Optical survey for space objects in high Earth orbital region

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ABSTRACT

The growing population of space debris is an increasing threat for operational spacecraft and some unique orbital environments. Optical survey is the main technique for searching space objects, and it is especially efficiency for detecting MEO and GEO objects. Here a survey performing with a large field of view (about 20 square degrees) 50-cm refracting telescope is presented. In our survey, first the dynamical features of space object in high Earth orbital region are investigated to restrain the survey regions, then the searching areas are scheduled accordingly to improve the efficiency. During observation, the survey field is divided into 240 sub-fields in horizonal system, each sub-field is the same size as the field of view of our telescope and the stare mode is adopted during exposure, the field is switched every minute, acquiring around 15 raw CCD images for each sub-field. Within one night, about 4 hours are taken to complete the survey, and around 4800 square degrees of the sky are scanned. A dedicated image processing pipeline is developed to detect objects automatically. To improve the detection efficiency and robustness, in the pipeline several innovative algorithms are introduced to eliminate the noises and promote the object detection ability, e.g. mathematical morphology transformation and iterative linear extrapolation linking for images. Each raw image takes about 4 seconds to extract the information of the objects, which means the raw images can be reduced in real time. The survey was lasting for a month, and for each night not affected by weather condition and the moonlight, around 700 tracklets can be obtained, the efficiency of our reduction technique is evaluated, and the correlation of objects is investigated.

1. INTRODUCTION

Optical means is an effective way to perform space debris surveys [1]. As one kind of passive detecting methods, it is more costless and exhibits lower requirements in terms of power than other ways, e.g. radar and laser ranging [2], hence it is especially efficient for surveying and cataloging space debris with higher altitude, such as the ones in Medium Earth Orbital (MEO) and Geostationary Earth orbital (GEO) region. Optical surveys for space debris in high Earth orbital region have been performed worldwide by a number of nations and organizations [3-5], the surveying strategy, data reduction principles as well as results have also been published. Continuous observations and information collections of space debris can be helpful for catalogue maintaining and space situation awareness, hence the related techniques deserve further and sequential development.

Here an improved survey is performed, the survey strategy as well as the image processing pipeline is optimized and further developed. In the survey, the wide FOV telescope is utilized, and benefited from the relative wide FOV, several objects can appear in the same CCD frame while surveying the high Earth orbital region, hence the object detection efficiency can be improved distinctly. Based on the researches of the dynamical characteristics and evolutions of space debris in GEO ring and other high Earth orbital regions [6], the selections of survey fields are guided and the searching fields are optimized accordingly. The pipeline is improved to detect the images with high centroid precision and low false detection rate as well as low time cost, which reduces the raw data in real time.
In Section 2, the overview of our survey is introduced, the improved image processing technique is presented in Section 3. The results are shown and investigated in Section 4 while the conclusions are drawn in Section 5.

2. SURVEY STRATEGY

A wide FOV telescope is adopted in our survey. The telescope is refracted optical design and with short focal length, the parameters are shown in Tab. 1. The relatively wide FOV improves the efficiency for space debris survey significantly, although the detection ability is limited by the aperture. In addition, it should be noticed that due to the high frame rate in observation, the mechanical shutter of the CCD camera is removed, hence the smear noises are distinct, causing additional difficulties for object extracting. Meanwhile, the optics defects of the wide FOV design are also inevitable, the aberration of the refraction system affects the imaging quality and leads to the vignetting at the edge of the frame.

Tab. 1. Parameters of our wide FOV telescope.

Aperture	500 mm
Field of view	4.4*4.4 degrees
Size of frame	2048*2048
Pixel scale	7.73''
CCD operating mode	Full frame
Mechanical shutter	None
Readout channels	4

According to the dynamical features of high Earth orbital objects, stare mode is the best choice for the exposure, which makes the candidate images shown as points and maximize their signal noise ratio for detecting, hence in our survey this mode is adopted, which means after the telescope turns to the scheduled horizonal pointing, consecutive images are acquired with the same azimuth and elevation.

