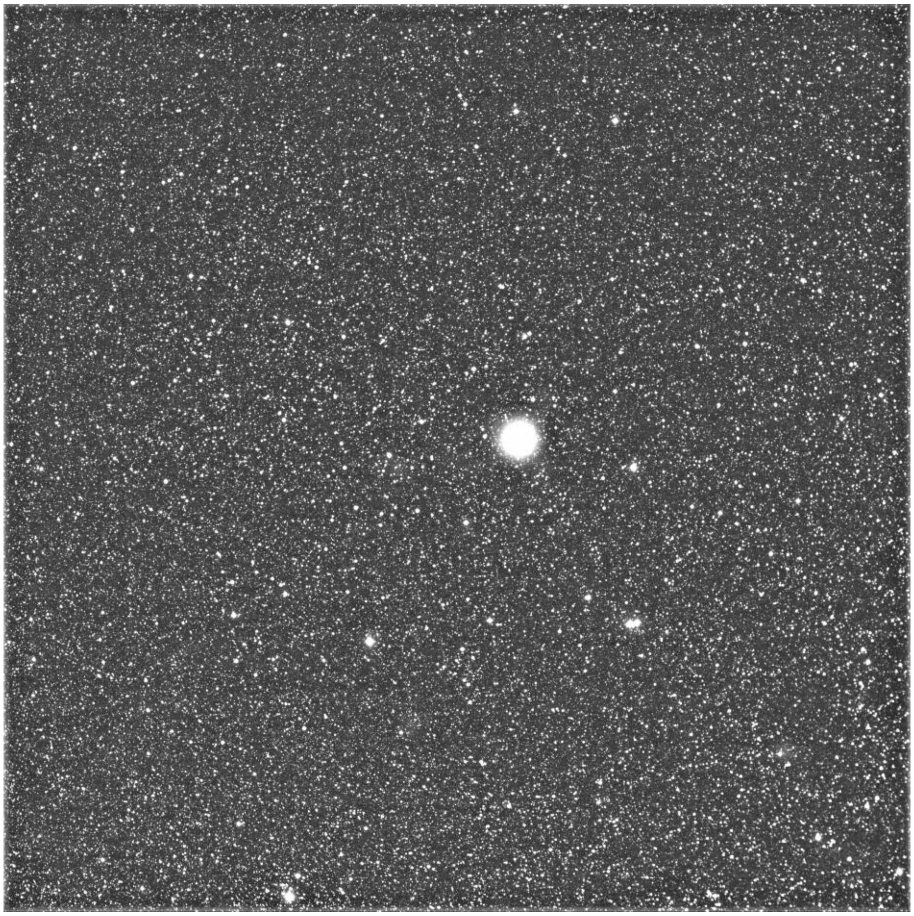

Fig. 4. This is a typical image of CHES survey program, the exposure is 30 sec. The magnitude limit is about 17.2 Gmag at elevation of 40°. The stars get so crowded that moving object trail definitely will get contaminated by stars, partially because of the chromatic aberration of refractor.

3 SURVEY SCHEME

CHES support different kind of survey schemes, based on the user input, such as GEO region repeated survey, GW possible field survey or something else. There is a multi-user web interface for plan proposing and management. However, due to the 600 sq.deg coverage, this system is more suitable for all sky survey if no special event to care about.

The site latitude is about 25 degree, so the sky coverage can reach 30 deg of southern hemisphere. We use 6 x 6 degrees size to make the field grid, considering the overlapping to reduce the effect of vignetting and degradation, the overlapping size is 0.5 deg on each side. The whole sky can be divided into 1160 fields of 36 sq.deg, but the visible sky as we defined the site local elevation above 25 deg (the airmass is about 2), is about 12000 sq.deg. It means about 332 ~ 340 fields at any time, as the field center is above 25 deg. For the all sky survey, these 12 telescopes could take care of these fields together to implement the fast visit.

The 280mm CHES telescope can reach 17.5mag in 30s, but hard to get deeper due to the large pixels (too much sky background, too much bright star contamination). Considering this limitation, we set a survey scheme with multiple exposures. Multiple consecutive exposures can help to inhibit the false alarm by confirming one possible signal on each frame. Also, we can go deeper with frame stacking and increase the dynamic range a little bit. Most important for space debris, these frames can be used for image differential, to detection the fast-moving objects and get significant length of tracklets with multiple samples.

Currently, we use a combination of 5 exposures, four 10s exposures with one 1s exposure in the middle. The 4 exposures scheme is to lower the moving object's residual while doing image median stacking. One shorter image is used for brighter end to enlarge the dynamic range more over and give a relative high precision sample for very fast bright objects, to constrain the error along the track. In addition of slewing time and readout time, the total time for one field is less than 1 min, so it will be less than half an hour for one round with 340 fields. The cadence is usual for massive survey for transient or variable stars, so does all the higher orbit objects that have observable period longer than half an hour.

