Follow-up observatory for low Earth orbit objects with a detection algorithm using streaks

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ABSTRACT

Orbital object catalogue maintenance capability should be improved to correspond to future orbital environment because space objects population grows continuously. This paper proposes a follow-up observatory consists of uses of our new image-processing algorithm and the multi-telescope observation method. The algorithm enables to improve SNR of streaks by summing their signal intensities. The observatory applies the algorithm to recover SNR of objects unintentionally appeared as streaks in field of view. However, the improvement capability is limited to a square root of streak length as maximum, theoretically. The proposed observatory uses multi-telescope sets to recover rest of degraded SNR. The feasibility of the algorithm is confirmed by an application test to actual observation datasets. The test resulted that the algorithm enables to detect an object appeared with streaks darker than background noise, e.g. 0.66. This paper summarizes that the observatory can recover observation efficiency degradation due to unintentional appearance as streaks without on-site operation or complex instrument.

1. INTRODUCTION

Risks of orbital debris against current and future space development and its utilizations are continuously increasing due to accidents and experiments. There are several countermeasures to reduce the risks such as the core systems shielding by spacecraft's body, the collision avoidance maneuver and the active debris removal. However, it is required to understand current situation of orbital environment correctly to apply the countermeasures effectively and sufficiently. The requirement has motivated a study field called SSA (space situational awareness). SSA activities receive attentions from agencies such as ministry of defense [1].

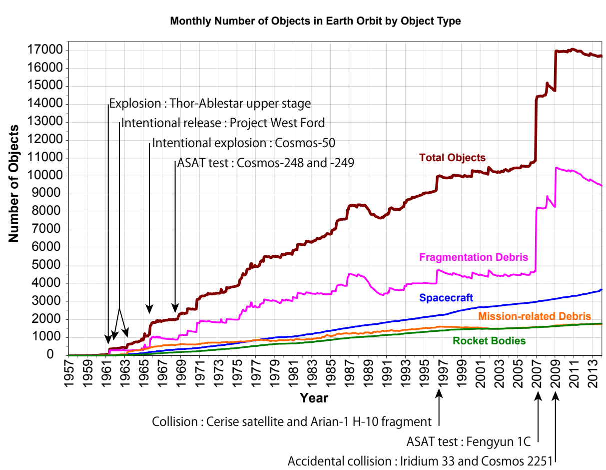

Fig.1. Historical growth of orbital objects number and major accidents and experiments on orbit

Orbital object catalogue maintenance is an important part in SSA activities. The catalogue maintenance capability should be improved to correspond to future orbital environment. Innovative technology research center (ITRC), Japan aerospace exploration agency (JAXA) conducts research and development in this field [2][3]. An optical observatory is a candidate methodology to improve catalogue maintenance capability. However, typical optical observatory requires on-site operations to keep a target into a pixel to achieve ideal observation condition because the target often moves in its field of view due to errors in preliminary determined orbit or telescopes motion especially for low Earth orbit (LEO) objects. This paper proposes a use of our new image-processing algorithm to solve the problem off-site, after observations, to correspond such LEO object observations.

An algorithm to detect objects by using their streaks in images is originally developed to enhance an effectiveness of optical observations. The algorithm improves a signal-to-noise-ratio of streaks of tens of pixels length by summing signals along expected direction of the streaks. There is a similar former study uses statistical method to detect streaks while the former study is for long streaks, e.g. 100~ pixels. It is confirmed that the algorithm enables to detect objects appeared with faint (weaker than background noise) streaks by an application test to GSO survey datasets.

The proposed observatory in this paper aims to recover a SNR of an object unintentionally appeared as streaks. A multi-telescope use is also proposed to recover SNR more.

2. OBJECT DETECTION ALGORITHM USING FAINT STREAKS

Orbital objects often appeared as streaks for optical observation and it causes signal intensity degradation because the signal is divided into pixels. Our new algorithm improves a signal-to-noise-ratio of a streak using its divided signal.