Based upon the study of the two-dimensional phase plane structure of the motion of space debris orbiting the geosynchronous ring, the libration centers as well as the libration half widths are obtained, which can be used for optimizing and constraining the survey fields. Here a strategy includes 240 fields is proposed, the size of each field is the same as the FOV of our telescope and it is switched every minute, leading to a 4 hours survey. The single exposure is 2 seconds, for each field around 15 raw CCD frames can be acquired, considering the readout time of the CCD camera and the pointing setting of telescope. The schedule of the survey fields in the horizon system is shown in Fig. 1.

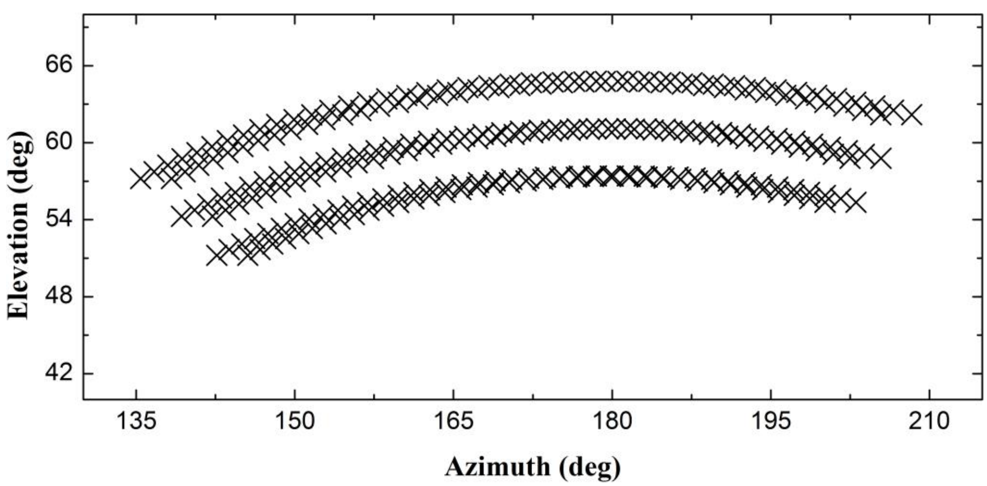

Fig. 1. Illustrations of the survey fields in the horizon system.

As shown, the survey azimuth is scheduled from 136 degrees to 207 degrees, and the elevation is arranged from 51 degrees to 65 degrees.

3. DATA REDUCTION PIPELINE

while the large amount of raw data is obtained, checking whether the set of images for a single observing field is acquired with the right guides is crucial, e.g. the scheduled pointing and exposure time, hence the checking is performed by two steps. The first step is shown as follows.

1) Obtaining the storage size of all the images of the same set and checking whether all the images are captured and stored rightly. If any file is found with variable storage size, there are errors in storage and it will be erased.

2) Reading the header information of all the images in the set and checking the pointing values (azimuth and elevation) as well as the exposure time, if the values are not the same as scheduled, the image with incorrect header will also be erased.
3) Checking the standard deviation of each image. If the standard deviation equals zero, it means additional errors of the sensor occur during acquisition or the pixel values overflow the full well of the camera. The image will also be erased.

The second step is checking the plate constant with which the equatorial coordinates are derived. For our wide FOV sensor, the count of background stars is sufficient, and it can reach up to several thousands, extracting all of them to perform calculation seems inefficient and time consuming. Here a simple way is applied, first the Tycho2 catalogue is utilized, stars brighter than 12 magnitude are selected and the equatorial coordinates of them are transformed to the observing epoch, then the theoretical position of each star in the CCD frame is obtained, a range gate with fixed size is set around it, at last for pixels within the range gate, the threshold is taken as threes times of the fluctuations higher than the background level. For pixels with values greater than threshold, they are taken as signals, and the modified moment technique is used to obtain their centroids. It should be noticed that if the count of pixels with value greater than the threshold is less than 5, it will not be taken as signals. Assuming n stars are extracted from the frame and totally there are N stars theoretically from the catalogue, if $n/N < 0.3$ the frame will be erased, since due to several reasons there are not enough sources extracted, e.g. large areas of cloud or errors of pointing, it will also affect the object detection. Otherwise, the plate constants which derive the equatorial coordinates from the measurement coordinates for each frame are obtained, which will be used to perform the transformation for object later. Meanwhile, the zero point of magnitude for the frame is also obtained.

