

CHES: A rapid all-sky survey system for SSA

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ABSTRACT

Space situational awareness is a kind of observation resource dependent task, it relies on the coverage of time, sky field and observation depth. To maximize the detecting efficiency, a flexible survey scheme is introduced. With the combination of general survey and specific survey, objects of different types can be considered. Also, the whole system is benefit by a data center which is dealing with all the quest management, data reduction and observation feedback. Based on the scheme, the first system CHES (CHanging Event Survey) has been built last year. It consists of a dozen of 280mm refractors which cover 600 sq. deg. in total, two 800mm prime focus reflectors which cover 8 sq. deg. in total. This system will survey the local visible sky every minute down to 10th mag, every 30 minutes down to 16th mag, and specific orbit belt down to 19th mag such as GEO. The large telescopes also responsible for the follow ups of events of interest to meet the problem of short tracklet, relative low precision and low SNR in large field survey. All the scheduling work is done with a data center dynamically, which includes user interface, observation feedback and response strategy system, so the telescope can run flexible and unattended, and the observation network can be extended easily. CHES and the data center will be fully operational late this year, and other off-site survey systems are in preparation. The current survey strategy and corresponding reduction method are carefully designed and tested in the routing observation.

1. INTRODUCTION

Space situational awareness is important for the safety of space activities, and it relies on the management ability of space debris, especially the space debris discovery ability. With the help of large field optical telescope, it's a feasible way to deploy telescope array to archive sky coverage for optical surveillance[1]. For example, the Optical Telescope Array of Purple Mountain Observatory[2] is a fixed array to cover low altitude sky fully for LEO survey. But the conflict of field coverage, detection depth and efficiency make it more complex. To maximize the observation efficiency, observing strategy adaptation is needed for different types of object.

For different types of objects, the obvious difference is moving velocity on local sky, makes different cadence and requirement of observation. To cover more objects, we decide to use a combination of several survey schemes for the whole night other than single working mode as OTA, and the target is mainly large size objects in HEO and GEO. Under this circumstance, we put the scheme into practice with a newly designed telescope array CHES.

2. CHES: CHANGING EVENTS SURVEY SYSTEM

CHES is a general survey telescope array with extreme large field coverage, for both time domain astronomy and space surveillance, the idea is for data multiplexing as much as possible. It consists of 12 independent telescope units, each of which has a 280mm APO 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 management.

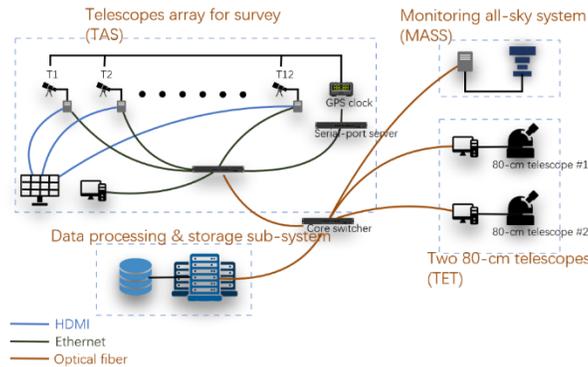


Figure 1 Structure of CHES system

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 band of SDSS r' and i' .

The detector is FLI ProLine09000 whose sensor is ON Semi KAF-09000 front illuminated 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 wheel, 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 lock is triggered 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.



Figure 2 280mm and 800mm telescopes of CHES

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 feed back 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.

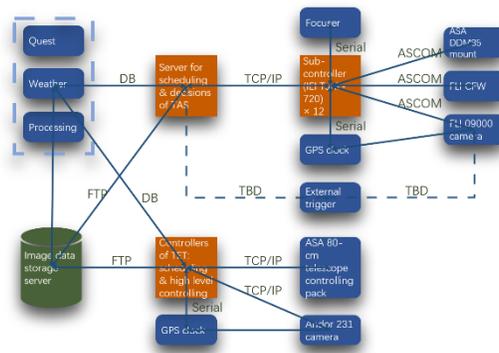


Figure 3 Connectivity of CHES

With this set of telescope array, we can schedule different kind of observation for different purpose. In the SSA work, what we care about using this facility is HEO and GEO, so we design several observation strategies and corresponding pipeline for moving objects searching and track association. Next, we will discuss the current survey strategies for space surveillance work.

