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DETECTING GEO DEBRIS IMAGES VIA VOTING OF MOTION TRAJECTORY FEATURES

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In this work, we propose a novel technique to detect and track images of debris on Geosynchronous Earth Orbit (GEO). As for ground-based observations using high-resolution CCD camera, some effective techniques have been proposed to detect and track the debris images for the GEO region in the past studies. Most of them treat stepwise methods starting at image preprocessing, such as binarization, noise removal, etc. However, image preprocessing algorithms sometimes need to adjust the parameters included in them in arbitrary manner, and they may cause enormous computational time or removal of faint and small debris images. In this study, aiming at more directly estimating debris trajectories from the original time-series imagery, a detecting and tracking method for the debris images based on a voting algorithm is proposed. Focusing on a search observation approach, most of the stars and the debris on GEO appear to be point-like in the image frames, and the trajectories of them are approximated to be line segments in the spatiotemporal domain for relatively short time slot. While the star images are more populous and brighter than the debris images in the image frames, their motion trajectories are more distinguishing than the trajectories of debris images. Therefore, considering such characteristic motions of the celestial objects in the image sequence, the star images are effectively removed by a histogram voting. Consequently, the exact debris images can be detected as the trajectories which linearly move in constant velocities in the group of the remaining debris candidate objects. The effectiveness of the proposed method is validated through a test measurement using real image sequences.

I. INTRODUCTION

Recent years, some ground-based and space-based approaches to measure distribution of space debris have obtained a reliable orbital debris environment model for the Low Earth Orbit (LEO) region. On the other hand, for the Geosynchronous Earth Orbit (GEO) region around the altitude of 36,000 km, the distribution of the objects including micro-debris under 10 cm has not been estimated sufficiently.[1],[2]

Focusing on the ground-based measurement, a couple of methods to detect and track GEO debris images using efficient image processing techniques have been proposed in the past studies.[3],[4],[5] Most of them treat stepwise methods starting at image preprocessing. However, image preprocessing algorithms sometimes need to adjust particular parameters in arbitrary manner. For example, in a stacking method,[3],[4] medians of luminance values for local block image containing a faint object are calculated from a series of the image frames. This process eliminates noise signals and unexpected bright star images, which finally makes the locations of the debris images clear. Since it needs to consider unknown motion of the debris in the image frame, computational load usually becomes enormous while applying a random search algorithm.

On the other hand, debris tracking methods such as a line-identifying technique[3],[4] and an optical flow algorithm[5] more effectively detect debris image motions as long as the debris images appear in two sequential image frames. However, these methods can lead to false detection unless the numbers of the debris candidate ob-

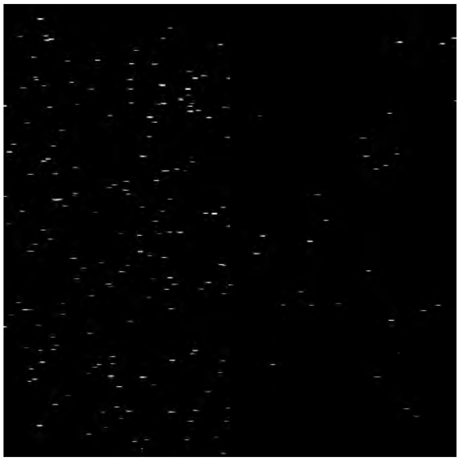

Fig. 1: A binarized image frame taken from a search observation.

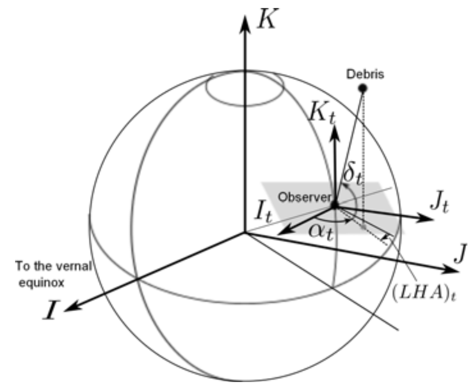

Fig. 2: A topocentric equatorial coordinate system $(I_t J_t K_t)$. α_t, δ_t, and $(LHA)_t$ describe the right ascension angle, the declination angle, and the local hour angle in the topocentric coordinate system, respectively. IJK shows a geocentric equatorial coordinate system.

jects are sufficiently reduced in advance by a binarization and removal algorithm for irrelevant stellar images. While applying those preprocessing algorithms, a threshold value for the binarization and shape parameters to detect star images should be carefully adjusted so that they neither cause much computational load to process enormous number of the objects nor remove faint and small debris images.