After data checking, if the file count of the image set is still greater than 10, this set will be reduced further, otherwise this set will be discarded. Too few images affect the length of the tracklets and it may not make any sense for orbit determination and catalog. Generally, data checking eliminated less than 5% data in our survey, since the errors are rare.

Due to the optics defects of the wide FOV, to improve the precision the object detection is performed with segmentation and connected domain of the images. For reducing the time cost of the pipeline, we pick the first 5 and last 5 frames of a set, then the TopHat transformation is performed [7], it works as a non-linear high-pass filter, and eliminates the effects of non-uniform background and the smear noises, after transformation the global threshold and binary segmentation can be utilized to extract the connected domain, which improves the timeliness. It should be noted that if the count of pixels of a connected domain is less than 5, this connected domain will be erased and not considered as signals. Then a simple median of the 10 frames is performed, and the connected domains remained in the frame are GEO candidates, their centroids are estimated and saved as aprior information for further precise measurement.

After the GEO candidates are detected, we recognize the domains of background stellar and eliminate them, then the rest domains are correlated to test whether they belong to the same tracklet. According to our strategy, the stare mode is adopted during exposure and the pointing of telescope is invariant, so the relative movement of the background stars between consecutive frames can be estimated with the exposure interval, angular velocity of the diurnal motion of background stars, pixel scale of the CCD sensor. It should be noticed that for non-sidereal tracking, the background stars move along right ascension, and for alt-azimuth mounting telescope, the movement of the stars is not horizontal or vertical in continuous frames, the parallactic angle can be obtained as follows:

$$\tan\sigma = \frac{\cos\phi \sin t}{\sin\phi \cos\delta - \cos\phi \sin\delta \cos t}$$

where σ is the parallactic angle, ϕ is the observatory latitude, t is the hour angle and δ is the declination of telescope pointing.

With this information, all the connected domains of the 10 frames are shifted and registered, the median of them is generated, and with which the reference frame of the background stellar is obtained. Then the reference frame is re-shifted and registered to each frame and the connected domains of stars as well as domains of GEO objects are eliminated, leaving only the slow-moving object images and a few discrete noises. Assuming for ith frame, a connected domain with estimated information (Xi, Yi, Ti), where (Xi, Yi) is the estimated centroids and Ti is the time interval between ith frame and the first one of the set. For n=i+1…10 frames, each domain (Xn, Yn, Tn) is linear fitted with (Xi, Yi, Ti), then the estimated positions of the candidates on all frames are obtained and matched with the domains left. If more than half of the candidates can be matched, it is taken as a tracklet and the aprior information will be saved, otherwise it will be erased. After traversing all the frames, all the moving candidates are found and the aprior information is extracted.

After the aprior information of the GEO and slow-moving candidates are obtained, their tracklets are extracted from the raw data. Here all frames of the set are adopted, the estimated positions of the GEO objects are derived directly while the ones of the slow-moving objects can be extrapolated from the trace obtained last step. As applied for the background stellar, the same way is adopted to obtain the centroids of objects. with the plate constant and zero point of magnitude derived at the data checking step, the equatorial coordinates and the magnitude of the candidate is obtained. If more than 50\% candidates of the trace are extracted successfully, the related tracklet is generated and exported.

4. RESULTS AND DISCUSSIONS

The overview results of the survey with the first strategy are shown in Tab. 2. The survey is performed in 24 nights from mid-December 2017 to end of January 2018, in each night 4 hours are cost. It is easily found that in average more than 700 tracklets can be acquired each night, and 115 space objects are correlated with the ratio around 97\%. The high survey efficiency is evident, meanwhile all the raw data is reduced in real time.