3. OBJECT CLUSTER SURVEY

The most significant difference between earth orbital objects and other celestial bodies is the moving velocity in the sky, so tracking with apparent motion velocity is the most feasible way of observing these objects. To large field telescopes, tracking mode is suitable for specific orbit search, as known orbital velocity. This is useful for launching objects, accompanying objects, malfunction objects and break-up objects survey. But the most common use is GEO objects survey.

GEO object is stationary relative to local station, so it's moving reverse sidereal. Staring observation mode is a usual way which means local tracking velocity is zero. For this scenario, we build survey plan of the GEO region with staring mode and develop the pipeline based on these images.

We divide the GEO region[3] into 72 6 x 6 square degrees fields other than 7 x 7 square degrees, considering the vignetting of the optics. On each field several 4 sec exposures are taken which lasts 3 minutes[4], and it costs 18 min for the whole region survey. Each field's images are grouped as a sequence. On these images, all the stars are stretched into streaks and only objects of interest are spots and stay at the same pixel position on every image.

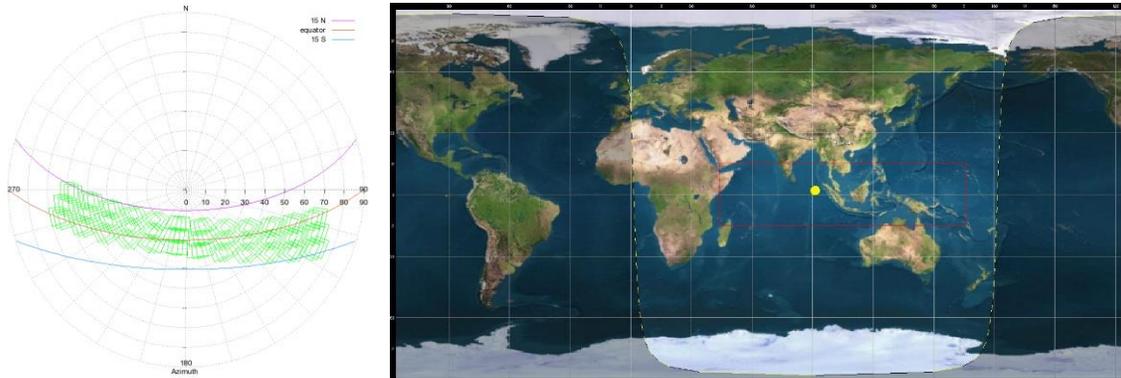


Figure 4 Survey fields for GEO

After the pre-reduction, all the images are stacked with median algorithm. Cause all the spots other than target objects are moving in the pixel space, it means for a specific pixel, only one frame will be illuminated by a source. Considering the source density, if there are enough frames, the median process will eliminate all the other spots, and left only the target spots. So far, a full field source extraction using SExtractor[5] can extract all the relative still objects, then back to the original image frames and find all spots at the known position. The astrometry results of all these spots make up the object's tracklet. The tracklet can be used directly in the latter orbital procedure.