In this work, we propose a novel technique to detect and track images of debris on Geosynchronous Earth Orbit (GEO). Aiming at more directly detecting debris trajectories from the original time-series imagery, we derive a method based on a voting algorithm.

As shown in Fig. 1, the most populous objects seen in the observation image frames are the star images. Since they have unique characteristic properties for the direction of motion and the displacement in the image frames, they can be removed through a statistical processing utilizing the amount of the characteristics. Also, the exact debris trajectories can be detected by statistically evaluating the object displacements between two continuous image frames.

In the rest of this paper, after describing the characteristics of the GEO debris motion in image sequence, a stepwise method to remove the irrelevant star images and to detect exact debris trajectories in an observation image sequence is proposed. Finally, a measurement test is conducted using a series of real image sequences to validate the effectiveness of the proposed method.

II. OBJECTS MOTION TRAJECTORIES IN OBSERVATION IMAGE SEQUENCE

This study treates a search observation approach to observing GEO debris. A series of observation images are taken for the same area with a telescope fixed in a topocentric, Earth-fixed coordinate system, which is equivalent to a topocentric equatorial coordinate system [6] described in Fig. 2. If GEO debris is defined as an object not exactly on geostationary orbit but around it, its camera image taken in the above coordinate system appears to be point-like for small exposure time, and moves across the night sky images depending on its actual orbital elements. At the same time, trajectories of the debris images depict line segments in a short time range as shown in Fig.3, and slope angle of the line segment varies with each debris.

On the other hand, the same image frames include many irrelevant objects such as the stars and the noises added during image processing. The most populous objects are the star images which are relatively bright and large ones scattering around the image frames as shown in Fig. 1. In the case of the search observation approach, while trajectories of the star images are also linear, the slope angles of the trajectories are almost the same because they are approximately fixed in

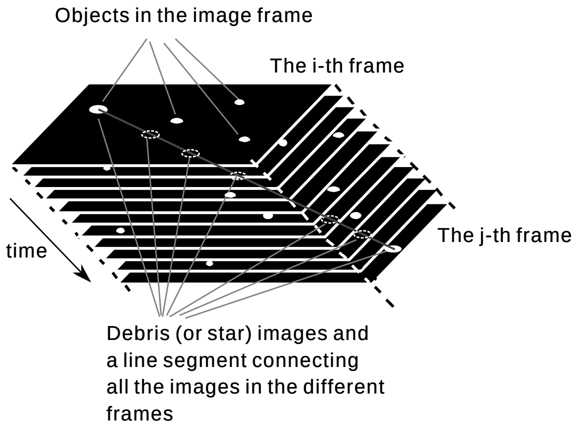

Fig. 3: A linear trajectory of debris or star images depicted in the spatiotemporal domain.

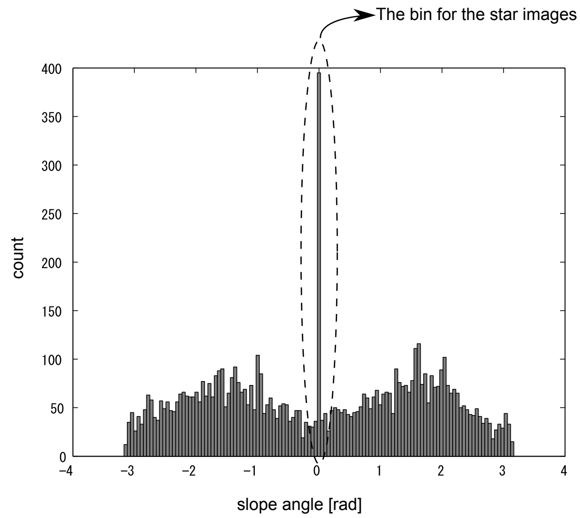

Fig. 4: The histogram to detect the star images based on the slope angles of the linear trajectories of the labeled image objects.

the earth-centered referential coordinate system in relatively short span of time and motions of the star images only depend on the earth rotation. Therefore, the star images can be identified considering their characteristics in image motion.

III. A VOTING ALGORITHM TO DETECT DEBRIS TRAJECTORIES

Considering some characteristics of the object motion in the image sequence, a stepwise method to detect GEO debris trajectories is proposed. It consists of four steps as follows:

STEP 1: A binarization is conducted based on a threshold luminance value for all the frames in an image sequence. Then, after labeling the binarized images, centroid coordinates for all the labeled images are computed.