Tab. 2. Results of our survey.

Date of observation	Tracklets count	Correlated objects	Correlation Ratio (%)	Observed fields
20171217	734	123	96.2	240
20171221	712	121	94.2	240
20171222	740	127	94.1	239
20171223	762	120	94.1	240
20171225	739	125	96.8	240
20171227	612	104	96.2	234
20180104	792	125	95.8	240
20180105	810	132	96.4	240
20180106	797	126	95.6	240
20180107	718	114	95.7	240
20180108	726	114	96.4	240
20180109	703	112	97.4	240
20180114	760	125	97.5	239
20180115	745	108	98.5	239
20180116	742	110	97.0	240
20180117	683	103	96.9	237
20180118	691	110	98.1	239
20180119	686	111	97.2	240
20180120	659	107	97.9	240
20180123	710	115	97.2	237
20180124	673	108	97.8	239
20180125	652	112	96.9	240
20180126	649	116	98.5	240
20180127	679	111	97.8	238

For further investigation, we pick the results with date 20180105 as examples. The mean motion of the objects detected on 20180105 is shown in Fig. 2, while their inclinations are shown in Fig. 3. It should be noted that a few objects (less than %3) with mean motion >6 are not listed. It is evident that not only objects with mean motion around 1 are extracted, a few objects with mean motion between 2 and 4 is detected as well. Meanwhile, a few objects with inclination around 60 degrees are also surveyed, they mainly belong to the Molniya orbital region, which is further proved in Fig. 4.

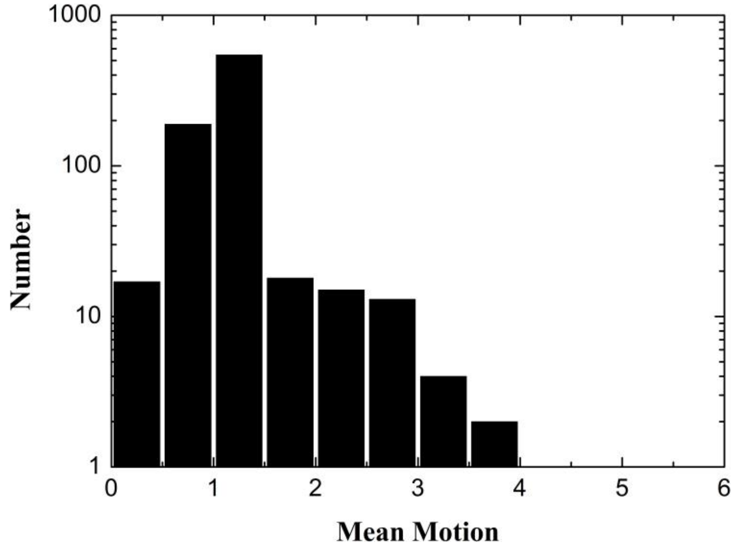

Fig. 2. Mean motion of the objects detected on 20180105.

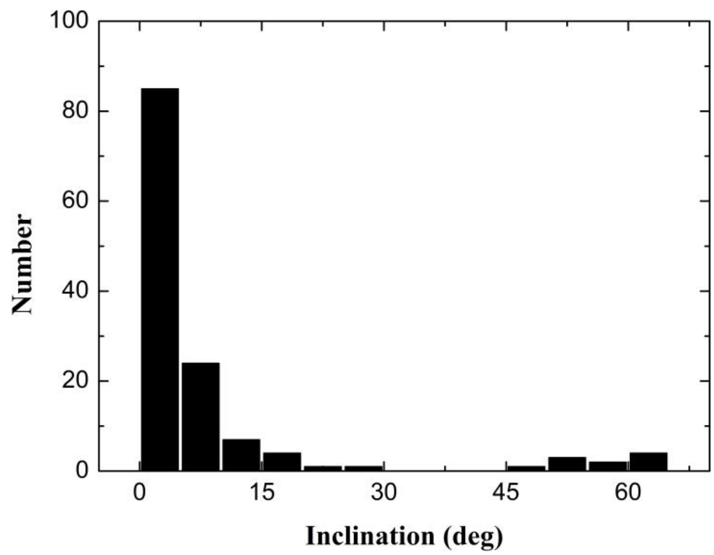

Fig. 3. Inclination of the objects detected on 20180105.