The survey scheme is also simple, we have a record of all fields' last visit time. We treat all the telescopes as the same position, so if any telescope is available, its daemon process will find a field to observe. In detail, once the daemon find it is available and no other plans in waiting list, it will calculate all the fields that higher than 25 degree. Then query all these field records to determine whose visit time is the oldest one, if the time is the same (nearly impossible after running a significant period), slewing time is in consideration. After covering the field, the field will be tagged with new timestamp. All the process is based on the database system, the global write lock is used to avoid the conflict of several telescopes query the same record. Furthermore, on site data pre-reduction will be done right after the exposure, and the image quality will be assessed by the image magnitude limit. If the exposure is not good enough, the last visit time will be restored. So, this scheme will keep all the telescopes work together for the whole sky survey, and cover as much as possible.

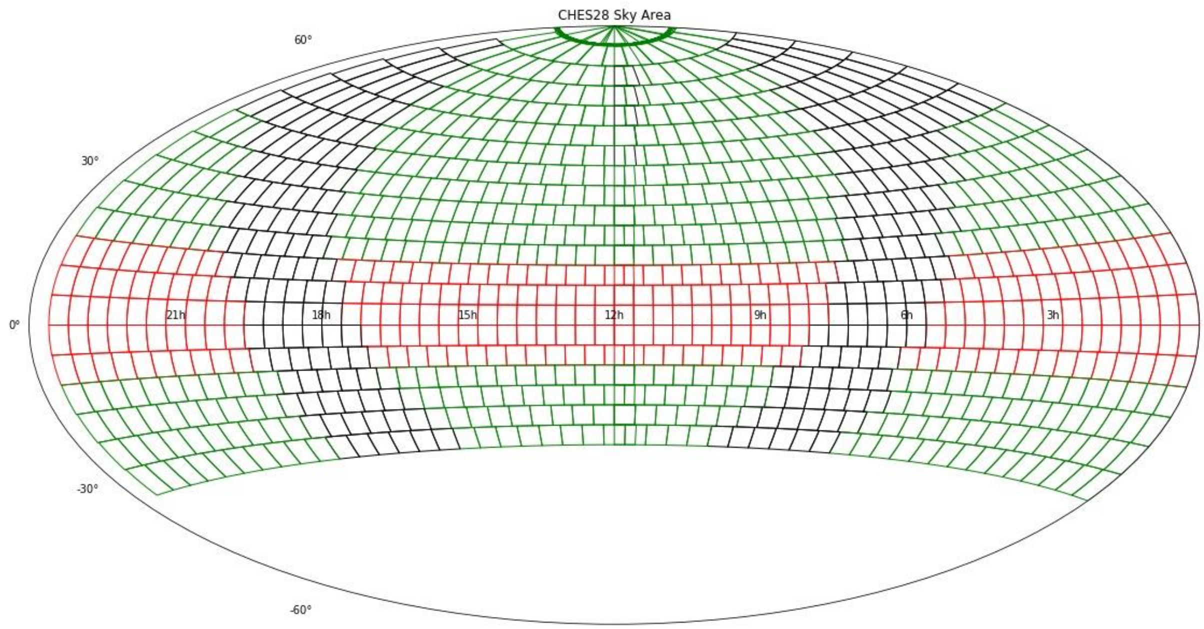

Fig. 5. Field coverage for CHES.

4 DATA REDUCTION

The purpose of this system is image data multiplexing to improve the efficiency, so the images will be reduced with different pipelines based on the different scientific goals, such asteroids, GRBs or CVs. Here, we will only discuss the space debris detection based on the astrometry and photometry information from pre-reduction process.

4.1 Candidates

Image differential is a common technic for transient detection, because for faint signal, any kind of description will cause the information loss, so the direct image manipulation is more reliable than catalogue manipulation. Usually, each survey telescope has a set of template images, produced by the stacking of a lot of good images taken at different epoch, which covers the whole visible sky from the site. For every frame, the template will be matched to it to be the reference image, in astrometry photometry and morphology way, then the subtraction of two images will leave only changing parts. This method is useful for SNe, GRB detection, and most of the residuals are moving asteroids. But we don't need to detection such slow objects, so classical template is not that suitable for space debris case.

Considering the significant movement of space debris, we decide to use local template other than the global template as described above. Each field, we will get 4 frames with the same exposure and sidereal coordinate in one minute, so the observation condition will not change much. This simplified a lot, that we do not need to match the morphology and photometry, only doing the astrometry alignment. The template is made from median, all the fast-moving objects will be erased simply, then the difference of original frame and template is the changing signal in several seconds, obviously most of them are space debris. This method is effective for star and moving object overlapped spots deblending.