STEP 2: For the labeled image objects obtained in STEP 1, all the line segments between any two objects on different image frames are identified, in which more than three objects from different image frames are included.

STEP 3: A histogram is computed for slope angles of the line segments identified in STEP 2, then the objects on the line segments corresponding to the peak value are removed from the list of the debris candidates. (See Fig. 4)

STEP 4: For the remaining line segments after STEP 3, means and standard deviations (σs) of the displacements between two objects in continuous image frames are computed. Then the line segments for the exact debris trajectories are detected by measuring that all the object displacements on the line segment lie within 1σ of the mean. (See Fig. 5)

In the above algorithm, STEP 1 shows a typical image preprocessing, and STEP 2 describes a conventional line-identifying technique[3],[4]. As for STEP 1, the past studies need to select an appropriate threshold luminance value so that they neither increase the number of the objects to process nor remove faint and small debris images. Also, in an extra step which is not included in the proposed method, they need to adjust parameters to remove all the star images considering their sizes in pixels and (ellipsoidal) shapes of the images. The parameter adjustment based on the object sizes and shapes is usually arbitrary and it not only requires effort of readjustment but also may remove necessary pixel data for the debris images during the processing.

In contrast to the past studies, the proposed method removes the star images by voting for their motion directions as shown in STEP 3. Furthermore in STEP 4, through a statistical eval-

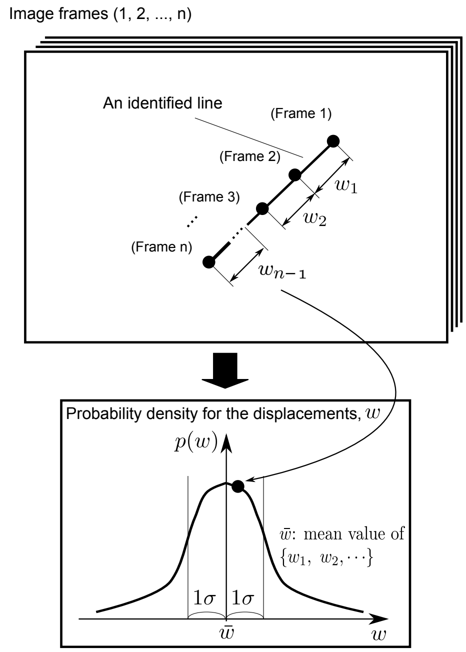

Fig. 5: The statistical evaluation to detect the exact debris trajectories.

uation, only reliable line segments corresponding to the exact debris trajectories are detected.

Since STEP 3 and STEP 4 in the proposed method don't contain adjustment of arbitrary parameters and are independent from the way to select the threshold value in STEP 1, the results are more reliable than those from the previous methods.

IV. TEST MEASUREMENT USING REAL IMAGE SEQUENCE

In order to validate the effectiveness of the proposed method, a test measurement was conducted by applying a series of real image sequences. The observation conditions are shown in Table 1. For this test measurement, ten data sets called "A","B", $\cdots$, and "J", in which exact debris images were previously detected by Japan Aerospace Exploration Agency (JAXA) were treated. When the proposed stepwise method was applied to these data sets, the threshold values for the binarization in STEP 1 were set so that the remaining number of the pixel data was less than 2.0×10^4 except that it was less than 1.0×10^4 for Data set A, considering the

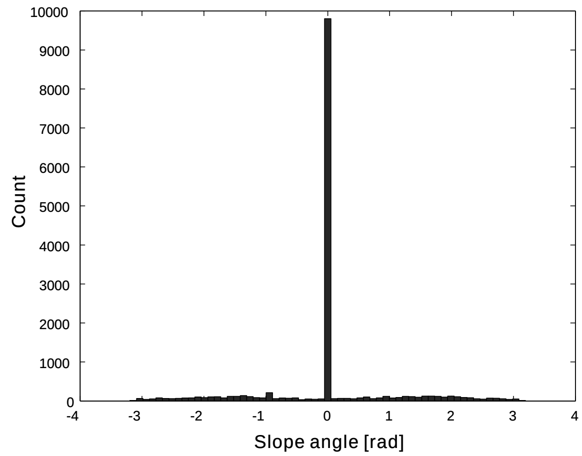

Fig. 6: The histogram for the slope angles of the line segments (Data set E).

density of the image objects included in the image frames. In STEP 4, even if an image object was missing in some image frames on the same identified line segment (which can occur because of blinking of the debris, incidentally disappearing during the image processing, etc.), the object displacement between the continuous image frames was computed assuming that the object has constant velocity on the linear trajectory.