Considering that our strategy surveys the fields periodically, surely a number of objects may be detected more than one time, which means one object exhibits several tracklets, it increases the effective arc length of observation and certainly helps to determinate the orbit and make the prediction more precisely. The number of the repeated observations is shown in Fig. 5. It is demonstrated that in average each object can be surveyed more than 5 times and a few objects can be observed 14 times at maximum. The distribution of the repeats and the eccentricity of objects is shown in Fig. 6. It indicates that objects in GEO region and Molniya region are more possible to be surveyed several times, which can be demonstrated from Fig. 7 as well.

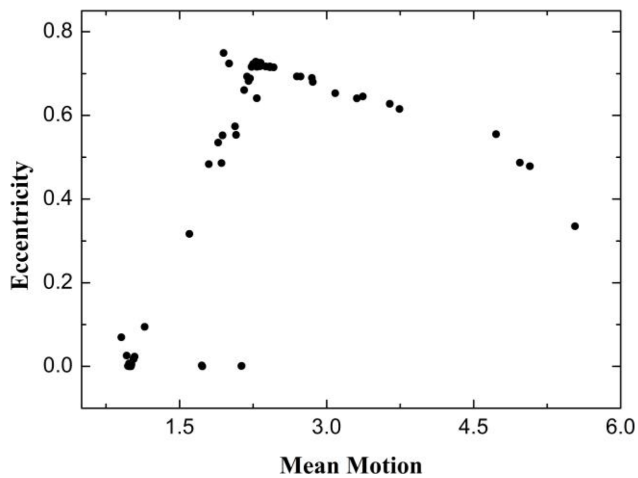

Fig. 4. Mean motion and eccentricity of the objects detected on 20180105.

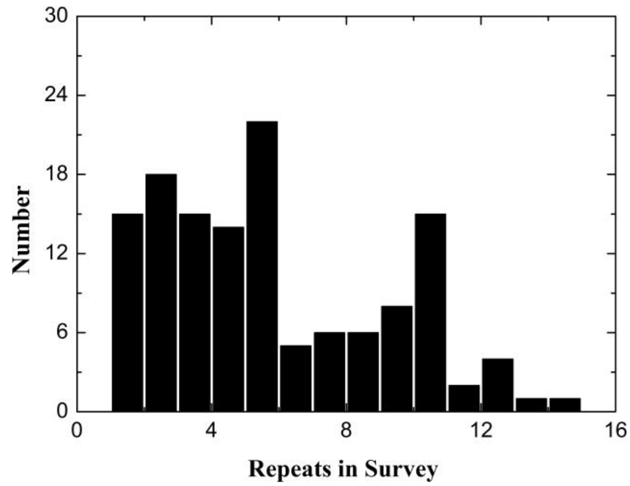

Fig. 5. Repeats of the observations of the objects detected on 20180105.

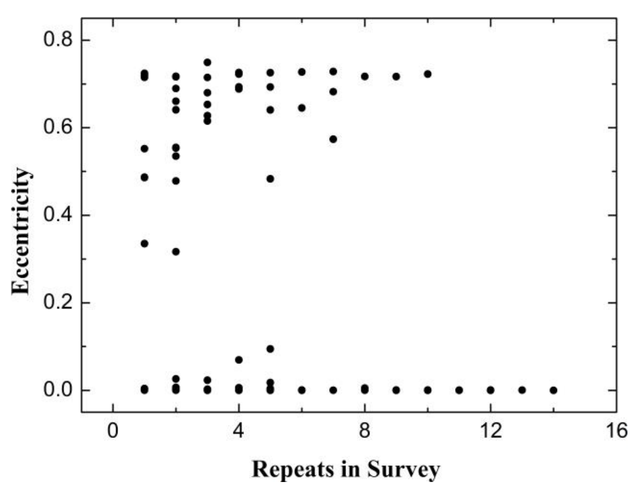

Fig. 6. Repeats of the eccentricity of the objects detected on 20180105.