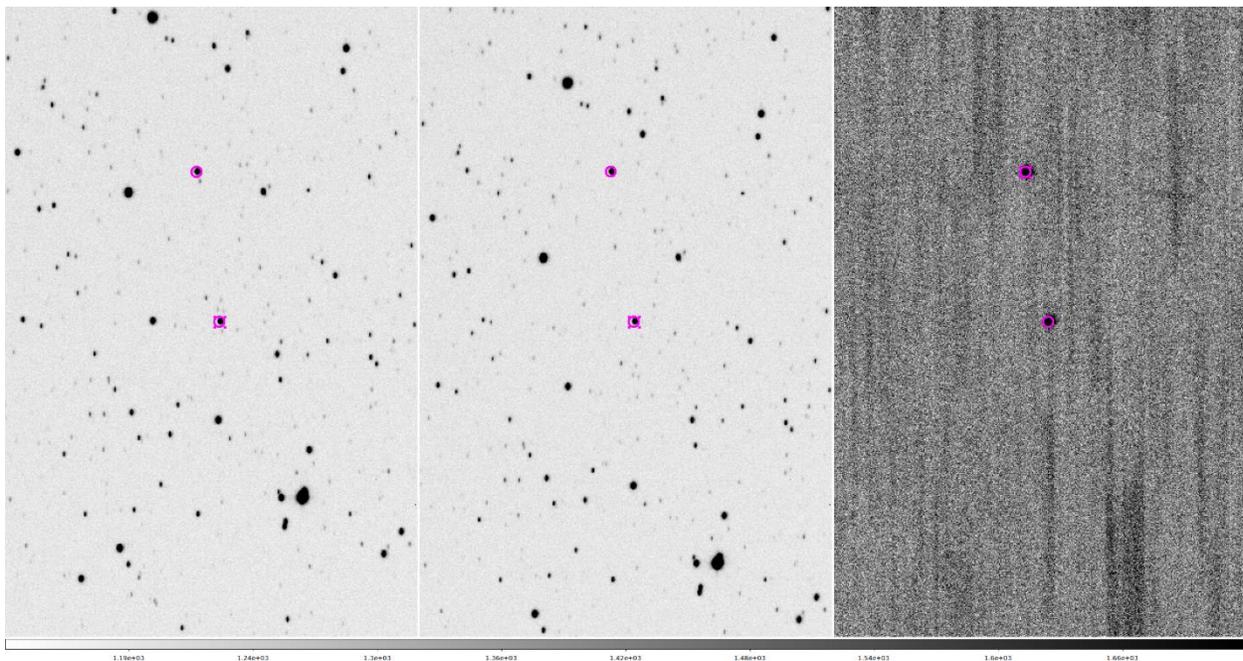


Figure 5 Objects extracted, the 1st and 2nd image come from different time, and the 3rd image is the median. The advantage of this method is simple enough, and the stacking method can raise the S/N a bit, even if the object is too faint in original image, it can be extracted after stacking, only the astrometry accuracy will be worse. The disadvantage is also obvious, the tracking velocity need to be precise. Take the example of GEO objects, usually we define they are objects whose mean motion is between 0.99 and 1.01, but in this case, the condition is more restrict. As a set of 2 minutes images sequence, 7 pixels movement can still be extracted after the stacking, which means 30 arcsec per minute. This threshold limits 200 objects out of 500 GEO objects in NORAD TLE set[6], and it fits the

detection result.

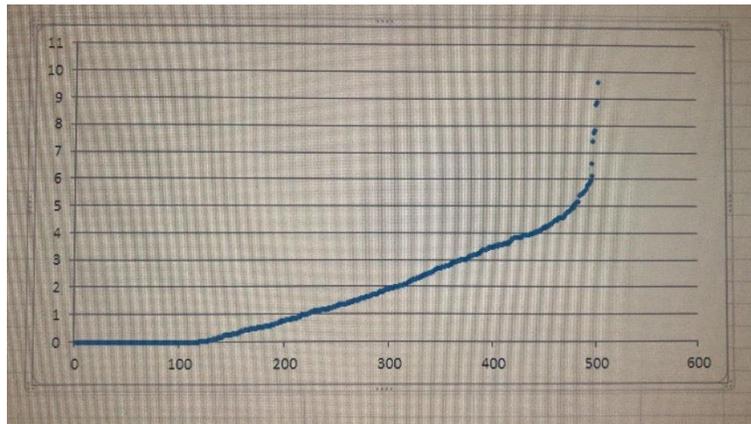


Figure 6 Visible GEO number vs shifting velocity cutoff in arcsec/second

4. GEO REGION SURVEY

The disadvantage of tracking mode will miss a lot of objects across the field, so the efficiency of observation is not high enough for the routine work. For GEO region survey, not only the absolute geostationary objects are visible, there are a lot of quasi-geostationary objects, zero inclination semi-geostationary such as GPS and other objects across the equator. The moving velocity of these objects are differed from each other greatly.