Table 2 shows the number of the line segments identified in the image sequences after the processing in STEP 2, STEP 3, and STEP 4, respectively. Fig. 6 shows a histogram for the slope angles of the line segments identified in Data set E, in which the transverse axis is divided into 61 bins for the range between -2π [rad] and 2π [rad].

As shown in Fig. 6, a peak value is seen around a slope angle of zero radians since the camera is fixed in the topocentric equatorial coordinate system, which implies that the fixed stars relatively move parallel to equatorial plane, that is, almost all the star images move horizontally in the image frames.

Table 2 describes that the number of the line segments decreases by eliminating the ones corresponding to the trajectories for the star images in STEP 3. It still decreases as a function of the number of the exact debris trajectories in STEP 4. We should note here that the number of the finally obtained line segments is not necessarily equals the one of the detected debris images because the algorithm of the line-identifying tech-

Table 1: The observation conditions at JAXA's Mt. Nyukasa optical observation facility.

Observation site (WGS84)	JAXA Mt. Nyukasa Observation Facility Latitude: 138°10′18″E Longitude: 35°54′05″N Altitude: 1870 m
Specification of CCD camera	CCD format: 2048×2048 pixels Pixel scale: 2.25” Field Of View: 1.28 deg×1.28 deg,
Observation period	2010/3/13-19, 11:00-19:00 UTC (20:00-28:00 JST)
Observation zone (The equatorial coordinates for the image center)	RA: 113.88-120.48 deg, Dec: 7.97-8.95 deg
Frame-to-frame time	Approx. 14 sec/frame (Exposure: 3 sec, Read-out time: 11 sec)
The number of the frames for each image data set	18 frames/set

Table 2: The number of the line segments identified after each step in the proposed method.

Data set	STEP 2	STEP 3	STEP4
A	25634	23360	32
B	17140	6868	108
C	8762	1480	133
D	9230	1940	41
E	14673	4868	131
F	13459	4473	127
G	14118	4369	125
H	71774	64399	22
I	14825	4998	193
J	18321	7149	68

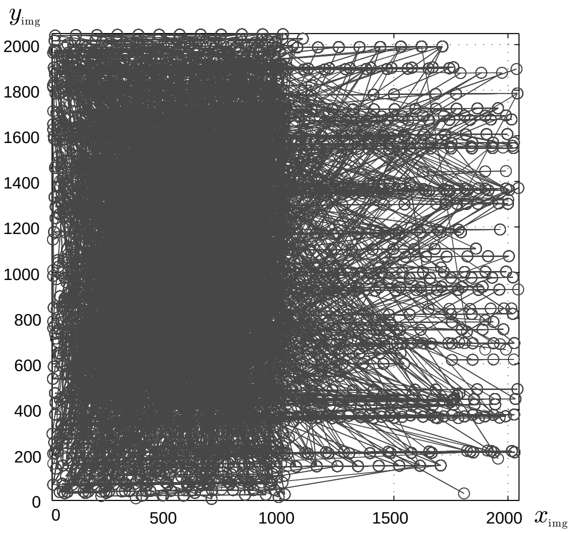

Fig. 7: A result from the processing in STEP 2 (Data set E).

nique counts all the line segments between any two objects in the different image frames which can overlap for the same debris trajectory.

Fig. 7 shows identified line segments in STEP 2 for Data set E. As shown in this figure, because of enormous number of the identified lines, it is impossible to find the exact debris trajectories by visual measurement at this step.

Figs. 8 to 11 show results of the line segments finally obtained from the proposed method for the data sets A, E, G, and I, respectively. All of them show the exact debris trajectories, which were identified in the past measurement approaches. On the other hand, only one trajectory which was previously detected is missing for the data sets E and G, and also one false trajectory is found for Data set A.

For the other data sets applied to the test measurement, all the exact debris trajectories are detected as in the past studies. Different from the results of the conventional line-identifying technique, false detections are not seen in the results of the proposed method except for Data set A.