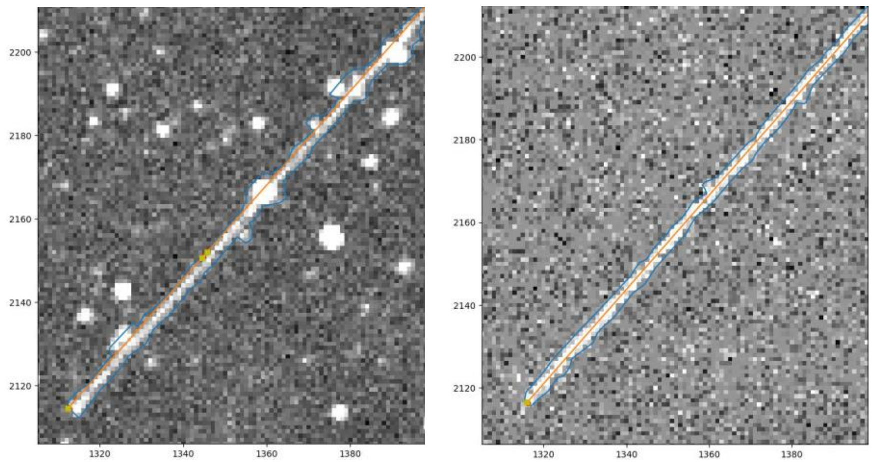

Fig. 6. Star de-blending from object trail. Left is original image and right is the differential image. Blue line is the streak boundary, and orange line is the fitted line center (gray scale line fitting with 2nd order polynomial). From the images, we can see that, no matter the boundary or line center are serious biased by the overlapping star spots. Moreover, if we meet the rapid light changing object, there should be a lot of star like spots on the trail, this increase the complexity and we cannot just remove the star like spots. So differential image with local template is a better choice, as seen on the left image.

After the pre-reduction, the 10s images are stacked. We choose using the reproject [6] python package with wcs from previous step to do the image resampling and ccdproc [7] python package to do the stacking, making sure the stacking quality in case the pointing deviation during the consecutive exposures, because sometimes we need the dithering exposures for flatting and de-fringing. The differential image will be produced from median template and projected frames.

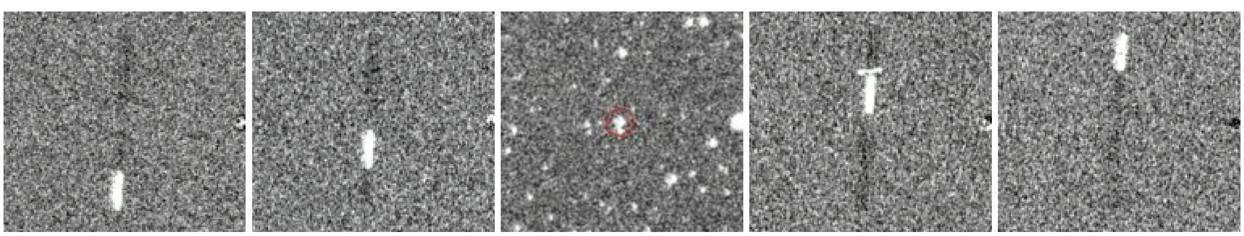

Fig. 7. Consecutive image sequence of a GEO object. The stars of 10 sec image (1,2,4,5 frames) have been subtracted by differential with local template. The 3rd image is 1 sec exposure and the spot in red circle is the objects. Obviously, it is short enough for more precise positioning, and we can see a lot of stars near the object. In fact, the middle exposure can be reduced to 100ms for more general survey.

The leftovers on the differential image are the candidates of moving objects. They are streaks of different length. Usually, the detection is done by SExtractor [8] with optimal parameters, such as "DETECT_MINAREA", "DEBLEND_MINCONT" and sometimes "FILTER". For faint streaks with luminosity deviation, streaks usually get broken, the filtering sometimes can fix the connection. But of course, SExtractor is not designed for streak detection, so longer streak detection is not well enough. We use ASTRiDE [9] python package for streak detection too. This package is based on the boundary tracing technic, using boundary shape parameter to distinguish the streaks. Also, the pyradon [10] package using radon transform is a feasible choice for streak detection.

4.2 Tracklets

Usually, the slowest object we care about is GEO object. In 10 sec, they will move 150 arcsec, about 18 pixels on CHES 8.25’’/pix image. It is a significant trail, so using angle related connectivity to find next candidate can be possible. In intensive survey mode, there are dozens of frames per field, so Hough transform line detection in catalogue domain is feasible [11]. But here only 4 streaks per object, so traverse all the combination of candidates on first and third image to test the existence of candidates at mean position on second image won’t take long. The fourth image can be the double check of the tracklet. The shape information will help to identify the tracklet to lower the false alarm, if we want to go down deeper.

5 CONCLUSION AND DISCUSSION

From the trial on the CHES system, we can see that consecutive multiple exposure can be a good choice for large field survey, it provides both community good images, uncontaminated star and debris images separately. This can help both communities to increase usable resource for resource dependent research, more effective than time division scheme.

Currently, the data reduction is still preliminary. First is the detection depth, the trajectory makes the signal distributed in different pixels, so the depth is limited by moving speed not integration time. Moving direction integration can be used to find ultra-low signal. Second, the astrometry of streak is limited by the streak calculation. For now, only streak shape has been used to determine the streak center point. We believe that using all the gray scale pixels can improve the calculation of center, even the center line (in fact, we found that long track basically is at least 2^{nd} order curve). If we can make sure the endpoints of the streak, the measurements can be more regarding the fact that there are only 4 streak frames.

6 ACKNOWLEDGEMENTS

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