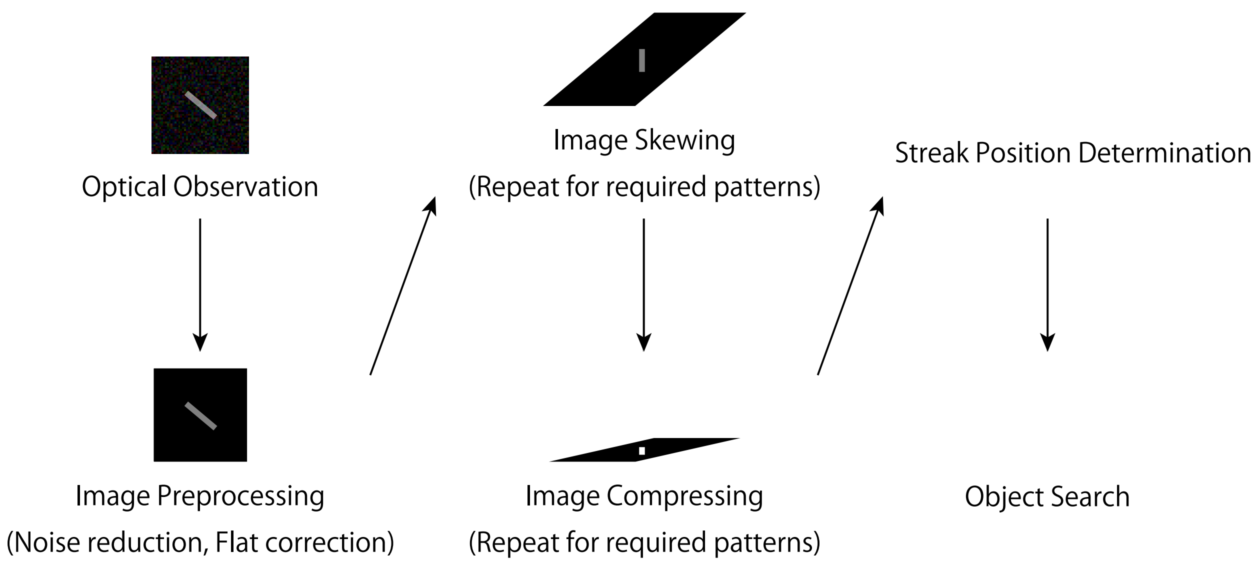

Fig.2. Object detection flow-chart using our algorithm

Fig.2 represents conceptual flow of our object detection algorithm using streaks. The algorithm preprocesses time-series images taken by an observatory, firstly. The preprocess sequence reduces noises and correlates flat pattern for each image. A key of our algorithm is signal summation along streaks to improve their signal-to-noise-ratio. Our algorithm morphs images to achieve the signal-to-noise-ratio improvement. The image morphing consists of two parts; one is skewing and the other is compressing. The image skewing part intents to plumb the streak to ease the compressing part. The image compressing part sums each pixel's intensity along vertical axis with defined summation window width. If background noise of each image can be treated as ideal Gaussian noise, the compressed streak's signal-to-noise-ratio is improved with proportional to a square root of the summation window width, practically. The theoretical limitation of SNR improvement is limited to a square root of length of a streak. In short, compression with 9 pixels window width makes a signal-to-noise-ratio 3 times greater, theoretically. These image-morphing parts enable to discover a faint streak, however, the image compression part degrades resolution of images. Therefore, position information of the streak is also degraded.

The degraded position information should be recovered to search and detect objects by our algorithm. Our algorithm applies moving average function to neighbor pixels of roughly determined streak position.