V. DISCUSSION

While the effectiveness of the proposed method is shown in the previous section, some issues still remain. One is concerned with the missing debris trajectories which were detected

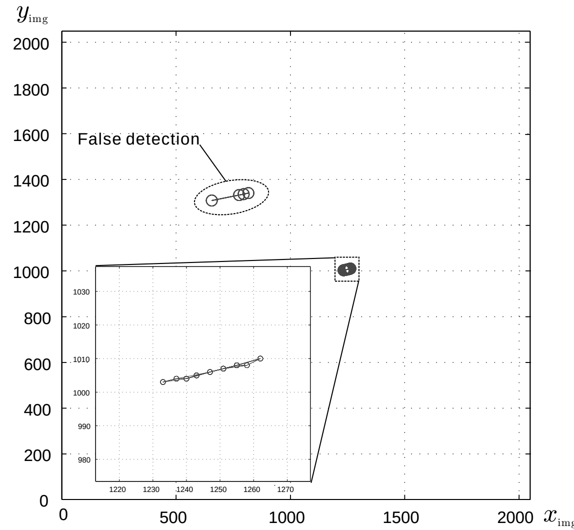

Fig. 8: A result of the test measurement of Mt. Nyukasa image sequence for Data set A. The series of the circles show the trajectories of the objects detected in the CCD image coordinates.

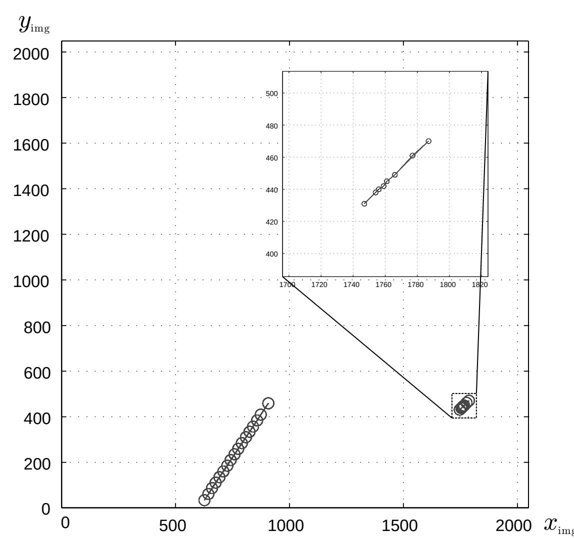

Fig. 9: A result of the test measurement of Mt. Nyukasa image sequence for Data set E. The series of circles show the trajectories of the objects detected in the CCD image coordinates.

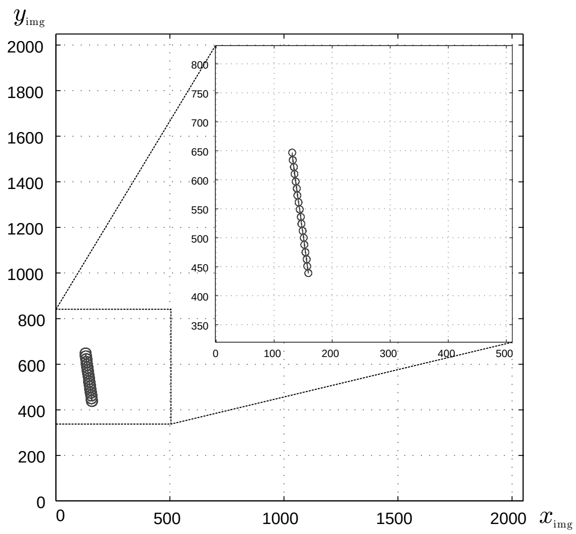

Fig. 10: A result of the test measurement of Mt. Nyukasa image sequence for Data set G. The series of circles show the trajectories of the objects detected in the CCD image coordinates.

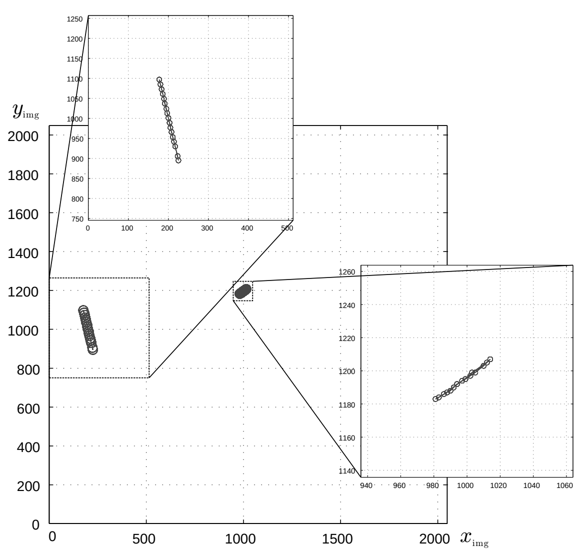

Fig. 11: A result of the test measurement of Mt. Nyukasa image sequence for Data set I. The series of circles show the trajectories of the objects detected in the CCD image coordinates.