So sidereal tracking is a better choice to make all stars still in pixel space. Base on this, we apply the similar strategy as before, but using sidereal tracking during a group of exposures. The exposure time is also 4 seconds and the whole group of exposure lasts for 3 minutes each field. Every frame is reduced immediately on local computer and output the source catalogue with astrometry calibrated coordinates. After finishing the whole group, the image sequence will be sent to the disk array and reduced by a custom pipeline in Python.

With all the catalogues read into memory, cross matching each catalogue with the set of all the other catalogues in world coordinate system can match all the stars, and the left over are candidates of moving objects. Using the set of all the other catalogues is to make sure filtering faint stars around the detection limit as much as possible. Then put all the candidates together and map the them onto a new image to do the track detection, to filter the candidates by motion characteristic furthermore. The basic idea is to use multiple loose filters to converge to the accuracy result, single filter with too tight threshold is often hard to adapt to common case.

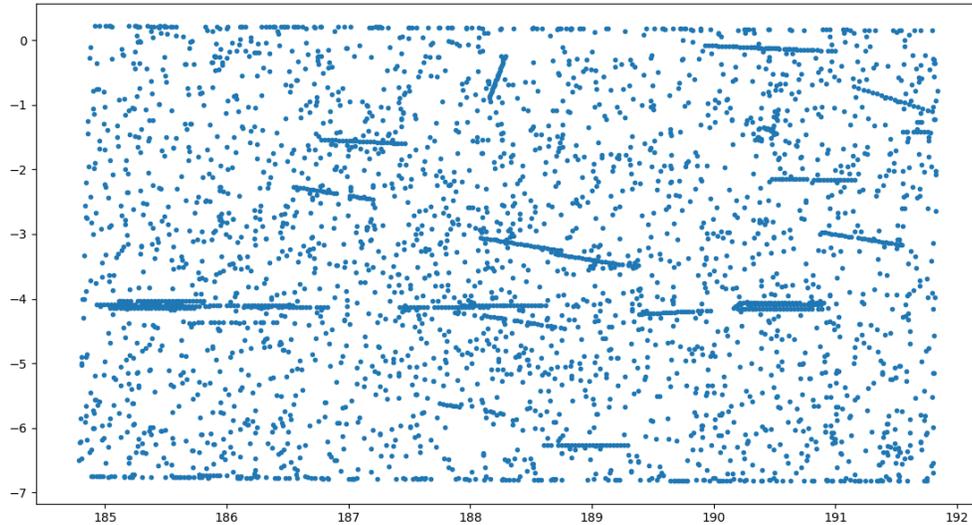


Figure 7 Candidates map from catalogue cross matching

The first filter is based on line detection, as the object's track approximates straight line in pixel space. After comparing several line detection methods, we choose probabilistic Hough transform, and use the implementation from scikit-image python package[7]. Compared to the original Hough transformation, this function has parameters of minimum line length and the line gap that influences line merging, so it detects the line segments other than lines.

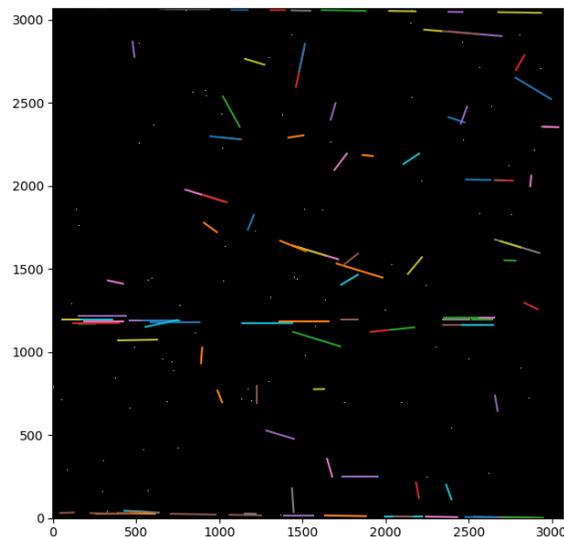


Figure 8 Line segments detection in candidate mapped image

Line segments only have correlation in space, and this is not strong enough to extract all the spots that belong to one object. So, the next filter uses the correlation with time. The RA and Dec are linear with time during short time. Sometimes, there may be more than one track in a segment, especially in GEO region because of the high density of objects, so we could not just kick the outliers with line fitting. We find the RANSAC algorithm and use the implementation from scikit-learn python package[8]. This kind of line fitting can tolerate great number of outliers that definitely not belong to the target object. So, iteration with outliers can separate several tracks from one data set.