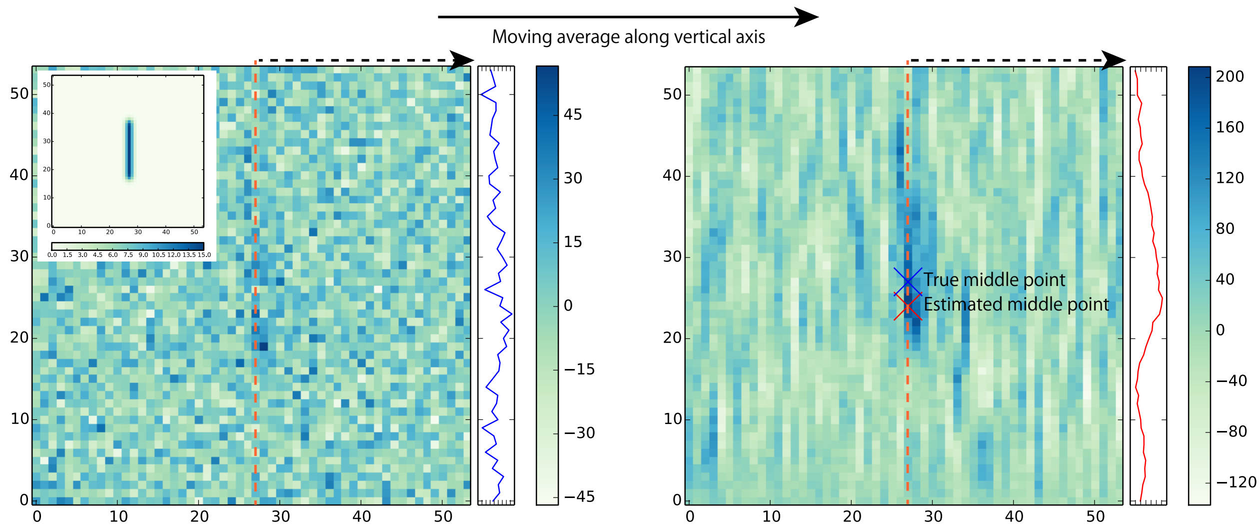

Fig.3. Streak position determination by applying moving average function

Fig.3 shows an example of the streak position determination using moving average function. The example based on theoretically generated background noise and a faint streak. Shape and position of the faint streaks is shown in upper left of left figure. The faint streak's signal intensity is assumed as 1.0σ (standard deviation) of background noise. The blue fluctuating line represents signal intensity of neighbor pixels. It is impossible to determine the streak's position using such noise dominant data. Even for such faint streak, the skew and the compression steps can determine its approximate position. The right image of Fig.3 represents moving averaged result of the generated image. The red smoothed curve is signal intensity of neighbor pixels. It can be seen that averaged signal intensity rises around the streak position. By using this averaged signal's transition and window size of moving average, the middle point of the streak can be determined. In this test case, the streak's position is determined with 3 pixels error in vertical axis. This error corresponds to tens of arcsec for telescopes owned by ITRC/JAXA.

These steps obtain estimated position for each streak candidate in each image. The next step is the object search using these 3 dimensional (x, y, t) dataset. It is assumed that objects move as linearly and uniformly in images.

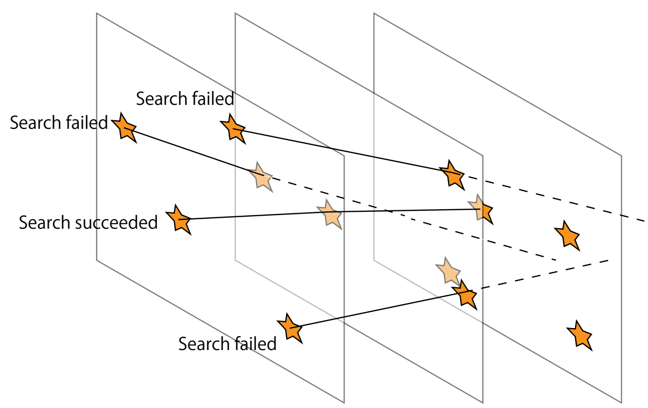

Fig.4. Object search concept

Fig.4 is the conceptual diagram of the object search step. This object search step discovers sets of points move as close to linear and uniform motion. However, there are many false discoveries of streaks because the threshold is set to search object appeared with faint streaks. This step applies criteria to choose more probable object search result. The applied criteria are number of estimated point correlated to an object candidate, linearity and uniformity of motion. The minimum criterion of the number of estimated points in a candidate is 9. The linearity and uniformity criteria are assumed by "tolerance-box" in the search. The tolerance-box tolerates horizontal and vertical position errors from predicted position for ±1 and ±5 pixels, respectively. It should be noted that this object search step allows stepping-stone-like appearance of streak positions.

The feasibility of this object detection algorithm is confirmed by application test to actual observation datasets. An observatory called Australia remote observatory (ARO) acquired the dataset. Its field of view was 3.17 degrees square and resolution was 5.6 arcsec. The observation date is 7/Jun./2013. The primary target of the observations was a geosynchronous orbit object. The skew angle pattern is assumed as 21 cases between -16.0 and 16.0 degrees from vertical direction (almost equal to North-South direction), and the compression window size pattern is assumed as 9 and 18 pixels. The threshold value for each compression window size is assumed as 2.0 σ.