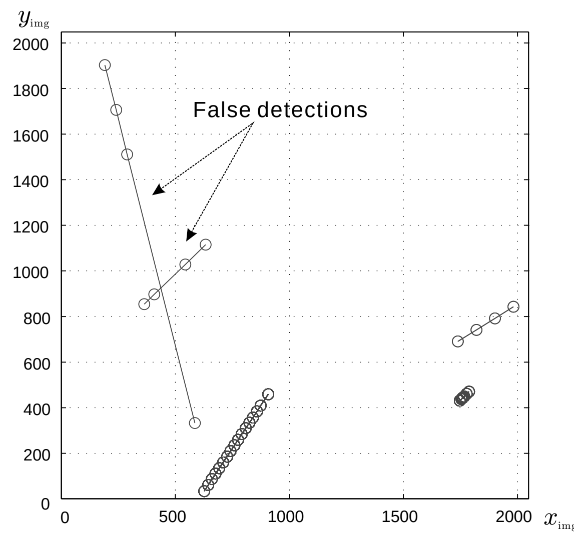

Fig. 12: A result of the test measurement for Data set E (obtained after the parametric relaxation).

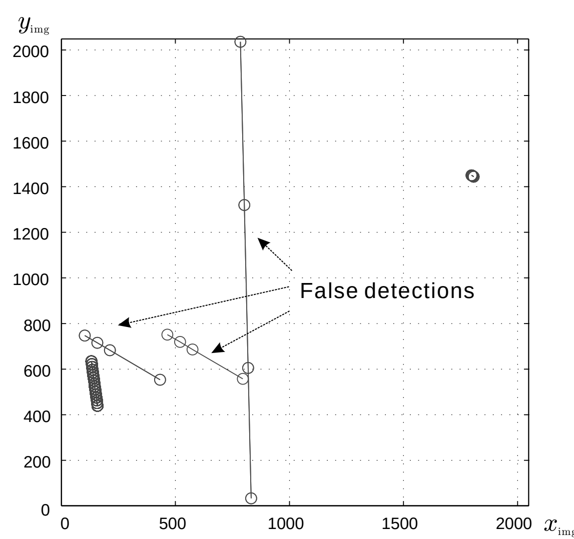

Fig. 13: A result of the test measurement for Data set G (obtained after some parametric relaxations).

in the past approaches. As for the debris trajectories missing in the data sets E and G, they have a couple of unique properties which are not seen in the other data sets. For those two data sets, the debris appear in few image frames (not more than four among eighteen frames). Especially for Data set G, the debris image irregularly appears (at intervals from one to five frames) in the image sequence. The trajectories for such debris images can be detected by relaxing some statistical constraints in STEP 3 or in STEP 4. For example, in the case of Data set E, if the limit of the range to evaluate the reliability in STEP 4 is changed from 1σ to 3σ, the missing trajectory is detected, which is shown as the one containing four objects around $1700 \leq x_{\mathrm{img}} \leq 2000$ in Fig. 12. In the case of Data set G, the missing trajectory can be detected if the other relaxation on a statistical constraint is applied adding to the previous one. In the above test measurement, the binarized image occupying only one pixel was removed considering the possibility of unreliable image noise. After relaxing this constraint, as shown in Fig. 13, the exact trajectory in the range around $1700 \leq x_{\mathrm{img}} \leq 1800$ is detected. Unfortunately, in the both cases, the performances of detecting the debris trajectories are not necessarily improved because the false detections increase in response to the constraint relaxations.

VI. CONCLUDING REMARKS

This work proposes a novel technique to detect and track images of debris on GEO. Different from the past methods to detect the GEO debris in the image sequence, the proposed method does not need to adjust certain arbitrary parameters during image preprocessing. The effectiveness of the proposed method was validated through the test measurement applied to the real image sequences.

In order to improve practical performance, the issues on accuracy for the finally obtained debris trajectories should be discussed in future work.

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