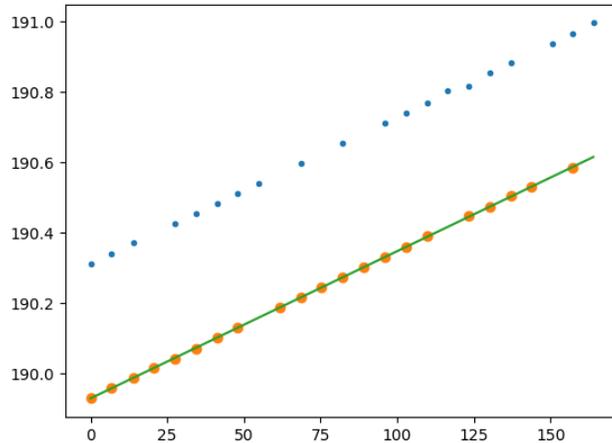


Figure 9 RA vs time fitting using RANSAC, to kick the outliers

Finally, using this track information to trace back to the original catalogues and extract all the possible spots that belong to one object. These tracks can be used directly. During our trial, there will be more than 1000 objects in GEO region survey for one night, covers over 90% of the catalogued GEO objects, 80% of the catalogued semi-GEO objects, and many other objects in HEO. With 4 sec exposure, the faintest detection is down to over 16 V mag. This array can survey the GEO region for dozens of times a night, and this is redundant for GEO and semi-GEO objects. For orbit determination, what matters is the valid span of the observation, not the quantities of data. So, in the routine observation, we will schedule 3 times of GEO region survey, sunset sunrise and midnight, this will take up about 1 hour in total and should be enough for SSA. In fact, because of the skylight background at sunset and sunrise, it is not suitable for night astronomy, so only takes up 20 minutes of normal survey time.

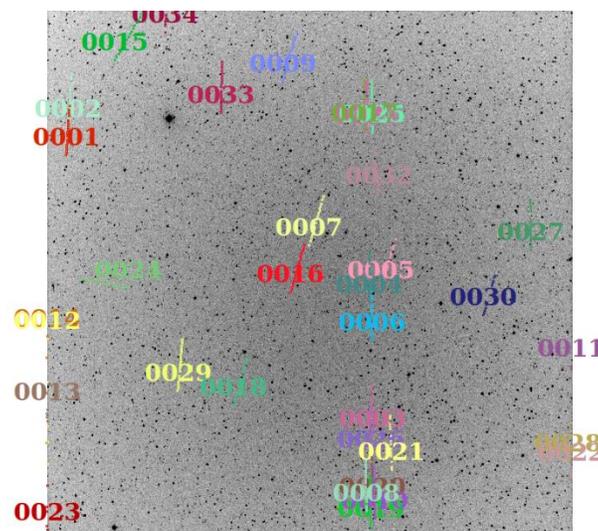


Figure 10 All the detections mapped to one image

5. GENERAL SURVEY

Besides the GEO survey and specific plans, there should be a general survey for other time. This mode is the most common usage and should take care of both space surveillance and time domain surveillance. Survey strategies mentioned before is designed for space surveillance, compared to astronomy observation, the greatest difference is

the exposure time. Using short exposure time to keep the object's spot relatively small is suitable to get high precision position, but in general survey, it is difficult to take care of all kinds of orbital objects. In fact, short exposure means the read-out time become more significant, and waste the limited observation time. Using longer exposure to get object's streak is our choice.

We design a survey strategy of split exposure. It is to split the long exposure of astronomy observation into a combination of a set of exposures, using a little more read-out time but not that much as short exposure. It will be the set of 10s-10s-1s-10s-10s, and it will take about 1 min for one field. Consider the whole local sky above 25 degree in altitude, the array will survey them in about 20 minutes. That means the system will cover all the events whose cadence is longer than 20 minutes and all the earth orbital objects whose transit time is longer than 20 minutes.