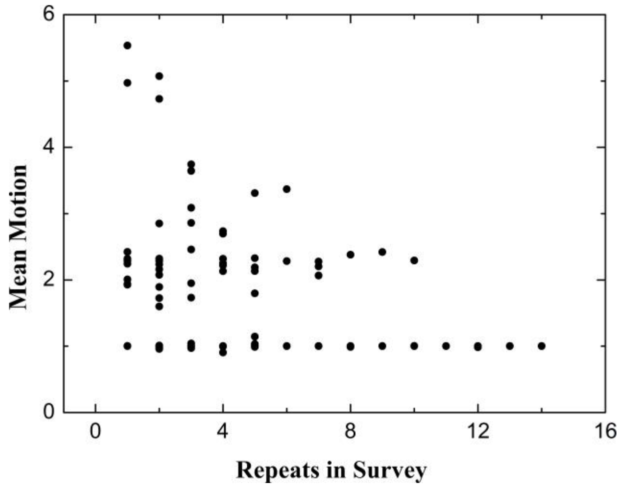

Fig. 7. Repeats of the mean motion of the objects detected on 20180105.

The distribution of the apparent magnitude for objects is shown in Fig. 8. The peak of the distribution is around 12. Due to a number of reasons the detection ability for faint objects is affected, e.g. the relatively short exposure and the impulse noises, the former is limited by the refracted optics which may lead to an extremely spread image in the frame under long exposure circumstance, and the latter is caused by the instability of the refrigerating system of the CCD camera. However, it should be noticed that with our effective strategy and pipeline, utilizing only one wide FOV telescope over 100 objects in high Earth orbital region can be routinely surveyed and catalogued, the results exhibit high correlation ratio and can be obtained in real time, the efficiency is evident.

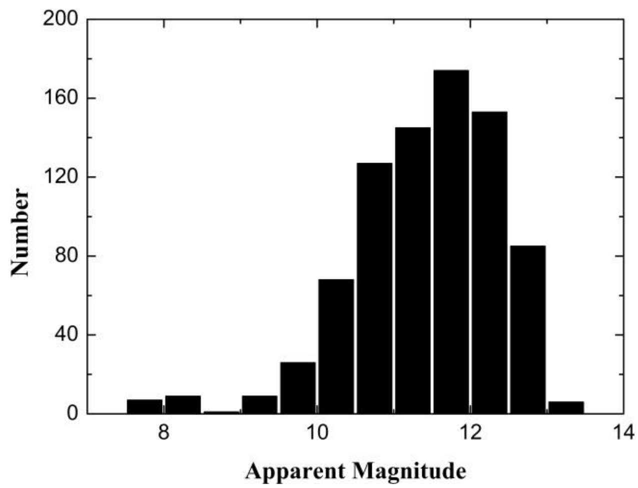

Fig. 8. Apparent magnitude of the objects detected on 20180105.

5. CONCLUSIONS

In our paper an optical survey for high Earth orbital region is performed with a wide FOV telescopes. Due to the 20 square degrees FOV of the telescope, the survey efficiency is promoted distinctly since several objects can appear in the frame at the same. In our survey, first the dynamical features of space object in high Earth orbital region are investigated and the survey regions are restrained accordingly, the strategy is proposed of which one includes 240 fields and takes about 4 hours. Improved image processing pipeline for detecting the objects from large amount of CCD frames with low false detection rate and in real time is developed. Trial observations are performed, it is demonstrated by the results that our pipeline exhibits a detection rate around 97\%, and more than 100 objects can be routinely surveyed and catalogued just utilizing one wide FOV telescope. The efficiency and optimization of our survey are further proved. Our research provided an efficient solution for optical survey of space debris in high Earth orbital region and surely it can be widely used in applications.

6. REFERENCES

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