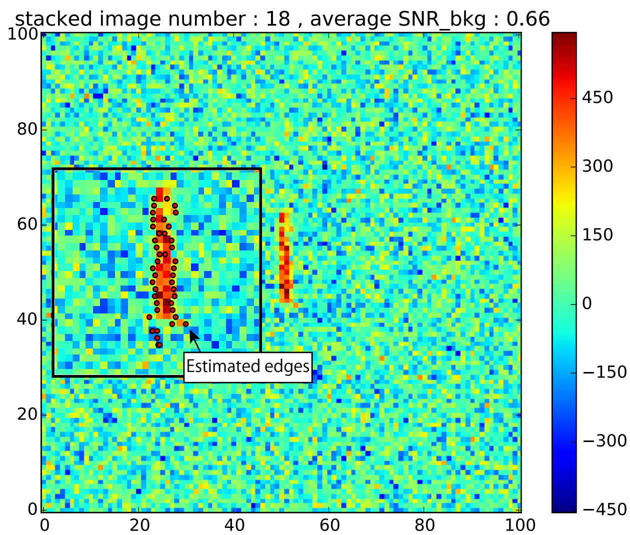

Fig.5. A stacked image around detected streaks correlated to a MEO object

The application test results that we can detect objects appeared with streaks darker than 1.0 σ as exemplified in Fig.5. Fig.5 represents a stacked image of all 18 frames with a central focus on estimated streak position in each frame. Edges of the stacked streak are estimated to calculate an average SNR of each pixel in each image. The detection is correlated to a mid Earth orbit (MEO) object COSMOS 2456. Its apparent magnitude is estimated as 10.56. While the estimated magnitude is relatively bright to ARO, its signal is divided into tens of pixels. Therefore, each pixel's SNR is too low to detect by our conventional detection method.

3. A FOLLOW-UP OBSERVATORY CONSISTS OF MULTI-TELESCOPE SETS

A follow-up observatory should try to keep a target in a pixel during an exposure to observe the target in ideal condition. However, a target can move in field of view because of errors in preliminarily determined orbit and it degrades SNR of the target's appearance. While our image-processing algorithm can recover the SNR, it is still degraded because the SNR improvement capability is limited up to square root of the target's streak length. Therefore, this paper introduces a use of multi-telescope to recover the degraded SNR more.

A signal-to-noise-ratio of an observation can be improved by combining multi-frames that focused into the same region at the same time. This improvement capability is based on that noise profile in the each frame differs. This is a same concept of the PAN-STARRS observatory [5] and it enables to improve SNR with a proportional to the number of telescopes. The proposed follow-up observatory is assumed to consist of two sets of such multi-telescope.

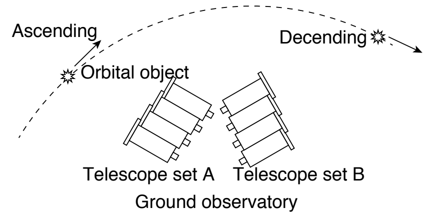

Fig.6. Concept of the follow-up observatory

Fig.6 shows the concept of the proposed observatory. Each multi-telescope set is introduced into apparent ascending or descending region after target's ephemerides are provided. After the first introducing, both of sets are assumed as being fixed. It enables to operate observations with relatively simple instruments. As mentioned, this observatory focuses on follow-up operations. Therefore, we should try to keep the target into a pixel to achieve ideal observation condition at first. However, the target can move because of errors in orbital information or orbit perturbations. The proposed observatory recovers such unintentionally moved objects by applying the image-processing algorithm introduced in this paper. Even if the objects appeared with four pixels length streak, its SNR can be recovered close to SNR of ideal observation condition by using the algorithm and four-telescope sets, theoretically. As an initial conceptual study, it is concluded that the proposed combination concept of the algorithm and the multi-telescope can improve observation efficiency degradation caused by objects' unintentional appearance as streaks. It indicates that the follow-up observatory does not require complex instrument or on-site operation to track an object by turning telescope to achieve ideal observation conditions.

4. SUMMARY

This paper introduced a new concept of orbital objects follow-up observatory. The observatory combines the use of the new image-processing algorithm and the multi-telescope method. The feasibility of the algorithm is confirmed through the application test to actual datasets. The application test resulted that the algorithm enables to detect objects appeared with streaks even each pixel in streaks is darker than background noise. The algorithm improves SNR of streaks with proportional to square root of summation window width. The multi-telescope method, the other key of the concept, can also improve SNR by taking images of same region by telescopes. As an initial conceptual study, it is summarized that the proposed follow-up observatory enables to recover SNR of unintentional appearance of streaks.

5. ACKNOWLEDGEMENT

This work was supported by Grant-in-Aid for JSPS Fellows Number 264297.

6. REFERENCES

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