The reason of using the combination of several inconsistent exposure is to utilize observation resource as efficient as possible, for multiple scientific goals. With stacking technology, we can get signals from 1 second to 40 seconds exposure, it is an extension of dynamic range. Usually it will be 7 magnitude for one exposure, and it will extend 4 magnitude in this mode. Also, multiple exposures mode is an opportunity of promoting reliability of detections, decrease false alarm[9]. Within dense fields, using short exposure image can get more reliable astrometry calibration results, considering the spot size of bright stars comes from the chromatic aberration of refractor makes the stars overlapping to each other.

For fast moving objects' streaks, we have opportunity to get 4 full line segments with head and tail and 1 precise spot. So, we have a track and 9 positions with timestamp in 1 minute, it is enough for object recognition and simple linear extrapolation, if the object is interesting and need orbital determination for precise orbit, the follow-up plan can be added to the planning database immediately to guide the AZ800 telescope, thanks to the dynamic management. The long streak increases the probability of overlapping to stars, and this will interfere the calculation of position. To solve this, median stacking is also the solution. On the differencing image of each image and median stacking image which worked as local template, only moving objects and a little residual left, even the overlapping spots are also be separated.

In each field, once sidereal tracking set, 5 images are taken in one time, stored into a multi-extension fits (MEF) file and transferred to the cluster. Source extraction and astrometry calibration are proceeded with 1 sec image and the WCS will applied to other images. Then median stack the 4 10 sec images to get the local template and do the differencing to eliminate most of the stars. Finally, do the streak extraction with boundary-tracing method, what we use is the one of python implementation from ASTRiDE[10]. The endpoints are also calculated in the process. Like the association of GEO survey, we can classify all the streaks to each object and numbering them, then find the corresponding spot on 1 sec image. At this point, all the moving objects' information are extracted from the images set, and the local template is clean and suitable for publication to astronomy society.

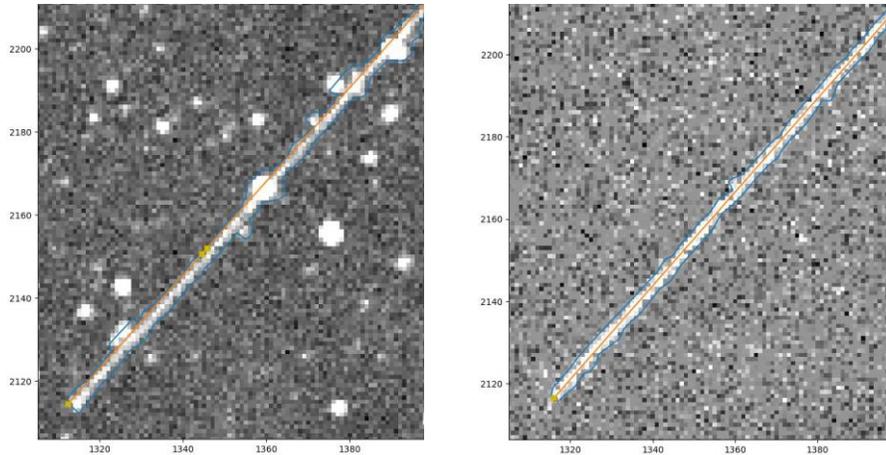


Figure 11 This is the streak interfered by star spot

For now, the general survey is still in optimization, especially the semi-realtime follow-up guidance system. The plans for the two AZ800 is the same as mentioned, just smaller FOV and deeper detection, which can used for small debris deep detection. The special part is the follow-up observation and orbital object follow-up is more complicated than astronomical transit event.

6. CONCLUSIONS

As described above, CHES is a powerful tool for high orbit space surveillance, thanks to the large field coverage. But more important, the flexibility of the observation system and corresponding optimized observation strategy helps greatly. With the combination of different survey strategy, the observation resource including instruments and clear skies is well used. And this pattern is replicable on software level. So, it will be a good reference for other general survey and time domain astronomical survey facilities, and this will reinforce the space surveillance capability.

7. REFERENCES

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